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**Chapter 2, Section 2.4, Pages 21-28 (Development of a conceptual model)**

'Agent-Based Modelling, a Quiet Revolution in Asset Management', paper presented to IPWCA Conference NZ: Leading Tomorrow's Infrastructure - Collaborate, Transform, Deliver (Auckland), 26-28 June 2014.

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## CO-AUTHORS

<table>
<thead>
<tr>
<th>Name</th>
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<tr>
<td>Theuns Henning</td>
<td>Reviewed and commented on the structure and content of the paper.</td>
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<tr>
<td>Andrea Raith</td>
<td>Reviewed and commented on the structure and content of the paper.</td>
</tr>
<tr>
<td>Jason Ingham</td>
<td>Reviewed and commented on the structure and content of the paper.</td>
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</table>

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<thead>
<tr>
<th>Name</th>
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<tr>
<td>Jason M. Ingham</td>
<td></td>
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<tr>
<td>Andrea Raith</td>
<td></td>
<td>6/7/2017</td>
</tr>
<tr>
<td>Theuns F. P. Henning</td>
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<td>Theuns Henning</td>
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<tr>
<td>Andrea Raith</td>
<td>Reviewed the paper and commented on content, structure and mathematical notation.</td>
</tr>
<tr>
<td>Jason M. Ingham</td>
<td>Reviewed the paper and commented on the content and the structure.</td>
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A systems-thinking approach to improving the freight performance of New Zealand’s state highway bridges

Simon John William Bush

A thesis submitted in [partial] fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering, the University of Auckland, 2018.
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<tr>
<td>ASCE</td>
<td>American Society of Civil Engineers</td>
</tr>
<tr>
<td>BCA</td>
<td>Benefit Cost Analysis</td>
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<tr>
<td>BDI</td>
<td>Belief Desire Intent</td>
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<td>BSI</td>
<td>British Standards Institute</td>
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<td>GA</td>
<td>Genetic Algorithm</td>
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<tr>
<td>HPMV</td>
<td>High Productivity Motor Vehicle</td>
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<td>ISO</td>
<td>International Organisation for Standardization</td>
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<td>FHWA</td>
<td>Federal Highway Authority</td>
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<td>NAMS</td>
<td>NZ Asset Management Support</td>
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<td>NZ</td>
<td>New Zealand</td>
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<td>NZD</td>
<td>NZ Dollar</td>
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<td>NZDIA</td>
<td>NZ Department of Internal Affairs</td>
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<td>NZMoT</td>
<td>NZ Ministry of Transport</td>
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<td>NZOAG</td>
<td>NZ Office of the Auditor General</td>
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<tr>
<td>NZTA</td>
<td>NZ Transportation Agency</td>
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<tr>
<td>PSR</td>
<td>Pressure State Response</td>
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<td>PV</td>
<td>Present Value</td>
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<td>StatsNZ</td>
<td>Statistics NZ</td>
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<tr>
<td>USD</td>
<td>United States Dollars</td>
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<tr>
<td>USGAO</td>
<td>United States Government Accountability Office</td>
</tr>
<tr>
<td>VKT</td>
<td>Vehicle Kilometers Travelled</td>
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<tr>
<td>VOC</td>
<td>Vehicle Operating Costs</td>
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Abstract

A significant proportion of the world’s bridges are unable to support the modern load demands placed on them. As an example, because of the 2010 amendment to the vehicle mass and dimension regulations, 18% of New Zealand’s bridges are now functionally obsolete. The inability to support modern loads impacts the efficient movement of freight, and thus the economic efficiency of the country where the bridges are located. Accordingly, it is imperative that these bridges are effectively managed. To address the network level problems created by functionality obsolete bridges, a systems-thinking based asset management framework was created. The framework comprises an agent-based bridge asset management model and an integrated system of performance measures. By creating the new model, the use of agent-based asset management models is furthered, as the new model focuses on bridge strength rather than pavement condition. The new model also incorporates a national highway network, which was not present in the existing agent-based asset management models. The addition of a national highway network also furthers the development of bridge asset management models, as these models have typically only incorporated small numbers of bridges on a localised network.

The bridge model comprises a set of bridge agents, haulier agents and a decision-making agent. In the model, the haulier agents adapt to the bridge strengthening strategies proposed by the decision-making agent. This adaptation, in combination with a newly developed genetic algorithm, is then used to identify bridge strengthening strategies that maximise the highway network’s functionality. Using the model, the maximum identified benefit-cost ratio was achieved for a budget 94% less than the budget identified by the planning agency. Alternatively, when the same budget as the planning agency was used, the model increased the benefit-cost ratio by 250%. Thus, the model provides valuable new insights into potential network level bridge strengthening strategies.

To support the implementation of the identified bridge strengthening strategies, the bridge asset management model was used as the basis for deriving a system of performance measures. By integrating the computational model with a system of performance measures, an organisation can use the integrated framework to rationally identify bridge strengthening strategies and can subsequently monitor the success of the identified strategies. Consequently, the integrated bridge management framework provides a solution for managing the world’s functionally obsolete bridges.
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The development of the following thesis has been a journey that has provided many challenges and like all journeys, you meet many interesting people along the way who provide support and humour that keeps you going. The following are the people that I have met.

Many years ago, I embarked on my master’s research. This is when I first met my supervisor, Dr Theunis Henning. I would like to thank Dr Henning for setting me on the path that led to the PhD and the support he has provided throughout. I only knew the path existed because of him.

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All long journeys require funding and support from wider teams and sponsors. Accordingly, I would like to thank Opus International Consultants for their financial support and for their flexibility when it came to working hours. This understanding made the whole endeavour possible.

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The final, and largest, thank you goes to my partner, Anna, who provided support and encouragement as she transitioned from finishing a PhD. You provided insights into the journey, and helped to keep me on track. Without you, I never would have made it through the ups and downs and over the final hill.
Chapter 1 Introduction

The following chapter details the background to the research including a description of the asset management process, details of the on-going problem of managing functionally obsolete bridges, and the development of a model to effectively manage these bridges. Also, covered in this chapter are the research objectives and a description of the thesis’ structure.

1.1 The changes to asset management

The following research is based on the asset management process, which comprises a structured methodology for guiding decision-makers when investing in the maintenance and upgrading of public infrastructure, such as roads and bridges. Given the changes that have occurred in asset management over the last two decades and the effect that these changes have had on decision-making practices, these changes and their impact on bridge asset management are introduced below.

In 1999 the goal of the asset management process was to efficiently allocate maintenance and management funds (Byrne, 1991; McNeil et al., 2000). Similarly, in a review of Federal Highway Authority (FHWA) transportation asset management practices (Cambridge Systematics and Meyer, 2007) the reviewers recommended that asset management should “draw on economics, as well as engineering; and at its most basic level should link together condition, performance, and availability with system management and investment strategies”. By 2010 asset management was considered to be “a philosophy and discipline through which organisations are enabled to more effectively deploy their resources to provide higher levels of customer service and reliability while balancing financial objectives” (Too, 2010). These two definitions highlight the evolution of asset management from a technically focused process to an integrated process that incorporates social and technical aspects. The requirement to consider the social aspects of asset management is also a central philosophy of the internationally recognised asset management standard, ISO 55000 (ISO, 2014). The ISO 55000 standard describes asset management as a process that should not “focus on the asset itself, but on the value that the asset can provide to the organisation” and this value should “be determined by the organisation and its stakeholders”.
The requirement to model the intangible human elements such as goodwill, morale and reputation is also evident in the wider asset management literature (BSI, 2008; ISO, 2014; NAMS, 2011). Nonetheless, the omission of key stakeholders led Godau (1999) to recommended that “all key players in infrastructure management including policy makers, regulators, infrastructure managers, operational staff, users, and future generations must be considered when developing infrastructure management systems”. As a result of the omission of stakeholders, Godau (1999) noted that “traditional management [decision-making] approaches for infrastructure systems are no longer effective in meeting the needs of the stakeholders”. To account for the social influences present in asset management Dijkema et al. (2013) recommended that asset management should be viewed as sociotechnical process, rather than a technical process. Others also recommend that because assets are embedded in society they are subject to societal changes, and as such asset management should be viewed as a sociotechnical process (Herder and Wijnia, 2012; Kroes et al., 2006). Accordingly, the asset management models that have been created to solve technical problems must be changed to incorporate the social perspective (Bernhardt and McNeil, 2008; Kroes et al., 2006; Osman, 2012). The following research contributes to the identified sociotechnical literature by creating a new sociotechnical bridge asset management model that can be used to heuristically optimise a large network of spatially distributed sub-standard bridges. The bridge asset management model achieves this by incorporating a set of user agents that interact with a spatially accurate model of a bridge network. To identify infrastructure improvement strategies the hauliers adapt their travel behaviours based on each strategy that is presented to them by a planning agent. Using the knowledge that is gained from this process the planning agent is then able to identify its preferred network level bridge management strategy. The planning agent does this using a heuristic search methodology that was developed as part of this research.

Further to the development of the sociotechnical model, and in order to improve the effectiveness of the strategic decision-making process, Dyson et al. (2007) recommended that in conjunction with a model of the real-world system a set of performance measures should be created, as these measures provide the link between the virtual and real-world systems. As such, the sociotechnical model and the performance measurement system should be integrated. Accordingly, in addition to the development of the sociotechnical model a system of measures was also developed. The system of measures integrates with
the agent-based model by drawing on attributes used in the model. Thus, creating the link highlighted by Dyson.

1.2 The performance of New Zealand’s highway bridges

The following section outlines the problem of managing functionally obsolete bridges, where a functionally obsolete bridge is one that no longer provides the required performance level. In this research, the performance metric being studied is the ability to carry heavier freight vehicles. The models that are currently used to manage functionally obsolete bridges are also introduced and compared to the current requirements detailed in ISO 55000 and the research literature identified in Section 1.1.

The bridge asset was chosen as the area of study, because of the continued debate, both within New Zealand and internationally, on how best to manage the network functionality and user safety problems created by the aging post-war bridge stock (ASCE, 2013; Hartgen et al., 2013; NZOAG, 2010; USGAO, 2008). In the United States the American Society of Civil Engineers (ASCE, 2015) forecasted that 20.5 billion USD would have to be spent over a 15 year period, if the problem of aging bridges was to be mitigated. Similarly, in New Zealand over the 30-year period between 2012 and 2042, up to 600 state highway bridges will be 100 years old or older, approximately 13 % of the bridge stock. These bridges are detailed in Figure 1-1 and are those that are aged between 70 and 100 years old. Considering that these state highway bridges only account for 23 % of the total national stock (NZTA, 2010), the national impact of functionally obsolete bridges will be higher. This potential is evident in a study carried out by Hastings District Council’s (Rose et al., 2012), which identified that 30 % of all the authority’s bridges were unable to carry the desired loads. Nonetheless, only 5% were officially reported (NZTA, 2013). Given the geographic distribution of the older obsolete state highway (Refer Figure 1-2) and local authority bridges, their economic impact will affect multiple regions across New Zealand. If optimal bridge strengthening strategies are to be identified, the impact of the spatially heterogeneous effects of differing bridge strengths must be addressed.
In an international context, the model developed herein will be directly applicable to the management of the functionally obsolete and structural deficient bridges found in the United States. The new bridge asset management model is applicable because these bridges also no longer meet modern loading requirements or have deteriorated to a point where they can no longer support the required design loading. Accordingly, these bridges must be effectively managed if their negative impact on the functionality of the highway network is to be minimised.
1.3 The vehicle mass and dimension regulations

In 2010 the New Zealand government amended the vehicle mass and dimension regulations (NZMoT, 2010, 2015; Reynolds and Goodall, 2014). The regulations were amended to allow New Zealand freight hauliers to operate more efficiently, by allowing increased gross mass vehicles and by allowing increased axle weights on their vehicles. The vehicles were also allowed to be longer than present freight vehicles. The increase in mass and volume facilitates a larger amount of freight to be carried on one vehicle, thus reducing the number of trips and the vehicle kilometres that had to be travelled. By reducing the distance travelled by the hauliers each haulier reduces its operating costs and thus contributes to the improved freight efficiency target (NZMoT, 2017). From a bridge management perspective, the introduction of heavier vehicles requires each bridge to support these vehicles, which results in a higher overall load capacity requirement. For newer bridges designed to current loads the increase in load posed no problems (Reynolds and Goodall, 2014), but for the older state highway bridge stock the increase in load resulted in 18% of the stock (Waldin et al., 2015) being unable to support the new high productivity motor vehicles (HPMV). Accordingly, to develop a sociotechnical relationship between the hauliers and the bridge network, the relationship between the route-finding behaviour of individual hauliers and the strengthening of obsolete bridges must be understood.

1.4 Bridge asset management models

The following sections details the recent developments in sociotechnical asset management decision-making models. Based on these developments and the identified technical focus of bridge management models, a set of modelling requirements is identified.

To create the new bridge management model, and to address the changes in the asset management process, the old modelling paradigm should be challenged. By challenging the long standing paradigms that are in place new insights can be gained on the type of data to collect, whether the data being collected is appropriate, whether chosen mitigation solutions are working or whether the core dynamics of the system are truly understood (Epstein, 2008). Similarly, North and Macal (2007) highlighted that existing paradigms are challenged by creating new models of the same system. The expectation that new and alternative views of the asset management process are required can also be inferred from the comments raised by asset management auditors (NZDIA, 2013; NZOAG, 2004, 2010; USGAO, 2008), with these auditors all finding that decision-makers, while describing operational activities in
significant detail are not adequately reporting on the delivery of higher level strategic
governmental outcomes.

To account for the social and technical interactions found in asset management, a small but
growing number of researchers have developed computational models that include both the
social and technical components of asset management (Bernhardt and McNeil, 2008; Moore
et al., 2008; Mostafavi et al., 2014; Nikolic and Ghorbani, 2011; Osman, 2012). One of the
first groups to develop a sociotechnical asset management model was Bernhardt and McNeil
developed an infrastructure asset management model that had a focus on pavement
management. Osman concluded that, including stakeholders in asset management models
would “help [to] improve the consistency and defensibility of asset management decisions,
leading to increased transparency”. On review, these new sociotechnical asset management
models could be categorised as either large-scale or small-scale models. The large-scale
models incorporated many thousands of simple agents that were used to represent the
technical and social components, whereas the small-scale models utilised fewer, but more
complex agents. In the context of the asset management process the large-scale models were
being used to investigate how networks of assets adapted as a result of societal influences
(Nikolic and Dijkema, 2010) and the small-scale models were being used to investigate the
effects that deteriorating pavements had on stakeholder satisfaction levels (Bernhardt and
McNeil, 2008; Moore et al., 2008; Osman, 2012) or to investigate innovative ways of closing
the infrastructure funding gap (Mostafavi et al., 2014; Mostafavi et al., 2015). Even though
successful, the small-scale models developed by Osman (2012; 2012) and Bernhardt and
McNeil (2008) were primarily used to investigate whether computational methods, such as
agent-based modelling and systems-dynamics, were appropriate for simulating the
sociotechnical asset management process and whether useful results could be obtained from
these models. Based on these early investigations, the small-scale modelling paradigm was
shown to be appropriate. Nevertheless, these early asset management models were found to
require further development, such as improvements to the governmental and geospatial
models (Bush, 2013). While a more refined sociotechnical model was created by Mostafavi
et al. (2015), the model was created to investigate the impact that different procurement
strategies would have on infrastructure condition, rather than strategies that addressed the
management of obsolete bridges. Furthermore, both the Mostafavi et al. (2015) model and
the models created by others (Moore et al., 2008; Osman, 2012) did not take into account
the geospatial nature of the asset, which as highlighted earlier must be addressed if the effect that obsolete bridges have on network functionality and haulier behaviour are to be understood. Furthermore, in the Osman (2012) agent-based model the asset was treated as a collection of individual unrelated pavement lengths, rather than a spatially connected network. Also, in a systems-dynamics model created by McMillan and Ault (2007) the asset was treated in a single deterioration model was used to represent the overall condition of the asset. To understand the impact that individual assets have on the functionality of an interconnected network, a connected network model must be created, which requires an understanding of how users interact with the network and how they adapt as the decision-maker improves each individual bridge on the network. The network model that was developed herein is a bottom-up strategic decision-making model. The model is a bottom-up model, because each bridge, haulier and decision-maker in the model has its own characteristics and these characteristics define the action of the whole integrated system. The model is also a strategic model, rather than a detailed planning model, because it provides information on what should be done to deliver on the improved freight efficiency outcome, which is different to a planning model, which provides detailed information on the timing and exact type of intervention that should be undertaken.

Based on the review of current bridge asset management models and of recent developments in sociotechnical asset management models, to model the network interaction and to identify optimal bridge management strategies, a bridge asset management model must include the social, organisational, geospatial and technical bridge components.

1.5 Developing the bridge model

A model’s development follows three evolutionary stages comprising generator, mediator and predictor (Heath et al., 2009). At the generator stage little is known about the system being modelled and the models are created primarily to test the validity of concepts and theories developed by researchers (Heath et al., 2009). At the mediator stage models are created with a sufficient level of detail that the model outputs can be used to gain insights into the system’s behaviour (Heath et al., 2009). A predictor model represents the highest level of model evolution, and is used to predict probable future outcomes. The small-scale sociotechnical condition focused asset management models that have been created to date should be considered as generator models, as they were created to test whether agent-based modelling or systems-dynamics would provide a feasible method of simulating the asset
management process. The following improvements were identified to transition these early models from being generators to mediators:

- User agents must adapt to changes in the asset performance. Adaptive users are required to assess the impact that asset management strategies have on network functionality. Presently, user agents randomly interact (Osman, 2012) with the asset and provide feedback, which limits the opportunity to investigate preferred routes, thus leading to all assets being treated equally. Accordingly, a method of representing the adaptive route finding behaviour of hauliers is required.

- In the existing agent-based asset management models the planning agent utilises simple worst first, asset centric, improvement strategies, whereby the asset with the worst performance is selected first. Worst first strategies do not consider the impact that individual assets have on network operation. To identify optimal network management strategies the bridge asset management model must account for the large combinatorial problem resulting from the ability to improve a set of functionally obsolete bridges.

It is hypothesised that by creating a new sociotechnical bridge management model, new insights into optimal management strategies will be developed.

### 1.6 Performance measurement and management

Developing a new bridge asset management model and identifying effective improvement strategies comprises only one part of an effective asset management process. The success of a strategy must also be monitored as it is being implemented. To monitor the effectiveness of a strategy, performance measures are required.

An effective performance management framework is required because auditors (NZOAG, 2004, 2007, 2010; USGAO, 2008) found that no clear relationship existed between the operational activities being undertaken by bridge asset managers and the delivery of regional and national strategic outcomes. To achieve performance improvements Seddon (2008) recommended that the performance of the whole delivery system should be assessed. Thus, if effective strategy development is to be carried out, performance measures must be created that reflect the operation of the whole system (Boland and Fowler, 2000; Henri, 2004; Neely et al., 2005; Taticchi et al., 2010). While guidance documentation (Félio and Lounis, 2009; NAMS, 2006, 2015) recommends that social measures must be included in performance measurement systems, the tendency is to model the technical aspects of bridge performance.
(Frangopol and Duygu, 2011; Ghasemi and Hooks, 2010). Consequently, bridge management models continue to focus on deterioration related effects or the reliability of the individual bridges or the bridge network (Bocchini and Frangopol, 2011b; Morcous et al., 2002; Orcesi and Cremona, 2010; Orcesi et al., 2010). The development of these technical measures facilitates improved bridge management, but the narrow technical focus results in only half of the sociotechnical system being represented. If the social system is omitted, the cause of a change in the bridge network and the effect that change has on users cannot be understood, and as such only limited insights can be obtained on whether the strategy that has been implemented will deliver the required improvements. Accordingly, to effectively manage the sociotechnical bridge management system the following objectives must be addressed:

- The technical and social measures must be identified and incorporated into the model.
- Systems-thinking must be used to identify the causal relationship between the social and technical systems and the effect that the two interacting systems have on each other.
- The identified performance measures must be structured in such a way they can be used to monitor the success of implemented bridge management strategies.

It is hypothesised that the development of the bridge management model will naturally lead to the required performance measures being identified and that causal link between the social and technical performance measures will be created. Thus, providing a performance measurement framework that can be used to effectively manage a network level bridge improvement program.

1.7 Research objectives

To indentify the potential bridge management strategies and to address the gaps in bridge management and performance models, the following objectives were set:

- Develop a model that describes the real-world sociotechnical system.
- Further advance the development of agent-based asset management models, by improving the realism of the model.
- Understand the impact that proposed planning agency strategies have on network performance and assess the level of improvement that can be gained by using a network focused sociotechnical bridge asset management model.
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- Investigate whether the new bridge asset management model provides new insights into network level bridge strengthening strategies.
- Use the bridge management model to develop a set of performance measures that can be used to monitor whether the freight efficiency objective has been met. These measures must link operational activities to the national level freight efficiency outcome.

1.8 Thesis structure

As highlighted, asset management is now considered to be a sociotechnical process (Godau, 1999), which led to the realisation that the technical asset management models are incomplete (Moore et al., 2008), as only half of the asset management system is described. Consequently, in Chapter 2 the effects of changing to a sociotechnical viewpoint is explored in more detail. The effect is explored by comparing the older asset management process with the hierarchy of systems developed by Boulding (1956). The outcome of this review is a conceptual bridge management model that can be used as the basis for developing the new bridge asset management model. In Chapter 3, a mixed method data collection methodology is defined. The choice of methodology reflects the need to develop both the social and technical components of the bridge asset management model. Chapter 4 details the development of the technical model and Chapter 5 details the development of the social model. The technical model includes the spatially related bridge agents and the social model includes the haulier and decision-making planning agent. To identify bridge strengthening strategies, a genetic algorithm is also developed (Refer Chapter 5). The algorithm works in combination with the asset and haulier models to identify heuristically optimal bridge strengthening strategies. In Chapter 6 the effectiveness of the GA identified bridge strengthening strategies is compared to the strategies identified by the planning agency, and new improved bridge strengthening strategies are identified. In Chapter 7, a framework of bridge strengthening measures is developed. The identified performance measurement and management framework is based on a combination of a systems-thinking approach to performance measure categorisation and the attributes used in the agent-based bridge asset management model. Using these two sources the cause-effect link between social and technical measures is created. In Chapter 8, the future development of the agent-based bridge management models is explored. The discussion incorporates the findings from the model development process. Chapter 9 details the research conclusions.
Chapter 2 Literature review: Identifying the conceptual modelling framework

The first stage of critical systems thinking, critical awareness (Jackson, 1991; Midgley, 1996), encourages those investigating a system to examine and challenge any taken for granted assumptions. Further to the critical systems-thinking methodology, O'Sullivan and Perry (2013) noted that the “first step in any modelling process is the development of the conceptual model”. A conceptual model is created, because it “will bring a variety of abstract concepts into play” (O'Sullivan and Perry, 2013). Accordingly, the following chapter comprises a parallel review of systems-thinking ideas and the asset management literature. The parallel reviews being used to identify conceptual models that can be used in an integrated performance measurement and decision-support framework. The examination and conceptual model development process detailed below is divided into five parts comprising a review of bridge asset management processes, a systems-thinking based examination of the bridge asset management process, a review of systems-thinking ideas, the development of a conceptual asset management model, and the development of a conceptual bridge asset management model. To convert the conceptual bridge asset management model into a computer based model, a computational modelling framework is also identified.

2.1 The bridge asset management process

In the asset management sector the desire to understand the whole decision-making system can be seen in the publicly available literature (ISO, 2014; NZOAG, 2007), but this desire is arguably not being met with the NZOAG (2007) noting that local authorities “had struggled to link their performance measures with their decision-making processes”. Similarly, the New Zealand Department of Internal Affairs auditors noted that asset management decision-making is not being treated holistically (NZDIA, 2013), which led to the recommendation
that the relationship between strategic objectives, levels of service and actions carried out at the operational level should be clearly stated. Similarly, in a review of bridge asset management practices Moon et al. (2008) noted that bridge systems comprise engineered, natural and human sub-systems and that these systems should be treated in a holistic manner in order to effectively allocate scarce funding resources. Nonetheless, even though stakeholders are highlighted by Moon et al. (2008), stakeholders are not integrated into the performance modelling process. The same strong technical focus was also found in other bridge related literature such as the Management of Highway Structures Code of Practice (Roads Liaison Group, 2005), which again focused on the development and management of work programmes and the operational management of the bridge stock. In a more recent Austroads publication “A guide to bridge asset management, covering the life cycle performance management of bridges” (Maguire, 2009), bridge management was considered to be “a comprehensive and structured approach to the long-term provision and maintenance of physical road infrastructure using sound engineering, economic, business and environmental principles to facilitate the effective delivery of community benefits”. Although, Maguire also noted that the aim of bridge management was to deliver a specific service level to the community, little attention was paid to the social aspects of bridge management. A later study into bridge performance measures, again had a technical condition focus (Lake and Seskis, 2013). The strong technical focus continues to be evident in bridge asset management research (Cambridge Systematics and Meyer, 2007; Cambridge Systematics et al., 2005; Cambridge Systematics et al., 2006; Hawkins and Smadi, 2013; Kotze et al., 2015; Smadi et al., 2008; Wang et al., 2012). A condition focused viewpoint was also found to exist in New Zealand bridge asset management practices. In a survey of New Zealand bridge asset management practice Bush et al. (2012) found that many bridge asset managers had a poor understanding of what strategic outcomes were being targeted and what was required to deliver these targets, which again highlighted the disconnect between strategic and operational outcomes. It is thus considered that a focus on operational activities helps to address some issues, such as collecting more data to understand asset condition or the development of more comprehensive and complicated decision-making models, but a continued operational focus will not address the interrelated nature of the operational and strategic systems and of the sociotechnical system, and will therefore not address the auditors comments regarding connecting the operational and strategic systems (Refer Section 1.4).
To provide the required operational guidance the International Infrastructure Management Manual (NAMS, 2015) details what should be done at each stage of the asset management decision-making process. In the document five decision-making stages are presented (Refer Figure 2-2) including setting direction, understanding existing infrastructure performance, needs analysis (modelling performance gaps), programme development and implementation. Again, the decision-making process has a strong technical focus, with stakeholders only being explicitly accounted for at the direction setting stage. Similarly, Too et al. (2006) detailed a decision-making process that includes problem analysis, solution choice and solution implementation. In this process, problem analysis is the process of identifying the strategy that will deliver the best customer outcomes, solution choice (decision-making) is the identification of appropriate intervention options, and solution implementation is the delivery of the solution. The Too et al. (2006) decision-making process is similar to the one presented in Figure 2-1. Consequently, the stakeholder is again only implied, rather than being explicitly incorporated. Even when stakeholders are clearly referenced (Félio and Lounis, 2009), no clear guidance is provided on how to integrate their effects.

Figure 2-1  Asset management decision cycle (Adapted from NAMS, 2011)
Chapter 2 – Literature review: Identifying the conceptual modelling framework

Based on the review of the bridge management literature, there was found to be a clear focus on the management of the technical aspects, but limited reference to the social aspects. Even when the social aspects were identified there was no clear guidance on how to integrate stakeholders into decision-making models. Similarly, in the wider asset management literature, the technical aspects of asset management were well described, but when stakeholders were discussed there was again found to be no clear guidance on how to integrate stakeholders into decision-making models. To address the omission of stakeholders in asset management decision-making models the wider systems-thinking literature was reviewed.

2.2 A systems-thinking examination of asset management

It has been identified that the bridge asset management model should integrate both the social and technical aspects of asset management. The existence of two discrete but interdependent parts creates a system. Thus, a systems-thinking viewpoint was taken. A systems-thinking (Anderson and Johnson, 1997; Hitchins, 2003; Von Bertalanffy, 1972) centric review was used, because systems-thinking has been successfully applied to asset management problems (Herder and Wijnia, 2012; Thissen and Herder, 2009) and other business related fields (Forrester, 1991; Hammer et al., 2012; Ostrom, 2010; Seddon, 2008; Skarzauskiene, 2010). The systems-thinking methodology was successful because it led to the interactions between the component parts of the system being fully investigated. Thus, by carrying out the review, systems-thinking ideas are identified and explicitly integrated into the decision-making model. To provide insights into the development of the sociotechnical bridge management model, systems theory, complex systems, hard and soft systems, systems-thinking, sociotechnical systems, complexity and complicatedness, and holism and reductionism were reviewed.

Identifying a single definition of systems-thinking was difficult, because users of systems-thinking describe the process in the context of their own experience. For example, Seddon (2008) promulgates the view that systems-thinking constitutes a review of the whole system and the goal of this review should be the minimisation of waste, the time spent on re-work and the removal of bottle-necks, such as those created by inappropriately skilled staff. Seddon’s view has many similarities to the lean processes described by Sugimori et al. (1977), whereby the process flow of the whole operation is considered. In contrast to the qualitative approach used by Seddon (2008), operational methodologies such as lean use
quantitative mathematical models to describe the system and to understand the systems’ operation (Anderson and Johnson, 1997; Hitchins, 2003; Sterman, 2002). In some cases a more abstract view of systems-thinking is used, such as when the system’s operation is represented by pure logic (Weinberg, 2001). While the identified viewpoints used by those employing systems-thinking was found to differ, they all incorporated similar ideas, as they all took a holistic view of the system under consideration, and all the methodologies that were employed were used to identify the components of the system and the relationships between the identified components.

The methodological approach used in systems-thinking is an extension of complex systems theory. Originally Von Bertalanffy (1972) defined a complex system as one “where the properties and modes of action of higher levels are not explicable by the summation of the properties and modes of action of their components taken in isolation”. Similarly, Jackson (2003) defined a complex system as one “having a large number of sub-systems that are involved in many loosely structured interactions, the outcome of which is not predetermined”. A complex system is also considered to be a system with a set of loosely structured interactions, which affect the systems overall operation (North and Macal, 2007). Others, such as Gallagher and Appenzeller (1999), more simply state that a complex system “is one whose properties are not fully explained by an understanding of its component parts”. A complex system is also a system where the component parts of the system form a structured hierarchy (Jennings, 2001). The structure present in complex systems thus differentiates it from a heap, which has many unstructured components (Nikolic and Kasmire, 2013). The combination of a structured hierarchy and many interacting sub-systems implies that the system is complicated to understand, but this implication does not always hold true. One example of a simple, but complex, system is the game of life (Conway, 1970). In the game of life three simple rules are used, but from these rules complex life is created with multi-cell cellular automata living, dying, giving birth to new off-spring and moving around the model world (Conway, 1970; Wainwright, 1974).

The ideologies of complexity and complicatedness give rise to two schools of thought that can be used to think about complex systems, comprising reductionism and holism. In a reductionist methodology, each individual component of the system is identified and studied in detail. The system is then described by aggregating the behaviour of the modelled components (Andersen, 2001; Gallagher and Appenzeller, 1999; Porcellinis et al., 2009). An application of a reductionist approach can be found in the search for a gene for
intelligence or a gene for sexual preference. In these areas, following a reductionist methodology has led to a detailed description of the genome, but the final aggregated model still fails to describe why living entities do what they do (Gallagher and Appenzeller, 1999). If applied to the asset management process, reductionism would lead to an in-depth and complicated understanding of each component of the decision-making system, but it would also fail to describe the complex interactions that occur between each component.

In contrast to reductionism, holism “puts the study of the whole before that of the parts” (Jackson, 2003). Nevertheless, not everyone subscribes to holism being an improvement on reductionism. As an example, Porcellinis et al. (2009) argued that holism models a system at too high a level of abstraction, which results in knowledge of the low level interdependencies being lost. Based on this belief, Porcellinis, Oliva et al. (2009) promoted the use of a mixed reductionist-holistic viewpoint. The mixed approach thus ensured that aggregated systems-thinking ideals were balanced against the detail obtained from a reductionist approach. Even though Porcellinis, Oliva et al. (2009) promoted a mixed holistic-reductionist approach as a new method, in reality the approach is similar to the systems-of-systems modelling process. In the system-of-systems methodology lower level systems models are used as inputs into higher level models (Hitchins, 2003; Jennings, 2001). Thus, if a component of a system is viewed as a black box process with an input and an output, the black box is itself a system. Accordingly, to model a multi-layered hierarchical system, a systems-of-systems approach can be used without resorting to the mixed reductionist-holistic approach developed by Porcellinis, Oliva et al. (2009).

If the identified complicatedness versus complexity viewpoint is applied to asset management models, there can be seen to be increasingly complicated approaches being used to solve the problems created by deteriorating assets (El-Basyouny and Sayed, 2011; Kang et al., 2008; Orcesi and Frangopol, 2006; Wang et al., 2012). Nevertheless, the identified approaches do not fully address the complexity present in asset management, as they do not fully address the relationships between individual social and technical components. Thus, any new bridge model must allow for the effects of complexity by addressing the sociotechnical nature of asset management.

The interaction between the interrelated parts of the system must be modelled as the interaction between these parts causes feedback. Feedback can be both positive and negative (Hitchins, 2003; Smith and van Ackere, 2002), with negative feedback leading to balance.
and stability after an event and positive feedback leading to instability and change (Hitchins, 2003; Smith and van Ackere, 2002). Positive feedback leads to instability because positive effects are cumulative, which can force the system into a new equilibrium. In asset management condition assessment and modelling results in a stabilising feedback loop, as equilibrium between funds and condition is being sought, whereas a change in policy or level of service is a form of positive feedback, as there is limited certainty regarding what effects the policy change will have on the rest of the system.

In addition to the learning effects gained from incorporating and studying feedback, feedback between a system’s components can potentially create a non-linear response within a complex system, with this non-linearity leading to unforeseen behaviour (Forrester, 1994; Malanson, 1999), known as emergence (Andersen, 2001; Hitchins, 2003). Emergence can be defined by a number of criteria including (Railsback and Grimm, 2012):

- it is not simply the sum of the properties of the components of the system;
- it is different from the results produced by the individual system components; and
- it cannot be easily predicted from the properties of system components.

Not all researchers subscribe to the idea of emergence, with some noting that it may be a function of the observational blindness created as a result of unknowingly omitting parts of the system from the model (Weinberg, 2001). Others, such as Bankes (2002) also question whether emergence exists, noting that a modeller is usually the sole arbiter of emergence identification. In some cases, the inability to foresee future patterns partly arises because a complex system is one whose evolution is very sensitive to the initial starting conditions (Ladyman et al., 2013). Even Railsback and Grimm (2012), who acknowledge that emergence exists, emphasise that the modeller should consider whether the identified emergent behaviour is either a function of the model’s operation or the methods used to create the model. Nonetheless, if the modeller is confident with respect to the model’s development, the factors that are creating emergent patterns should be investigated and quantified (Railsback and Grimm, 2012), as these provide useful insights into the system’s operation. The idea of rationally searching out the causal factors that influence the system also adds scientific rigour to the modelling process and overcomes the common complaint that the development of complex systems models tends toward being an unscientific process (Heath et al., 2009; Railsback and Grimm, 2012). Thus, the exploration of emergence is essential to understanding the system and leads to a deeper understanding of why and how
the system produces emergent patterns (Kurtz and Snowden, 2003) and thus how these outcomes may be more effectively managed. Furthermore, Kurtz and Snowden (2003) noted that studying emergent behaviour in a complex system is the only way to learn what might happen in real-world systems, because of the inability to predetermine the outcomes of the real-world system prior to them occurring. Accordingly, potentially emergent behaviour should be explored in the sociotechnical asset management system.

Asset management comprises interacting social and technical systems. To understand the effects that the social elements have on the asset management process these elements must be included in asset management models (Dijkema et al., 2013; Godau, 1999; Herder and Wijnia, 2012). Including stakeholders in the model changes asset management from being technical to being sociotechnical. In systems-thinking a sociotechnical system comprises an interconnected social network and physical network of technical artefacts, with each of these networks affecting the other (Dijkema et al., 2013; Ropohl, 1999; Trist, 1981). A sociotechnical system is also a system that cannot function without the agents and the infrastructure they interact with (Kroes et al., 2006; Osman and Nikbakht, 2014). The interaction that occurs between the social and technical systems leads to feedback, which results in self-organisation of the system (Dijkema et al., 2013), as the system changes as a result of human intervention. Adaptation in asset management systems occurs because the asset manager changes the physical system, because of stakeholder feedback. Based on these changes the users of the physical system change their usage patterns, which in-turn leads to further system adaptation.

Potentially, the social asset management system can be viewed as a soft system, where a soft system is “relevant to arguing about the world, not models of the world; this leads to ‘learning’ replacing ‘optimising’ or ‘satisficing’; this tradition talks the language of ‘issues’ and ‘accommodations’ rather than solutions” (Checkland, 1985). The soft system perspective is in contrast to that used to represent hard systems, which draws on technical models. If the hard system perspective is taken “the world contains systems which can be ‘engineered’, hence models of those systems can be made; it talks the language of ‘problems’ and ‘solutions’ which eliminate problems” (Checkland, 1985). The idea that soft systems are not about optimising is well known in social science (Epstein, 2008; John and Scott, 2007), but is in contrast to the hard systems approach found in bridge asset management decision-making research (Frangopol and Bocchini, 2012; Kyle et al., 2002; Orcesi and Cremona, 2010), which focuses on the sole objective of managing technical issues. The different
approaches to conceptualising hard and soft systems was highlighted by Freeman et al. (2010) in their state of the art review of stakeholder theory, where they noted that the use of a hard systems viewpoint led to the creation of models that do not include stakeholder influences. Thus, to create a sociotechnical model, influential stakeholders must be included (Freeman et al., 2010). Similarly, Osman (2012) noted that the traditional asset-centric asset-management decision-making approaches “may not necessarily achieve technical, societal and political objectives”. During an investigation of the sociotechnical trade-off in construction, Neal (1995) found that many projects are dependent on a balance between the hard engineering aspects of the project and the softer customer expectations. The idea that construction and contract management can be viewed as a sociotechnical system was also explored by Altamirano et al. (2008). In an asset management context the hard and soft system dichotomy is central to the reason for the ongoing development of new sociotechnical models (Mostafavi et al., 2015; Osman, 2012; Osman and Hassan Ali, 2012) and why a new sociotechnical strategic bridge model is being developed as part of this research.

Based on the review of systems-theory and systems-thinking ideas, consideration should be given to the level of detail which is included in the sub-system models, and the investigation of the emergent effects arising from the interaction between the social and technical components of the asset management model. Such an investigation has the potential to provide new insights into the system’s operation or the interaction between the model’s components. Furthermore, to integrate stakeholders into the sociotechnical model benefit can be derived from taking a soft systems viewpoint, along with the hard systems viewpoint being used to model the assets.

2.3 Identification of a strategic asset management system

In the following section systems-thinking ideas are used to identify a model of asset management decision-making that explicitly integrates the sociotechnical model and the performance measurement system that is used to monitor the effectiveness of a strategy as it is implemented.

A general conceptual model that creates a link between real (practice) and virtual (theory) systems was developed by Checkland (1985), who noted that theory affects practice and practice is used to update theoretical ideas. The adaptive system presented by Checkland (1985) has many similarities with the twin decision-making cycles detailed in the strategic
decision process developed by Dyson et al. (2007). In the identified twin cycle conceptual model, the first cycle relates to strategy enactment, which is used to monitor the level of performance that is being achieved by the organisation and the second cycle provides a virtual model of the business environment that is used to improve decision-making. The virtual model improves decision-making outcomes as it can be used to rehearse strategies before they are implemented. The performance measurement framework provides the link between the rehearsal and enactment cycles, by ensuring common measures are used to understand the results that are obtained from virtual models and in the monitoring of the real-world system. By developing the link between the real-world and virtual-world systems, a connection is created between the organisationally focused management control system and the strategy implementation system (Langfield-Smith, 1997).

Given that the strategic decision process presented by Dyson et al. (2007) and the asset management process have many similarities including modelling, performance measurement and strategy enactment, a modified version of the Dyson et al. (2007) process was used as the new conceptual model of the asset management process (Refer Figure 2-2). The strategic decision-making process developed by Dyson is the same as the new conceptual model of the asset management process detailed in Figure 2-2, except that herein asset management specific terminology has been incorporated. Furthermore, a model updating link has been created to reflect the practice-theory relationship developed by Checkland (1985). The new conceptual model of the asset management process highlights the importance of creating a link between real and virtual systems and shows the role of performance measurement and management, data collection and strategy implementation. In contrast to the original asset management process (Refer Figure 2-1) the new conceptual model of the asset management process more strongly reflects the ideas of system-thinking as it explicitly identifies the component parts of strategy development and the feedback loops between these parts.
While the new conceptual model of the asset management process is an improvement on the original asset management process depicted in Figure 2-1, the decision-maker is still omitted from the decision-making cycle, which is important as the decision-maker directly affects the process (Hammer et al., 2012). In the conceptual asset management process the decision-maker affects both the strategy enactment cycle and the strategy rehearsal cycle. With respect to the strategy enactment cycle the decision-maker sets the strategic goals, assigns resources and identifies and manages the performance measurement framework. All these management actions are carried out in reaction to the changing expectations of the stakeholders the organisation interacts with. In the strategy rehearsal cycle the decision-maker explores the effects of virtual strategy enactment by exploring the effects that different strategies have on the internal and external environments. Accordingly, the decision-maker must be incorporated in to the rehearsal cycle. By incorporating the decision-maker in the rehearsal cycle, the impact that potential strengthening strategies have on network functionality can be explored.

By utilising the modified strategic decision process as the starting point for developing the new conceptual model of the asset management process the ideas of systems-thinking have been included, and the goal setting, strategy development and strategy delivery tasks detailed
in the original asset management cycle have been integrated. Furthermore, in the new conceptual stakeholders and decision-makers are integrated into the strategy rehearsal models, which addresses the recommendation of Hammer et al. (2012).

2.4 A conceptual model of a sociotechnical asset management system

The strategic asset management process provides the overarching asset management framework that links the performance measurement and management framework, and the sociotechnical bridge asset management model. In the following section a conceptual sociotechnical model that integrates both stakeholders and decision-makers is identified and further modified to address the relationships that occur in asset management.

Based on a review of the literature (Achterkamp, 1997; Bromiley and Rau, 2011; Eisenhardt and Zbaracki, 1992; Idenburg, 1993; Jonassen, 2012; Klein, 2008; Lipshitz et al., 2001; Müller et al., 2013; Nusrat and Yamada, 2010; Prelec and Loewenstein, 1991; Simon, 1959, 1979; Stokman et al., 2000; Stokman and van Oosten, 1994; Sun and Naveh, 2004; Wierzbicki, 1982), there was found to be a number of methodologies being used to develop sociotechnical decision-making models, with these methodologies arising from the schools of thought that a model should adopt a normative, prescriptive or descriptive framework for representing the decision-making behaviour of the social agents. A normative methodology being one that describes how perfectly rational agents decide what should be done (Peterson, 2009). A normative methodology always assumes that perfect information exists. A normative methodology differs to a descriptive methodology, which describes the real decision-making behaviours that are occurring and takes in to account the effects of intuition and biases of the decision-makers. Accordingly, a descriptive decision-making process acknowledges that perfect information does not exist (Simon, 1959). No clear description exists for a prescriptive methodology, but herein a prescriptive methodology is considered to be one that employs rational decision-making practices, but within the context of known information and human decision-making limitations (Takemura, 2014). In the bridge asset management model, a descriptive methodology was adopted, as the agents use rational decision-making methodologies to identify their preferred courses of action (Refer Chapter 5).

The development of the social component of the conceptual model was further complicated by whether the cognitive behaviours of individuals within an organisation had to be modelled
or the organisation itself had to be modelled (Bromiley and Rau, 2011; Sterman, 1989). If treated as a single system, the organisation would be represented as one component that reviewed information and made decisions. If represented as multiple systems, the different departments or individuals within the organisation would have to be modelled. To simplify the development of the sociotechnical asset management model, a higher level of model abstraction was employed, which resulted in the asset management organisation being described as a single system. The level of abstraction was selected, as the aim was to describe the relationship between the technical and social components and not to describe the complex structure of the asset management organisation.

To identify a sociotechnical conceptual model that could be used to manage functionally obsolete bridges, the original asset management process (Refer Figure 2-1) was used as the starting point for searching the operational research literature. Based on the search the original asset management process was found to be a linear decision-making process (Amekudzi and Meyer, 2011; Byrne, 1991; NAMS, 2015; Srividya et al., 2012). Linear processes are considered linear because they are methodical, directed and sequential (Chaffee, 1985) and have limited feedback between each strategy development cycle (Dyson et al., 2007; Sterman, 2001). A representation of a linear asset management process is presented Figure 2-3. The linear processes presented in Figure 2-3 is based on the event oriented view of the world developed by (Sterman, 2001). Both the four-stage process illustrated in Figure 2-3 and the five stage processes illustrated in Figure 2-1 have many similarities. In the five-stage asset management process the organisation first decides what goals should be targeted (Figure 2-3 stage 1a) and what direction to take (Figure 2-3 stage 1b). Second, data is collected to understand the performance levels being achieved by the asset and to identify the gap in performance that exists (Figure 2-3 stage 1b). Following on from the data collection process the third stage comprises a “needs analysis” to understand what is required to achieve the desired goals (Figure 2-3 stage 3). After the needs analysis stage, an optimised set of interventions, that meet the goal criteria, are then developed and added to a work program (Figure 2-3 stage 4). The fifth and final stage is the enactment of the optimised work program (Figure 2-3 stage 4).
In the both linear decision-making methodology and the asset management process, the decision-making process is idealised as being a “rational progression from strategy formulation to strategy implementation” (Langfield-Smith, 1997). As highlighted by Chaffee (1985) linear decision-making processes are particularly useful when those responsible for setting organisational direction have significant control over what actions are taken, which is the case for asset management organisations focusing on the effective allocation of maintenance funds (Cooksey et al., 2011). However, the idea of a single point of management changes with the introduction of stakeholders and the creation of a sociotechnical system. Based on the research of Chaffee (1985) and others (Bromiley and Rau, 2011; Idenburg, 1993; Sterman, 1989), the linear system currently used in asset management was found to be no longer applicable, as there is no longer a single controlling entity. It is thus considered that if the simplified linear approach is continued to be used the models that are developed will continue to represent a real-world viewpoint that no longer holds true or which fails to reflect the complex sociotechnical relationships found in the modern asset management process. Consequently, if asset management models are not updated to reflect the sociotechnical system they must represent, their accuracy will start to decline, and the inaccuracies will start to affect decision-makers’ trust in them. Eventually, the mistrust of the modelled outcomes will lead to policy resistance (Sterman, 2001).

To effectively model more complex systems, Boulding (1956), in his generalised view of systems theory, promulgated that a model must reflect the complexity of the real-world
system being represented. To guide the development of increasingly more complex models, Boulding (1956) described nine levels of complex system including frameworks, clockworks, thermostats, cells, genetic-social, animal, human, social-organism and the as yet unidentified transcendental system. In the Boulding (1956) hierarchy a system progresses from being static and unchanging, through dynamic and open systems, to complex social systems with strong interrelationships between constituent parts. If the strongly technical asset management models are compared to the nine different hierarchies the process has similarities with the lower order systems such as cells, thermostats and clockworks. In an abstract sense, assets can be considered as cells because they consume material and funds to sustain their existence, and in setting goals and working to achieve these goals asset management organisations also act like a thermostat. The predictable characteristics of clockworks are also evident in the maintenance allocation models (Fickler et al., 2009; Orcesi and Cremona, 2011; Tsunokawa and Hiep, 2008) that are used to predict, albeit stochastically, the future state of the asset. The difficulty arises when trying to align the strongly technical asset management viewpoint with the higher level systems described by Boulding (1956). The inability to compare technical asset management models to the higher level systems defined by Boulding (1956) occurs because of the omission of social interactions from the technical modelling process. It could be argued that stakeholders are included in asset management models, but in reality they are not modelled in sufficient detail to understand the impact they have on decision-making outcomes (Moore et al., 2008; Osman, 2012). If stakeholders are added to decision-making models, the inability to compare existing asset management models to higher level systems ceases to exist. By including stakeholders, and with the resulting change to a sociotechnical viewpoint, asset management suddenly has closer similarities with a genetic-social system. The similarity between the sociotechnical asset management system and the genetic-social system occurs, because by including stakeholders there is an understanding that governments, asset management organisations and contractors all influence the achievement of organisational goals (Moore et al., 2008; Osman and Nikbakht, 2014), which results in feedback based adaptations to the organisation, user and asset systems. The effects that increasing system complexity has on decision-making methodologies was also acknowledged by Chaffee (1985). To address these complexities Chaffee (1985) promoted the incorporation of an adaptive agent.
In a more abstract sense, Kroes et al. (2006) argued that a physical object only becomes a technical artefact when agents interact with the object, which requires the context the artefact is used in to be understood. In an asset management context assets thus remain as physical objects until users interact with them. Thus, a bridge only becomes a technical artefact in the sociotechnical system, when it is viewed by the social agent. Transportation network modellers use a similar technical and human interaction conceptual framework to that referenced by Kroes et al. (2006). Although the nomenclature is different the construct is similar, as the network and the activity on the network (Cascetta, 2009; Sheffi, 1985) are both defined. In a sociotechnical model the network becomes the technical aspect of the model and the social interaction with the network is the activity model. The interaction between the two systems thus leads to a user management problem, rather than a system management problem (Magnanti and Wong, 1984). Consequently, because of changing from an asset centric context to a sociotechnical context, asset management models evolve into transportation models that incorporate adaptive agents. Thus, sociotechnical asset management models that incorporate infrastructure networks can use similar modelling methodologies. To address such a transportation management problem Franzen (1999) created a sociotechnical model of a transportation network. The conceptual model has many similarities with existing agent-based models, as it includes the government agent, users (travellers), goals and preferences of individual parties, and the environment the users interact with (the transportation system). The conceptual model developed by Franzen (1999) visualises how the separate transportation systems and the user systems are integrated. Although the model provides a useful starting point, the original model was found to be too specific for modelling the bridge network problem. Accordingly, a more abstract conceptual model was created that more closely reflected the bridge asset management problem (Refer Figure 2-4). The transportation models, such as the one depicted in the Figure 2-4, like the Dyson et al. (2007) strategic decision-making process, omit the effects of the decision-maker. Accordingly, the abstract conceptual model should integrate the network users, the environment and the decision-maker.
A conceptual model of a complex sociotechnical system, that can be used to explore the relationship between the technical bridge artefacts, the perception of those that use the bridge network and the impact on those that manage the network, is the feedback view of the world (Sterman, 2001). In this conceptual model, the aspects not covered by the present organisational bridge management models are addressed, including the side effects occurring because of a solution being implemented and how each agent in the decision-making process perceives other agents and the technical environment they interact with. The adaptive relationship between the users, decision-makers and the environment they manage and interact with is also evident in models used to represent coupled human-natural systems (An, 2012; An and López-Carr, 2012; Yang and Dong, 2010). In the coupled human-natural systems the agents react to the changing nature of the environment and subsequently adapt the environment to suit their expectations and requirements, which creates a feedback loop between agents and the environment they operate within. A similar, coupled system idea is represented in the Sterman (2001) feedback view of the world. In the Sterman model the decision-makers interact and change the environment, and other users react to these changes, which subsequently affects the decisions made by the organisation that is working to change the environment. Given the Sterman (2001) feedback view of the world incorporates decision-making agents, other stakeholders and an environmental model, the model was used as a starting point for developing the new bridge asset management model (Refer Figure 2-5). The feedback view of the world was used because it was created by Sterman to addresses
the weaknesses of the event orientated view (Refer Figure 2-3), which as identified has many similarities to the original asset management process (Refer Figure 2-1). In the Sterman (2001) feedback view of the world the main aspects of a sociotechnical system are accounted for by including the environment that the agents interact with and the influence that stakeholders have on the environment and each other. Notwithstanding the fact that asset management has many similarities with the feedback view of the world, the conceptual model was found to mainly apply to companies that operate in a competitive market. By taking a competitive perspective, the environment is affected by all the agents, as all agents are directly competing for the same market share. The direct competition modelled in the feedback view of the world does not occur in public infrastructure asset management, because the asset management organisations responsible for public infrastructure control their own allocated regional area. By compartmentalising infrastructure management functions, the interaction between the decision-maker, other management agents and the environment is altered. Furthermore, in public infrastructure asset management stakeholders do not directly affect the environment, but work through the asset management organisation or governmental representatives (Bernhardt and McNeil 2008; Osman 2012). Thus, the feedback view of the world was modified so that the stakeholders only interact with the asset manager / decision-maker. In the new conceptual model, the abstract idea of a decision has also been replaced with the less abstract decision-making asset manager, thus facilitating the development of a decision-maker model. Lastly, the goals of the other agents have been changed to reflect the action orientated process of perceiving the asset and subsequently influencing the asset manager based on the perception of the service quality. The new conceptual model of bridge asset management (Refer Figure 2-5) compares much more closely with the ideals described in modern industry asset management literature (NAMS 2011; Hawkins and Smadi 2013; ISO 2014) as stakeholders, decision-makers and assets, and the sociotechnical interactions between these elements are all accounted for. It is considered that the new conceptual bridge asset management model diagrammatically illustrates the ideas expressed, but not visualised, by the developers (Moore et al., 2008; Osman, 2012) of other sociotechnical asset management models. The ideas are now explicitly expressed as the key stakeholders and their impact on asset management strategies are now clearly defined.
2.5 Identification of a computational modelling framework

The new conceptual model of bridge management provides a useful visualisation of the sociotechnical asset management process, but to investigate the impact that decision-makers have on the long-term performance of the asset, a computer model is required. In this section, the methods that potentially could be used to model a sociotechnical system were investigated. The methods that were reviewed comprise mathematical modelling, systems-dynamics, discrete event simulation, and agent-based modelling. The primary criteria that were considered when searching for an appropriate modelling framework were:

- The modelling approach must be able to simulate stakeholders and the interaction between these stakeholders, thus providing insight into the effects of these interactions on asset management outcomes.
- The modelling approach must be able to simulate the geospatial and heterogeneous nature of the asset, thus providing a realistic representation of the real-world environment.
- The modelling approach must be able to simulate the interaction between stakeholders and the asset, thus reflecting the sociotechnical interactions that occur in asset management.

Based on a review of the identified modelling methodologies (Refer Appendix A), an agent-based modelling framework was selected. Agent-based modelling framework was selected because of the broad range of topics it has been applied to and the parallel nature of these topics to the asset management process. Furthermore, agent-based modelling is superior for
Chapter 2 – Literature review: Identifying the conceptual modelling framework

creating small-scale asset management models, as geospatial models can be easily integrated, which is required when modelling a network of bridges.

2.6 Modelling software

A review of the available agent-based modelling software was carried out to identify which platform would be used to create the sociotechnical bridge asset management model (Refer Appendix B). Based on the review, Netlogo was selected (Wilensky, 1999; Wilensky and Rand, 2015). Netlogo was selected as it included a geospatial extension, was recognised has having low entry level requirements, but a high development ceiling, and was acknowledged as being a platform that could be used for rapid prototyping (North and Macal, 2007). Furthermore, extensive literature existed that could be used to learn the Netlogo programming language.

2.7 Summary

In this chapter, the aim was to identify and develop a sociotechnical framework for developing the bridge asset management model. To achieve this outcome a review the asset management process and systems-thinking literature was carried out. The following summarises the findings from this review.

Bridge asset management decision-making was found to be a complex process, but while guidelines and standards cover many aspects of the asset management process they do not directly address the complexity that arises from the interactions that occur between the social and technical systems. Furthermore, the asset management literature does not detail how the numerous systems comprising real-world systems, virtual systems, organisational systems and performance systems, work together as an integrated whole. To address the complexity arising from the interrelated asset management systems a systems-thinking based examination of the asset management process and asset management decision support models was carried out. In this examination of asset management practice the asset management decision-making process was compared to those highlighted in the literature and found to have the same form as a linear decision-making system. In the linear paradigm, the underlying assumption is that the decision-maker has full control of the decision-making process, which is adequate when managing technical problems, as the asset manager can define what actions should be taken. Nevertheless, with the incorporation of social elements into the asset management process a linear system was found to be insufficient, as the linear
system cannot be used to manage the decentralised adaptive effects that occur in sociotechnical systems. As highlighted by Boulding (1956), as a system increases in complexity so should the models that are used to represent the system. Accordingly, two conceptual models for improved bridge asset management were identified. The first conceptual model to be developed was the new conceptual model of the asset management process. Illustrated in this conceptual model is the relationship between the virtual and real-world systems. The second conceptual model to be developed comprised the sociotechnical organisational model, which was embedded in the strategy rehearsal cycle of the asset management process. By creating the new sociotechnical organisational model the ability to investigate the effects, on the technical environment and the social user environment, arising from the strategies proposed by the planning agent has been created. Furthermore, the identification of the organisational model provides a useful visualisation of the components and connections present in a sociotechnical bridge asset management model. The organisational conceptual model also, diagrammatically illustrates the ideas expressed in the agent-based asset management modelling literature.

To turn the organisational model into a computational model agent-based modelling was identified as the preferred methodology. Agent-based modelling was chosen because it can represent the soft social agents and the hard-technical assets all in the same modelling framework. Thus, providing the ability to fully represent the spatially heterogeneous sociotechnical bridge management system. Agent-based modelling has also been successfully trialled as a potential asset management modelling platform.

By creating a fully integrated conceptual framework of the bridge asset management decision system support will be provided to decision-makers when developing sociotechnical bridge asset management strategies. Developing the sociotechnical model will also force a connection to be made between the cause and effect of an event and how the ongoing feedback between cause and effect gives rise to potential emergent system level characteristics. Furthermore, because of the new conceptual bridge management model, the bridge modelling process will naturally consider the social and technical aspects of bridge management. The benefit of agent-based sociotechnical models has already been proven, but further research is required to improve these models, move them towards a New Zealand context and to integrate bridges into the decision-making process. The data required to develop the bridge asset management model is identified in the following chapter.
Chapter 3 A mixed methods data collection strategy

The data collection methods used in small scale social research, the identification of stakeholders and the interview and survey questions used to elicit the data used to the develop the social and the technical models are detailed in this chapter. Additionally, other data inputs, such as records from the New Zealand national bridge management system, are detailed. In some cases, when the data sets were reviewed, the required data was missing, accordingly how this missing data was imputed is also covered.

3.1 Research design

To create the agent-based bridge asset management model requires knowledge of how the agents interact and their social topology (Macal and North, 2010). Agents being a set of computational entities that have attributes and characteristics that are used to represent their real-world counterparts. Even though the ideas present within agent-based modelling have been used for many years (Coleman, 1974), agent-based model development is still a relatively new process (Macal and North, 2010), accordingly no standard approach to creating agent-based models was found to exist. Similarly, Smajgl et al. (2011) also found that there was no standard methodology for empirically developing agents. Primarily, the absence of a standard approach arises because of the variety of problems agent-based models can be used to investigate. This variety has led researchers to use methodologies that incorporated census data, field or lab experiments, structured interviews and role playing games (North and Macal, 2007; Smajgl et al., 2011), empirical comparisons with available datasets (Janssen and Ostrom, 2006; Knoeri et al., 2014; Smajgl et al., 2011) or consulting with stakeholders on the validity of the model after the model was created (Osman, 2012). To improve the quality of qualitative research Kitto et al. (2008) recommended that multiple data collection methods should be combined. As identified in Chapter 2, the asset management system comprises both soft social and hard technical agents. Accordingly, a
Chapter 3 – A mixed methods data collection strategy

A mixed methods approach to data collection was employed. The justification for using a mixed methods approach is presented below.

As highlighted by Smajgl et al. (2011) the choice of data collection methodology is directly related to the size of the population being modelled. The use of each type of dataset being dependent on how precise the representation of the cognitive process must be. If an accurate individualised model is required, lab experiments are used. If a country’s general populace is being represented in a model, then large datasets such as census data are used. In the context of the bridge asset management model, where accurate models of small groups are required Janssen and Ostrom (2006) recommended the use of interviews, surveys or ethnographic studies. As described by Smajgl et al. (2011) and Denscombe (2010) an ethnographic study is where the researcher or scientist is embedded in the social group and documents daily life. As an ethnographic study is a form of participant observation the researcher must be present to record daily activities. Although used to develop some agent-based models (Gilbert and Yang, 2008), participant observation was not used to develop the social bridge asset management agents, as the decision-making process that had been used by the planning agency had already occurred, and thus no opportunity existed for recording the decision-making processes of key stakeholders. Accordingly, a combination surveys and interviews were used to collect the data used to develop the social bridge asset management agents. Surveys were used, because as highlighted by Denscombe (2010) they can be employed to understand what people do and how they think about a problem. Furthermore, the ability to use surveys to collect data on both large numbers of people or to investigate specific issues in small groups makes them useful as a small-scale social research tool (Denscombe, 2010). In this research, a survey was used for the following reasons:

- The survey ensured the required data was obtained from participants.
- If participants did not want to be recorded, or the interview location was inappropriate for recording, the survey provided a simple method of recording observations or comments made by the interviewee.
- The survey provided an opportunity for raising awareness of the topics to be covered, prior to meeting with the stakeholders.

Further to the above points surveys were also used to identify the social system topology and the interactions that occurred between social and technical agents, and to identify the general processes and practices that were used to agree which group of bridges on each of the
identified routes would be selected for strengthening. To reflect the different agent types and their own specific decision-making contexts the questions were subtly altered, while maintaining the general structure and meaning.

As an extension of the survey methodology Delphi has been used to aggregate survey findings into a consensus viewpoint that can be used to form the basis of the behavioural models used for each agent type. The Delphi method comprises a structured process for eliciting feedback from experts and usually occurs over up to five rounds (Linstone and Turoff, 1975; Okoli and Pawlowski, 2004; Skulmoski et al., 2007). If the researcher, modeller, and stakeholders are to work in close collaboration a participatory model development technique is used (North and Macal, 2007; Prell et al., 2007). The main difference between these two techniques being that in the Delphi method individuals maintain a level of anonymity (Linstone and Turoff, 1975), whereas in participatory methods the group acts together to develop the final consensus. In the Delphi method the benefit of maintaining the anonymity of each stakeholder during the model development process, is the ability to collect judgemental information from those involved (Okoli and Pawlowski, 2004). By collecting this judgemental insights into the processes and beliefs of the individual stakeholders involved can be obtained. In both methods the level of interaction between the stakeholder groups and the researcher depends on the level of heterogeneity of the target audience and the complexity of the problem (North and Macal, 2007; Skulmoski et al., 2007).

In the first round of the Delphi process the researcher issues a survey and obtains feedback from the participants. The researcher then reviews the feedback and draws conclusions from the findings. In the second round the findings are presented to the participants. Thus, over each round each participant is provided with the opportunity to alter their opinion based on the aggregated feedback they receive. At the end of the Delphi process the aim is to derive a common consensus between all participants.
Chapter 3 – A mixed methods data collection strategy

The situations appropriate to this research, where the Delphi technique has been successfully used, are as follows:

- gathering data that is not accurately known (Linstone and Turoff, 1975; Skulmoski et al., 2007);
- providing insights into the causal relationships in complex economic or social phenomena (Linstone and Turoff, 1975); and
- when the goal is to improve the understanding of a problem (Skulmoski et al., 2007).

Although Delphi has been successfully applied there have been situations where the research outcome was less successful (Linstone and Turoff, 1975). The factors that led to these research projects being less successful were (Linstone and Turoff, 1975; Skulmoski et al., 2007):

- The view and preconceptions of a problem were imposed on the respondent group by over specifying the structure of the Delphi and not allowing the contribution of the perspectives related to the problem to be identified.
- Assumptions were made that the Delphi technique could be used as a surrogate for all other communication in each situation.
- Poor technique was used in summarising and presenting the group response in subsequent rounds.
- Ignoring and not exploring disagreements, resulting in dissenters dropping out of later rounds. Thus, the outcome that was obtained was an artificial consensus that did not reflect reality.
- The demanding nature of Delphi technique was underestimated, and thus impact the process has on those stakeholders that are involved, which are often busy because of their expertise.

The original intent was to use either the Delphi or the participatory methods to develop the model, but early difficulties in obtaining willing participants resulted in neither method being used. The use of a participatory methods was also rejected, because of the infeasibility of getting key stakeholders to be present in one meeting space, especially given the numbers of stakeholders involved in the vehicle mass and dimension project and given that these stakeholders were located throughout the country. Consequently, a mixture of interviews and surveys was used to obtain the required data. Interviews comprise an unstructured
dialogue based on open questions (Denscombe, 2010) and surveys comprise a set of structured questions with predefined answers, that are completed via e-mail, telephone or in person (Denscombe, 2010; Smajgl et al., 2011). A semi-structured combination of interviews and surveys was used, because as highlighted by Devers and Frankel (2000), while structured instruments lead to quicker data analysis and reporting there is a danger that the researcher will find what is expected. Through the use of a semi-structured approach the required information on agent topology and interaction was able to be obtained, thus overcoming the potential problem of applying a known model, rather than the model that most appropriately described the situation (Prell et al., 2007). Furthermore, by using the semi-structured process a deeper understanding of the context in which the stakeholders made their decisions could also be investigated. A deeper understanding was achieved because the use of a semi-structured process provided those involved with the opportunity to discuss the wider remit of their work, along with the scope of their activities as they related to the problem. A semi-structured approach also made more effective use of the available time, given that a one hour time constraint was placed on the survey / interview process.

On completion of the interview process, the use of a semi-structured process was found to be justified, as the data that was required was obtained, but further to the insights provided from the structured data other insights were also provided from the wider contextual discussions that occurred, with these insights being used in the development of the social model. For example:

- One bridge management participant provided insights into truck driver route choice behaviours, which led to the understanding that hauliers are both distance and journey time reliability optimisers.
- A transportation economist provided insights into the movement of freight by road, noting that heavy primary loads, such as lumber, tend not to be hauled great distances because of the limited return values resulting from empty vehicles being used in one direction. Freight advocacy groups also talked extensively on the typical origin and destination points of their members.
- The effectiveness of the HPMV working group created by the national road controlling authority could be assessed and their method of working inferred. This group comprised both freight industry and road controlling authorities. As supported by interviewees, the creation of this group led to a more collaborative working environment.
Census data was not used in the development of the agent-based model, because in this case the model was not being used to simulate changes in the national or regional populations. Although census data was not used, a range of other sources were used to develop the technical models, including data stored in bridge management databases, geospatial data and data presented in national and international design and bridge management standards (Refer Sections 3.5 and 3.6).

Although lab experiments and role playing games are highlighted as separate data collection methodologies (Janssen and Ostrom, 2006), they are in effect part of a continuum of techniques that combine empirical data with agent-based modelling. Based on the research presented by Janssen, both lab experiments and role playing games are feasible methodologies for investigating the combined decision-making process that occurs in social asset management networks (Janssen and Ostrom, 2006). Role playing games are often used as a methodology for understanding how “real agents” make decisions and react to different situations and thus affect the overall balance of the system being studied (Barreteau et al., 2001). One example of a role playing game is the asset management game (The Centre of Expertise, 2014; Van den Boomen, 2012). The asset management game is used to provide insights into the roles of each party and the types of communication that occurs between the game’s members. The aim of the players is to maximise their personal asset management development level, known in the game as asset management maturity. Feasibly, games could be used to provide insights into the mental processes of asset management agents and the structure of the social networks. Nevertheless, a role-playing game was not used because detailed knowledge of the process being considered is required before the game’s rules can be developed. Added to the requirement to develop rules, role playing games are sometimes cumbersome and slow to develop and comparisons between different experiments is difficult, since the many parameters in a role playing game are not controlled (Barreteau et al., 2001).

In summary, alternative data collection methods that could be used for small-scale social research were investigated. The final solutions that were used comprised structured interviews using a survey to develop the social models. A survey was also used to develop the bridge performance model.
3.2 Stakeholder identification

The following section details the methods used to identify key stakeholders. The stakeholders that were finally modelled are also identified.

As defined by Freeman et al. (2010) a “business can be understood as a set of relationships among groups…which have a stake in that business” and may include stakeholders that are both internal and external to the business, with these stakeholders comprising shareowners, employees, customers, suppliers, lenders, and society. Thus, how an organisation works is a function of how these groups interact to create value (Freeman et al., 2010). In creating a sociotechnical model Kroes et al. (2006) noted that one way of setting the boundaries to the model, and thus which stakeholders to include, is to assume “anything in the system that is necessary for performing its intended design” should be included. Similarly, Macal and North (2010) noted that the agents that are included in a model are those actively seeking to affect the system, as agents are active entities that work to achieve their own internal goals, rather than being passive and reactively responding to other agents and the environment. Thus, those stakeholders impacting the freight efficiency outcome were all considered. As implied by Freeman et al. (2010), all stakeholders are easily identifiable, as the business managers know who they interact with. Nevertheless, in developing a new agent-based model of a socio-ecological system Prell et al. (2007) identified a number of challenges with respect to the choice of stakeholders, including:

- The dialectic between problem definition and stakeholder identification. The issue must be defined before stakeholders are involved, but stakeholders help to define the issue. Thus, the challenge arises in understanding which stakeholders affect the system and which to initially interview.
- The potential for stakeholders to not understand how the research affects their daily lives and a potential level of apathy because of time constraints.
- Accounting for the varied perceptions and hidden conflicts that occur between stakeholders.

Potentially, a number of stakeholders are involved in the development and attainment of asset management outcomes, but only a few stakeholders will ever directly influence the final outcome (Donaldson and Preston, 1995; Sharp et al., 1999). As highlighted by Prell et al. (2007) many academics initially choose the core set of stakeholders based on their relative power, influence and legitimacy (Mitchell et al., 1997), but often overlook the role of
communication networks. Consequently, the process of understanding communication networks, rather traditional stakeholder identification methodologies was used. The added advantage of using the communication network approach was no assessment of the relative power of stakeholders was required, which would have been difficult given the fact that there was initially little knowledge of who the important stakeholders were.

To identify the structure of the communication network Sharp et al. (1999) recommended that a baseline stakeholder should be identified first, with those that influence the system being those that affect the baseline stakeholder. Thus, by identifying a baseline stakeholder, other stakeholders are identified. The identified group can then be further expanded through the use of the snowball identification technique (Denscombe, 2010; Patton, 2005). In a snowball approach the baseline stakeholder is questioned with regards to those that influence their decision-making processes. The idea of a baseline stakeholder linked with a snowball methodology works to explicitly develop an understanding of both the agent topology and the interaction dynamics. A similar method was used by Neal (1995) to develop an understanding of the stakeholder topology in a project. To identify stakeholders Neal reviewed the delivery chain and identified the stakeholders that provided the required viewpoints. Thus, a number of baselines were created, rather than the single baseline used by Sharp et al. (1999). Although the Neal methodology more readily identified the candidate stakeholder groups, the methodology only works if the supply chain can be outlined at the start. In Neal’s situation an outline understanding of the supply chain existed and so the method could be used, but as highlighted by Prell et al. (2007) this is not always the case. To maximise the likelihood of gaining a full understanding of the stakeholder network, the final methodology that was used combined the methods of Neal and Sharp. Accordingly, key stakeholder groups were used to set multiple baselines with the topology further developed through a process of snowballing. To develop a baseline list of stakeholders, a review of the asset management literature was undertaken. The review is detailed in the following sections.

In a general asset management context, Godau (1999) recommended that policy makers, regulators, infrastructure managers, operational staff, users, and future generations must be considered when developing infrastructure management systems. Similarly, Lewe (2005) included the public, industry and indirect stakeholder agents in a model of a transport system. In his research on road management, Talvitie (1999) highlighted that government guidance influences the performance of road systems. Elias et al. (2002), who investigated
stakeholders’ involvement in research and design projects, provided an expanded list of stakeholders and included suppliers, internal organisational stakeholders, customers, financial, media, community, citizen action, special interest groups. Though not directly related to asset management, the list of stakeholders developed by Elias et al. (2002) led to further feasible baseline stakeholders. Based on the Elias stakeholder set, freight hauliers and the national and regional freight advocacy groups were also included.

In existing agent-based models, the agents comprise the government, road users and the decision-making planning agent (Moore et al., 2008; Osman, 2012). Even though government agents were included in the initial stakeholder set, many simplifications were made in these models, which resulted in the government being represented as one agent. The larger government framework is relatively complex and on review comprised a central government (ministry/department), an executive agency, a regional agency and an operational delivery unit. The government can therefore be seen to comprise a multitude of stakeholders.

Table 3-1 details the baseline list of stakeholders that was used to develop the list of potential interviewees. In Table 3-1 each stakeholder is highlighted, along with an initial assumption of whether they were considered to influence the operation of the agent-based model. The justification of whether a stakeholder influences the system is included in the “commentary column”. In total eight stakeholder’s groups were considered and six were assumed to affect the operation of the system. In the selection process, the ministerial role was excluded from the stakeholder baseline list, as this was a process that could not be easily simulated, as government ministers change on regular cycles and so do government policies. Furthermore, in the context of the proposed freight model the role of the minister can be taken by the modeller, as the aim of the model is to assess the impact of possible policy changes or other exogenous changes that may occur, such as restructuring port operations or altering the vehicle mass and dimension regulations. Bridge asset management consultants were not considered to be influential, because the final bridge improvement decision was identified in the interview process as being made by the planning agency. Nonetheless, bridge managers were included in the later stages of the data collection process, as they had bridge posting related information data and data relating to the cost of upgrading bridges. Specific knowledge on the conversion of rating data stored in the bridge database to posting data was also held by the bridge managers and particularly relevant to the development of the bridge vehicle load model.
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<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Influence</th>
<th>Baseline</th>
<th>Commentary on the reason for including or excluding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government ministers</td>
<td>Y</td>
<td>N</td>
<td>An influencer, but can be more easily modelled as an exogenous effect.</td>
</tr>
<tr>
<td>Government departments</td>
<td>Y</td>
<td>Y</td>
<td>Considered, as this group was included in existing models.</td>
</tr>
<tr>
<td>Suppliers</td>
<td>N</td>
<td>Y</td>
<td>Suppliers were not considered influencers, as they were considered not to affect outcomes, but they were surveyed as they hold relevant technical bridge data.</td>
</tr>
<tr>
<td>Road users / freight hauliers</td>
<td>Y</td>
<td>Y</td>
<td>Hauliers use the network and influence the route selection process and so were included in the baseline list. Based on the selected routes the planning agency then upgrade these routes, if sufficient benefits are derived.</td>
</tr>
<tr>
<td>Media</td>
<td>N</td>
<td>N</td>
<td>Media companies report on the state of the infrastructure and thus impact political opinion, but they were not considered to be influencers, as they have no direct impact on which bridges are upgraded by the planning agency.</td>
</tr>
<tr>
<td>Advocacy groups</td>
<td>Y</td>
<td>Y</td>
<td>Advocacy groups all liaise with the freight industry and the planning agency and thus affect the freight efficiency outcomes. Accordingly, these were included in the initial interviewee list as along with the hauliers they impact the bridge selection process.</td>
</tr>
<tr>
<td>National planning agency</td>
<td>Y</td>
<td>Y</td>
<td>The agency influences the management of the national bridge stock and so was included in the baseline interviewee list.</td>
</tr>
<tr>
<td>Local planning agencies</td>
<td>Y</td>
<td>Y</td>
<td>Territorial local authorities manage the local infrastructure that is used to gain access to the national road infrastructures. To gain an insight into their management practices these were included in the interviewee list.</td>
</tr>
<tr>
<td>Utilities</td>
<td>N</td>
<td>N</td>
<td>Utility companies do not directly affect which bridges are upgraded to improve freight efficiency and so were not included.</td>
</tr>
<tr>
<td>Emergency services</td>
<td>N</td>
<td>N</td>
<td>Emergency services were not included, as they were not considered to be relevant to the movement of freight.</td>
</tr>
<tr>
<td>Bridge management consultants</td>
<td>N</td>
<td>Y</td>
<td>Included in the baseline list because of their knowledge of the bridge network. The consultants were not formally interviewed, but discussions were held on the technical aspects of bridge management including posting and rating.</td>
</tr>
</tbody>
</table>

Based on the snowballing process one extra interviewee was identified, a transportation economist. The economist did not influence the bridge improvement projects, but did have detailed knowledge of the freight industry and the planning processes that were used to identify freight related strategies.
The final list of interviewees comprised people from the following:

- the Ministry of Transport;
- New Zealand Treasury;
- National planning agency;
- Freight hauliers;
- Freight advocacy groups;
- Local planning agencies; and
- Transportation economists.

Using the baseline methodology in conjunction with snowballing technique proved to be successful, as the stakeholders influencing the decision-making process and those with wider knowledge of the decision-making process were all identified.

### 3.3 Research study sample size

The choice of sample size and sampling methodology can affect qualitative research outcomes, as low sample sizes may impact the assumptions that are made in the model. Furthermore, the choice of interviewees may impact the final model, as biases can be created if interviewees are selected using a path of least resistance methodology (Denscombe, 2010). In this section, the method of choosing the specific stakeholders is detailed, along with the impact of the proposed and final sample sets.

To identify the recommended sample size that should be used when developing a model, the literature relating to small scale social research was reviewed. In general the size of a sample set can vary from three to in excess of one hundred participants (Skulmoski et al., 2007), with sample sizes of between six and ten participants (Goossens and Cooke, 2005) and between 20 and 30 people all being noted. In one of the identified studies the aim was the development of an organisational taxonomy (Skulmoski et al., 2007), which resulted in lower participant numbers. Using these sample sizes as a guide an initial sample set was developed (Refer Table 3-2).
Chapter 3 – A mixed methods data collection strategy

<table>
<thead>
<tr>
<th>Interviewees</th>
<th>Proposed</th>
<th>Final</th>
<th>Data collection method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government</td>
<td>2</td>
<td>3</td>
<td>Structured interview</td>
</tr>
<tr>
<td>Planning agency</td>
<td>3</td>
<td>1</td>
<td>Structured interview</td>
</tr>
<tr>
<td>Freight hauliers</td>
<td>10</td>
<td>2</td>
<td>Structured interview</td>
</tr>
<tr>
<td>Advocacy groups</td>
<td>4</td>
<td>2</td>
<td>Structured interview</td>
</tr>
<tr>
<td>Regional planning agencies</td>
<td>10</td>
<td>3</td>
<td>Structured interview</td>
</tr>
<tr>
<td>Transportation economist</td>
<td>0</td>
<td>1</td>
<td>Structured interview</td>
</tr>
<tr>
<td>Bridge management consultants</td>
<td>16</td>
<td>7</td>
<td>Survey</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>45</strong></td>
<td><strong>19</strong></td>
<td></td>
</tr>
</tbody>
</table>

As the interviews were arranged the numbers of interviews changed from the proposed to the final numbers detailed in Table 3-2. The reason for these changes and their impact is covered below.

The number of government agents was initially set at two, as the assumption was made that two representatives from each department, comprising the Treasury and the Ministry of Transport would be interviewed. In the final interview process two Ministry of Transport staff attended the interview, which raised the total to three.

The number of interviewees identified for the national planning agency was initially based on the assumption that more than one person would have to be interviewed to obtain an insight into how the planning agency carried out its task. In the final list of interviewees this changed to a single person, with this person being the manager responsible for the whole vehicle mass and dimension rule change project. The interviewee provided a detailed insight into the issues that were faced by the planning agency and the way in which the planning agency solved the problems it encountered. Thus, the organisational aspects could all be covered by one person, rather than the three initially envisaged.

The most significant difference between the initially planned interviewee set and the final set occurred in the freight haulier group. In total, two of the ten planned haulier organisations were interviewed. Ten were initially selected as this would provide opportunity to interview hauliers from different sectors and different company sizes including lumber, aquaculture, dairy, general freight and aggregates. Although recognised practices, such as direct contact via telephone (Allen et al., 2012) were used to make the initial contact, many organisations
failed to reply or were unwilling to take part in the interview process. The generally low numbers of returns accorded with the typical response rates found in other freight research (Allen et al., 2012). The low response rates eventuated because the haulier organisations viewed their operating strategies as commercially sensitive (Samimi et al., 2009) and as a result were unwilling to share their operational information. The organisational representatives, when contacted, were also busy because of their senior positions in the company. Although the final number of interviewees was small, the number of hauliers that were finally interviewed did not impact the final modelling process, as the organisations that participated provided sufficient insight into their practices, which were used to create the haulier model. The information provided by the hauliers was also supported by, and in some cases expanded on, by other interviewees such as those in the local authorities and the transportation economist. Furthermore, the limited amount of route related data constrained the complexity of the haulier model. Nonetheless, the final set of interviewees in conjunction with the available travel dataset was sufficient for developing the route-finding model that was used to represent the haulier agents.

In New Zealand a number of advocacy groups represent the hauliers at the governmental and planning agency level, including the New Zealand Heavy Haulage Association (NZHHA, 2016) and the Road Transport Association (RTA, 2016). Four advocacy groups were originally selected to address the regional and national perspective. Nevertheless, only one regional and one national representative replied, but both interviewees provided insight into their role and the behaviours of their members.

Finally, the bridge management consultants were omitted from the initial interview stage, as the national planning agent highlighted that the bridge management consultants had limited impact on the decision-making process. These insights were used to understand how information was transferred between the hauliers and the planning agent.

Even after the changes occurred between the proposed and final sample sizes, the final number of interviewees compared favourably with that of Mostafavi et al. (2014), who interviewed 15 subject matter experts in order to create a model of over 200 agents including 100 investors, 50 state level department of transport agents, and one national infrastructure agent. The final bridge management model comprised one planning / decision-making agent and 100 haulier agents that were used to represent the identified origin and destination pairs.
Accordingly, the final sample set that was used to create the haulier and planning agency model was considered appropriate.

### 3.4 Qualitative data collection for the social model

To elicit the information that was required to model each of the social agents, and to ensure a level of consistency was created between each interview, a set of survey questions was developed. The survey was based on the data collection methodology presented in Figure 3-1. The development of the questionnaire framework being influenced by the modelling ideas presented in the book *Managing Business Complexity* (North and Macal, 2007) and by the types of interactions that were being included in existing asset management models (Osman, 2012).

**Figure 3-1  A questionnaire framework for agent-based models**

Based on the modelling requirements the survey was divided into four parts, comprising a general details section and three main model development parts. Part one, the general details section was used to gain information on the role of the interviewee. Part two was used to understand what influenced the agent, and part two was used to understand agent behaviours and part three was used to understand who and what the agent influenced. Part four was an open question section that was used to obtain details of other information the interviewee considered to be important. For each of the identified interviewee groups the survey was modified to reflect the individual roles of each interviewee. Accordingly, a survey was
created for the hauliers, for the planning agent, for the freight advisory groups and for the government officials.

Prior to each interview the survey questions were provided to each interviewee, which allowed each interviewee to understand the general topics to be discussed, and if required to think about the answers they would like to provide. Interviewees also collated information that proved useful to the model development process, such as the information provided by the planning agency, which included details of the economic assessment methodology they used to rank each of the routes they wished to upgrade. The freight haulier questions that were used are presented in Table 3-3 and a copy of all the survey questions is provided in Appendix C.

Table 3-3 The freight survey questions used in the semi-structured interviews

<table>
<thead>
<tr>
<th>No.</th>
<th>Questions used in the structured interviews</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>General details - Please state your title and describe your role</td>
</tr>
<tr>
<td>2</td>
<td>Part 1 - What influences your route choice? Describe how these factors influence your choices?</td>
</tr>
<tr>
<td>3</td>
<td>Part 2 - At what point do the factors/stakeholders start to influence your route choices? Describe the tipping points when you to change what you are doing?</td>
</tr>
<tr>
<td>4</td>
<td>Part 2 - Within your organisations what types of things do you do to manage the route choice problems created by stakeholders and other factors?</td>
</tr>
<tr>
<td>5</td>
<td>Part 2 - How do you decide which is the most effective action to take to improve the situation? Describe any tools, process, methods or rules-of-thumb you use and how they work.</td>
</tr>
<tr>
<td>6</td>
<td>Part 2 - How do you assess whether the course of action you used was successful and how does this affect your future decision-making processes? Describe the success factors and how your decision-making processes change.</td>
</tr>
<tr>
<td>7</td>
<td>Part 3 - Assuming you cannot achieve your desired outcomes who do you work with outside of your organisation to improve the outcomes for your organisation? Describe these actions in terms of who you contact, what you do and why you do it and when you make contact.</td>
</tr>
<tr>
<td>8</td>
<td>Part 3 - Assuming you are achieving your desired outcomes are there any actions you take to further improve the current situation? Describe these actions in terms of who you contact, what you do, why you do it and when you do it.</td>
</tr>
<tr>
<td>9</td>
<td>Part 4 - Is there anything else you wish to add that would help us understand how and why you choose the most efficient routes?</td>
</tr>
</tbody>
</table>

Following on from the stakeholder interview process, the next step in model development “is to capture, codify, integrate and represent stakeholder perceptions of system structure and function, and integrate this with the knowledge of researchers as expressed in peer-
reviewed literature” (Prell et al., 2007). To some extent a similar process was used in the development of existing agent-based asset management models, as accepted theoretical models were used to define government behaviour (Bernhardt and McNeil, 2008) or to define how different users might perceive the asset they interact with (Osman, 2012). In this research, the semi-structured interview transcripts were analysed and behaviours were coded according to the responses that were provided by interviewees. Similar to the cognitive mapping process used by Prell et al. (2007) the conceptual organisational bridge management model (Refer Chapter 2) in combination with the general structure presented in Figure 3-1 was used to identify the roles of agents and their behaviours. As highlighted by Denscombe (2010) computer assisted qualitative analysis or discourse analysis can then be used to analyse interview records. To carry out the computer assisted qualitative analysis the software NVivo (QSR, 2012) was used. In using the software, applicable excerpts from the source transcripts were collated under set of thematic headings. Based on these excerpts recognised models were then identified that could be used to convert the behavioural data into a computational social model (Refer Chapter 5). The main thematic categories comprised agent communication, agent decision-making, asset specific considerations, general issues and wider information that related to the freight industry. Agent-communication was used to store data on the agent topography and the ways in which information flowed between each agent and agent decision-making was used to store data on how each agent processed the information they collected and then acted on the processes data. The asset specific area, covered issues that specifically related to bridges, pavements and general network operations. The general freight area was used to collate freight related data, such as routes that were used by the hauliers and potential changes to bridge and freight regulations that could impact route operation. An extra category was also used to store details of other potential stakeholders identified during the interview process.
Table 3-4 details the general decision-making processes and other model related aspects that were identified during the interview process.

<table>
<thead>
<tr>
<th>Agent.</th>
<th>Behavioural traits of the social agents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning agent</td>
<td>The planning agency used benefit-cost analysis to decide which bridges on which routes to strengthen. To collect the data the planning agency undertook extensive stakeholder consultation.</td>
</tr>
<tr>
<td>Haulier agents</td>
<td>The national freight advocacy groups undertook, on behalf of some haulier companies, an analysis to understand which vehicles would be most commercial viable, which was used to consider the increased costs operating a HPMV (e.g. compliance and vehicle maintenance costs). Typically, heavy freight loads such as lumber only travel over short distances, as the profit margin is low. Thus, these routes will be shorter in the model. For freight vehicles travelling to the South Island the drivers change at the midway point and return with another load (For modelling purposes, the full route was considered). Inter-regional freight hauliers have logistic centres at all the main centres in the North Island.</td>
</tr>
<tr>
<td>Government agents</td>
<td>The treasury detailed their advocacy process. Based on this information they were identified as not being involved in the operational decisions made by the planning agency. Similarly, the Ministry of Transport were found not to influence the operational decisions of the planning agency, but they did set the vision for freight in New Zealand and they also develop the freight strategy documentation. Accordingly, these groups were omitted from the list of modelled agents (Refer Chapter 5).</td>
</tr>
</tbody>
</table>

### 3.5 Quantitative data collection for the technical model

A qualitative research strategy was used to gain insights into the soft social system, but a quantitative approach was used to develop the technical models used to represent the highway network and the bridges located on the highway network. The bridge models include the bridge strength model and the bridge management cost model. The highway model comprises an accurate representation of the North Island state highway network.
Chapter 3 – A mixed methods data collection strategy

Based on the recommendations of Washer et al. (2014), when developing a technical model a number of expert inputs should be elicited. In the context of this research these experts included the following:

- bridge inspection experts;
- bridge management engineers;
- bridge maintenance engineers;
- materials engineers;
- structural engineers; and
- other independent experts (e.g. asset valuation expert).

3.5.1 Bridge capacity data

The bridge strength model was primarily based on a combination of the data found in the New Zealand Transport Bridge Manual (NZTA, 2014), the information collected as part of the survey and the data stored in the National bridge system (NZTA, 2009). Other data used in the model included cost estimates presented on the planning agency’s website (since removed) and the list of obsolete bridges that are currently affecting the operation of the state highway network.

Design loadings have changed in the period since 1932, which results in several load limits that bridges can potentially be rated as carrying, depending on whether the bridge has been reassessed. The lower design standard of older bridges creates the potential for these bridges to have a much lower margin of capacity as the ratio between the actual load using the bridge and the design load is lower. The capacity margin is reduced because of the increasing loads being used to transport freight. An analysis of the data identified bridges that had been reassessed and their capacities updated, while other bridges had not been reassessed. The effect of updating only some of the records can be seen in Figure 3-2, as some older bridge design loads have been altered to the modern HN-HO-72 design loading, and thus these bridges are out of context for their age. The years where there are bridges that are out of context include 1935, 1938, 1958, 1959 and 1963. Thus, where bridges had been reassessed the data was used, but even though other bridges could be assumed to be stronger the original data was used. Finally, all bridges that were identified as being weak were assumed to be financially viable for strengthening to modern standards.
To ensure the correct bridge capacities were used in the model, a combination of data sources were used including the bridge data system, reports published by the planning agency and information presented on the planning agency’s website. The bridge data system stores capacity data for transoms, complex decks with non-homogenous cross-sections, influence lines, timer decks, concrete decks, and simple beam elements. Using the identified models, a simplified representation of a complex bridge can be created. For example, an arch bridge can be represented as a set of beams, transoms and a deck, and a concrete bridge can be represented as a bridge deck and a set of beams. To simplify the computational methods used in the bridge asset management model only the beam data was used, as flexural capacity was being considered. When data was found to be missing from the bridge database the missing records were added using imputation, where imputation is the “adding of missing data with plausible values” (Schafer, 1999). The important data being width, overall length, span length and bridge capacity, as these were used in the bridge management model. In the bridge database, a bridge’s strength is defined using three parameters including age, the rated assessment value, which is defined as a function of the design load, and the general description of the design load inputted into the bridge strength database. The order of priority for these was bridge data, the rated assessment value, and finally the age of the bridge.
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To address the issue of missing data a combination of techniques was used including:

- Out dated data was updated to reflect more current sources, such as the data provided by the New Zealand Transport Agency on their HPMV website, which detailed which routes that could support the heavier vehicles. The data published on the website, when used in combination with published conference papers (Reynolds and Goodall, 2014) could be used to impute updated bridge strengths.
- Missing rating data was inferred from a combination of the bridge’s age or the design loading detailed in other data columns.
- If age, rating and design loading data was missing from the database, the strength of a bridge was inferred from the neighbouring bridges. Neighbouring bridges can be used as typically bridges in a similar location are constructed at similar points in time.
- Generally newer bridges have longer spans and are wider. To account for the increasing dimensions of bridges the average width and length for each decade was used.

Out of the 1268 bridges used in the model the following records were imputed:

- age – 2 records;
- length – 1 record;
- width – 8 records;
- longest span – 82 records;
- design loading type – 14 records; and
- bridge rating percentage – 113 records

To improve the bridge management model, a future agent-based model would be more accurate if it linked directly to the OPermit system and used the system to assess route viability, as this system takes information from the bridge data system. The use of other systems within the agent-based simulation is similar to the middleware solution detailed by Crooks et al. (2008).

3.6 Other data used to develop the bridge asset management model

The following sections details other sources of data including websites and open data sources that were used for developing the network model.
3.6.1 Data used to develop the bridge strengthening cost model

The bridge strengthening cost model was based on data presented on the planning agency’s website. The dataset included 37 bridges being strengthened in each regional area of the North Island and the cost of strengthening. Using the cost data in conjunction with the area of each bridge the cost per square metre to strengthen a bridge was calculated (Refer Chapter 4).

3.6.2 Data used to develop the network model

Open source data (Koordinates.com, 2013) were used to create the network model. The datasets included height point clouds and network models. These datasets were used to create the network the haulier agents interacted with and to incorporate the gradient of the highways. The gradients were incorporated as they impacted the cost of operating a vehicle.

3.6.3 Data used to develop the haulier model

To develop the haulier model a number of other data sources, in addition to the interview records, were used including a freight study (NZMoT, 2014, 2016a) and Ministry of Transport freight measures (NZMoT, 2016a, 2016b). To develop the trip distribution model (Refer Chapter 5) the number of tonnes that were identified in the freight study as being hauled between regions was used. The number of tonnes being converted into number of trips, based on an assessment of the average load being hauled. The average load hauled was based on the identified ministry freight measures (NZMoT, 2016a, 2016b).

3.7 Summary

Based on the requirement to develop both a social and a technical model a mixed methods research design was developed. The mixed methods design comprised a set of structured interviews that were used to gather the data that was used to develop the social model and to identify the topology of the social system. A combination of surveys and available data was used to develop the technical model.

To develop the bridge strength models the data stored in the national bridge management system was used. Missing data was imputed using a combination of methods including bridge age and the bridge’s location relative to similar bridges, or using mapping software. The data from databases was then combined with the survey-based technical data to create
the bridge model. The development of the technical bridge and network models is detailed in Chapter 4.

To develop the social model, the output from the interviews was transcribed and a thematic analysis completed using NVivo. The analysis comprised taking extracts of the transcribed dialogue from each interviewee and coding it under a common thematic category. The information derived from the analysis was then used to identify appropriate social models that could be used to represent each social agent. The development of the social model is detailed in Chapter 5.
Chapter 4 The bridge strength and network models

A sociotechnical model describes the interaction that occurs between the social agents and technical components of the interconnected environment they interact with (Dijkema et al., 2013; Kroes et al., 2006). In order to create the bridge asset management model, the technical model must include the resources the agents can exploit, control or consume when working towards the achievement of their organisational goals (Hahn et al., 2009; Zambonelli et al., 2003). To understand how each social agent adapts to changes in its environment, a technical model must address the spatial and temporal nature of asset performance. In the bridge asset management model freight hauliers exploit the load carrying capacity of individual bridges to fulfil their organisational objectives and the planning agency works to actively manage the network so that the network level effects that accrue from strengthening a set of bridges is maximised. To actively manage the network requires the planning agent to understand the load carrying capability of individual bridges and how these bridges work together as an interconnected group to provide the service the freight hauliers consume. To create the spatial model the following approach was taken:

- A geospatial model to provide a structured environment for the agents to interact with was developed.
- A load factor model was created to model the vehicle load carrying capability of individual bridges.
- A vehicle loading model was created that correlated the three available vehicle types and the load they induced on each bridge.
- A bridge strengthening cost model was created to derive the network upgrade costs.

4.1 The New Zealand state highway network

New Zealand comprises two islands named the North Island and the South Island. The North Island was included in the bridge asset management model as over 75% of the 4.6 M population is located there (StatsNZ, 2016b). The North Island is also the economic hub of
Chapter 4 – The bridge strength and network models

the country, contributing 76.7 % to the national gross domestic product of $241.2 billion NZD (StatsNZ, 2016a).

The following sections details the development of the bridge network graph that was used to model the North Island state highway road and bridge network (Refer Figure 4-1). A graph $G$ being defined as follows:

$$ G = (V, E) $$

Equation 4-1

In the graph, the edges $E$ comprise a set of highway links that connect the junction, bridge and origin and destination vertices $V$. Each edge has an associated length $l$. The graph that was developed to represent the state highways was undirected, as haulier agents could travel in both directions on any given edge. A geospatial model was used, because of the ease of converting available geospatial data into the required format and because a geospatial representation provides an instantly recognisable spatial reference.

Figure 4-1 The national state highway network for the North Island of New Zealand
The network that was created comprised 1268 bridges and 7185 highway sections. To create the network graph, highway geospatial data was obtained from the open source website Koordinates.com (2013). The data was then processed using geospatial software QGIS (QGIS Development Team, 2014). Data processing was required, as the dataset comprised road sections that were not connected, which is required for the routing algorithm to find the shortest distance between an origin-destination (O-D) pair. To simplify the model, the network was further reduced to the road centreline and all the state highway bridges were moved to the centreline. Accordingly, unidirectional edges where vehicles only travel over a bridge in one direction were considered as bi-directional edges, and thus bridges located on unidirectional edges were assumed to be used in both directions. Fully loaded freight vehicles were also assumed to travel in both directions. Freight vehicles can travel partially loaded on return journeys, but from a planning agency perspective bridge upgrades are unlikely to occur in one direction and not the other.

To test the accuracy of the geospatial model, distances between known locations (Refer Table 4-1) were compared with the modelled distances and the errors noted. As highlighted in Table 4-1, the maximum difference between the actual and modelled distances was 2.48%. The identified differences arose because in the network model the number of nodes was reduced to minimise the computational effort placed on the routing algorithm.

<table>
<thead>
<tr>
<th>Id</th>
<th>Origin</th>
<th>Destination</th>
<th>Model (km)</th>
<th>Actual (km)</th>
<th>Difference (km)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cape Reinga</td>
<td>Wellington</td>
<td>1048</td>
<td>1063</td>
<td>8</td>
<td>0.76 %</td>
</tr>
<tr>
<td>2</td>
<td>Tauranga</td>
<td>Auckland</td>
<td>207</td>
<td>202</td>
<td>-5</td>
<td>2.48 %</td>
</tr>
<tr>
<td>3</td>
<td>New Plymouth</td>
<td>Tauranga</td>
<td>314</td>
<td>311</td>
<td>-3</td>
<td>-0.96 %</td>
</tr>
<tr>
<td>4</td>
<td>Taupo</td>
<td>Gisborne</td>
<td>318</td>
<td>328</td>
<td>10</td>
<td>2.74 %</td>
</tr>
</tbody>
</table>

To account for New Zealand’s undulating terrain, the length of each highway section was weighted to reflect the gradients found along each section of road. Table 4-2 details the vehicle operating costs accrued from travelling on increasing gradients. The costs are those reported in the New Zealand Economic Evaluation Manual SP6-3 worksheet (NZTA, 2016a).
Chapter 4 – The bridge strength and network models

To reflect the different terrain, the change in efficiency of freight vehicles resulting from increasingly large gradients was modelled. As limited data was available regarding average speeds, the following assumptions were made regarding the relationship between gradient and speed:

- Up to a 3 percent gradient vehicles were assumed to be travelling between 71-90 km / h.
- Up to a 6 percent gradient vehicles were assumed to be travelling between 51-70 km / h.
- Up to a 9 percent gradient vehicles were assumed to be travelling between 31-50 km / h.
- Up to a 12 percent gradient vehicles were assumed to be travelling between 10-30 km / h.

Table 4-2 Vehicle operating costs per km for specified speeds and gradients

<table>
<thead>
<tr>
<th>Gradient (%)</th>
<th>Vehicle speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10-30</td>
</tr>
<tr>
<td>0</td>
<td>1.70</td>
</tr>
<tr>
<td>1 to 3</td>
<td>1.79</td>
</tr>
<tr>
<td>4 to 6</td>
<td>2.14</td>
</tr>
<tr>
<td>7 to 9</td>
<td>2.62</td>
</tr>
<tr>
<td>10 to 12</td>
<td>3.09</td>
</tr>
</tbody>
</table>

In the network model, the weighted distances for each edge length were related to a vehicle travelling up to 90 km / h on level terrain (Refer Table 4-3). Thus, if a vehicle travels along an edge that has a gradient of 10 % the vehicle will incur an operating cost impact of 1.87 times more than the level ground operating cost. Thus, if the actual length of level ground was 1.0 km the effective length that was used was 1.87 km. To calculate the gradients of each edge, the height point data that was obtained from Koordinates.com (2013) was used. To use the data a raster image was created and the heights of the specific points, which included road nodes, O-D point and bridge points, for each vertex were extracted by comparing the raster and vector datasets.

The development of the spatially accurate bridge network model advances the environment models used in existing agent-based asset management models (Moore et al., 2008; Osman, 2012). The advancement is derived as the technical model now uses an interconnected network of assets, rather than the highlighted (Refer Chapter 1) group of unconnected assets.
4.2 Modelling each bridge's load carrying capability

To assess whether haulier agents can use a route, and for the planning agent to understand which of the highway bridges can support a 44 tonne, 50 tonne or a 62 tonne vehicle, the load carrying capability of individual bridges was modelled. To assess the capacity of individual bridges three methodologies were found that could be used (After Rücker et al., 2006):

- experience based judgement (Qualitative and measured);
- partial factor based assessment; and
- reliability assessment (Target and probabilistic assessments).

Experience based judgement is used to undertake the simplest form of bridge assessment. In a qualitative assessment, the engineer undertakes a visual inspection to judge whether the condition of the bridge will have a deleterious effect its load carrying capabilities. The simple experience based methodology is further improved by comparing previously assessed load capacity envelopes with the load envelope developed by the vehicle that intends to use the bridge. If the vehicle load envelope falls within the capacity envelope the bridge is adequate. Based on discussions with the bridge asset managers responsible for assessing loads, a load envelope comparison was found to occur, albeit using the more complex automated bridge permitting and management system (NZTA, 2009). The same envelope based assessment was also used to carry out an initial scan of the bridge stock that was used to assess the cost of upgrading the national bridge stock to meet the vehicle mass and dimension amendments (Reynolds and Goodall, 2014). Based on the simplified assessment a set of sub-standard bridges was identified. The set of sub-standard bridges was then reduced by assessing their load carrying capabilities using more accurate techniques such as
grillage analysis. The process of using more advanced assessment methods provided some indication that if a future increase in load requirements was to occur then the use of advanced assessment techniques could lead to improvements in bridge capacity ratings without major bridge strengthening work occurring. Thus, potential benefits would be gained from developing a reliability based model, because reliability based models are less conservative than partial load factor design and assessment methodologies (Nowak, 2004).

4.2.1 Reliability based bridge assessments

A bridge reliability methodology would provide a less conservative assessment than the partial load factor of experience based judgement, as bridge specific or bridge type models are developed. Furthermore, by using bridge reliability the following benefits can be derived:

- The approach can be used to model the relationship between load and strength. By understanding the relationship between load and strength an acceptable margin of safety can be identified (Ellingwood and Mori, 1993; Frangopol and Duygu, 2011; Nowak, 2004).
- The deterioration of reliability with time can be assessed, and thus the impact of this deterioration can be managed.
- Reliability methods lead to the more efficient use of a bridge’s load capacity as they are less conservative than deterministic approaches (Stewart, 2001).

The reliability function is based on the limit state function \((g)\), which is expressed as follows:

\[
g = R - S
\]  
Equation 4-2

Where:

\(R\) A probability distribution representing a bridges strength, given the variability in materials used to construct the bridge

\(S\) A probability distribution representing the load applied to the bridge

It follows that for a bridge to be safe one must have \(g \geq 0\) (Nowak, 2004). Based on Equation 4-3 the probability of failure \(P_f\), (Moses, 1977; Nowak, 2004) is calculated as follows:
Chapter 4 – The bridge strength and network models

\[ P_f = P(R - S < 0) = P(g < 0) \]  

Equation 4-3

Reliability is the probability \( P(g \geq 0) \). Thus, a safe level of reliability is the area under the surface defined by \( R \) and \( S \) where \( P(g \geq 0) \). To identify the desired level of safety bridge reliability indices are often used (Essahli and Madanat, 2012; Melchers, 1999; Stewart, 2001; Wang et al., 2011). The reliability index \( \beta \) being approximately equal to (Frangopol and Duygu, 2011; Moses, 1977):

\[ \beta = \frac{E(R) - E(S)}{\sqrt{\sigma^2(R) + \sigma^2(S)}} \]  

Equation 4-4

Where:
- \( E(R) \)  
Mean value of bridge strength
- \( E(S) \)  
Mean value of the vehicle loads applied to the bridge
- \( \sigma(R) \)  
Standard deviation of strength
- \( \sigma(S) \)  
Standard deviation of the vehicle loads applied to the bridge

To ensure a safe bridge, an agreed value of \( \beta \) is preselected. When selecting an appropriate value of \( \beta \) the risk and the cost of designing and building increasingly more reliable bridges is accounted for. A \( \beta \) value of 3.0 is considered adequate, but the value can be higher or lower depending on the associated failure risk.

The original intent was to use reliability theory to model the load carrying performance of each bridge, as the methodology had been successfully used to model bridge performance (Ng and Moses, 1996). A reliability index also creates a unifying framework that can be used to create a set of indices that can be used to report on how well a bridge is performing relative to a chosen performance metric. For example, reliability can be used to assess bridge strength, seismic resilience, scour resilience and any other real-world influences that are derived from the relationship between a desired performance level and an in-situ performance level. The use of a single performance metric framework would also simplify the model development process, as only one approach to dealing with the performance metric being used would have to be developed. Nevertheless, based on a review of the New Zealand Transport Agency’s bridge manual and of the data stored in the bridge data system, the data was found to be based on a combination of the load factor method and a computational based
expert judgement system (NZTA, 2014). Thus, a load factor based approach was used to model the load carrying capability of each bridge.

### 4.2.2 The load factor model

To model the strength of a bridge element $R$ two methodologies are used comprising a vehicle rating and a vehicle posting assessment (NZTA, 2014). The vehicle rating process is used to assess the induced load effect of an overweight vehicle carrying an indivisible load and the posting assessment is used to assess the effect of a vehicle with a divisible load. Posted vehicles have weights up to 44 tonnes, but have higher factors of safety because of the potential for variability of the load. The variability in posted loads occurs because of the inability of hauliers to accurately load a vehicle with lumber and aggregates. In contrast, as overweight vehicles are permitted the planning agency has much greater control over the configuration of the vehicle and how the mass of the load is distributed. The planning agency also has a greater awareness of the actual load being moved, as this forms part of the permitting process. The combination of vehicle configuration control and greater knowledge of the load distribution leads to a greater level of certainty regarding the loading impact the vehicle will have on a bridge. Accordingly, the load factors used in the rating process are lower than those used for the posting process. The rating live load capacity of a bridge is given by (NZTA, 2014):

$$R_0 = \frac{\phi R_i - \gamma_D DL - \sum \gamma(Other \ Effects)}{\gamma_0}$$  \hspace{1cm} Equation 4-5

Where:

- $R_0$ Overload capacity
- $R_i$ Section strength of an element under consideration
- $\phi$ The strength reduction factor which is used to account for the deterioration of the section
- $DL$ Self-weight effects resulting from the mass of the element
- $\gamma_D$ An ultimate limit state load factor applied to dead load
- $\gamma_0$ An ultimate limit state load factor accounting for overload vehicles
- $\gamma$ Specific load factors for aspects such as surfacing
Equation 4-6 differs to the posting equation, which has the following form:

\[ R_L = \frac{\phi R_l - \gamma_D DL - \sum \gamma(Other \ Effects)}{\gamma_L} \]  

Where:

- \( R_L \) Live load capacity
- \( \gamma_L \) An ultimate limit state load factor accounting for live load vehicles

The data from the bridge data system was used to develop the bridge capacity model, but this data is based on the rating process and not the posting process. As a HPMV is considered using a posting assessment, the rating data stored in the bridge data system was converted to reflect a posting limit, rather than a rating limit. Based on discussions with two bridge managers, the conversion was based on a comparison between the rated and posted vehicle impact factors and the posted and rated vehicle partial load factors. To convert the rated strength of a bridge to a posted strength the following conversion was used by the planning agency.

\[ H_N = \frac{\gamma_L}{\gamma_O} \frac{I_L}{I_O} \times HO \]  

Where:

- \( H_N \) Posting class of a bridge
- \( HO \) Rating class of a bridge
- \( I_L \) Axle impact applied to a posting vehicle
- \( I_O \) Axle impact applied to rating vehicle

In the bridge manual, the loading and impact factors are \( \gamma_L = 1.9, \gamma_O = 1.45, I_L = 1.43 \) and \( I_O = 1.3 \), resulting in a strength conversion factor 1.16 \( HO \). Thus, if a bridge is fully capable of carrying the design load \( HN-HO-72 \) it will have a rating of 1.20 \( HO \), resulting in a posting of 1.39 \( HN \). The load demand placed on a bridge by a 44 tonne vehicle is less than the design load and is equivalent to 0.85 \( HN \). Accordingly, bridges must have a posting greater than 0.85 \( HN \) to be able to support the heavier HPMV. In the bridge database, an overall rating, based on the worst element, was used to provide insight into the overweight load carrying capability of each bridge. The value in the database, factored in accordance with Equation 4-8, was used in the bridge model. The distribution of postings used in the model is
illustrated in Figure 4-2. The bridges detailed in Figure 4-2 are those with a posting less than 0.95 $HN$, which is the requirement for bridges with spans longer than 25 m. Although 336 bridges were identified as having postings less than 0.95 $HN$, because of the relationship between span and posted capacities only 186 required strengthening, which equates to 14.7 % of the bridges. Similarly, Waldin et al. (2015) identified 18.0 % of the bridge asset as being unable to support HPMV. Based on the planning agency records, only seven north island bridges were inadequate for the 50 tonne vehicles and these bridges were located on parts of the network that were being considered for upgrades. As the assessment process widened to include other parts of the network, further bridge assessments were being carried out, which may have increased the initial set of seven.

4.2.3 The load model

The load effects $S$ used to model the three different vehicles present on the network were the same as those developed Reynolds and Goodall (2014), and included the 44 tonne vehicle (Class 1), the 50 tonne vehicle (50Max) and the 62 tonne vehicle (Full HPMV). The 50 tonne vehicle was an HPMV, but was created by allowing the axles on the vehicle to reach the full extent of the limits presented in the 44 tonne axle weight limit tables. In the vehicle mass and dimension regulations three types of vehicles are defined comprising unpermitted as-of-right vehicles, HPMV and overweight vehicles. The as-of-right vehicles can travel anywhere on the network and must comply with the axle and gross vehicle limits that are defined for this vehicle type. The HPMV can carry greater mass, but it is limited to the roads that have been assessed as able to carry the heavier vehicles. In the part of the regulations referring to HPMV, if the maximum axle limits are used the gross limits will be
exceeded. Thus, a HPMV must be carefully designed to ensure the axle and the gross limits comply with the regulations. The 50 tonne vehicle draws from the as-of-right axle limit tables and the HPMV gross limit tables to create a vehicle that has as-of-right axle weights, but also has the gross vehicle mass of an HPMV. The 50 tonne vehicle was developed by the planning agency to minimise the amount of bridge strengthening that was required across the New Zealand state highway bridge network, while maximising the ability of individual hauliers to use the new HPMV. Given that 93.0% of bridges in New Zealand have short spans less than 25 m (NZTA, 2009), they are never subjected to the gross vehicle mass as many vehicles are also less than 25 m long. Thus, these short span bridges are only affected by a vehicle’s axles. Given the axles of the 50 tonne vehicle are the same as the 44 tonne vehicle, a bridge with a span of less than 25 m experiences no increase in applied load. Beyond the 25 m span length a bridge starts to be influenced by the gross vehicle load and the possibility of other vehicles being present on the span at the same time (Refer Table 4-4). To assess the impact that each of the three vehicle types had on the national bridge stock, the planning agency used their vehicle permitting system OPermit (Reynolds and Goodall, 2014). Shear effects were not accounted for, as this data is typically missing from the database. The data is missing, because in prior assessment methodologies if the flexural capacity of a bridge element was found to be adequate then the shear capacity was also assumed to be adequate. In more recent assessments the shear capacity of a bridge beam is being included. If the data becomes available shear capacity effects can be added to the load and capacity modelling process.

<table>
<thead>
<tr>
<th>Load type</th>
<th>Span length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 - 25</td>
</tr>
<tr>
<td>HPMV loading</td>
<td>0.90 HN</td>
</tr>
<tr>
<td>50 tonne</td>
<td>0.85 HN</td>
</tr>
<tr>
<td>44 tonnes</td>
<td>0.85 HN</td>
</tr>
</tbody>
</table>

The network level effects resulting from the identified vehicles are illustrated in Figure 4-3, where the thickest lines depict the network available to HPMV and the moderately thick lines depict the network available to 50 tonne vehicles. The remainder of the network, as depicted by the lighter grey lines, is available to 44 tonne vehicles. The black points detail the O-D used by the hauliers.
By creating the network model, the bridge model and the vehicle load model the network attributes the hauliers use to select their preferred routes have been defined. The shortest path process, the hauliers use to decide which of their preferred routes they select, is detailed in Chapter 5.

![Diagram](image.png)

**Figure 4-3** The sections of the network available to increased mass vehicles

### 4.3 The bridge strengthening cost model

To evaluate the fitness of each upgrade strategy, each bridge in the model was assumed to be strengthened to 1.0 $HN$. The cost of strengthening a sub-standard bridge to meet the 1.0 $HN$ strength limit was based on the information presented by the New Zealand Transport Agency. The identified New Zealand state highway network was found to have a set of 65 bridges that were proposed for strengthening, as they failed to meet the 50 tonne and 62 tonne loading expectation (Reynolds and Goodall, 2014), 37 of these bridges were located on the North Island of New Zealand. The identified 37 bridges were grouped by the NZTA and the strengthening costs for the different groups were noted. The identified bridge projects are presented in Table 4-5. In Table 4-5 the bridge set area is the sum of the deck
areas $A$ of the bridges identified in the bridge set. The deck area being based on the data stored in the bridge management system (NZTA, 2009). Using the identified cost information and the known bridge areas, an estimate was made of the average cost to upgrade a bridge. It should be noted that during the development of this thesis the highlighted planning agency strategies were removed from the planning agency’s website. Accordingly, an original reference has not been included.

<table>
<thead>
<tr>
<th>Bridge set ID</th>
<th>Number of bridges</th>
<th>Planning agency estimate (NZD)</th>
<th>Bridge set area</th>
<th>Unit rate (NZD / m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auckland 1</td>
<td>6</td>
<td>1,450,000</td>
<td>883.50</td>
<td>1,641.19</td>
</tr>
<tr>
<td>Auckland 2</td>
<td>1</td>
<td>1,000,000</td>
<td>1247.61</td>
<td>801.53</td>
</tr>
<tr>
<td>Gisborne 1</td>
<td>2</td>
<td>550,000</td>
<td>1549.26</td>
<td>355.01</td>
</tr>
<tr>
<td>Hamilton 1</td>
<td>3</td>
<td>1,150,000</td>
<td>1003.75</td>
<td>1,145.71</td>
</tr>
<tr>
<td>Hamilton 2</td>
<td>3</td>
<td>1,000,000</td>
<td>1320.38</td>
<td>757.36</td>
</tr>
<tr>
<td>Hamilton 3</td>
<td>3</td>
<td>1,200,000</td>
<td>1070.85</td>
<td>1,120.61</td>
</tr>
<tr>
<td>Palmerston 1</td>
<td>13</td>
<td>7,700,000</td>
<td>5185.49</td>
<td>1,484.91</td>
</tr>
<tr>
<td>Taranaki 1</td>
<td>2</td>
<td>600,000</td>
<td>1161.56</td>
<td>1,161.56</td>
</tr>
<tr>
<td>Wellington 1</td>
<td>4</td>
<td>4,100,000</td>
<td>7369.23</td>
<td>556.37</td>
</tr>
</tbody>
</table>

To address the uncertainty in bridge improvement cost estimates, a three point PERT-Beta Distribution (Davis, 2008) was used in the bridge asset management model. The PERT-Beta distribution was chosen because of its use in modelling systems with minimal information and because of its use in modelling expert opinion. The Beta distribution is defined by the following probability density function:

$$P(x) = \frac{1}{B(\alpha, \delta)} x^{\alpha-1}(1 - x)^{\delta-1}$$  \hspace{1cm} \text{Equation 4-8}$$

Where:

- $B$ The normalising beta function (Abramowitz and Stegun, 1972)
- $\alpha, \delta$ Shape function
- $\alpha, \delta > 0$ Shape function limits
- $0 \leq x \leq 1$ Probability of occurrence limits
To derive the Beta distribution shape factors from the pessimistic \( a \), expected \( m \) and optimistic \( b \) cost estimates, the following equations were used (Davis, 2008):

\[
\alpha = \left( \frac{2(b + 4m - 5a)}{3(b - a)} \right) \left[ 1 + 4 \left( \frac{(m - a)(b - m)}{(b - a)^2} \right) \right] \\
\delta = \left( \frac{2(5b - 4m - a)}{3(b - a)} \right) \left[ 1 + 4 \left( \frac{(m - a)(b - m)}{(b - a)^2} \right) \right]
\]

Equation 4-9

Equation 4-10

Where \( m = 930.86 \), \( a = 355.01 \) and \( b = 1641.19 \). The expected value \( m \) was based on the total cost of improvement nominated by the planning agency and the total area of bridges present in the bridge set. In the bridge cost model, the calculation of each bridge’s strengthening cost is based on two Gamma distributions. Two Gamma distributions were used because Netlogo (Wilensky, 1999) does not have a beta random number generator. Thus, assuming \( X \) is a random number drawn from the first \( Gamma(\alpha, 1) \) distribution and \( Y \) is second independent random number drawn from a \( Gamma(\delta, 1) \) then \( Z \) has a \( Beta(\alpha, \delta) \) distribution, where (Ahrens and Dieter, 1974):

\[
Z = \frac{X}{X + Y}
\]

Equation 4-11

Given that the standard Beta distribution has the limit \( 0 \leq Z \leq 1 \), \( Z \) is further modified so the limits become \( a \leq m \leq b \).

### 4.4 Summary

To create an environmental model that the agents could interact with required the spatial and heterogenous nature of a bridge network to be modelled. To achieve this outcome the original intent was to integrate a geospatial model and a bridge reliability model. Nevertheless, based on data restrictions an expert-based load-capacity factor model was developed. The load factor model comprises two parts including a bridge strength model and a vehicle load model. Using the load factor model, each of the individual bridges was then created with its own unique strength and dimensional characteristics, which affected the types of loads each bridge could support. By developing the spatially accurate bridge network model, the realism and the accuracy of current agent-based models (Moore et al., 2008; Osman, 2012) is improved, as the agents now interact with an accurate representation
of the real-world system. The creation of the spatially accurate model allows bridge asset managers to easily identify the routes that hauliers are a likely to use, which removes the requirement to manually identify which route should be upgraded, which is the approach used in some reliability models (Liu and Frangopol, 2005). The bridge model also provides a different viewpoint on network functionality, as other bridge models have tended to focus on traffic flows (Orcesi and Cremona, 2010) rather than freight movement. Accordingly, the objective of developing a spatially accurate model that supports the advancement of existing agent-based and bridge management models has been achieved.
Chapter 5 Models of the social agents

A significant part of the social model’s development comprised the identification of appropriate theoretical approaches and the synthesis of these approaches into a cohesive framework. Accordingly, the following chapter details the conceptual ideas underpinning each of the agent models including the high-level ideas used to create the social model and the individual sub-models used to describe each agent class.

The use of agent-based modelling is often cited in the literature, but limited information was found on the detailed development of such models, with texts mainly describing the typical processes that should be considered when creating a model (Chmieliauskas et al., 2012; Chmieliauskas et al., 2013; Nikolic and Ghorbani, 2011; North and Macal, 2007; Osman, 2012). Consequently, a framework had to be identified that facilitated the full description of the agent-based bridge asset management model, and furthermore ensured the central concepts were considered. Similarly, Grimm et al. (2010) also identified the requirement for adequate documentation of agent-based models and accordingly developed the Overview, Design Concepts and Detail (ODD) framework. The Grimm framework was later extended by Müller et al. (2013). Müller’s extended framework was used to describe the bridge asset management social model and to guide the development of the model, as the framework specifically dealt with models that incorporated human decision-makers, whereas the Grimm et al. (2010) framework mainly focused on ecological agents.
Chapter 5 – Models of the social agents

The Grimm ODD methodology comprised:

- Overview (purpose, entities, state variables and scales).
- Design concepts (Basic principles, emergence, adaptation, objectives, learning, prediction, sensing, interaction, stochasticity, collectives and observation).
- Details (initialisation, input data and sub-models).

The extra considerations that were included in the Müller et al. (2013) framework comprised:

- Design concepts (Theoretical background, individual decision-making, individual sensing, individual prediction, agent heterogeneity).
- Details (implementation details).

Using the ODD as the central development approach, a set of conceptual models was identified and selected. Each aspect that was considered is detailed in the following sections and includes an overview of the model, the design concepts that were considered when selecting each agent model, and the detailed model design. The detailed model design describes how the agents make decisions and interact with each other and how the selected models reflect the real-world behaviours of the agents.

5.1 Model overview

As outlined in the ODD, the model overview comprises a description of the model’s purpose, the entities in the model and the scales used in the model. Accordingly, each are highlighted below.

5.1.1 The purpose of the model

In line with the original research question, the bridge asset management model was developed to understand the impact that human decision-makers have on the bridge asset management process, especially when developing optimal network level strategies. A second aim was also to advance existing agent-based asset management models by making the models more closely reflect real-world asset management decision-making problems. Through the development of such a model the aim was to provide improved decision support when selecting a set of bridges to upgrade that will, when strengthened, maximise the freight
efficiency of the network. By creating the bridge asset management model, a solution is also created that can be used to manage any set of obsolete highway bridges.

5.1.2 The modelled entities

The entities included in the bridge asset management model comprise a set of static bridge agents, a set of dynamic reactive user agents and a static planning agent (Refer Figure 5-1). In the model, the hauliers interact with the network of bridges and the planning agent interacts with the network and the hauliers. The bridge agents are static agents as they do not move, but they do affect the operation of the network. For instance, if a bridge agent has its strength changed, the operation of the network is altered. Similarly, the set of bridges selected for improvement by the planning agent also alters the network’s functionality and thus how the dynamic haulier agents interact with the network. The haulier agent is the only dynamic agent, as it is the only agent that transits the network and consumes the service provided by the interconnected network of bridge assets. In the model, the haulier agents interact with the network of bridges by selecting which route to travel between their defined O-D pairs. The planning agent uses the knowledge of how the haulier agents move and the details of which bridges are functionally obsolete to select an improvement strategy that maximises the freight efficiency of the network. To identify a preferred strategy the planning agent uses a genetic algorithm. The algorithm works by heuristically maximising the efficiency of all hauliers for a set budget limit.

Figure 5-1 The structure of the bridge asset management model

Although the agents in the bridge asset management model are similar to other agent-based asset management models, the bridge asset management agents are more advanced than those found in existing models (Moore et al., 2008; Osman, 2012). The haulier agent is more advanced than existing asset management agents because it now interacts with a network of
interconnected bridges and can decide how to structure its operations to maximise its own profitability. By interacting with a structured network, the hauliers select the routes they prefer to use and thus their behaviour more closely reflects the behaviour of actual haulage companies. The incorporation of a network based haulier is a significant advancement, because in other agent-based asset management models the user agents randomly interact with a set of unconnected network sections. In the random interaction model each user selects a set of road sections and reviews their condition. Based on the overall views of the users the planning agent decides which road sections to maintain.

In the proposed bridge asset management model, the planning agent is also more advanced than the decision-making agents used in other (Moore et al., 2008; Osman, 2012) agent-based asset management models. The planning agent is more advanced, because the agent is now able to manage a network of interconnected bridges. The planning agent is also able to differentiate between bridges that are weak and require upgrading and bridges that are weak and do not require upgrading. The planning agent is also able to identify and select a set of obsolete bridges for strengthening that maximises the freight efficiency of the interconnected network.

In the existing agent-based asset management models (Moore et al., 2008; Osman, 2012) the government was included as an agent. In a personal communication with Osman (Bush, 2013), Osman noted that government agents required further development to more accurately reflect the real-world behaviours. Based on Osman’s comment, the impact of different government departments was investigated. Accordingly, the Treasury and the Ministry of Transport were interviewed. Based on the interview findings, both organisations were identified as having a limited direct influence on the bridge upgrade process, as their key role was the development of strategic publications and supporting and challenging the ministerial office. The Ministry of Transport interviewees also specifically highlighted that the New Zealand Transport Agency was solely responsible for managing the state highway bridge stock. Accordingly, in the context of this research the government agent was not included in the agent-based model. Furthermore, when developing a model, the choice of modelling perspective directly affects the choice of which agents should or should not be included. If the perspective that is being taken is the management of individual bridges then a bridge specific model is used. If a network of bridges is being managed, then a geospatial representation of a network with bridges is required. If government officials wish to understand how effective their funding will be then the model should include the bridges and
the agents that manage the bridges. If a government agent is included in the model the question must be raised – who is the model for? Arguably, if a government official is included the focus of the model is investigating the impact that the whole delivery chain has on a defined asset management outcome. Nonetheless, as the focus of the bridge model was the management of obsolete bridges, and in accordance with stakeholder theory (Freeman et al., 2010), only those stakeholders with direct influence were included, which resulted in the government agent being omitted. Similarly, the contracting agent present in some agent-based asset management models (Moore et al., 2008) was also omitted. The contractor was omitted, because the purpose of the model is to understand where to strengthen bridges, rather than the effect that construction resources have on the delivery of bridge improvement work programmes. Consequently, the structure of the bridge asset management model differed to existing agent-based asset management models (Moore et al., 2008; Osman, 2012), which included the government and contracting agents.

5.1.3 State variables and scales

The state variables include the behavioural attributes and model parameters (Grimm et al., 2010) used by the agents. As highlighted there are three agents in the bridge asset management model including bridges, hauliers and a planning agent. The bridge agent’s variables comprise its strength rating, which is a function of its span and design age. The rating is adjusted to 1.0 $HN$ if the bridge is strengthened. The cost of strengthening the bridge is also defined and this is based on a unit cost rate and the bridge’s area. The haulier agent’s state variables comprise the O-D pair it travels between, the number of trips it must take using a 44 tonne vehicle and the vehicle kilometres it must travel between the O-D pair. The factor that is used to calculate the reduction in the number of trips the haulier makes if it uses a larger capacity vehicle is also used. Consequently, the total vehicle kilometres travelled ($vkt$) by the haulier is a function of the total number of trips, the vehicle being used, and the route available to the haulier. The preferred route selected by the haulier is the route with the minimum total annual $vkt$. The planning agent considers the subset of bridges that require strengthening, the total strengthening budget and the total $vkt$ travelled by all the hauliers and the vehicle operating cost per kilometre.

Traffic models comprise microscopic, mesoscopic and macroscopic viewpoints of how vehicles move through a network. Microscopic models are used to represent the lane changing behaviours of individual vehicles, macroscopic models are used to represent the
traffic stream and how it flows through a section of road and mesoscopic models utilise aspects of both microscopic and macroscopic models (Casas et al., 2011). A mesoscopic viewpoint was used in the asset model to represent the haulier behaviours. The model is macroscopic as the network level route finding behaviours of individual haulier agents are considered.

5.2 Model design concepts

The modelling concepts detailed below include the development level of the model and agent-behaviours. Model development refers to the intended use of the model and how the intended use impacts the level of validation. Agent behaviour details how the agents interact with each other and the world, how they make individual and collective decisions, and how they work to understand the consequence of their actions.

5.2.1 The bridge model’s development level

The following section sets the context for how the model will and can be used, based on the data that was available to develop the model.

As highlighted in Chapter 1, three model development levels exist including generator, mediator and predictor models. Generator models are used to understand whether a modelling form is applicable for use, mediator models are used to provide insight into the relative effectiveness of differing strategies and predictor models are used to forecast the future. Each require increasingly stringent levels of validation and accordingly require increasingly more data. To accurately describe the model two ratings were used. The first to describe the sub-models and the second to describe the main model. Two ratings were required because the creation of accurate sub-models does not imply that the main model is also accurate.

The initial aim was to develop a predictor model. To develop such a model sufficient data is required to fully validate each of the sub-models including the haulier model, the planning agent model and the bridge model and to validate the output from the overall agent-based bridge asset management model, instead. Given the data restrictions that were encountered a mediator model was developed. The data restrictions that limited the development of a predictor model included limited bridge rating data and limited heavy commercial vehicle data relating to travel time reliability and average speed, and limited O-D data.
Consequently, an agent-based model that could be used to assess the relative effectiveness of bridge strengthening strategies was the most appropriate.

Based on an assessment of the sub-models and how they interact, the overall bridge asset management model is a mediator model. It is considered that a strategic network level bridge management model can never be a predictor model, as changes in the asset management systems occur over long periods of time, and as result other exogenous factors change the behaviours of the agents. Thus, by the time the developed strategy is fully implemented the system will have changed to a point where the agent-models become irrelevant. Similarly, Kurtz and Snowden (2003) also noted that the emergent affects arising from a strategy can only be known ex-post.

### 5.2.2 General concepts used in the agent models

Agent behaviours comprise agent sensing, agent learning and individual and collective decision-making. These behaviours are used to describe how individuals act and how they make their individual decisions and how these decisions affect how they interact with each other and the environment. In the following section, the general approaches that can be used to model agent behaviours are investigated. Based on the investigation the selected approaches are then further developed in the detailed design section.

#### 5.2.2.1 Individual decision-making

The haulier agents must decide which route to use between their O-D pairs and the planning agent must decide which combination of bridges to upgrade. Accordingly, as both agents must make individual decisions the approaches that are used to model the decision-making process are reviewed.

A decision is the “act of selecting an alternative from a group of alternatives” (Takemura, 2014). A decision comprises five elements including the aforementioned set of alternatives \( A \), a set of states \( \Theta \) that can be achieved, a set of results \( X \) likely to be produced by the action that is taken, the mapping \( f : A \times \Theta \to X \), and the preference structure \( (X, \succeq) \) of the decision-maker (Simon, 1955; Takemura, 2014). In the bridge asset management model, each freight haulier selects from three alternative vehicle types and selects its own route. The different combinations of bridges that will be strengthened will result in different routes being available to each haulier. Thus, from each haulier’s perspective the state of the system is the
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state of the bridge network after a set of bridges has been strengthened. For all available routes, the annual $vkt$ is based on the number of trips the haulier makes when using the selected vehicle and the length of the route that is being used. In some cases, a vehicle type may not be available to individual hauliers for certain combinations of bridges. If a route is not available to a specific vehicle type the distance the haulier must travel is infinite. The preferred solution for each haulier is the minimum $vkt$ it must travel in a year given the bridge strengthening combination selected by the planning agent. From the planning agent’s perspective, the alternatives are the different combinations of bridges it can select to strengthen. The states are defined by the different budgets available to it. The budgets available to strengthen a group of bridges and the reaction of the hauliers to the proposed combination of bridges results in a total network $vkt$ that all the hauliers travel. The selection of the preferred solution for the planning agent is based on the maximum benefit that can be derived for a certain budget. The outcome for the planning agent can be reported as either a benefit-cost ratio, if the aim is to maximise the return on investment for a given budget constraint, or as an incremental benefit-cost ratio if the relative benefits of more expensive projects are being explored. The latter incremental benefit-cost assessment was used as the national level benefits are not necessarily maximised if the highest benefit-cost ratio is used. The decision-making process and the effects of the hauliers’ decisions on the planning agent are depicted in Figure 5-2. In Figure 5-2 the planning agent selects a set of bridges $A_i$ that meets the specified budget requirements $d_j$. The hauliers then select a route and vehicle type $V_q$ combination that minimises their individual $my - vkt$. The choice of route they select is affected by the network configuration resulting from the bridge set selected by the planning agent. The individual choices of each haulier then affect the network $net - vkt$, which influences the final bridge set selected by the planning agent.
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Alternative methodologies that have been used to model how individuals make decisions include the Recognition Primed Decision model (Klein, 2008), and the Belief Desire Intention model (Hahn et al., 2009; Norling et al., 2001). The recognition primed decision (RPD) was developed as people do not follow rational preference structuring to decide what must be done, but use a combination of intuition and conscious mental analysis to arrive at a chosen solution. In RPD intuition is initially used to derive a set of alternatives, but contiguous with intuitive choice the agent mentally simulates the likely future impact of the preferred course of action resulting from the choice, and thus updates the initial choice structure based on the learning from this mental simulation. In the bridge asset management model, both the planning agent and the hauliers carry out their own “mental” simulations to identify preferable solutions. In the RPD model the agent takes cues from the environment as the decision-making process occurs. Similarly, the haulier and planning agent take cues from the environment and from each other to identify a preferable solution.

The second feasible methodology that was investigated comprised the Belief-Desire-Intent (BDI) model. BDI was investigated because it has been used to model individual decision-making (Hahn et al., 2009; Norling et al., 2001). In the BDI model the agent has a set of objectives (desires), knowledge of the environment (beliefs) and a plan (intent) that is based on a set of feasible actions.

The BDI model has parallels with the five elements of individual decision-making including:

---

### Figure 5.2  The interconnected decision-making processes of the planning and haulier agents

#### The planning agent’s personal decision matrix

<table>
<thead>
<tr>
<th>Bridge strengthening Alternatives</th>
<th>Budget states d</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$ (Combination 1)</td>
<td>$d_1$ (nat-vkr)</td>
</tr>
<tr>
<td>$A_2$ (Combination 2)</td>
<td>$d_2$ (nat-vkr)</td>
</tr>
<tr>
<td>$A_i$ (Combination $x$)</td>
<td>$d_3$ (nat-vkr)</td>
</tr>
</tbody>
</table>

#### Haulier 1’s personal decision matrix

<table>
<thead>
<tr>
<th>Vehicle type alternatives V</th>
<th>Network configuration for haulier 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$ (44 tonnes)</td>
<td>$X_{11}$ (my-vkr)</td>
</tr>
<tr>
<td>$V_2$ (50 tonnes)</td>
<td>$X_{12}$ (my-vkr)</td>
</tr>
<tr>
<td>$V_3$ (62 tonnes)</td>
<td>$X_{13}$ (my-vkr)</td>
</tr>
</tbody>
</table>

#### Haulier h’s personal decision matrix

<table>
<thead>
<tr>
<th>Vehicle type alternatives V</th>
<th>Network configuration for haulier h</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$ (44 tonnes)</td>
<td>$X_{11}$ (my-vkr)</td>
</tr>
<tr>
<td>$V_2$ (50 tonnes)</td>
<td>$X_{12}$ (my-vkr)</td>
</tr>
<tr>
<td>$V_3$ (62 tonnes)</td>
<td>$X_{13}$ (my-vkr)</td>
</tr>
</tbody>
</table>

The combination of bridges (x) to strengthen affects the network configuration for haulier (h).

The choice of haulier 1’s and haulier h’s route affects the network vkr (nat-vkr).
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- Beliefs have similarities to environment states, as these are inputs into the decision-making process and are also like the process of recognition in the RPD model.
- Intention is like the alternatives used in individual decision-making, as the process is based on a pre-defined set of plans.
- Desires, like results, are the desired output arising from the selected plan.

The approach used in the agent-based asset management model comprised the identified individual decision-making process, but by following the individual decision-making process, the elements of the BDI framework were also incorporated. Table 5-1 details the individual decision-making model in the context of the BDI model.

<table>
<thead>
<tr>
<th>Agent</th>
<th>Beliefs</th>
<th>Desires</th>
<th>Intent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hauliers</td>
<td>They believe they can use certain routes based on their knowledge of the load capacity of the bridges. Their beliefs are based on their experience and the data provided by the planning agency.</td>
<td>To maximise the load carrying capability of their vehicles, as expressed as a gross vehicle weight.</td>
<td>Their intent is to use one of three vehicles. To select the optimal route-vehicle combination each haulier uses a shortest path algorithm to calculate the vehicle-route combination $vkt$.</td>
</tr>
<tr>
<td>Planning</td>
<td>The agent believes it can improve the operational functionality of the network for minimal cost.</td>
<td>At a strategic level, the agency’s desire is to realise the national freight efficiency improvement objective, but at a planning level the desire is to minimise the expenditure.</td>
<td>Select the minimum number of bridges required to realise the national freight objective. To select the optimal set a search heuristic is applied that is based on network $vkt$.</td>
</tr>
</tbody>
</table>

As highlighted, to identify the preferred route and truck combination to use, the haulier agents calculate the shortest route available to them, given the bridge restrictions located between their individual O-D pairs. Each haulier then decides which route-vehicle combination leads to their individual minimum $vkt$. Table 5-2 details the decision-making process used by each haulier.
Table 5-2 The five decision tuples used in the haulier agent decision process

<table>
<thead>
<tr>
<th>Tuple</th>
<th>Decision criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X$</td>
<td>Individual $vkt$ arising from the choice of each vehicle type and the proposed bridge strengthening combinations</td>
</tr>
<tr>
<td>$A$</td>
<td>A choice of three different vehicle types that can be used to achieve the haulier’s objective of minimising operational performance, and choice of route.</td>
</tr>
<tr>
<td>$\theta$</td>
<td>The combination of bridges that is proposed by the planning agent, which leads to different network upgrade configurations.</td>
</tr>
<tr>
<td>$\rightarrow$</td>
<td>The route choice shortest path model that is used to assess the $vkt$ that can be travelled given the type of vehicle being used.</td>
</tr>
<tr>
<td>$(X, \preceq)$</td>
<td>The route with the shortest $vkt$.</td>
</tr>
</tbody>
</table>

Similarly, the planning agent’s five tuple decision process is defined in Table 5-3. The planning agent bases its decision on the total network $vkt$ and the imposed budgetary constraint. As is evident the service considered by both the planning agent and the hauliers is $vkt$, but both view $vkt$ in different ways when utilising it in their individual decision-making process. Accordingly, and in accordance with Ferber and Gutknecht (1998), a unifying communication language has been created by using $vkt$.

Table 5-3 The five decision tuples used in the planning agent decision process

<table>
<thead>
<tr>
<th>Tuple</th>
<th>Decision criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X$</td>
<td>The total network $vkt$ arising from proposed bridge management strategies</td>
</tr>
<tr>
<td>$A$</td>
<td>The combination of bridges that can be upgraded given the budget constraint</td>
</tr>
<tr>
<td>$\theta$</td>
<td>The budget that is available to the planning agent.</td>
</tr>
<tr>
<td>$\rightarrow$</td>
<td>The haulier’s decision-model that describes each the haulier agent’s reaction to the bridge improvement strategy, namely their route choice and vehicle choice given the considered combination of bridges being strengthened.</td>
</tr>
<tr>
<td>$(X, \preceq)$</td>
<td>The bridge combination that minimises the network $vkt$ for a given budget.</td>
</tr>
</tbody>
</table>

5.2.2.2 Agent-sensing

Agent sensing relates to how agents learn about the world that they exist in and occurs as a result of the interaction with each other and their environment (Müller et al., 2013). In the context of the asset management model, sensing represents how individual agents collect the data that is required to make their individual decisions. Thus, through sensing individual agents determine what changes have occurred to the environment they operate in. In the
bridge asset management model, the changes to the world occur because of individual obsolete bridges being strengthened. The hauliers sense the network to understand how it is structured and use this knowledge and their knowledge of obsolete bridges to identify their preferred route and vehicle type combinations. The haulier agent was assumed to have access to information on obsolete bridges, as the real-world hauliers also had access to the same information through the information provided by the planning agency. The route and bridge information was provided via a website (NZTA, 2017). In the interviews, the website was demonstrably being used to inform the hauliers routeing and vehicle combinations.

The planning agent senses the network by reviewing the bridge ratings of individual bridges and assessing the network level $vkt$ improvements that can be gained by strengthening a set of obsolete bridges. In the interviews with the planning agent the interviewee referred to the New Zealand Economic Evaluation Manual (NZTA, 2016a) as the document that the bridge management consultants used to assess the viability of strengthening the bridges on a route. The identified routes were then prioritised centrally by the planning agency. To gather the bridge strength information the planning agency used a combination of the bridge rating data stored in the bridge data system (NZTA, 2009) and the overweight permitting system (NZTA, 2016b). Based on vehicle-route choices of the hauliers the planning agent senses the total network level $vkt$. The agent undertaking the assessment of which routes are viable differs between the real-world and the model, as the hauliers are assumed to carry out the assessment process. In reality, the planning agency defined the routes. A second, but significant difference between the real-world process and the modelled process is the modelled planning agent takes a holistic network viewpoint, whereas the real-world planning agent only took an individual O-D pair viewpoint.

### 5.2.2.3 Agent learning

Agent learning is the process that is used to describe how agents alter their decision-making processes over time. In cognitively realistic models agents have two forms of memory, the first relates to tacit knowledge and the second is procedural knowledge (Anderson et al., 1997; Sun and Naveh, 2004). Tacit knowledge being the knowledge gained over time from the use of procedural processes. Thus, learning is the transfer that occurs between procedural and tacit knowledge.
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If agent learning is reviewed in the context of the conceptual model of the asset management process (Refer Figure 2-2), for true learning to take place a connection must be made between the model and the world external to the organisation. In the asset management process this connection is made using performance measures and stakeholder consultation. Advocacy is also used by user groups, such as hauliers, to elicit their desired outcome. Accordingly, by following the asset management process procedural knowledge is developed which affects the beliefs of the planning agent, which affects the actions it takes, which impacts the behaviours of the hauliers, which affects the tacit knowledge. In the bridge asset management model, no learning occurs as no transfer between procedural and tacit knowledge occurs, as the agents follow procedural decision-making methodologies. Other asset management models (Bernhardt and McNeil, 2008) also have limited learning, as the government agent, for example,

reacts procedurally to maintenance feedback provided by the travelling public. If the feedback is poor the budget is increased and if the feedback is good the budget is decreased. Learning was not required in the bridge asset management model as the procedural genetic algorithm used by the planning agent identifies the preferred solution and thus no tacit knowledge is required for any of the agents to fulfil their objectives.

In the bridge asset management model, the haulier agents use a procedural approach to identify the routes and the vehicle combinations available to them and subsequently choose a preferred route-vehicle combination that minimises their $vkt$. In the procedural approach, the haulier assess the relative efficiency gains of using an increasingly heavy vehicle by investigating the $vkt$ for a 44 tonne, the 50 tonne and 62 tonne vehicle. The haulier’s procedure was structured to reflect real-world behaviours, as identified during interviews. Similarly, the planning agent employs a procedural methodology to identify the preferred combination of bridges to strengthen. To identify the preferred combination the planning agent offers different combinations of bridges to the haulier agents and compares the relative network level $vkt$ that is achieved after strengthening has occurred. A genetic algorithm was created to improve the effectiveness of the offered strategies. The algorithm is detailed in Section 5.3.2.

5.2.2.4 Agent prediction

In the context of the conceptual model of the asset management process (Refer Figure 2-2), prediction refers to the modelling of the real-world environment to understand the potential
ramifications of a proposed strategy. Similarly, Heath et al. (2009) referred to prediction as being the ability to create a future representation of the real-world system. In the context of an agent-based model, prediction relates to the data and methods the agents use to understand what the future state of the system might be and what impact these changes will have on their ability to achieve their desired objectives (Müller et al., 2013). As noted by Müller et al. (2013) the modelled agents can base their predictions on the actual observation of the system they are operating in, on experience or a combination of both of these methods. To model prediction Railsback and Grimm (2012) detailed a Bayesian updating approach, where the new information the agent obtains on the state of other agents is used to update the choice the agent finally makes. Alternatively, the agent can store the knowledge it has gained since the initiation of the model and use the data it collects as an input into a linear regression model, whereby the model is used by individual agents to predict the direction the measured variable is taking. Thus, the agents can learn and adapt to the management strategy based on the knowledge they gain. In the existing agent based models that were reviewed (Moore et al., 2008; Mostafavi et al., 2015; Osman, 2012), prediction was not employed by the agents, but deterioration models were included, and so prediction could have been easily incorporated. The omission of prediction in these models was appropriate, as the models were being used to investigate the impacts of potential management strategies or funding levels. In the bridge improvement model, prediction was included, as the planning agent had to understand which of the proposed improvement strategies would provide the greatest improvement in network efficiency. To identify the future state of the system the planning agent provides the hauliers with different combinations of bridges it intends to strengthen. The hauliers then react to these combinations. Based on the combined reactions of all the hauliers to each of the proposed bridge strengthening combinations, the planning agent identifies its preferred strategy. The haulage agents also predict the future state of the system by assessing the vehicle-route combination they will use given the combination of strengthened bridges proposed by the planning agent. Once the hauliers understand the future state of the system they select their preferred vehicle-route combination.

5.2.2.5 **Collective decision-making**

Herein, collective decision-making is where groups of agents work together to arrive at a mutually agreeable course of action. In the context of the bridge asset management
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interviews collaboration was a central theme raised by all interviewees, each noting how the planning agency had collaborated with them to identify bridge restrictions and routes that were available. Four methods of collective decision-making were reviewed including game theory, negotiation, social exchange models, and logic. These were reviewed because in each a group of agents “works together” to arrive to develop a rational mutually agreeable solution.

A game-theoretic approach studies the decisions in which the outcome depends partly on what other people do, and in which this is known to be the case by each decision-maker (Peterson, 2009). To model the collective decision-making Osman and Nikbakht (2014) developed a three player asset management game comprising an decision-maker, a political agent and a user agent. To improve the condition of pavement segments, the asset manager can apply either a preventive low-cost policy (Policy A) or a higher cost reactive policy (Policy B). As highlighted by Osman and Nikbakht (2014), two non-dominated strategies were identified, but from the perspective of the asset manager there is no difference in the maintenance strategy that is used, as both strategies adopt an early rehabilitation approach. In both cases the politician also follows the same strategy by increasing the budget early, followed by a decrease in the budget and a final increase. The only identifiable differentiator in the game’s outcome is whether the users decide to complain or not. Thus, the best course of action that was identified was to implement an early intervention strategy. The important aspect to note is the difficulty in developing the story of which action to take, based on deciphering the results. The process while relatively easily carried out by the modeller, would be clearly more complex for an agent. Thus, supporting the idea that a game theoretic is difficult to implement in agent-based models (Wooldridge and Jennings, 1999).

In two similar, but alternative games (Bell, 2000; Laporte et al., 2010), two players were developed, comprising a user and an evil agent, which was used to represent the failure of network edge. The aim of the evil agent being to maximise the user’s disutility and the aim of the user being to maximise its utility. In both games, the evil agent is used to understand how users will potentially react to unforeseen changes in network service provision. By assessing the outputs of the model both Bell and Laporte obtained insights into the preferred choices of the users, and thus the strategies that could be developed to more effectively manage the network. Although a network element is added to the identified models, as the models were used to investigate and manage edge failures, the model was used to represent
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a resilience assessment more than the general operational asset management process. Accordingly, the models were not directly implemented.

Social exchange theory (Emerson, 1976) defines how goods or services are traded between individuals, so that the agents involved in the trade arrive at a mutually agreeable outcome. To model this type of collaborative interaction between agents Coleman (1974) developed a normative social exchange model.

In the social exchange model, the following are defined:

- The agents involved in the exchange.
- The level of interest that each agent has in the goods or services being traded.
- The amount of control that each the agent can exert over the other agents.

Given the interest from the haulage industry in maximising the opportunities provided by the new vehicle dimension and mass amendment rule, and with each stakeholder possessing a level of control of the outcome, both agents are interested in the implementation of the vehicle mass and dimension regulations. Nevertheless, each of the hauliers has only limited ability to exert control over the assets related outcomes, as the planning agent is the only agent to have the delegated power to upgrade the network. Given the limited effective power of the hauliers, in this case, to influence the outcome exchange modelling was not implemented in the model.

Negotiation is considered to be a process whereby a number of entities work in a coordinated way to arrive at a mutually agreeable policy solution (Earnest, 2008). In the case presented by Earnest there are two agent types comprising state agents and constituent agents. In the negotiation model the level-one, state-level, negotiator agents are influenced by level two constituency agents. Similarly, in the bridge model the advocacy agent represents the aggregated opinion of the haulier agents they represent. The advocacy groups were also constituents that worked with the state agent to develop appropriate policy. In cases where true negotiation takes place the highlighted negotiation model would have been appropriate. Nevertheless, in the case of route identification true negotiation did not take place, as only information was transferred by the haulier agent to the planning agent. Consequently, a negotiation model was not used.
Based on the review of game theory, social exchange theory and negotiation models, no form of collaboration was occurring, as only one agent had the power to enact the final strategy. Thus, what was being viewed as collaboration by key stakeholders was really consultation. As highlighted by Stokman et al. (2000), institutionalising the final choice of action to take is an appropriate strategic decision-making behaviour, as a single empowered organisation must make the final decision. Consequently, a logic model was used to represent the interaction between the haulier agents and the planning agent. In a logic model, an agent’s decision-making processes simply comprise a procedural methodology. Although implicitly easier to employ, difficulties arise with logic models, because, as highlighted by Hayes (1971), an agent must understand how the world around it changes as time passes. In the context of the bridge model, time is easily accounted for through the agent-sensing process, as both the planning and haulier agents are continually collecting data on the state of the bridge asset. The second problem relating to logic models refers to how agents react to changes in the environment they interact with, what Hayes (1971) termed the frame problem. When the environment changes, each agent requires further logic that describes the rules of the new world. The argument being that the rules describing the world are more complex than the rules describing what the agent should do. The frame problem is widely described and the scope and potential solutions for the problem are numerous (Hayes, 1971; Korb, 1998). In a complex world, where the future state of the world cannot be easily described, the rules the agents require to understand the world are numerous. Nevertheless, in the bridge asset management model only the strength of each bridge changes, and as such the world can be defined in terms of this change. The implemented decision-making strategy that was used in the bridge asset management model is presented in Table 5-4.

5.3 Detailed design of the bridge asset management model

The following section covers the detailed design of the bridge asset management model’s planning and haulier agents.

5.3.1.1 Freight haulier model

The freight haulier model focuses on the hauliers that carry heavy loads. The focus was placed on these as the mass of a vehicle and the strength of a bridge are related. Other hauliers may take advantage of the HPMV as these vehicles also have greater volumetric capacity, which is useful for carrying more general freight, but these loads do not affect a
bridge’s strength. In the haulier model, the aim of each haulier is to maximise the profitability of its operation by carrying the same tonnage using fewer trips. The $vkt$ the hauliers travel are based on the route length and the number of trips they must make, which is influenced by the maximum mass of the vehicles they can use, which is in turn influenced by the strength of the bridges on the routes the hauliers want to use.

<table>
<thead>
<tr>
<th>Model stage</th>
<th>Planning agent</th>
<th>Haulier agent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial setup</td>
<td>The planning agent senses which bridges are functionally obsolete and creates a set of these bridges.</td>
<td>Each haulier calculates the minimum possible $vkt$ that can be travelled between their $O-D$.</td>
</tr>
<tr>
<td>The group decision-making process</td>
<td>The planning agent offers a bridge improvement strategy, which strengthens a sub-set of the obsolete bridge set. The planning agent also calculates the cost of upgrading the sub-set.</td>
<td>The haulier assesses the viability of using each of the three truck forms based on the combinations of bridges being offered. The preferred truck-route combination is the one that minimises the $vkt$.</td>
</tr>
<tr>
<td>Planning agent decision-making</td>
<td>The group decision-making process is repeated $n$ times. A meta-heuristic search algorithm is used to arrive at a preferred strategy.</td>
<td></td>
</tr>
</tbody>
</table>

As highlighted by Samimi et al. (2009) and others (Cambridge Systematics et al., 2012; Hunt and Stefan, 2007) the four step process is commonly used to model freight movement. The four models that describe freight movement are the trip generation model, the trip distribution model, the mode choice model, and the route assignment model. The trip generation model describes the number of trips being generated by each origin point and the trip generation model details the number of vehicles moving between each O-D pair. In the haulier model, mode choice refers to the vehicles each haulier has available to it.

5.3.1.1.1 The trip generation model
As detailed by Ortúzar and Willumsen (2011) trip generation comprises the prediction of the number of trips being generated by an O-D pair. Herein, the development of the trip
geneneration model was omitted, because the freight demand study (NZMoT, 2014) provided the distribution matrices that detailed the number of tonnes being hauled between regional areas. The tonnes of freight was then converted to the number of trips (Refer Section 5.3.1.1.2).

The planning agency maintains an overweight vehicle permitting system called OPermit (NZTA, 2016b), which they use to manage the permitting of HPMVs. As this system was used to record the movements of all the permitted vehicles, the data stored within it would have proven useful for developing the trip generation model. Nonetheless, due to the system storing potentially commercially sensitive data, access to the data was not forthcoming. Similarly, Samimi et al. (2009) also noted that data used in freight modelling can be particularly difficult to obtain, again because of the commercially sensitive nature of the information.

5.3.1.1.2 Freight volume distribution

The following section details the methodology that was used to develop the trip distribution model, which comprises a trip distribution matrix. To develop the trip distribution matrix, freight volume, measured in tonnes, was used as the starting point for estimating the number of trips being generated by each origin. To derive the freight volume distribution matrix for HPMVs, the number of tonnes moving between regions was converted to the number of vehicle trips based on the average laden weight of a freight vehicle and the proportion of the fleet that was estimated to use HPMVs. The edge flows arising from the identified trips were then compared to the annual average daily truck traffic flow data published by the New Zealand Transport Agency (NZTA, 2016c) and the trips for each O-D pair was adjusted until the difference between the actual and the generated edge flows was minimised. The detailed methodology is covered in the following sections.

The freight demand study (NZMoT, 2014) detailed the number of tonnes of road freight being hauled between the North and South Island regions and within regions located on each island. Accordingly, the demand study was used for developing the trip generation matrix. The following equation was used to convert the number of tonnes being moved per year into the number of daily trips $n_{daily}$, which was then compared to the annual average daily traffic figures published by the planning agency (NZTA, 2016c).
Equation 5-1

\[ n_{daily} = \frac{q}{365 \left( \frac{t}{w \varepsilon} \right)} \rho \]

Where:

- \( \rho \): A factor representing the growth in the number vehicle movements. Used to convert the 2012 freight study data to 2015.
- \( t \): The annual total tonnage of heavy goods moved within and between regions.
- \( q \): The proportion of the freight fleet that is likely to use the increased mass limits.
- \( w \): The average weight of freight being moved on each vehicle.
- \( \varepsilon \): A factor representing the increase in average load carried per vehicle. Used to convert the 2012 freight study data to 2015.

In the freight demand study, the number of tonnes that were being uplifted to the South Island of New Zealand was also included. To address the movement between both islands within the trip distribution matrix, the road freight travelling to or from the South Island was assumed to move through the Wellington port. The assumption was made as the Wellington port provides the only freight transit ferry service between the North and South Island. The regions illustrated in Table 5-5 are those detailed in the freight study and comprise Northland (Nor), Auckland (Auc), Waikato (Wai), Bay-of-Plenty (Bay), Gisborne (Gis), Hawkes Bay (Haw), Taranaki (Tar), Manawatu (Man), Wellington (Wel), and Wellington Port (Wep). Table 5-5 was used to calculate the number of vehicle movements being generated by each of the identified locations.

<table>
<thead>
<tr>
<th>Table 5-5</th>
<th>Million tonnes of freight being moved annually (Adapted from NZMoT, 2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tonnes (M)</td>
<td>Nor</td>
</tr>
<tr>
<td>Nor</td>
<td>0.1</td>
</tr>
<tr>
<td>Auc</td>
<td>0.9</td>
</tr>
<tr>
<td>Wai</td>
<td>0.1</td>
</tr>
<tr>
<td>Bay</td>
<td>0.2</td>
</tr>
<tr>
<td>Gis</td>
<td>0.1</td>
</tr>
<tr>
<td>Haw</td>
<td>0.2</td>
</tr>
<tr>
<td>Tara</td>
<td>0.1</td>
</tr>
<tr>
<td>Man</td>
<td>0.3</td>
</tr>
<tr>
<td>Wel</td>
<td>0.7</td>
</tr>
<tr>
<td>Wep</td>
<td>1</td>
</tr>
</tbody>
</table>
The tonnes a freight moved includes all freight vehicle types, but only a proportion of the freight vehicle fleet will be able to increase the load on a vehicle, by taking advantage of the vehicle mass and dimension regulation changes. Based on the vehicle mass and dimension discussion document 25% of the freight fleet had converted to using HPMV in 2015. In Table 5-6 the “all freight” column refers to the distribution of freight types for all load types. The “all HPMV” column assumes 25% of the HPMV freight task is pro-rated across the load types that are fully able to utilise the vehicle mass and dimension rule change. Given that bridge strength is only affected by the heavier mass vehicles, the estimated proportion of mass limited vehicles is presented. Items such as general freight were considered unlikely to be affected by the load capacity of a bridge, as these types of vehicles are limited by the volume of freight they can carry rather than the mass of freight they can carry. The potential uptake is also limited by the usability of HPMV. As example, one haulier was transferring iron sands from a quarry in Taupo to a stockpile located in Auckland. To carry out the transfer between Auckland and Taupo an HPMV was used, but smaller vehicles were then used to distribute the iron sands locally, as the smaller vehicles provided easier site access as they were more manoeuvrable. Specific comments on why loads were included or omitted are provided in the final column of Table 5-6. Based on the assessment of HPMV the proportion of vehicles that will take advantage of increased mass limits \( q \) was assumed to be 6.1\%. The value of 6.1\% was used for sensitivity testing. In the bridge asset management model, a value of 3.0\% was used. A lower value was used because the 2014 weigh-in-motion report noted that only 10.3\% of the fleet was using HPMV and 50 tonne vehicles (NZTA, 2015), which is less than half of the reported value of 25\% (NZMoT, 2015). An upper value of 7.3\% was also used with the upper limit being based on a 20\% increase in the use of HPMV. The upper limit was used to understand whether other strategies would become viable if a minor increase in HPMV numbers was to occur.

The growth in vehicle movement numbers \( \rho \) was extrapolated from the freight indicators maintained by the New Zealand Ministry of Transport (NZMoT, 2016b). Based on the years 2011-2014 the annual growth for 2015 was estimated. The identified growth in vehicle movements \( \rho \) was estimated to be 3.6\%. Finally, to estimate the mass of a load \( w \) the Ministry of Transport data (NZMoT, 2016a) was used and again projected forward to 2015. The identified average annual gain in the mass of a load \( \varepsilon \) was identified as being 1.7\%. Based on the annual gain and previous average loads a vehicle load \( w \) of 9.6 tonnes was used.
### Table 5-6 An estimate of the likely uptake of HPMV (Adapted from NZMoT, 2014)

<table>
<thead>
<tr>
<th>Freight types</th>
<th>All freight (%)</th>
<th>Likely to use HPMV (%)</th>
<th>All HPMV (%)</th>
<th>Mass limited HPMV (%)</th>
<th>The reasons for selecting the modelled value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk and dairy</td>
<td>11.0</td>
<td>N</td>
<td></td>
<td></td>
<td>Based on interviewee feedback, dairy tends to be local movements with loads reaching a maximum at the end of a collection circuit.</td>
</tr>
<tr>
<td>Logs and timber</td>
<td>16.0</td>
<td>Y</td>
<td>4.9</td>
<td>3</td>
<td>As highlighted in interviews. Lumber has low margins of profitability, and so any improvement in efficiency is likely to be used.</td>
</tr>
<tr>
<td>Livestock, meat and wool</td>
<td>4.0</td>
<td>Y</td>
<td>1.2</td>
<td>0.5</td>
<td>Only livestock and a proportion of refrigerated meat movements are likely to use a load increase. Wool is likely to be volumetrically limited.</td>
</tr>
<tr>
<td>Other agriculture</td>
<td>4.0</td>
<td>N</td>
<td></td>
<td></td>
<td>It was assumed that agriculture will continue to use existing haul methods and thus are therefore unlikely to adopt HPMV.</td>
</tr>
<tr>
<td>Petroleum and coal</td>
<td>6.0</td>
<td>Y</td>
<td>1.8</td>
<td>0.5</td>
<td>Assumed coal and a proportion of the petroleum industry will use HPMV. A conservative estimate was used, since much of the North Island’s fuel is moved by pipeline.</td>
</tr>
<tr>
<td>Aggregates, building materials, fertilisers and other minerals</td>
<td>19.0</td>
<td>Y</td>
<td>5.8</td>
<td>2</td>
<td>Based on the interviewee comments there is a preference for using smaller vehicles locally, as they have better manoeuvrability. However, some materials are being hauled between regions and a small number of HPMV are being used to haul aggregates locally, as highlighted by a regional network manager.</td>
</tr>
<tr>
<td>Steel and aluminium</td>
<td>2.0</td>
<td>Y</td>
<td>0.6</td>
<td>0.1</td>
<td>It was assumed a small proportion of the group will take the opportunity to use HPMV.</td>
</tr>
<tr>
<td>Manufactured goods</td>
<td>16.0</td>
<td>Y</td>
<td>4.9</td>
<td></td>
<td>Assumed to be volumetrically limited, based on the interview with the planning agency and the transportation economist.</td>
</tr>
<tr>
<td>Waste</td>
<td>3.0</td>
<td>N</td>
<td></td>
<td></td>
<td>Assumed to be local traffic only and thus using lower weight vehicles.</td>
</tr>
<tr>
<td>General freight</td>
<td>19.0</td>
<td>Y</td>
<td>5.8</td>
<td></td>
<td>See manufactured goods.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0</strong></td>
<td><strong>25.0</strong></td>
<td><strong>6.1</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The identified regional daily traffic demand is detailed in Table 5-7. The figures presented in Table 5-7 are the number of daily trips between the identified regional O-D pairs. The vehicle movement numbers presented in Table 5-7 are based on the total freight vehicle fleet.
and as such do not have the likely uptake factor \( f \) included. The uptake factor was omitted as it was used as part of the sensitivity testing process. In Table 5-7 the trip distribution matrix is defined in the terms of the regions that freight is being hauled within and between, but the specific O-D pairs are not identified. As an example, Auckland has many production centres including regions of South Auckland and the Auckland Port. Accordingly, the remainder of the trip generation section details the methodology that was used to identify the O-D pairs that were used in the bridge asset management model and the number of trips that were occurring between each O-D pair.

<table>
<thead>
<tr>
<th></th>
<th>Nor</th>
<th>Auc</th>
<th>Wai</th>
<th>Bay</th>
<th>Gis</th>
<th>Haw</th>
<th>Tar</th>
<th>Man</th>
<th>Wel</th>
<th>Wep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nor</td>
<td>3669</td>
<td>541</td>
<td>28</td>
<td>256</td>
<td>57</td>
<td>28</td>
<td>114</td>
<td>370</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auc</td>
<td>256</td>
<td>10914</td>
<td>684</td>
<td>826</td>
<td>28</td>
<td>142</td>
<td>142</td>
<td>370</td>
<td>342</td>
<td>399</td>
</tr>
<tr>
<td>Wai</td>
<td>28</td>
<td>1225</td>
<td>6782</td>
<td>883</td>
<td>57</td>
<td>85</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Bay</td>
<td>57</td>
<td>541</td>
<td>513</td>
<td>5756</td>
<td>28</td>
<td>57</td>
<td>28</td>
<td>85</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Gis</td>
<td>28</td>
<td>28</td>
<td>57</td>
<td>912</td>
<td>57</td>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haw</td>
<td>57</td>
<td>57</td>
<td>285</td>
<td>142</td>
<td>2109</td>
<td>28</td>
<td>199</td>
<td>28</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Tar</td>
<td>28</td>
<td>57</td>
<td>114</td>
<td>85</td>
<td>57</td>
<td>1738</td>
<td>85</td>
<td>28</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Man</td>
<td>85</td>
<td>28</td>
<td>57</td>
<td>256</td>
<td>541</td>
<td>1624</td>
<td>427</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wel</td>
<td>199</td>
<td>28</td>
<td>28</td>
<td>256</td>
<td>1824</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wep</td>
<td>285</td>
<td>28</td>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Methods were found that could be used to generate a more detailed trip distribution matrix, but these methods required a-priori knowledge to be obtained from older O-D datasets (Cascetta and Nguyen, 1987; Cheng et al., 2014; Hazelton, 2001) or an understanding of the variability in traffic flows at given network locations (Hazelton, 2003). Given the limited O-D data, a method similar to that developed by Sherali et al. (1994) was used to develop the trip generation matrix. In the Sherali et al. methodology, for a given road network with \( V \) vertices and \( E \) edges, each trip between an O-D pair was considered to generate flows on the network, all of which contribute to the overall edge flow vector \( \tilde{f}_{e} \), where \( e \in E \). Thus, an optimal solution is one that minimises the difference between the actual and estimated traffic flows observed on each edge. In minimising the difference between the actual and estimated edge flows, Sherali et al. acknowledged that a unique solution may not exist, and that because of inaccuracies in the measurement of traffic flows, there may still be
differences between the actual and calculated edge flows. Accordingly, the three trip
distribution matrices that were identified using the selected methodology were used to test
the sensitivity of the bridge asset management to different trip distributions.

The following methodology was used to develop each of the three distribution matrices:

- A simplified network was created that represented the combined freight flows between
  the regions identified in the region level trip generation matrix. The traffic flows between
  regional areas were calculated based on published traffic flow data.
- The origins used in the model used to identify the trip generation matrix were based on
  regional production centres. The destinations were selected by the model based on their
  effect on individual edge flows.
- Each haulier used a shortest path algorithm to identify its preferred route.
- Once all the haulier routes were known the edge flows were calculated based on the sum
  of all trips across an edge.
- A search heuristic was used to identify the trip distribution matrix. To minimise the
  difference between the actual edge and the calculated edge flows the search heuristic
  selected the destination points and the proportion of the trips allocated to each destination
  point.

To model the North Island state-highway network a simplified graph was used (Refer Figure
5-3). Figure 5-3 also details the origin and destination points that were used. To reduce the
number of intermediate edges the number of routes between O-D pairs was reduced. As an
example, there are two possible routes that can be used between Whangarei (Vertex 1) and
Auckland (Vertex 3) comprising State Highway 16 and State Highway 1. In the simplified
network graph both routes are modelled using edges 1-23 and 23-3. The total number of
movements between the O-D pair being the sum of traffic flows from both State Highway 1
and State Highway 16. In developing the simplified network graph 20 urban centres, 29
intermediate vertices and 58 edges were used. A set of intermediate vertices was used in the
model to represent the midpoints between urban centres and to provide potential destination
points. The intermediate vertices were included after testing identified that the difference
between the actual and calculated edge flows was lower if they were included. The actual edge flows were derived from the traffic flow information provided by the New Zealand Transport Agency (NZTA, 2016c).

To identify the trip distribution matrices that minimised the difference between the calculated and the actual observed traffic flows, a meta-heuristic was used. In the search algorithm, the hauliers select the shortest path between their O-D pairs. Once all the hauliers had selected their shortest path the total traffic flow on an edge was calculated. The objective function that was used is illustrated in Equation 5-2. The aim of the objective function is to minimise the difference between the actual and the calculated edge flows. The objective function that was used was based on the mean percentage error. Mean percentage error was used instead of the mean square error, as by using the mean square error large edge flows were found to take priority, which resulted in rural areas with low traffic flows being overshadowed. As an example, an edge with a daily traffic flow of 23 vehicles will never
have a mean square error large enough to affect the objective function outcome, especially when some edges had traffic flows of more than 3000 vehicles per day. To identify the trip distribution matrix that led to the required edge traffic flows two metaheuristic methods were initially trialled. The search methods comprised Simulated Annealing (SA) and a Genetic Algorithm (GA). Based on testing of the two methods SA provided improved solutions over the GA. To identify a solution that minimised the objective function the model was run 20 times. Each model was run for 30000 iterations.

\[
f(x) = \min \left[ \frac{100}{z} \sum_{e \in E} |f_e^o - f_e^{calc}| \right]
\]

Equation 5-2

Where:

- \(f_e^o\) The observed traffic flow on an edge \(e\)
- \(f_e^{calc}\) The calculated traffic flow on an edge \(e\)
- \(z\) The number of edges

To account for inter-region freight movement the search heuristic selected from a sub-set of vertices, which were used to represent the region the freight was moving to (Refer Figure 5-4). As an example, if the destination region was identified as being Taranaki in the freight demand study, the search heuristic when deciding which destination to select, could choose from any of the vertices in the Taranaki region (14, 29, 42, 43, and 44). Similarly, for freight that moved within a region the search heuristic selected from all the other vertices within the region. An O-D pair was not allowed to comprise the same vertex. Given that some origin points were responsible for many trips, the trips at these points were shared across up to four co-located origins. When an origin generated between 100 and 300 trips the trips were shared across two collocated origins. If the origin generated between 300 and 500 trips, the trips were shared across three collocated origins. For origins with greater than 500 trips four collocated origins were used. To allocate a proportion of the total vehicle flows to each of the origins, the search heuristic randomly selected from a predefined list ranging between 10 % and 100 % and assigned the proportion of the total flow to each collocated origin. If the total was greater than 100 %, the total assigned to each origin was prorated. In total 102 origins were used to represent the flow of mass limited HPMV.

To compare the relative proportion of the observed and the calculated edge flows a visual assessment was undertaken. The assessment was used to identify whether the actual traffic
flows along an edge and the calculated traffic flows were similarly distributed spatially. The actual daily freight traffic flows on each edge are detailed in Figure 5-4. The mean percentage error for the solution depicted in Figure 5-5, was 87%. The error is relatively large because of the differences that occurred on several edges. The differences occurred because the sum of the observed traffic flows for the network was 25,340 compared to the calculated traffic flows of 39,180 resulting from the freight data. As shown in Figure 5-5, Whangarei, Auckland, the Bay of Plenty and Wellington have the greatest percentage errors. While the differences in the observed and the calculated traffic flows are large in the highlighted locations, the aim of this stage of the modelling process was to identify credible destination locations from a small set of potential regional locations. The process successfully achieved this outcome, but differences between the observed and calculated traffic flows did arise because of variations between the two available data sources. To ensure the credible strategies would be developed, two further trip distribution models with the lowest mean error were used in sensitivity testing.

Figure 5-4 The actual daily traffic flows on each network edge
The trips used in the traffic model are detailed in Table 5-8. In Table 5-8 the origins are defined as $O$, the destinations as $D$ and the daily vehicle trips between each O-D pair as $C$. As an example, the Northland Origin 1 generates 611 vehicles that travel to destination 21. Origin 1 also generates 29 vehicles that travel to Destination 19. Given Auckland is the largest city in New Zealand it generates the most vehicle movements. The following trip numbers were multiplied by 365 in the bridge asset management model to assess the annual $vkt$. 

Figure 5-5   The mean percentage error of edge traffic flows
5.3.1.1.3 Route assignment

Route assignment refers to the process of mapping the identified journeys to the transport network, which results in an understanding of how users move through the transport network. In the freight model, an agent-based approach to route assignment was used, whereby the hauliers selected their own routes. An agent-based approach was used for the following reasons:

Table 5-8 The daily full fleet HPMV count used in the trip generation model
• To allow the hauliers to optimise their operations based on the location of the obsolete bridges. Given the set of obsolete bridges will change over time, the effect of haulier behaviour on network efficiency can thus be assessed.

• To be able to easily alter the hauliers’ behaviours based on the strategies proposed by planning agent. Thus, allowing the planning agent to readily assess the impact of its strategy.

In the freight management model, the route assignment process comprises each haulier travelling along the shortest route available to each vehicle type. The ability to use a vehicle type is limited by the capacity of the bridges that are found between the haulier’s O-D pair. Based on a haulier’s route choice, the sections of the network the haulier agents prefer to use are identified.

The route assignment model was applied to the spatially accurate network graph. The addition of the geospatial model required the user agent to make a rational choice regarding the route to use for the 44 tonne, 50 tonne and the 62 tonne vehicle. To model such effects in a freight haulier context two methods were identified comprising commodity flow and actual logistical routes (Allen et al., 2012; Samimi et al., 2009). As highlighted by Holguín-Veras and Thorson (2000), if the focus of the study is the logistical routes used by operators, then individual vehicles should be modelled. Given that the aim of the model was to identify which routes were used by hauliers, and hence which bridges were to be strengthened, the haulier agent model was based on the logistical routes used by the hauliers. As highlighted by Magnanti and Wong (1984) specialised algorithms are used to recalculate the shortest route that a road user will take when an edge $e$ has been removed from the network graph $G$.

In the context of the freight model an edge is removed when an obsolete bridge that is unable to carry the required mass of vehicle is located on the edge. In models where operators are free to choose their own routes, the shortest path taken by a haulier is influenced by their education, route details such as scenery and organisational aspects such as travel time variability (Refer Table 5-9). In the freight model, vehicle operating costs were used. Other factors were not used as the routes used by the hauliers are managed by the planning agency, thus limiting the choice available to individual hauliers.
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To calculate the minimum distance a haulier has to travel, the Dijkstra (1959) shortest path algorithm was used. The algorithm was used, as it was packaged with Netlogo (Wilensky, 1999), the agent-based modelling software used to develop the bridge asset management model. The actual distance travelled was modified to reflect the increased operating costs incurred from using routes with greater gradients (Refer Chapter 4). Thus, a haulier will select a potentially longer, but more efficient route, if lower vehicle operating costs are available.

<table>
<thead>
<tr>
<th>Table 5-9</th>
<th>Factors influencing route choice behaviours</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Influencing factors</strong></td>
<td><strong>Source</strong></td>
</tr>
<tr>
<td>Drivers</td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td>Knorring et al. (2005).</td>
</tr>
<tr>
<td>Income</td>
<td>Knorring et al. (2005).</td>
</tr>
<tr>
<td>Hazards avoided</td>
<td>Knorring et al. (2005).</td>
</tr>
<tr>
<td>Journey (Congestion, reliability, availability, length, speed, time of day)</td>
<td>Knorring et al. (2005), Stephanedes and Kwon (1993), Fowkes (2007), Feng et al. (2013).</td>
</tr>
<tr>
<td>Passing an urban area</td>
<td>Feng et al. (2013), Fowkes (2007).</td>
</tr>
<tr>
<td>Personal (Scenery, restaurant facilities)</td>
<td>Stephanedes and Kwon (1993), Feng et al. (2013).</td>
</tr>
<tr>
<td>Organisational</td>
<td></td>
</tr>
<tr>
<td>Journey time expectations / requirement</td>
<td>Fowkes (2007), (Bone et al., 2013).</td>
</tr>
<tr>
<td>Vehicle operating costs</td>
<td>Fowkes (2007), (Bone et al., 2013).</td>
</tr>
<tr>
<td>Vehicle size, axle configurations and axle weights</td>
<td>Feng et al. (2013), Reynolds and Goodall (2014).</td>
</tr>
<tr>
<td>Infrastructure characteristics</td>
<td></td>
</tr>
<tr>
<td>Road category (higher)</td>
<td>Feng et al. (2013).</td>
</tr>
</tbody>
</table>

To assess the annual $vkt_{ij}$ arising from using either a 44 tonne, 50 tonne or a 62 tonne vehicle between each O-D pair $ij$, Equation 5-3 was used.
Equation 5-3

\[
a_{ij}^{type} = \begin{cases} 
\frac{n_{annual}d_{ij}^{min}}{1 + \Delta_{eff}^{type}}, & \text{if a route is available} \\
\infty, & \text{otherwise}
\end{cases}
\]

Where:
- \(d_{ij}^{min}\) is the minimum distance that can be travelled between an O-D pair \(O_{ij}\) in kilometres, given the type of vehicle being used and the capacity of each bridge located on the network.
- \(\Delta_{eff}^{type}\) is the efficiency gain from using either a 40 tonne, 50 tonne or 62 tonne truck-trailer combination. Efficiency is a fraction.
- \(\infty\) is a switch that is used if a vehicle type cannot travel because of bridge capacity restrictions.

As the aim of developing the bridge asset management model was to identify the bridges on which routes should be strengthened, the only restriction placed on where the haulier agents could travel was the capacity of the bridge stock. Thus, allowing the freight haulage agents to identify their preferred set of routes. By allowing hauliers to select their preferred routes, the strategy employed by the normative planning agent in the bridge management model differed to the strategy employed by the planning agency, who had preconceived ideas of the routes they wished to upgrade. The preconceived ideas being based on the identification of predefined routes of national significance.

In the haulier route choice model a 44 tonne vehicle was assumed to provide 0% improvement in load carrying capability, as prior to the rule change this was the baseline vehicle. The 50 tonne vehicle was assumed to provide a 13.6% \((50 / 44)\) improvement in efficiency over the 44 tonne vehicle and the 62 tonne vehicle was assumed to provide a 40.9% \((62 / 44)\) improvement when compared to the 44 tonne vehicle. Thus, if the 62 tonne vehicle can be operated on the shortest possible route the haulier agent can carry 40.9% more load, when compared to a 44 tonne vehicle. An increase of 40.9% is conservative, as up to a 70.0% increase in payload can occur (Reynolds and Goodall, 2014). Assuming the hauliers are maximising the mass of their vehicles the increase in mass equates to the same reduction in route \(vkt\) and route operating costs. The percentage savings that were used in the model are presented in Table 5-10 and include both the conservative and the optimistic estimates.
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<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Conservative estimate (%)</th>
<th>Optimistic estimate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 tonne</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>50 tonne</td>
<td>13.6</td>
<td>25.0</td>
</tr>
<tr>
<td>62 tonne</td>
<td>40.9</td>
<td>70.0</td>
</tr>
</tbody>
</table>

5.3.1.1.4 Vehicle choice
The ability to select between three vehicles ensures the planning agency can identify a bridge strengthening strategy that maximises the opportunity for hauliers to carry greater mass loads. The ability to select from a fleet of vehicles also creates a point of difference to other bridge management models (Bocchini and Frangopol, 2011a), which typically only identify whether the bridge is open or closed.

Once the actual route costs for each O-D pair and each truck type have been assessed, the haulier chooses the vehicle which provides the lowest overall route distance travelled \( c_{ij} \). Accordingly, if the 62 tonne vehicle can be used it becomes the preferred vehicle, as it maximises the efficiency of the haulier. If the identified 62 tonne route was 40.9% longer than a 44 tonne vehicles route, a tie will result. If a tie occurs, the preferred route is selected randomly from the equally viable routes. In such cases the potential exists for different routes to be used and thus for different sets of bridges to be identified for upgrading. Equation 5-4 details the decision-making process used by each haulier agent.

\[
c_{ikjk} = \min(a_{ij}^{\text{type}}, \infty)
\]

Equation 5-4

Where:
- \( c_{ikjk} \) The minimum annual \( vkt \) travelled by a haulier \( k \) between its O-D pair \( ij \).
- \( \infty \) A switch that is used if no viable routes are available.

5.3.2 The planning agency benefit-model
The following section details the normative benefit analysis used by the planning agent to decide which strategies should be selected. To maximise the efficiency of the road network the planning agent first develops an improvement strategy, which comprises a set of the functionally obsolete bridges. To assess the network level efficiency gains from implementing the strategy the planning agent informs the hauliers who then adapt their
behaviours based on the proposed strategy. Using the heuristic search algorithm presented Section 5.4.3, the planning agent incrementally improves the solution quality, until no further improvements are made.

In the bridge asset management model, the objective of the planning agent is potentially twofold. One, obtain the maximum benefit-cost ratio for a given funding allocation. Two, identify the funding required to achieve full 50 tonne compliance or to achieve full HPMV (62 tonne) compliance. In the haulier model each agent maximises its own financial return by minimising its operational costs. To minimise the operational costs of the group of hauliers, the planning agent selects and upgrades a sub-set of the functionally obsolete bridges.

The potential annual network level benefit gained from strengthening a set of functionally obsolete bridges is thus defined as follows:

\[
\begin{align*}
    b_{net} &= \sum_{k=1}^{r} \Delta c_{ik,jk} \\
    \Delta c_{ik,jk} &= \text{The reduction in } v_{kt} \text{ obtained by each haulier } k \text{ when travelling between their O-D pair } ikj. \text{ Calculated by assessing the annual network } v_{kt} \text{ before and after an upgrade has taken place.} \\
    r &= \text{The number of O-D pairs / hauliers}
\end{align*}
\]

Equation 5-5

**5.3.3 Identifying a preferred bridge strengthening solution**

To identify a preferred set of bridges to strengthen, a heuristic search methodology was used. The heuristic that was used has similarities to the real-world process, as the planning agent first develops an initial bridge strengthening strategy and then passes the set to the hauliers, who then assess the impact of each strategy on their operational efficiency. The planning agent then reviews the network level reduction in \( v_{kt} \). In following rounds, the planning agent offers alternative strategies based on the most successful previous strategies. To achieve improvements in the network level reduction in \( v_{kt} \) the planning agent used a Genetic Algorithm (GA) (Deb, 2000; Holland, 1973). The development of the GA and the reason for its selection are detailed below.
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The large number of bridges in the obsolete bridge set and the potential to select any number of these bridges to develop the preferred bridge strengthening strategy creates a combinatorial problem. If, for example, there is a potential set of 100 bridges anywhere between 1 and 100 bridges could be strengthened, which leads to $2^{100}$ potential strengthening strategies, given the combination of bridges is important. Accordingly, a method of searching such a large decision-space was required. Furthermore, the search method had to be able to account for the interconnected spatial nature of the road network and the adaptations that could occur in haulier behaviour resulting from proposed bridge strengthening strategies. To address the search problem a GA was developed. A GA was used, as GAs are well suited to identifying solutions for large combinatorial problems (Sutton, 2011) and have been used in other network design (Prasad and Park, 2004) and bridge asset management problems (Bocchini and Frangopol, 2011b; Furuta and Kameda, 2005; Natsuaki et al., 1995).

GAs were first developed by Holland (1973) to mirror the process of natural selection, which over time leads to an outcome that is better suited to its environment. In such algorithms, a standard procedure is followed, which comprises the creation of the initial population set of chromosomes corresponding to individual solutions, the evaluation of an individual chromosome’s fitness, the selection and cross-over of the parent chromosomes that are used to create child chromosomes, and finally, the mutation of the child chromosomes. Further to these standard procedures, stopping conditions and strategies to ensure past solutions are not lost, along with constraint handling and chromosome filtering processes are also considered. These procedural stages are covered in the following section.

When developing the GA, the methodology proposed by Deb (2000) was investigated, as the identified methodology could have potentially minimised the computational effort by reducing the number of chromosomes that had to be assessed. The Deb (2000) method achieved a reduction in computational effort by assessing whether a set of predefined limits were contravened prior to passing them for detailed assessment. The methodology was not used herein, as the planning agent had to assess all the chromosomes to identify the cost of the solution. The final fitness function is presented in Equation 5-6. The first part of the fitness function comprises the objective function and the second part of the error constraint function.
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\[ F = \frac{\sum_{k=1}^{n} a_{ikjk}}{\sum_{k=1}^{n} f_{ikjk}} + w(e_g - d)^2 \]  

Equation 5-6

Where
- \( g \) A single strategy vector represented by a single chromosome
- \( e_g \) The cost in million dollars of upgrading the bridges identified in the strategy
- \( d \) The budget in million dollars assigned to strengthening the bridges
- \( w \) A weighting applied to the difference between the strategy cost and the allocated budget.
- \( f_{ikjk} \) The absolute minimum distance a haulier \( k \) must travel between its O-D pair, assuming the network has no obsolete bridges. Used as a normalising function.

A normalising function was used for the objective function, otherwise the total \( vkt \) was found to be overly large when compared to the budget constraint, which resulted in the GA initially focusing on the \( vkt \) rather than the difference between the budget and the identified strengthening costs. By normalising the total distance travelled, the objective function \( \frac{\sum_{k=1}^{n} a_{ikjk}}{\sum_{k=1}^{n} f_{ikjk}} \) only influences the overall fitness function \( F \) when the difference between the budget and the cost is small. Based on testing \( w \) was set as 0.5.

The aim of the encoding process is to develop a so-called chromosome that represents a single solution vector. Each part of the solution vector is called a gene. In traditional GAs the genes of a chromosome are binary, but genes can also be encoded using real values (Herrera et al., 1998). In a real valued GA, each gene can be any value within a defined range of values. The use of real-coded values for the genes changes the gene switching process as a methodology for searching the full range of values coded in each gene is required (Deb, 2000). Herein a traditional binary chromosome was used. In a traditional binary coded GA, the information can be coded using either genotype or a phenotype methodology. In a genotype derived chromosome the information must be decoded to yield the solution, but in a phenotype derived chromosome the solution is directly encoded in the chromosome (Srividya et al., 2012). In a genotype encoding methodology a look up table or set of lookup tables is used to decode the solution. The bridge asset management genetic algorithm constitutes a phenotype genetic algorithm, as each bridge is included in the chromosome. If a bridge is present in the strategy the gene is turned-on (i.e. set to 1), and if a bridge is omitted from the strategy the gene is turned off (i.e. set to 0). Given each bridge is directly encoded in the chromosome, the length of the chromosome is thus proportional to the number of
obsolete bridges being considered. To evaluate the fitness of each solution, each bridge in the chromosome was strengthened to the required standard, which was 1.0 HN. The strengthening costs of these bridges was based on the total area of the bridge deck.

A set of 65 obsolete bridges that failed to meet the 50 tonne loading expectation was identified (Reynolds and Goodall, 2014), 27 of which were located on the North Island of New Zealand. Furthermore, when the 62 tonne load limit was compared to the data in the bridge management system (NZTA, 2009) the number of substandard bridges located on the north Island rose to 186. Thus, the chromosome that was used to represents these obsolete bridges was 186 genes long. Each potential combination of genes in each chromosome thus represents a unique bridge improvement strategy. Thus, the aim of the search process is to identify a combination of genes that maximises the network benefit. The maximum benefit is achieved by minimising the network $vkt$ of the hauliers.

Herein, in the first iteration of the GA, whether a bridge is to be included or omitted from a strategy, is based partially on random selection and partially on predefined strategies. Predefined strategies were used as the output from a GA is improved if quality strategies are used at the start. In the selection process the genes within the chromosome are assigned using a uniform distribution. The random selection was found to work well for budgets that required a chromosome with a selection of active and inactive genes. Nonetheless, for budgets near to the do-nothing or the fully upgrade options, the likelihood of all genes being turned off or all genes being turned on is low. Accordingly, chromosomes with fully activated gene sequences and fully inactive gene sequences were incorporated into the initial population set. Further to the fully active and fully inactive chromosomes a set of predefined strategies was also incorporated. The strategies that were incorporated comprised the individual route improvement strategies proposed by the planning agency, as provided on the planning agency’s website. A reference has not been provided because the webpage is no longer active. By incorporating known strategies, the planning agent was provided with the opportunity to retain the descriptive strategies developed by the planning agency.

Each of the chromosomes that is created represents an individual bridge strengthening strategy. A set of strategies is known as a population. In the bridge management GA, the set of obsolete bridges may vary, as over time bridges are being managed and new bridges are being added and removed from the initially identified set of obsolete bridges. To accommodate this variation, the population size was varied dynamically in proportion to the
length of the chromosome. Thus, if a greater number of obsolete bridges are found on the network, a larger initial population is created. The dynamic management of the population ensured a balance was struck between maintaining the diversity of the population and the speed of evaluation. Based on testing, a factor of 0.3 was chosen, which resulted in an initial population of 55 chromosomes given there were 186 bridges in the obsolete bridge set.

In evolution past traits can still be present in current populations, even though the trait no longer provides an evolutionary advantage. These residual effects remain because the random process of chromosome splitting and recombination will sometimes miss specific genes. Similar effects also occur in a GA. In the bridge strengthening example the GA selects a set of bridges for upgrading. The hauliers then react to the solution by selecting a set of edges to travel along. In some cases, the obsolete bridges selected for strengthening may not be located on the set of edges selected by the hauliers and therefore have no impact on the objective function. To identify the true cost of upgrading the network bridges not on routes used by the hauliers are removed from the chromosome and their genes set to zero. The probability of unwanted bridges appearing in the solution set can be minimised by using an alternative fitness function (Refer Equation 5-7). The likelihood of unwanted bridges occurring in the preferred strengthening set is lower because the fitness function works in a way that encourages the GA to minimise the overall cost of the preferred strategy. In the proposed fitness function, once the difference between the cost is less than the budget it becomes inconsequential. After a bridge strengthening cost lower than the budget has been identified, any extra bridge strengthening costs associated with extraneous bridges are also reduced $e_g$. Nevertheless, given the potential for gene skipping to occur, unless the bridges are physically removed from the strategy there will always be a small chance a bridge not located on an edge being used by the hauliers will be present in the final bridge strengthening strategy. Once the modified chromosome has been created it is then added into the population set.

$$F = \frac{\sum_{k=1}^{r} a_{ijk}}{\sum_{k=1}^{r} \hat{f}_{ik,jk}} + w(e_g - d)^2 + e e_g$$

Equation 5-7

Where 
- $\epsilon$ A small weighting to ensure cost is minimised if it leads to the same or similar $\sum_{k=1}^{r} a_{ijk}$. 

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The cross-over rate defines the number of parent chromosomes that are used to create a set of child chromosomes. In this GA, a value of 80% was used, which results in 80% of the population being used as potential parents for the next generation. The remaining 20% of parents are directly cloned and so copies of selected parents are made and added to the next generation. Thus, the next generation comprises a mixture of cloned and recombined parent chromosomes from the previous generation. To choose which chromosomes become the parent chromosomes, tournament selection was used. The tournament was based on a similar process to that developed by Deb (2000) and used by others (Prasad and Park, 2004). In the tournament two sets of three potential parent chromosomes are selected at random from all chromosomes. The winner of the tournament is the pair of parent chromosomes with the lowest fitness function scores. The two winning parents for each tournament round are then used to create two new child chromosomes. When the child chromosomes are created a single point cross-over is used (Refer Figure 5-6). As identified in Figure 5-6 the number of genes crossing into child 1 or child 2 varies depending on the cross-over point. As the location of the cross-over point is chosen at random the point will vary for each pair of parents.

Once the new set of child chromosomes has been created, mutation of the chromosome is carried out. In each of the new child chromosomes each gene has a 0.5% chance of being mutated. During this mutation process the gene can either be changed from zero to one or from one to zero, thus representing the omission or addition of a bridge to the strengthening strategy. This mutation helps to improve the likelihood that the algorithm will move on from a local optimum. Once the child chromosomes have been mutated they become the parents for the following round of fitness assessment.

The GA used to identify bridge strengthening strategies was further modified to include an elitist strategy. An elitist strategy is a recognised way (Herrera et al., 1998) of ensuring that previous winning strategies are not lost to future generations. In a GA, the potential to lose
previous winning strategies occurs because of the perturbations created by the cross-over and mutation process, which can move any given solution vector away from a previously identified winning solution. To maintain what was previously a winning bridge strengthening strategy, the chromosome with the worst fitness was replaced with the stored winning strategy. A winning strategy is only superseded if a new winning strategy is identified by the GA.

The genetic cross-over and mutation process will carry on forever, unless stopping conditions are implemented. In the GA, a fixed upper limit and a dynamically assessed limit were placed on the number of generations that were used to obtain a bridge strengthening strategy. The fixed limit ensured that no more than 300 generations were used to find a solution. A second limit was also used to stop the assessment process if the algorithm had become trapped in a local optimum. To address this possibility the generation number that the elitist strategy resulted from was identified and stored. If the algorithm then progressed more than 20 generations beyond the best generation round, without any improvement in the fitness score, the algorithm was prematurely terminated. The limit was identified by monitoring the typical number of generations that are likely to occur between improvements in a solution vector. The limit does not affect early rounds were the algorithm makes round-by-round improvements, but it does affect later rounds where there are longer periods between successive solution improvements.

Output from the GA process is illustrated in Figure 5-7, which shows that the GA efficiently searches through potential solutions sets. Despite the GA having up to 300 generations to find a preferred solution, between 10 and 30 generations were taken. In Figure 5-7, the three plotted lines represent the overall fitness function result, the normalised $vkt$ objective function and the error function. Two charts are presented. The first for a budget of 6.0 m NZD, and the second for a budget of 50.0 m NZD. The two budgets represent two funding extremes. In the 6.0 m NZD model, the GA obtains the best solution at the 7th generation and terminates at the 26th generation. In the 50.0 m NZD model, the GA obtains the best solution at the 10th generation and terminates at the 31st generation. Prior to the 10th generation the GA explores a solution that results in a cost that is lower than previous cost estimates, which lowers the error. Nevertheless, the solution results in a higher network $vkt$. Based on the presented results the GA that was developed was found to quickly identify good solutions.
5.4 Summary

Existing agent-based asset management models use differing topological layouts to represent the interaction between the different individual stakeholder groups. The agents in existing models include contractors, users, government and decision-makers. In the bridge asset management model, the hauliers and the decision-making planning agent were included, but the government agent was omitted. Several reasons exist for omitting the government agent including the government’s limited direct impact on day-to-day decision-making processes and because the funding effects could be modelled without the government agent. Furthermore, if the government agent is included in the organisational bridge management model the context the model should be used in becomes unclear. The omission of the government agent also removes the requirement to simulate the complaints process, which was being used to represent the complex decision-making process used by governments departments. By removing the government agent, budget changes can be more easily modelled and the organisational model is further simplified. Removing the government agent also clarifies the reason for the model, as government departments can use the model to understand what level of service could be obtained at a network level, given a defined level of funding that is invested where it is most useful to network users (hauliers).

An objective of this research was to add a geospatial model. It was found that by adding the model a more complex haulier agent had to be created. In previous agent-based asset management models a network model was not included and users simply randomly drew interacted with a set of highway sections. Through the random selection process insight was provided into how users perceived the average condition of all the highway sections. The random selection process does not represent real-world behaviour, as users do not randomly interact with a single section of the infrastructure. To reflect real-world behaviours the hauliers (users) now collect information on the bridge network and adapt to the bridge strengthening projects proposed by the planning agent. Thus, the addition of the network model improves the realism of existing agent-based asset management models. Furthermore, the haulier agents can now decide which truck-route combination to use, to maximise their productivity. To do this the haulier agent assesses all available route options and chooses the route option that maximises its return. By including multiple vehicle choices an accurate representation of the service level setting exercise has been developed (NAMS, 2015).
The new bridge management model includes a more advanced planning agent. The agent is more advanced when compared to the agents used existing agent-based asset management models. The agent is more advanced because it can understand and manage the effects arising from numerous obsolete bridges, multiple O-D points and hauliers that can choose from three vehicle types. To incorporate these factors, the agent uses a GA, with the objective function based on $vkt$. The GA is new and arose out of the requirement for the planning agent to identify good management strategies, given the complexities associated with managing a network of obsolete bridges.

By including the geospatial model and by developing the more advanced route finding and decision-making agents, the behavioural accuracy of current agent-based asset management models has been improved. Consequently, the bridge asset management model can be used
to provide insight into which bridge strengthening strategies will provide the greatest improvement in network efficiency.
Chapter 6 Identifying new bridge strengthening strategies

The two objectives of developing the bridge asset management model were to understand the impact that proposed planning agency strategies have on network performance and to investigate whether the new bridge asset management model would provide new insights into network level bridge strengthening strategies. To provide a benchmark that the modelled outputs could be compared to, the benefit-cost ratio of the proposed planning agency strategy generated was investigated. The planning agency strategy was then compared to the bridge asset management model identified strategy. The bridge asset management model strategy used the same budget as the planning agency strategy. Further to comparing the planning agency and GA bridge strengthening strategies, the bridge asset management model was also used to identify the strategy with the highest benefit-cost ratio. In addition to identifying the highest benefit-cost ratio strategy, the bridge asset management model was also used to understand why the identified bridge strengthening strategies were particularly successful. To compare strategies the network level $vkt$ being travelled by each vehicle type. To assess the viability of using increasingly large budgets an incremental benefit-cost assessment was carried out. The strategy used in the incremental benefit-cost assessment was the strategy with the highest benefit-cost ratio. The budgetary tipping point for transitioning to 62 tonne vehicles was also investigated. Thus, by investigating the highest benefit-cost ratio strategy, by assessing the type of vehicle being used and by carrying out an incremental benefit-cost assessment, insights into potential new bridge strengthening strategies could be obtained. Finally, the sensitivity of the bridge asset management model’s outputs was assessed. The sensitivity assessment investigated the effects that the following factors had on the modelled effectiveness of identified bridge strengthening strategies:

- The percentage of the fleet likely to convert to HPMV;
- Decreased and increased discount rates;
- More optimistic efficiency gain estimates for 62 tonne vehicles; and
The impact of different trip generation models.

6.1 Benefit-cost assessment parameters

The following section details the parameters that were used in the benefit-cost assessment process including the vehicle operating costs, the discount period, the discount rate and the present value adjustment factors that were used for the costs and for the benefits.

The vehicle operating cost refers to the cost incurred from operating a vehicle and addresses aspects such as maintenance and fuel usage. Vehicle operating cost is expressed as the cost to travel one kilometre. Assuming an average speed of 60km / h, a vehicle operating cost of 1.615 NZD / km was used.

In the evaluation spreadsheet accompanying the economic evaluation manual (NZTA, 2016a) the operating costs are assumed to be the same for the 44, 50 and 62 tonne vehicles. Thus, the same assumption was used in the model. The constant cost assumption is not the case, as hauliers highlighted they carried out their own assessments for each of the vehicle types. The hauliers undertook the assessment because there was a complex trade-off between utilisation of the vehicle and increased road user charges and other operating costs, such as fuel consumption.

Equation 6-1 details how the vehicle operating costs \( (voc) \) for a route were calculated.

\[
voc = \nu b_{net}
\]

\( v \)  The vehicle operating cost for each kilometre of travel.

\( b_{net} \) The potential network level \( vkt \) gained from strengthening a set of functionally obsolete bridges is thus defined as follows – Refer Equation 5-5.

In accordance with the New Zealand economic evaluation manual (NZTA, 2016a) the present value of the benefits and the costs are identified for each strategy. Present value is used to calculate the current worth of a future benefit or cost stream. Present value analysis is used because the benefits derived from strengthening a set of obsolete bridges will accrue over several years. To calculate the present value for the benefits and the costs, and in accordance with the economic evaluation manual (NZTA, 2016a) a discount rate of 6 % was used. Alternative rates of 4 % and 8 % were also used for sensitivity testing. The discount period used in the present value assessment was 40 years.
Chapter 6 – Identifying new bridge strengthening strategies

The present value of a uniform series of benefits and costs was calculated using Equation 6-2.

\[ PV \text{ factor} = \frac{1 - (1 + z)^{-x}}{\log_e(1 + z)} \]  

Equation 6-2

\( z \) Discount rate, expressed as a decimal.
\( x \) The year the cost or benefit is incurred.

In the bridge asset management model, the analysis of the network was assumed to take place in year zero, the strengthening of the bridges in years one to five, and the net benefits that were derived from strengthening a set of obsolete bridges were assumed to accrue from years six to 40. The net annual benefits being the difference between the \( vkt \) the hauliers must travel before and after a set of functionally obsolete bridges has been strengthened. Table 6-1 details the PV adjustment factors that were used for the identified discount rates.

<table>
<thead>
<tr>
<th>Discount rate (%)</th>
<th>PV adjustment for costs</th>
<th>PV adjustment for benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>0.89</td>
<td>15.34</td>
</tr>
<tr>
<td>6.0</td>
<td>0.84</td>
<td>10.83</td>
</tr>
<tr>
<td>8.0</td>
<td>0.80</td>
<td>7.93</td>
</tr>
</tbody>
</table>

As an example, if the total improvement costs are 5.0 m NZD and the annual net present benefits accrued from strengthening a set of bridges is 1.0 m NZD and a discount rate of 6 % is used. The net present value for the improvement costs is 5.0 * 0.84 and the net present value for operating costs is 1.0 * 10.83, which results in a benefit-cost ratio of 2.58.

6.2 A traditional bridge management strategy

International report cards (ASCE, 2013, 2015) describe the current state of the infrastructure. In these report cards, there is an implication that for the network to provide the required functionality, the whole bridge stock must be made to comply with the desired performance standard. The development of such a strategy is expensive, as all the obsolete bridges must be strengthened. In the bridge asset management model, the present value cost to strengthen the identified 186 functionally obsolete bridges is 583.53 m NZD and the present value \( vo\)c benefits derived from strengthening these bridges is 239 m NZD, which results in a benefit-
cost ratio of 0.41. The benefit-cost ratio is significantly below the expected limit of 3.0 (NZTA, 2016a). Accordingly, strengthening the whole obsolete bridge set is not a viable strategy. It also highlights that realistic bridge management expectations must be identified, rather than the fiscally expensive management strategies inferred in the identified report cards.

6.3 The planning agency’s proposed improvement strategy

In the agent-based model developed by Bernhardt and McNeil (2008) a risk-based worst-first strategy was used to select the pavement sections that were maintained. Similarly, the planning agency also employed a form of worst first strategy, whereby the benefit-cost ratio achieved across individual routes was assessed and the obsolete bridges located on the routes with the highest benefit-cost ratios were strengthened first. To assess the effectiveness of the planning agency’s strategy, their proposed set of bridges were strengthened in the bridge asset management model, and the $\nuoc$ benefits, derived from altered haulier travel patterns, were noted.

The planning agency identified 37 functionally obsolete bridges located throughout the North Island (Refer Figure 6-1). The estimated cost of strengthening the identified bridges being 18.75 m NZD, which resulted in a present value cost of 15.75 m NZD. Assuming only 3.0% of the freight fleet transferred to using 50 tonne and 62 tonne vehicles, the present value $\nuoc$ benefits that could be achieved are 32.08 m NZD, resulting in a benefit-cost ratio for the planning agency’s strategy of 2.0. Accordingly, the network level strategy provides moderate national $\nuoc$ benefits.

As expected, the routes where increased benefits are derived are located on the busiest sections of the network and include the Auckland Motorway and the link between the Tauranga port and the Hamilton inland port. All the hauliers using these main routes developed individual benefit-cost ratios in excess of 3.0, the desired minimum set by the planning agency (NZTA, 2016a). Interestingly the proposed bridge strengthening projects between New Plymouth, Wanganui and Palmerston North were not identified as being cost effective. The identification and strengthening of less financially viable routes also accords with the planning agency’s strategy, which was to upgrade the primary transportation routes, such as the Auckland network, and then to upgrade the routes with lower benefit-cost ratios, such as the New Plymouth route.
6.4 Heuristically derived bridge improvement strategies

In the following section, an improved bridge management strategy is identified. The strategy is an improvement on the planning agency’s strategy because it has a higher benefit-cost ratio and a lower cost. To assess the effectiveness of the planning agency’s strategy the bridge asset management model was constrained to the same budget reported by the planning agency. Finally, to identify a more expensive, but viable bridge strengthening strategy, an incremental benefit-cost analysis was also carried out. The assessment was carried out, as the planning agency believed there was no incremental benefits to be gained from investing in increasingly higher budgets. All the following strategies were based on the most conservative HPMV fleet usage proportion of 3.0 %.
6.4.1 The highest benefit-cost ratio strategy

To identify the optimal budget range, the total bridge strengthening budget was incrementally increased from 1.0 m NZD to 65.0 m NZD. For each budgetary constraint level, the fitness rating, the cost of improving the network, the benefit-cost ratio and the bridges being upgraded were noted. The results of the modelling process are presented in Figure 6-2. In Figure 6-2, each point represents one of the 748 identified bridge strengthening strategies, and the frontier refers to the maximum benefit-cost ratio that was identified for the budget being used. The budget is the total budget with no discounting and the benefit-cost ratio is discounted.

The maximum identified benefit-cost ratio was 23.01 and was achieved at a budget of 1.17 m NZD, which equates to a present value cost of 0.98 m NZD. If the identified strategy was used, the strategy could have saved the planning agency 17.58 m NZD.

![Figure 6-2 The benefit-cost ratio from increasing budget allocations](image)

To assess how consistently the bridges and routes that were present in the highest benefit-cost ratio strategy were being selected the strategy was compared to the second and third winning strategies. The alternative two strategies had a benefit-cost ratio of 20.61 and 20.35 respectively. The alternative bridge strengthening strategies are detailed in Figure 6-3 as grey squares and as grey triangles. As is evident from Figure 6-3, although three different bridge strengthening strategies are selected, the location of the obsolete bridges identified for strengthening is consistent from strategy to strategy, and includes the North Auckland network, the Whangarei region and the Palmerston North and Wanganui regions. Consequently, an increased level of confidence can be taken that the Auckland and
Chapter 6 – Identifying new bridge strengthening strategies

Palmerston – Wanganui regions are preferable locations where the bridge stock should be strengthened.

Figure 6-3 Comparing the optimal and moderately optimal bridge improvement strategies

6.4.2 Assessing the effectiveness of the planning agency's improvement strategy

The original planning agency strategy was found to provide, on average, a benefit-cost ratio of 2.0, given the identified bridge strengthening costs of 18.75 m NZD. To assess the full benefits that could be provided for the same budget, the bridge asset management model was run with the same budget limit. By using the same budget as the planning agency, the bridge improvement model obtained a network level benefit-cost ratio of 5.1, which is 250% percent higher than benefit-cost ratio achieved by the planning agency. The present-value benefits derived from the planning agency strategy were 32.08 m NZD and the benefits derived from the equivalent bridge model strategy were 80.4 m NZD, an increase of 48.32 m NZD. The higher benefit-cost ratio was derived by making better use of the network. Better
use of the network occurred by encouraging an increased number of hauliers to use the same road sections (Refer Figure 6-4). In Figure 6-4 the widest lines have four or more hauliers that have started to use the same edge section and the thinnest lines represent that single hauliers have started using the edges. The GA identified bridge strengthening strategy also leads to a greater number of hauliers using the heavier 62 tonne vehicles. In the planning agency strategy 14.6 % of the $vkt$ travelled by hauliers was from heavier the 62 tonne vehicles, whereas in the GA identified strategy 34.9 % of the $vkt$ was from heavier 62 tonne vehicles. The strategy identified by the GA was consistent with known areas of productivity located between Hamilton, Tauranga and Auckland. Accordingly, the bridge strengthening strategy was credible. The multiple use and the sharing of costs across the multiple O-D pairs contrasts with the single O-D pair approach used by the planning agency. Accordingly, the improvement model provides new insights into the problem of identifying and quantifying the network efficiency benefits gained from strengthening bridges.

![Figure 6-4](image.png)

**Figure 6-4** Route sharing improvements using the planning agency's budget
6.4.3 Identifying strategies with increased national benefits

Even though the winning bridge strengthening strategy identified by the bridge asset management model provides the greatest benefit-cost ratio, the national level benefits are modest compared to the maximum achievable. Given that the aim of improving freight efficiency was to positively impact the national economy, a greater level of benefit must be generated. As depicted in Figure 6-5, the benefits generated from using increasingly large budgets is non-linear. In Figure 6-5, strategy 1 (S1) represents the previously identified budget of 1.17 m NZD and strategy S2 is the maximum benefit strategy, which occurs at total budget level of 58.75 m NZD and generates an annual benefit of 235.73 m NZD. Based on the network analysis that was carried out a significant improvement in the overall efficiency of the network only occurred for budgets over 30.0 m NZD, as is evident in Figure 6-5.

To identify further viable bridge strengthening strategies that developed increased national level benefits, an incremental benefit-cost analysis was undertaken, where the incremental benefit-cost is defined in Equation 6-3. Based on Equation 6-3, each of the identified 748 bridge strengthening strategies was compared to the benefits and costs of the strategy that generated the maximum benefit-cost ratio (Refer Figure 6-2). The strategy with the highest benefit-cost ratio being the preferred bridge strengthening strategy.
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\[ \Delta_{bc} = \frac{B_{alt} - B_{pref}}{C_{alt} - C_{pref}} \]  

Equation 6-3

Where:

\[ \Delta_{bc} \]  
The incremental benefit-cost ratio.

\[ B_{pref}, B_{alt} \]  
Benefits generated by the preferred and alternative strategies.

\[ C_{pref}, C_{alt} \]  
The cost of the preferred and alternative strategies.

The Economic Evaluation Manual (NZTA, 2016a) states that an incremental benefit-cost ratio of greater than or equal to 3.0 is preferred. As is evident in Figure 6-6, the incremental benefit-cost ratios, as depicted by the grey points, declines between budget limits of 8.0 m and 30.0 m NZD. Nonetheless, at higher budget levels, 199 alternative strategies were identified that have incremental benefit-cost ratios that are greater than 3.0. These strategies start to provide significant incremental benefit-cost ratios more than 3.0 at budget levels greater than 48.84 m NZD. The travel benefits that were derived were 127.45 m NZD. Consequently, investing more than the proposed budget is viable, given the incremental benefits that can be achieved. Thus, if the budget was raised to 48.84 m NZD from the proposed amount of 18.75 m NZD a significant improvement in the efficiency of the network could be achieved.

6.4.4 An investigation of fleet usage tipping points

To identify the tipping point when the proportional savings (Refer Table 5-10) at a network level where calculated. The tipping point was assumed to be a point midway between the
proportional savings that could be obtained for a 50 tonne and 62 tonne vehicle (i.e. 27.3 %). The selected strategies were those that resided on the identified benefit-cost frontier, where the frontier is again the maximum benefit-cost ratio that can be achieved for a defined budget. The results from the analysis are presented in Figure 6-7. In Figure 6-7 both a linear and a polynomial (quadratic) regression was used to identify the budgetary transition point.

![Figure 6-7 The financial tipping point for transferring to HPMV](image)

Based on the tipping point analysis the budget required to have 50.0 % of the $vkt$ travelled by a 62 tonne vehicle was found to be 27.64 m NZD when a linear regression was used, and 31.75 m NZD when a polynomial regression was used. Accordingly, another 8.89 m NZD would be required to be spent before 62 tonne HPMV comprise the majority of vehicles being used.

### 6.5 Sensitivity testing

The following sensitivity tests were carried out to assess the bridge asset management model’s reaction to changes in the critical modelling variables. The tests that were carried out comprised:

- An assessment of changes to the vehicle uptake percentage
- The effect of using different discount rates.
- An investigation of the effect of using an efficiency gain of 70 % for the 62 tonne HPMV.
- An assessment of the effects of using different trip generation models on the derived budget benefit-cost relationship.
6.5.1 The effect of increased use of mass limited vehicles

The strategies developed thus far were based on the premise that 3.0 % of the freight fleet would use mass limited HPMV. The impact of the increasing HPMV is directly proportional to the increase in the uptake percentage, as the increase in usage proportionally affects the vehicle operating benefits that are derived. Figure 6-8 details the impact of increased HPMV usage on the benefit-cost frontier. Based on the identified result, if 6.1% of the mass limited freight fleet converted to HPMV all strategies would meet the minimum benefit-cost ratio of 4.0 expected by the planning agency. Given that the analysis is based on a conservative estimate of 3.0 % of the freight fleet using HPMV, a small increase of 3.1 % leads to all the identified strategies that are located on the benefit-cost frontier being viable.

![Figure 6-8](image)

Figure 6-8 The sensitivity of the benefit-cost ratios to higher vehicle numbers

6.5.2 The effect of different discount rates

In the final sensitivity test used to assess the impact of altering the model’s input variables, and in accordance with the economic evaluation manual (NZTA, 2016a) the discount factor was varied. In accordance with table 6-1 4.0 %, 6.0% and 8.0 % were used. The sensitivity test was undertaken for strategies with the highest identified benefit-cost ratio.

<table>
<thead>
<tr>
<th>Discount rate (%)</th>
<th>PV costs (NZD m)</th>
<th>PV benefits (NZD m)</th>
<th>Benefit-cost ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>1.04</td>
<td>32.00</td>
<td>30.76</td>
</tr>
<tr>
<td>6.0</td>
<td>0.98</td>
<td>22.59</td>
<td>23.01</td>
</tr>
<tr>
<td>8.0</td>
<td>0.94</td>
<td>16.54</td>
<td>17.69</td>
</tr>
</tbody>
</table>
Chapter 6 – Identifying new bridge strengthening strategies

It was found that the impact of using a discount factor of 8.0 % was to reduce the benefit-cost ratio by 23.1 %. The impact on all the bridge strengthening strategies is to make the strategies that have budgets between 22.0 m and 52.0 m NZD fall moderately below the required benefit-cost ratio of 4.0. Nevertheless, the lowest benefit-cost ratio is still only 2.7. The changes in the benefit-cost ratio, resulting from the higher discount factor as presented in Figure 6-9.

![Figure 6-9 The benefit-cost frontier when using an 8.0 % discount factor](image)

6.5.3 The impact of using increased vehicle efficiencies

In the bridge asset management model, a base increase in efficiency of 41 % was assumed for the 62 tonne vehicle fleet. As reported by Reynolds and Goodall (2014) the upper bound efficiency gain for HPMV is potentially up to 70 %. Accordingly, the impact on the network efficiency of changing vehicle efficiency was assessed. The assessment was carried out for the reported efficiency gains of 41 % to 70 %. Each limit was investigated for budgets comprising 1.0 – 55.0 m NZD. The strategies used in the assessment were those that resided on the benefit-cost frontier. In Figure 6-11 the proportion of $vkt$ accrued from using a 50 tonne and a 62 tonne vehicles is compared. As is evident in Figure 6-10, the transition to generally using the 62 tonne vehicle occurs at the same point irrespective of whether an efficiency improvement of 41 % or 70 % is used, which is approximately 30.0 m NZD. The continued use of the 50 tonne vehicle occurs because the 62 tonne routes and the 50 tonne routes are the both the same. Thus, the larger set of obsolete bridges that are unable to carry the 62 tonne vehicles must be strengthened. Given the higher number of obsolete bridges not meeting the higher standard the bridge asset management model prefers to strengthen more bridges to meet the 50 tonne limit. Nevertheless, once the financial tipping point has
been surpassed the rate at increases. Thus, the use of different efficiency gains did not impact the bridge strengthening strategies that were being identified.

![Figure 6-10 Assessing vehicle type selection as a result of increased HPMV efficiency](image)

6.5.4 The effect of different trip generation models

The selected trip generation model was used as it led to the minimum percentage error between the calculated and the observed annual average daily truck traffic flows on each network edge. Although the trip generation model used in the analysis had the best alignment between calculated and observed edge flows, two alternative trip generation models provided fitness scores of 88.46 and 89.23, compared to the selected fitness score of 87.68. To understand how different the two alternative trip generation models were from the trip generation model that was used, the Hamming Distance (Hamming, 1950) of the destination points selected by the trip generation algorithm was calculated. The Hamming distance is calculated based on the number of differences between two strings. Thus, a string of 1000 and a string of 1001 have a Hamming distance of one. Based on the Hamming distance assessment 63 differences were found for the second trip generation model and 56 differences were found for the third trip generation model, which given there was 102 O-D points equated to 62 % and 55 % of the destination points being different from the trip generation model that was used. Thus, the second and third trip generation models were significantly different. Nevertheless, based on the results presented in Figure 6-11, the bridge strengthening strategy differences created by the different models was minimal, as the peak benefit-cost ratios occurred within the same budgetary region and the benefit-cost profile of the alternative strategies also mirrored the selected strategy. The only difference being that alternative trip generation model 2 resulted in lower network level benefits being derived from the same bridge strengthening programs.
6.6 Model validation

Given the bridge asset management model was selecting bridge strengthening strategies using a fundamentally different approach to that used by the planning agency, the validation of the modelled outputs proved difficult. To assess whether the outputs from the bridge management model were credible the 18.75 m NZD strategy selected by the model was compared to the same budget strategy proposed by the planning agency. The outcome of the comparison is presented in Figure 6-12. The black squares are the bridges selected by the planning agency, the black circles are the bridges selected by the bridge asset management model and the triangular points are those selected by the model and the planning agency. In total, the model selected 24% of the bridges proposed for strengthening by the planning agency. Many of the obsolete bridges selected by both the GA and the planning agency were located on routes located in the New Plymouth – Palmerston North regions, the same routes the planning agency aimed to upgrade. Given the model provided results that were generally focused on the geographic areas that were being considered by the planning agency, the bridge improvement model was assumed to provide credible results and as such the bridge asset management was appropriate for use as a mediator model.

6.7 Feedback and emergence in the bridge model

It was hypothesised that by using a systems-thinking methodology the emergent properties of the complex sociotechnical asset management system would be identified. While haulier-asset and haulier-planning agent feedback is explicitly included in the bridge asset management model, no emergent behaviours were found to occur because of the feedback
between these two agents and between the agents and the asset environment. No emergent behaviours were considered to have occurred because the non-linear response of the travel benefit stream to increasingly large budgets and the identification of bridge strengthening strategies that maximised the shared use of network edges are all, in hindsight, expected results. Nonetheless, it is foreseeable that if different user types are included in the same environment and of the asset manager must trade-off competing user expectations, unforeseen emergent reactions to proposed strategies may occur.

![Figure 6-12](image)

**Figure 6-12** Comparing the GA improvement strategy and the planning agency strategy

### 6.8 Summary

The combination of adaptive hauliers and complex network, led to a non-linear relationship between the benefits being derived from strengthening obsolete bridges and the cost of strengthening. Without the bridge asset management model, a planning agency would have no way of maximising the network level freight efficiency, given the complexity of the problem. Furthermore, given the identified non-linearity of the $vkt$ response to bridge
strengthening projects and the considerable number of potential bridge strengthening combinations the planning agency is unlikely to be able to identify network level bridge strengthening strategies that maximise freight efficiency. Thus, the creation of the bridge asset management model now provides planning agencies with an approach that can be used to identify network level bridge strengthening strategies.

Based on an investigation of the potential bridge management strategies, the current planning agency strategy was found to provide a moderate improvement in network benefits, but the GA and associated bridge asset management model identified a strategy that provided significantly more benefits. Although an improvement could be found to the planning agency’s proposed bridge strengthening strategy, the strategy with the greatest benefit-cost ratio was obtained for a significantly smaller budget of 1.17 m NZD. To strengthen the bridges to maximise the use of the 62 tonne vehicle would cost more than 58.75 m NZD, with the tipping point for increased HPMV usage starting to occur at 30.0 m NZD. Based on the highlighted findings, the new bridge management model has the potential to provide significant benefits with respect to strategy development and funding level assessments for large networks of obsolete bridges.
Chapter 7 A system of bridge performance measures

In the following chapter, the insights gained from developing the systems-thinking based bridge asset management model are used to develop a set of sociotechnical bridge strengthening performance measures. To develop the bridge performance measurement and management framework the following methodology was used:

- A review of the existing performance measurement and management frameworks was carried out. The review was used to identify an appropriate systems-based methodology.
- The insights gained from the review of the existing frameworks, along with the insights gained from the development of the bridge asset management model, were then used to create a sociotechnical performance management framework.
- Based on knowledge gained from the development of the bridge asset management model, the identified performance measures were generalised.
- The identified system of performance measures was then extended to understand how multiple service improvements could be traded-off at a network level.

7.1 Identification of a performance measure framework

The conceptual model of the asset management process, developed in Chapter 2, identifies three important parts of the decision-making process including the strategy rehearsal cycle, the strategy enactment cycle and the performance measurement framework linking these two cycles together. Accordingly, in the following section performance measurement and management frameworks were reviewed. The identified frameworks were then combined to create the conceptual framework that was used to structure the bridge strengthening performance measures identified during the development of the bridge asset management model.
Chapter 7 – A system of bridge performance measures

7.1.1 Background to performance measurement

The field of performance measurement is relatively new (Power, 2000) and is the process of quantifying action, where measurement is the process of quantification and action leads to a performance improvement (Neely et al., 2005). Good performance measurement “remains to this day, an important element for politicians and administrators focused on improving government’s performance” (Van Thiel and Leeuw, 2002) and is “central to the evaluation of new initiatives” (Blalock, 1999). In an organisational context performance measurement plays a key role in the development of strategic plans and evaluating achievement objectives (Henri, 2004) by linking economic inputs with economic outcomes (Adcroft and Willis, 2005). Performance measures do this as they are the inputs into the decision-making process and the decision-making process is used to develop strategies which deliver the desired outcomes (de Lancer Julnes and Holzer, 2001; OECD, 2001). Consequently, it is important to undertake performance measurement correctly, as “what you measure is, after all, what you get” (Kaplan and Norton, 1992). It is also important that a sufficient number of measures are used, as you cannot manage what you do not measure (Kravchuk and Schack, 1996). Similarly, Keeney (2002) raised the point that if you have inadequate measures you cannot understand what the consequences of your decisions are and cannot trade-off competing objectives. Performance management and measurement, particularly the choice of measures, is therefore central to good decision-making.

Given the increasing complexity of the asset management decision-making process, the use of greater amounts of more detailed measurement information is implied. Nonetheless, creating more measures does not imply a greater level of knowledge is gained or improved outcomes are obtained, as performance measure paradoxes start to occur (Seddon, 2008; Van Thiel and Leeuw, 2002), whereby the intent of the originally designed measures is not realised. The intent is not realised, because those using the measures select individual measures to focus on. Conversely, good performance management and measurement provides feedback to the decision-maker allowing strategies to be monitored and shaped. Accordingly, to mitigate the likelihood of performance paradoxes at set of integrated performance measures is required. Thus, in the following section performance management frameworks that incorporate the ideas of systems-thinking are reviewed.
7.1.2 Existing performance measurement and management frameworks

Numerous performance measurement and management models have been created (Neely et al., 2005; Taticchi et al., 2010). Using citation/co-citation analysis Taticchi et al. (2010) identified 6,618 journal papers with performance measurement in the title, keywords or abstract. From these 6,618 authors 115,547 citations were identified, the most frequently cited authors being R. S. Kaplan, A. Charnes, A. Neely and R. D. Banker. Taticchi’s review of performance measurement creation therefore focused on the work of Kaplan and Neely as these were the most prominent authors. Charnes and Banker were omitted as they were mainly involved with the development and use of Data Envelopment Analysis, and not performance measurement model creation (Taticchi et al., 2010). Accordingly, Kaplan was used as a starting point for developing the bridge performance measurement and management framework.

The balanced scorecard was developed by Kaplan and Norton (1992). The scorecard, provides a holistic viewpoint that accounts for the financial measure perspective, the customer’s perspective, the internal perspective of organisation delivery and learning and growth strategies. An asset management version of the scorecard is presented in Figure 7-1. While the scorecard can be used to identify a set of organisation performance measures, it does not provide the decision-maker with the ability to rehearse strategies, as no link is created between the causes of the change in one area and the effects of that change in another area. Thus, if the organisational vision and goals changed there is no way these changes could be easily traced through the system to understand the effect on the learning and growth measures. Similarly, Taticchi et al. (2010) highlighted the need to link cause and effect in the decision-making process. Although not explicitly noted by Taticchi et al. (2010), creating a link between the cause and effect of a change requires the relationship between the two to be understood. Thus, a beneficial approach to performance measure development is to investigate the factors that cause the measure to change and to quantify the relationship between the cause of the change and the impact on the measure of that change.

![Figure 7-1](image-url) The balanced scorecard (Adapted from Kaplan and Norton, 2001)
In an infrastructure management context the OECD (2003) developed the Pressure-State-Response (PSR) performance measure framework. The aim of creating the framework was to provide the decision-maker with the ability to affect positive change when managing a water system. In the PSR framework, performance measures are used to describe the pressures on the system, the state of the infrastructure and the response to be taken to influence change. The PSR model was used by Félio and Lounis (2009) to define policy outcome levels and to create links between strategic and operational levels for critical core infrastructure. Similarly, Jeon and Amekudzi (2005) used the PSR model because “linkage-based frameworks for indicators and metrics [should] capture the full range of indicators and metrics that cause particular conditions affecting sustainability, the impacts of these causes, and corrective actions that can be taken to address them”. If used, the PSR approach leads to an understanding of the causes of any pressure, and the effect on the system as it responds to the changes that are occurring, given its current state. However, like the Kaplan and Norton (1992) framework, when the PSR model is used to create a performance measurement framework there is no way to undertake strategy rehearsal, as the link between the cause of an event and the effect of an event is not created. Thus, the causal relationship highlighted by Taticchi et al. (2010) is not created.

As identified, the balanced scorecard and PSR models result in a list of measures that, while well thought-out, cannot be used effectively because they have no causal link. Consequently, strategy rehearsal cannot be undertaken. The approaches that generate lists of measures are the same approaches used in current New Zealand asset management plans (NZTA, 2011) and in much of bridge asset management (Ghasemi et al., 2009; Maguire, 2009; Roads Liaison Group, 2005). The list of measures approach to performance management and measurement are considered by auditors to be falling short, as they do not provide the required level of strategic control (NZOAG, 2004, 2007). Thus, an improved approach to performance management must define the systems of measures and the relationships between the measures.

Boland and Fowler (2000), highlighted that because of the causal loops present in performance management, the general principles of systems-thinking provides a useful framework for creating performance measures. More specifically, Boland recommended the use of a system-of-systems approach to modelling performance measures whereby, a set of interrelated measures is used to monitor the overall system. The closed loop system, developed by Boland also shows that each node in the system can be both a cause and an
Chapter 7 – A system of bridge performance measures

effect. An asset management centric representation of a Boland performance framework is presented in Figure 7-2. In the performance framework both the input system and the output system are detailed, each of which also have performance measures that are used to understand them. In Figure 7-2 the input system effects change in the asset management system and the output system is affected by changes in the asset management system. The asset management system of performance measures, in the context of this research, are the measures that are used to understand whether the network level freight efficiency target is being met and the impact that bridge strengthening work has on network efficiency.

![Figure 7-2 A closed loop system and sub-systems (Adapted from Boland and Fowler, 2000)](image)

Extending the systems-thinking approach to developing a performance measurement framework, Boland subsequently categorised performance measures into system measures, discrepancy measures and control measures. In the Boland framework, the system measures are directly connected to the discrepancy measures and the discrepancy measures are connected to the control measures. The control measures are also connected to the system measures, thus creating a closed loop feedback cycle. The measures reflect the pressure, state, response measures, as they define the current state of the system and therefore the gap, and the response that can be used to control the system. Although there are similarities between the Boland and PSR frameworks, the Boland Framework is an improvement as it encourages the asset manager to assess the relationship between the identified measures and in doing so creates the causal relationship identified by Taticchi et al. (2010). The system, discrepancy and control categories provided by Boland thus provide a useful framework that can be used to structure the bridge asset management performance measures.

To overcome the many shortcomings of the balanced scorecard Bianchi and Montemaggiore (2008) used a systems-dynamics model to represent a water management organisation. By creating the systems-dynamics model feedback loops were created between the different
performance measures that were used to represent the organisation. Thus, creating a relationship between cause and effect. The Bianchi and Montemaggiore (2008) model thus uses the same principles as those detailed by Boland, but goes on to formalise the details in a computational model. Thus, facilitating strategy rehearsal. In developing the feedback model Bianchi detailed the key stages in the decision-making process and subsequently utilised metrics that could be both modelled and used as organisational performance measures. By linking organisational measures with those used in the computational model, the Bianchi and Montemaggiore (2008) methodology leads to a similar system to that created by Dyson et al. (2007), as a link is created between the strategy rehearsal and strategy enactment cycles. A simplified version of the Bianchi model is detailed in Figure 7-3. In both models the asset is noted, as are the key stakeholders. Thus, in accordance with Godau’s (1999) recommendations both the asset and the influencing stakeholders have been included. In the Bianchi model, the service performance measures are used to link the asset measures and the stakeholder satisfaction measures. The Bianchi model is thus comparable to the bridge asset management model developed herein, as the relationship between the asset, service and stakeholder is identified and described. Nonetheless, while the Bianchi model proves the benefit of modelling the cause-effect relationship there is limited structure to the measures. Furthermore, the effect that the planning agency has on the system is also not included (Hammer et al., 2012). Given the Boland framework structures the performance measures more effectively and includes control measures which can be used to reflect the effects of the planning agency, it was used to develop the bridge strengthening performance measure framework.
7.1.3 A conceptual model for developing bridge performance measures

Using the Boland framework, a conceptual performance measurement and management framework was created (Refer Figure 7-4). In the framework, the target performance and discrepancy monitoring process has similarities to the goals / service levels and asset description identified in the conceptual model of bridge management developed herein. The similarities occur because both the target and goal services levels are the desired performance, and the asset description details the current state of the system. Even though there are similarities between the Boland influence diagram and the sociotechnical conceptual model of bridge management, the Boland system did not explicitly account for the stakeholders or the asset and thus did not explicitly account for the combined sociotechnical performance aspects. Consequently, both the stakeholders and technical aspects must be included, as the sociotechnical system of the stakeholder and bridge asset gives rise to the discrepancy in performance that must be managed.
In the PSR model exogenous factors act on the system and these factors work to destabilise the system. Similarly, in other systems (Dyson et al., 2007; Sterman, 2001) the exogenous factors were included. Given the universe to be modelled is not clearly defined in the Boland system the exogenous factors that affect the stability of the system are omitted. To address the omission in the new bridge performance framework, the universe boundaries have been clearly defined as they relate to the service attribute being modelled. Through the addition of the exogenous factors, insight is provided into the desired future state of the system and thus the discrepancy that must be closed if the performance target is to be met.

Although the presented framework is like the Boland system, the framework functions differently. As identified by Seddon (2008) imposing targets on the system can lead to performance paradoxes (Van Thiel and Leeuw, 2002), as those involved try to maximise the enforced target in order to gain funding. Such targets also lead to ceilings being created that are worked towards, but little effort is made to aim for a higher target, even if the target is achievable (Seddon, 2008). Thus, the strategy rehearsal cycle (Dyson et al., 2007) has been explicitly identified. In the defined process, the performance target is used in conjunction with the control measures to understand what is being achieved and what can be achieved. By creating such an internal cycle and by using the performance framework in conjunction with bridge asset management model, a method of rationally identifying an achievable
performance target is created. Thus, in the identified performance framework system (Refer Figure 7-5), a performance target is only set after strategy rehearsal has been completed.

A sociotechnical structure for the Boland inspired bridge performance measurement and management framework is depicted in Figure 7-5. The more generalised depiction is provided because the Boland system does not represent the layered complexity of the bridge asset management model. In the layered perspective of performance management provided in Figure 7-5, the bridge assets comprise the physical system layer being actively managed by the planning agency and the hauliers are the users and thus reflect the service being provided. The network measures are the measures the planning agency use in their decision-making (control) processes. The network measures thus emerge because of the aggregated behaviours of all the hauliers. In the identified layered framework, the exogenous factors act the system to create change, which leads to a service discrepancy. The effect on the asset system are then reviewed and controlled by the planning agency. The loop then closes because the planning agency affects the system by enacting its strategy, which affects the behaviours and perceptions of those that use the system. In the context of this research, the vehicle mass and dimension regulation change was the exogenous event that changed the network service that led to a service discrepancy between the required and current bridge performance. The enacted bridge strengthening strategies then altered the system, which subsequently affected the behaviours and perceptions of the hauliers using the system.

7.2 The bridge strengthening performance measures

In the following section, the exogenous inputs and the system measures relating to the individual layers, the discrepancy and the and control measures are detailed. The identified measures are also further extended, based on system improvements identified during the development of the bridge asset management model. These measures were identified during the development of the bridge asset management model.
Chapter 7 – A system of bridge performance measures

Figure 7-5     A layered depiction of the the bridge performance management framework

7.2.1 Exogenous inputs

The following section details exogenous events identified during the development of the bridge asset management model.

Regulatory change was the primary destabilising effect that was identified and the one that led to the creation of the bridge asset management model, but clearly the number of potential exogenous events is infinite, as a change in the bridge system can arise from any number of potential challenges including climate change, new mass limits or new demands placed on the asset from growing numbers of people using the infrastructure system. Example exogenous events are presented in Table 7-1. Even though the number of exogenous events is infinite, there is a finite set of bridge management performance measures that can be influenced including geometric, load carrying ability and durability. Each of these measures can be expressed in a number of ways including time to failure, reliability, deterioration rates, width, and clearance (Frangopol and Duygu, 2011; Henning et al., 2013). Thus, exogenous factors must be understood to frame the model and to understand which of the technical performance measures is being impacted and in the sociotechnical context, which of the key stakeholders will be impacted.
### Table 7-1 Exogenous events that impact the stability of the bridge feedback system

<table>
<thead>
<tr>
<th>ID</th>
<th>Exogenous event</th>
<th>Event effect</th>
<th>System impact (model focus)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>Regulatory change: vehicle dimension and mass amendment regulations.</td>
<td>The change to the regulations raises the allowable mass limits.</td>
<td>Imposed loading on the technical bridge asset.</td>
</tr>
<tr>
<td>E2</td>
<td>Regulator change: other</td>
<td>Affect the strength to be provided by bridges or any other design factor.</td>
<td>Bridges must be constructed to higher design standards, which leads to a greater number of functionally obsolete bridges that require management.</td>
</tr>
<tr>
<td>E3</td>
<td>Climate change</td>
<td>The impact of climate change includes a greater number of more intense storms, which impacts the water level in rivers.</td>
<td>Affects the clearance of each bridge and its susceptibility to flood events</td>
</tr>
</tbody>
</table>

### 7.2.2 System performance measures

The following sections details the system performance measures that were identified during interviews and which were used in the bridge asset management model, and include the bridge performance measures, haulier performance measures and the network performance measures.

#### 7.2.2.1 Bridge performance measures

The bridge performance measures used in the bridge asset management model comprise the posted capacity of each individual bridge. Posted capacity was used as overweight vehicle movements were not being assessed. If potential overweight routes were being identified, then bridge rating capacity should be used. As highlighted in Chapter 4, the posting assessment uses higher partial load factors compared to rating assessments, as the likelihood of axle and gross vehicle mass non-compliance is higher. In the bridge performance measure framework, the cumulative distribution of individual bridge postings was used to understand how the distribution changed with time. The cumulative change in the measure was recorded, as discrete asset performance distributions are often multi-modal (Refer Figure 4-2), which presents challenges when using the arithmetic mean. At the initialisation of the model 70% of the bridge stock was adequate with respect to the HPMV load, which created a right skewed mean posting of 1.1867 $HN$, where the maximum posting was 1.39 $HN$.  

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Accordingly, the network could be considered adequate. Nevertheless, the distribution and number of substandard bridges was found to lead to a sub-optimal network. The subtle changes that occur in the posted value, because of bridge strengthening activities is illustrated in Figure 7-6. In Figure 7-6, while the bridge stock has been strengthened and the proportions of bridges located in each loading capacity bin has altered, only a minor change has occurred to the left and right tails of the distribution. For the strategy with the highest identified benefit-cost ratio the mean posting after the selected bridges were strengthened was 1.1875 $HN$, compared to the mean posting prior to improvement of 1.1867 $HN$. Even if all the bridges that are used by the hauliers are strengthened the mean bridge capacity is still only raised to 1.217 $HN$. Consequently, if the arithmetic mean was used the effect that strengthening program had on posted capacities would be lost. Accordingly, skewness and standard deviation are two measures that must also be used to accurately report the performance state of the bridge asset.

![Figure 7-6](image)

**Figure 7-6** The distribution of bridge capacity before & after bridge strengthening

Another performance measure pertinent aspect related to managing the strength of bridges is condition. Condition is pertinent as at increasingly poor condition states the load carrying capability of a bridge is affected. Furthermore, the effective long-term management of the bridge asset requires condition to be actively managed. If condition is not actively managed the outcome is an unaffordable programme of rehabilitation works (ASCE, 2013, 2015). Accordingly, the condition has been included in the bridge performance measure set. Table 7-2 details the performance measures identified during the bridge asset management model’s development and those measures detailed in this section.
Chapter 7 – A system of bridge performance measures

Table 7-2 Bridge strengthening performance measures

<table>
<thead>
<tr>
<th>ID</th>
<th>System measure</th>
<th>Description</th>
<th>Performance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Bridge loading capacity (without condition effects).</td>
<td>The posted capacity of a bridge or a bridge’s rating. The measure is used to understand which bridges require upgrading.</td>
<td>( %U_R = 100 \times \frac{R_L}{R_i} ) ( \text{Where: } %U_R \text{ refers to the posting utilisation, } %U_O \text{ refers to the overweight utilisation.} )</td>
</tr>
<tr>
<td>B2</td>
<td>Weighted mean of all bridge postings.</td>
<td>The area weighted capacity of the bridge network. Used to understand the average posting of the whole bridge stock.</td>
<td>( \frac{R_L}{R_i} = \frac{\sum_{i=1}^{B} AR_i}{\sum_{i=1}^{B} A} ) ( \text{Where: } A \text{ is bridge area and } B \text{ is the number of bridges located on the network.} )</td>
</tr>
<tr>
<td>B4</td>
<td>Standard deviation of capacity.</td>
<td>Used to understand how much the extent of the distribution differs from the mean.</td>
<td>( \sigma_R )</td>
</tr>
<tr>
<td>B3</td>
<td>Skewness of capacity.</td>
<td>Used to understand how the load rating of the whole bridge asset is distributed.</td>
<td>( k_R = \frac{\hat{R}_L - R_L}{\sigma} ) ( \text{Where: } \hat{R}_L \text{ is the mode of the posting distribution and } \sigma \text{ is the standard deviation of bridge posting. Skewness may also be used for overweight } R_O \text{ vehicles.} )</td>
</tr>
<tr>
<td>B4</td>
<td>Weighted mean of bridge condition.</td>
<td>The condition state of each bridge. Reported as weighted sum of all bridge components.</td>
<td>( \bar{C} = \frac{\sum_{i=1}^{B} AC}{\sum_{i=1}^{B} A} ) ( \text{Where: } C \text{ is bridge condition.} )</td>
</tr>
<tr>
<td>B5</td>
<td>Standard deviation of condition.</td>
<td>Used to understand how much the extent of the distribution differs from the mean.</td>
<td>( \sigma_C )</td>
</tr>
<tr>
<td>B6</td>
<td>Skewness of condition.</td>
<td>Used to understand how the condition of the whole bridge asset is distributed.</td>
<td>( k_C = \frac{\hat{C} - \bar{C}}{\sigma_C} )</td>
</tr>
<tr>
<td>B7</td>
<td>Bridge loading (with condition effects).</td>
<td>The loading capacity of each bridge with its condition state considered.</td>
<td>( \bar{R}<em>L = \frac{\sum</em>{i=1}^{B} \phi AR_i}{\sum_{i=1}^{B} A} ) ( \text{Where: } \phi \text{ is a deterioration reduction factor that is applied to each bridge.} )</td>
</tr>
</tbody>
</table>

7.2.2.2 Haulier measures

The haulier measures are those used by each haulier to understand which of the three vehicle-route combinations minimises the vkt they must travel given the location of each functionally obsolete bridge. The performance measures used in the haulier model included
the number of trips taken and \( vkt \). Further to the distance based measures, a potential future measure is the vehicle hours travelled and journey time reliability.

It was assumed in the haulier model that the cost to operate each vehicle type was the same. Accordingly, the derived travel benefits for each vehicle was a function of the number of trips made by each haulier the \( vkt \) for the selected route and the efficiency gain that could be obtained from each vehicle type. In future bridge asset management models, journey time and journey time reliability should also be included, because as noted in interviews, some hauliers are distance optimisers and those that must make connections, such as the one to the South Island ferry, are journey reliability optimisers. To account for the time and distance functions a haulier utility function should be used. The edge lengths can then be used to represent both distance and likely travel time. The utility function for each haulier is detailed in Equation 7-1. Thus, if a haulier is a time optimiser the weight of \( w_1 \) would be set to zero. In the current model, the weight of \( w_2 \) is zero, as only distance was accounted for. The identified current and future haulier measures are detailed in Table 7-3.

\[
U_{ij}^{type} = \begin{cases} 
\min (w_1 a_{ikj}^{type} + w_2 h_{ikj}^{type}) & \text{If a route is available} \\
\infty & \text{otherwise} 
\end{cases} 
\]

Equation 7-1

Where:

- \( w_x \): Weightings to represent how strongly each haulier is focused on time or distance, where \( w_1 + w_2 = 1.0 \)
- \( h_{ikj}^{type} \): A time metric used to understand how long the journey will take for each haulier between their O-D pair. Includes a reliability metric.

### 7.2.2.3 Network measures

The network measures are used by the planning agency to decide which bridges on which routes should be strengthened. The identified network measures were also used to provide a deeper insight into why some bridge strengthening strategies provided greater travel benefits than others. The measures detailed below include total network \( vkt \), the proportion of \( vkt \) travelled by each vehicle type, and the overall freight efficiency improvement obtained from strengthening a set of obsolete bridges.
Table 7-3  Individual haulier performance measures used in the bridge management model

<table>
<thead>
<tr>
<th>ID</th>
<th>System measure</th>
<th>Description</th>
<th>Performance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>Trips</td>
<td>An indication of how busy the route is compared to other routes. Effects the level of benefit derived for the route as it impacts the annual $vkt$.</td>
<td>The number of trips between an O-D pair.</td>
</tr>
<tr>
<td>H2</td>
<td>Vehicle kilometres</td>
<td>The effective distance travelled by individual hauliers. Effective distance is used as the edge distance of the graph is altered to reflect the gradient of the edge.</td>
<td>$c_{ij} = \min[a_{ij}^{\text{type}}, \infty]$</td>
</tr>
<tr>
<td>H3</td>
<td>Vehicle time taken</td>
<td>The typical travel time taken to traverse an edge</td>
<td>$\tau_{ij} = \min[h_{ij}^{\text{type}} + \varphi, \infty]$</td>
</tr>
<tr>
<td></td>
<td>Haulier journey utility</td>
<td>The personal journey utility derived by a haulier from travelling a route (Refer Equation 7-1)</td>
<td>$U_{ij} = \min[w_1a_{ij}^{\text{type}} + w_2h_{ij}^{\text{type}}, \infty]$</td>
</tr>
</tbody>
</table>

In the bridge asset management model, the total $vkt$ was used to model the aggregated behaviours of the hauliers and was used by the planning agency to understand what freight efficiency improvements had been derived from strengthening a set of obsolete bridges. Similarly, the Economic Evaluation Manual (NZTA, 2016a) and other studies (Paling et al., 2014; Samimi et al., 2009) also used $vkt$ to quantify freight movement. Given the potential future use of travel time by each haulier to select their preferred route-truck combination, total network travel time must also be assessed.

Although total $vkt$ is a useful measure for identifying bridge strengthening strategies, the measure was found to provide little insight into why a strategy was successful. Accordingly, to provide this insight the proportion of $vkt$ by each vehicle type was calculated. As identified in Chapter 6 by calculating the usage proportions the tipping point for transferring between mainly using 50 tonne vehicles and mainly using 62 tonne vehicles could be assessed. Such a measure would have been useful for the planning agent, as their initial focus was on maximising the use of 50 tonne vehicles.

The aim of introducing the vehicle mass and dimension regulations was to improve freight efficiency. Based on the economic evaluation manual (NZTA, 2016a) freight efficiency comprises the reduction in the number of trip numbers, which is influenced by the load carrying capacity of a vehicle. Similarly, herein, annual $vkt$ both before and after a selected
set of obsolete bridges had been strengthened was used to assess the improvement in network efficiency. The identified planning agent and haulier agent measures, along with the other system measures are detailed in Table 7-4.

<table>
<thead>
<tr>
<th>ID</th>
<th>System impact</th>
<th>Description</th>
<th>Performance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>Vehicle kilometres travelled</td>
<td>The distance travelled by the hauliers before and after any bridge improvements have been carried out.</td>
<td>$\sum vkt$ of all the hauliers.</td>
</tr>
<tr>
<td>N2</td>
<td>Vehicle hours taken</td>
<td>The time taken by hauliers to complete their journey. Measured before and after any bridge improvements have been carried out.</td>
<td>$\sum \text{vehicle hours taken}$ of all hauliers.</td>
</tr>
</tbody>
</table>
| N3 | Usage proportion                       | The proportion of $vkt$ travelled by each vehicles type was recorded. Start refers to the network prior to any bridge improvements and end refers to the state of the network after bridge improvements have been carried out. | \[
%\text{vkt}_{62} = \frac{\sum \text{vkt}_{62}}{\sum \text{vkt}} \times 100
\]
Where: $\text{vkt}_{62}$ is the distance travelled by the 62 tonne vehicles.

\[
%\text{vkt}_{50} = \frac{\sum \text{vkt}_{50}}{\sum \text{vkt}} \times 100
\]
Where: $\text{vkt}_{50}$ is the distance travelled by the 50 tonne vehicles.

\[
%\text{vkt}_{\text{end}} = \frac{\sum \text{vkt}_{\text{end}}}{\sum \text{vkt}_{\text{start}}} \times 100
\]

| N4 | Percentage improvement                 | The $vkt$ before and after bridge improvements have been carried out.                           | $\%\text{inc} = \left(1 - \frac{\sum \text{vkt}_{\text{end}}}{\sum \text{vkt}_{\text{start}}} \right) \times 100$ |

### 7.2.3 System discrepancy measures

Herein, discrepancy refers to the difference between the current state and the desired state of the network, as defined by the performance target. The achievable performance being identified using the bridge asset management model. Based on the modelling process the identified budget limits are 1.17 m NZD and 54.63 m NZD. The lower budget delivers the maximum benefit-cost ratio and the higher budget delivers the maximum national travel benefits. Thus, the achievable target is variable depending on the available budget. To define the target the relationship between cost and benefit or cost and incremental-benefit is used. Consequently, the discrepancy is the difference between the current state and the target. The achievable targets, as informed by the computational model, are detailed in Table 7-5. By setting an achievable target the arbitrary identification of performance targets (Seddon, 2008) is removed. Furthermore, as the targets are an emergent property of a linked
performance framework the likelihood of system paradoxes is also minimised by using a computational model, because the ability to focus on one measure over another is removed.

Table 7-5 Discrepancy measures used in the bridge management model

<table>
<thead>
<tr>
<th>ID</th>
<th>System impact</th>
<th>Description</th>
<th>Performance measure</th>
</tr>
</thead>
</table>
| D1 | Achievable - benefit | Vehicle operating cost $V_oC$ is used to define the benefit that can be achieved from a defined budget. | $V_oC = v \sum_{k=1}^{r} \Delta c_{ikj} \ $  

$V_oC$ is travel benefit gained from strengthening a set of obsolete bridges. |
| D2 | Achievable benefit-cost ratio | Used to provide insight into which strategies provided the required level of financial return. Typically, a desired target is set at 4, but it can range between 3 and 5 (NZTA, 2016a). | $b_c = \frac{V_oC}{C}$  

Where $C$ is the upgrade cost for a defined set of obsolete bridges |
| D3 | Achievable Incremental benefit-cost | Used to provide insight into the viability of increasingly more expensive bridge strengthening projects. Typically, a desired target is set at 4, but it can range between 3 and 5 (NZTA, 2016a). | $\Delta b_c = \frac{B_{alt} - B_{pref}}{C_{p,alt} - C_{p,pref}}$ |

7.2.4 System control

The system control measures are used by the planning agent to select its preferred strategy and include the measures used in the fitness function and the budget available to strengthen a set of functionally obsolete bridges.

The budget is a control measure as it constrains the planning agent, thus controlling the number of functionally obsolete bridges it can strengthen. The objective of minimising the $vkt$ of each haulier and meeting budget expectations both define the fitness function. The fitness function being used to identify the number and location of bridges to strengthen. Thus, the fitness function controls the strengthening of the bridge system. If travel time benefits are also included, then the objective function is based on the sum of the utility score of each haulier. Thus, the fitness function comprises a haulier utility function and a budget control function.

Although many measures are used to provide insight into the bridge strengthening process, the fitness function is the defining control measure, which is based on the network level
vehicle operating cost and the available budget. All the other identified measures are useful, but only in the context of understanding why particular strategies are successful or why particular bridges are being strengthened. Accordingly, a clear causal link between the strategic decision-making measures and the operational measures now exists, thus providing the required level of strategic control missing from existing performance measurement and management systems (NZOAG, 2004, 2007). The control measures used in the bridge asset management model are detailed in Table 7-6.

<table>
<thead>
<tr>
<th>ID</th>
<th>System impact</th>
<th>Description</th>
<th>Performance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Solution fitness</td>
<td>The minimum fitness that can be achieved for a given budget.</td>
<td>[ F = \frac{\sum_{k=1}^{r} a_{ikj}}{\sum_{k=1}^{r} f_{ikj}} + w(e_g - d)^2 ]</td>
</tr>
<tr>
<td>C2</td>
<td>Budget</td>
<td>The budget available to carry out the required work.</td>
<td>d</td>
</tr>
</tbody>
</table>

Based on the experience gained from developing the identified bridge performance measures, the rationalisation of many measures to a set of key performance indicators can only be carried out if a model is created, otherwise the measures are not linked to a controlling fitness function. Furthermore, the key performance measures can only be identified if the asset, the user (haulier) and the decision-maker (planning agent) is included. If the traditional asset management view is taken and only the asset is included the key performance indicators reduce to those related to the operational management of the asset.

### 7.3 A general framework of bridge performance measures

The Boland inspired feedback influence diagram can also be extended and used to trade-off competing service level outcomes. As a greater number of service level universes are created that affect the technical bridge system and as a greater number of controls are created the complex interrelationship between measures can be mapped and the controls used to identify achievable performance targets for each service level that is being focused on. These service levels may include not only freight efficiency, but safety and network resilience and any other service level focus that is important to the planning agency. Given the non-linear relationship between budget and the benefits derived from strengthening obsolete bridges (Refer Chapter 6), such a model will provide planning agencies with the ability to explore
the impact that alternative bridge management strategies have on each benefit stream and thus agencies will be able to effectively assign funding to each benefit stream.

Based on the bridge strengthening model the identified set of bridge performance measures were generalised for use with any improvement situation. The generalised framework of measures is illustrated in Figure 7-7. In the context of a generalised measurement framework the exogenous effects are those that disturb the existing equilibrium state of the bridge sociotechnical system and the associated expectations of the hauliers. In the strengthening model bridge posting was used. In the general framework bridge reliability is used, as a reliability index can be applied to any bridge related performance criteria. Furthermore, reliability can easily incorporate the effects of deterioration to any aspect of the bridge system. Through the identified measures the adaptation of the bridge system and the ensuing effect that these adaptations have on the users can be monitored. The impact of the planning agent’s choices with respect to benefit-cost expectations and budget can also be assessed. In Figure 7-7 the core framework has been extended to include several services, other than improving freight efficiency. In the identified framework, the output from each service strategy is an improvement programme, which is compared to the overall budget available to the planning agency. Thus, by extending the framework the requirement exists to trade-off the budget available to each service. To provide a rational way of trading off the budget a second fitness function has been added, which controls the budget allocated to each service attribute. To trade-off the budget allocated to each service attribute, the budget control process awards different budgets to each service attribute and evaluates the overall fitness based on the fitness reported by the individual service processes. The budget controlling fitness function is thus able to work towards an allocation that either minimises or maximises the identified fitness scores for each service. If the selected budget allocation can never attain the expected service, then either the budget must be increased or the service targets must be reassessed. The resulting service level assessment process, follows the recommendations of the International Infrastructure Management Manual (NAMS, 2015).

### 7.4 Summary

The original hypothesis was that by using a structured systems-thinking approach to developing the computational bridge asset management model the performance measures required to management the bridge system would be identified. It was also hypothesised that the cause of a change to the bridge system and the effect of the change would be
identified and through the development of the computational model the effects of a change to the system could be explored.

In this chapter, a range of measures were identified and these measures can be used to model the causal relationship in the bridge asset management system. Nonetheless, although the development of the computational model readily identified the required performance measures, there was no structure to the measures, which led to a poor understanding of which measures were the most important. Structure was provided by using the performance measurement framework developed in this chapter. By developing this framework and in conjunction with development of the computational model, deeper insights into which measures should be used to provide information, and which measures should be used to make decisions was identified. Thus, by combining the development of a computational model and the performance framework key performance indicators can be identified. Accordingly, the creation of the bridge asset management model did support performance measure identification, but further categorisation of the identified performance measures was required to understand the role of the identified measures in the decision-making process.

![The generalised bridge performance management framework](image)
It was also identified that the bridge performance measure and management framework could also be easily extended to other services. The extended framework provided insights into how future computational asset management models may joined to trade-off competing services. In the identified example, each service was modelled in a separate environment and a central budget controller was used to assess the optimal cross-service budget allocation.
Chapter 8 Discussion

In this thesis, a systems-thinking approach was used to develop a new bridge asset management model and to provide insights into the identification and categorisation of bridge management performance measures. The insights gained from developing the bridge asset management model and the system of performance measures are detailed in the following chapter. The following chapter also details whether the identified sociotechnical bridge asset management system was found to exhibit the properties of a complex system.

8.1 A new sociotechnical bridge asset management model

It was identified that asset management had changed from being a technically led endeavour to sociotechnical process that now incorporates the desires of stakeholders (Dijkema et al., 2013; Godau, 1999) as well as the technical asset focused considerations of maintenance and improvement. To address the changes in the scope of asset management, researchers have recommended (Bernhardt and McNeil, 2008; Osman, 2012; Osman and Hassan Ali, 2012) that asset management models should be updated to incorporate stakeholders, as current technical models fail to address the complex interactions between the social and technical systems. Consequently, agent-based and systems-dynamics models of the asset management process were investigated as potential solutions (Bernhardt and McNeil, 2008; Osman, 2012; Osman and Hassan Ali, 2012). The identified asset management models were found to have the following limitations:

- an unclear purpose;
- a focus on condition; and
- they did not model a geospatially complex transport network.

A model should only include the elements that are required to gain insights into the system being considered. Consequently, the model should reflect the perspective and interests of the modeller. In the case of the existing agent-based asset management models the purpose of the model was found to be unclear, as the identified models included every agent involved in the decision-making process including government agents, user agents, decision-making
agents, contractor agents and asset agents. Given the intent of the existing agent-based asset management models was to gain insight into the effectiveness of asset management strategies, the same objective was found to be achievable with fewer agents. Accordingly, in the agent-based bridge asset management model the agents were rationalised to solely comprise the users (hauliers), a planning agent (decision-maker) and the asset agents. The government agent was removed, because the only effect this agent had in the existing models was budgetary related, and budgetary variation could be more easily managed as an exogenous effect on the modelled universe. The removal of the government agent also removes the necessity to model the complexities of government. The contracting agent was also removed, as the effects this agent has on the network can be modelled stochastically. Similarly, the resourcing effects created by contracting agents can also be easily modelled as constraints on annual work quantities. By removing the government and contractor agent the model becomes a useful tool for planning agencies optimising their budgetary spend, rather than assessing the impacts the supply chain has on delivery. Thus, research into the structure of the bridge improvement model aided in the rationalisation and simplification of future agent-based asset management models.

In the existing models, the agents were found to interact with sections of roads in an unstructured way. The interaction was considered unstructured as the interaction was modelled as a random draw with replacement. Accordingly, each agent selected several road sections, viewed these road sections and replaced them for others to draw. In real-world networks, the users do not randomly interact with a network, they follow routes that work to maximise their own utility. Consequently, users follow paths that are based on their own tacit knowledge of the network. In the bridge management model, the addition of the network facilitated the structured interaction between the users (hauliers), the network and the bridge asset. Accordingly, the addition of the network further added to the realism of the agent-based asset management models that have been developed. The addition of the network model also provided a greater level of insight into the routes that are preferred by the users. Adding the network model also required the further development of the user / haulier model, as the haulier had to interact with the network in a structured way. Interestingly, the development of the haulier model moved the focus of the bridge asset management model away from being asset focused to being network focused. Thus, the agent-based asset management models had to incorporate a traffic flow model, and thus a four-step process was used to create the trip distribution model. The routing model was
based on a shortest path algorithm with the edge distances being based on the actual distance travelled and an efficiency penalty which was based on the gradient of the edge. The hauliers then adapted their travel patterns based on the obsolete bridges the planning agent strengthened. Furthermore, the haulier was also able to select from three vehicle types including a 44 tonne vehicle, a 50 tonne vehicle and a 62 tonne vehicle, each providing incrementally larger efficiency gains. The only limitation on the user of the heavier vehicles was the ability of each bridge to carry the increased loads. Based on the obsolete bridge strengthening strategies proposed by the planning agent, each haulier selects their preferred route-vehicle combination. By assessing the network level travel saving the planning agent is then able to identify strategies that maximise network level freight efficiency. Consequently, the new haulier model more accurately reflects the real-world behaviours of road users, when compared to the existing agent-based asset management models.

It is considered that the bridge asset management model is a true asset management model, as it incorporates a network of spatially connected assets, adaptive haulier agents and an adaptive planning agent that can develop strategies in reaction to the adaptive hauliers. Accordingly, the agent-based bridge asset management model developed herein is considered to advance the existing agent-based asset management models (Bernhardt and McNeil, 2008; Osman, 2012; Osman and Hassan Ali, 2012).

8.2 New bridge strengthening strategies

In New Zealand in the next 30 years over 600 bridges will potentially become functionally obsolete. Similarly, in the United States in excess of 307.5 billion US dollars (ASCE, 2015) will have to be spent to manage functionally obsolete bridges. The spatially distributed nature of the numerous obsolete bridges in conjunction with mitigation actions results in hard a combinatorial problem. In the bridge asset management model, there was up to $2^{186}$ possible bridge strengthening strategies, given the 186 obsolete bridges that were identified. To identify potential bridge strengthening strategies a new GA was developed. A GA methodology was used because of the applicability of GAs for identifying solutions to combinatorial problems (Sutton, 2011). In the bridge asset management model, the GA is used by the planning agent to identify heuristically optimal bridge strengthening strategies. Given the developmental flexibility of the modularised modelling methodology and the ability to apply the GA to any network, a modelling solution has been created that can be
used to manage the significant obsolete bridge management problem not only found in New Zealand, but in the United States as well.

To manage the set of obsolete bridges the planning agency was following a single route improvement strategy. The strategy identified 37 bridges to be upgraded on the North Island of New Zealand, at a total cost of 18.75 m NZD. When the proposed strategy was implemented in the model an average benefit-cost ratio of 2.00 was obtained. Alternatively, for the same budget the GA identified a strategy that provided a network level benefit-cost ratio 5.1, which was 250% percent higher than the proposed strategy. Furthermore, the strategy identified by the planning agency, while providing a network improvement, was found to be in an area between two strategies that would have provided either a higher benefit-cost ratio or higher benefits. If the budget was reduced an increased benefit-cost ratio of 23.01 could be achieved for 1.17 m NZD or incrementally higher benefits could be achieved for budgets ranging between 30 m and 58 m NZD. The increased budgets, based on the modelled outputs, provided significant incremental benefit-cost ratios with these ratios ranging between 1.0 and 4.0. Consequently, if the lower cost strategy was implemented the planning agency could have saved 17.58 m NZD. In the lower cost strategy, the increased benefit occurred because of the more complex management strategies that were identified by the bridge asset management model. The strategies were more complex because the model identified routes that combined flows from multiple O-D pairs to maximise the travel benefits obtained from the bridge strengthening costs. Given the complexity of the network, the number of bridges that required strengthening and the vehicle choices available to the hauliers, the bridge asset management model developed strategies are highly unlikely to have been identified by the planning agency. In the higher-cost higher-benefit strategies suitable solutions were found because of the models, ability to identify strategies that maximised the usage of route sections. Thus, the bridge asset management model would prove beneficial to asset managers planning network improvements. Thus, even though the planning agency’s proposed strategy increases the efficiency of the bridge network, potentially the increase could have been markedly higher, which would have positively impacted the freight efficiency of New Zealand’s road network. Thus, the new bridge management model has a place in supporting network level strategic decision-making.
8.3 Improved performance measures

It is recommended in the literature that asset management is viewed as a sociotechnical system. Accordingly, the performance measures used to provide insights into the effectiveness of strategies must also reflect the sociotechnical nature of asset management. The new sociotechnical paradigm also implies that a systems-thinking model must be utilised, given the integration of the social, technical and decision-making systems. To incorporate the social and decision-making aspects of asset management into a performance measure framework, a user based perspective was incorporated into the traditionally technical bridge performance measure frameworks. By taking a user based perspective the potential now exists for multiple user types and multiple performance measures to be incorporated into a single model environment, which is different to the technical bridge performance viewpoint that has been used (Ghasemi and Hooks, 2010; Maguire, 2009; Patidar et al., 2007), and thus provides asset managers with the ability to trade-off many performance attributes and their associated mitigation activities. The ability to trade-off interventions is important, because as identified by Thaler (1990, 1999) dividing budgets in to separate funding streams leads to counter intuitive practices such as developing over specified solutions and deferring work because the existing funding stream has been exhausted. By being able to trade-off technical and social outcomes for any number of user types, agent-based asset management models provide a rational methodology for optimally apportioning budgets. Thus, agent-based models can be used to maintain the fungibility principles of money and thus obviate the requirement for the inefficient use of divided funding streams (Thaler, 1999).

Based on a review of the performance measurement and management literature, performance measures should be linked to create a relationship between the cause of a system change and the effect on the system of a change. To create a causal relationship a systems-thinking methodology was used herein. Unlike past approaches to performance measure development (Bush et al., 2012; Félio and Lounis, 2009), the bridge asset management model was used as a starting point for measure identification. The model was used as a starting point for two reasons. First, to create an effective computational model, the causal relationship between each performance measure had to be developed, as the outputs from the technical system are the inputs into the social system. Second, by creating a computational model a set of measures had to be derived that could be used by the model to represent the real-world. It was assumed based on these two underlying ideas that new performance measures that could
be used to manage the functionally obsolete bridge stock would be identified. However, no new measures were identified, as typically measures such as $vkt$, benefit-cost, and bridge rating were already used to manage bridges. Nevertheless, because of the modelling process, a firmer link between the cause of a change and the effect of a change was created, which addresses the weakness of traditional performance measurement systems, such as the balanced scorecard (Taticchi et al., 2010). In systems, such as the balanced scorecard (Kaplan and Norton, 1992) and the pressure-state-response model (OECD, 2003), the measures while being well considered are only loosely tied to the decision-making process. In each of these systems the relationship between each measure is also omitted. As an example, no relationship between the pressures on the system, the state of the system and the response that should be taken is defined in the pressure-state-response model. A further benefit of basing the performance measures on the modelled measures, is that when used in conjunction with a performance measure framework, a clear demarcation between key performance indicators and general information performance indicators is identified. The key performance indicators being those used in the fitness function to decide what bridge strengthening strategies should be used. All other measures were considered as general information performance measures as they were used to investigate the underlying reasons that a strategy was successful. Thus, the modelling approach to performance measure development was found to provide new insights into how performance measures could be rationalised, which was an unexpected discovery. Without such a method, all the performance measures would be considered as equally important. Given that many of the identified secondary measures were comparable to those used in the fitness function, double accounting and a focus on unimportant aspects is likely to occur. As an example, the network freight efficiency gain was based on the vehicle kilometres travelled by hauliers, which was also used in the fitness function.

To apply the modelling approach does not necessarily imply a detailed model must be constructed, only that when developing performance measures, consideration should be given to how the measures will be used in a model and whether the measures will be used in the optimisation process or simply in understanding the results of the model. Accordingly, the model led performance measure identification process provides a rational method of identifying new performance measures and of ensuring the causal relationship between each measure is understood. Thus, the new methodology adds an alternative to the methodologies detailed above.
Chapter 8 – Discussion

8.4 An assessment of complexity

In Chapter 2, three complex system attributes were highlighted including feedback, emergent behaviour and non-linearity. By creating of a sociotechnical model there is an implication that the three complex system attributes will be present. In the bridge asset management model feedback between the social and technical systems did occur, emergent behaviour did not occur, and non-linearity occurred but was not a function of the other two.

Feedback is a function of complex systems and occurs because one sub-system inputs in to another sub-system which effects the initiating system. Typically, such feedback results in either the system maintaining its current equilibrium state or the system becomes temporarily unstable until a new stable state is found. In the bridge strengthening model the stakeholders provided feedback to the planning agent regarding their preferred strategies and the planning agent subsequently develops and enacts its own bridge strengthening strategy. The enactment of the strategy thus closes the feedback loop. In such a system, the transition between the current and the desired state is monotonic as any normatively selected strengthening strategy will improve the state of the network. Depending on the effectiveness of the identified strategies the resulting effects can be weakly or strongly monotonic. Thus, the natural feedback state of the bridge asset management system is to be negative, as small changes in the input strategy do not have a disproportionally unforeseen large effect on the output. The only effects that create positive feedback are exogenous and result from a change in service level expectations. In the model developed herein the disturbance was the change to the vehicle mass and dimension regulations. In the bridge asset management model, no feedback occurred between the system inputs and the system outputs, because the presupposition with destabilising feedback is that the final state of the system is unknown, whereas in the identified case the ultimate final desired state was known. Nevertheless, the bridge improvement model that was developed was highly simplified. If an asset management model was created that incorporated multiple competing objectives and multiple stakeholders, the unforeseeable effects of feedback are highly likely to arise because of the added level of complexity, and as such emergent and unforeseen system effects are also likely to occur.

Although true emergent behaviour did not occur, as unforeseen patterns did not arise, an interesting, but foreseeable pattern did occur. The interesting insight is the non-linearity between the budget and the efficiency of the network. In the model, the relationship between
funding and efficiency was found to be strongly non-linear. Based on the non-linearity of
the system there exists a clear requirement to use even the simplest of bridge asset
management models to decide which bridge to strengthen, especially when networks have
multiple alternative routes. If a model is not used, the considerable expenditure that is
required to upgrade the obsolete bridge stock will have a significant likelihood of being
ineffectively allocated. Furthermore, as a greater number of services are incorporated into
the bridge asset management model, the likelihood of ineffective strategies being created
will rise. Thus, agent-based models of complex systems, or models with similar capabilities,
are recommended when modelling the effects of competing performance measures.

8.5 Improving the bridge asset management model

An aim of the research was to develop a mediator model that could be used to compare bridge
strengthening strategies and to provide insights into alternative bridge strengthening
strategies that were not evident prior to the development of the model. This aim is considered
to have been met, as new insights were provided in to alternative bridge strengthening
strategies that were not previously considered. To further advance the bridge asset
management mediator model to a predictive model, several areas require further
improvement including the following:

- the freight user model;
- the quality of the traffic data; and
- The bridge load and capacity model.

The freight user model defines how the hauliers move around the network. In the wider
literature (Feng et al., 2013; Fowkes, 2007; Knorring et al., 2005) existing freight models
are more complex and take into account aspects such as education level, scenery and tacit
knowledge of route reliability and journey times. In the bridge improvement model a
simplified shortest path methodology was used, which was considered appropriate given the
aim of developing a mediator model. To further improve on the newly developed mediator
model, and to aid in the creation of a predictive model, improved geospatial data is also
required. The geospatial data that is required includes percentage vehicle type usage,
average speed data, journey reliability data, scenery classifications, gradient data, and
horizontal curvature data. These datasets can then be used to assess the routes that will be
taken and the efficiency of the vehicle when it does use the route. Accordingly, updating the publicly available planning agency dataset would prove useful.

Further improvements are also possible by including the operating costs of the different vehicles. Presently, the vehicle operating costs for each vehicle type are assumed to be the same, but as highlighted in interviews, there is a complex balance that must be struck between the road user charges incurred from operating the heavier vehicles, the amount of fuel used by these vehicles and the efficiency gain that is obtained. To address the problem of one operating cost the analysis presented in the Economic Evaluation Manual (NZTA, 2016a) should be updated to include the cost of operating the different vehicle types. Another future improvement to the existing traffic model would be to add travel time. Travel time was omitted because the available data set did not include details on the average speed of vehicles along an edge. If the variability in edge speed was known, then travel time reliability could also be modelled.

It was hypothesised in the introduction that up to 600 bridges would have to be replaced should a further increase occur to the limits allowed by vehicle mass and dimensions regulations. Based on existing assessments only a small dedicated portion of the state highway network can achieve the HPMV load requirements. If a future regulatory increase occurred further improvements in the bridge network are unlikely to be achieved by using traditional load factor assessments, as these are inherently conservative. To achieve further savings and based on the ideas promulgated in the literature, the use of a reliability based assessment methodology is recommended, as this approach develops bridge specific models that result in a more detailed understanding of the bridges capacity limits and thus make more effective use of the bridge stock (Nowak, 2004; Nowak and Zhou, 1990). Nevertheless, based on a review of the current data, and the attempted use of this data to develop such a model, the data storage system requires further development so that the properties detailed in Table 8-1 are understood. Only if these data collection practices are implemented will the planning agency be able to make use of the more advanced techniques and thus avert potential bridge upgrade costs.
A further improvement to the model, and one which would provide greater opportunity to develop improved strategies, is the incorporation of multiple bridge performance measures and multiple users. By including the full range of users, the impact of competing measures can be understood and optimal multi-service asset management strategies developed. Potential bridge performance measure considerations and the impacts that these measures have on users are presented in Table 8-2.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Potential source</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live load</td>
<td>Weigh in motion sites located across New Zealand</td>
<td>Includes vehicle live load data and is used in the assessment of the reliability index.</td>
</tr>
<tr>
<td>Dead and super-imposed loads</td>
<td>Bridge assessment data</td>
<td>Used to calculate bridge reliability indices.</td>
</tr>
<tr>
<td>Material properties</td>
<td>Tests that are used to manage the bridge stock and in the development of stock level models</td>
<td>Used to understand the distribution of material properties, which is an important consideration when assessing the reliability index.</td>
</tr>
<tr>
<td>Element posting and rating factors</td>
<td>Bridge assessment data</td>
<td>An overall load factor is reported at present. If a reliability based assessment is not used the reporting of element level posting and rating factors would prove beneficial and remove the need to modify the existing rating data.</td>
</tr>
<tr>
<td>Deteriorated load ratings</td>
<td>Bridge assessment data</td>
<td>To aid the optimal management of the bridge stock the effects of deterioration on the element should be included, but as a separate factor.</td>
</tr>
</tbody>
</table>
Table 8-2 Bridge related performance metrics that impact network operation

<table>
<thead>
<tr>
<th>Metric</th>
<th>Stakeholders</th>
<th>Network effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live load</td>
<td>Freight, public service vehicles, buses, and normal vehicles</td>
<td>As modelled herein the live load capability affects heavy vehicle operation. Under certain load combinations normal vehicles can also be effected. Agent-based behavioural models and/or traditional four step models should be used.</td>
</tr>
<tr>
<td>Bridge width</td>
<td>Peak time users (freight, public service vehicles, buses, and normal vehicles such as cars)</td>
<td>Flow capacity is a network level consideration. The width of a bridge affects the peak flow and thus impacts journey time reliability, total journey times and average speed. Like the model developed herein, an agent-based model can be used to represent route finding behaviours.</td>
</tr>
<tr>
<td>Resilience considerations</td>
<td>Emergency services and general network users (freight, public service vehicles, buses, and normal vehicles)</td>
<td>Major events affect emergency operations and the return to normal service. A loss of service requires a random event model such as those developed by Bocchini and Frangopol (2011c). Such a model in combination with an agent-based user model would prove beneficial to understanding which routes users would take.</td>
</tr>
<tr>
<td>Condition</td>
<td>Asset managers and general users</td>
<td>Good asset management minimises the whole of life costs of the asset (NAMS, 2015). Poor condition assets can also impact network operation. Consequently, the life-cycle cost of maintenance strategies must be assessed.</td>
</tr>
</tbody>
</table>

8.6 The future of asset management models

If agent-based asset management models, such as the one developed herein, and by others (Bernhardt and McNeil, 2008; Osman and Nikbakht, 2014), are compared to those that exist in the computer video game world, the asset management models can be considered to be crude reflections with simple mechanics, even though planning style video games are themselves considered inaccurate (Minnery and Searle, 2014). Nevertheless, urban planning and management computer games such as SimCity have been used in a teaching context before and have been used to test the efficacy of asset management and planning strategies (Adams, 1998). In these games, the player acts out the role of an asset manager and must develop and maintain their own town and so must purchase water, remove waste, develop storm and waste-water systems, plan roads and develop urban zoning strategies. It is envisaged that asset management models will develop to a similar level of complexity, and in doing so will provide asset managers with the ability to truly test their integrated asset management strategies. Thus, creating a convergence between asset management inspired games and real-world asset management models, similar to the convergence seen in other planning simulations (Minnery and Searle, 2014). The development of such games is
required because asset management is a high stakes game (Kunreuther et al., 2002) with significant financial and social repercussions if poorly defined strategies are enacted. By creating realistic models of the asset management process, a safe sandbox is created where asset managers can test their strategies. The sandbox can be used to provide insights into potential social side-effects or into risk management strategies that must be implemented. Thus, minimising the potential risk associated with enacting ineffective asset management strategies. To realise the game based asset management future and to achieve the desired convergence between the real-world application and asset management games, further development is required, as the game mechanics are often unrealistic (Minnery and Searle, 2014; Raghothama and Meijer, 2014). Furthermore, while the existing game based simulations represent an incremental improvement over and above the exiting asset management models, these game environments still fail to include a method of identifying an optimal solution. While the asset management model developed herein incorporated a GA to identify such a solution, improved search methods will be required to deal with the spatial complexity of managing a town over long temporal windows. A development would therefore be to use normative decision-making and optimisation tools that can operate in such complex situations. If accurate simulation environments are linked with improved optimisation tools, asset managers will be able to experiment with true sociotechnical models, and will thus be able to fully implement the strategy rehearsal cycle recommended by (Dyson et al., 2007).
Chapter 9 Conclusions

In the following section, the original objectives that were set out at the start of this research are reviewed. The following objectives were set:

- Develop a model that describes the real-world sociotechnical system.
- Further advance the development of agent-based asset management models.
- Understand the impact that proposed planning agency strategies have on network performance and assess the level of improvement that can be gained by using a network focused sociotechnical bridge asset management model.
- Investigate whether the new bridge asset management model provides new insights into network level bridge strengthening strategies.
- Use the bridge management model to develop a set of performance measures that can be used to monitor whether the freight efficiency objective has been met. These measures must link operational activities to the national level freight efficiency outcome.

By creating the bridge asset management model and by incorporating a network of bridges and by also incorporating more advanced user agents and a decision-making agent, the modelling objectives of this research have been met. They have been met because the new agent-based bridge asset management model further extends the use of agent-based modelling in asset management and increases the realism of agent-based asset management models. Furthermore, by creating a framework that is scalable the agent-based asset management model addresses the identified constraints of existing bridge asset management models, which typically have only incorporated small numbers of bridges (Refer Chapter 1). Accordingly, with the development of the bridge asset management model, there now exists a methodology that can be used to address the complex problem of managing the increasing number of functionally obsolete post war bridges. A problem, which the US estimated would cost up to 20.5 billion USD (ASCE, 2015) to address. Furthermore, by creating the associated performance framework the effectiveness of identified strategies can be monitored as they are implemented.
Chapter 9 – Conclusions

The justification of the identified contribution is detailed in the following section, and covers the advancement of agent-based asset management models, new insights into bridge strengthening strategies and the development of a new bridge performance measure framework.

9.1 Advancement of agent-based asset management models

Asset management models have changed little in the last 20 years (Bernhardt and McNeil, 2008), even though asset management has altered from being primarily a technical endeavour to sociotechnical endeavour (Godau, 1999). As highlighted by Boulding (2009), as systems change and become more complex, so should the models that are used to understand them. To address the complexity inherent in asset management Godau (1999) recommended that stakeholders should be included in asset management systems. Later, Bernhardt and McNeil (2008) identified the same problem, but also created a computational model that could be used to investigate the impact that operational asset management activities, such as pavement maintenance, had on a stakeholder’s perception of the service being provided by the assets it used. At a similar time, Osman (2012) independently created a computational model that integrated stakeholders, which could be used to assess how these stakeholders were impacted by maintenance activities. Both researchers used agent-based modelling, a computational methodology that requires the behaviours and actions of each stakeholder to be assessed and incorporated into the model. Thus, by using agent-based modelling the insights recommended by Godau (1999) are naturally incorporated into asset management decision-making. Although the identified models provided a computational representation of the modern sociotechnical asset management system, they still required further development. The models required further development, as they omitted the geospatial aspect of infrastructure asset management. In the identified models, the users were found to interact in an unstructured way with the assets that were being modelled. The interaction was unstructured, because the users drew assets (pavement sections) from a set of assets, reviewed the asset’s condition and replaced the asset for redraw. Based on the interaction between the asset and several users, the user’s perception of the overall condition of the asset was assessed. Users interact with a network asset, such and roads and bridges, in a more structured way. The interaction is structured, because users move around a network and use a set of preferred routes. Accordingly, sections of the asset are not used. To reflect this real-world behaviour, a spatially accurate road network was created. Given
the focus of the research was improving the freight performance of New Zealand’s road bridges, the users were hauliers. The hauliers, unlike the user agents in existing agent-based asset management models, select their routes using a shortest path analysis. The hauliers also have the choice of three vehicles to use comprising a 44 tonne, 50 tonne and a 62 tonne truck. The choice of vehicles being defined by the planning agency (Reynolds and Goodall, 2014). The only constraint to using the heavier vehicles is the load carrying capability of the bridges found on the network. By creating a haulier model that represents real-world behaviours the haulier model developed herein is considered an advancement on the users found in existing agent-based asset management models. The final bridge asset management model comprised 1268 bridges, 186 of which were functionally obsolete, 7185 highway sections and 102 hauliers.

The decision-makers in the identified agent-based asset management models use simple asset strategies to identify which assets should be improved, strategies such as worst first (Moore et al., 2008). Herein, a genetic algorithm (GA) was created to identify a set of improvement strategies. A GA was used as GAs are suited to solving combinatorial problems (Sutton, 2011). In the model, a set of functionally obsolete bridges are being managed. The bridges are functionally obsolete, because their age results in a load carrying capability that no longer conforms to current design standards. In total 186 obsolete bridges were identified. The fact that there are $2^{186}$ possible bridge management strategies creates a combinatorial problem. The decision-making process used in the bridge asset management model is an advancement on the decision-making models used in previous agent-based asset management models, because the GA can select heuristically optimal strategies that maximise the freight efficiency of a network of bridges. Thus, by creating a network that agents can interact with and by creating a GA that can identify bridge strengthening strategies that can maximise the freight efficiency of the network, the bridge asset management model advances current agent-based asset management models.

## 9.2 New insights into bridge strengthening strategies

The new bridge asset management model provided new network level insights into bridge strengthening strategies not previously identified by the planning agency.

The bridge asset management model was used to develop the testing benchmark. The benchmark was derived by inputting the planning agency’s proposed bridge strengthening
strategy. The performance measures that were used to set the benchmark were cost and the vehicle kilometres travelled benefits. Travel time was not used, because of the limited data that was available. Once the planning agency benchmark had been identified, the bridge asset management model was then used to identify an alternative bridge management strategy with the same budget. The bridge asset management model was also used to identify a strategy with the highest benefit-cost ratio and the highest incremental benefit-cost ratio.

The proposed planning agency strategy comprised 37 bridges to be strengthened, at a total cost of 18.75 m NZD. The new bridge asset management model identified a strategy that was 250% more efficient than the strategy proposed by the planning agency, when the same budget was used. The planning agency strategy led to a benefit-cost ratio of 2.0, whereas the bridge asset management model identified a strategy with a benefit-cost ratio of 5.1. The improvement arose because the model could make more efficient use of the funding, by encouraging more hauliers to use the same routes. The strategy differed to the planning agency’s, which was to identify single origin-destination pairs and strengthen the obsolete bridges between these pairs. Thus, the bridge asset management model provided a new network level insight into an alternative bridge strengthening strategy.

The bridge asset management model was then used to identify the strategy with the highest benefit-cost ratio. To achieve this outcome the model was run for total strengthening budgets ranging between 1.0 m and 58.0 m NZD. The upper limit being the cost to upgrade all the bridges located on the routes used by the hauliers. Based on the model runs, the strategy with highest identified benefit-cost ratio had a cost of 1.17 m NZD and a benefit-cost ratio of 23.01. If the lower cost strategy was implemented the planning agency could have saved 17.58 m NZD, when compared to their reported budget of 18.75 m NZD. While the identified bridge strengthening strategy had the highest benefit-cost ratio, it also resulted in moderate national benefits. Accordingly, to identify a bridge strengthening strategy with increased national benefits an incremental benefit-cost analysis was carried out. The present value travel benefits that were derived were 135.87 m NZD, compared to the planning agency’s strategy which resulted in travel benefits of 32.0 m NZD. Thus, by using the bridge asset management model new insights were provided into higher cost bridge strengthening projects that would maximise the freight efficiency of the New Zealand state highway network. Accordingly, the objective of providing new modelling insights has been met.
Chapter 9 – Conclusions

9.3 Development of a new bridge performance measure framework

It was identified that performance measures should be linked to create a relationship between the cause of a system change and the effect on the system of a change. To create a causal relationship a systems-thinking methodology was used. A systems-thinking methodology was used, as no causal link between each performance measure was identified in past asset bridge management performance frameworks (Félio and Lounis, 2009; Frangopol and Duygu, 2011; Ghasemi and Hooks, 2010). The omission of such links, can potentially lead to performance paradoxes (Van Thiel and Leeuw, 2002), such as a strong focus on one measure. Furthermore, the interrelated and unforeseen effects on other measures, resulting from focusing on one measure, cannot be easily understood in an unlinked system. Accordingly, the performance measure framework developed herein was based on a combination of the pressure-state-response model and the systems-thinking framework developed by Boland and Fowler (2000). The framework, like Boland’s, comprises system measures, discrepancy measures and control measures (Refer Figure 7-4). The system measures are used to describe the asset and those that use the asset, the discrepancy measures, like the PSR model detail the difference between the current state of the asset and the service it provides and the desired state. Finally, the control measures are those used by the planning agent to decide which bridges to strengthen. Given the complexity of the bridge asset management model, the system measures were divided into asset, user and network measures to reflect the interaction that occurs between the hauliers and the bridge network. The network measures being an aggregation of individual haulier measures. These aggregated measures then formed the input into the decision-making process used by the planning agent. Further to the identified performance measure types, exogenous events that affect the asset system are also recorded. The state of the system and the behaviours of the users, that result from exogenous events, are identified by the bridge asset management model and appropriate performance targets are selected. Given the measures used in the bridge performance framework integrate strategic (the fitness function), user (haulier) and operational measures (asset measures), the measures provide a strong link between national outcomes and operational activities. Because of the framework, a set of performance measures that can be used to manage the freight efficiency target have been identified and these measures now link operational and strategic objectives (NZDIA, 2013). Furthermore, the performance measurement and management framework developed herein, when used in conjunction with the bridge asset management model, addresses the recommendation that stakeholders must
be integrated into asset management decision-making (Godau, 1999). Thus, the final objective of using the bridge management model to identify a set of performance measures and then using these measures to link operational and national level efficiency outcomes has been met.

9.4 Summary

In conclusion, the aim of developing the bridge asset management model was to further advance current asset management models and to provide a methodology for rationally managing a network of functionally obsolete bridges. A second aim was also to develop a bridge performance measurement and management framework that links the real and virtual worlds and thus facilitates the rehearsal of asset management strategies.

The new bridge asset management model further advances current agent-based asset management models, as the new model more accurately reflects the behaviours of key stakeholders and these stakeholders now interact with an interconnected network of assets. The bridge asset management model was considered to provide new strategic insights, as significantly improved network level bridge strengthening strategies were identified, when compared to those proposed by the planning agency. The lower cost strategy that was identified by the bridge asset management model provided an increased benefits-cost ratio, but was 17.58 m NZD less than the planning agency’s strategy. The higher cost strategies identified by the bridge asset management model provided incremental benefit-cost ratios more than the desired 3.0. The ability to achieve the identified incremental benefit-cost ratios was counter to the belief of the planning agent. When provided with the same budget that was being used by the planning agency, the bridge asset management model was also able to identify a strategy that was 250 % more effective than planning agency’s proposed strategy. Accordingly, the development of the bridge asset management did provide new insights into alternative network level strategies that could be used to manage functionally obsolete bridges.

Finally, the development of the bridge asset management model, in conjunction with the performance measurement and management framework, led to a methodology that could be used to rationally identify bridge performance measures. Thus, ensuring the paradoxes such as focusing on a single measure are mitigated. Such paradoxes are mitigated, because the
methodology ensures the casual relationship between all performance measures is created. Thus, one measure cannot be focused on without the other measures being affected.

As detailed, the systems-thinking approach that was used herein to develop the bridge asset management model and the performance measurement and management framework resulted in improved bridge strengthening strategies and a rational methodology for performance measure creation. Accordingly, the objectives of this research were met.
Appendices
Appendix A Identifying the modelling methodology

The new conceptual model of bridge management provides a useful visualisation of the sociotechnical asset management process, but to investigate the impact that decision-makers have on the long-term performance of the asset, a computer model is required. In this section, the methods that potentially could be used to model a sociotechnical system were investigated. The methods that were reviewed comprise mathematical modelling, systems-dynamics, discrete event simulation, and agent-based modelling. The primary criteria that were considered when searching for an appropriate modelling framework were:

- The modelling approach must be able to simulate stakeholders and the interaction between these stakeholders, thus providing insight into the effects of these interactions on asset management outcomes.
- The modelling approach must be able to simulate the geospatial and heterogeneous nature of the asset, thus providing a realistic representation of the real-world environment.
- The modelling approach must be able to simulate the interaction between stakeholders and the asset, thus reflecting the sociotechnical interactions that occur in asset management.

A mathematical model comprises a set of independent variables, a set of dependent variables and an explicit relationship between these variables (North and Macal, 2007; O'Sullivan and Perry, 2013) and can be classified as dynamic or static, discrete or continuous, deterministic or stochastic. An asset management system is a dynamic system that can be modelled deterministically or stochastically using a discrete time or continuous time representation. Stochastic mathematical models are often been used to simulate structural deterioration (Aboura et al., 2008) and have proved useful in optimally allocating funds (Frangopol and Liu, 2007; Golabi and Shepard, 1997). Nonetheless, these models tend to represent deterioration in an aggregated way, as they group all similar asset types into one model. The aggregation of assets may be appropriate for the context they were used in, but some
Appendix A – Identifying the modelling methodology

performance measures, such as resilience or improving freight efficiency require an understanding of how a bridge network functions as a system. To provide this insight mathematical models (Bocchini and Frangopol, 2011b; Lounis, 2005) are sometimes set within a computational framework. Implicit in the use of a computational framework is the requirement to represent the more complex asset management system. The present computational models (Bernhardt and McNeil, 2008; Moore et al., 2008; Osman, 2012; Osman and Hassan Ali, 2012; Osman and Nikbakht, 2014), include deterioration models of individual assets, users, and the government as a funding agency. The present models, nevertheless still omit the decision-maker and thus the impact of the decision-maker on the attainment of strategic outcomes (Hammer et al., 2012). Furthermore, the present models have a strong focus on condition and do not account for other performance measures, such as bridge strength. Consequently, further development of the present models was required. Improvements in the computational bridge models can be achieved either through the development of the existing models or by using a recognized modelling methodology that more readily includes social models. The computational methods that were investigated comprised systems-dynamics, discrete event simulation and agent-based modelling.

Systems-dynamics is an equation based computational method that is used to investigate how complex systems change over time (Forrester, 1991; North and Macal, 2007; Sterman, 2001). In systems-dynamics the changes in the modelled attributes are represented as a set of interrelated ordinary differential equations (Wilensky and Rand, 2015). By modelling the interaction between these equations, systems-dynamics models are able to simulate the feedback effects between the modelled components (Suryani et al., 2010). The ability to simulate the feedback that occurs between individual system components facilitates the investigation of the emergent effects that can potentially arise from strategy changes (Macal and North, 2010). Another benefit of using systems-dynamics is the ability to include stakeholder models in the general modelling framework (Kunc and Morecroft, 2007; North and Macal, 2007; Osman and Hassan Ali, 2012). The ability to model both the social and engineering systems has led to systems-dynamics being used as an asset management decision-support tool (Bianchi and Montemaggiore, 2008; de la Garza and Krueger, 2007; Mostafavi, 2013; Osman and Hassan Ali, 2012). Nevertheless, as these models focus on condition management the assets are modelled in aggregated way, which is reflected in the use of a single condition index. Potentially a network of heterogeneous bridges could be created within a systems-dynamics environment, as models have been created with
geospatial representations, but to date these models have only used cellular automata to
represent large tracts of land (Ahmad and Simonovic, 2004). Cellular automata by their very
nature are useful for modelling patches and areas of land or even simple relationships
(Conway, 1970), but they cannot be used in bridge asset management problems, because the
interconnections in the system cannot always be modelled by simple neighbour relationships.
Thus, systems-dynamics can be used to model a social system and is adequate for simulating
aggregated performance measures such as condition, but is currently inappropriate for
modelling the performance of individual but interconnected assets.

Discrete event simulation is a process that models the impact that successive events have on
each other and the whole system (Choi and Kang, 2013; North and Macal, 2007; Siebers et
al., 2010) and is considered to be discrete because time is represented as discrete blocks. In
an asset management context discrete event simulation has been used to simulate the effect
that different maintenance strategies have on the reliability of offshore windfarms (McMillan
and Ault, 2007). Thus, discrete event simulation provides the ability to simulate the
engineering system. Similarly, discrete event simulation models like systems-dynamics
models treat condition in an aggregated way. The requirement to model condition in an
aggregated way occurs because discrete event simulation models, like systems-dynamics
models, focus on process flow rather than the agents present in the system (North and Macal,
2007; Siebers et al., 2010). Thus, like systems-dynamics, discrete event simulation is
currently inappropriate for modelling the performance of individual but interconnected
assets.

As an alternative to discrete event simulation others have used agent-based modelling.
Agent-based modelling covers a number of research areas including complexity science,
artificial intelligence and game theory (Borshchev and Filippov, 2004), but is considered
here to comprise the modelling of individual agents and their behaviours. In agent-based
modelling each component, such as a road user, a bridge manger and even a bridge are treated
as an individual agent, with each agent being defined by a set of states and a set of rules
detailing how these agents behave. In the case of animate agents such as roads users or
decision-makers the agents also have a set of choices they can take to improve their situation.
Agent-based models include an environment that contains resources the agents can exploit,
control or consume when working towards the achievement of their goals (Hahn et al., 2009;
Zambonelli et al., 2003). In some models this environment may be spatially accurate
(Crooks et al., 2008).
Agent-based models can be used in many ways. In one implementation large numbers of relatively simple agents are created, which are then used to investigate emergent behaviour such as flocking, predator-prey interaction, foraging (Railsback and Grimm, 2012) or how groups interact with spaces (Macal and North, 2010). Other agent-based models use fewer agents, but these agents have more realistic cognitive behaviour (Sun and Naveh, 2004). Agent-based asset management models also generally take one of these two forms and include many hundreds of thousands of agents or smaller numbers of more intelligent agents. The larger scale agent-based asset management models are often used to investigate how networks of assets and stakeholders adapt as a result of societal influences (Nikolic and Dijkema, 2010) and the smaller scale models are used to investigate the impact that deteriorating assets have on stakeholder expectation (Bernhardt and McNeil, 2008; Moore et al., 2008; Osman, 2012). Smaller agent-based models have also been used to investigate the effect that different procurement strategies have on asset condition (Mostafavi et al., 2015). Thus, agent-based modelling has a history of being used in asset management simulations, can be easily scaled to incorporate an increasing number of heterogeneous assets or agents, and can incorporate a geospatial representation of a network (North and Macal, 2007). For these reasons agent-based modelling was considered superior for simulating the sociotechnical bridge asset management process.

In summary, four methods can potentially be used to create a computer model of the asset management process including mathematical models, agent-based modelling, discrete event simulation and spatial systems-dynamics. Nonetheless, and given the broad range of topics that agent-based modelling has been applied to and the parallel nature of these topics to the asset management process, agent-based modelling is superior for creating small-scale asset management models. Accordingly, agent-based modelling was the chosen computational modelling method.
Appendix B  Identifying the modelling software

To create a model in which agents can interact with a geospatial environment Brown et al. (2005) detailed three approaches comprising agent-based model centric, GIS centric and an hybrid approach that used both an agent-based model and a geospatial model that was linked by a middleware platform. The authors preferred the hybrid middleware methodology, as it utilised the characteristics of both agent and GIS platforms, but option one, agent-based models, was quickly discounted, as the agent-based platforms were considered at the time to be ill equipped to manage spatial data. Nevertheless, with the speed of development in agent-based modelling (Heath et al., 2009) agent-based systems are continually being developed with over 70 systems now being available (Wikipedia, 2014), many of which integrate agent-based modelling and geospatial elements into one single platform. Two examples of these platforms are Netlogo (Wilensky, 1999) and GAMA (Taillandier et al., 2012). In the case of Netlogo the geospatial ability is provided using an extension, and in the case of GAMA the platform was specifically created to solve the problem of creating geospatial agent-based models. Thus, agent-based platforms are no longer ill equipped for simulating the interactions that occur between agents and their environment and thus there is less of a requirement, at least in the early model development stages, for using a middleware platform or for creating agent behaviours using a GIS platform.

No single point of reference exists for guiding first time developers in choosing which of the 70-available agent-based modelling platforms could potentially be used to model a spatially explicit asset management problem. Accordingly, to choose which of the many potential platforms would be used, a subjective assessment process was developed. The ratings that were applied comprised a 1, 2 or 3 and were informed from reviews (Nikolai and Madey, 2009; Railsback et al., 2006; Zheng et al., 2013), books on agent-based modelling that specifically noted the platform (North and Macal, 2007) or reference texts that gave detailed insights into the platform (Railsback and Grimm, 2012; Wilensky and Rand, 2015). In the assessment, the rating categories were based on the prior level of programming knowledge (PK), the ability to create many agents (MC), the ability to develop complex agents (AC),
geospatial capabilities (GIS), documentation quality (DQ) and platform cost (CST). In the
case of learning and programming skill a 3 was considered to reflect a high degree of
difficulty, whereas model or agent complexity a 3 was more a reflection of how well the
platform could carry out the task of simulating a geospatial asset management problem.

The final list of software platforms that were reviewed were included because they could be
used to simulate a network of bridges, which resulted in platforms that used cellular
automata, such as TERRAME and Brahams, being discounted. Platforms created in Excel,
such as VisualBots, were also removed from the list because of the limitations created by
excel models (North and Macal, 2007). Framsticks was also discounted, as it was unclear
how a network of bridges and users interfacing with the bridges could be created. The
difficulty in conceptualising an asset management problem in Framsticks (see
FramSticks.com) arose because Framsticks focuses on how artificial life develops, rather
than providing a generalised platform for creating computational simulations, such as those
included in Table D-1. The last to be removed from the initial list was Behaviour Composer.
The platform was discounted because of the limited set of agent-behaviours that could be
modelled.

<table>
<thead>
<tr>
<th>ID</th>
<th>System</th>
<th>PK</th>
<th>MC</th>
<th>AC</th>
<th>DQ</th>
<th>CST</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Netlogo</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>Anylogic</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>GAMA</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>MASON</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>RePast</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>SWARM</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>9</td>
</tr>
</tbody>
</table>

The RePast, SWARM and MASON platforms all have a rating of 3 for PK due to their
reliance on Java as a programming language, which requires a higher level of learning than
the languages used in Netlogo and GAMA. Considering that SWARM, RePast, AnyLogic
and GAMA are all able to simulate large scale models all systems are considered appropriate
for modelling the complexity found in bridge asset management systems (MC). GAMA,
RePast, Anylogic and Mason can all be used to develop agents with complex behaviours and
so a rating of 1 is provided for AC, whereas Netlogo is known to be good for rapid
prototyping (North and Macal, 2007) or for the development of relatively simple animalistic
type agents (Railsback and Grimm, 2012). The documentation quality of many of the systems was frequently highlighted as being poor, but GAMA and Netlogo both had good documentation. In considering the cost this was not an issue for many of the software systems, as they are open source or free to download. Only Anylogic required a commercial license. For this reason, the Anylogic software scored the highest. The overall rating, which is a sum of the scores provided for each of the categories, indicates that several systems could feasibly be used to create the asset management simulation, but Netlogo was finally chosen because of the ease of learning the language and the quality of documentation. Furthermore, even though many believe Netlogo to be relatively simplistic platform (North and Macal, 2007), it still compared well when trialled against other platforms (Railsback et al., 2006).
Appendix C Structured interview survey pro-forma

The following is the example survey pro-forma that was used in the haulier structured interviews.

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
Faculty of Engineering

Project Title
A Network level approach to optimising the performance of New Zealand’s road bridges

Name of Researcher: Simon Bush
Degree: PhD
Department: Civil & Environmental Engineering
Research Supervisor: Dr Theuns Henning

Questionnaire aim
Increasing freight productivity is a government target, with increased road freight productivity being affected by the gross mass and axle weights of the vehicles that can travel on the highways and the load carrying capability of the bridges that are to be crossed. This study is focusing on the High Productivity Motor Vehicles (HPMV) as these are central to increasing freight productivity. To help us understand your role in the development of HPMV routes we wish to know the following:

- The factors and people influence your route choice process, factors such as restricted bridges
- The process you use to choose the best routes to take
- Who you work with outside of your organisation if you feel your route choices are becoming limited or you wish to open new routes that are currently not available
- Other factors you wish to discuss that have not been covered above
Appendix C – Structured interview survey pro-forma

Please state your title and describe your role.
e.g. Operational manager responsible for…

Part One – The people and other factors that influence your route choice
What influences your route choice? Please rate their level of influence (using a 1-5 scale) and describe how these factors influence your route choice.
e.g. seasonal markets or projects, weather, customers etc

Part two: Your route choice processes
At what point do the factors/stakeholders start to influence your route choices? Describe the tipping points when you to change what you are doing?
e.g. profitability

1 1 = no influence, 2 = slightly influential, 3 = moderately influential, 4 = very influential, 5 = extremely influential
Within your organisations what types of things do you do to manage the route choice problems created by stakeholders and other factors?

How do you decide which is the most effective action to take to improve the situation? Describe any tools, process, methods or rules-of-thumb you use and how they work.

How do you assess whether the course of action you used was successful and how does this affect your future decision-making processes? Describe the success factors and how your decision-making processes change.
Appendix C – Structured interview survey pro-forma

Part three: The people you work with or influence to maximise your efficiency
Assuming you cannot achieve your desired outcomes, who do you work with outside of your organisation to improve the outcomes for your organisation? Describe these actions in terms of who you contact, what you do and why you do it and when you make contact.
e.g. permitting officers

Assuming you are achieving your desired outcomes are there any actions you take to further improve the current situation? Describe these actions in terms of who you contact, what you do, why you do it and when you do it.

Part four: Open section
Is there anything else you wish to add that would help us understand how and why you choose the most efficient routes?
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References


References


References


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