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BETTER RESILIENCE EVALUATION: REFLECTIONS ON INVESTMENTS IN SEISMIC RESILIENCE FOR INFRASTRUCTURE

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ABSTRACT

In the context of infrastructure and natural hazard planning, a new agenda for applied research is emerging which, focused on resilience, integrates government, hazard science, engineering and economics. This paper sets out the context and key tenets guiding the direction of this topic of enquiry, including the New Zealand legislative and policy context under which infrastructure decisions are made, core principles implied by the resilience objective, current norms and challenges in the practice of infrastructure planning, and key criteria for decision-support tools. While decision-making processes strongly informed by cost-benefit analysis (CBA) continue to be common in the New Zealand policy process, this paper demonstrates that there are certain distinguishing features of infrastructure networks that make it challenging to effectively and validly apply standard CBA approaches, particularly when resilience values are at stake. To help address this challenge, a new conceptual framework is presented to assist in the critical review and selection of decision-making tools to support infrastructure planning. This framework provides a synthesis of the ways through which contextual uncertainties influence the relative advantages and appropriateness of different decision support tools. Ultimately, we seek to promote a diverse but also nuanced approach to analysis supporting infrastructure planning under seismic and other natural hazard risk.

INTRODUCTION

Infrastructures are among a set of core services and products widely recognised as essential to the functioning of modern economies and societies [1]. Investments in infrastructure ordinarily involve costly capital items that are accessed by many users, over long time periods, and contribute to interconnected networks [2]. Infrastructure providers are involved in public-good decisions regarding the level of redundancy and resilience required for infrastructure networks to cope with seismic and other natural hazards. Valuing the resilience (and other) benefits of alternative investment options tends to be difficult, due not only to complexity in the relationships between infrastructure functioning and societal wellbeing, but also uncertainty in the timing and realisation of any resilience benefits. The decision-making process is therefore challenging, requiring numerous trade-offs between objectives under budget constraints, and balancing of risk and uncertainty. Nevertheless, failing to fully account for resilience benefits could lead to long-term capital investments in sub-optimal configurations and heightened risk of cascading failure of infrastructure and other services.

Standard decision-making processes strongly informed by cost-benefit analysis (CBA) may be common in the New Zealand policy process, but they face theoretical and methodological challenges to incorporate resilience of complex networks within their approach. The ‘economics of resilience’ is an emerging field of research, involving collaboration between infrastructure providers, scientists and the engineering and economic disciplines. Building on literature developed to address the interdependencies and complexities of infrastructure across many industries and sectors [3], this paper explores the current and emerging analytical and decision support tools to assist infrastructure planning and investment decision making. We propose that there is a spectrum of tools available, and the selection of tools should be strongly guided by the nature of the problem, particularly the range and types of uncertainties present.

To bring into focus the context within which infrastructure planning for seismic hazards occurs, this paper begins by exploring the concepts of seismic risk reduction and resilience and examines the extent to which such concepts have been taken up in New Zealand through strategic documents, laws and regulations. Given that CBA is the preferred applied economic tool used in investment planning, especially at the central government level, this paper also reviews this approach and describes the particular challenges that arise in its application to infrastructure planning, especially in terms of its ability to incorporate resilience considerations. To complete the paper, we provide a conceptual framework for the consideration and selection of tools to support infrastructure planning. This framework provides a synthesis of the types and degrees of uncertainties that may exist, and in turn, the methods or tools that are most appropriate to apply. We promote a nuanced and context-appropriate approach to the provision of analysis to support infrastructure planning.

SEISMIC RISK AND RESILIENCE

Resilience is defined as the ability of a system, community or society exposed to hazards to resist, absorb, accommodate and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions [4]. Resilience is multiscale with capacity at an individual, organisational,

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community and societal level [5-7]. Although building resilience will typically involve components at all scales, most studies on resilience focus on just one scale: for example, businesses or sectors [8]. Few analyses measure resilience at a systems level [9], and none provide an approach or a methodology that allows an analysis at several levels simultaneously [6].

Resilience, especially infrastructure resilience, is also influenced by interdependencies between sectors [5]. Infrastructure does not operate in isolation, but rather, with co-dependencies and facilitation functions across other infrastructure services. An efficient urban transport network, for example, requires a functioning power network (for traffic lights, information boards, etc.), and conversely, the power network also relies on transport networks for its operation (for accessing power generation and distribution sites, transporting fuel, etc.). Furthermore, technological advancement and internet connectivity is transforming and strengthening the connections between infrastructure classes, posing a challenge for engineers and economists in planning for resilience [3].

In part, building resilience entails a shift in focus from managing disasters, through relief and rebuild, to managing risk with the aim of preventing losses through preparedness [10, 11]. A decision maker focused on preparedness policy requires *ex ante* evaluation tools to decide how best to plan and invest in infrastructure. Although common resilience-enhancing actions will include adding robustness and redundancy to infrastructure systems, the future benefits of these measures are typically challenging to quantify, since these will be realised only in times of adverse events, and the timing and extent of such events is uncertain.

The resilience perspective has also entailed an increasing shift in focus from simple protection of buildings, infrastructure and other assets, towards building adaptive capacity. This changes the concentration of evaluation away from static metrics, such as loss estimation and damage measurement, to dynamic metrics such as measuring the speed at which economic production activities resume [3, 12, 13]. A focus on adaptive capacity and adaptive management also implies an emphasis on flexibility, continual learning and adjustment, and a concern not only with capacity to respond to system change but also an ability to influence and shape the system itself [14].

CONTEXT: PLANNING RESILIENT INFRASTRUCTURE IN NEW ZEALAND

The resilience concept now dominates mainstream natural hazards planning discourse in New Zealand. There has also been a marked increase in the interest in, and extent of, this discourse over recent years, to a large extent spurred by recent experiences under the Canterbury (4 September 2010, 22 February 2011) and Kaikoura (14 November 2016) earthquake sequences.

At a strategic level, strong support for resilience has been recently affirmed by the release of the National Disaster Resilience Strategy. While the strategy is issued pursuant to the Civil Defence Emergency Management Act 2002 (CDEM Act) and thus has the specific aim of outlining the Crown's goals in relation to civil defence emergency management, it takes a holistic and systemic approach to resilience, with a focus much wider than emergency management. The strategy calls for integration of proactive risk management and resilience building within all parts of society, and by the full range of societal organisations and members. In terms of risk management, specific directions are given in the strategy towards identifying and understanding risk scenarios to inform decision-making and understanding the economic impacts of disasters and disruptions and investments in resilience. Importantly, New Zealand has also endorsed the Sendai Framework for Disaster Risk Reduction 2015-2030 with the aim of strengthening resilience, described in the framework as: "the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries". The framework similarly requires an all-of-society engagement and partnership for disaster risk reduction. The framework has among its priorities (1) improving understanding of disaster risk and (2) investing in disaster risk reduction for resilience.

When considering the role of resilience at a strategic level, it is also important to acknowledge the strong connections between resilience and 'wellbeing' [15], as the latter concept has taken on a particularly strong focus for policy and planning in the New Zealand context. For example, in the Treasury's Living Standards Framework (LSF); the high-level framework guiding analysis and measurement of intergenerational wellbeing for use in Treasury's policy advice processes, risk and resilience sit as critical elements of the framework, right alongside the domains of wellbeing (e.g. health, environment) and the capitals that combine and underpin wellbeing generation [16]. With specific regards to seismic and other natural hazard risks, it is also insightful that in the Treasury's organisational strategic document, natural disasters are indicated as among the most important risks to intergenerational wellbeing [17].

As we move from high-level strategies and policy documents through to laws and regulations, specific uses of the term 'resilience' become largely absent. Nevertheless, the ambit and language of key legislation is generally sufficient to support a resilience focus, alongside other key objectives. In addition to the CDEM Act mentioned above, the most important laws and regulations currently controlling infrastructure-related decisions and investments are the Local Government Act 2002 (LGA) and Resource Management Act 1991 (RMA). The LGA sets out the roles, powers of, and obligations of local government in New Zealand. Among the core functions of local government is its role in providing good quality infrastructure and public services for the current and future needs of the community (Section 10). A core service to be considered in performing this role is the avoidance or mitigation of natural hazards (Section 11A). The stated purpose of the RMA is to promote sustainable management, with this defined as the management of natural and physical resources in a way that enables people and communities to provide for their social, economic and cultural wellbeing and for their health and safety (Section 5). It includes within its provisions the powers and procedures through which local government can set policies and assessment frameworks to guide and control land use and development, including for the purposes of avoiding or mitigating natural hazards (Sections 30 and 31). The management of significant risks from natural hazards is also listed as a matter of national importance, which must be recognised and provided for by all persons exercising functions and powers under the Act (Section 6).

POLICY BACKDROP: COST-BENEFIT ANALYSIS IN NEW ZEALAND

In New Zealand, CBA has for long time been recognised as the key economic evaluation tool supporting the executive arms of government in undertaking their public duties, including when making decisions around infrastructure planning and investment. At the level of proposing new laws, central government agencies must perform a Regulatory Impact Analysis when considering a new national-level policy, and the Treasury encourages the use of CBA to support important public-sector decisions [18-20]. The costs and benefits of introducing the Earthquake-Prone Building Policy in 2012 were, for example, calculated as part of the Regulatory Impact Analysis of the policy [21]. For finance/investment decision-making, Treasury encourages the use of its Better Business Case framework, with the framework also mandated for use in all significant investment proposals from state sector agencies.[1] Importantly, CBA is indicated as an available method or tool for use when developing the 'economic case' component of Better Business Cases. As well as publishing a general guide to CBA, the Treasury publishes various online resources including a CBA spreadsheet model and current discount rates. Notably, the New Zealand Transport Agency (NZTA) also maintains a CBA-based evaluation manual that sets out an assessment framework for transport investment planning [22]. The latter is currently under review.

CBA appears to play a lesser role in decision making outside of central government. Although Section 32 of the RMA formally places an obligation on local authorities to include a consideration of benefits and costs of alternatives in their planning processes, this need not necessarily follow the structure of a formal CBA. In practice a mixture of qualitative, quantitative, monetised and non-monetised information is collated in assessments, and while CBA is sometimes employed in assessing proposals of higher scale and significance, other approaches including multi-criteria analysis are also used [23]. In practice a range of evaluation approaches are also employed by local governments when meeting their duty under Section 77 of the LGA, which requires councils to, in the course of decision making, consider all reasonably practicable options and assess options in terms of their advantages and disadvantages.

Over recent times, concerns have been expressed over the use of CBA. A recent survey of government agencies in New Zealand and Australia identified several shortcomings of public sector CBA evaluations [24]. With regards to strengthening buildings to resist earthquakes, Smith [25] cautioned against the use of CBA due to the inadequate representation of risk in a cost-benefit approach, and Grimes [2] identified several shortcomings of using a CBA for infrastructure project evaluation. In the context of flood management, Kind *et al.* [26] highlight some of the important problems and limitations arising out of common CBA practices, including the practice of valuing benefits as the reduction of expected annual damages, which by implication, ignores risk aversion. Similarly, in the recent report of the Government Inquiry into the Auckland fuel security disruption the inquiry members noted, referencing the report provided by Smith *et al*. [27], the difficulties in applying cost-benefit analysis to situations involving mitigation of disruption events, particularly the complexity in determining and appropriate 'social risk premium' [28]. This paper builds on these observations with the objective of encouraging deeper scrutiny of the way in which information and modelling is being applied, thereby promoting improved practice in the use of tools and processes to support decision making. The following section summarises some of the key challenges associated with applying the CBA approach in an infrastructure planning context.

COST-BENEFIT ANALYSIS FOR INFRASTRUCTURE RESILIENCE

CBA is a useful economic tool for methodically comparing alternative courses of action. Through the course of a CBA, options are evaluated by identifying and quantifying all of their relevant effects. Costs and benefits accruing in future periods are discounted and expressed in present value terms.[2] The ratio of all discounted benefits to discounted costs gives an option's benefit-cost-ratio (BCR), and, all else equal, an option with a higher BCR should be preferred to an option with a lower BCR. A CBA thereby provides a direct numerical comparison of options while making explicit the nature, size and timing of their expected costs and benefits [2].

A CBA differs from a business case or financial analysis in that it is not constrained to the consideration of costs and benefits accruing to the agency undertaking the project. The CBA framework can, in theory, incorporate all social costs and benefits whether they are private or external, tangible or intangible [2]. This ability to account for a wide spectrum of socially relevant factors has made CBA the dominant decision-making tool for public sector resource allocation, including infrastructure investment decisions [29].

Resource allocation for infrastructure resilience has however certain distinguishing features that make the CBA approach less adequate for guiding investment decisions with resilience considerations. The first difficulty stems from the low-probability high-impact nature of natural hazards, particularly seismic hazards, and the associated difficulties in valuing the benefits of improved resilience. In CBA studies, uncertain benefits (or costs) are often quantified simply as the 'expected monetary value', that is the calculated monetary benefit under each contingency, multiplied by the probability of that contingency occurring. Given that the major benefits of investing in resilience are the avoided losses should an event occur, this benefit metric can also be thought of as the reduction of expected annual losses. The major limitation of this approach is that it is risk neutral, as it equally values low-probability/high-consequence events and high-probability/low-consequence events. However, there is ample experimental evidence and survey findings [30-32] suggesting that many individuals are risk adverse, particularly toward low probability high impact events, to the extent that they are willing to pay to avoid losses significantly higher than expected monetary losses.

The difference between the expected monetary benefits and willingness-to-pay is often termed the 'risk premium'. The typical economic justification for the existence of risk premiums and risk aversion rests on the concept of declining marginal utility of income (or consumption or wealth). That is, if we accept that a person would value the loss of a dollar of income more greatly the poorer they become, it can be demonstrated that in many situations he or she is willing to invest in strategies that reduce risks to income levels, even when the 'expected monetary benefit' is less than the cost of the strategy (refer to [26] for a worked example). In these cases, we would say that while the expected monetary benefit is negative, the 'expected utility' is positive. Although in recent times expected utility theory has been critiqued on the basis that it cannot alone fully explain people's behaviour under risk [33], and that there are a variety of psychological factors also underpinning people's behaviour [31, 34, 35], the situation remains that risk aversion is an important feature of human preferences. Furthermore, CBA presupposes that it is

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[1] Cabinet Circular CO(15)5

[2] In CBA, future benefits and costs are discounted relative to present benefits and costs for two basic reasons: (1) there is strong evidence that people generally prefer to consumer now rather than later and (2) there is an opportunity cost of delaying a benefit for the future. For a general introduction to the mechanics and theory behind discounting readers are referred to Chapters 6 and 10 of [39].

the role of government when selecting among options to select that which best reflects society's preferences.

At least in the case of flood mitigation investment, it has been claimed valuing benefits as reduction in expected annual losses originates from the risk-based approach, in which risk is defined as consequence multiplied by probability [26]. This practice is however also prevalent within the economics discipline itself [36]. Over the last few decades much recourse has been given to the study of Arrow and Lind [37] which showed that when populations are sufficiently large and risk is spread amongst the population, risk premiums converge to zero, indicating that risk neutrality is appropriate. This reasoning does not, however, stack up when systems are not actually in place, and indeed may not even be possible for sharing all manner of risks, including provision of adequate schemes for compensation to persons when affected; which is often the case for large scale hazard events.

A further likely reason behind the frequent absence of consideration of risk preferences in CBA studies is simply the desire by analysts and evaluators to avoid theoretical and computational difficulties when attempting to quantify an appropriate 'societal risk premium' [36]. Not only is there no uniformly accepted utility function appropriate to represent risk preferences, the ability to measure/quantify risk aversion to seismic events is challenged by the complexity of such events. Generally, individuals will not have full information and will not be able to comprehend the complete range of outcomes of such events, and so will not have adequately turned their mind to determining how much they are willing to pay for mitigation or avoidance. Adding further to the complexity, risk preferences vary significantly among individuals and with respect to different types of risk [38] and so when choosing among policies impacting many individuals, there will be contention over the appropriate level of resources that should be committed towards risk avoidance.

The second major challenge in the application of CBA has to do with the general category of 'system complexity'. Infrastructure can be conceived as multiple components that interact in complex systems to deliver service functions ultimately important to communities. Interactions and feedbacks occur not only between components within each type of infrastructure, but also between infrastructure types and between infrastructure and wider socio-economic systems. Such complex systems interactions create a variety of methodological challenges for the application of CBA.

One challenge that has been highlighted by Grimes [2] is the existence of so-called network effects of infrastructure projects, these are important under normal conditions of operation but are also very important in the disaster context. For example, investing in backup generators for water pumping stations may create little additional benefit in a disaster context if other nodes in the water supply system are not robust, or if the roading network is not sufficiently robust to allow for the delivery of fuel to generators. Such network interactions imply that the benefits received from increasing resilience for one infrastructure project or policy are highly sensitive to the context in which that infrastructure will operate. Accurately incorporating such context in assessments is challenging, not only because of the complexity of these systems and uncertainty in how network cascades will happen, but also due to the presence of uncertainties in the way infrastructure networks will evolve over time, including other future investments/policies that may occur. Building on this latter point, we further note that since the benefits derived from a group of resilience-oriented projects considered together will often be higher than those generated by summing the benefits of individual projects considered separately, the results of a CBA are highly dependent on the way projects or policy options are framed.

Still on the topic of system complexity, the methods typically suggested for valuing benefits and costs in a CBA are essentially partial-equilibrium methods, best suited to focusing on direct or first-round impacts [19]. Partial equilibrium-methods consider impacts in a single market at a time, with all other sectors and their interactions held constant. Impacts on secondary markets, i.e. those not directly affected, are often ignored. Such an approach may be justified if price adjustments in secondary markets (or related primary markets) are negligible, or if the methods for measuring changes in primary markets account for equilibrium price/quantity changes in other markets [39]. However, multiple indirect or cascading consequences, including price changes, as well as disequilibrium in economic markets, tend to be characteristic of disruptions caused by seismic and other hazard events. To further complicate matters, measuring benefits and costs in primary markets themselves also tends to be highly difficult, given that there are no markets in which avoided infrastructure disruptions or improved infrastructure resilience are traded [40]. Although markets for some types of insurances such as business interruption insurance may have relevance, attempts to attribute the value of benefits of individual infrastructure investment or policies from the willingness to pay for insurances will likely be problematic. Additionally, given the complexity of the systems involved, there are also information failures associated with understanding the full consequences of events that restrict abilities to accurately estimate willingness to pay [41].

Other methods commonly used in practice to estimate benefits/costs from losses in services of the type provided by infrastructure systems also tend to be based on changes in consumer and producer surplus and rely on estimates of price elasticities in the calculations [39]. Nevertheless, due to problems of market failure, infrastructure services often do not have pricing systems from which it possible to generate such elasticities. Furthermore, where prices are available, given the relatively limited occurrence of significant infrastructure disrupting events, it is tempting to use elasticities generated from marginal changes under normal operating conditions. Particularly for significant events, this will fail to address the complexity of relationships between infrastructure functioning and societal wellbeing. For a service such as municipal water delivery, price responsiveness will reflect a heterogeneity of demands, some of which are of relatively little necessity or value to consumers such as water for gardening, while others will be essential such as drinking water [42]. As supply becomes more and more scarce, the more essential functions become threatened and obviously willingness to pay to avoid this situation increases. Thus, assuming constant price elasticity, and applying elasticities generated under different conditions may markedly misrepresent the values at stake. Equally important is recognition that socio-economic systems may operate quite differently under times of disruption or stress compared to normal operating conditions. People may, for example, be more willing to cooperate with one another and share resources and information, they may be more resourceful and adaptive [27]. This adaptive capacity in times of stress is another reason why it may inappropriate to infer values at stake based on system behaviours under normal conditions.

Overall, decision making on infrastructure resilience needs to deal with defining attributes of complex systems such as dynamic and non-linear interactions, feedback loops, interdependencies and complementarities. Tools to evaluate such investments must be dynamic, adaptive, and have the ability to reflect the potential for cascading failure due to interdependencies in critical infrastructure services and the prospect of disequilibrium conditions and adaptation during the recovery and rebuild period.

TOOLS AND TECHNIQUES TO SUPPORT INFRASTRUCTURE DECISION-MAKING

Infrastructure decision making takes many forms and occurs at a variety of scales, from major capital investments which have resilience enhancement as a clear and specific objective, new rules and policies implemented in district and regional plans, decisions by infrastructure providers on repairs and maintenance, through to individual organisation's financial analysis of how much to invest in insurance versus other options. Resilience considerations are also increasingly relevant in the development of central government 'programme business cases', which tend to involve managing complex change towards a strategic vision through many interrelated projects[3] (see, for example, [43]), as well as in portfolio option analyses where investments in different groups of infrastructure are compared.

Coordinating policies and investments in infrastructure requires tools that complement and extend traditional economic approaches. The selection of appropriate tools is also highly context-specific and will reflect particularly the nature and types of uncertainties that exist.

Figure 1 provides a framework for conceptualising the different types or degrees of uncertainty that may be encountered in planning problems. Beginning with the vertical axis pertaining to 'knowledge of outcomes': at the one extreme, and rarely occurring, end of the uncertainty spectrum are those situations where there is certainty in the outcomes that will occur under different options. At the other end of the spectrum are situations where there exists no knowledge of outcomes or indeed 'ignorance'. Moving closer towards the middle, 'risk' based situations, sometimes also termed 'statistical uncertainty' occur when there is reasonably unproblematic knowledge of the range of outcomes that will occur, and the possibility of each outcome can also be described by a probability distribution. When alternative outcomes can be identified but cannot be assigned a probability, the situation is often referred to as 'uncertainty', although note that as is the case in this paper, the term can also be used more generally to refer to the full range of different types of incomplete knowledge.

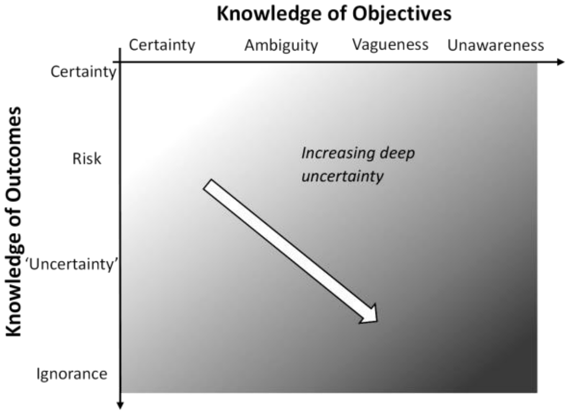

***Figure 1: Uncertainty matrix** – dark shading indicates deep uncertainty.*

While in many analyses supporting decision-making the consideration of uncertainty occurs only in the sense covered by the vertical axis, it is equally important to recognise that decisions must also be made with varying levels of 'knowledge of objectives'. The horizontal axis in Figure 1 therefore depicts another uncertainty spectrum where at one end there is complete certainty in what is sought to be achieved, while at the other end is pure unawareness of the objective sought. Even when significant work has been undertaken in defining stakeholder or community values and associated goals and objectives, a degree of uncertainty may exist around the 'ultimate' objective of policy or investment options because multiple objectives may be expressed (e.g. maximise economic growth, save lives) and options rank differently for objectives, and/or different stakeholders identify different objectives, so it is ambiguous which option performs better. Also possible is that identified objectives are expressed vaguely (e.g. enhance sustainability) so that it is difficult to determine under each option considered the extent to which progress towards objectives is achieved.

Although inspiration for the use of an uncertainty matrix to frame selection of decision-support tools comes from Stirling [44], the matrix in this paper differs from that of the previous author in that the two categories 'knowledge about possibilities' and 'knowledge of probabilities' are collapsed into the single axis 'knowledge of outcomes'. By including 'knowledge of objectives' as the second axis, the current framework accords well with the concept of 'deep uncertainty', which has become recently influential in planning and decision-making discourse [45].

Having defined the uncertainty framework, we can now turn to consideration of different types of decision-support techniques. The various techniques specified in Figure 2 and described in more detail in Table 1 are a mixture of qualitative and quantitative and range in type from formal decision-making frameworks, types of modelling approaches (e.g. probabilistic modelling) and approaches that can be used generally across different modelling techniques and decision frameworks (e.g. sensitivity analysis). We do not attempt to provide an exhaustive classification but rather illustrate the range and variation of techniques that may be appropriate, depending on the nature of uncertainties present. Given also that one of the key roles of decision-support techniques is to indeed reduce uncertainty, it is worthwhile distinguishing between uncertainty that exists at the commencement of the decision-making process, with that which occurs at the end. Our placement of decision-support techniques provided in Figure 2 is undertaken based on uncertainty existing at the *commencement* of the process.

It has been suggested that CBA is best suited only to situations of certainty or risk-based uncertainty [44]. Nevertheless, as has been explained above, even when outcome uncertainties are sufficiently understood such that they can be described statistically, CBA suffers methodological challenges in the incorporation of societal risk preferences. This can also be conceived as ambiguity in the ranking of options due to incomplete knowledge of society's objectives regarding risk, including how risk avoidance ranks or is weighted against other social objectives. Although sensitivity analysis is most often thought of as a quantitative modelling technique, whereby uncertain model parameters are varied to test impacts on modelled results (i.e., addressing 'uncertainty' as it is defined in the vertical axis), it can also be a useful technique to extend a cost-benefit approach to address, at least in part, ambiguities relating to risk preferences [46]. For example, in the context of flood risk management, Kind *et al*. [26] suggest that a pragmatic approach to the problem of risk aversion is to take the reduction in expected damages as a starting point, and use a multiplier to address the risk premium, with multipliers also potentially differentiated according to household

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[3] The purpose and procedure for preparing a Programme Business Case is described on The New Zealand Treasury's website www.treasury.govt.nz.

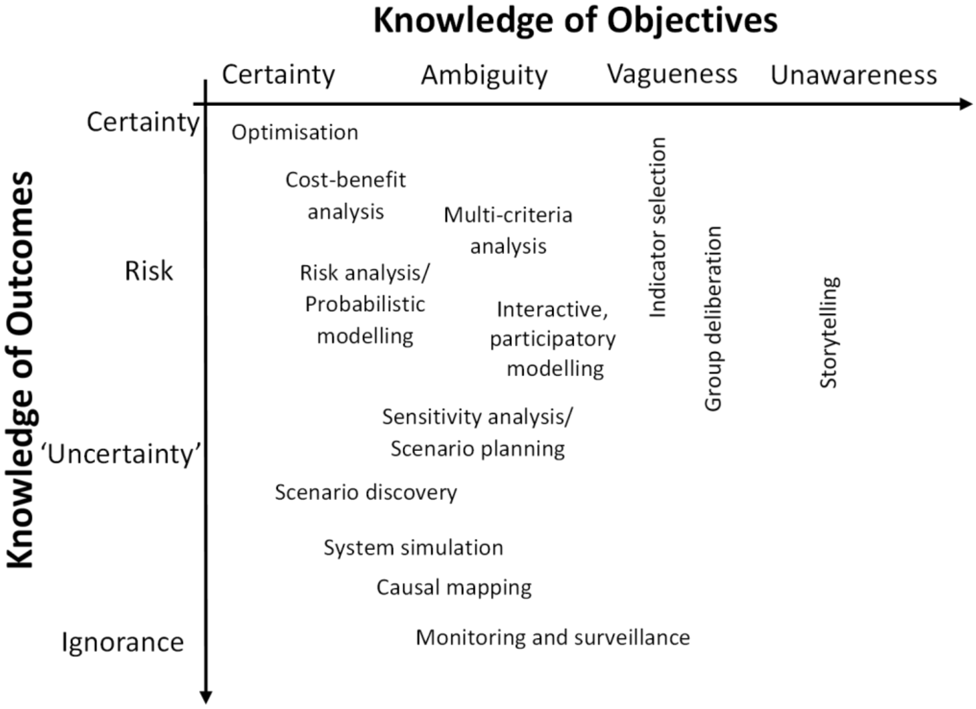

Figure 2: Uncertainty matrix and decision support tools and techniques.

incomes. A sensitivity analysis on such multipliers would also be highly informative to decision makers. We note that it is already common practice to test alternative discount rates in cost-benefit analysis, which similarly reflects the presence of objective-related uncertainty or contention, namely differing opinions on society's obligations towards future generations as well as appropriate risk aversion.[4] Applying a range of discount rates and risk premiums in an evaluation helps to communicate to decision makers the sensitivity of the results to different choices about the appropriate discount rate and/or social risk preference.

Multi-criteria analysis is typically put forward as the major alternative to techniques such as CBA which necessarily rely on monetary valuations. Under multi-criteria analysis, options are evaluated, using potentially a variety of qualitative and quantitative approaches, against a set of criteria which have been established to measure progress towards key objectives. Criteria scores can be combined to give an overall score or ranking of options. Although multi-criteria analysis is openly based around the judgement of the particular decision-making team, it brings a degree of structure and openness to classes of decision that lie beyond the practical reach of monetary valuation [46, 47]. It also lends towards implementation of policies and strategies, such as Treasury's LSF, that cannot easily be reduced or reconfigured to a single objective.

In any review of infrastructure planning it also becomes apparent the strong inter-disciplinary nature of the process. Although option evaluation tools such as CBA and multi-criteria analysis may originate within economics and public policy/decision analysis, much of the information required would be unknown without appropriate input from engineers and, in the case of seismic resilience, also hazard experts. RiskScape is a key New Zealand example of an engineering- and hazard science tool supporting decision making in the natural hazard context.[5] It is created using vulnerability curves (based on damage functions), applied to property and asset exposure. Although the majority of relationships in this tool are already defined in probabilistic terms (i.e. already reduced to risk-type uncertainty), it is also a tool for helping to communicate the types of outcomes that may occur *at scales relevant to infrastructure planners*. For example, the numbers of casualties or values of building damage across a whole city under alternative policy options. Furthermore, with new capabilities to undertake full probabilistic assessments from hazard-through-to impacts, it will also be able to contribute towards pushing such information more towards the 'risk' part of the spectrum.

Models from within the economics discipline itself are also used to help improve knowledge of outcomes. For example, Computable General Equilibrium (CGE) models are used to simulate economic systems consisting of multiple markets interacting, including through competition for resources and commodity supply-demand relationships (see, for example, [48]). Such models can therefore be used to help reduce uncertainties associated with second round or indirect economic effects, which as explained above, would otherwise be difficult to ascertain when utilising partial equilibrium type approaches. Specifically in the New Zealand context, MERIT (*M*odelling the *E*conomic *R*esilience of *I*nfrastructure *T*ool) is

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[4] In recent years, contention over the use of discount rates has arisen particularly in the context of environmental and sustainability research and decision making. Any benefit or cost that falls outside or around 30 years or one generation will have minimal impact on the results of an analysis applying common discount rates of, say, 6% per annum. It has therefore been claimed that discounting favours myopic policies or projects that exaggerate unsustainable resource use and fail to account for society's obligations towards future generations (cf. [95]). Other commentators have argued that people's time preference is a legitimate concern that needs to be taken into consideration by decision makers, and that policy issues arising out of considerations of intergenerational equity are best dealt with independently from the discount rate [96]. As many of the decisions made regarding infrastructure will have impacts that are long-term or multi-generational, for example shaping how a city grows and evolves, the debate around appropriate application of discount rates is also relevant to the infrastructure decision making.

[5] RiskScape is developed through a GNS and NIWA strategically funded programme. It draws on the expertise of some 30 specialist team members to provide a supported software system to government, research and private sector users. https://www.riskscape.org.nz/

Table 1: Description and examples of decision support techniques.

Decision Support Technique	Description	Background references	Examples from natural hazards/ resilience decision-making
Causal mapping	Eliciting and formalising knowledge of complex systems through creation of a visual diagram depicting how different variables in the system are interrelated.	[61]	[62]
Cost-benefit analysis	A method of systematically comparing alternative options. Involves itemisation of individual costs and benefits of each option, and quantification of costs and benefits using a common metric of net present value.	[39], [46]	[63], [64]
Group deliberation	A communication process in which groups engage in a rigorous analysis of issues and engage in a social process that emphasizes equality and respect.	[66]	[58], [67]
Indicator selection	The selection of phenomena to measure or monitor as a proxy for the state of a complex system.	[68]	[58], [69]
Interactive participatory modelling	Models co-designed and applied through dialogue between researchers and stakeholder participants.	[70], [71]	[72], [73]
Monitoring and surveillance	To observe and check progress over a period of time; keep under systematic review.		[74], [75]
Multi-criteria analysis	A method of systematically comparing options by reference to an explicit set of objectives that have been identified, and for which it has been established measurable criteria to assess the extent to which the objectives have been achieved.	[46], [47]	[76], [77]
Optimisation	Seeking the optimal (maximum or minimum) solution to an objective while ensuring system constraints are maintained.	[78], [79]	[80], [81]
Probabilistic modelling	A representation of a real-world system that incorporates some aspect of random variation, often by including probability distributions of at least one event or phenomenon within the system.	[82], [83]	[84], [85]
Risk analysis	The process of evaluating the risks that have been identified and developing data that quantifies the scale of risk.	[82]	[84], [86]
Scenario discovery	An analytical or qualitative procedure for identifying a small sub-set of scenarios that are useful from a policy perspective in that they collectively cover-off the characteristics of many possible scenarios and demonstrate the range of variation within possible scenarios.	[52], [87]	[88]
Scenario planning	A process of developing alternative scenarios or "different futures" as a way of identifying and highlighting key uncertainties, bringing attention to expectations of diverse stakeholders, testing policies and strategies, and an opportunity to 'rehearse the future' promoting leaning and adaptation.	[54], [89]	[90], [91]
Sensitivity analysis	A quantitative method to help understand how sensitive a model result is to changes in individual variables. Sensitivity analysis can be useful to prioritise topics for future research to reduce uncertainty, select inputs to vary when developing scenarios that will cover the widest range of outcomes, or to test the effect of changing assumptions around variables that cannot be scientifically quantified (e.g. values-based variables)	[46]	[92]
Storytelling	The elicitation of personal stories to form narrative accounts of meaning and value.	[93]	[94]
System simulation	Creating virtual models of complex systems to aid in the learning process about that system by: focusing thinking about complex matters, providing a platform for sharing and communicating of knowledge, allowing the consequences of assumptions to be explored and enabling emergent system behaviours to be identified.	[71]	[27]

bespoke decision-support tool designed to enable researchers and stakeholders to test the economic consequences of mitigations, adaptations and resilience-building responses.[6] As the core economic 'engine' within the system simulation model is designed around a CGE model, it also helps to provide improved knowledge on the indirect or flow-on impacts of disruptions within economic systems. However, unlike many CGE models, MERIT is formulated as a fully dynamic economic model, programmed with finite difference equations. This provides improved capabilities to simulate both short- and long-term consequences, transition pathways and out-of-equilibrium dynamics [49]. Furthermore, MERIT contains modules specifically designed to capture agent's (businesses, households, government) behavioural changes during and following disruption events [50]. In this way MERIT enables improved understanding of likely economic consequences, specifically the ways in which adaptation within the socio-economic setting influences ultimate outcomes. Combined RiskScape and MERIT applications also enable infrastructure providers to test out prioritisation and scheduling of infrastructure to create resilience faster.

Even with tools such as RiskScape and MERIT, the economics of resilience is an emerging topic of enquiry and, given the complexity of relationships between infrastructure planning and societal wellbeing, much uncertainties remain. Uncertainty quantification methods, such as monte carlo analysis, are typically used hand-in-hand with probabilistic models and enable quantification of the uncertainty (i.e. risk) in the outcome of a calculation/model, given the quantified uncertainty in each of the model inputs. As already identified, sensitivity analysis is also a useful technique for helping to reduce outcome-based uncertainty. By showing for a model such as MERIT how sensitive model results are to changes in individual variables or assumptions, it can be useful for prioritising topics for further research. A joint research programme between GNS Science, M.E Research and Resilient Organisations targeted at testing some of these techniques in the context of integrated RiskScape-MERIT modelling[7]. Ultimately, we cannot expect that all uncertainties can be eliminated or even quantified; in most cases decisions must be made with imperfect knowledge.

Stirling [44] provided the thought-provoking observation that expert advice is generally considered most useful to policy when it is presented as a single 'definitive' interpretation which places pressure on experts to simplify their advice. However, failing to fully acknowledge uncertainty, and focusing too narrowly on just risk-based uncertainties is an inadequate response to incomplete knowledge. He explains further that the more we support methods such as those placed towards the middle and outer parts of the Uncertainty Matrix, the more plural and conditional methods for science advice become. It seems Stirling's interpretations align well with the literature on decision making under 'deep uncertainty'. Per Halegatte *et al.* [51], deep uncertainty occurs under the presence of one or more of the following elements: (1) multiple possible future worlds without relative known probabilities, (2) multiple divergent world views, including values used to define criterial of success, and/or (3) decisions which adapt over time and cannot be considered independently.

Whereas traditional decision processes typically seek to first reduce uncertainty by agreeing on assumptions and future conditions, practices for decision-making under deep uncertainty defer on agreement until options have been analysed under many different assumptions/conditions [45, 52]. While it is recognised that such processes might still draw on traditional decision metrics such as net present value from CBA, alternative assessment criteria from maximising the net present value of expected utility may be tested, such as minimise the worst-case regret [53]. The need to test options under a wide range of futures and assumptions, in a context where parties to the decision will often differ in how they value outcomes, implies that decision-making will often be most successful when built upon participatory processes and close interactions between experts and decision makers [45].

Thinking about multiple possible futures often entails the development of scenarios [54]. Scenario planning has been described as the process of creating a coherent and credible set of stories of the future as a mechanism for testing plans or projects or increasing coherence [55]. As well as a means of dealing with 'uncertainty' in the outcomes sense, scenarios are also recognised as assisting with values or objective-based uncertainty in that they are tangible and provide a common lens or focus for debate, for example fostering debate on the appropriate level of societal investment in mitigation steps [27].

Given that scenario futures cannot be characterised by probability distributions entails also that the performance metrics or decision-making frameworks applied will embody the concept of *robustness,* i.e. seeking options that perform well under a range of future conditions or assumptions [56, 57]. In some literature on decision making under deep uncertainty, a distinction is made between situations where there is only a limited set of plausible futures or scenarios and situations where there are many. Robust Decision Making (RDM) is an example of an exploratory modelling approach that involves stress testing strategies over myriad plausible assumptions and future conditions. Typically, it includes a scenario discovery process whereby a smaller workable set of policy-relevant scenarios are identified that collectively cover-off the characteristics of many possible scenarios and demonstrate the range of variation within possible scenarios [52].

As already explained, this discussion on available tools and techniques is not exhaustive. Nevertheless, one method that we have chosen to highlight as potentially useful in the context of 'deeper' objective-based uncertainty is indicator development. While indicators are ultimately utilised as a means of benchmarking and/or tracking progress towards objectives, the very process of creating indicators can also operationalise what may be initially vague concepts. That is, by providing at least loose boundaries around what is and is not being measured, outcomes sought to be achieved become more tangible and can be debated by stakeholders [58]. Also, on the topic of addressing values or objective based uncertainty, group-based deliberation on information presented in workshops has been shown to help establish shared or group-based preferences through a transformative process of deliberation, learning and 'moralisation' [59]. The process of storytelling has also been suggested as a technique that can assist in bringing new insights into people's values and preferences [59] that may ultimately help to manifest societal objectives.

Although not strictly a form of decision-making technique, nor a technique targeted towards reducing uncertainty, a final point to note is the important role of building adaptive capacity, essentially the skills and aptitudes that enable

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[6] MERIT was initially developed under the Ministry of Business Innovation and Employment (MBIE) funded Economics of Resilient Infrastructure (ERI) programme (2012-2016) by ME Research, GNS Science and Resilient Organisations. https://www.merit.org.nz/merit/

[7] Towards robust decision-making in natural hazard risk management: Uncertainty quantification for RiskScape-MERIT modelling. https://www.naturalhazards.org.nz/NHRP/Funding/Contest-2017/More-information/2017-Final-Reports

effective decision making and change, in achieving resilience. As uncertainty is likely to remain a prevalent feature of society, and not all risks can be foreseen and planned, resilience is also about building the qualities and characteristics that foster adaptive capabilities – i.e. good leadership and culture that fosters innovation and creativity and information flow, strong networks and relationships and a change-ready ethos [60].

CONCLUSION

Infrastructure planning is characteristically complicated and challenging, due in a large part to the complex 'system of systems' within which infrastructure components and networks operate, and furthermore the complex arrangements through which infrastructure functioning contributes towards, and indeed helps shape, socio-economic systems. In countries such as New Zealand, where there exists relatively significant seismic and other natural hazard risk, the planning situation becomes even more complicated by the need to value and balance the resilience benefits of alternative infrastructure options alongside other societal objectives. In the future the task placed on decision makers is not likely to become any easier, as there are indications that infrastructure interdependencies and interconnectivities will only further increase.

As well as through New Zealand's commitment to the Sendai Framework for Disaster Risk Reduction, that resilience is an important strategic objective in the New Zealand context has been affirmed recently by the release of the National Disaster Resilience Strategy. Both documents call for a systemic and all-of-society approach to resilience. Resilience is also important at a strategic level given its close connectively to wellbeing, a concept that has taken on an even stronger focus in policy and planning. While the term 'resilience' does not feature specifically in legislation, the ambit and language of key Acts generally supports a resilience focus.

Moving from strategies to decision making in practice, the way in which resilience is achieved and balanced alongside other societal objectives becomes more open to question. Scientists, engineers, economists and other technical experts supporting infrastructure planners will often find themselves in the position of being expected to provide information that supports single and definitive conclusions. However, in many contexts this will be an unfair and misguided expectation. Certainly, there are a range of tools and techniques that can be employed by experts to evaluate and communicate the consequences of alternative infrastructure planning options including resilience implications, and such tools continue to be developed and improved. Nevertheless, given the complexity of the systems involved and the long time-horizons over which infrastructure planning influences, decisions will often need to be made in situations where important uncertainties remain present. For example, in the case of infrastructure planning it has been shown that values-based uncertainties around the appropriate level of investment in resilience or the 'social risk premium' tend to be particularly important. If such uncertainties are fully acknowledged and recognised, alternative viewpoints or dissenting interpretations will be apparent, thereby promoting more robust and democratically accountable decision processes.

We have presented an uncertainty matrix as a means to frame the selection of decision-support tools. The aim has not been to dismiss CBA as a valid tool to support infrastructure planning, but rather to succinctly describe the key challenges of the approach in addressing some types of uncertainties and highlight the range of alternative tools and techniques that may be useful. In some infrastructure planning contexts CBA may logically remain the preferred choice of tool, provided effort is always directed towards ensuring best practice in its use. In some cases, this may entail using supporting tools to investigate cascading or indirect effects of disruptions, where these are likely to be important aspects of the problem under consideration. Depending on the situation, other best practice techniques might involve inclusion of sensitivity analysis around key assumptions and/or investigating outcomes under a set of carefully constructed future scenarios that help illustrate the range of values and outcomes at stake. Yet in other situations, the nature of uncertainties will be such that it is better to start with entirely different qualitative or quantitative tools with the aim of best supporting decision makers.

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