Developing a method for quantifying transport interdependencies

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Abbreviations and acronyms

CC	corridor criticality
CIrcle	Critical Infrastructures: Relations and Consequences for Life and Environment
GIR	geographic interdependency rating
ICE	Institution of Civil Engineers
ICT	information and communications technology
ISO	International Organization for Standardization
MC	maximum criticality
MERIT	Measuring Economically Resilient Infrastructure Tool
ONRC	One Network Road Classification
UoA	University of Auckland

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Executive summary

Our modern society is becoming increasingly reliant on transportation networks, as well as the interdependent infrastructures and technologies that interact with them. Given this reliance, maintaining uninterrupted service is a key objective for infrastructure owners and operators. This requires a particular focus on building resilience to hazards that have potential to affect the functioning of infrastructure, including both natural and man-made hazards. Building resilience requires an understanding of the complex relationships between transportation networks and their interdependencies. This understanding can then provide a rationale for strategic interventions to inform transportation network risk management.

From late 2019 to mid-2020, Waka Kotahi NZ Transport Agency engaged Tonkin & Taylor Ltd and XDI Pty Ltd to undertake research in New Zealand into critical infrastructure interdependencies in relation to the transport network and ways these could be understood and assessed better. The key objectives of the research were to build on the existing body of knowledge defining the interdependencies; identify and review existing methods, tools and platforms for assessing infrastructure interdependencies; develop a methodology to assess interdependencies relating to the transport network and wider infrastructure; and enable the identification of a range of potential 'treatment options' that would allow better management of interdependencies.

Interdependencies

A dependency exists when one infrastructure system has a direct impact on the performance of another infrastructure system. An interdependency occurs when there is a mutual connection between the two systems, a bidirectional relationship through which the state of each infrastructure influences (or is correlated to) the state of the other. For the purposes of this research, the term interdependency has been used when discussing both dependencies and interdependencies.

While interdependencies may appear conceptually simple, their relationships can be very complex, especially within complex infrastructure networks. To support the classification of interdependencies, four distinct typologies were identified from the literature: physical, digital, geographic and organisational. In addition, three dimensions have been used to characterise them: order (relating to the number of 'cascades' in a downstream direction), directionality (either unidirectional or bidirectional), and strength (referring to the level of impact on a downstream infrastructure caused by the failure of an upstream infrastructure).

Review of existing models

Several existing interdependency assessment approaches/methods were reviewed to identify those that might be most appropriate for application within the transport sector:

- CIrcle Tool – Deltares
- XDI Platform – XDI Pty Ltd
- University of Auckland (UoA) Infrastructure Interdependency Model – UoA
- MERIT – GNS Science/Market Economics/Resilient Organisations
- DOMINO – Polytechnique Montréal.

The review found that each of the models had a different purpose and associated strengths and weaknesses. None of the tools adequately addressed all the key interdependency typologies identified, nor did they evaluate interdependencies incorporating criteria such as strength.

Proposed interdependency, criticality and risk assessment approach

An approach to assess interdependencies that aligned with the review and addressed the gaps within the existing tools and platforms has been developed. Importantly, the proposed approach links to a broader assessment of criticality and risk. A risk assessment can then allow the inclusion of, and integration with, other information such as hazard impacts and infrastructure vulnerabilities.

The proposed approach consists of a core module to assess interdependencies and criticality, with additional modules that can be added to assess hazards, vulnerability and risk. The core module is designed to accept the input of asset network data; allow the user to create linkages between interdependent networks; and evaluate interdependencies and link this to a ‘modified criticality’.

Given the focus on physical infrastructure (and the scope of this research), the proposed assessment approach focuses on physical, digital and geographic interdependencies. However, given the fundamental differences between these, the following two different approaches have been developed:

- Physical and digital dependency assessments: These both act in a similar, linear manner and have an associated strength, order and directionality. These typologies involve connectivity between infrastructures, with the output of an upstream infrastructure being the input to a downstream infrastructure. This assessment requires the development of an interconnected network across infrastructures and sectors and thereby allows the evaluation of the propagation of failure and outage.
- Geographic interdependency assessment: This typology occurs where there is co-location of multiple assets within a corridor. This is different in nature to physical and digital interdependencies; the interdependency exists because of the risk of failure of one infrastructure leading to the damage or failure of a nearby/co-located infrastructure. This is commonly known as an infrastructure ‘hot spot’.

Common to each approach is the input of a ‘base criticality’ score (based, for example, on the number of customers the infrastructure serves) and the generation of a ‘modified criticality’ score, which is an output from the interdependency assessment and reflects the influence of an interdependent relationship.

The proposed process for assessing physical and digital dependencies involves the following three steps:

- Step 1: Identify independent relationships and develop a causal network. This involves attributing all relationships with dimensions (eg base criticality and strength).
- Step 2: Calculate dependency rating and modified criticality. This uses a set of matrices to calculate a downstream dependency rating derived from its base criticality and strength of the relationship with the upstream infrastructure. The modified criticality of the upstream infrastructures is then calculated based on the maximum dependency rating and number of downstream dependencies.
- Step 3: Extend the modified criticality along the road network. This is to ensure that a modified section of road only connects to an equal- or higher-criticality road (along the shortest pathway to the highest-criticality road).

The proposed process for assessing geographic interdependencies involves the following three steps:

- Step 1: Establish corridors and identify geographically co-located infrastructures. This is achieved by dividing the primary infrastructure (eg roads) into equal intervals buffered by a set width to create corridors. All infrastructures are overlain to identify those within each corridor.
- Step 2: Determine the geographic interdependency rating (GIR). This is calculated as the sum of the criticality of all infrastructures within a corridor.

- Step 3: Determine the modified criticality for a corridor. This is calculated using a matrix that references the GIR with the maximum criticality (MC) within each corridor.

A pilot study for each of the two interdependency assessment approaches was conducted using data from the Queenstown-Lakes District.

Additional (optional) modules

As discussed above, the core interdependencies module (which is the focus of this research) could be integrated with a ‘hazard and vulnerability module’, a ‘risk and resilience module’ and an ‘economic impact module’. The hazard and vulnerability module would be used to assess the direct impact/damage occurring as a result of an external hazard. This module would involve the input and assessment of hazard data, combined with data relating to the infrastructure vulnerability to a given hazard, to estimate the level of impact or damage from a hazard.

The risk and resilience module would integrate outputs from the ‘core interdependencies and criticality assessment’ with the ‘hazard and damage’ module. This would assess both the direct risk to infrastructure and the propagation of outage and impact through dependent infrastructures. An economic impact module would utilise the output of the risk and resilience module to evaluate the cascading financial and economic losses resulting from disruption or failure of infrastructures.

Implementation

As with any conceptual methodology, the ability to implement it consistently and at scale across distributed networks is key. This would require the development of a geospatial platform or tool, a simple and effective visualisation process that could reference the geospatial data and be integrated within workflows to partially or fully automate the analysis. Effective methods of eliciting data from stakeholders (infrastructure owners/operators) would be important, as this would provide an opportunity to verify and validate the dependent infrastructure relationships and parameters.

Risk treatment toolbox and investment decision making

As per the ISO 31000 *Risk management – Guidelines* (International Organization for Standardization [ISO], 2018), risk treatment is a key step within risk management. Risk treatment involves the development of potential options to address priority risks and commonly includes one of the following four categories: avoid, mitigate, transfer and accept. The evaluation of a preferred option should follow a robust process, which may include cost–benefit analysis, multi-criteria assessment or real-options analysis. The choice of decision-making method will depend on the context and the quality of the data available.

Some example options for mitigating high risks are:

- improving the robustness of infrastructure, possibly by improving asset designs or materials
- constructing systems that can ‘fail safely’, allowing failure modes to be understood and controlled, leading to a reduction in the duration of an outage by enabling fast restoration of service
- providing additional redundancy within a network to reduce the strength of interdependencies (eg by providing an alternative connection/route or on-site backup)
- improving emergency management processes, including preparedness, response and recovery.

Summary and recommendations

The proposed interdependency approach developed in this study provides a practical and transparent method for infrastructure providers to understand and manage their critical networks better with regard to the hazards they face and the failures that may occur. The interdependency approach developed assesses both ‘physical and digital’ and ‘geographic’ typologies, using different methods. The output of the assessment is a modified criticality for infrastructure elements within the network that can support the development of risk treatment options.

A range of next steps or further developments are suggested:

- Pilot the proposed methodology presented with key stakeholders and potential end users. This would involve reviewing and refining the example tables/ratings/matrices within the assessment approach and testing sensitivity.
- Evaluate whether the proposed approach can be incorporated within the existing UoA model. This would require the inclusion of additional parameters such as strength and modified criticality.
- Develop a user interface to support operator use and collaboration.

Abstract

Our modern society is becoming increasingly reliant on transportation networks, as well as the interdependent infrastructures and technologies that interact with them. The increasing complexity and interconnectedness of infrastructure networks makes them susceptible to impact not only directly from external shocks but also indirectly from the failure of dependent infrastructures.

Simply put, an interdependency exists when one infrastructure has a direct impact on the performance of another. This research, which was conducted in New Zealand by Tonkin & Taylor Ltd and XDI Pty Ltd from late 2019 to mid-2020, builds on the current literature about infrastructure interdependencies, reviews the existing assessment tools, and based on the gaps identified, develops an approach to assessing interdependencies across two key typologies: physical/digital and geographic. These approaches are framed within broader concepts of criticality and risk management. Pilot studies demonstrate the implementation of the two assessment approaches.

The proposed approach generates interdependency and criticality ratings as outputs, which can then be used alongside natural hazard and infrastructure vulnerability data to assess risk and understand failure propagation within networks, as well as the wider consequences of failures and outages. This provides greater insight into the potential consequences of infrastructure failure, specifically with respect to dependent infrastructures. This knowledge, combined with an understanding of natural hazards and asset vulnerabilities, can support specific risk treatment responses, which in turn improves wider community resilience.

1 Introduction

Tonkin & Taylor Limited and XDI Pty Ltd were engaged by Waka Kotahi NZ Transport Agency to undertake research into critical infrastructure interdependencies in relation to the transport network to examine how these could be better understood and assessed. Ultimately, developing this understanding will contribute to developing a transport network and communities that are more resilient.

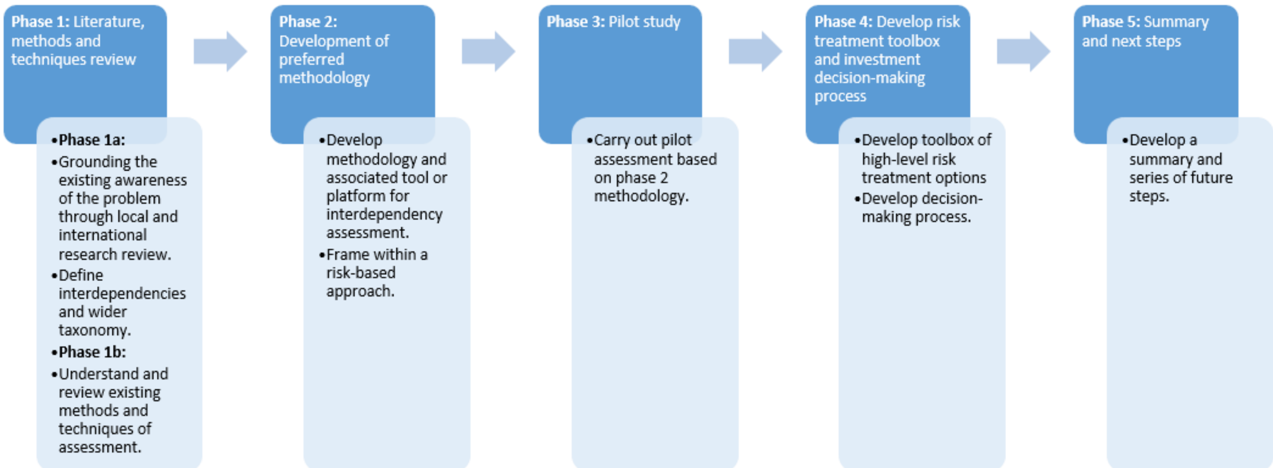
Specifically, this research aimed to:

1. build on the existing body of knowledge defining the taxonomy of interdependencies between transport and other infrastructure utilities
2. identify and review existing methods, tools and platforms to assess infrastructure interdependencies
3. develop a methodology to assess interdependencies of the transport network and wider infrastructure and demonstrate these within a pilot study
4. enable the identification of a range of potential ‘risk treatment options’ to allow better management of interdependencies.

The project consisted of the following five phases (summarised in figure 1.1):

- Phase 1a: Literature review and gap analysis
- Phase 1b: Methods and techniques review
- Phase 2: Development of preferred methodology
- Phase 3: Pilot study assessment
- Phase 4: Development of risk treatment toolbox and investment decision-making process
- Phase 5: Conclusions, summary and next steps

Figure 1.1 Project phases summary



2 Background

2.1 Why this research is needed

The value of New Zealand's road and rail network is estimated at NZ$80 billion (National Infrastructure Unit, 2015), and it serves a vital function within society: moving people and goods; connecting communities, transport hubs and critical facilities; and facilitating the tourism sector. When the relationships between the transport network and these other elements and sectors within the economy are factored in, the combined value of the transport network increases exponentially.

With the wide reliance on these transportation networks, the dependence on the infrastructures and technologies that support them, and the wide range of shock and stress events (natural or man-made) that can affect them, it is increasingly obvious that we need to:

- understand the complex relationships between the transportation networks and their interdependent systems and processes, particularly lifeline utilities, to increase overall operational resilience
- provide a rationale for strategic interventions to ensure better coordination, efficacy and outcomes from transportation network risk management measures.

Understanding the interdependencies and managing the risk of damage or failure (via natural or man-made hazards) are, therefore, a major priority for developing a transport network and communities that are more resilient.

The following are considered key drivers for an increased focus on risk and resilience within critical infrastructure (Hughes & Healy, 2014):

- increasing incidence of extreme events (including those exacerbated by climate change) that can affect infrastructure systems
- a growing realisation that our ability to predict hazards, failure and consequential impacts is limited, as seen in the occurrence of rare/'black swan' events (Taleb, 2010) or 'unknown-unknown'[1] events, in addition to 'known' hazard events
- increasing complexities of infrastructure networks and associated interdependencies, which can lead to unanticipated failures and far-reaching impacts
- increased community expectations relating to levels of service during both business-as-usual and post-event periods.

Each of these drivers is discussed in more detail below.

2.1.1 Extreme events

Globally, extreme events continue to cause damage and strain to infrastructure networks. The World Economic Forum's *Global Risks Report 2019* highlighted that the three highest risks facing the globe are extreme weather events, natural disasters and the failure of climate change adaptation and mitigation (World Economic Forum, 2019).

In North America, there have been five category 5 hurricanes in four years within the Gulf of Mexico. Hurricane Dorian's intensification to category 5 level marked the fourth year in a row the Atlantic basin has

[1] Unexpected risks that would not be considered.

had at least one hurricane reach that strength in the Atlantic, the highest number of consecutive years on record ('Hurricane Dorian', 2019).

While Hurricanes Imelda (2019) and Harvey (2017) were both category 4 events that affected the US states of Texas and Louisiana, they resulted in very different consequences. Imelda resulted in five casualties and US$5 billion of damage (Smith, 2020). Harvey was more catastrophic, resulting in more than 100 casualties and US$125 billion of damage, tying with Hurricane Katrina (2005) as the most financially destructive hurricane to hit the US (United States National Hurricane Center, 2018). The difference was because Harvey caused significant flooding in metropolitan areas such as Houston, whereas Imelda's high rainfalls and extensive flooding occurred in less densely populated areas. This demonstrates that the damage is not only a function of the hazard intensity but also what societal assets are exposed.

A further example is that of Hurricane Michael (2018). While it had a slightly lower pressure than Katrina, this did not necessarily mean that it was as damaging. Katrina (2005) reportedly claimed more than 1,000 lives because of infrastructure failures and the mismanagement of emergency resources, rather than because of its position on the record charts (Letzter, 2018). This highlights the need to focus on infrastructure resilience, both pre- and post-event.

In November 2019, Australia experienced record-breaking temperatures with high winds, which resulted in unprecedented wildfires across numerous states. These conditions are normally experienced in late summer; that is, February or March (Doherty, 2019).

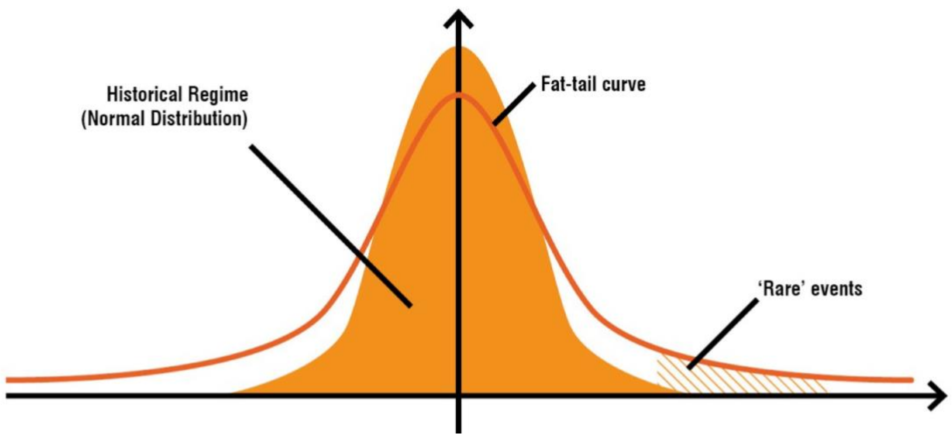
In New Zealand, the damage from events and associated infrastructure failures continues to cause severe impacts on communities, both directly and indirectly. Recent history includes natural hazard events that had a significant impact on the transportation sector, with significant consequences for communities and economies. For example:

- The 2016 Kaikōura earthquake resulted in loss of service to State Highway 1 from Picton to Christchurch (Davies et al., 2017). This initially led to severe effects to the New Zealand freight network, with lengthy delays in Auckland and Napier Ports due to the increasing volume of freight being transported down the country via sea, rather than road (Herbert et al., 2018).
- The 2019 washout of the Waiho Bridge at Franz Josef had significant regional impact on the tourism sector, with loss of business from visitors resulting in significant financial losses, as well as the damage to lifeline infrastructure located on the bridge resulting in downstream outages ('Waiho Bridge washes away', 2019).
- A 2017 landslip closed the Ngaio Gorge Road in Wellington, one of the main roads connecting the city with residential suburbs. This caused increased traffic on the limited alternative routes. It took 18 days to re-open two out of the original four lanes, restoring partial functionality (Wellington City Council, 2017).
- In 2017, landslips in the Manawatū Gorge resulted in the closure of State Highway 3 through the area. Freight trucks had to utilise alternative routes, leading to additional damage to roads that were not suitable for heavy vehicles (Lawrence, 2017; 'NZTA decides', 2018).
- The 2011 Christchurch earthquake produced landslips that closed Sumner Road, which was the key over-dimension road and dangerous goods route. The closure of the road reduced traffic volume in and out of Lyttelton Port and increased travel times for freight vehicles (Ellis, 2019).

2.1.2 Ability to predict events

There is a growing body of evidence that historical analysis of extreme events and their probability distributions fail to predict extreme events correctly. Historically, random extreme events were assumed to follow a normal distribution, with 95% of possible events falling within two standard deviations from the mean and 99.7% within three standard deviations. In fact, it is becoming apparent that events that may be at the extreme end of a normal distribution are occurring with much higher frequency than predicted, particularly those that are climatic and weather related (Berger et al., 2008; Mello, 2005). Not only is the frequency of these events often significantly underestimated but so is the damage they can cause. This can be seen in the 'fat-tail distribution' shown in figure 2.1.

Figure 2.1 Conceptual illustration of a fat-tail distribution (Hughes & Healy, 2014, p. 80)



Taleb (2010) named these rare events 'black swans' and developed three characteristics to describe them:

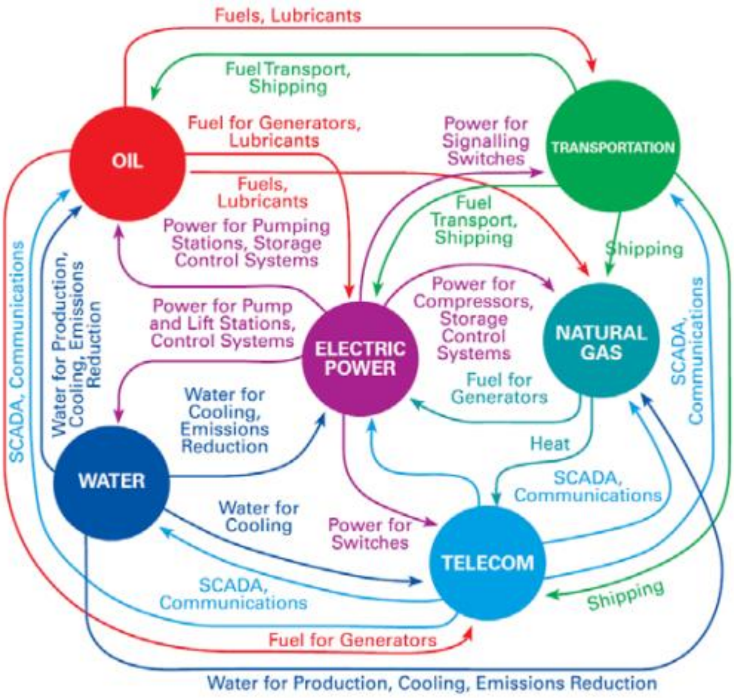
1. They lie outside the realm of regular expectations because nothing in the past can convincingly point to their possibility.
2. They carry an extreme impact.
3. Although they are outliers, people concoct explanations for them after the fact, trying to make them explainable and predictable.

2.1.3 Complex networks

Modern infrastructure networks are increasingly complex and interconnected. These interdependencies and their many dynamic and multi-dimensional parts necessitate a 'system of systems approach' (Croope, 2010; Kahan et al., 2009) to fully understand and assess where vulnerabilities lie and where resilience could be improved. This is illustrated in figure 2.2 and discussed further in section 3. While these complex, interconnected systems create benefits and efficiencies at times of normal operation, they also involve vulnerabilities and operational challenges, especially during unexpected circumstances or hazard events. Extensive analysis of complex engineering systems has revealed that in many cases, 'failure' is at best a statistical inevitability or, at worst, a part of 'normal' operation (Perrow, 1984).

Interdependencies can result in a wide range of potential failure modes and the emergence of previously unidentified hazards that can cause failure. Hollnagel (2011) categorised the range of failure modes as simple-linear (or cascade) failure, complex-linear failure (caused through hidden interdependencies or latent conditions) or complex-nonlinear failure resulting from the concurrence of unexpected events.

Figure 2.2 Complex interdependencies between infrastructure systems (Peerenboom et al., 2001; Rinaldi et al., 2001, p. 15)



SCADA = supervisory control and data acquisition

2.1.4 Increasing customer expectations

Generally, there is low customer tolerance for failures in systems during business-as-usual operations. Research has also shown that during events, customers expect a rapid service recovery time for certain critical sectors (Petersen et al., 2018). However, today's infrastructure systems are complex and interconnected.

Buller (2015) noted an 'expectation gap' between what the public *expects* infrastructure operators can provide following an event and their ability to do so. For example, Sperry (2013) found that most people expected telephone lines and electricity to be restored quickly after an event, even though this was not usually what happened. Similar expectations were found in US communities affected by Hurricane Sandy in 2012, where only a small percentage of the residents had anticipated they would be without electricity for a 'sustained period' (Baker et al., 2012).

2.1.5 Discussion

Providing resilient networks, along with the careful management of risk, is of central importance for infrastructure agencies, including those that manage transportation. To this end, Waka Kotahi has developed a key outcome that 'communities are less exposed to, and better prepared to deal with, the economic, physical, social, cultural and environmental impacts of risks and shocks from natural hazards and other disruptive events' (New Zealand Transport Agency, 2018b, p. 2).

The results of this research project can inform targeted, consistent management of risk to the transport network, which in turn may provide for improved allocation of funding and resources to identified areas of high risk. Understanding interdependencies is key to a risk-based approach through the establishment and prioritisation of critical points and sections of the transport network. The following sections describe in more detail some key concepts relating to interdependencies in the broader context of risk and resilience.

3 Key concepts relating to interdependencies

An understanding of three key concepts related to interdependencies and their relevance for infrastructure is required: resilience, risk and criticality. These are discussed in the next sections.

3.1 Resilience of infrastructure

Infrastructure is globally recognised as being a critical element for healthy economies and stable communities. It enables commerce and the movement of people, goods and information, and it facilitates society's daily activities. Croope (2010, p. 10) stated, 'Critical infrastructure not only responds to the needs of society for the smooth daily continuation of activities, but also provides the basis on which society exists and relies'.

Godschalk (2003) listed two reasons for the importance of resilience in infrastructure:

- Because the vulnerability of technological, natural and social systems cannot be predicted, the ability to accommodate change without catastrophic failure in times of disaster is critical.
- People and properties in resilient cities fare better during disasters. Fewer buildings collapse, fewer power outages occur, fewer businesses are put at risk and fewer deaths and injuries occur.

Societies increasingly rely on transportation networks for their daily activities. The ability of a transport system to function during adverse conditions and quickly recover to acceptable levels of service after an event is fundamental to the wellbeing of people within society (Hughes & Healy, 2014).

The current increased focus on resilience has been driven by the recent natural hazard-caused disasters in New Zealand (eg the Christchurch and Kaikōura earthquakes) and natural and human-caused events globally (eg the Fukushima nuclear disaster, Hurricane Katrina and the Deep Water Horizon oil spill). In addition, climate change is affecting the severity and frequency of hazard events, as well as creating new hazards. Awareness of unpredictable, 'rare' events is increasing, and it is recognised that societies need to build their resilience to these in ways that were not required in the past. Finally, the complex interdependencies in modern infrastructure networks mean we need to look further afield than the principal sector (eg the roading network) to other interdependent sectors (eg electricity, telecommunications) to identify potential failure modes and hazards.

Many of the recent natural and technological catastrophes have highlighted:

1. a failure to predict extreme events, and
2. an inability to understand the complex systems involved and the potential range of failure possibilities.

Park et al. (2013, p. 357) emphasised this ignorance: 'not the assumption that future events are expected, but that they will always be unexpected'.

The National Infrastructure Unit (2011, p. 14) developed the following definition of resilience:

> *The concept of resilience is wider than natural disasters and covers the capacity of public, private and civic sectors to withstand disruption, absorb disturbance, act effectively in a crisis, adapt to changing conditions, including climate change, and grow over time.*

This definition acknowledges that the service the infrastructure delivers will be disrupted because of the infrastructure undergoing damage; however, the possibility of failure of the service is reduced and it can adapt and recover from a disruptive event and/or gradual external changes over time. The definition is also broad enough to encompass an approach that allows for 'unknown' as well as 'known' hazards.

More specifically, in the context of transport systems resilience, can be defined as the:

> *system's ability to enable communities to withstand and absorb impacts of unplanned disruptive events, perform effectively during disruptions, and respond and recover functionality quickly. It requires minimising and managing the likelihood and consequences of small-scale and large-scale, frequent and infrequent, sudden and slow-onset disruptive events, caused by natural or manmade hazards.* (New Zealand Transport Agency, 2018b, p. 1)

This definition is appropriate for use here, in that it addresses the broad transportation system, has a customer/community focus and refers to a range of hazard events.

3.2 Risk

Risk management approaches provide a useful, practical and largely accepted approach to managing risk to infrastructure. By determining infrastructure elements at high risk, through a robust risk assessment framework, risk mitigation initiatives can be developed and prioritised.

The ISO 31000 standard on risk management sets out international best practice for risk management. It defines risk as 'the effect of uncertainty on objectives' and explains that 'risk is usually expressed in terms of risk sources, potential events, their consequences and their likelihood' (ISO, 2018, section 3.1). This definition provides flexibility, as it anticipates and provides for risk to be described or characterised in different ways, depending on the phenomena being considered and the context, while maintaining the underlying focus on uncertainty.

Risk sources are typically referred to as hazards. Hazards can be categorised into three general types: natural, technological and social/political (Hughes & Healy, 2014). These can be broken down further into 'shock' events, which are short-term and sudden change processes (eg earthquakes) and 'stress' events, which are long-term and gradual change processes (eg climate change). In addition, a hazard can be either from an external factor (eg flood or earthquake) or internal to the network (eg pipe burst).

Climate change is an example of a phenomenon that exhibits significant uncertainty in several aspects: relating to the physical processes driving change; the consequences of climate change and timing of those consequences; and the effects of those consequences on the objectives of different communities and societies. Historically, a risk analysis approach has been used to identify risks and develop management/mitigation approaches. However, as many hazards and failure modes are unknown or inadequately understood, some argue that risk analysis is inadequate and arguably impossible (Park et al., 2013). Recent disasters have highlighted this uncertainty and the inability of risk analyses to predict future events and cope with the complexity of various systems, their possible failures and the implications that may be caused by such failures (Hughes & Healy, 2014; Park et al., 2013).

Various authors have suggested that risk analysis requires the hazards to be identifiable, and therefore, to prepare for the unexpected, a focus on resilience rather than risk is emphasised. Key differences between a traditional, risk-based approach and a resilience approach are as follows (Park et al., 2013; Snowdon, 2011).

1. A risk-based approach looks to mitigate failure through probability and scenario-based analysis of known hazards. A resilience approach looks to minimise the consequences of failure by investigating scenarios with unidentified causes.
2. A risk-based approach would involve incrementally modifying existing designs in response to emerging hazards, whereas a resilience approach would involve adapting to changing conditions and potentially allowing controlled failure (a 'safe-to-fail' design) at a sub-system level to reduce the possibility of broader loss of function within the larger system.

Despite these subtle differences, the two approaches are considered complementary and applicable in different circumstances. They are not mutually exclusive, and their use depends on the context of the assessment being undertaken and the understanding of the relevant hazards. While this paper does not intend to explore risk and resilience approaches in detail, it seeks to highlight that it is important to understand these approaches and the way an understanding of infrastructure interdependencies can inform better management of risk and resilience.

Risk, as defined by ISO 31000 (ISO, 2018), can be represented as shown in figure 3.1, illustrating the key components of 'likelihood' and 'consequence' that are typically used in frameworks to evaluate and quantify risk.

Figure 3.1 Equation showing risk as a product of likelihood and consequence

Likelihood: The word 'likelihood' is used to refer to the chance of something happening, whether defined, measured or determined objectively or subjectively, qualitatively or quantitatively, and described using general terms or mathematically (such as a probability or a frequency over a given period) (ISO, 2018). This can relate to a natural hazard recurrence interval or an assessment of the likelihood of an uncertain event (a technological or social hazard).

Consequence: A consequence is the outcome of an event that has an effect on objectives. A single event can generate a range of consequences that can have both positive and negative effects on objectives. Initial consequences can also escalate through cascading and cumulative effects. Typically, consequences are measured against agreed criteria that are important to the interests or values at stake. These can include criteria relating to economic consequences or social, environment, cultural or reputational consequences. When assessing risks for infrastructure networks, consequences relate directly to the *criticality* of a section of the network. The higher the criticality, the higher the consequence of failure (NAMS Group, 2006).

The greatest risk can be identified by an established risk-rating matrix that reflects the organisation's risk tolerance (NAMS Group, 2006). An example of a typical risk-rating matrix is shown in table 3.1, along with descriptions of the coloured risk ratings and response requirements shown in table 3.2.

Table 3.1 Example risk matrix showing risk in relation to the likelihood and consequence of an event

Likelihood	Consequence				
	Negligible (1)	Minor (2)	Moderate (3)	Major (4)	Catastrophic (5)
Almost certain (5)	5	10	15	20	25
Likely (4)	4	8	12	16	20
Possible (3)	3	6	9	12	15
Unlikely (2)	2	4	6	8	10
Rare (1)	1	2	3	4	5

Table 3.2 Example risk descriptions and response requirements

Risk description	Response requirement
Extreme risk (20–25)	The process, task or activity in question must not occur, or it must cease until actions are taken to eliminate the hazard or minimise the risk. CE/Board oversees specific review of effectiveness of new or additional controls before the process, task or activity can commence or recommence.
Very high risk (15–16)	Actions must be taken to eliminate the hazard or minimise the risk. The relevant Executive Manager oversees action plans and receives reports on progress. Specific consideration of control effectiveness and new or additional control options should be considered.
High risk (10–12)	Actions must be taken to eliminate the hazard or minimise the risk. General Manager oversees action plans and receives reports on progress. Periodic consideration of control effectiveness and new or additional control options should be considered.
Moderate risk (5–9)	Actions must be taken to eliminate the hazard or minimise the risk. Relevant Business Unit Manager oversees action plans and receives reports on progress. Periodic consideration of control effectiveness and new or additional control options should be considered.
Low risk (1–4)	The process or activity in question continues with existing controls. Continue monitoring existing control effectiveness (within agreed business-as-usual arrangements). Continue to reduce the risk by adopting any improvements in safety that the business becomes aware of.

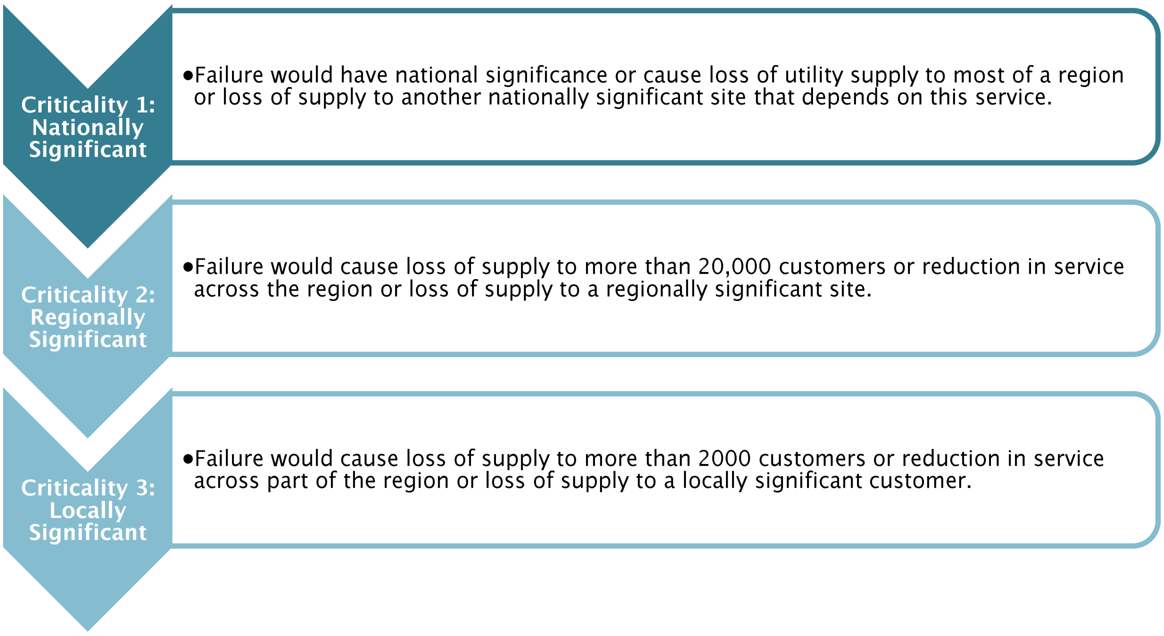
The management of risk is a key business activity within all infrastructure organisations. While an understanding of the likelihood of uncertain events is important, it is the consequence of failure that is of most interest and relevance to this paper, particularly as it relates to criticality.

3.2.1 Criticality

Critical assets are defined as those that 'are especially significant to societal wellbeing and that therefore merit priority attention by utilities in emergency response and recovery' (New Zealand Lifelines Council, 2017). They are also defined as those that have a 'high consequence of failure' (NAMS Group, 2006). For example, a transport route could be critical because it carries high volumes of traffic, or it could be the only access route to a hospital.

Generally, critical assets are ranked into different 'levels' to represent their relative importance. In New Zealand, the National Lifelines Council has developed a 3-tier national ranking, as shown in figure 3.2.

Figure 3.2 Defining critical lifeline infrastructure assets (New Zealand Lifelines Council, 2017)



Understanding and managing critical assets involves an understanding of lifeline infrastructure requirements as defined by the Civil Defence and Emergency Management Act 2002, as well as the principles and practices of asset management, including the principles of risk management, services of importance to customers and the interdependencies with other utilities' critical infrastructure. As discussed in preceding sections, a fundamental step in managing risk in infrastructure systems (including roading networks) is to understand the criticality of the system itself and the various assets and elements within the system, so efforts can be prioritised. In the context of this study, the term 'criticality' is informed (defined) by the consequence of the asset failing. That is, if there would be an unacceptable consequence if a particular asset failed, then that asset would be classified as being of high criticality. Therefore, the level of risk can be estimated as the likelihood of failure (or hazard impact) multiplied by the level of the consequence, as illustrated in figure 3.1. In the context of network infrastructure, criticality can be determined by consequence.

While there are clear high-level definitions for critical infrastructure in New Zealand, there are no consistent frameworks for establishing criticality within and across sectors. Most utilities and authorities have their own methods for determining criticality (generally scored from 1-Low to 5-Vital) and may use different approaches and criteria for this purpose. These methods are often based on the consequence of the asset failing and may relate to factors such as customer impact, financial loss, environmental damage and corporate image. There is potential for some of these to outweigh others, depending on the business priorities.

3.2.1.1 Criticality for transport

In the context of roading networks, many authorities develop hierarchical classifications of asset types to describe the function that different types of road provide. Generally, these classifications help to guide the management, operation and use of the road corridors to improve safety and efficiency and provide a consistent level of service for road users.

The Road Efficiency Group (a collaboration between local government and Waka Kotahi) has developed the One Network Road Classification (ONRC) to categorise all roads into seven functional classifications (National High Volume through to Access Roads), according to the following range of criteria (New Zealand Transport Agency, 2016):

- Movement of people and goods – based on four criteria: annual average daily traffic, heavy commercial vehicles, buses, active modes.
- Economic and social – based on six criteria: linking places, connectivity, ports, airports, tourism, hospitals.

Hughes (2016) demonstrated that these common systems of hierarchy for different level roads generally imply a level of ‘criticality’. However, they often omit key criteria, including:

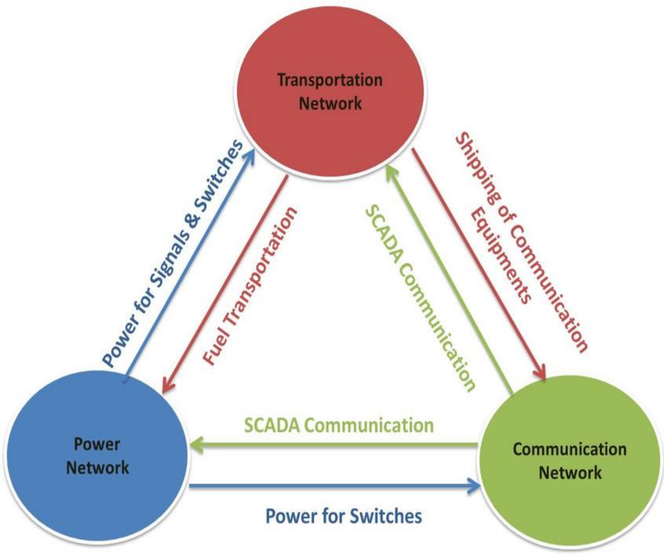
- Access to lifeline utilities: This would explicitly cover routes that are priority lifeline routes or provide access to major lifeline facilities, such as key utilities for water supply and power generation.
- Access to essential services: This would explicitly cover routes that provide access to essential services as identified by a given community or region (not captured in the current ONRC). These can include large aged-care facilities, petrol stations, ambulance, fire, police and emergency operations centres, welfare centres, key retail outlets (hardware stores, construction resources and supermarkets), schools, sector posts and major industry.

Hughes (2016) proposed that the criticality of a transport route should be modified from its ONRC according to both the number and individual criticality of interdependent locations served by the route. This was further tested and developed by Rebello et al. (2019). That is, a route that served a large number of high-criticality locations would have a higher ‘modified’ criticality.

4 Interdependencies

A dependency exists when one infrastructure has a direct impact on the performance of another infrastructure system (Rinaldi et al., 2001; Zorn & Shamseldin, 2015). An example of this is the reliance on power supply to operate traffic lights that control the operation of a road. An interdependency indicates a mutual connection between two systems; that is, a ‘bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other’ (Rinaldi et al., 2001, p. 14). This is illustrated in figure 4.1.

Figure 4.1 Example of the interdependencies within the transportation, power and communications network infrastructure (Banerjee, 2017, p. 6)



When two infrastructures are dependent on each other, they are said to be interdependent. To simplify the terminology for the purposes of this report, we use the term ‘interdependency’ when discussing both dependencies and interdependencies. This term is conceptually simple, defined here as the connections between different infrastructures in a general system of systems. However, in practice, interdependencies dramatically increase the complexity of the ‘system of systems’ (Rinaldi et al., 2001).

The complex relationships between the various infrastructure systems can be characterised by connection directionality and the respective intricate branching topologies, often forming a complex web (see figure 4.1). Given the intricate complexity of these systems and common dependence among the infrastructures, it can be almost impossible to evaluate the effects of indirect impacts affecting them. Therefore, the interconnected infrastructures must be considered, with their associated interdependencies, in a holistic manner.

4.1 Typologies of interdependencies

Infrastructure can be dependent and interdependent in many ways, with varying characteristics and resulting in a range of impacts on one another (Ouyang, 2014; Rinaldi et al., 2001). Various authors have characterised typologies of interdependencies, often deriving similar classifications. The Institution of Civil Engineers (ICE, 2013) proposed four distinct typologies: physical, digital, geographic and organisational, as summarised in table 4.1.

Table 4.1 Typologies of interdependencies (adapted from ICE, 2013, p. 6)

Typology	Description	Examples (Ouyang, 2014)
Physical interdependency	• A transfer of resources, the output of one element becoming the input of another (eg transfer of people, fast-moving consumer goods, supply chain). • A shared physical dependency between the two elements on a third resource (eg utilising the same staff, access to other critical infrastructure). • Hazard reduction function (eg coastal defence, stop-bank, flood exceedance route).	Outages in power systems caused the failures of traffic signals, water supply pumping stations and automated teller machines, as well as the closure of businesses.
Digital interdependency	• A cyber transfer of information (eg traffic management and control systems). • A shared dependency between the two elements on the transfer of information from a third-party source.	Disruptions to communication services affected the situational awareness and control of electric power (or water) systems and caused their partial failures due to lack of observability.
Geographic interdependency	• The elements are located in the same place or within close proximity (ie hotspots and co-location).	Watermain breaks flooded co-located utility systems. In the case of the 2001 World Trade Center attack, the water flooded rail tunnels, a commuter station and the vault containing all the cables for one of the largest telecommunication nodes in the world.
Organisational interdependency	• The elements are linked through a financial or logical mechanism. • The elements are organisationally linked by shared ownership, governance or oversight. • The elements are mutually dependent on the services provided by a third-party organisation.	Following the 2001 World Trade Center attack, debris-covered streets could not be used by both emergency response personnel and financial district workers (the lack of the latter could disrupt financial services).

While these four broad types are supported by a range of authors (see table 4.2), the typology names vary subtly across the literature. For example, the ICE (2013) definition of ‘organisational interdependency’ aligns with the definition of ‘logical interdependency’ presented in Rinaldi et al. (2001). Other examples of naming include the distinction between cyber and digital in the name, even though they have very similar definitions. Various other authors have developed similar names with broad definitions that align with, or directly reference, Rinaldi et al.’s typologies, as shown in table 4.2. Therefore, these four typologies were considered representative and appropriate.

Table 4.2 Summary of interdependency typologies identified in the literature

Typology	Rinaldi et al. (2001)	Carhart & Rosenberg (2015)	ICE (2013)	Trucco et al. (2012)	AECOM (2017)	Dudenhoeffer et al. (2006)	Wallace et al. (2003)	Zhang & Peeta (2011)
Physical	✓	✓	✓	✓	✓		✓	
Digital	✓	✓	✓	✓	✓	✓	✓	
Geographic	✓	✓	✓	✓	✓	✓	✓	
Organisational	✓	✓	✓	✓	✓	✓		✓

4.2 Defining interdependencies

Three attributes or dimensions can be used to define interdependencies: order, directionality and strength. These are discussed in the next sections.

4.2.1 Interdependency order

One attribute used to define interdependencies is its location in relation to other dependencies, in terms of a cascade of impact in a downstream direction. To represent the impact to downstream infrastructures within a system, a causal chain of services can be developed to understand how failures can propagate impacts across the system (Bigger et al., 2009). Because of the complexity of the concept of ‘system of systems’, failures can be characterised according to an ‘order’ of dependencies. That is, the order of the dependency relates to its downstream position within the causal chain: a ‘first-order dependency failure’ cascades from an initial infrastructure failure to a downstream one; a ‘second-order dependency failure’ results from a sequence of two successive infrastructure failures; and in general, an ‘n^{th}-order dependency failure’ stems from *n* cascading infrastructure failures subsequent to an initial event (see figure 4.2).

Figure 4.2 Example of order (level) of interdependencies with infrastructure downstream effects from initial failures to the energy, communication, water/wastewater and transportation sectors (Bigger et al., 2009, p. 207)

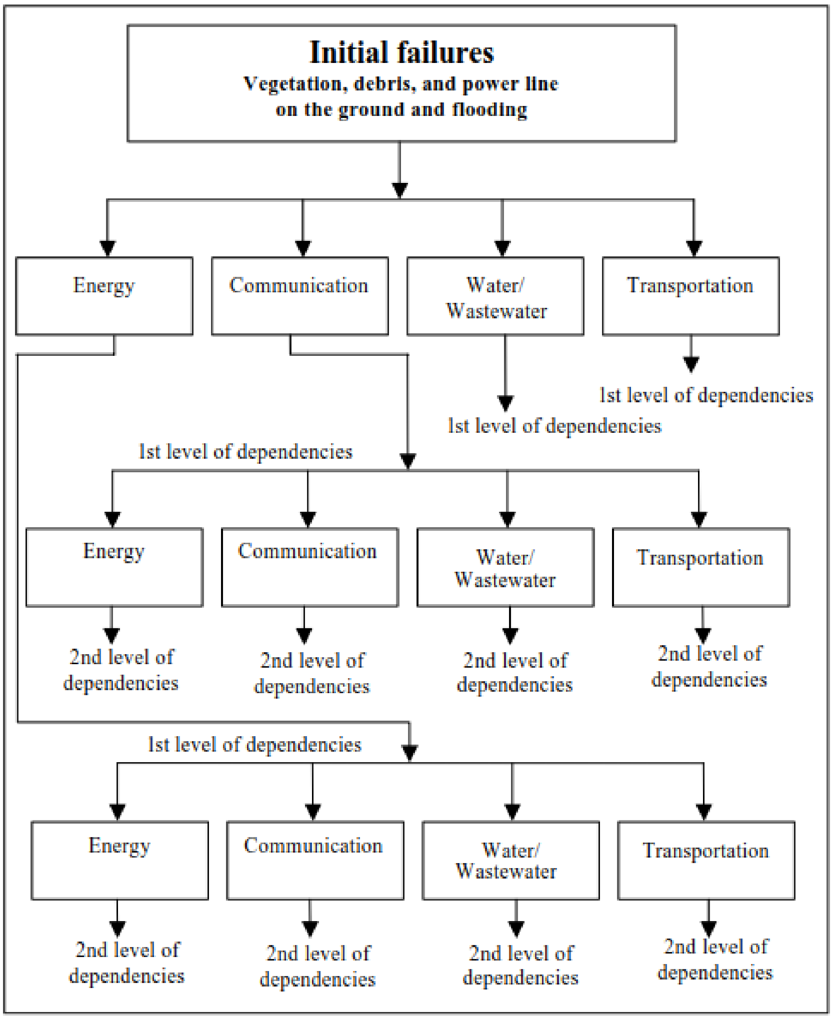


Figure 4.2 shows how the initial failure of powerlines caused by debris fall could result in a first-order dependency relating to the communication network. A second-order dependency would relate to the energy, communication, water/wastewater or transport systems.

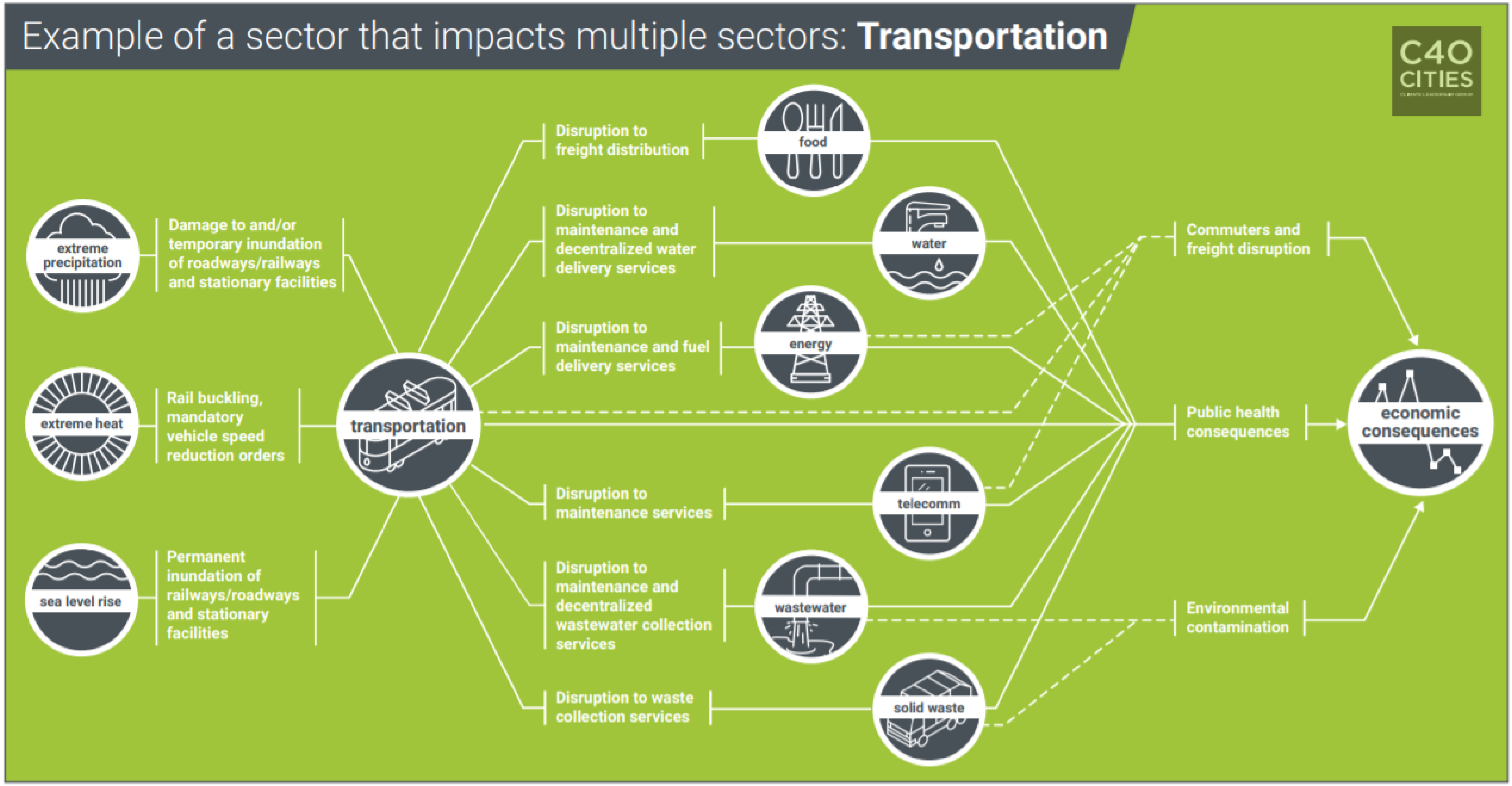
The issues from cascading interdependencies are prevalent within complex and distributed systems, where the impacts and outages caused by external hazards may disrupt networks and related functions/services. For example, a power outage caused the failure of the KiwiRail control centre in Wellington, which in turn, caused failure of the Auckland commuter rail service because it was controlled by the Wellington centre ('Investigation after Auckland rail failure', 2012).

The C40 Cities research (AECOM, 2017; see figure 4.3) provides an example of the way climate change hazards can affect transportation networks, with subsequent cascading impacts on maintenance and delivery functions, which in turn lead to public health, environmental and economic consequences. Thus, a failure of the transportation network can lead to first-order dependency impacts on the food, water, energy, telecommunications, wastewater and solid waste sectors.

Transport is not necessarily always a first-order dependency, with cascading impacts following downstream. Examples of where transport may be a second (or third) order dependency include:

- loss of inward access (upstream roads closed)
- power failure (traffic signals stop working)
- telecommunications failure (signal controls, traffic data capture)
- water mains burst below road
- tree failure causing street closure.

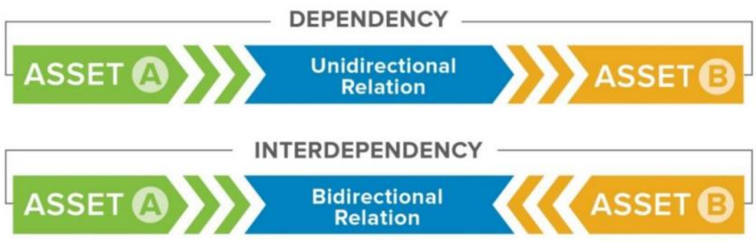
Figure 4.3 Example of the cascading impacts to infrastructures/sectors dependent on the transport sector (AECOM, 2017, p. B-3)



4.2.2 Directionality of interdependencies

The dependency of an infrastructure asset/service on another infrastructure asset/service can be characterised by the directionality of the relationship. By definition, interdependency requires a two-way relationship between the infrastructures, referred to as being 'bidirectional' (Rinaldi et al., 2001). However, if the dependency relationship between two infrastructures is one way, it is referred to as being 'unidirectional' (see figure 4.4). The terms 'input' and 'mutual' interdependency relationships can also be used to describe the concepts of unidirectional and bidirectional (Eusgeld et al., 2011). Johansson and Hassel (2010) presented the novel idea that the scale of the 'system' could sometimes affect the way directionality was viewed. They suggested that at a macro/system level, a bidirectional relationship could exist; however, a unidirectional dependency could exist at a component level specific for inputs and outputs.

Figure 4.4 Examples of the directionality of dependent relationships between infrastructures (Petit et al., 2015, p. 8)



The 'flow' of the dependency between infrastructures with unidirectional relationships can be further categorised into two types (Petit et al., 2015, p. 8):

- Upstream dependencies: The inputs into one infrastructure from another external infrastructure that are required to maintain operation – for example, upstream for transport may be those systems/utilities whose failure would have an impact on the functioning of its transport network (eg failure of electricity for signals).
- Downstream dependencies: The consequences to infrastructures that are reliant on the maintained operation of another critical infrastructure – for example, downstream may include the systems/utilities that would be affected by failure of the transport network (eg the failure of a road providing access to a power station causes it to be shut down).

Although less common, failures can propagate upstream from a failure point. An example of this is a pipe break resulting in loss of pressure, affecting other elements of the network.

4.2.3 Strength of interdependencies

The level of impact to a dependent infrastructure caused by the failure of an upstream dependency can be categorised as the strength of the relationship between the infrastructures (AECOM, 2017; New Zealand Lifelines Council, 2017). This strength relates to whether, for example, the primary infrastructure offers beneficial but non-essential support, or whether the loss of the dependency would result in complete failure of the dependent infrastructure (Carhart & Rosenberg, 2015).

For some interdependencies, strength can increase during or following a disaster event (New Zealand Lifelines Council, 2017). For example, following a major disaster, there could be an increase in demand for fuel to maintain all other services, as electricity power supply would probably be disrupted and fuel-dependent generators would be required. This illustrates additional temporal complexity relating to the way interdependency strengths can change according to different operating environments.

4.3 Identifying and quantifying interdependencies

As discussed in the preceding sections, interdependencies can interact in multiple ways and can be classified according to their typology, order, strength and directionality. Given that infrastructure owners need to understand the complexities of both their own infrastructure and other dependant critical infrastructure, developing methods to clearly identify/quantify interdependencies is essential. This section presents example methods for both identification/modelling and quantification of interdependencies.

4.3.1 Interdependency identification

A range of methods for identifying and modelling interdependencies exist, as summarised in table 4.3.

Table 4.3 Summary of interdependency assessment methods

Interdependency assessment method	Description
Network and graph theories	This approach uses nodes and links to model different types of infrastructure. In generic terms, nodes represent infrastructures that provide or consume a particular resource, whereas a link is the way that resource travels. An example would be an electrical network; power is usually carried from generators to substations, all connected by electrical conductors, where generators to substations are represented by nodes and electrical conductors are represented by links (Satumtira & Dueñas-Osorio, 2010). Network theory extends this idea to consider the capacity of the network infrastructures, to evaluate the effect of any failure – for example, using the data for the road-carrying capacities with respect to the number of vehicles travelling, to model congestion (Ouyang, 2014).
Topological models	Topology-based or structural approaches generally identify discrete states for each component (node or link), usually with two states (failed and normal); ie each node is either fully working or completely non-functional. To implement these approaches in their basic formulation, it is enough to have the topological structure of the infrastructure (which are quite easy data to obtain). This static formulation can capture the ‘structural’ properties of the network. These approaches usually examine failures at the node or link level and then examine cascading failures to other nodes or links within the network. They are used to evaluate the robustness of a network from the topological perspective, using centrality measures (Albert et al., 2004; Setola & Theocharidou, 2016).
Petri-nets	Petri-net is based on graph theory and is used for modelling and analysing the network characteristics. A basic Petri-net contains two kinds of nodes: ‘place’, which describes the states of the system; and ‘transition’, which describes the actions. Places and transitions are connected by directed arcs. The arc expressions describe the way the state of the Petri-nets changes when the transitions occur. Each place contains a set of tokens. The transition fires by removing tokens from their input places and creating tokens that are distributed to their output places (Bobbio, 1990; Murata, 1989).
Agent-based models	This type of computational model is used to simulate the actions and interactions of independent agents to assess their effects on the entirety of a system (De Porcellinis et al., 2009).
Matrix representations	These simple, visual representations indicate the relationships between interdependent infrastructures. The matrices can also indicate the direction and strength of interaction.

Hierarchical and holographic risk models	The term ‘hierarchical’ refers to an understanding of risks that exist at different levels in a hierarchy (ie the system-of-systems level, individual-system level, sub-system level and component level). The term ‘holographic modelling’ means a multi-view image of a system with regard to identifying vulnerabilities. This method has been applied to study risks for US government agencies such as the President’s Commission on Critical Infrastructure Protection, the FBI, NASA, Virginia Department of Transportation and the National Ground Intelligence Center (Eusgeld et al., 2008).

4.3.2 Interdependency quantification

To date, most efforts relating to quantifying independencies have focused on the strength and direction of relationships between critical infrastructures (Laugé et al., 2015; AECOM, 2017; New Zealand Lifelines Council, 2017). Analysis has generally been qualitative or semi-quantitative.

One novel approach by Laugé et al. (2015) surveyed critical infrastructure experts from around the world to analyse what would happen to a failed infrastructure if it was not able to provide its service and what the associated impacts would be. The questionnaires sought responses about the effect on critical infrastructure of differing durations of outage. Each question required an answer on a six-point scale, where 0 represented ‘no effect’ and 5 represented ‘very high effect’. The approach involved a holistic analysis concerning a small number of critical infrastructures and incorporated a dynamic perspective that was based on the length of outage for the critical infrastructure and the cascading impacts over time. Tables 4.4 and 4.5 show the results of this survey for a two-hour outage and a one-week outage, respectively.

The rows in the tables indicate the ‘failed’ critical infrastructure and the columns indicate the dependant infrastructures that would be affected. The first row in table 4.4 shows the impact that an energy outage of two hours would have on other critical infrastructure: a minor impact on information and communications technology (ICT) (0.86) and a moderate impact on transport (2.40). However, the dependencies for these examples increase when critical infrastructure is down for more than one week, as shown in table 4.5. The first row in table 4.5 shows that an energy outage of more than one week would have a severe impact on both ICT (4.57) and transport (4.20).

Interestingly, for all the dependant infrastructures relating to transport, the strength of dependency increases from the two-hour outage to the one-week outage. This makes intuitive sense, given that with a longer duration of outage, the transport network would become more critical in terms of access.

Table 4.4 Dependencies among critical infrastructure elements that are down for less than two hours (Laugé et al., 2015, p. 19)

Effect on / Failed CI	Energy	ICT	Water	Food	Health	Financial	Order and safety	Civil admin.	Transport	Chemical and nuclear	Space and research
Energy	–	0.86	1.33	2.89	1.40	2.67	1.67	0.40	2.40	4.67	1.33
ICT	2.67	–	1.00	1.67	2.20	2.33	2.67	1.40	2.40	2.67	1.00
Water	0.83	0.57	–	1.56	1.20	0.00	1.00	0.60	0.20	1.00	0.67
Food	0.00	0.14	0.00	–	0.60	0.00	0.33	0.20	0.00	0.33	0.33
Health	0.50	0.14	0.00	0.78	–	0.00	1.67	0.60	0.00	0.33	0.00
Financial	0.17	0.71	0.00	1.22	0.20	–	0.33	0.00	0.60	1.33	0.00
Order and safety	0.83	0.43	0.33	1.00	1.00	1.67	–	1.40	0.80	1.00	0.00
Civil admin.	0.33	0.86	0.00	0.38	1.00	0.33	1.00	–	0.20	1.00	0.00
Transport	1.17	1.00	0.00	1.11	1.40	1.00	2.00	0.60	–	0.00	0.00
Chemical and nuclear	1.50	0.29	0.00	0.22	0.40	0.00	2.00	1.40	0.20	–	0.00
Space and research	0.17	0.57	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	–

Table 4.5 Dependencies among critical infrastructure elements that are down for more than one week (Laugé et al., 2015, p. 20)

Effect on / Failed CI	Energy	ICT	Water	Food	Health	Financial	Order and safety	Civil admin.	Transport	Chemical and nuclear	Space and research
Energy	–	4.57	4.67	5.00	5.00	4.67	5.00	4.20	4.20	5.00	4.33
ICT	4.67	–	3.67	4.89	4.00	4.67	4.33	3.40	4.60	5.00	4.00
Water	3.50	3.43	–	4.22	3.80	1.00	3.67	3.00	2.60	3.67	3.00
Food	3.17	2.57	2.00	–	4.00	0.33	4.00	3.00	0.80	1.33	3.00
Health	3.00	2.00	1.33	3.11	–	0.67	5.00	3.60	1.20	1.00	2.00
Financial	3.00	2.43	2.00	4.22	2.40	–	2.00	0.75	2.20	2.67	3.00
Order and safety	3.67	2.57	2.33	3.56	2.60	4.33	–	3.40	2.80	2.00	2.67
Civil admin.	2.50	2.57	1.33	2.50	3.20	1.67	2.00	–	2.40	2.33	3.67
Transport	3.83	3.00	3.67	4.78	3.80	3.67	4.33	3.40	–	3.67	3.67
Chemical and nuclear	3.17	2.14	3.00	2.33	2.40	0.00	3.33	1.80	1.40	–	1.00
Space and research	1.50	2.29	0.67	1.00	0.60	0.00	1.33	1.00	0.60	0.00	–

The San Francisco Lifelines Council took a qualitative approach that was more simplistic (AECOM, 2017). To understand the strength of the interdependencies among infrastructures and to establish processes that would enable restoration of lifelines following an event, they developed a matrix of the interdependencies among 12 significant lifeline systems. The diagram in figure 4.5 indicates the strength of interdependency (ie strong, moderate, limited). The relationships among the interdependencies are also shown on the scallop diagrams (figure 4.6), where the darker lines indicate a stronger dependency. Both the matrix and the scallop diagram show that in San Francisco, fuel is an infrastructure service upon which almost all other lifeline utilities depend heavily.

Figure 4.5 Interdependencies of infrastructure systems in place in San Francisco (AECOM, 2017, p. 19)

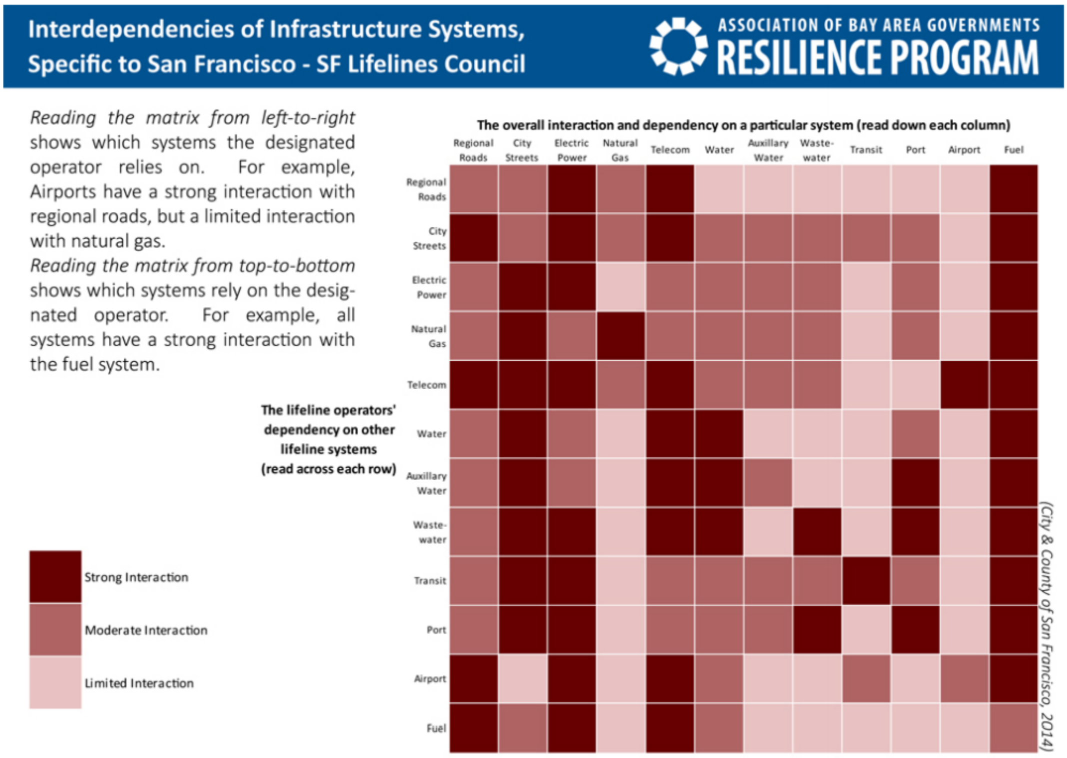
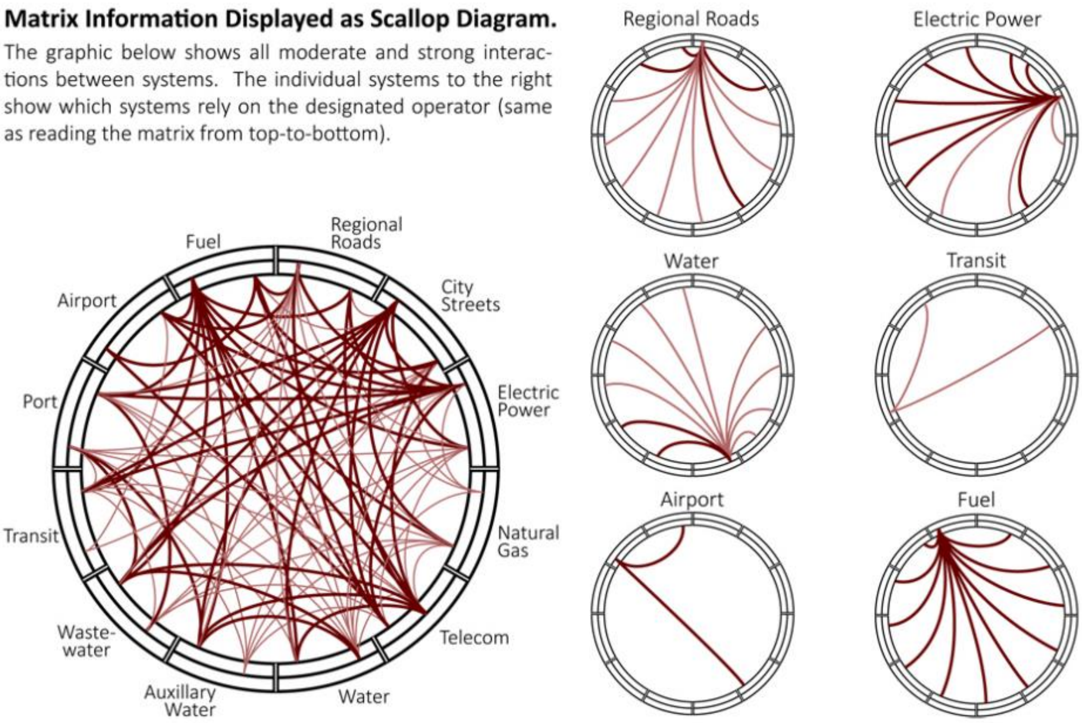


Figure 4.6 Scallop diagram showing strength of interdependencies (AECOM, 2017, p. 19a)



The New Zealand Lifelines Council (2017) developed two interdependency matrices: one for business as usual (see table 4.6) and one for during/post event (see table 4.7). Interestingly, they identified roads as the second most important ‘utility’ assessed during both business as usual and during/post event, with only electricity and fuel scoring higher.

The use of a matrix approach can demonstrate not only the interdependencies among specific systems but also the strength and direction of interaction associated with each interdependency. The strength and directional relationship can feed into a method to rank each of the individual interdependencies, as shown in these tables.

Table 4.6 Interdependency matrix for business as usual (New Zealand Lifelines Council, 2017, p. 38)

The degree to which the utilities listed to the right are dependent on the utilities listed below	Roads	Rail	Sea Transport	Air Transport	Water Supply	Wastewater	Stormwater	Electricity	Gas	Fuel Supply	Broadcasting	VHF Radio	Telecomms	Total Dependency
Electricity	1	2	3	3	3	3	2		2	2	3	3	3	30
Roads		3	3	3	2	2	2	2	2	3	2	2	2	28
Fuel	2	3	3	3	2	2	2	2	2		2	2	2	27
Tele-comms	2	2	2	2	2	2	2	2	2	2	2	3		25
Water Supply	1	1	1	2		3	1	1	1	1	1	1	2	16
VHF Radio	2	2	2	2	1	1	1	1	1	1	1		1	16
Stormwater	2	1	1	2	1	1		1	1	1	1	1	1	14
Wastewater	1	1	1	2	1		1	1	1	1	1	1	1	13
Rail	1		1	1	1	1	1	1	1	1	1	1	1	12
Sea Transport	1	1		1	1	1	1	1	1	1	1	1	1	12
Air Transport	1	1	1		1	1	1	1	1	1	1	1	1	12
Gas	1	1	1	1	1	1	1	1		1	1	1	1	12
Broadcasting	1	1	1	1	1	1	1	1	1	1		1	1	12

Key: 3 = required for service to function; 2 = important, but can partially function and/or has full backup; 1 = minimal requirement for service to function

Table 4.7 Interdependency matrix for during/post event (New Zealand Lifelines Council, 2017, p. 38)

The degree to which the utilities listed to the right are dependent on the utilities listed below	Roads	Rail	Sea Transport	Air Transport	Water Supply	Wastewater	Stormwater	Electricity	Gas	Fuel Supply	Broadcasting	VHF Radio	Telecomms	Total Dependency
Fuel	3	3	3	3	3	3	3	3	3		3	3	3	36
Roads		3	3	3	3	3	3	3	3	3	2	2	3	34
Tele-comms	3	2	2	2	3	3	3	3	3	2	2	3		31
Electricity	1	2	3	3	3	3	2		2	2	3	3	3	30
VHF Radio	2	2	3	3	2	2	2	2	2	2	2		2	26
Broadcasting	2	2	2	2	2	2	2	2	2	2		2	2	24
Air Transport	2	1	1		2	2	2	2	2	2	2	2	2	22
Water Supply	1	1	1	2		3	1	1	1	1	1	1	2	16
Stormwater	2	1	1	2	1	1		1	1	1	1	1	1	14
Wastewater	1	1	1	2	1		1	1	1	1	1	1	1	13
Rail	1		1	1	1	1	1	1	1	1	1	1	1	12
Sea Transport	1	1		1	1	1	1	1	1	1	1	1	1	12
Gas	1	1	1	1	1	1	1	1		1	1	1	1	12

Key: 3 = required for service to function; 2 = important, but can partially function and/or has full backup; 1 = minimal requirement for service to function

4.4 The transport context

The transport context is unique, as restoration of the transport network following an event is generally required first, to allow subsequent access to restore other dependant services that may be damaged. Typically, road transportation can operate even with reduced functionality, without dependent infrastructures; for example, without power to operate traffic signals. This indicates that impacts to road transportation would typically be of first order and result in cascading impacts to the second- and higher-order infrastructures dependent on road transport and access. For transport systems, first-order impacts are typically physical interdependencies (as shown in section 6.3) with roads providing access to other key infrastructure. Geographic interdependencies are common as well, such as pipes and cables running along main road routes or across bridges.

As demonstrated in the previous sections, interdependencies are multi-faceted in typology, strength, order and direction, which allows their quantification. The quantification of interdependencies within an infrastructure system can inform its relative criticality and allow for prioritisation within a risk framework and, ultimately, the identification and development of mitigation/resilience measures. This can result in mitigation strategies to reduce dependencies on upstream infrastructure, enabling full or partial operation to be maintained.

Given the complexity within networked systems (which include transport) and the difficulty of identifying interdependencies, priority should be given to assessing first- and second-order dependencies. These interdependencies are easier to define, whereas third and higher orders are typically more difficult, due to the often abstract and removed nature of these relationships within the complexity of a ‘system of systems’. Therefore, transportation is typically one of the first infrastructures that need to be restored, to allow the restoration of other infrastructures.

4.5 Summary

The above sections have presented the various typologies of interdependency (physical, digital, geographic and organisational), along with dimensions that aid in characterising and quantifying interdependencies (strength, order and directionality). They have discussed the benefits of understanding interdependencies, as well as the way this can contribute to assessing and managing risk.

The next section compares and reviews a range of existing interdependency assessment approaches and models.

5 Review of existing approaches and models

This section presents a range of existing approaches and methods developed to identify and assess critical interdependences, with a view to identifying approaches that may be most appropriate for application within the transport sector.

5.1 Overview of interdependency modelling approaches

Numerous models have been developed to assess the performance and operation of critical infrastructure. These models support the planning, maintenance and retrofit decisions required by infrastructure owners and investors, private and public utilities, and government entities to ensure reliability, economic vitality and security (Satumtira & Dueñas-Osorio, 2010). These models can be interactive dynamic, coupled, cascading, failure propagation, agent-based, input–output, matrix representation or game-based. Some examples of these were discussed in section 4.3.1.

As the context varies widely across different model applications, it is often difficult to compare the approaches directly. A modelling approach, as well as its outputs, is influenced by the quality and availability of data, intricacy of the systems, complexity of interactions among systems and implications and sensitivity of the results (Pederson et al., 2006). Buxton (2013, p. 19) wrote that the variations in approaches to modelling are ‘due in part to the different aims, objectives and purposes of the work’. These differences can ‘result in unintended bias applied as a result of the differing model set ups, with no single modelling tool/approach providing a holistic solution for all interdependency analysis’.

Despite the range of models that have been developed, there is no standard categorisation of models in the literature; some of the category descriptions may be interchangeable, or a model may fit into a number of category descriptions. Pederson et al. (2006) classified models according to their maturity and provided the following clear definitions for them:

- Research: highly conceptual without vetted application in the real world.
- Developed: applied and validated against real-world infrastructure, used by internal and external customers but still undergoing substantial development.
- Mature analytic: has reached a high level of code stability and is part of a vested internal analytical process, with the results appearing in external reports but the model usage being strictly internal to the organisation that developed it.
- Mature commercial: a commercial licensed product.

5.2 Assessment methodology

This research reviewed the pre-existing models (applications) for assessing network- and infrastructure-related interdependencies. The following section describes the methodology used to gather data and assess the relevance, strengths and weaknesses of each model in relation to the transport sector.

5.2.1 Desktop research

The research conducted a desktop (web-based) study to identify available interdependency models (tools/platforms) of interest. This resulted in a list of potential models requiring further investigation into their methodologies, strengths and limitations. The long list of potential models included:

- CIrcle Tool – Deltares
- XDI Platform – XDI Pty Ltd
- Multi-Period Model for Disruptive Events in Independent Systems
- Measuring Economically Resilient Infrastructure Tool (MERIT) – GNS Science/Market Economics/Resilient Organisations
- DOMINO – Polytechnique Montréal
- Climate Globe – Risk Frontiers
- University of Auckland (UoA) Infrastructure Interdependency Model – UoA
- Dependencies Model – National Infrastructure Simulation and Analysis Centre.

The providers of these models were contacted via email and invited to complete an initial questionnaire.

5.2.2 Questionnaire and interview

A questionnaire was developed and provided to the relevant model providers to obtain high-level background information on the model. Complete responses were received from the following organisations:

- CIrcle Tool – Deltares
- XDI Platform – XDI Systems Pty Ltd
- UoA Infrastructure Interdependency Model – UoA
- MERIT – GNS Science/Market Economics/Resilient Organisations
- DOMINO – Polytechnique Montréal.

Appendix A provides a copy of the questionnaire. A follow-up interview was conducted with the five organisations who provided complete responses to the questionnaire. The purpose of the interview was to provide a detailed understanding of each model and determine specific details about how it might be utilised within the transport sector.

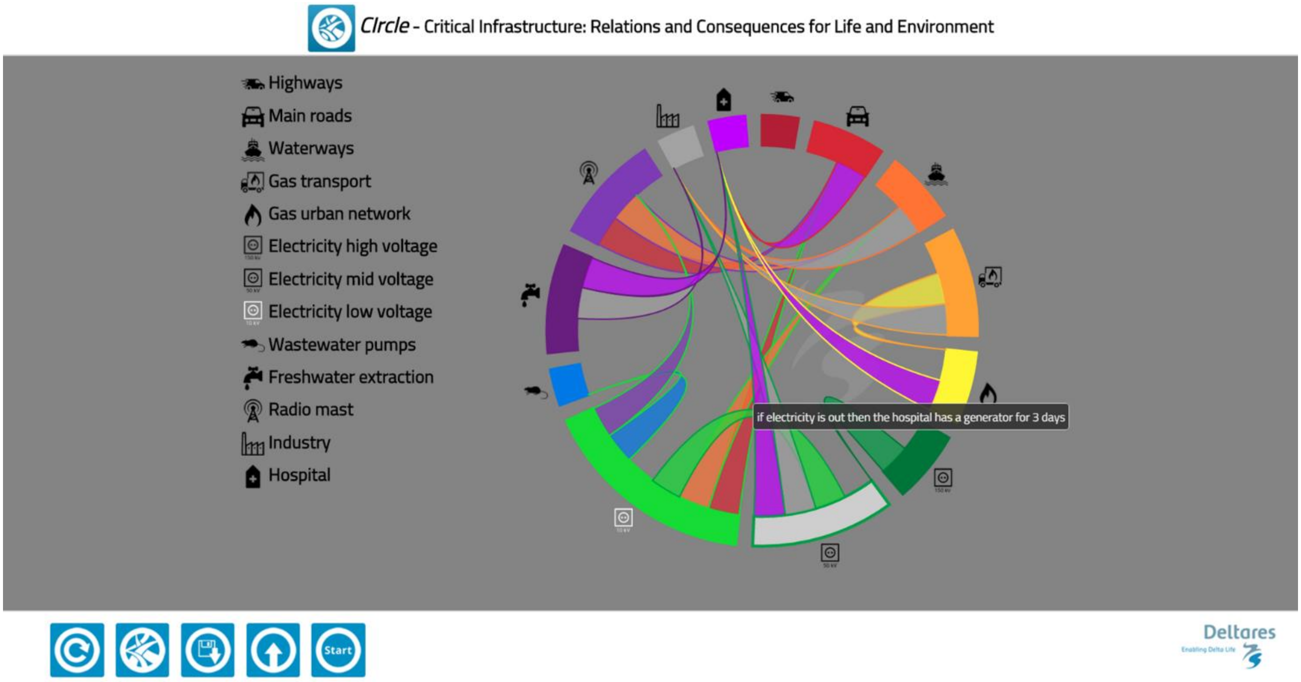
5.3 Review of interdependency models

This section summarises the assessed interdependency models, describing their attributes and applications, as well as their strengths and weaknesses.

5.3.1 Deltares CIrcle Tool

CIrcle (Critical Infrastructures: Relations and Consequences for Life and Environment) is primarily a digital elicitation approach used in workshop settings to discuss and draw dependencies between networks or objects based on stakeholder feedback (see figure 5.1). CIrcle uses open data and Deltares' own models in combination with the information provided by the workshop participants to analyse and visualise the effect of cascading impacts on critical infrastructures. The knowledge and experiences that are collected with the CIrcle tool are stored in the CIrcle knowledge database. This knowledge helps users to understand the differences between case studies in which CIrcle methodology was employed both objectively (through physical impacts and possible cascading effects) and subjectively (pertaining to differences in resilience and risk perception in differing settings). These causal relationships are very important for the identification of cascading effects. Without them, time-dependent analyses and automated GIS analyses are not possible.

Figure 5.1 CIrcle example output when examining the dependant infrastructure types that rely on power supply (Deltares, n.d.)



5.3.1.1 Commentary

The CIrcle tool is primarily designed for stakeholder engagement and there are minimal background analytical processes behind the tool to determine key interdependencies across a given network. CIrcle is a 'developed' model, as it has been applied and validated against real-world infrastructure and has been used by internal and external customers while still undergoing some development.

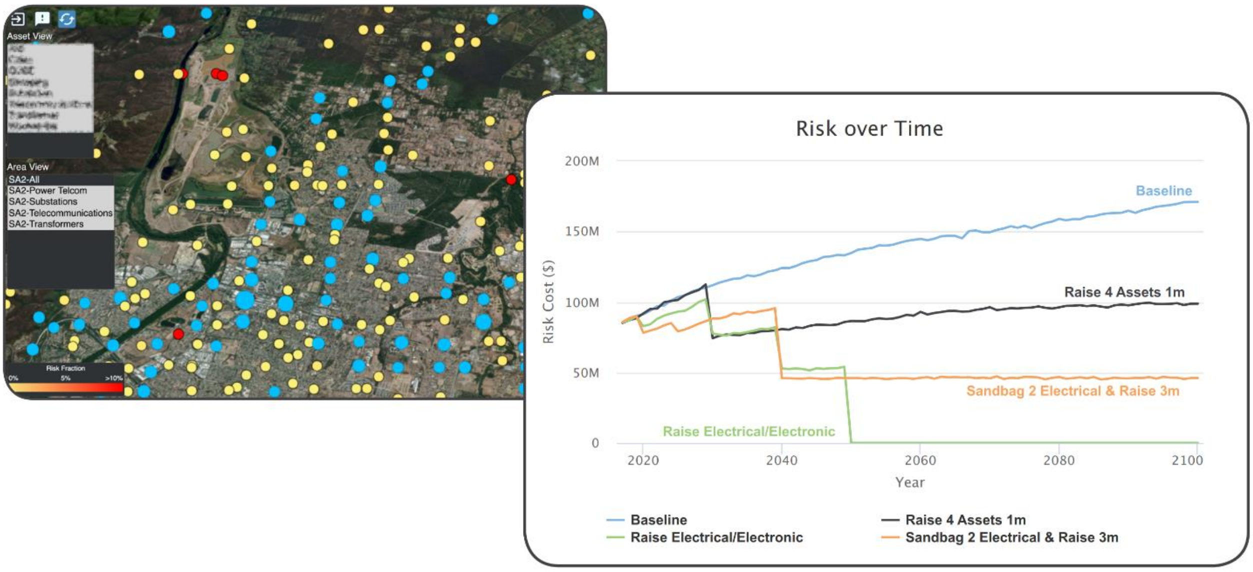
5.3.2 XDI Cross-dependency Initiative Platform

The XDI Platform brings together asset datasets and climate models to provide analysis of an asset-owner's exposure to climate change and extreme weather risk. Assessments can be conducted at both a high level and a granular level, and can include probabilities of failure that can feed into business cases for adaptation. The platform carries out an analytical assessment to evaluate a network's or asset's exposure to climate risk and by identifying the network vulnerabilities (based on network and asset characteristics), it identifies key interdependencies, probabilities of failure and changing risk over time (see figure 5.2).

The XDI Platform identifies the source and direction of risk transfer between dependent infrastructures and provides quantification of them. It uses location-specific climate hazard data and asset engineering data to compute likelihood and damage consequences and the associated financial or user risk for critical infrastructure. The risk transfer to dependent or cross-dependent assets can then be calculated and assigned.

The XDI Platform assumes that most critical infrastructure assets are 'blind' to the systems within which they operate, and it therefore has algorithms that create a first-order network 'on the fly'. This effectively finds the highest-criticality power station, communications node, water and transport supply facilities that the asset needs in order to operate and then computes the transfer of risk to/from these system assets.

Figure 5.2 XDI example output showing power and telecommunications assets as well as changing risk over time (XDI, 2019, p. 2)



5.3.2.1 Commentary

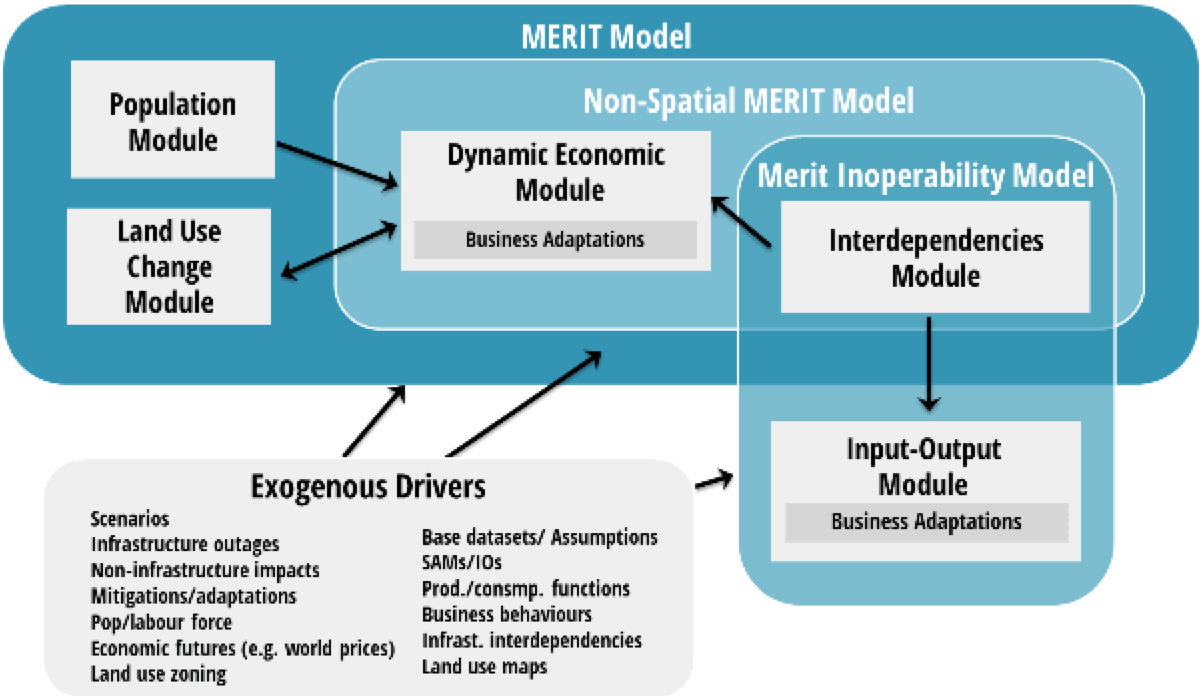
The XDI Platform is a 'mature' model (as per section 5.1) that is licensed and commercially available. It can provide multiple types of outputs and can be considered a risk-based model, as well as, to an extent, a failure propagation model or cascading model. While the platform has very useful climate change hazard and extreme weather modelling capabilities, the interdependency approach is relatively simplistic, in that it considers only first-order relationships.

5.3.3 Measuring Economically Resilient Infrastructure Tool

MERIT is a jointly owned partnership by Market Economics, GNS Science and Resilient Organisations. It is an integrated spatial decision support tool that models the socio-economic impacts of disruption events as a result of infrastructure failure (ranging from individual failure through to wider failure events that are more complex). MERIT does this by propagating the economic impact (of infrastructure failure) through considering the impact of shocks on various components of the economy, such as household spend and gross domestic product. The economic model is structured from a set of economic accounts that contain 106 industries and 205 commodity types. These can be aggregated as appropriate, depending on the context of the assessment (the economic model is set up to take any selected industry/commodity concordance).

In theory, all forms of infrastructure can be addressed, as long as the necessary inputs for the economic model are generated through appropriate interfacing models. The Business Behaviours Model, which has been constructed primarily out of information from the Christchurch earthquakes, is one of the core interfacing models available. It examines the way losses in service from lifelines infrastructure affect business 'operability', which is then input into the economic model. The Business Behaviours Model works best for electricity, telecommunications, water and wastewater, while also considering the way premises and neighbourhoods are affected. It has been modified for the Wellington Lifelines Regional Resilience Project to address series outages from transport (isolation). The structure of the model and its components is shown in figure 5.3.

Figure 5.3 MERIT model components (MERIT, 2020)



SAMS = social accounting models; IOs = inputs–outputs

5.3.3.1 Commentary

MERIT is a 'mature' analytical model that has reached a high level of code stability and is part of a vested internal analytical process. In general, the tool's usage is limited to internal application by the organisations that developed it, although it has been deployed for analyses and reporting for external clients. For example, Waka Kotahi has adapted MERIT for the development of an online tool for rapid economic evaluation of road closure scenarios (New Zealand Transport Agency, n.d.).

MERIT is limited to considering economic impacts from shock events to the infrastructure system. It relies on having hazard and interdependency information input into the tool to be able to generate the potential economic impacts from a given event.

5.3.4 University of Auckland Infrastructure Interdependency Model

The UoA Infrastructure Interdependency Model was developed as part of an ongoing research project (Zorn & Shamseldin, 2015; Zorn et al., 2018). The model's main aim was to assess the direct and indirect impacts of infrastructure outages. This was subsequently extended to consider the way localised failure from a natural hazard event propagates across multiple dependent networks with respect to spatial extent and level of disruption (see figure 5.2). The model can be applied for a range of resolutions, from local through to national scales (Zorn et al., 2020).

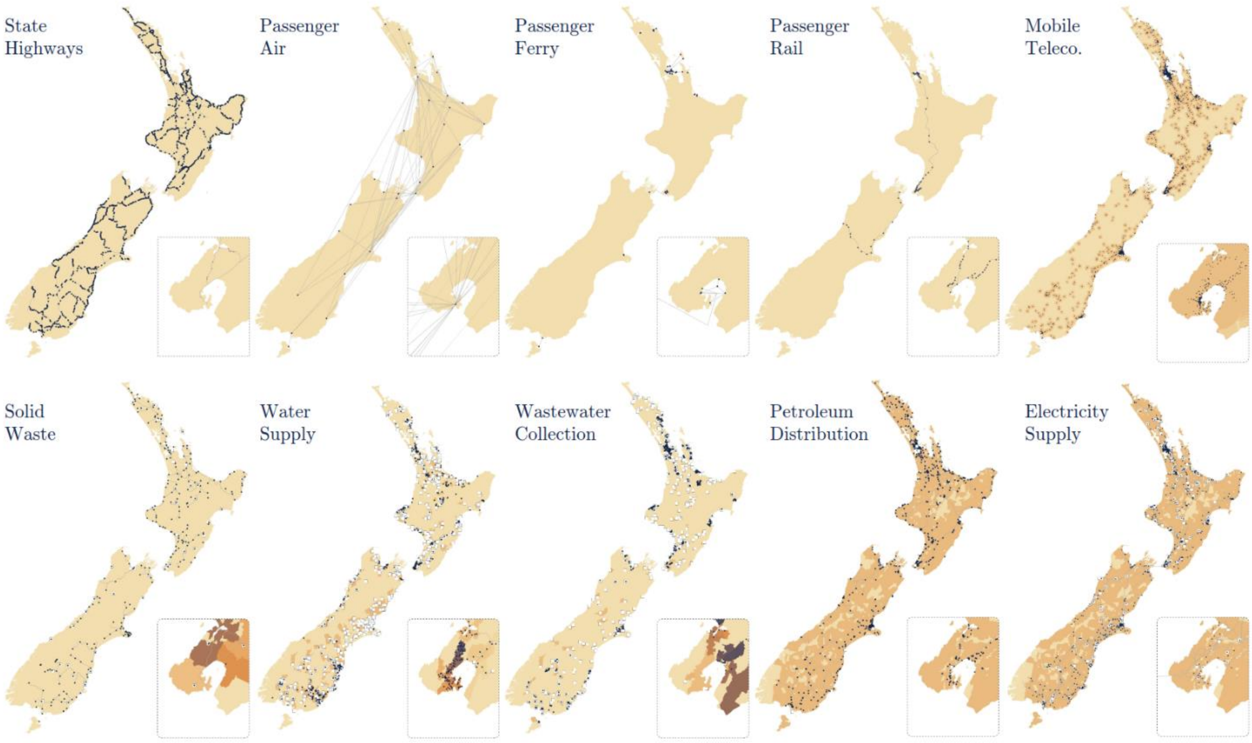
The model is currently a series of Python scripts using a framework combining 1) model build, 2) disruptive scenario, 3) failure propagation, and 4) disruption metrics. To build the model (step 1), the users configure the networks using spatial infrastructure data and create source-sink connectivity paths within and between dependent infrastructures, while customer demand is attributed to the spatial area units. The disruptive scenario (step 2) is characterised as direct damage to assets estimated using a user-input hazard scenario and asset-specific vulnerability functions. Failure propagation (step 3) assesses how upstream failures and dependent infrastructures are affected by the direct damage, rerouting services if possible. Disruption is assessed (step 4) based on the reduced level/loss of service and spatial analysis to model the outage extent and number of people affected.

5.3.4.1 Commentary

The UoA model is a ‘research’/‘developed’ analytical model that has reached a high level of code stability and is part of a vested internal analytical process. The model’s usage is limited to internal application by the UoA.

The model is hazard agnostic and allows for user input for hazard and damage data. The model primarily focuses on infrastructure damage and level of service (figure 5.4), but there is the potential for it to integrate with economic models such as MERIT. The model is customisable, with additional features easily added, such as characterisation of dependencies. As there is no user-interface for the model, it requires advanced expertise to input datasets and run the models with Python scripting.

Figure 5.4 Representations of the studied infrastructure networks developed by the UoA model, with insets for the Wellington region (Zorn et al., 2017)

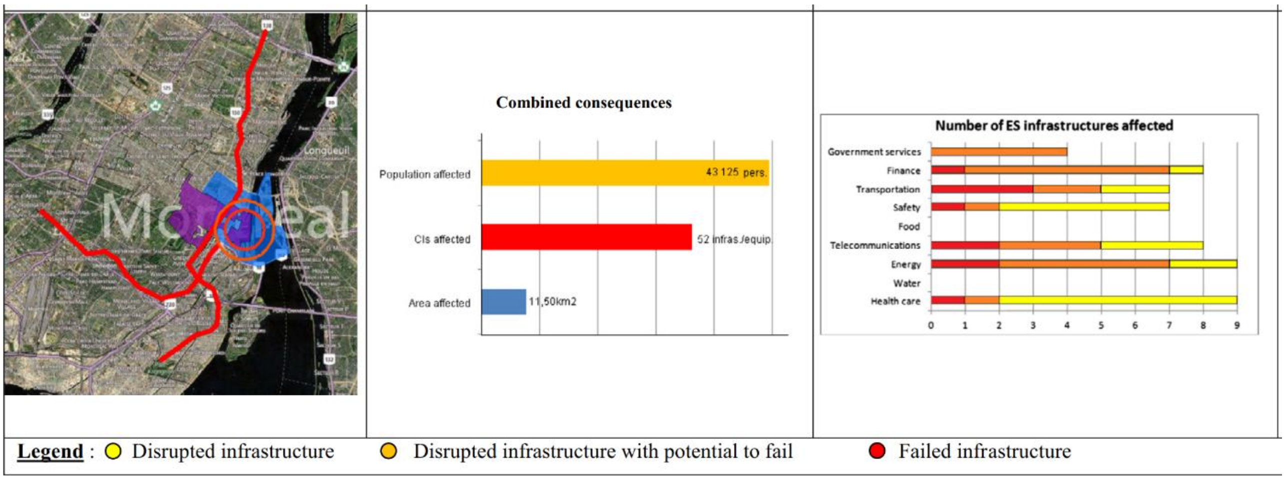


5.3.5 DOMINO

DOMINO is the result of a collaboration between critical infrastructure managers and the Centre Risque & Performance of Polytechnique Montréal (Polytechnique Montréal, n.d.). It is a decision support tool that anticipates and models the spatial and temporal spread of domino effects between interdependent infrastructures. The functioning of the tool is based on a consequence-based risk management approach, which aims to assess the impact of the failure of a critical infrastructure element without considering the causes that led to this failure. The results produced by DOMINO allow infrastructure managers to put in place coherent prevention and protection measures, allowing them to mitigate risks related to interdependencies.

Infrastructure providers upload their own data, which are either the exact location (represented by a point) or an area it is situated within. At this point, the infrastructure provider can identify dependencies and from where they receive relevant services; for example, for a pump station, this may be the relevant power substation providing power. If the site has any specific on-site mitigation (backup) options, a ‘traffic-light’ rating (green/yellow/orange/red) is assigned, along with a time duration, to represent the impact to the site’s function due to loss of input from the dependent infrastructure. For example, a pump station that loses power supply from the grid might have on-site generation and be able to function at full capacity (green) for six hours, or a further 12 hours at significantly reduced output (orange), after which it will cease output (red). This allows for a temporal representation of not only the cascading effects due to an initial infrastructure failure but also the way that changes over time across the area. An example output is shown in figure 5.5 (Delvosalle et al., 2017).

Figure 5.5 DOMINO model example (Delvosalle et al., 2017, p. 30)



5.3.5.1 Commentary

The DOMINO model is a ‘developed’ analytical model that has reached a high level of code stability. Currently, the model’s application is restricted to cities in Canada, but development so it can be applied to other international centres is underway.

The model is hazard agnostic and allows the user to input either a failure point in the network or an external hazard. The model focuses primarily on modelling infrastructure level of service and failure propagation. It is designed to accept stakeholder-generated asset information and allow operators to run the model and analyse the output.

5.3.6 Summary and comparison of models

Table 5.1 provides a summary comparison of each of the interdependency models against a set of categories that relate to the specific questions asked in the interviews.

Table 5.1 Summary table comparing interdependency models

Category	XDI Platform	CIrcle	UoA	MERIT	DOMINO
Model overview	A suite of tools that can be used to assess direct and cross-dependent services affected by climate hazards.	Interactive stakeholder engagement tool for creating and viewing dependent critical services in a visual workshop environment.	Academic model developed as part of a PhD project to assess the way impacts from a natural hazard event propagate across dependent infrastructures.	An economic model for assessing the disruption to a range of sectors and the way that affects the economy.	Used in Montreal and Quebec City but looking at the wider Vancouver Emergency Management office for Montreal, validated for Quebec City. Networks created for infrastructure. Failures created using radius, polygons, individual infrastructure and input from GeoJSON. Provides time stamps and the way outages propagate. A planning tool, but could be used in a crisis. Limit on simulations is 72 hours, based on the stakeholder feedback.
Model user interface (software, GIS platform, other)	Inputs the exposure datasets, infers the relationships and presents the information back to the clients.	Web-based or desktop application for user use.	Python script.	Application built using Vensim®. Model interfaces typically programmed in R, Microsoft Excel.	Web-based spatial map system.
Primary purpose of the model	Risk/vulnerability assessment for climate hazards at an asset level. Cross dependency concerns supply chain risk.	Engagement tool to identify cascading effects between infrastructures.	Risk, exposure and interdependency analysis.	Assesses economic interdependencies.	Assessing infrastructure interdependency. Outages assessed based on time and level of service of infrastructure site.
Data visualisation format	Secure web-based interface for maps, detailed information graphs and summary available.	Visualised as a simple illustrative diagram (see figure 5.1).	Spatial and data tables.	Output can be viewed as graphs in the software, or exported as data for post processing in other data visualisation packages (eg R, GIS).	Spatial, data logs, tables and auto-generated reports. Can email to specific pre-defined sectors.

Category	XDI Platform	CIrcle	UoA	MERIT	DOMINO
Infrastructure/sectors considered by the model	All built assets (eg transport, utilities, commercial premises).	No limitations, user dependent.	No limitations, user dependent.	Economic model is structured from a set of economic accounts that contain 106 industries and 205 commodity types.	Added by infrastructure provider manually for points, line and polygons. Bulk upload available to DOMINO.
Consideration of hazard and/or damage	Global climate hazard datasets, assesses damage using engineering standard failure modes.	The web-based version of the tool is tailored for flood, but the desktop version can include other hazards.	Yes.	N/A	Can incorporate hazard footprints as polygons, GeoJSON footprint. Binary damage/failure.
Consideration of asset outage degree (eg partial, complete)	Engineering standards failures modes can assess both types of damage, which could lead to partial or full failure of the asset.	The tool appears to assess damage/disruption, but no comment on how it does this.	Dependent on the asset and vulnerability characterisation.	This work is typically undertaken by GNS Science, using their RiskScape model and related resources.	Yes.
Maximum number of interdependent elements	No limit.	Typically limited to 10 different infrastructures for the workshop.	No limit.	N/A	No limit.
Includes economic analysis	No.	No.	No, but could be modified.	Yes.	No.
Interdependencies formed automatically or manually	Automated model infers at a first pass, before refinements.	User-defined interdependencies between infrastructures as part of a workshop.	User-defined interdependencies when developing the network, some logical assumptions in the code.	Economic interdependencies are automatically derived. Infrastructure dependencies are derived by GNS Science.	Infrastructure providers add asset data (not DOMINO developers). Dependency was developed in a workshop environment by all providers.
Characterisation of typology	No.	Only considers physical and digital.	Only considers physical, digital and geographic typologies.	No – focuses on economic interdependencies.	Only considers physical and digital.

Category	XDI Platform	CIrcle	UoA	MERIT	DOMINO
Characterisation of interdependencies (eg directionality, strength)	Assesses points of redundancy, upstream risk assessment and transfers to downstream.	Directionality between infrastructures can be defined from users.	Characteristics can be added into the code.	Not in the economic model.	Directionality is part of the relationship definition. Strength is partially related to the mitigation provided on site, through the 'level of operation' rating.
Number of cascades the model can assess	First order.	No limit to the order, only limited by the number of infrastructures input.	No limit.	No limit for the economic model.	No limit.
Data input and output formats	Can be static or connect via application programming interface.	Does not input asset data.	Currently a static approach based on available data.	Project dependent.	Infrastructure providers add their own asset data, either the exact location or the zone in which their asset is situated.
External input data licensing	Regular update cycle if the client is a 'software as a service' customer. Regular updates with public domain assets as well as some specific purchased hazard datasets.	Does not use asset data.	Has not been explored.	On a case-by-case basis.	Relies on providers to maintain the updated data.

5.4 Discussion

Each of the models reviewed has different purposes and associated strengths and weaknesses. The CIrcle model by Deltares is primarily a stakeholder-driven tool for use within workshop situations. In contrast, the XDI, UoA and DOMINO models can all be classified as infrastructure interdependency models. The XDI tool has an integrated climate hazard engine and has been designed primarily to model climate hazard impacts on infrastructure and assess first-order interdependencies. In contrast, the UoA model has been developed specifically as a model to propagate infrastructure failures across complex (multiple-order) interdependent networks and assess impacts in terms of outage and number of people affected. The DOMINO tool also allows specific user input of interdependencies. Then it models the spatial extent of impacts and can incorporate an operational status via a 'traffic light' system. Finally, MERIT has been designed to assess the economic impacts that result from an external shock and model the cascading effects. It does not model infrastructure interdependencies.

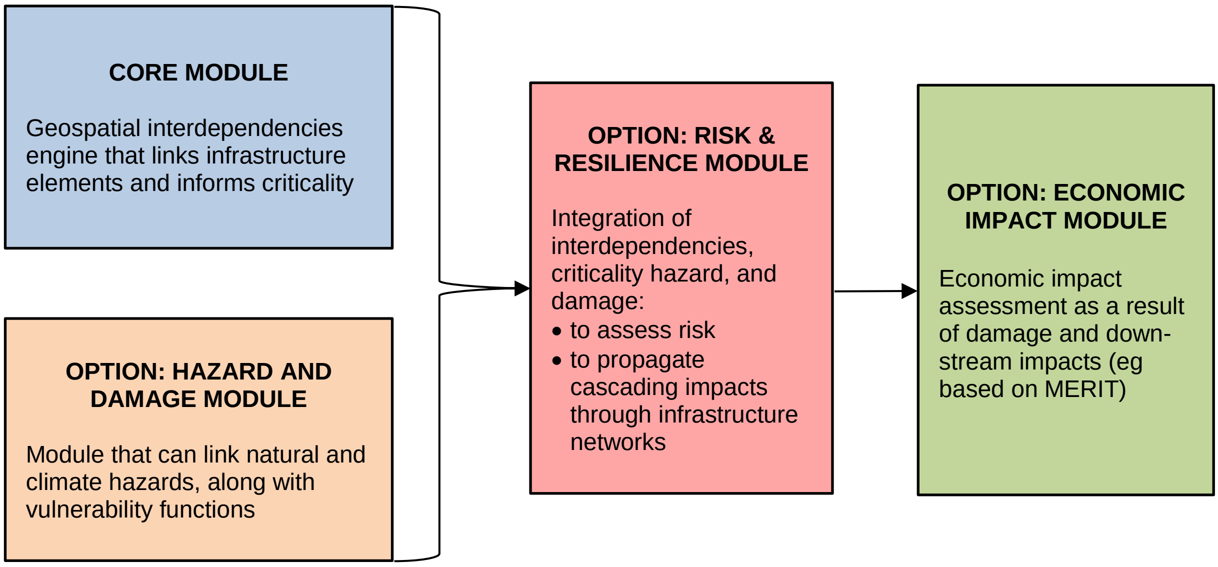
Each of the systems reviewed has its own strengths, particularly the propagation functions within the UoA tool and DOMINO, as well as the operational status 'traffic light' functionality within DOMINO. In addition, the UoA tool can be linked to hazard and damage information to model outage extents and population affected. However, none of the tools adequately address all the key interdependency typologies identified (particularly geographic), nor do they rate interdependencies incorporating criteria such as strength.

Section 6 takes forward the information from the previous sections and this review of available tools and proposes an approach for assessing interdependencies that aligns with the literature review and addresses the gaps within the existing tools and platforms.

6 Recommended assessment approach for Waka Kotahi

This section proposes an approach for assessing interdependencies that aligns with the findings of the literature review and addresses the gaps within the existing tools and platforms reviewed in section 5. The proposed framework consists of a core interdependencies module, with optional modules that could be added to provide additional/enhanced functionality (see figure 6.1).

Figure 6.1 Proposed interdependency framework



The core module would link geospatial infrastructure data, evaluate interdependencies and link to criticality. The hazard and damage modules could be included to input hazard shocks and stresses, as well as generate estimates of damage based on asset vulnerability functions. The UoA model and XDI Platform currently have this functionality, with the XDI Platform focusing on climatic hazards. Other sources of datasets could be hazard assessments such as the Global Earthquake Model, the New Zealand National Seismic Hazard Model (GNS Science) or developed flood models. Vulnerability functions could be obtained from a range of sources or from published material such as the US-developed HAZUS tool (Federal Emergency Management Agency, 2013) and the New Zealand-developed RiskScape (Reese & Ramsay, 2010).

The risk and resilience module could bring together the various components of hazard, asset damage and interdependency analysis, developing a comprehensive ‘risk and resilience’ picture. In addition, failures propagated through interdependent networks and outage spatial and/or temporal extents could be estimated, along with numbers of people and businesses potentially affected. An economic impact module could be incorporated to assess the economic impact to the wider economy resulting from infrastructure damage, such as tourism, retail and gross domestic product. MERIT would offer this functionality, and there is the potential for datasets to integrate.

These option modules are presented only as a concept at this stage, bearing in mind that the core focus of this research is on interdependency modelling. They are described in greater detail in section 6.2.

6.1 Core module: interdependency and criticality assessment approach

The proposed core interdependency module is the ‘engine’ into which different infrastructure datasets (eg roads, rail, power) can be incorporated into a geospatial model, together with the relevant dependency characteristics (ie strength, directionality and order).

At a high level, the core module would:

- accept input asset network data
- allow the user to create linkages between interdependent networks
- evaluate interdependencies and link this information to a modified criticality.

As discussed in section 4.1, there are four interdependency typologies: physical, digital, geographic and organisational. Given the focus of this research on physical infrastructure, the proposed assessment approach focuses on physical, digital and geographic dependencies only, addressing these three typologies separately, as follows.

- Physical and digital interdependency assessment: These both act in a similar, linear manner and have an associated strength, order and directionality (see section 4.2). For these typologies, there is connectivity between infrastructures, with the output of an upstream infrastructure being the input to a downstream infrastructure. This assessment requires the development of an interconnected network across infrastructures and sectors and thereby allows an evaluation of the propagation of failure and outage.
- Geographic interdependency assessment: This typology exists where there is co-location of multiple assets within a corridor and it is different in nature to physical and digital interdependencies. In this case, the interdependency exists because of the risk of failure of one infrastructure leading to the damage or failure of a nearby/co-located infrastructure. This is called an infrastructure ‘hot spot’ (New Zealand Lifelines Council, 2017).

Further, this research proposes that physical and digital interdependency assessment should apply primarily to critical infrastructure sites/locations (eg power generation sites, wastewater treatment facilities and hospitals) and geographic interdependency assessment should apply primarily to linear infrastructure only (eg water supply pipes, power and telecommunication cables). The reason for this differentiation is that geographically co-located infrastructures are typically linear, occupying the same infrastructures corridors, without any direct dependencies between them. In contrast, physical and digital interdependencies typically exist between key sectors and sites/locations. These interdependent relationships at a site level are reliant on the service provided by linear roads, cables or pipes. These linear elements have a level of criticality that should be related to the site or location(s) served and form the basis of the proposed assessment approach outlined below.

6.1.1 Criticality assessment approach

As discussed in section 3.2.1, an assessment of interdependencies influences and informs an understanding of criticality. Therefore, this research proposes a combined approach for assessing both interdependencies and criticality. Currently within New Zealand, there is no consistent or agreed approach for assessing or ranking criticality across different infrastructure types. While this development is beyond the scope of this research, this is a key parameter to enable the implementation of the interdependency assessment approach detailed in this report.

The proposed approach for assessing interdependencies utilises a common criticality rating of 1 (low) to 5 (high). This aligns with commonly applied criticality ratings and can provide adequate resolution for the assessment. Table 6.1 contains a proposed criticality rating with some example descriptors for a national-level assessment (adapted from Hughes, 2016). These criticality descriptors can vary, depending on whether the context is at the local, regional or national level.

Table 6.1 Proposed criticality ratings, with descriptors for a national assessment (modified from Hughes, 2016, p. 12)

Colour	Category	Example description (national-level context)
1	Minimal	A local infrastructure element whose failure would have a minimal local economic or social impact.
2	Minor	A local infrastructure element whose failure would have a moderate to serious local economic or social impact, or it is a locally important lifeline, ensuring access or continuity of supply of essential services during an unforeseen event.
3	Moderate	An important infrastructure element whose failure would have a significant economic or social impact to a region, or it is a significant lifeline, ensuring access or continuity of supply of essential services during an unforeseen event.
4	Major	A major infrastructure element whose failure would have a significant economic or social impact to more than one region, or it is a regionally significant lifeline, ensuring access or continuity of supply of essential services during an unforeseen event.
5	Vital	A vital infrastructure element whose failure would have a nationally significant economic or social impact, or it is a nationally significant lifeline, ensuring access or continuity of supply of essential services during an unforeseen event.

The proposed interdependency assessment approach suggests two forms of criticality for the purposes of this assessment:

- Base criticality: This is an input and relates to the number of people, users or properties served by an infrastructure element. An example of this for the New Zealand road network is the Waka Kotahi ONRC, which classifies roads primarily according to traffic volume (New Zealand Transport Agency, 2016, 2018c). Importantly, the base criticality should not incorporate considerations of downstream infrastructure criticality, to avoid double-counting with the modified criticality described in the next point.
- Modified criticality: This is an output and reflects the influence of the interdependency relationship on the base criticality of an upstream infrastructure (see section 6.1.2) or corridor (see section 6.1.5). The approach for assessing modified criticality will be different for the physical and digital interdependency and the geographic interdependency typologies, as discussed in the next section.

6.1.2 Physical and digital typology assessment approach

Assessing physical and digital interdependencies requires an understanding of the directionality and strength of the interdependency relationships. While it is important to understand order, this aspect does not form part of the proposed assessment because order can change and will be specific to where a failure occurs within a network of interconnected infrastructures. In the context of transportation, a transport link is generally the initial failure in a causal chain, leading to a first-order impact on a downstream infrastructure.

The proposed process for assessing physical and digital interdependencies has the following three steps, which are detailed in the following subsections.

- Step 1: Identify interdependent relationships and develop causal network.
- Step 2: Calculate dependency rating and modified criticality.
- Step 3: Extend the modified criticality along the road network.

The process that is outlined below contains a range of example assessment matrices. These will need to be reviewed and sensitivity tested prior to any implementation, as discussed in section 8.

6.1.2.1 Step 1: Identify interdependency relationships

Step 1, assessing physical and digital interdependencies, identifies the links and relationships among the infrastructures, expressed using a causal chain. The dependency dimensions (directionality and strength) are then added as attributes to each relationship, along with the base criticality. Directionality is either unidirectional or bidirectional.

To assess the strength of a dependency relationship, a three-level (low/moderate/high) rating is proposed, using classifications based on the New Zealand Lifelines Council (2017), shown in table 6.2.

Table 6.2 Proposed strength rating

Strength rating	Strength descriptor
Low	Minimal requirement to maintain functionality/full level of service during business as usual and post-event.
Moderate	Minimal requirement to maintain functionality/full level of service during business as usual BUT important in maintaining at least a partial level of service post-event.
High	Required for 100% of level of service during business as usual and post-event.

The strength of dependency relationships can increase in the change from a business-as-usual environment to a post-event environment (see section 4.3.2), as reflected in the descriptors used in table 6.2. For example, access to a cell tower is not often required during a business-as-usual environment, but following an event, access for repair and maintenance would be required to restore the cell tower service. This would result in a strength parameter of ‘moderate’ for the relationship between road and cell tower.

6.1.2.2 Step 2: Calculate dependency rating and modified criticality

This step is undertaken with interdependent pairs, working from the furthest downstream infrastructure in an upstream direction. Two sub-steps (2a and 2b) are undertaken for each pair, prior to moving to the next upstream pair. For example, in figure 6.2 (section 6.1.3), this would mean starting with the hospital and substation, followed by the substation and road 1.

Steps 2a and 2b are iterative, in that the dependency rating for the most-downstream infrastructure will result in a modified criticality for the next-upstream infrastructure. This modified criticality is used to calculate the dependency rating for the next most upstream infrastructure and so on.

Step 2a: Calculate dependency rating

This involves developing a dependency rating based on the strength of the dependency relationship and downstream criticality, using tables 6.3 and 6.4.

Table 6.3 Dependency rating table combining strength of the relationship and downstream infrastructure

Dependency rating		Criticality of downstream infrastructure*				
		Minimal	Minor	Moderate	Major	Vital
Strength	Low					
	Medium					
	High					

*This should be the downstream modified criticality if this has been calculated.

Table 6.4 Dependency rating key

Colour	Category	Description
1	Negligible	Upstream infrastructure has a negligible impact on the downstream infrastructure level of service.
2	Minor	Upstream infrastructure has a minor impact on the downstream infrastructure level of service.
3	Moderate	Upstream infrastructure has a moderate impact on the downstream infrastructure level of service, resulting in a partial reduction in functionality.
4	Significant	Upstream infrastructure has a significant impact on the downstream infrastructure level of service, resulting in a significant reduction in functionality.
5	Essential	Failure of upstream infrastructure results in a complete loss of functionality of the downstream infrastructure.

For example, if a particular road serves a downstream water treatment plant of criticality 4 (significant) and that road has a moderate strength rating (see table 6.2), then a dependency rating of 4M is generated (see table 6.3) which is classed as significant.

As noted above, where an infrastructure receives a modified criticality (step 2b), this should be used as an input for calculating the dependency rating.

Step 2b: Evaluate modified criticality

Previous work by Hughes (2016) and Rebello et al. (2019) explored an approach to assessing the criticality of roads based on the ONRC and the number and criticality of lifeline and essential services that are accessed by the road. While this approach modifies the criticality of the road from its base criticality derived from the ONRC, it does not consider the strength of the dependency relationship(s) between the road and the critical infrastructure(s) served. Therefore, this research proposes a modified criticality score for a given infrastructure, based on the dependency rating (step 2a) and the total number of downstream dependencies (using tables 6.5 and 6.6).

Table 6.5 Example modified criticality table combining the maximum dependency rating and the number of downstream infrastructure dependencies within a corridor

Modified criticality		Maximum dependency rating based on relationships with downstream infrastructures				
		Negligible	Minor	Moderate	Significant	Essential
Number of downstream infrastructure dependencies	1					
	2–4					
	5–10					
	> 11					

Table 6.6 Modified criticality key

Colour	Category
1	Minimal
2	Minor
3	Moderate
4	Major
5	Vital

6.1.2.3 Step 3: Extend the modified criticality along the road network

Following the calculation of the modified criticality for all infrastructure, the criticality of the modified road network is extended for sections of adjacent network to ensure that a modified section of road only connects to an equal- or higher-criticality road (along the shortest pathway to the highest-criticality road). This follows the approach presented in Rebello et al. (2019). For example, for a criticality 3 road providing access to a criticality 5 hospital, the entire pathway would be modified to criticality 5 until it reached the state highway. Trace routines with geospatial networks of the road can support the implementation of this (see section 6.3 for further information).

6.1.3 Physical and digital interdependency example

An example of the physical and digital interdependency assessment is presented below for the network shown in figure 6.2 and detailed in table 6.7. This shows a road network consisting of three roads, each servicing a power substation, a hospital and water supply tanks. Water supply tank 2 and the power substation also serve the hospital. Criticality ratings for each of the six elements are shown in brackets and the strength ratings are shown adjacent to the connecting lines.

Step 2 is completed by applying the dependency matrix (see table 6.3) and modified criticality (see table 6.5), using the example causal chain. As mentioned above, the iterative process starts at the furthest downstream infrastructure, which in the example is the hospital. The outputs of the dependency ratings and maximum criticality (MC) for the infrastructures are shown in table 6.8.

Figure 6.2 Example infrastructure dependency network as a causal chain

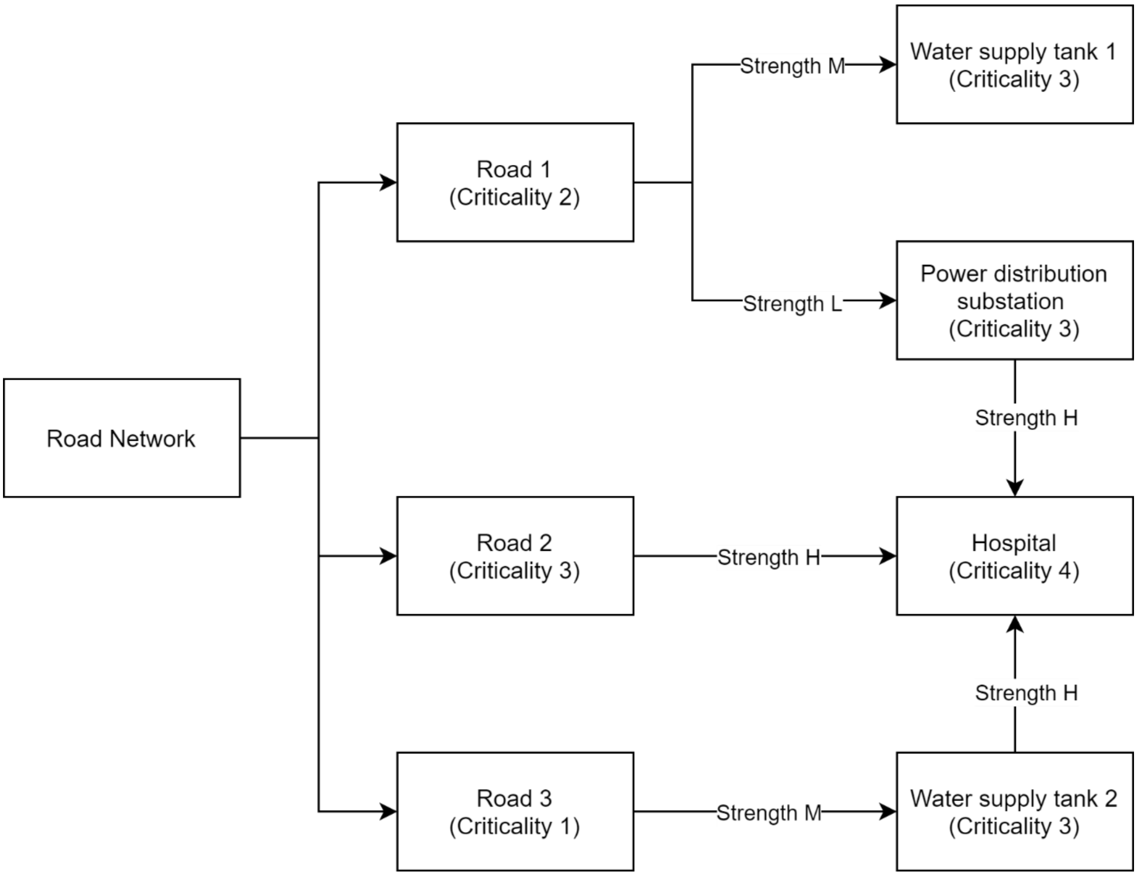


Table 6.7 Example infrastructure dependency relationship dimensions

Upstream infrastructure (base criticality rating)	Downstream infrastructure (base criticality rating)	Order from road network	Strength	Comment regarding strength
Road 1 (C2)	Water supply tank 1 (C3)	1st	M	Road access is sometimes required for staff to conduct maintenance.
Road 1 (C2)	Power distribution (C3)	1st	L	Road access is rarely required for staff to conduct maintenance.
Road 2 (C3)	Hospital (C4)	1st	H	Road required for hospital access and operation.
Road 3 (C1)	Water supply tank 2 (C3)	1st	M	Road access is sometimes required for staff to conduct maintenance.
Power distribution (C3)	Hospital (C4)	2nd	H	Essential for operation.
Water supply tank 2 (C3)	Hospital (C4)	2nd	H	Essential for operation.

Table 6.8 Step 2: Dependency rating and modified criticality output for the example infrastructure network in figure 6.2 and table 6.7

Downstream infrastructure	Strength	Upstream infrastructure	Dependency rating (see table 6.3)	Modified criticality for upstream infrastructure (see table 6.5)
Hospital (C4)	H	Power distribution (C3)	4	C4
Hospital (C4)	H	Water supply tank 2 (C3)	4	C4
Hospital (C4)	H	Road 2 (C3)	4	C4[a]
Water supply tank 1 (C3)	M	Road 1 (C2)	3	C3[c]
Power distribution (C4)[b]	L	Road 1 (C2)	2	
Water supply tank 2 (C4)[b]	M	Road 3 (C1)	3	C3[d]

[a] The modified criticality for road 2 is derived from the maximum of the base criticality (3) and modified criticality (from table 6.3) relating to the single dependency with the hospital with criticality (4).

[b] Criticality is increased from a base level of 3 to a modified level of 4, because of the dependency rating with the hospital.

[c] The modified criticality for road 1 is derived from the maximum of the base criticality (2) and modified criticality (3). The modified criticality is derived using table 6.5, based on there being two dependencies with an MC of 2 – relating to the power substation (2) and water supply tank (2).

[d] The modified criticality for road 3 is derived from the maximum of the base criticality (1) and modified criticality (from table 6.4), relating to the single dependency with the water supply tank with a criticality of (3).

As presented in table 6.8, in all cases the modified criticality of the upstream infrastructure (road or water supply tank) increases due to the higher criticality of the hospital (2nd order) and high strength of the dependencies. This, in turn, produces a greater modified criticality than the base criticality for each of the dependent infrastructures. For road 1, given there are multiple dependencies, the modified criticality is higher than the individual modified criticalities for each (refer to table 6.4).

For this example, step 3 is not presented because it requires an understanding of the broader network. This is demonstrated in the next section.

6.1.4 Physical and digital interdependency pilot study

This section presents a pilot study application for the physical and digital interdependency for an area within the Queenstown-Lakes District. This makes use of the same causal network presented in figure 6.2. For this pilot study, four infrastructure types are considered:

- roads
- power distribution substation locations
- water supply pump station locations
- hospital.

The spatial data for each infrastructure type listed are characterised with criticality ratings from 1 (minor) to 5 (vital) (see table 6.9) and then mapped (see figure 6.3).

Table 6.9 Infrastructure data sourced for the assessment

Infrastructure type	Criticality comment
Roads	Reclassified the six ONRC levels to 1–5 by aligning the top two ONRC classes ‘regional’ and ‘national’ to the top criticality of 5, and the other four remaining at 1–4.
Water supply tanks	Refer to figure 6.3 for the criticality rating.
Power distribution substations	Refer to figure 6.3 for the criticality rating.
Hospital	For the purposes of this assessment, the hospital is classified at the highest level, 5.

Through applying the proposed approach for assessing physical interdependencies, the output modified criticality is presented in figure 6.4. In the output from the pilot assessment, the modified criticality is greater than the base criticalities for the roads, substation and water supply tank (T5) that services the hospital. This is because of the high strength (3) and criticality (5) of the hospital. The modified criticality of the road that provides access to the water supply tank (T5) and substation is not greater than the base criticality, as the base criticality of the access road was already the maximum (5, a state highway). The road that provides access to the two water supply tanks (T2 and T3) receives a modified criticality from its base of 2 to 3, given there are two dependent infrastructures and a maximum individual modified criticality of 2. In contrast, the modified criticality of the road that supplies access to T1 does not change because of the strength of the relationship and having only one infrastructure on the road segment.

Following the calculation of each infrastructure’s modified criticality due to dependencies, the wider adjacent road network is then augmented (step 4). This is to ensure the criticality of any road segment along the shortest path, from the modified segment to the highest-criticality road, is equal to or greater than the modified segment. In the below example, this occurs for the roads near the hospital, as well as the northern access road to the airport. As the direct roads serving the hospital receive a criticality 5 rating, the roads joining to the state highway are also augmented to have a modified criticality of 5. This also occurs for all roads that provide access to the water supply tanks. An example is the road that provides access to water tank T7, which is calculated to have a modified criticality of 3. Subsequently, all the road segments leading east to connect to the highest-criticality road are also increased to the same modified criticality.

Figure 6.3 **Infrastructures considered in the physical and digital interdependency assessment pilot study for Queenstown**

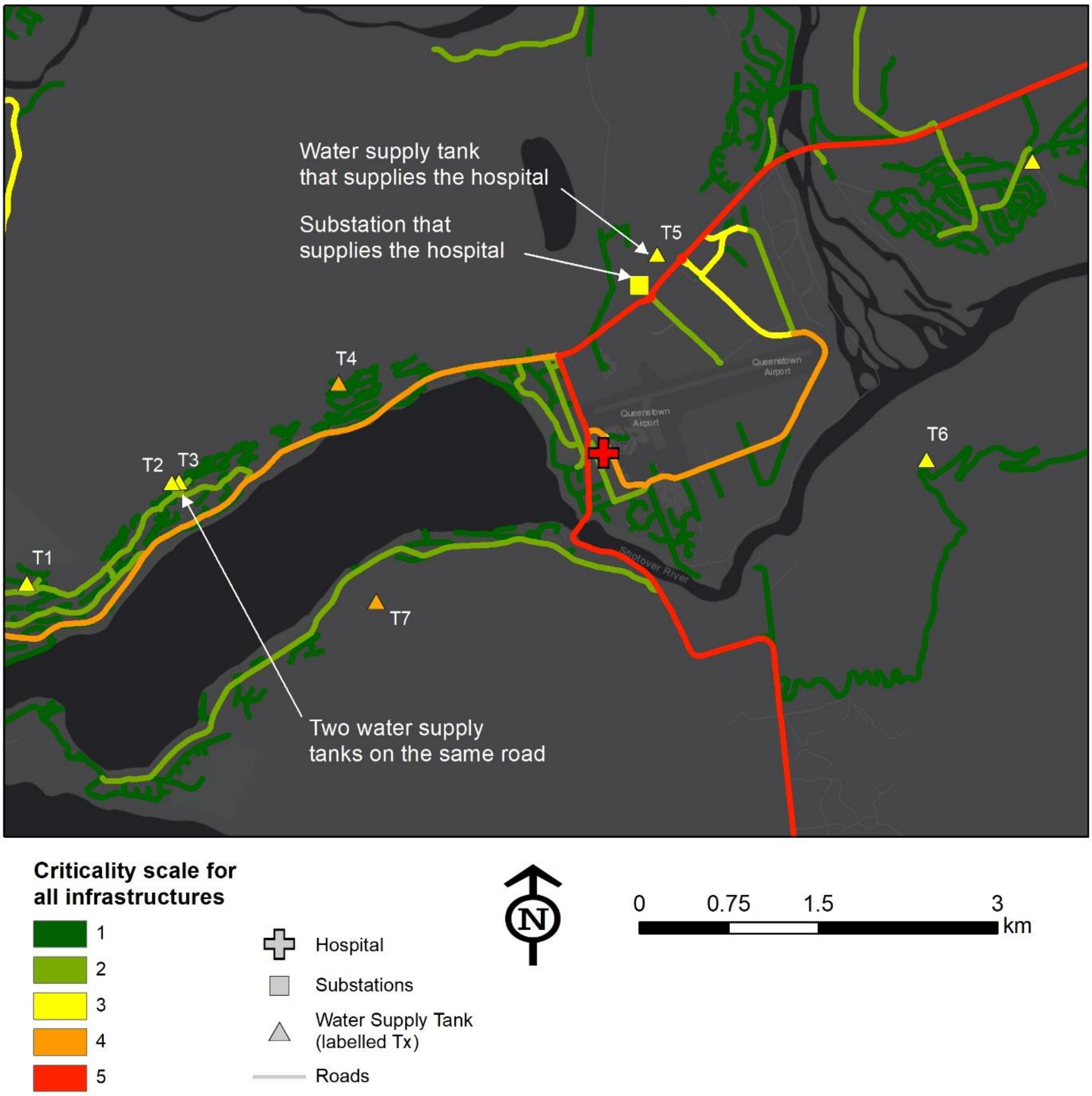
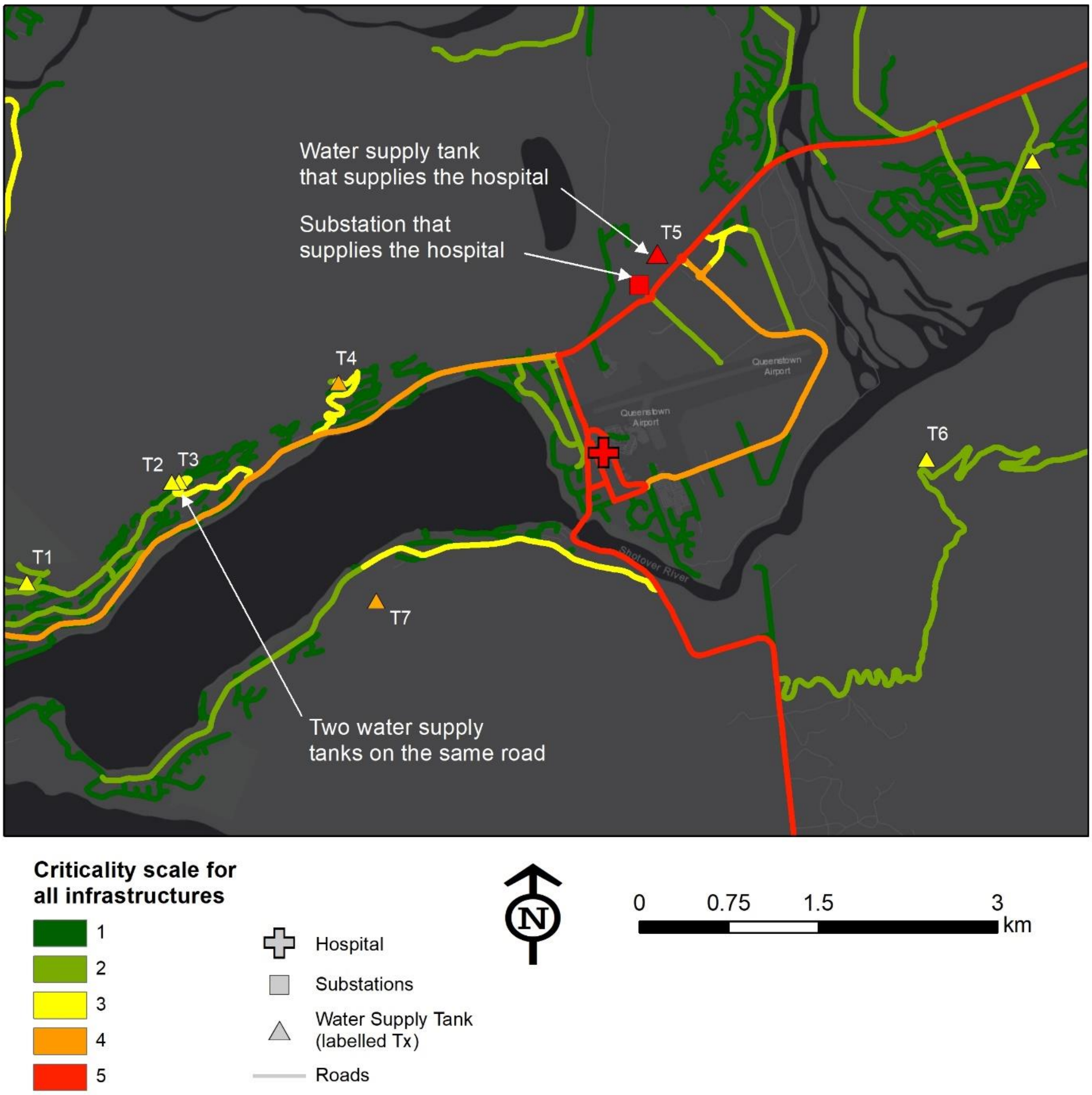


Figure 6.4 Output for the modified criticality ratings for the pilot study in Queenstown



6.1.5 Geographic interdependency assessment approach

The proposed approach to assessing geographic interdependencies requires the identification of the number and criticality of co-located infrastructures within defined area units. These units could be, for example:

- a grid with a defined cell size – eg 500 × 500 m, or
- a pre-defined corridor length – eg 100-metre-long segments of road with a defined width.

Given the transport emphasis for this assessment, the pre-defined length of roads should be used as corridors, classified depending on the land use or structure they are situated within, using the following three corridor classes:

- road reserves (road on the ground)
- bridges
- tunnels.

Bridges and tunnels are defined as corridors for their entire length, as they are largely homogenous throughout. Road reserve corridor units are defined by a pre-determined length.

Differentiating between the corridor and the infrastructures within the corridor is important, as it allows an independent assessment of the vulnerability of the corridor in relation to an external hazard event, using an appropriate vulnerability function (see section 6.2.1). For example, if assessing a road that is situated within a road reserve for damage from an earthquake, a road vulnerability function for earthquake hazard should be applied. However, if a road is situated on a bridge, then a bridge vulnerability function for earthquake hazard should be used. The difference in the corridor's primary construction allows an understanding of the duration of outage and ease of restoration.

The proposed process for assessing geographic interdependencies involves three steps, as detailed in the following subsections.

- Step 1: Establish corridors and identify geographically co-located infrastructures.
- Step 2: Determine the geographic interdependency rating (GIR).
- Step 3: Determine the modified corridor criticality (CC).

6.1.5.1 Step 1: Establish corridors and identify geographically co-located infrastructures

The first step is to identify the infrastructures within the assessment, typically spatially, using a geospatial platform. Corridors are established using the determined unit length (eg 100-metre-length units as described above) and buffering by an agreed corridor width to form the corridor areas within which to assess the co-located infrastructures.

6.1.5.2 Step 2: Determine GIR

The proposed approach to assessing geographic interdependencies involves calculating the sum of the criticality of each of the co-located infrastructures within a corridor. This follows equation 6.1 below.

$$geographic\ interdependency\ rating = \sum_{i=1}^{n} criticality_i$$

(Equation 6.1)

An example of this is a road reserve corridor consisting of a road with a criticality of 1, a buried gas main with a criticality of 5, and a power distribution line with criticality of 2. In this example, this would output a *GIR* = 1 + 5 + 2 = 8.

Further information can be aggregated to provide a greater resolution than just the GIR alone. Capturing the number of critical elements as well as the criticality rating of each means this information can be weighted collectively to determine an overall rating. For example, a single road with a criticality of 5 would have the same GIR as a corridor with five infrastructures of low criticality (1), but the number (N) and the MC would provide a greater level of detail for the corridor, which is then utilised within step 3. If the approach is implemented within a geospatial environment, the calculated parameters for each infrastructure can each be symbolised, allowing users to visualise the output.

6.1.5.3 Step 3: Determine modified CC

The next step of the proposed geographic interdependency assessment is to evaluate the modified criticality of the corridor by relating, for a given corridor, its GIR from step 2, and the MC. This approach provides a weighting for corridors with multiple co-located infrastructures towards those with higher criticality. A matrix approach (as shown in tables 6.10 and 6.11) provides a consistent rating using a scale of 1 to 5.

Table 6.10 Example modified CC table combining the GIR and MC

Modified CC		MC infrastructure in the corridor				
		Minimal	Minor	Moderate	Major	Vital
GIR	1–5					
	6–10					
	11–15					
	16–20					
	> 20					

Table 6.11 Modified CC key

Colour	Category
1	Minimal
2	Minor
3	Moderate
4	Major
5	Vital

The bands for the GIR have been set at a level deemed to give an appropriate spread. For example, at the low end, a GIR of 1–5 could result from one single infrastructure within the corridor of criticality of up to 5, or two of moderate/major criticality. A GIR of > 20 would result from, for example, 10 infrastructure elements with a criticality of two, or four elements with a criticality of 5.

6.1.6 Geographic interdependency example

An example of the geographic interdependency assessment is presented in figure 6.5. This illustrates two different roads of different base criticalities, each with three corridors within them. The blue section represents a bridge crossing a watercourse. The outputs based on steps 1 and 2 are presented in table 6.12.

Figure 6.5 Example to demonstrate the geographic interdependency assessment

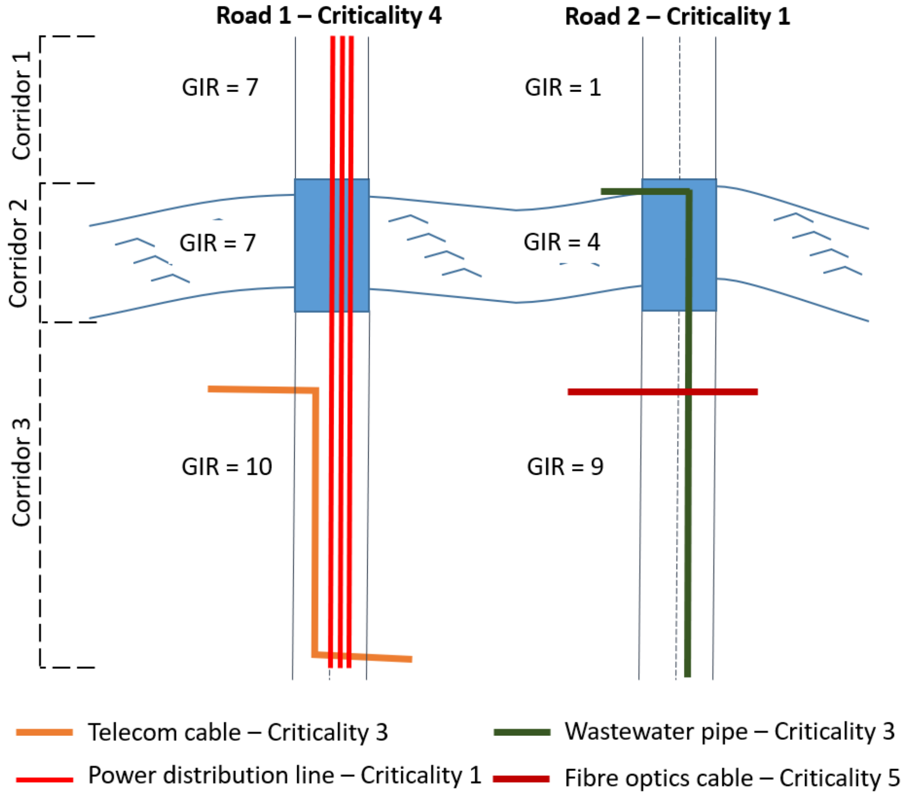


Table 6.12 Geographic interdependency assessment outputs for examples in figure 6.5

Road	Corridor	Corridor type	GIR	Number of infrastructures (N)	MC	Modified CC
Road 1	Corridor 1	Road reserve	7	4	4	4
Road 1	Corridor 2	Bridge	7	4	4	4
Road 1	Corridor 3	Road reserve	10	5	4	4
Road 2	Corridor 1	Road reserve	1	1	1	1
Road 2	Corridor 2	Bridge	4	2	3	2
Road 2	Corridor 3	Road reserve	9	3	5	5

In the example above, the outputs from road 1 corridor 3 (R1C3) when compared to road 2 corridor 3 (R2C3) demonstrate the difference when assessing geographic interdependencies with GIR alone, compared with the use of the MC. In R1C3, there are five infrastructures, with three infrastructures of criticality 1, one of criticality 3 and one with an MC of 4 (the road itself). This generates a GIR of 10, and a modified CC of 4. In contrast, R2C3 consists of three infrastructures, one of criticality 1 (the road itself), one of criticality 3 and one of criticality 5. This generates a GIR of 9 and a modified CC of 5.

This comparison indicates that R2C3 as a corridor is more critical overall, as it contains the criticality 5 fibre optic cable and the criticality 3 wastewater pipe, despite the road itself being only criticality 1.

6.1.7 Geographic interdependency pilot study

This section presents a pilot application for the geographic interdependency approach using data obtained from the Queenstown-Lakes District. Five infrastructure types are considered in this pilot study:

- roads
- critical lifeline locations
- power transmission and sub-transmission lines
- water supply pipes
- wastewater pipes.

The spatial data for each infrastructure type listed are characterised with criticality ratings of 1 (low) to 5 (high) (see table 6.13). A zoomed-in extent of the main centre of Queenstown is presented in figure 6.6.

Table 6.13 Infrastructure data sourced for the assessment

Infrastructure type	Criticality comment
Roads	Reclassified the six ONRC levels to 1–5 by aligning the top two ONRC classes, ‘regional’ and ‘national’, to the top criticality of 5.
Power transmission and sub-transmission lines	For the purposes of this assessment, all transmission and sub-transmission lines are classified at the highest level, 5.
Critical lifelines locations	For the purposes of this assessment, all critical lifelines locations are classified at the highest level, 5.
Water supply pipes	Characterised with a 1–5 criticality rating from Queenstown Lakes District Council.
Wastewater pipes	Characterised with a 1–5 criticality rating from Queenstown Lakes District Council.

Figure 6.6 Infrastructures considered in the geographic interdependency assessment pilot study

Road reserve corridors (see section 6.1.5) were determined using the road line data divided into 100-metre-long subsections with a width of 20 m. Bridge corridors were determined based on their full length. Geospatial analysis was carried out with the infrastructure data to calculate the following outputs, shown in figure 6.7:

- GIR
- number of infrastructures (N)
- MC
- modified CC.

In the output from the pilot study, two example roads were used to demonstrate the process in further detail:

- Shotover Street (SH6)
- Man Street.

The Shotover Street corridors contain a criticality 4 road. The water supply pipes within the corridor have an MC of 4 and the wastewater pipes have an MC of 2. The output GIR and N values for each corridor ranges from 11 to > 15 and 3 to 15, respectively. The MC for all corridors is consistently 4. Applying the CC assessment generates a modified CC of mostly 4 for all corridors on Shotover St, with some northern corridor segments at 5.

The Man Street corridors contain a criticality 2 road. The water supply pipes within the corridor have an MC of 5. Some of the corridors intersect with low-criticality wastewater pipes and the lower end of the road contains the sub-transmission power lines, with a criticality of 5. The output GIR for each corridor within Man St is mostly within the 11 to 15 range, increasing to 16 to 20 where the wastewater and/or power lines intersect. The N values of corridors along Man St vary where the wastewater and/or power lines intersect. The MC is 5 for all corridors because of the water supply main pipe running along all corridors; therefore, the modified CC generated for all corridors along Man St is also 5.

These two example corridors show how the criticality varies based on the number and MC of infrastructure that is co-located. Although Shotover Street can be considered more important because of the criticality of the road itself and the fact it contains more infrastructures, Man Street has the higher modified criticality score. This is due to the criticality of the water supply main and sub-transmission lines contained within the Man Street corridor.[2]

It can be seen that by applying this method in an automated geospatial process, the maps that are produced can identify criticalities by corridor segments across the network, as shown in figures 6.7 and 6.8.

[2] This example uses the supplied Queenstown Lakes District Council criticality ratings and is therefore limited by the degree of rigour/granularity used in determining these ratings.

Figure 6.7 Outputs from the geographic interdependency assessment for the pilot study in Queenstown: A) GIR; B) number of infrastructures (N)

Figure 6.8 Outputs from the geography interdependency assessment for the pilot study in Queenstown: C) MC; D) modified CC

6.2 Additional modules

Figure 6.1 (see the beginning of section 6) illustrates the way the core interdependencies module (which is the focus of this research) could be integrated with a 'hazard and vulnerability module', a 'risk and resilience module' and an 'economic impact module'. Each of these is discussed briefly below.

6.2.1 Hazard and vulnerability module

The hazard and vulnerability module can be used to assess the direct impact/damage resulting from an external hazard. This module can consist of input and assessment of hazard data (eg flood, earthquake) as well as data relating to the infrastructure vulnerability to a given hazard. Both these elements can then be used to estimate the level of impact or damage from a hazard. This module should cater for hazards that change with time, such those influenced and exacerbated by climate change.

6.2.1.1 Hazard

Hazards are often characterised by their recurrence interval, utilised primarily as part of computational model outputs. Recurrence intervals can be associated to a relative likelihood (see table 6.14) and this allows for different hazards, each with their own respective recurrence interval, to be assessed. The reason for using the hazard recurrence interval to represent the hazard likelihood is so the assessment is agnostic of the hazard type.

Table 6.14 Example hazard likelihood table

Likelihood	Rating	Recurrence interval	Hazard
Very likely	5	1 in 1–5 years	Flood, storm surge and landslide
Likely	4	1 in 5–10 years	Flood, storm surge and landslide
Moderate	3	1 in 10–100 years	Flood, storm surge and landslide
Unlikely	2	1 in 100–500 years	Flood, storm surge, landslide, earthquake, tsunami and volcanic eruptions
Rare	1	1 in > 500 years	Flood, storm surge, landslide, earthquake, tsunami and volcanic eruptions

The output of computational hazard models are typically a spatial hazard extent for a given recurrence interval, along with associated intensity metrics, which can vary across the hazard extent (see table 6.15 for examples). An example of this is for flooding, where the metric of flood depth is typically greater proximal to a river and low-lying land and shallower at elevated land and greater distances from the river. The spatial hazard extent and associated intensity metric can be attributed to the infrastructure asset data to determine the vulnerability, as discussed below.

Table 6.15 Example hazard and hazard intensity metrics

Hazard	Commonly applied hazard intensity metrics
Flood	Flood depth, flood velocity
Earthquake	Modified Mercalli intensity scale, Peak ground acceleration
Tsunami	Inundation depth, inundation velocity
Tropical cyclone	Wind speed
Volcanic ashfall	Ash depth, ash load

6.2.1.2 Vulnerability

The vulnerability of infrastructure relates to the expected level of damage to an infrastructure asset under a given hazard intensity. Published vulnerability (or fragility) functions are available for a range of asset types, materials and ages, as well as for a range of natural hazards. These can be used to estimate the degree of damage for a given asset type and the corresponding hazard intensity, as described above.

A fundamental limitation with assessing vulnerability is the availability of appropriate functions for each infrastructure and hazard combination. If functions are not available, then expert elicitation can be used to estimate levels of damage for different hazard intensities. The output of vulnerability functions is typically a damage percentage or probability of damage exceedance, which can then be related to a qualitative damage score (1–5 value) and descriptor (see table 6.16).

Table 6.16 Example damage bands based on damage percentage classifications

Damage score	Damage descriptor	Example damage percentage classification
1	Minor	0–20%
2	Moderate	21–40%
3	Major	41–60%
4	Significant	61–80%
5	Extreme	81–100%

6.2.2 Risk and resilience module

ISO 31000 (ISO, 2018) sets out international best practice for risk management. It defines risk as ‘the effect of uncertainty on objectives’ (see section 3.2). To support this, a risk and resilience module is proposed here, to integrate outputs from the interdependencies and criticality assessment (core module), and the hazard and damage module (see section 6.2.1).

Two levels of assessment can be undertaken, as detailed in the following subsections:

1. Direct risk to infrastructure
2. Propagation of failure and outage through dependent infrastructures.

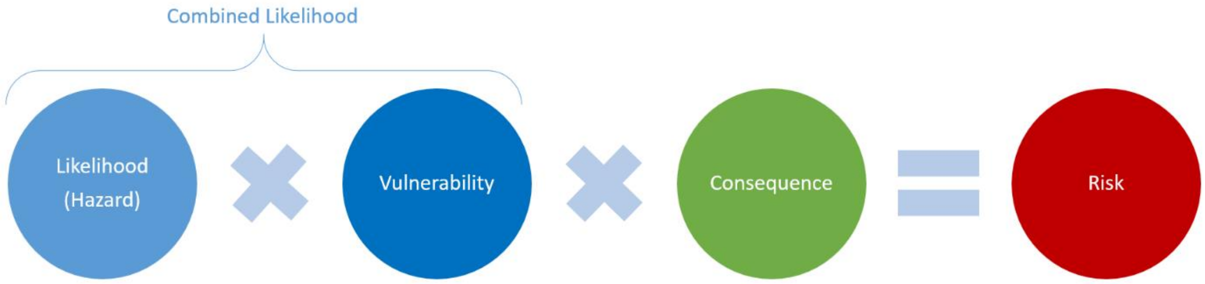
Note that propagation of outage applies only to physical and digital interdependencies, as such geographic interdependencies are considered only within step 1.

6.2.2.1 Direct risk to infrastructure

An approach to assessing risk to infrastructure from hazards has been developed based on a ‘likelihood’ and ‘consequence’ approach (in accordance with ISO 31000 and as detailed in section 3.2). For application within an infrastructure context, this approach has been modified to incorporate three key parameters that influence the level of risk: the hazard likelihood; the level of damage to the asset from its exposure to the hazard (vulnerability); and the consequence of the damage.

To manage these three key parameters within a ‘likelihood and consequence’ approach, a ‘combined hazard and damage likelihood’ parameter is proposed (figure 6.9). This parameter considers both the hazard likelihood and the infrastructure vulnerability to generate a combined likelihood of damage.

Figure 6.9 Proposed risk framework



The consequence parameter is linked directly to the modified criticality rating (output from the core module). The consequence/criticality is then integrated with the combined likelihood to determine the overall risk to the asset. Example assessment matrices are shown in tables 6.17 and 6.18.

Table 6.17 Example combined likelihood table integrating hazard likelihood and damage to the infrastructure

Combined hazard and damage likelihood		Hazard likelihood				
		Rare	Unlikely	Moderate	Likely	Very likely
Damage score (vulnerability)	Minor	1R	1U	1M	1L	1VL
	Moderate	2R	2U	2M	2L	2VL
	Major	3R	3U	3M	3L	3VL
	Significant	4R	4U	4M	4L	4VL
	Extreme	5R	5U	5M	5L	5VL

Table 6.18 Combined hazard and damage likelihood key

Colour	Category
1	R – Rare
2	U – Unlikely
3	M – Moderate
4	L – Likely
5	VL – Very likely

The relationship between combined hazard and damage likelihood (from table 6.17) and criticality (output from the 'core module' detailed in section 6.1) results in risk (see tables 6.19 and 6.20). This yields a final series of five possible risk ratings: very high, high, moderate, low and insignificant.

Table 6.19 Example risk matrix demonstrating the relationship between the combined likelihood and criticality (adapted from New Zealand Transport Agency, 2018a)

Risk		Criticality (modified criticality output from the core module)				
		Minimal	Minor	Moderate	Major	Vital
Combined hazard damage likelihood	Rare					
	Unlikely					
	Moderate					
	Likely					
	Very likely					

Table 6.20 Risk key with example definitions adapted from New Zealand Transport Agency (2018a)

Colour	Category	Description
1	Insignificant	The process or activity in question continues with existing controls. Continue to monitor existing control effectiveness (within agreed business-as-usual arrangements). Continue to reduce the risk by adopting any improvements in safety of which the business becomes aware.
2	Low	Take actions to eliminate the hazard or minimise the risk. Relevant Business Unit Manager oversees action plans and receives reports on progress. Periodically consider control effectiveness and new or additional control options.
3	Moderate	Take actions to eliminate the hazard or minimise the risk. General Manager oversees action plans and receives reports on progress. Periodically consider control effectiveness and new or additional control options.
4	High	Take actions to eliminate the hazard or minimise the risk. The relevant Executive Manager oversees action plans and receives reports on progress. Specifically consider control effectiveness and new or additional control options.
5	Very high	The process, task or activity in question must not occur (or must cease) until actions have been taken to eliminate the hazard or minimise the risk. CE/Board oversees specific review of effectiveness of new or additional controls before the process, task or activity can commence or recommence.

6.2.2.2 Propagation of failure and outage through dependent infrastructures

The propagation of failure to downstream infrastructure can be evaluated through the development of causal chains and linkages within interdependent physical and digital networks, which include both directionality and strength. This can be useful for both pre-event planning for infrastructure failures and their downstream consequences (eg for emergency response planning) or long-term risk (eg for strategic risk reduction). This can support a range of stakeholders such as infrastructure providers, local authorities and emergency management and can provide the following benefits:

- evaluation of the downstream infrastructure service extent and population affected from an upstream failure (outage) through propagation across the network – can also extend to business and economic impact (see section 6.2.3)

- evaluation of the operational status and extent of outage within an interconnected network through level-of-service output indicators (eg as per the DOMINO model – see section 5.3.5) – can also reflect the presence of mitigation (eg backup on site), discussed further below
- supporting the prioritisation of restoration of infrastructures within a network following an event, through an understanding of network connectivity and status following an outage (eg allowing priority restoration of critical upstream infrastructures)
- identify and assist in evaluating the wider benefit of mitigation options (see section 7) through understanding what critical dependencies are served downstream.

An additional feature that could be included within a network propagation model is the ability to present/communicate outage levels or states. These relate to the level of damage and the presence of any on-site risk mitigation options, such as temporary power backup generators. These types of risk mitigation options can provide temporary relief and prevent immediate shutdown of infrastructure due to loss of an upstream dependent infrastructure. For each of the mitigation options available to maintain operation, there will be a corresponding duration for which service can be maintained. An option that could be utilised is via a temporally based traffic-light colour scheme representing the outage level (see table 6.21). This is similar in approach to the DOMINO model (see section 5.3.5).

Table 6.21 Outage level colour with description

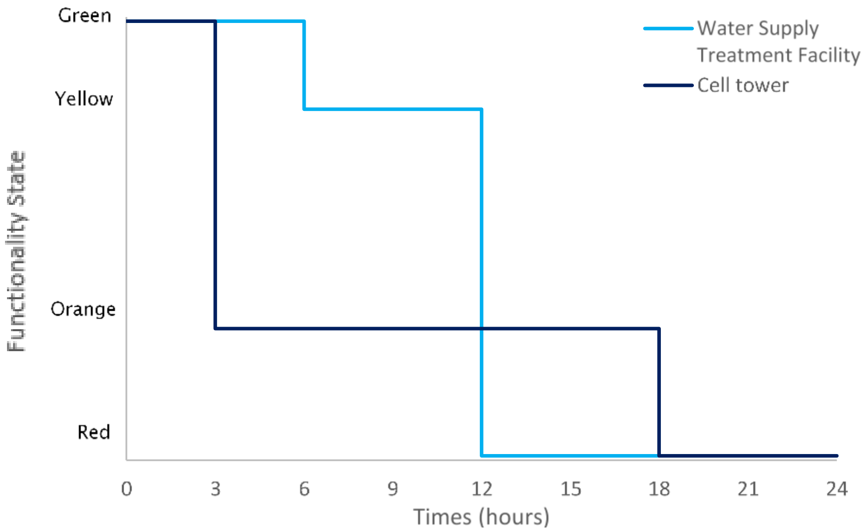
Outage level	Description
Green	Negligible (0–10%) reduction in level of functionality
Yellow	Minor (10–50%) reduction in the level of functionality
Orange	Major (> 50%) reduction in the level of functionality
Red	Complete (100%) loss of functionality

Different mitigation measures can affect both the outage level of the infrastructure and the length of time that level can be maintained. Table 6.22 illustrates the way outage level changes over time due to on-site risk mitigation at the downstream infrastructure, given the loss of upstream infrastructure. In addition, the change of outage level can be viewed as a function of time (shown graphically in figure 6.10). An assessment of outage level allows an understanding of which infrastructures are operational, at what capacity and for how long, given loss of dependent infrastructure. This can be viewed spatially on a network map and updated over time as outage levels change.

Table 6.22 Example changes in outage level due to potential on-site mitigation (the time is the duration the infrastructure can remain in that functionality state after initial loss of upstream infrastructure)

Upstream infrastructure	Downstream infrastructure	Outage level				Example on-site mitigation option at downstream infrastructure
		Green	Yellow	Orange	Red	
Power zonal substation	Tele-comm cell tower	3 hrs	3 hrs	18 hrs	> 18 hrs	Solar panel and battery
Power zonal substation	Hospital	2 hrs	6 hrs	12 hrs	24 hrs	On-site power generator

Figure 6.10 Example of functionality of service changes of the water supply treatment facility and cell tower due to mitigation strategies at a site over time since the loss of power supply from the distribution grid



6.2.3 Economic impact module

An economic impact module utilises the output of the risk and resilience module to evaluate the cascading financial and economic losses resulting from disruption or failure of infrastructures. This requires a range of additional assumptions (other than those relating to interdependency, damage and outage), including flows of goods and services within and across sectors, as well as restoration times and so on. Existing tools such as MERIT could be utilised for this (see section 5.3.3); however, further discussion on this proposed module is beyond the scope of this research.

6.3 Implementation

Several of the pre-existing tools should be reviewed as part of any implementation. These include whether the UoA model (see section 5.3.4) could be modified to integrate the methodology developed herein, or whether other tools such as RiskScape (a joint GNS Science and National Institute of Water & Atmospheric Research (NIWA) hazard and impact modelling platform) could be integrated to assess damage and risk.

Given the distributed nature of different infrastructures, the implementation of the approaches described in the previous sections should be carried out in a geospatial environment. This allows for simple and effective visualisation of outputs. GIS software such as ArcGIS and QGIS allow visualisation and can be integrated within workflows to either partially or fully automate the analysis.

A proposed implementation method is described below for each of the interdependency assessment types (geographic and physical/digital), followed by the overall risk assessment methodology.

6.3.1.1 Geographic interdependency assessment

The geographic interdependency assessment can be undertaken in a geospatial environment, using the following steps:

1. Obtain and import the spatial infrastructure datasets,[3] which should include the following:

[3] Note that a key limitation may be the availability of high-quality spatial asset information from infrastructure providers.

   a. infrastructure attributes such as type, material, age
   b. base criticality, which needs to be consistent in spatial scale and assessed consistently across infrastructures (eg 1 (low) to 5 (high)) (see section 6.1.1).
2. Create corridors using geospatial buffering tools, based on a user-defined length and width of corridor units.
3. Spatially join the co-located infrastructures.
4. Calculate the GIR (see the equation 6.1 in section 6.1.5.2).
5. Calculate the modified CC (see section 6.1.5.3).

By implementing this approach within a geospatial platform, the process can be automated using scripting or workflow managers, thereby allowing it to be scalable across large networks.

6.3.1.2 Physical and digital dependency assessment

The physical and digital dependency assessment can be undertaken in a geospatial environment as well. However, this assessment is more complex, given the requirements to traverse the infrastructure networks and dependency relationships. It involves the following steps:

1. Obtain and import the spatial infrastructure datasets, which should include the following:
   a. infrastructure attributes such as type, material, age
   b. base criticality, which needs to be consistent in spatial scale and assessed consistently across infrastructures (eg 1 (low) to 5 (high) (see section 6.1.1).
2. Create the infrastructure dependencies by developing automated spatially connected networks of infrastructure (discussed further below), including:
   a. directionality of the relationship, derived from a reference database
   b. strength of the relationship, derived from a reference database.
3. Iterate through the network, calculating the dependency rating and modified criticality. This can be undertaken using trace routines within GIS to traverse the network, and it can be conducted in an automated fashion.
4. Extend the modified criticality along the network. This can also be conducted automatically within a GIS platform, using trace routines.

Step 2 is the most complex to automate in a computational environment. Other interdependency assessment approaches such as DOMINO and the UoA model have developed partially automated methods. The DOMINO model automatically associates an infrastructure to the nearest upstream dependent infrastructure when the user defines there is a dependency relationship between sectors. For example, if a user uploads a pump station and defines a dependency with power supply, the dependency relationship defaults to the substation that services the area within which the pump station infrastructure is located. The UoA model has a series of pre-defined infrastructure relationships built into the model, which are formed when the spatial data are loaded.

However, neither the DOMINO nor the UoA approach considers the strength parameter of a dependency, and therefore the development of an automated approach for this would be needed. Initially, this step would require significant stakeholder engagement to define a set of rules to automatically assign default relationships and defined parameters, such as strength, across complex interconnected infrastructure networks. Following this development, a reference database could be used to look up these dependency parameters to enable a partial/fully automated approach. While this would provide an adequate representation of the network for use within the proposed assessment, given the complex nature of interdependencies, this might not fully reflect the network.

6.3.1.3 Hazard, vulnerability and risk assessment

The following elements are required to undertake a risk assessment:

- Hazard: commonly a geospatial hazard extent layer with associated return period (as shown earlier in table 6.14)
- Vulnerability: a function to assess direct damage in relation to a given hazard intensity attributed to an infrastructure type, with asset data including attributes that support the selection of an appropriate vulnerability function, such as asset type, age and material (see section 6.2.1)
- Modified criticality: developed using the methodology described above (see section 6.1).

The assessment should evaluate combined likelihood and consequence/criticality, following the example matrices in tables 6.17 and 6.19. This assessment could be implemented automatically and applied at scale across distributed networks.

6.3.1.4 Stakeholder input, user-interface and visualisation

Stakeholder input is an important component of any platform or tool. This provides an opportunity to verify and validate the dependent infrastructure relationships and parameters, such as the relative strengths. One approach could be to conduct workshops with different stakeholder groups and infrastructure providers, to provide an opportunity to discuss the dependencies between different infrastructures and the ways that failures can propagate through networks, and to validate parameters such as criticality and strength.

To encourage and improve user interaction, an elicitation method could incorporate a digital user-interface to support collaboration with stakeholders and infrastructure providers. The CIrcle tool by Deltares demonstrates the way a digital platform can be utilised within a workshop environment to elicit input from external parties and allow an understanding of the way infrastructures interact. In the context of this research, an interface could allow the input of relationship parameters such as the strength and temporary outage delay from on-site backup, as shown in figure 6.11 below (from the CIrcle tool).

Figure 6.11 Parameter inputs for the CIrcle tool (Deltares, 2018)

A visualisation tool that draws on the interdependency data and presents clear graphics and analytics enables infrastructure owners to comprehend interdependent relationships easily and can enable improvements in asset management decision making. These can include both static graphical network diagrams (eg CIrcle) and visualisations of outages and temporal change resulting from a failure that propagates through a network (eg DOMINO).

Further visualisation options could include dynamically identifying downstream dependent infrastructures related to a single upstream infrastructure (based on respective relationship parameters). This would allow for the rapid identification of those infrastructures downstream from one or more upstream infrastructures, and these could be presented spatially on a map. Such visualisation data could be used to create animations that illustrate the consequences from a hazardous event and could be presented to infrastructure providers to inform investment decisions regarding asset and risk management (Deltares, 2018).

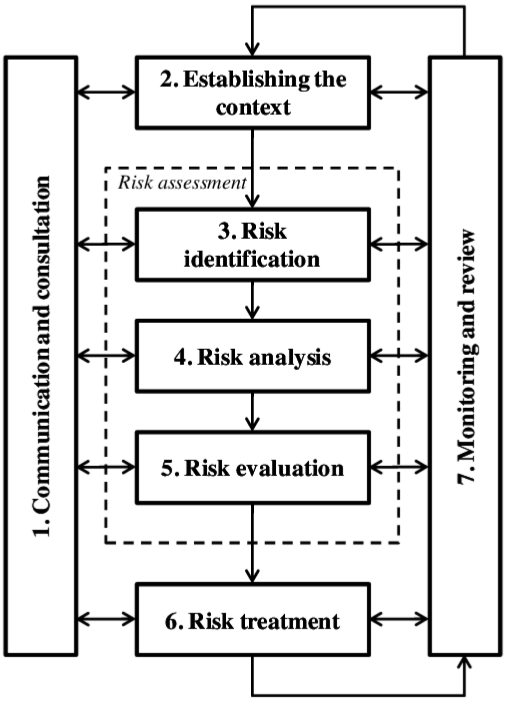
7 Risk treatment toolbox and investment decision making

Previous sections have presented detailed background, typologies and dimensions of interdependencies, as well as describing, in detail, methodologies to assess and quantify both physical/digital and geographic interdependencies. The approach to assessing interdependencies is linked to a modified criticality, and when it is integrated with hazard or asset vulnerability information, this can then inform a risk assessment, as described in section 6.3. The benefit of the proposed interdependencies assessment approach is that it provides a far greater level of understanding of criticality and therefore provides a risk assessment that is more detailed.

This section presents a standard, high-level approach to risk treatment. In the context of infrastructure management, management of networks should be based on a core understanding of risk. This risk-based understanding then informs and prioritises investment decision making, which should be applied within a robust 'business case' approach (New Zealand Transport Agency, 2020b).

The approach to risk treatment that is proposed here is similar to that presented in section 6.2.2 – that is, within the context of risk management (as per ISO 31000). This involves a staged approach to risk management, as shown in figure 7.1. The response to identified priority risks occurs as part of step 6, during risk treatment.

Figure 7.1 Risk management approach (adapted from ISO, 2018, fig. 1)



7.1 Risk treatment options

Risk treatment involves the development of potential options to address the risks identified and the prioritisation of them using an agreed methodology. Treatment options commonly include one of four categories: avoid, mitigate, transfer and accept. Each of these will have a different associated cost and will result in a remaining 'residual' risk of different degrees. These are discussed further in table 7.1.

Table 7.1 Risk treatment options

Risk treatment options	Description
Avoid	This is defined as measures to remove or eliminate a risk by, for example, relocating key infrastructure away from hazardous areas.
Mitigate/reduce	This could involve implementing physical works to reduce risk and improve resilience, such as the strengthening of infrastructure or buildings to resist earthquakes. Sometimes, the remaining risk can be transferred through the medium of insurance.
Transfer	In some situations, certain risks will be deemed preferable to transfer. There are several means of transferring risk, including insurance. By purchasing insurance, the asset owner effectively transfers part or all of the risk to a third party.
Accept	Based on an informed decision, an organisation or asset owner may decide to accept the risk. Their risk 'tolerance' or 'appetite' describes how much risk an organisation is willing to take on to attain the required standards of service and financial performance.

7.1.1 Decision making: selecting the best option for the treatment of risk

A wide range of approaches could be used to select the best option for the treatment of risk. Some of these are presented in table 7.2.

Table 7.2 Evaluating risk treatment options (adapted from OECD, 2015, p. 130)

Approach	Description
Cost–benefit analysis	Involves the calculation of the net present value costs and benefits across different options and evaluation of their results.
Multi-criteria assessment	Involves assessing the financial, social, environmental and cultural outcomes of a particular option.
Real options analysis	Considers the net present value of a project in consideration of the cost of opportunities and reduced options arising from its implementation (a pathways approach).
Expected utility and value methods	A probabilistic approach to considering the likely utility (realistic outcome or marginal benefit) or value (possible best outcome) resulting from an option.

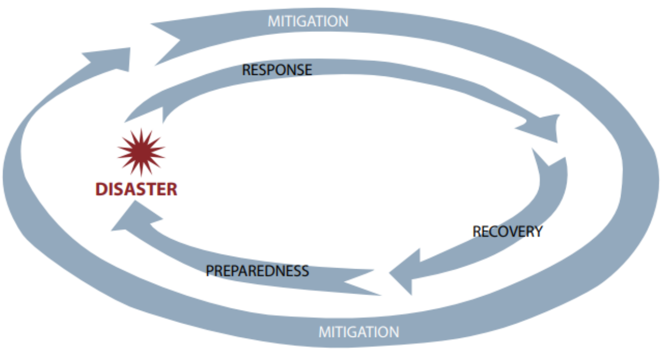
The choice of method will depend on the context and the quality of the data available. For example, if detailed risk treatment costs are quantifiable, along with the benefits (including avoided costs), then a cost–benefit analysis may be preferred. However, if the data are poor or have significant uncertainty, then a multi-criteria assessment may be more appropriate.

7.2 Risk treatment toolbox

The focus of this toolbox is to introduce a range of high-level risk treatment options that can address priority risks identified through the methods presented in section 6. These are detailed in table 7.3, grouped into the four risk treatment options noted above.

Table 7.3 Example risk treatment options

<table>
<tr><th>Risk treatment approach</th><th>Example options</th></tr>
<tr><td>Avoid</td><td>Avoiding a risk in the context of infrastructure generally means relocating an asset to an area that is not exposed. While this is possible theoretically, in many cases it may not be feasible, especially because much infrastructure is permanent or semi-permanent and is related spatially to the community it serves, making it difficult to relocate.</td></tr>
<tr><td>Mitigate</td><td>Risk mitigation can involve addressing any of the components shown in figure 6.9 (likelihood, vulnerability and consequence) as follows:
• Likelihood: In general, the hazard source (eg heavy rainfall, earthquake) is impossible to mitigate. However, the secondary hazard (eg flood, landslide) can be mitigated through engineered approaches.
• Vulnerability: Asset vulnerability can be reduced primarily by improving the robustness of the infrastructure (eg the asset design or materials).
• Consequence: Reducing the consequence of failure relates to reducing both the criticality of an asset and the duration of outage/disruption. Based on the relationships outlined in this report, this can be achieved by:
– providing additional redundancy within a network, which effectively reduces the strength of interdependencies (eg through providing an alternative connection/route or on-site backup)
– constructing systems that can ‘fail safely’ (Park et al., 2013; Snowdon, 2011), which allows failures to be understood and controlled, enabling faster restoration of service.
• Additional mitigation approaches integrating improved emergency management processes via preparedness (readiness), response and recovery, which are part of New Zealand’s four R’s of emergency management (Civil Defence and Emergency Management Act 2002), as follows (see figure 7.2):
– Preparedness relates to developing operational systems, capacities and capabilities before an emergency occurs, including making arrangements with emergency services, lifeline utilities and other agencies, as well as developing self-help and response programmes for the public (Ministry of Civil Defence and Emergency Management, 2015).
– Response involves actions taken immediately before, during or directly after an emergency to save lives and property and to help communities begin to recover (Ministry of Civil Defence and Emergency Management, 2015).
– Recovery involves coordinated efforts and processes to bring about the immediate, medium-term and long-term holistic regeneration of a community following a civil defence emergency (Ministry of Civil Defence and Emergency Management, 2015).

Figure 7.2 Phases of emergency management: the disaster life cycle (Schwab et al., 1998)

</td></tr>
</table>

Risk treatment approach	Example options
Transfer	Transferring risk generally means purchasing insurance, which enables the asset owner to transfer part or all of the risk to a third party.
Accept	Asset owners may choose to accept the risk of damage or failure. An organisation's risk tolerance or appetite describes the amount of risk an organisation is willing to take on to attain the required standards of service and financial performance.

8 Summary and recommendations

This report has shown that understanding and managing interdependencies between infrastructures is becoming increasingly important, especially given our modern interconnected networks, the dependence of communities on these critical networks, and the range of potential ways for failures to occur. Failures due to natural hazards are occurring more frequently, exacerbated by climate change. Assessing and understanding the interdependencies between infrastructure networks allows an understanding of failure propagation within networks and the wider consequences of failures and outages. This provides greater insight into the potential consequences of failures, especially with respect to dependent infrastructures, and can provide benefits from addressing the issues in an integrated fashion. This knowledge, combined with an understanding of natural hazards and asset vulnerabilities, can support specific risk treatment responses, which in turn improves wider community resilience.

The literature review component of this research identified two key typologies of interdependency: physical/digital and geographic. In addition, the review identified three key interdependency attributes: strength, order and directionality.

A review of existing interdependency assessment models illustrated a range of pros and cons for each in relation to how well they assess and characterise interdependencies. These models, tools and platforms included the UoA Infrastructure Interdependency Model, DOMINO, XDI, CIrcle and MERIT. As none of these models assessed interdependencies in a holistic manner (addressing the breadth of literature), a bespoke interdependency assessment approach was developed.

The proposed interdependency approach assesses physical, digital and geographic typologies via slightly different methods from those in other models. The output of the assessment is a modified criticality for infrastructure elements within the network. This modified criticality can then be utilised as part of a risk assessment by integrating it with specific hazard and vulnerability information to develop a risk rating. This risk rating can be used to prioritise risk treatment options (resilience improvements), which may include risk mitigation as well as risk avoidance, transfer or acceptance. Risk mitigation may include increasing the robustness of infrastructure, providing additional redundancy, designing for ‘safe failure’, or enhancing emergency preparedness.

The following range of next steps or further developments are suggested.

- Pilot the proposed methodology outlined in section 6 with key stakeholders and potential end users. This would involve reviewing and refining the example tables/ratings/matrices within the assessment approach and testing their sensitivity.
- Given the importance of accessing appropriate network data for all infrastructure types, conduct further work to agree on protocols and processes for data collection, sharing and maintenance.
- Evaluate whether the proposed approach can be incorporated within the existing UoA model. This would require the inclusion of additional parameters such as strength and modified criticality.
- Develop a user-interface to support operator use and collaboration.
- Link to communities and social vulnerability using Arataki (New Zealand Transport Agency, 2020a), which provides a view of what the transport system will need to look like in 10 years’ time, from both a place-based and customer and community perspective. These communities will vary across a range of potential measures, which may inform their inherent ‘vulnerability’ or ‘resilience’. These measures may include socio-demographic factors such as income, age, health status and ethnicity (Adger, 2006; Mason et al., 2019). There is potential for the interdependency/criticality assessment approach developed in this

research to incorporate infrastructure elements that provide service to ‘vulnerable communities’. This could also be considered part of the piloting of the tool.

- Investigate whether or how the approach could be used within Waka Kotahi’s Investment Decision-making Framework and broader organisational investments.

The development of this interdependency assessment approach, as presented within this report, provides a practical and transparent method for infrastructure providers to understand and manage their critical networks better in respect to the hazards they face and the failures that may occur. In addition, this approach presents an opportunity for infrastructure stakeholders to come together and discuss the ways networks interact. An important part of developing and implementing this approach is collaboration with stakeholders to identify and review both model inputs and outputs. Bespoke spatial and temporal visualisation approaches can be developed to provide user-friendly methods to elicit, capture and present this type of information. An improved focus on interdependencies and criticality, along with integration with risk-based assessments, will lead to better decision making, and ultimately infrastructure networks and communities that are more resilient.

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Glossary

Consequence	The outcome of an event. An event can lead to a range of consequences, which can be certain or uncertain and have positive or negative effects. Initial consequences can escalate through knock-on effects (Australian/New Zealand standard AS/NZS 31000:2009).
Criticality	When assessing risks for infrastructure networks, consequences relate directly to the criticality of a section of the network. The higher the criticality, the higher the consequence of failure (NAMS Group, 2006). Critical assets are also defined as those that 'are especially significant to societal wellbeing and that merit priority attention by utilities in emergency response and recovery' (New Zealand Lifelines Council, 2017).
Critical infrastructure	An approach for classifying the significance of lifelines (defined below) in terms of the numbers of customers with affected services and the impact of service failures on those customers (eg hospitals). New Zealand Lifelines Council (2017) presents three tiers (national, regional and local) of significance levels for assessing infrastructure, with each having a corresponding indicative criterion.
Directionality	Characterises the dependency relationship flow between two infrastructures. If the dependency relationship is one-way, it is referred to as being unidirectional, and if it is both ways, it is referred to as being bidirectional (Eusgeld et al., 2011; Rinaldi et al., 2001).
Event	Can be a hazard (defined below) or a failure of an infrastructure component.
Dependency	When one infrastructure element has a direct effect on the performance of another infrastructure element (Rinaldi et al., 2001).
Hazard	Can be categorised into three general types: natural, technological and social/political. These can be further broken down into 'stress' events, which are long-term and gradual change processes, and 'shock' events, which are short-term and sudden-change processes (Hughes & Healy, 2014).
Interdependency	A bidirectional relationship between two infrastructures, through which the state of each infrastructure influences or is correlated to the state of the other (Rinaldi, 2001).
Lifelines	An entity that provides power, gas, water, wastewater, telecommunications, or transportation (Civil Defence Emergency Management Act 2002).
Mitigation	The lessening of the adverse impacts of hazards through policy or structural strategies (United Nations Office for Disaster Risk Reduction, 2009).
Order	Relates to the downstream position within the causal chain from the initial infrastructure failure (Carhart & Rosenberg, 2015).
Risk	The effect of uncertainty on objectives, usually expressed in terms of risk sources, potential events, their consequences and their likelihood (Australian/New Zealand Standard AS/NZS 31000:2009).
Resilience	'[A] system's ability to enable communities to withstand and absorb impacts of unplanned disruptive events, perform effectively during disruptions, and respond and recover functionality quickly. It requires minimising and managing the likelihood and consequences of small-scale and large-scale, frequent and infrequent, sudden and slow-onset disruptive events, caused by natural or manmade hazards' (New Zealand Transport Agency, 2018b).
Strength (of a dependency)	The level of impact to a dependent infrastructure caused by the failure of an upstream dependency can be categorised as the strength of the relationship between the infrastructures (AECOM, 2017; New Zealand Lifelines Council, 2017).
Vulnerability	The characteristic of an element that makes it susceptible to the effects of a hazard (United Nations Office for Disaster Risk Reduction, 2009).

Appendix A: Model and platform review questionnaire

1. Provide a brief description of the model.
2. How is the model developed and run (user-interface)?
3. What is the primary purpose of the model (eg risk assessment, exposure assessment, loss assessment, interdependency analysis, other)?
4. How is data visualised?
5. What types of infrastructure/assets or sectors does it deal with and how are these input?
6. Does the model incorporate a hazard/damage dataset, either as input or implicit, as part of the assessment?
7. Does the model consider degrees of asset outage/failure (from partial to full outage) or is it binary?
8. What is the maximum number of receptors/assets analysed?
9. Is there an economic analysis component/module (eg modelling economic loss to local economies)?
10. Do users define interdependencies within the model or are they automatically derived?
11. Does it characterise interdependencies? If so, how (eg directionality, strength, order)?
12. How many ‘orders’/cascades does the platform assess?
13. How is data managed/input (eg from third parties)?
14. How is any data incorporated into the tool that is licensed, and how is it kept current?