CLIMATE CHANGE ADAPTATION AND INVESTMENT DECISION MAKING

REPORT TO

Waka Kotahi NZ Transport Agency

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Contact person

Dr Eilya Torshizian
eilya@principaleconomics.com

Authors

This report was prepared by Dr Eilya Torshizian, Eugene Isack, and Alina Fehling of Principal Economics.

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Address: Level 17, 55 Shortland Street, Auckland 1010, New Zealand.

Executive summary

Waka Kotahi commissioned Principal Economics to investigate how an adaptive decision-making (ADM) approach to climate change can be used for evaluating economic land transport activities in New Zealand. In this report, we identify the available methods for ADM in climate change and their pros and cons. We then provide suggestions for considerations of climate change adaptation within Waka Kotahi's Investment Decision Making Framework (IDMF).

Climate change is a source of deep uncertainty

Based on scientific studies and recent climate events in New Zealand, climate is beginning to exacerbate extreme "one-in-100-year" events. Higher temperatures mean more evaporation and moisture in the atmosphere and stronger storms, droughts and heat waves. Our knowledge of the likelihood of these large-impact events happening in shorter intervals is limited. Hence, climate change is commonly mentioned as a source of deep uncertainty, which occurs when decision makers and stakeholders do not know or cannot agree on how likely different future scenarios are.

For Waka Kotahi, the increasingly frequent weather events present a connected set of issues with potentially serious, costly impacts on infrastructure. Climate resilience means recognising that extremes are not necessarily extraordinary, and effective project evaluation methodologies are needed to support the ability to efficiently select between project alternatives, allowing Waka Kotahi to prepare, respond and recover quickly.

Adaptive Decision Making allows for flexibility in the process of decision making, which is essential in presence of deep uncertainty

The focus of an adaptive investment decision is to allow for flexibility by considering all possible outcomes when selecting options for further investigation. Under scenarios of deep uncertainty, adaptive decision making relies on plans that are designed to be adaptive over time in response to how the future unfolds as deep uncertainties are resolved. A wide range of futures are explored, with a plan of action to respond to signals for adaptation in the basic plan to meet objectives. The basic plan should be one that protects the plan against contingencies and vulnerabilities that may arise from deep uncertainty.

We recommend a range of Adaptive Decision-Making methods to complement the current IDMF framework

We used findings from our extensive literature review to identify a list of the available methods for ADM and their pros & cons. In consultation with the project's Steering Group, we identified a range of criteria for evaluating the importance of the pros & cons of each method. The preferred DMDU methods are as follows:

- Robust Decision Making (RDM): this is a process whereby deliberation is undertaken alongside analysis to iteratively generate and evaluate plausible scenarios to form robust strategies that protect against a range of plausible futures.
- Dynamic Adaptive Planning (DAP): this method focuses on implementing an initial prior plan before the resolution of all major uncertainties.
- Dynamic Adaptive Policy Pathway (DAPP): which focuses on the timing of actions and provides an overview of alternative future paths based on adaptation tipping points.

Accordingly, we suggest that the combination of DAPP/DAP/RDM with scenario testing currently recommended within Waka Kotahi's Monetised Benefits and Costs Manual (MBCM).

The recommendation will work for a wide range of projects and is consistent with national coastal guidance. It is broadly consistent with the MBCM and business case principles, requiring only minor changes to improve guidance. Further testing will help improve practice and capability.

The recommended method has implications for different steps in the IDMF

The findings of our report have important implications for the Programme Business Case (PBC) and Single Stage Business Case (SSBC) development. The investigation of climate change scenarios (scenario planning) and potential pathways, need to be considered within the strategic case, in the development of the business case. Hence, we recommend the following considerations within PBC and SSBC:

- Adaptation needs to be added to the benefits framework for the investment objectives considered
- The plausible scenarios and their different pathways need to be further investigated within the generation of alternative and options step
- Any uncertainties and assumptions need to be identified in the process of developing scenarios and the reasoning for considering any identified pathway needs to be clarified.
- For the development of scenarios and pathways, long-term investments need to consider a 100-year timeframe.
- For the assessment of identified scenarios (and pathways), we recommend using Scenario Analysis (and Real Option Analysis (ROA) where appropriate).
- We suggest the current sifting approach for shortlisting the options (Waka Kotahi 2021) provides a useful approach for shortlisting the identified scenarios (and their pathway).

Other recommendations and future research

Scenario-based decision-making, strategy development and re-evaluation offer a pragmatic approach to arriving at suitable assessments for infrastructure investments under deep uncertainty. However, while the merit and investment dynamics of individual projects can be determined in that way, how to arrive at valid comparisons of competing projects is less clear. A future study needs to provide further guidelines on capturing the impacts of uncertainty at the programme level.

The matter of intergenerational equity is becoming of increasing interest due to the potential damage from climate change effects. Intergenerational inequities are likely to occur when effects are long-lasting. Our recommended approach is already consistent with the MBCM and accounts for long-lasting effects by applying a longer period of benefit assessment and a lower discount rate within a scenario. Further guidelines will be required on the appropriate discount rates for evaluation of long-lasting impacts.

For prioritisation of investments, it is important to compare apples with apples. We suggest considering an extra portfolio at the GPS level for 'long-term investments'. This needs to be investigated further in a future study.

To provide a useful guideline for future analysis, it is critical to apply the methodologies identified in this report to a few case studies, with different features. The features of the identified projects with varying (low and high) lifespans and different exposure to uncertainty (or risk factors).

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1 Introduction

1.1 Purpose

Waka Kotahi NZ Transport Agency engaged Principal Economics to investigate how an adaptive decision-making (ADM) approach to climate change can be incorporated into the Waka Kotahi Monetised benefit and cost manual (MBCM) for evaluating economic land transport activities in New Zealand.

The research report aims to contribute to Waka Kotahi by:

1. Identifying the available methods for ADM in climate change and their pros and cons
2. Updating the consideration of risk and uncertainty for low-frequency/high-impact events
3. Recommending an approach, including a methodology, that can be considered for incorporation into Waka Kotahi's processes and procedures; that is, Investment Decision Making Framework (IDMF) and MBCM.

The report describes a framework and methodology that aims to provide a robust framework for the assessment of high-impact, low-frequency events in the decision-making process.

1.2 Project background

Waka Kotahi's MBCM provides the technical guidance and procedures for undertaking risk assessment of transport investments in accordance with the Waka Kotahi Investment Decision Making Framework (IDMF). The MBCM acknowledges the importance of considering uncertainty in different parts of a cost benefit analysis (CBA), including the assessment of demand, the sensitivity analysis and in relation to the assumptions used in the CBA.

To treat associated risks, the MBCM recommends further investigation to reduce one or more of the identified uncertainties (either physical investigations or more detailed assessment of risks) and to defer further processing of the activity until information comes available that helps reduce the uncertainties (Waka Kotahi NZ Transport Agency, 2021, p. 238). However, Waka Kotahi's MBCM does not provide a clear solution for capturing uncertainties.

1.3 Policy context

In practical terms, a CBA for a transport project sits within tiers of public policies. These tiers in New Zealand are described in this section.

1.3.1 Climate Change Response Amendment Act 2019

The Climate Change Response Act 2019 (commonly referred to as the Zero Carbon Bill/Act) sets up a framework to develop and implement clear and stable climate change policies that:

- Contribute to the global effort under the Paris Agreement to limit the global average temperature increase to 1.5°C above pre-industrial levels.
- Allow New Zealand to prepare for, and adapt to, the effects of climate change.

The National Adaptation Plan (NAP) due in August 2022 will include the government's objectives and strategies/policies/proposals for adapting to the effects of climate change. Waka Kotahi is currently working with wider government to support the development of the NAP.

1.3.2 Government Policy Statement and National Adaptation Plan

The link between the Living Standards Framework (LSF), key policies of the government of the day and land transportation is the Government Policy Statement (GPS) of land transport, presented as a three-yearly report. GPS 2021/22-2030/31 introduces improving people's wellbeing and the liveability of places as its purpose (New Zealand Government, 2020). The transport outcomes framework illustrated in Figure 1.1 shows the five key outcomes highlighted by the GPS to achieve a transport system that improves wellbeing and liveability. One aspect that has been focused on is the resilience of the transport system.

The climate change strategic priority of GPS 2021/22 is to develop a low-carbon transport system that supports emissions reductions, while improving safety and inclusive access. The primary outcome of this strategic priority is investment decisions that will support the rapid transition to a low-carbon transport system and contribute to a resilient transport sector that reduces harmful emissions, giving effect to the emissions reduction target that the Climate Change Commission recommended to Cabinet until emissions budgets are released in 2021.

The outcomes for the Climate Change strategic priority in GPS 2021 reflect the Government's move towards setting emissions budgets to ensure that New Zealand achieves its emissions reduction goals. The independent Climate Change Commission (the CCC) is developing emissions budgets, which will set a cap for emissions in five-year periods (2022–2025, 2026–2030 and 2031–2035). The CCC will provide advice on the direction of policy required for an emissions reduction plan for the first budget. All investment decisions will need to be consistent with the transport component of that plan, which will be informed by the Transport Emissions Action Plan.

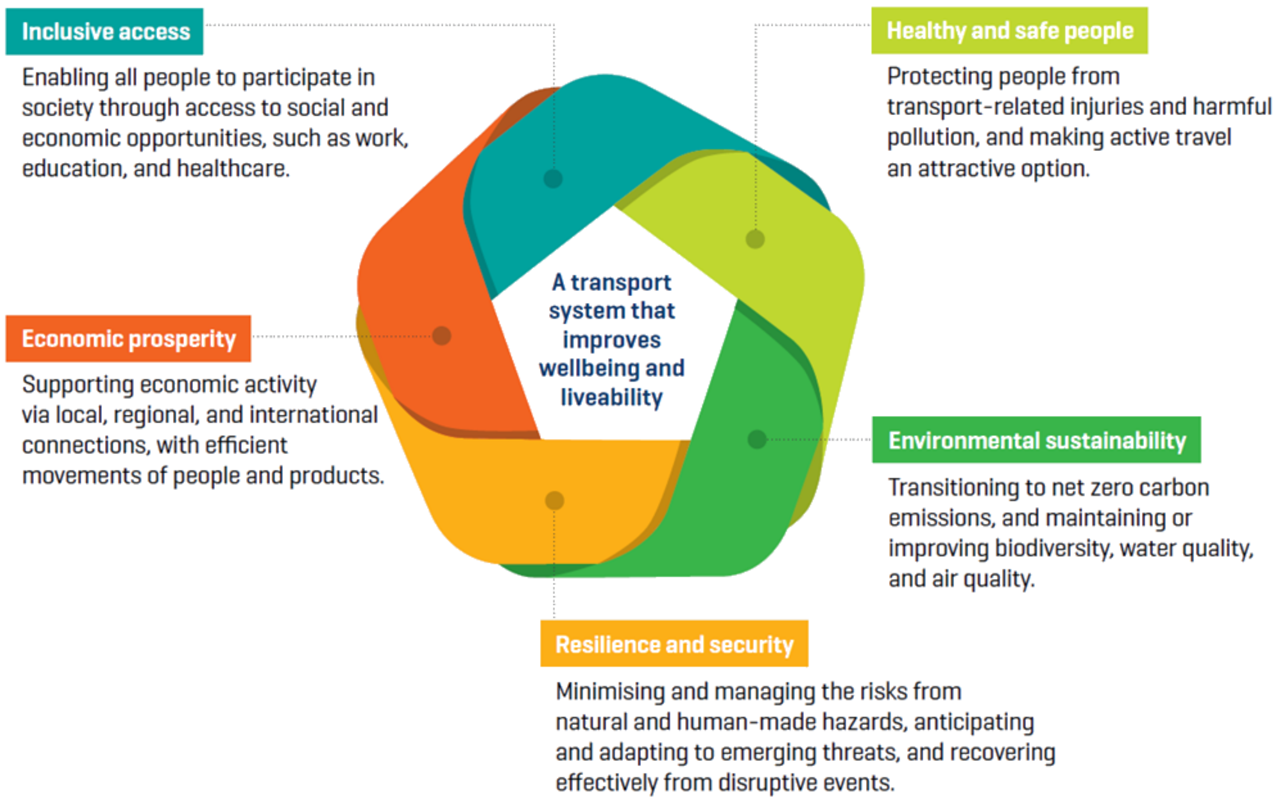
The National Climate Change Risk Assessment provides a national picture of the risks that New Zealand faces from climate change, including the risks to land transport infrastructure. It identifies the most significant risks that require urgent action. The Government will use the assessment to prioritise action to reduce the risks, including through the National Adaptation Plan, which will outline what will be required to respond to the risks (expected to be published by August 2022). This may influence investment choices made through the Fund.

The New Zealand Government's (2018) Government Policy Statement on Land Transport notes that:

> *"When access to the transport system is disrupted, it has flow-on effects both on direct users of the network and those who receive goods and services via the transport system. Often, taking a whole-of-system approach will create the best outcome [...] This involves considering all parts of the transport system and non-transport systems relevant to resilience [...] Climate change and low frequency-high impact events (such as earthquakes) are the key long-term issues that have significant implications for the resilience of the land transport system."*

The GPS is prepared by the Ministry of Transport on behalf of the Minister of Transport. The Ministry of Transport also monitors Waka Kotahi. In the 2021 statement, to deliver the strategic outcomes under climate change, the New Zealand Government (2021) commits to undertake relevant actions identified in the National Adaptation Plan (NAP) (Ministry for the Environment, 2022), which requires Waka Kotahi to "consider multiple risks to the land transport system from climate-related hazards – including sea-level rise, flooding and landslides. Waka Kotahi will lead, collaborate on and support land transport system adaptation, enabling climate-resilient transport networks and journeys, where people live, work and play". The NAP also requires Waka Kotahi to incorporate adaptation when it applies an intervention hierarchy to existing and new investments in the land transport system (Ministry for the Environment, 2022, pp. 67–68).

Figure 1.1 Transport outcomes framework



Source: New Zealand Government (2020)

1.3.3 Living Standards Framework and Better Business Cases

The Treasury provides a pan-government policy approach given its role as overseer of government funding allocation. Policy priority can vary as elected Members of Parliament change but a key focus across recent election cycles has been to raise the living standards of New Zealanders, applied through a Living Standards Framework (LSF)[1], and to undertake investment decisions in an objective manner, applied through the Better Business Cases (BBC) approach.[2]

Transportation infrastructure is one of the components of wealth, while transportation management is one of the institutional and governance arrangements that intermediate wealth and wellbeing within the LSF. The Framework is not considered all-encompassing,[3] but rather as a core tool for developing robust and evidence-based public policy.

1 https://www.treasury.govt.nz/information-and-services/nz-economy/higher-living-standards

2 https://www.treasury.govt.nz/information-and-services/state-sector-leadership/investment-management/better-business-cases-bbc

3 For example, The Treasury also uses a waiora framework to consider a Māori perspective on wellbeing.

Pertinent to this study, the LSF recognises 12 domains as being core to the wellbeing of individuals and collectives of people; these include being healthy, being safe and having access to quality natural and built environment. Attainment within these domains is measured with a range of indicators, including some that aim to identify deprivation. The only indicator directly related to transport is a recently proposed measure of public transport accessibility: "proportion of people aged 15+ finding it difficult or very difficult to use public transport (age standardised)".

The LSF also includes four prompts as guides to assessment of policy impacts: how policy will affect distribution, resilience, productivity – often measured by a CBA – and sustainability. The Treasury also provides a databank of policy effect estimates to be used within a CBA analysis, which are referred to as CBAx.[4] The CBAx guidance includes an appendix relevant for environmental impacts.[5]

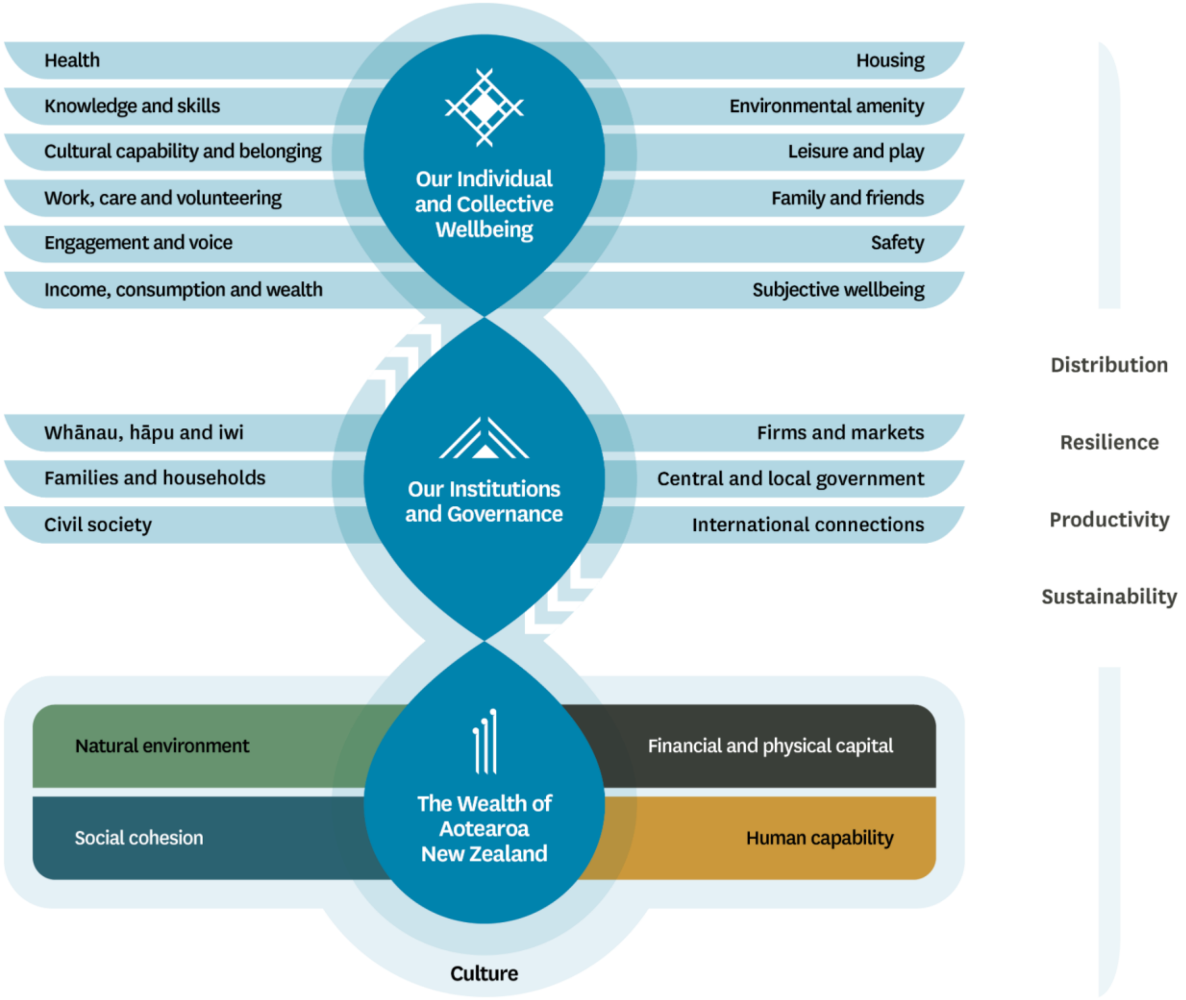
The New Zealand Treasury's (2021b) Living Standards Framework (LSF) intends to capture the issues that matter to New Zealanders' wellbeing, both now and in the future. As shown in Figure 1.2, the LSF includes three levels of outcomes: aspects of life for individuals, the role of institutions in facilitating the wellbeing of individuals, and the wealth of the nation. Across these three levels, the LSF introduced four analytical prompts that are the key lenses for analysing wellbeing:

- Distribution: "How is our aggregate wealth and wellbeing distributed across time, place and groups of people?"
- Resilience: "Do individuals, collectives, institutions, organisations and the environment have an ability to adapt to or absorb stresses and shocks?"
- Productivity: "How effectively is our wealth used to generate wellbeing and things of economic value?"
- Sustainability: "How well are we safeguarding our national wealth for the benefit of future generations?"

4 https://www.treasury.govt.nz/information-and-services/state-sector-leadership/investment-management/plan-investment-choices/cost-benefit-analysis-including-public-sector-discount-rates/treasurys-cbax-tool

5 The Appendix 5 of the CBAx guidelines provides details on the value of emissions and shadow emissions (The Treasury, 2021a, pp. 76–83). Further discussions of deep uncertainty are beyond the scope of the CBAx tool.

Figure 1.2 The New Zealand Treasury's Living Standards Framework



Source: The Treasury (2021b)

1.3.4 Waka Kotahi

Waka Kotahi NZ Transport Agency regulates the land transport system, manages the collection of hypothecated land transport charges, invests and distributes these funds – and other funds provided by central government from time to time – and manages the state highway network. The GPS sets the strategic direction for investment by Waka Kotahi, including quantifying the investment to be undertaken in 11 activity classes, including state highway improvements, and coastal shipping. Waka Kotahi employs an Investment Decision Making Framework (IDMF) to determine the projects and programmes that will be undertaken within each activity class. A CBA sits within this process and is required within the economic business case.

To provide useful decision support information, transport appraisals need to account for the outcomes sought by policies, which constantly evolve over time. Albuquerque (2013) discussed that Waka Kotahi's transport appraisal frameworks account for the shortcomings of the standard CBA by including strategic fit and effectiveness criteria in the selection process. Strategic fit scores the consistency of policies with government policy statement priorities and effectiveness to ensure that whole-of-system options have been considered.

1.3.5 National Policy Statement on Urban Development

Another influential arm of government at present, plus a potential beneficiary of findings from this research project, the National Policy Statement on Urban Development (NPS-UD) (MfE & HUD, 2020) tasks local councils with ensuring a well-functioning urban environment that "enables all people and communities to provide for their social, economic, and cultural wellbeing, and for their health and safety, now and into the future". To achieve this, Policy 1 of the NPS-UD 2020 clarifies a range of issues that need to be considered when evaluating the impact of planning decisions on the well-functioning urban environments. This includes, as a minimum, supporting reductions in greenhouse gas emissions, and resilience to the likely current and future effects of climate change (MfE & HUD, 2020; pp. 9–10).

Given the overlapping impacts on transport, housing and taxing policies, a comprehensive policy framework needs to account for all these impacts (Principal Economics, 2022).

2 Literature review

The purpose of this section is to provide a brief review of the relevant literature. A more extensive review is available from a range of recent studies in New Zealand, including Byett et al. (2017) and Ministry of Transport (2014). The focus of the literature review is to find a practical solution for incorporating uncertainty into the transport investment decision making process. We aim to avoid lengthy conceptual discussions in our review. The fit of the methods for the Waka Kotahi's MBCM will be investigated further in the next section.

2.1.1 Uncertainty and transport system resilience

Waka Kotahi's CBA guidelines define resilience as "the ability of systems (including infrastructure, government, business and communities) to proactively resist, absorb, recover from, or adapt to, disruption within a timeframe which is tolerable from a social, economic, cultural and environmental perspective." Accounting for the impact of resilience in transport CBA appraisals is particularly important, with further focus of public policy on climate change mitigation and adaptation.

While uncertainty is a feature of all appraisals, it is particularly prominent with respect to environmental disruption, both in terms of the likelihood of a disruption and how users respond. This uncertainty needs to be acknowledged and considered in investment appraisals. Waka Kotahi's report on the measurement of costs and benefits of resilience (McWha & Tooth, 2020) provides a discussion about the definition of resilience, and the methods and measures useful for capturing the impacts of resilience in transport CBA appraisals.

Waka Kotahi's MBCM recommends that:

> *"Where system vulnerability and redundancy benefits are expected to comprise a significant proportion of benefits, due to the renewal or replacement of vulnerable infrastructure, expected costs and benefits may be calculated using risk analysis and the infrastructure's probability of failure."* (Waka Kotahi NZ Transport Agency, 2021, p. 144)

A study of transport resilience in New Zealand by Money et al. (2017) suggested that resilience is about providing for a spectrum of stresses and that "there is an under-representation in the literature of longer run and accumulative disruptions (stresses). These are harder to account for because of the time horizons at play and the uncertain nature of these events" (Money et al., 2017, p. 7). We will discuss the issues around time horizons considered in evaluation of transport projects in Section 3.

Addressing the impacts of a changing coastal environment will require adaptation strategies that "fit" the changing coastal system dynamics and increasing risk. With that comes the need for governance arrangements, decision tools and processes that incorporate both the changing risk profiles and future widening uncertainties, to enable timely, sustainable and cost-effective adaptation. Current practice uses governance, tools and processes (such as predict-and-act using best, most-likely or worst-case estimates) that are not agile and adaptive to future changes and surprises. Critically, in coastal settings where increasing risk is driven by ongoing sea-level rise and pressures for new land-use development, decision-making tools are required that can address the issues associated with uncertainty and risk (Bell et al., 2017; Kwakkel et al., 2010).

2.1.2 Definition of uncertainty and risk

As will be discussed in the next section, the consideration of climate change requires decisions to account for deep uncertainties. To further clarify the scope of this study, it is important to distinguish between risk and (deep) uncertainty. There are unknowns involving risk and it is appropriate to talk in terms of means and variances. Other unknowns, like the effect of self-drive vehicles (SDVs), are uncertain. We can make judgements but there is no repeatable event drawn from a perceived probability distribution.

Based on this definition:

- Risk is present in situations where we do not know what is going to happen next but we do know what the probability/distribution looks like.
- Uncertainty is present in situations where we do not know what is going to happen next and we do not know what the possible distribution looks like.

Table 2.1 provides a useful definition for four intermediate levels of uncertainty, ranging between two extreme levels of uncertainty (determinism and total ignorance). Variations of this definition have been used in previous studies, with some differences in their approach to deep uncertainty, potentially depending on the purpose of the studies. For example, the Australian framework to uncertainty does not make a distinction between Levels 3 and 4a (Infrastructure Australia, 2021); their classification was adapted from Walker et al. (2010).[6] We adopt the definition of the intermediate levels of uncertainty from Marchau et al. (2019) and use multiple sources for providing further information about the appropriate analysis type. For the analysis of deep uncertainty there has been a range of Decision Making Under Deep Uncertainty (DMDU) tools, including scenario analysis,[7] recommended in the literature, which we will discuss further.

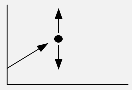
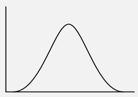
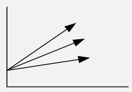
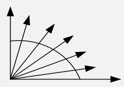
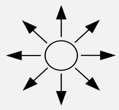
On the distinction between scenario modelling and DMDU tools, Marchau et al. (2019, pp. 10–11) noted: "When expert intuition is sufficient to link the policies to the relevant outcomes, then scenario planning may suffice. But in the future, the system, and/or the outcomes have the potential to surprise, a full DMDU analysis may prove valuable."

In the next section, we provide further explanation for these methods.

6 It is likely that the reason for the aggregation of uncertainty Levels 3 and 4a in the Australian framework is simplification of the guidelines.

7 In this report, we considered scenario discovery and therefore scenario analysis as a part of DMDU; there is no consensus around this.

Table 2.1 Progressive transition of levels of uncertainty

	Risk →					Uncertainty	
Level of uncertainty		**Level 1**	**Level 2**	**Level 3**	**Level 4 (deep uncertainty)**		
					Level 4a	**Level 4b**	
View of the future	**Complete determinism**	**A clear enough future**	**Alternate futures (with probabilities)**	**A few plausible futures**	**Many plausible futures**	**Unknown future**	**Total ignorance**
							
Suitable model type		A single (deterministic) model	A single (probabilistic) model	A few modelling scenarios	Many modelling scenarios	Unknown model – we only know that we do not know	
Model outputs		A point estimate for each outcome	A confidence interval for each outcome	A limited range of outcomes	A wide range of outcomes	Unknown outcomes; we only know that we do not know	
Analysis type to use		Sensitivity analysis of model parameters	Probability and statistics	Scenario analysis	Exploratory modelling and scenario discovery (What if? And then what?)		
Specific analysis types		Forecast the future and choose a suitable option	Use probabilities in accordance with risk attitude of the decisionmaker	Identify plausible futures and find a solution that works across most scenarios	Seek robust strategies that perform well over a wide range of plausible futures. Employ adaptive strategies that evolve over time and respond to new information.		

Source: Adapted from Marchau et al. (2019); Courtney (2001); Walker et al. (2003); Walker et al. (2010).

2.1.3 Uncertainty associated with climate change

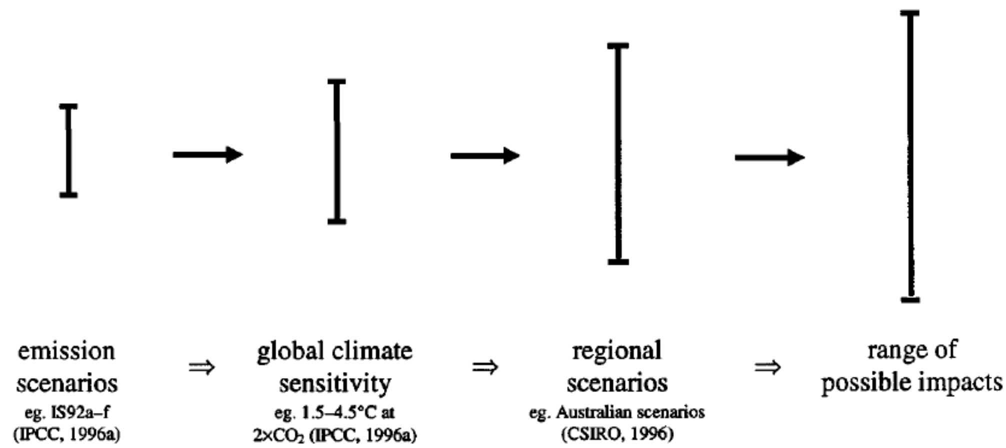
Climate change is commonly mentioned as a source of deep uncertainty (Marchau, Walker, Bloemen, et al., 2019). Therefore, the focus of our review is on deep uncertainty; that is, Level 4 in Table 2.1. Deep uncertainty occurs when decision makers and stakeholders do not know or cannot agree on how likely different future scenarios are (U.S. Climate Resilience Toolkit, 2022).

Currently, there is limited information available about the impact of the natural process on important climate variables, such as precipitation, storm intensities, and global temperatures, and the economic and social consequences of such climatic changes. This limited and incomplete knowledge about the functioning of environmental phenomena and processes leads to a wide range of uncertainty with the outcomes of climate change models. While there is consensus about the existence of global climate change (see, for example, Cook et al., 2013), there remains considerable uncertainty about the following issues (Hallegatte, 2009; IPCC et al., 2014; Marchau, Walker, Bloemen, et al., 2019; Ranger et al., 2010):

- The size and magnitude of climate change (with estimates of increased average temperatures differing greatly across a range of future scenarios)
- The speed of climate change (which determines how quickly policy actions need to be taken)
- The implications for specific areas and regions (even within sub-national regions, the direction of change is hard to determine)
- Impacts on the global carbon cycle
- Effects on global climate
- Modelling of physical and economic impacts
- Calculating the benefits of different adaption options
- The policies that should be implemented to mitigate and/or hedge against the adverse consequences of climate change (because of a lack of knowledge about the costs and benefits of different alternatives for protecting ourselves from the adverse consequences of climate change).

Ranger et al. (2010) described the prediction of future impacts and effectiveness of different adaption options as being fraught with uncertainty, with sources of uncertainty varying at each step that cannot all be quantified with confidence. As shown in Figure 2.1, uncertainty accumulates through the process of prediction of the impacts of climate change leading to a cascade or explosion of uncertainty (Jones, 2000). In this study, we attempt to provide a systematic solution for decomposing the *potential* sources of uncertainty and minimise the margin of error for an evaluation of transport infrastructure investment.

Figure 2.1 Explosion of uncertainty from global emissions to local economic impacts



Source: Jones (2000)

2.2 Adaptive decision making (ADM)

In this section, we first provide definitions for ADM, uncertainty and risk. We then discuss the implications of climate change for an ADM and transport system resilience.

2.2.1 Definition of ADM

The focus of an adaptive investment decision is to allow for flexibility by considering all possible outcomes when selecting options for further investigation. This often requires the use of CBA for all options (according to the relevant CBA guidelines).

Adaptive-decision strategies focus on modelling environmental policies where decision-makers can make midcourse corrections based on observations of the relevant environmental and economic systems. (Lempert et al., 1996)

Under scenarios of deep uncertainty, adaptive decision making relies on plans that are designed to be adaptive over time in response to how the future unfolds as deep uncertainties are resolved. A wide range of futures are explored, with a plan of action to respond to signals for adaptation in the basic plan to meet objectives (Kwakkel & Haasnoot, 2019).

Walker et al.(2001) defined the components of an adaptive policy. This is shown in Table 2.2. The components of adaptive decision making could be further considered using a range of methods, which will be presented in the next chapter.

Table 2.2 Components of an adaptive policy

Components	Description
Basic policy	An infrastructure option and one or more additional policy actions together with a plan for their implementation
Vulnerabilities	Potential adverse consequences of the policy associated with key uncertainties regarding the assumptions of the basic policy or "side effects" of that policy
Signposts	Information that should be tracked in order to determine whether defensive or corrective actions or a policy reassessment is needed
Triggers	Critical values of the signpost variables that lead to implementation of defensive or corrective actions or to a policy reassessment
Actions	Responses to specific contingencies or expected effects of the basic policy

Source: Adapted from Walker et al. (2001)

2.2.2 The features of a good ADM

Wiseman et al. (2011) discussed the factors that lead to a good adaptation and suggested that "Overall, good adaptation can be thought of as that which maximises benefits to both oneself and others, while minimising costs to the same". Uncertainty about the magnitude (and direction) of climate change impacts requires decision makers to keep as many opportunities or pathways open as possible – we will discuss this further in our review of "robust decision making". Climate change adaptation choices are often path-dependent (shaped by those made earlier) and path-creating (shape and limit subsequent choices). We will discuss this further in our review of Dynamic Adaptive Policy Pathways (DAPP).

2.2.3 Flexible and robust adaptation

Sarku et al. (2020) identified ADM as being characterised by the application of decision options that are ***flexible***, ***robust*** or both:

- Flexible options in ADM are those that can be adjusted or reversed over time when new information becomes available. Flexible options preserve decisions from dynamic uncertainty (Colombo & Byer, 2012).
- Robust options in ADM are those that are effective across a wide range of futures in response to different socio-technical-environmental conditions (Lempert et al., 2006).

Walker et al. (2013) elaborated on ADM approaches that are *static robust* and *dynamic,* where static means that *timing is not explicitly considered* and **static robust** means that the adaptation measures are *primarily anticipatory*. *Static robust* adaptive measures involve using deep uncertainty tools such as robust decision making (RDM), dynamic adaptive planning (DAP), adaptive *tipping points* and *trigger values*. We will provide further details on RDM and DAP in the next paragraphs and discuss them in further detail in the next section.

RDM is a process whereby deliberation is undertaken alongside analysis to iteratively generate and evaluate plausible scenarios to form robust strategies that protect against a range of plausible futures (Lempert, 2013, 2014, 2019). The policy architecture of RDM is one of protective adaptivity. The basic plan that is formulated from an RDM approach should be one that protects the plan against contingencies and vulnerabilities that may arise from deep uncertainty. The generation of policy alternatives and scenarios is an iterative process undertaken with collaboration between analysts and decisionmakers to ensure a robust plan (typically including static adaptive measures) that balances trade-offs with decisions of least regret.[8]

In DAP, the development of a plan includes adaptive measures to protect the goals of the system against vulnerabilities by establishing a monitoring system with a set of actions that are to be undertaken immediately when a specific trigger value is reached. DAP relies on identifying vulnerabilities of a plan (that is, how it might fail), and adding additional actions to be taken immediately when a vulnerability risk reaches a critical level to protect the initial goals and objectives (Kwakkel et al., 2010; Walker et al., 2013; Walker et al., 2001, 2019).[9,10]

Adaptative tipping points (ATP) refer to the point at which the current management strategy can no longer meet objectives. After that point, adaptive actions are needed for the basic plan to meet its objectives (Kwadijk et al., 2010). Related to adaptive tipping points are **trigger values**, which function as signals for adaptive action to the basic plan (typically occurring before tipping points) (Walker et al., 2001).

Dynamic adaptive measures can be *anticipatory, concurrent* or *reactive*. Dynamic adaptive measures include approaches such as adaptation pathways and dynamic adaptive policy pathways. These approaches explicitly consider the dynamic adaptation of the plan.

In the case of DAPP, the approach explores alternate sequences of decisions (adaptation pathways), assessing how different strategies would play out over time. Having clear consideration for different routes towards objectives, DAPP helps to limit the emergence of stranded assets and potential lock-ins and path dependencies (Haasnoot et al., 2019).

The main difference between the static robust and dynamic measures is how the actions are assessed over time. Where static robust measures plan for an uncertain future and the potential adaptative actions to be undertaken, dynamic measures plan for how those adaptive

8 For more details on RDM see Section 2.2.7.

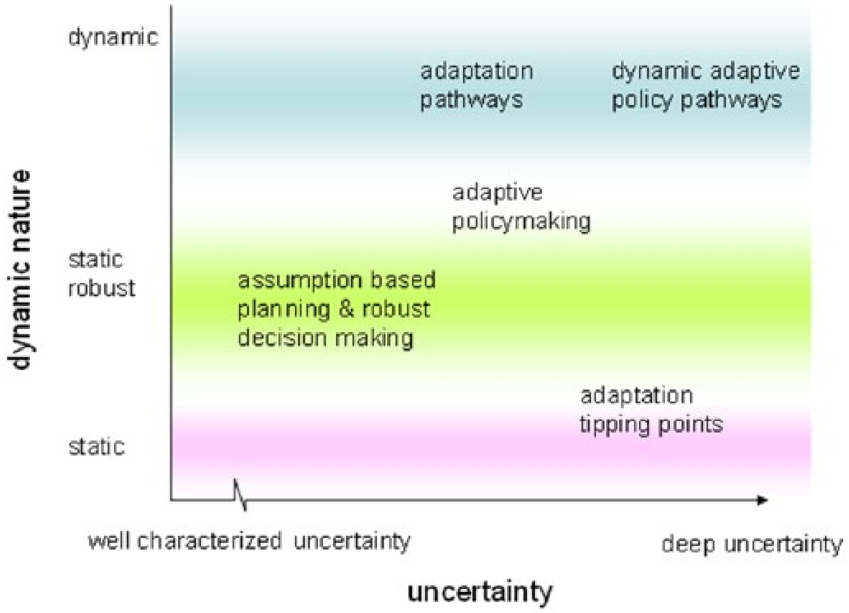
9 Referred to in Kwakkel et al. (2010) as dynamic strategic planning.

10 For more details on DAP, see Appendix C.

actions will influence future scenarios and subsequently how adaptation is to continue working *altered futures* to meet goals and objectives.

Figure 2.2 shows the combination of uncertainty levels, presented in Figure 2.2and the nature of ADM approaches (ranging from static to dynamic). For a static plan it is possible to use signposts to monitor the need for actions to either shape the future or to reduce the plan's vulnerability to uncertain future developments. This is called assumption-based planning (ABP), which is a first step towards adaptive planning. Unlike static robust plans, adaptive planning defines contingency plans and specified conditions, called signposts and triggers, under which the plan should be reconsidered and revised (Walker et al., 2013).

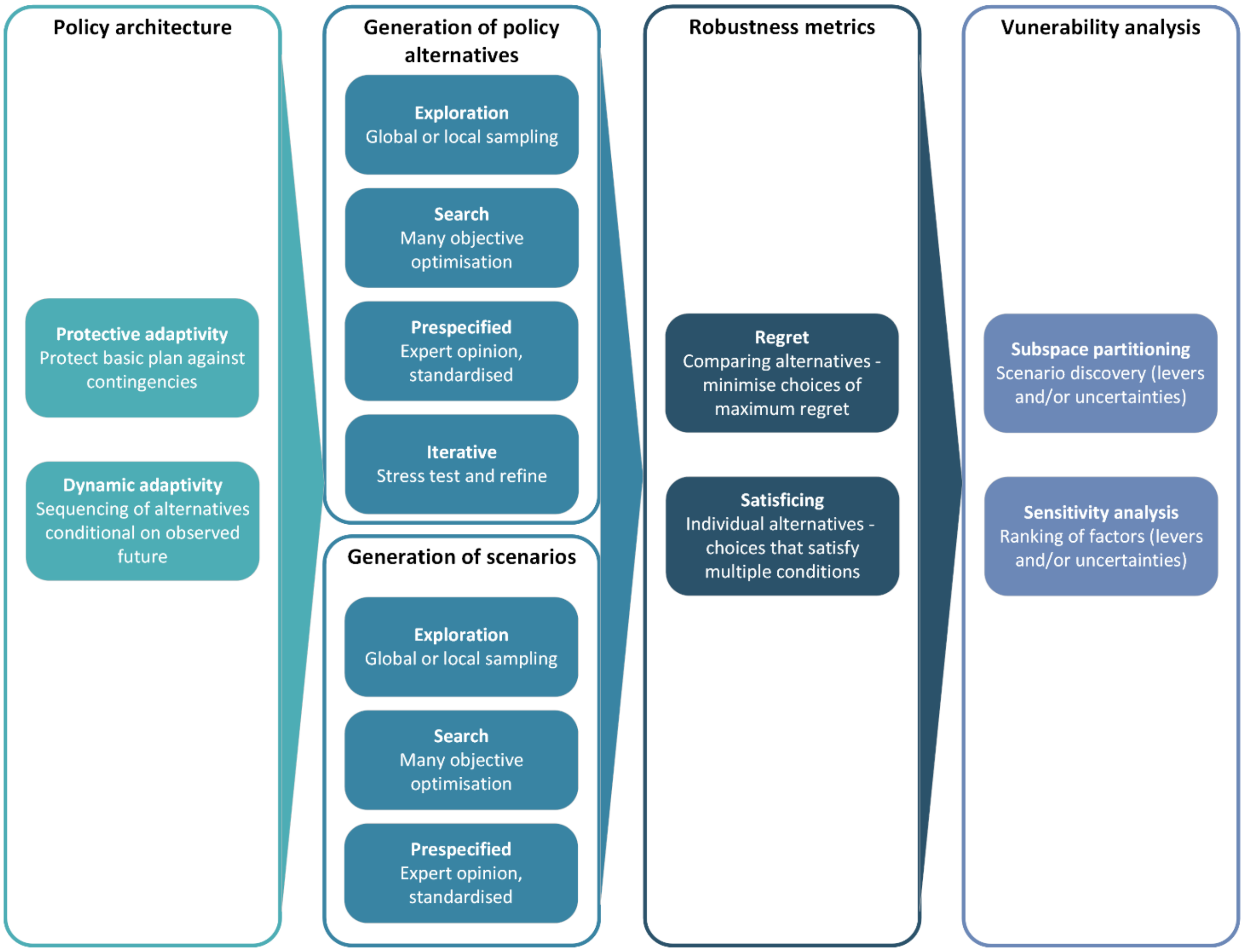
Figure 2.2 Approaches for developing adaptive policies according to their dynamics and level of uncertainty



Source: Walker et al. (2013)

Kwakkel and Haasnoot (2019) identified the similarities and differences between approaches for decision making under deep uncertainty. They provided a taxonomy of the approaches shown in Figure 2.3. Under this taxonomy, all approaches for DMDU are comprised of four parts.

Figure 2.3 Components of approaches and tools for decision making under deep uncertainty[11]



Source: Adapted from Kwakkel and Haasnoot (2019)

2.3 Available methods for ADM

There have been extensive discussions about appropriate methods for addressing deep uncertainty. We have observed a rapid growth in the literature over the last few years, with further consideration of DMDU methods over the probability-based approaches.[12]

Marchau et al. (2019) suggested that DMDU approaches are more useful when:

- The contextual uncertainties are deep, rather than well characterized

11 This is similar to the framework for adaptation decision-making defined by Ranger et al. (2010), albeit with a greater focus on deep uncertainty.

12 Lempert and Schlesinger (2000) suggested that using prediction-based analysis can lead to brittle policies, with little or no flexibility in cases of catastrophes, surprises, or other high-consequence, low-probability events. As such, robust strategies are needed in the case of deep uncertainty where the optimal strategy may be misleading. Lempert and Schlesinger suggested that climate change should be viewed as a contingency problem rather than optimisation problem. Lempert et al. (1996) compared simple adaptive-decision strategies with static alternatives and found that simple adaptive-decision strategies on average significantly outperform best-estimate policies unless predictions of the future are highly accurate – to the order of 95 percent. Adaptive-decision strategies benefit from their ability to make midcourse corrections and avoid significant errors.

- The set of policies has more rather than fewer degrees of freedom; uncertainties are well characterized and/or few degrees of decision freedom exist, DMDU approaches yield few benefits over traditional predict-then-act approaches
- System complexity is a heuristic for how well experts know and/or disagree on the proper models, probabilities, and/or system outcomes.

In this section, we review a list of available methods for decision making under deep uncertainty. Most of the methods considered in this section are DMDU tools. In addition to those, we consider real options analysis (ROA) because it has, until recently, been recommended as a useful method for the consideration of uncertainty. However, most studies acknowledge the potential issues with using ROA under deep uncertainty. We will discuss this further in the next section.

2.3.1 Real options analysis

2.3.1.1 Definition

"A real option itself, is the right – but not the obligation – to undertake certain business initiatives, such as deferring, abandoning, expanding, staging, or contracting a capital investment project" (Locatelli et al., 2020). The ROA approach is based on a method for valuing the total value of a firm. Myers (1977) discussed that the total value of a firm includes the potential of future growth, which depends on the current assets and the choices that are open due to these assets. A central challenge then becomes to assign value to these choices such that they can be included in the assessment of the total value of the firm. This is the main challenge for using ROA for DMDU.

2.3.1.2 Usefulness of ROA

ROA is commonly used to improve the available choices. This decreases the cost of actions that prove inappropriate with the benefit of hindsight. Real options provide flexibility and could be in the form of decisions to:

- Defer or abandon
- Ramp up or scale down
- Introduce flexible staging in a project
- Switch technologies or change platform/capability

Importantly, real options also include the option to invest in additional flexibility or in additional information before committing to an irreversible decision.

2.3.1.3 Real options in transportation planning and investment practice

Transport planners have traditionally worked with many of these concepts, although they may not have been termed "real options" and they may not have been assessed using modern real options methods. Thus, real option principles support the sorts of decisions commonly made by planners to:

- Purchase/retain a land corridor that is wider than initially needed to allow for future road-widening
- Preserve an unused rail corridor and use it for an alternative use temporarily or indefinitely, such as a cycle route
- Pilot new technology, such as new signalling or train controls

To determine whether there is a real need, analysts need to ask the following types of questions:

- Why do we need the investment?
- What are the size and scope of the impacts of not investing?
- Is the investment required now or in the future?
- Is the project standalone or part of a portfolio?

The ROA can be applied to improve the accuracy of economic evaluation and add a measure of robustness within an optimality-seeking framework[13] in which:

- Uncertainty is more "dynamic" than "deep"
- The project involves significant irreversible investments or creates/destroys significant capabilities that matter for future decision-making

Byett et al. (2017) provided four conditions where real options or adaptive management techniques should be used:

1. There is uncertainty or risk
2. Irreversible investments are to be made
3. The investor has flexibility in timing or at least some investment stages
4. The investor can learn about the nature of risk or uncertainty over the relevant planning horizon.

About the usefulness of ROA, Byett et al. (2017) noted that:

> *"If risk, but not uncertainty, exists then the planner can use quantitative real option techniques to price the option value of undertaking (or not undertaking) certain investment stages. If, instead, uncertainty (and especially deep uncertainty) exists, then the quantitative real option approach is less useful, or cannot be used at all."* (Byett et al., 2017)

This is because well-defined distributions do not exist for the evolution of key variables that affect the investment decision. As we discuss below, in some cases, the same real option concepts can still be used, but more qualitatively.

2.3.1.4 Pros and cons of ROA

Hallegatte et al. (2012) summarised the pros and cons of ROA as follows:

- Benefits
  - Attractive analytically because it can be readily incorporated into a social cost-benefit framework
  - Allows for explicit valuation of created and destroyed capabilities (expressed as options) in general investments, often not accounted for in standard CBA
- Constraints
  - Benefits of increased information and higher expected net present value in the future assumes some uncertainty will be resolved with time.

13 As discussed, Lempert and Schlesinger (2000) suggested that climate change should be viewed as a contingency problem rather than optimisation problem. Therefore, as will be discussed, ROA may not be appropriate for considerations of deep uncertainty.

- Complexity is much larger because multiple sets of decisions need to be included in the analysis, which sometimes leads to problems that are difficult or impossible to resolve.

2.3.1.5 Usefulness of ROA to climate change

ROA relies on the calculation of a positive option value; that is, an expected average positive return from deviating from the base path at a certain juncture. If the option value is zero or negative – or if no new information is expected to be available at that juncture that would suggest that a different path would be beneficial – then the methodology would favour pursuing the base path without an adjustment option at that point. That appears to be reliant on perfect ex ante information about the potential paths available over time and certainty about the lack of any relevant extra information emerging over a certain period. Therefore, it seems to ignore the influence of deep uncertainty, which is the key characteristic that is supposed to require the application of ROA in the first place.

In New Zealand, Lawrence et al. (2017) complemented a multi-criteria decision analysis with ROA and DAPP to provide decision support for addressing irreducible uncertainties in coastal areas and assess the ability of options and pathways to deliver risk reduction at the coast over the long term (100 years).

The Ministry of Transport (2014, 2016) highlighted the usefulness of ROA when there is uncertainty and the opportunity to build in flexibility. This is particularly for cases where there is high uncertainty, but better information may become available; for irreversible investment opportunities with longer horizons; and for projects that can be structured into multiple stages with options to continue, alter or delay at each stage.

Byett et al. (2017) made the distinction that if risk but not uncertainty exists, then the planner can use quantitative real options techniques to price the option value of certain investment stages. However, if uncertainty (and especially deep uncertainty) exists, the quantitative real option is less useful or cannot be used. Without well-defined distributions for how key variables affect the investment decision, real option concepts can still be used but in a more qualitative fashion.[14]

Based on this review, while ROA does not provide a robust framework for considerations of ADM under deep uncertainty, it remains a useful method if it will be used in combination with other available methods. We will discuss this further in Section 2.3.6.

2.3.2 Scenario analysis of climate change

2.3.2.1 Definition

A **scenario** is a plausible, often simplified description of how the future may unfold, based on a coherent and internally consistent set of assumptions about driving forces and key relationships (Solomon et al., 2007). In this report, **scenario planning** is used as a catch-all term for the range of ways in which plausible stories of the future are built and used to inform decisions about priorities and actions. A **climate scenario analysis** is a process of analysing (and planning) for plausible future scenarios involving the large-scale and complex nature of climate change.

14 Byett et al. (2017) provided a list of available methods for producing likely outcomes of the underlying asset price and optimal strategies within ROA. One method they referred to is a Monte Carlo simulation, which allows a wide range of pathways to be modelled. However, they suggested that the disadvantage of the Monte Carlo method is its potential lack of transparency. There is also some contention over the appropriate discount rate to use.

2.3.2.2 The use of scenario analysis

Wangsness et al. (2015) listed seven types of uncertainty that would lend themselves to scenario analysis: technological, demographic, relative price, national political, local political, local private sector development, and residual value of infrastructure.

Scenario analysis typically involves assessing a range of plausible potential future scenarios that enable key areas of uncertainty to be explored. Development of scenarios can include formal projections of population and climate such as those from Statistics New Zealand and Ministry for the Environment.

Scenario analysis involves identifying and applying drivers of change to establish a range of alternate scenarios of the future. A range of "shocks" related to areas of uncertainty (which can include but are not limited to population and economic growth, climate change and technology disruption) are applied to test scenarios in terms of how they perform given defined objectives and goals (Infrastructure Australia, 2021).

2.3.2.3 Scenario analysis in practice

Wangsness et al. (2015) reviewed 19 national and regional transport CBA guidelines to identify their recommended methods for analysing uncertainty, the available variables for the analysis and the presentation of uncertainty in the CBA. Their findings suggested that:

- Most guidelines recommend sensitivity analysis and many recommend simple or simulation-based scenario analysis as well
- Besides construction costs, the variable most often recommended for uncertainty analysis is predicted traffic growth
- The most common way to assess systematic uncertainty is by sensitivity analysis of the discount rate
- Highlighting uncertainty in a summary table was recommended by nine of the 19 guidelines.

In practice, Marchau et al. (2019) discussed that adaptation planners are often overwhelmed by the many choices involved in using climate projections for scenario analysis, including emissions scenarios, downscaling methods, model selection, and bias correction. This is because with new sets of climate models, or new downscaling methods, which are usually introduced every few years, practitioners feel compelled to redo the entire analysis to see whether results have changed. Consequently, when using climate projections as the starting point, the analysis is never complete, and the planner will and should always wonder if the results would be different if a different set of projections were used.

2.3.2.4 Pros and cons of scenario analysis

Hallegatte et al. (2012) indicated that one approach to decision-making would be to invest in research and investigation to determine which one of the possible futures is the most likely, and then to select the option that performs best in this future. Decision makers usually want to know the best prediction for the future in order to select the best option in this future. Under limited uncertainty levels – that is, if our knowledge base would make it possible to make forecasts for the future – this approach would be appropriate. However, under deep uncertainty, this approach does not work because it is impossible to determine which scenario is the most likely, or because several scenarios are equally plausible.[15] In such a situation, one

15 Identifying scenarios under deep uncertainty will be discussed further.

option is to attribute probabilities to the different scenarios and to use a cost-benefit analysis under uncertainty to determine the “best” strategy.

- Benefits:
  - Providing further information around a range of plausible futures
  - Consistency with the standard CBA framework
- Constraints:
  - Costly process of updating the scenarios as information emerges over time
  - Uncertainties about possible scenarios that could be considered and their timing
  - Difficulty using this method under deep uncertainty, given that the likelihoods of different scenarios are unclear (or difficult to estimate)

2.3.2.5 Usefulness of ADM in climate change

As discussed, scenario analysis provides an understanding of the future that can be predicted well enough to identify policies that will produce favourable outcomes in a few specific, plausible future worlds. Given the difficulties in identifying the scenarios, and the uncertainties regarding climate change models, most available literature considers scenario analysis useful for decision making under Level 3 of uncertainty – with a few plausible futures. However, scenario analysis remains a useful tool to inform DMDU, particularly when combined with other DMDU tools.

2.3.3 Dynamic Adaptive Policy Pathways (DAPP) and Dynamic Adaptive Planning

2.3.3.1 Definition

The DAPP is a DMDU approach that explores alternate sequences of decisions (adaptation pathways), assessing how different strategies would play out *over time*. Having clear consideration for different routes towards objectives, DAPP helps to limit the emergence of stranded assets and potential lock-ins and path dependencies (Haasnoot et al., 2019).

Dynamic adaptive planning (DAP) is a DMDU approach in which the development of a plan includes adaptive measures to protect the goals of the system against vulnerabilities by establishing a monitoring system with a set of actions that are to be undertaken immediately when a specific trigger value is reached. DAP relies on the identification of vulnerabilities in a plan (that is, how it might fail), and adding additional actions to be taken immediately when a vulnerability risk reaches a critical level to protect/review the initial goals and objectives (Kwakkel et al., 2010; Walker et al., 2013; Walker et al., 2001, 2019).[16]

2.3.3.2 Description of the method

The DAPP approach combines the work on adaptive policymaking[17] with the work on adaptation tipping points and adaptation pathways (Haasnoot et al., 2013, 2019; Walker et al., 2013).

Adaptation tipping points (ATP) are the point at which the current management strategy can no longer meet its objectives. After that point, adaptive actions are needed for the basic plan to meet its objectives. ATP reverses the traditional top-down approach to climate change to

16 Referred to as dynamic strategic planning in Kwakkel et al. (2010).

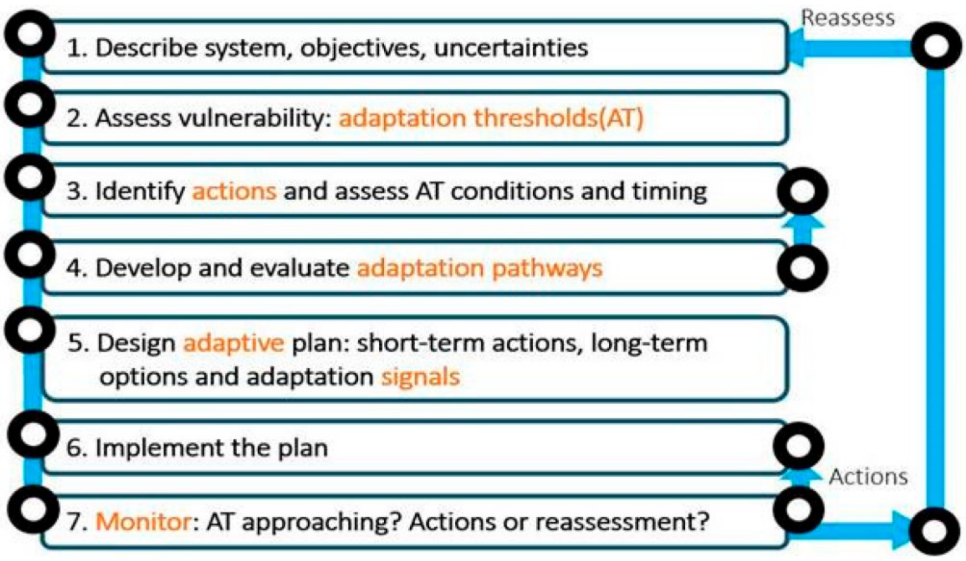
17 Also referred to as dynamic adaptive planning (DAP) (Walker et al., 2013).

a bottom-up approach. This reframes the question from *"What if climate changes according to X?"* to *"How much climate change can we cope with*?" (Kwadijk et al., 2010).

Adaptation pathways describe adaptive policy options that can be taken under different environmental conditions (or possible **futures**). Adaptive pathways consist of a range of individual policy options across a range of different futures (leading to having options available under a range of different scenarios). When the plan reaches the ATP, an alternate policy option is pursued.

Lawrence et al. (2019) suggested seven steps for undertaking the DAPP approach – as shown in Figure 2.4. The first step is to describe the system, objectives and uncertainties. This will inform the assessment of vulnerability and the definition **of** adaptation thresholds (AT). The next step is to identify actions and assess the timing of AT. In the fourth step, it is recommended to develop adaptation pathways and evaluate them. The next step is to design an adaptive plan and identify signals for short-term and long-term options. In the sixth step, the plan should be implemented, and then in the last step, monitoring will be required.[18] Haasnoot et al. (2013, 2019) outlined the steps involved in implementing DAPP in more detail; see Appendix D:.

Figure 2.4 Steps in undertaking the DAPP approach



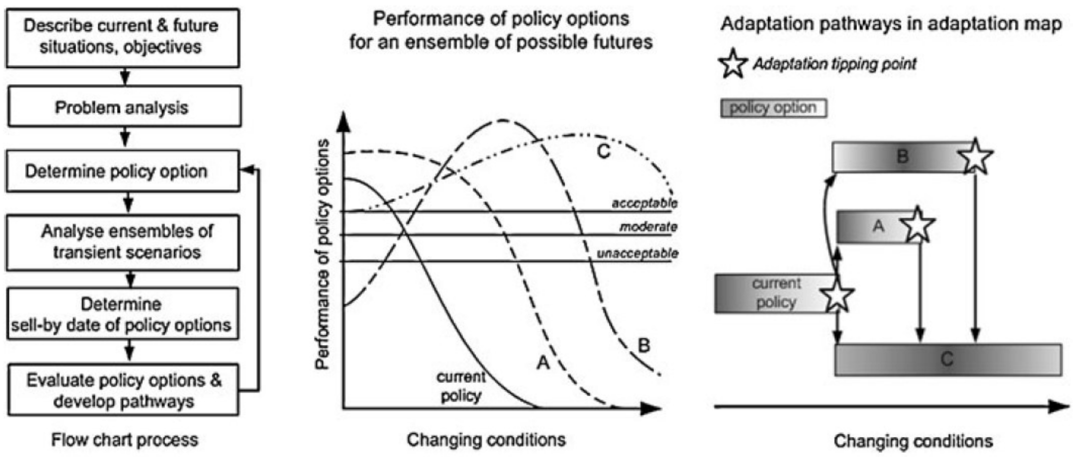
Source: Lawrence et al. (2019), adapted from Haasnoot et al. (2019).

Using a similar process, Haasnoot et al. (2012) provided an example of how an adaptation pathway can be created from an ensemble of policy options for different futures, using adaptation tipping points as option termination points. This is shown in Figure 2.5. The construction of adaptation pathways is based on the performance of individual policy options (A, B, C) for an ensemble of possible futures. After an adaptation tipping point, the point at

18 Bell et al. (2017) and Kwakkel et al. (2010) discussed that by assessing suites of possible actions and stress-testing them against a range of climate and socio-economic scenarios, pathways of alternative actions can be developed that enable a future shift between pathways, depending on how the future turns out. Therefore, the lifetime of investments and the conditions under which they cannot meet objectives can be made transparent. Intrinsic to this approach is the ability to monitor signals and triggers of the physical world and societal and environmental change over long timeframes so that actions can be taken before thresholds are reached and unbearable consequences occur.

which a strategy fails to meet its objectives, all policy options are considered. Individual policy options are identified based on objectives and current and expected vulnerabilities.

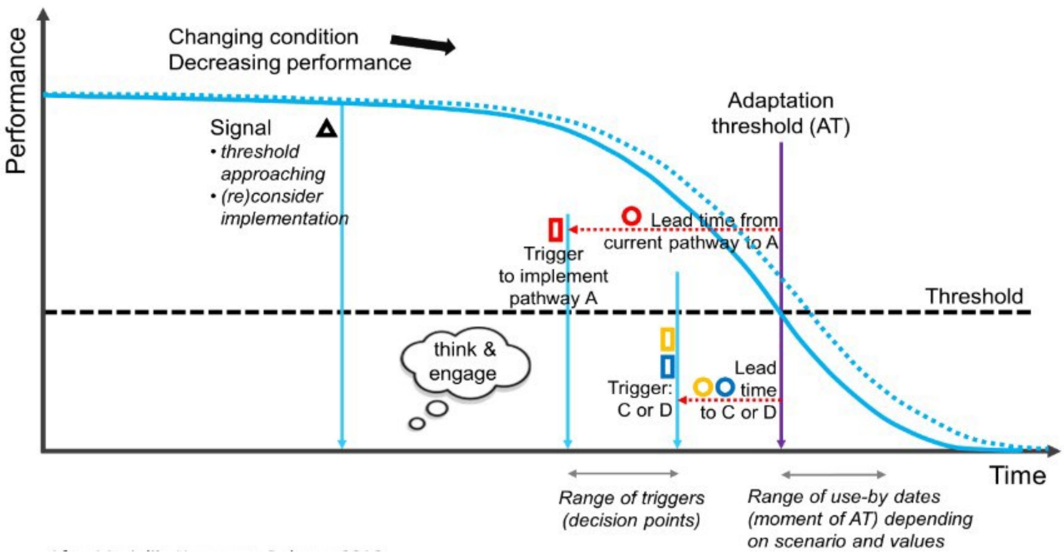
Figure 2.5 Construction of adaptation pathways using adaptation tipping points



Source: Haasnoot et al. (2012)

Combining these concepts, DAPP requires a set of indicators to monitor a signal that provides (a) an early indication of when to start re-engaging to review the adaptive plan, and (b) a trigger for when to switch to an alternate policy option (or pathway) before reaching an adaptation threshold or tipping point. It is important that signals and tiggers are positioned before adaptation thresholds to allow for lead times to review and implement adaptive policies (Lawrence et al., 2021).

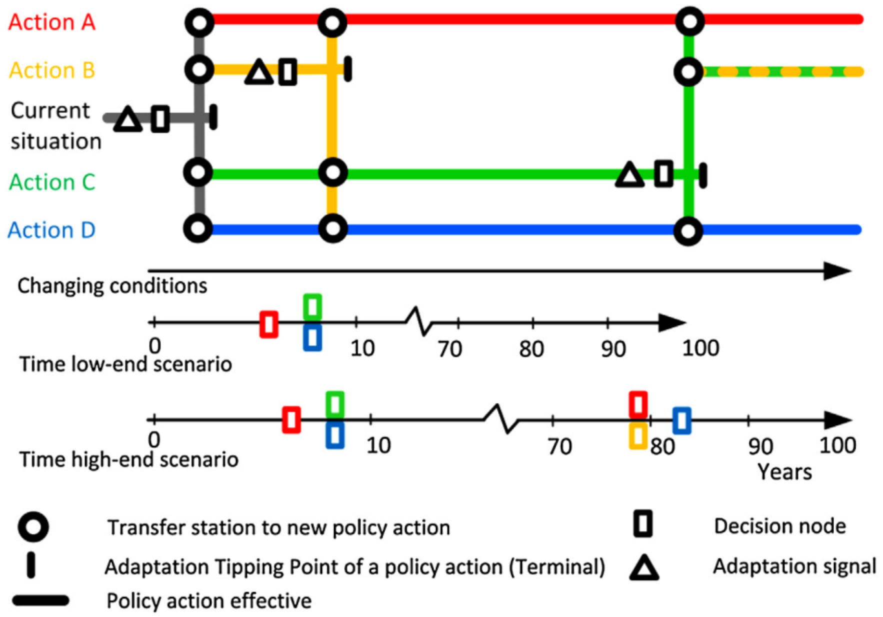
Figure 2.6 Construction of adaptation pathways using adaptation tipping points



Source: Lawrence et al. (2021)

Figure 2.7 provides a useful summary of using the DAPP approach. Under the current situation, a monitored indicator reaches an adaptation signal that informs planners that the condition for policy success is reaching a point at which its performance will no longer be tenable. This provides the lead time for decision makers to review their adaptive policy plan and decide which potential actions to pursue (A–D) at the pre-planned trigger point (decision node, shown as a rectangle) before conditions reach an adaptation threshold (or adaptation tipping point, shown as a vertical black bar). The DAPP adaptation pathways map shows all potential pathways under different decisions made in response to changing conditions (Lawrence et al., 2021).

Figure 2.7 The dynamic adaptive policy pathways approach (DAPP)



Source: Haasnoot et al. (2015)

Further notes on DAP

Adaptive policymaking, also referred to as dynamic adaptive planning (DAP),[19] is a DMDU approach where the development of a plan includes adaptive measures to protect the goals of the system against vulnerabilities by establishing a monitoring system and observing signals for a set of actions that are to be undertaken immediately when a specific trigger value is reached. DAP relies on identifying vulnerabilities of a plan (that is, how it might fail), and adding additional actions to be taken as soon as a vulnerability risk reaches a critical level to protect the initial goals and objectives (Kwakkel et al., 2010; Walker et al., 2013; Walker et al., 2001, 2019).[20]

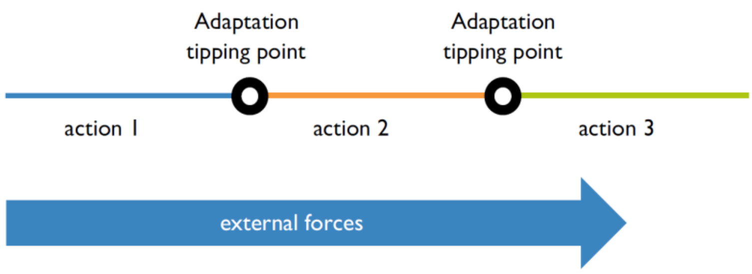
In contrast with DAPP, DAP does not specify how actions should be sequenced. In DAPP, adaptation tipping points are identified as triggers for where conditions for the main plan can no longer succeed at which point a new planned pathway is pursued. These differences between the two approaches are shown in Figure 2.8.

19 We discuss DAP in more detail in Appendix C.

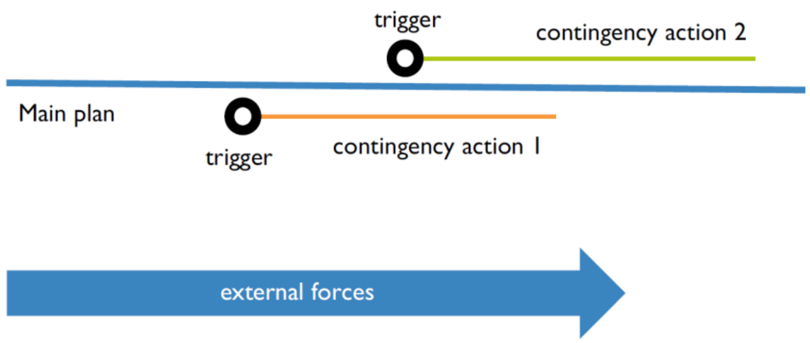
20 Referred to as dynamic strategic planning in Kwakkel et al. (2010).

Figure 2.8 Differences between DAP (top) and DAPP (bottom)

DAP



DAPP



Source: Kwakkel and Haasnoot (2019)

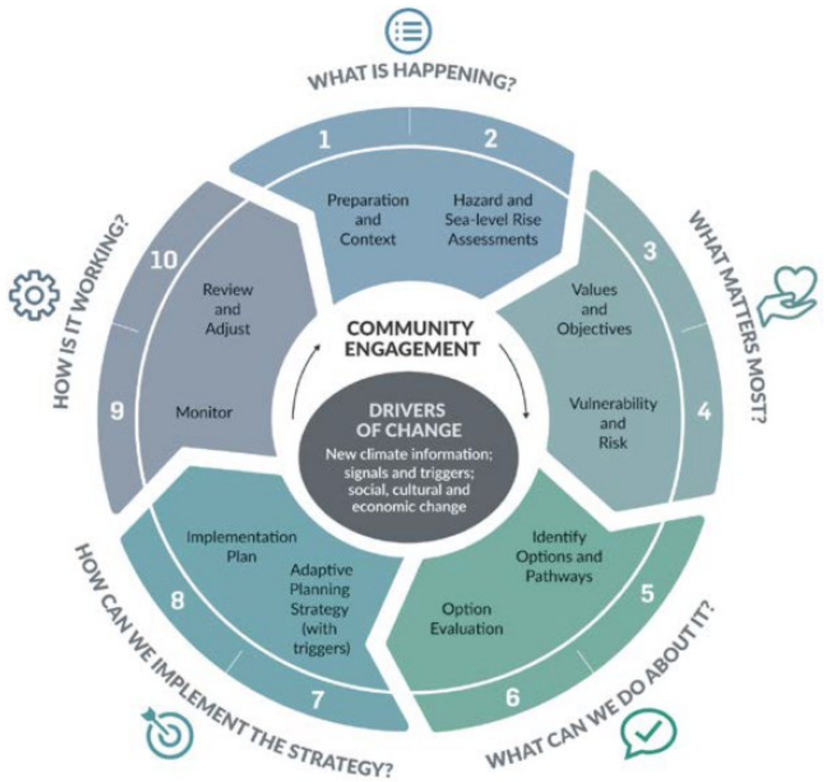
2.3.3.3 Pros and cons of DAPP

- Benefits:
  - Intuitive visual communication of policy options to non-technical stakeholders
  - Explicit requirement for long term planning under uncertainty, preventing ad hoc adaptation and keeping long-term options open
  - Explicit identification of 'lock ins' and path dependencies
- Constraints:
  - Difficulty in undertaking economic evaluation of pathways
  - Identification of appropriate monitoring signals can be technically or politically challenging in multi-stakeholder contexts
  - Alignment of adaptation pathways in complex multi-stakeholder contexts

2.3.3.4 Dynamic adaptive policy pathways in practice

In New Zealand, Bell et al. (2017) produced a guideline on how to adapt to coastal hazard risks from climate change, particularly hazard risks associated with sea-level rise. While sea-level rise is certain and the types of impacts are foreseeable, the report deals with the uncertainty relating to the magnitude and flow-on consequences of sea-level rise for each coastal area. Bell et al. (2017) provided a detailed step-by-step approach to assess, plan for and manage risks to coastal communities based on the dynamic adaptive policy pathways approach. The process is summarised into a 10-step process, as illustrated in Figure 2.9. This process is consistent with the recent internal thought piece at the New Zealand Ministry of Transport on how adaptive management might be used in future decision making (Ministry of Transport, 2017).

Figure 2.9 The 10-step decision cycle, grouped around five questions



Source: Bell et al. (2017) adapted from Max Oulton (University of Waikato) and UN-Habitat (2014)

2.3.4 Robust decision making (RDM)

2.3.4.1 Definition

Robust decision making is a process whereby deliberation is undertaken alongside analysis to iteratively generate and evaluate plausible scenarios to form robust strategies that protect against a range of plausible futures (Lempert, 2013, 2014, 2019; Wiseman et al., 2011).

2.3.4.2 Description of the method

The policy architecture of RDM is one of protective adaptivity. The basic plan that is formulated from an RDM approach should be one that protects the plan against contingencies and vulnerabilities that may arise from deep uncertainty. The generation of policy alternatives and scenarios is an iterative process undertaken with collaboration between analysts and decisionmakers to ensure a robust plan that balances trade-offs with decisions of *least regret*.

While it is not explicit in the outline of the RDM process, the outcomes are often adaptive and designed to evolve over time in response to new information (Rosenhead, 2001). The iterative approach of vulnerability analysis and trade-off analysis often helps in designing robust adaptive policies (Haasnoot et al., 2013; Lempert et al., 2003; Lempert & Groves, 2010; Walker et al., 2001).

RDM consists of the following five steps.

1. **Decision framing**

   Step 1 is for stakeholders to define the key factors in the analysis. This includes the objectives and criteria, and alternate actions to pursue those objectives. Uncertainties may affect the connections between actions and consequences and their relationships between actions, uncertainties and objectives.

2. **Evaluate strategy across different futures**

   Step 2 involves the evaluation of proposed strategies over many plausible paths into the future. It is often undertaken using simulation models.

3. **Vulnerability analysis**

   In Step 3, analysts and decisionmakers use data visualisation and analytics on model outputs to explore and characterise vulnerabilities across different strategies.

4. **Trade-off analysis**

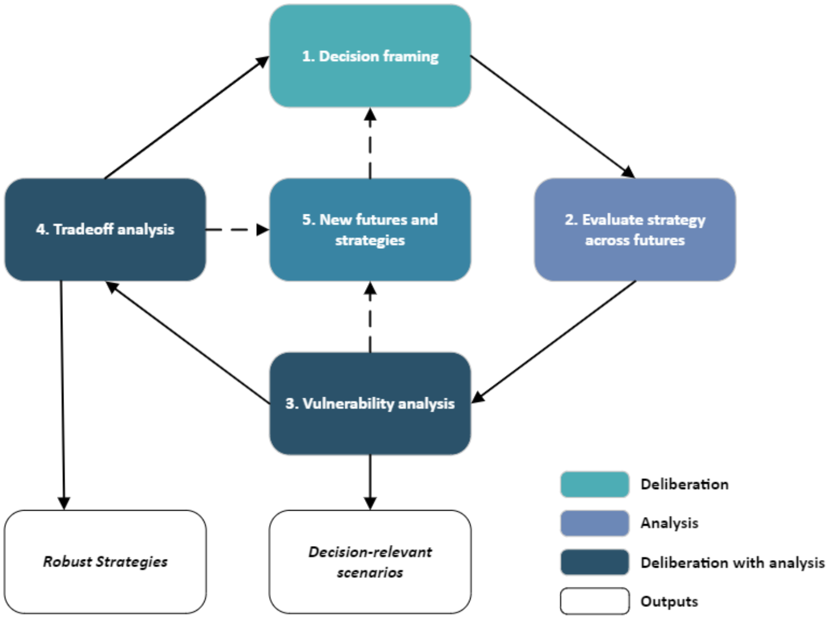
   In Step 4, analysts and decisionmakers assess the trade-offs between different strategies, including variables such as cost and reliability.

5. **New futures and strategies**

   In Step 5, analysts and decisionmakers use scenarios and trade-off analysis to identify and evaluate potentially robust strategies that provide better trade-offs than alternatives that have been assessed.

Figure 5 illustrates the iterative steps involved in undertaking the robust decision-making process.

Figure 2.10 Robust decision making (RDM)



Source: Adapted from Lempert (2019)

2.3.4.3 Pros and cons of RDM

Hallegatte et al. (2012) provided a summary of the pros and cons of RDM, as below.

- Benefits
  - Full vulnerability analysis of proposed projects
  - Transparent, reproducible, and exhaustive scenario discovery reduces over-confidence bias
  - Stakeholder process to define measures of success and potential futures builds consensus on project action even under diverse assumptions and priorities
  - Adaptive decision process explicitly addresses the limits of our ability to anticipate the future for any project
  - Project alternatives and plans evolve from existing project options
- Constraints
  - Time and cost intensive
  - Quality of the stakeholder process influences the relevance and efficacy of analysis, especially regarding the range of policies available, uncertainties considered, and choice of worst-case scenario
  - Requires extensive quantitative modelling of project area

2.3.4.4 Usefulness to ADM in climate change

RDM provides a useful approach for identifying the uncertainties. While time-consuming and costly, RDM provides a useful approach for ADM in climate change under deep uncertainty.

Kwakkel et al. (2016) compared ADM with DAPP and concluded that: “RDM offers insights into conditions under which problems occur, and makes trade-offs transparent. The DAPP approach emphasizes dynamic adaptation over time, and thus offers a natural way for handling the vulnerabilities identified through RDM. The application also makes clear that the analytical process of RDM is path-dependent and open ended: an analyst has to make many choices, for which RDM offers no direct guidance."

Hence, we suggest DAPP provides a more useful approach when combined with RDM for considering time-dependent and large impact infrastructure projects, while RDM remains useful for considerations of deep uncertainty for smaller projects/programmes.

2.3.5 Engineering options analysis (EOA)

Engineering options analysis (EOA) is related to ROA but differs in that while the objective of the latter is to find the correct price of an option, the former seeks to determine the best strategy for implementation in a system by examining the consequences of sequences of scenarios of both events and responses simultaneously. The approach imposes distributions on the system and obtains distributions of outcomes from the system, typically determined using simulation methods (De Neufville & Smet, 2019).

While EOA includes an assessment of the price of an "option", this is considered a secondary output of the approach (De Neufville & Smet, 2019). EOA is an approach that attempts to quantify the life-cycle value of a system that includes the likely responses by decision makers in response to uncertainty across many different scenarios (Cardin et al., 2015). As the EOA approach quantifies the life-cycle value of a system, it is possible to determine the value of flexibility based on the discounted cash flows of a static plan versus a flexible plan (de Neufville & Scholtes, 2011).

Table 2.3 Differences in EOA and ROA

Characteristics	Analysis basis	Engineering options analysis (EOA)	Real options analysis (ROA)
Options	Number	Many	Optimisation
Uncertainty	Distribution	Any	Random walk etc.
	Assumptions	Can vary over time	Past defines future
Quantitative results	Types	Distributions	1: Price
	Dimensions	Many	1
Qualitative results	Decision makers	Can choose amongst outcomes	No choice
	Guidance	Strategy	Buy or not

Source: Adapted from de Neufville (2017)

De Neufville and Smet (2019) described the EOA approach as being analogous to a game of chess, where players explore possible combinations and choose opening and subsequent moves to give themselves the best positions to respond effectively as the game develops in space and time.

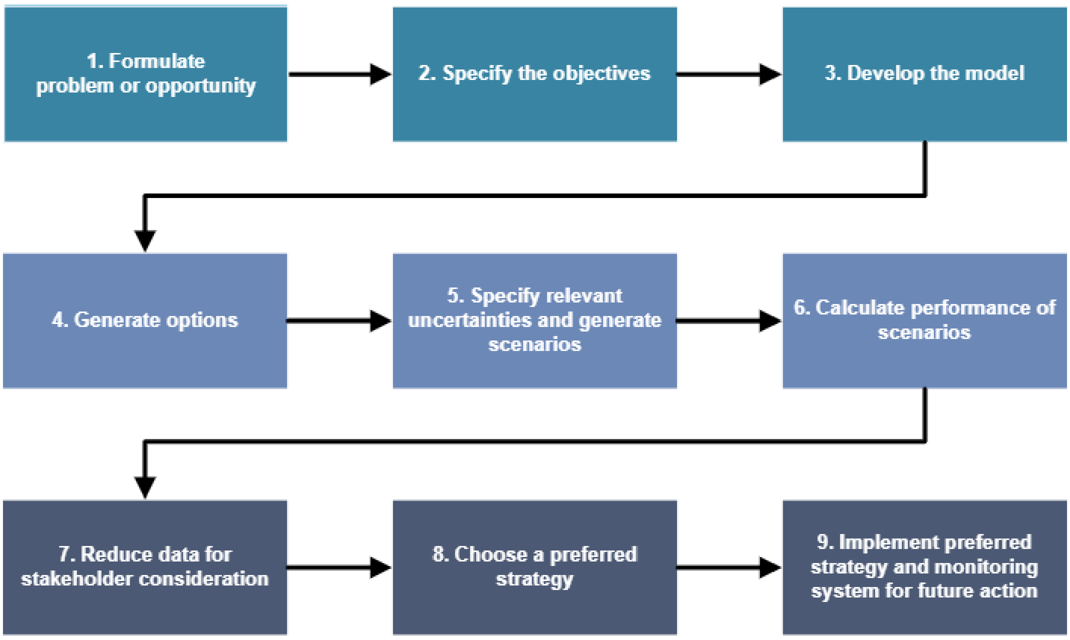
EOA explores the context widely, compares the range of possibilities, and proposes strategies, and thus opening decisions, that are most likely to be successful in the long run. (De Neufville & Smet, 2019)

Under conditions of deep uncertainty, we cannot predict the future exactly. Therefore, the most efficient and economic way to prepare is by undertaking flexible design choices that, by extension or adaptation, are able to meet several plausible futures (de Neufville, 2013). Therefore, the focus of EOA is not to provide a final investment pathway; instead, it provides decision makers with an understanding of potential pathways to best position themselves to move in a flexible adaptive strategy. Like DAP and DAPP approaches, EOA requires a monitoring system to track variables that may trigger actions and reassessment over the life of the plan (De Neufville & Smet, 2019).

2.3.5.1 Description of the method

De Neufville and Smet (2019) outlined nine steps in undertaking an EOA that align with the generic steps of decision making under deep uncertainty described by Marchau, Walker, Pieters, et al. (2019). In EOA, modelling and scenario generation is entirely up to the analyst. The EOA approach is dependent on computationally efficient models of the system to often simulate thousands of potential scenarios using the defined model and decision ruleset provided.

Figure 2.11 Steps to undertake an engineering options analysis



Source: Adapted from de Neufville and Smet (2019)

2.3.5.2 Usefulness of the EOA method

EOA provides a robust method for the considerations of ADM under deep uncertainty. However, the EOA is difficult to implement. For example, Stanton and Roelich's (2021) review of the application of DMDU approaches in 37 infrastructure case studies suggests that none of the studies used EOA.

2.3.6 Combined methods

Lawrence et al. (2017) complemented a multi-criteria decision analysis with ROA and DAPP to provide decision support for addressing irreducible uncertainties in coastal areas, and also (the authors) assessed the ability of options and pathways to deliver risk reduction at the coast over the long term (100 years). The authors identified the following limitations from their use of MCA/ROA/DAPP approaches:

- They explained the complexities of including planning controls, such as planning controls through rules and policies. They then suggested that excluding planning controls constrained detailed discussion of management options that could reduce the long-term risk, including the residual risk behind coastal protection, by signalling the temporary efficacy of the short-term actions.
- The relevant information was only available within certain timeframes. For example, the planning timeframes of short/medium/long-term constrained the assessment because each action or option has a different shelf-life (adaptation threshold) and there was no information on triggers for switching between options in a sequence or to other pathways assessed.
- The essential question in DAPP of "Under what conditions will the option fail?" (rather than "when will it fail?") was not wholly satisfied using the hybrid process due to its simplification into nominal timeframes. While the researchers and stakeholders understood the nominal nature of the timeframes, future decision makers and property owners could misunderstand that there are no guaranteed timeframes for each stage of the sequences.[21]

There was a dominance amongst the short-term options, of "known" preferred options. It was difficult for thinking to shift from designing a structure or action to last for a given design life to asking what strategy leaves options open for the changing climate risk. This was partly influenced by the dominance of existing and persistent erosion hazards and current actual and imminent risk at most of the priority coastal units assessed, combined with a high expectation that coastal protection works will solve the erosion problem (Blackett et al., 2010; Rouse et al., 2016). This highlights the importance of using the full DAPP approach, which is now embedded in national coastal guidance for New Zealand, to appraise the next adaptation threshold and enable a more detached discussion at the assessment phase.

2.4 International experience

2.4.1 Policy

The United Kingdom's Department for Transport (2021) provided an uncertainty toolkit that outlines the techniques for exploring uncertainty as part of transport modelling appraisal. The toolkit mainly focuses on uncertainty of *known knowns* and *known unknowns*, how it recognises *cataphoric disruption* as unknown unknowns to be characterised as *deep uncertainty*. Their toolkit states that *in extreme unknown unknowns, nothing is known, and analytical techniques are of limited value,* in which case it specifies techniques for understanding deep uncertainty. These techniques include robust decision making, dynamic

21 The authors suggest that for analysing condition-based pathways, it would be useful to have a sensitivity analysis that varies the timing of the different sequences of protection. They also suggest developing indices as signals and triggers to monitor.

adaptive planning, dynamic adaptive policy pathways, info-gap decision theory (IG), engineering options analysis and real options analysis.[22]

Infrastructure Australia's (2021) *Technical Guide to Risk and Uncertainty Analysis,* as part of their *Assessment Framework,* recommends using adaptive policies where options adapt over time as conditions change and learning takes place.[23] It also recommends ROA for understanding and managing assessment under deep uncertainty. It suggests that ROA is most useful in cases where investment proposals (a) include large and significant uncertainties, (b) are capable of staging or being designed to build in flexibility, and/or (c) are likely to be affected by rapidly changing technologies and climate change uncertainty is very large.

The Victorian Government of Australia provides guidelines for infrastructure investment evaluation, including a technical document for the use of real options analysis (ROA) for considering uncertainty. While the guidelines do not specify deep uncertainty, ROA is noted to be valuable for investments impacted by significant uncertainty. The Victorian Government suggested incorporating ROA into CBA to be undertaken by reporting the total project value (TPV) as net present value (NPV) + real option value (ROA), equivalent to the net value of flexibility to adjust to changes in central assumptions (Department of Treasury and Finance, Victorian Government, 2018).

The UK Green Book notes that longer-running programmes for larger projects over several years should maintain regular monitoring against updates of original projections (HM Treasury, 2020). For high-impact, low-frequency events, the Green Book notes that:

> "Low probability high impact risks should be noted in the risk register to make the decision maker aware. Effective risk costing will be supported if organisations put in place well designed risk assessment processes supported by effective routine data recording. Risks with low probability but high impact need to be considered seriously by policy makers." (HM Treasury, 2020, p. 49)

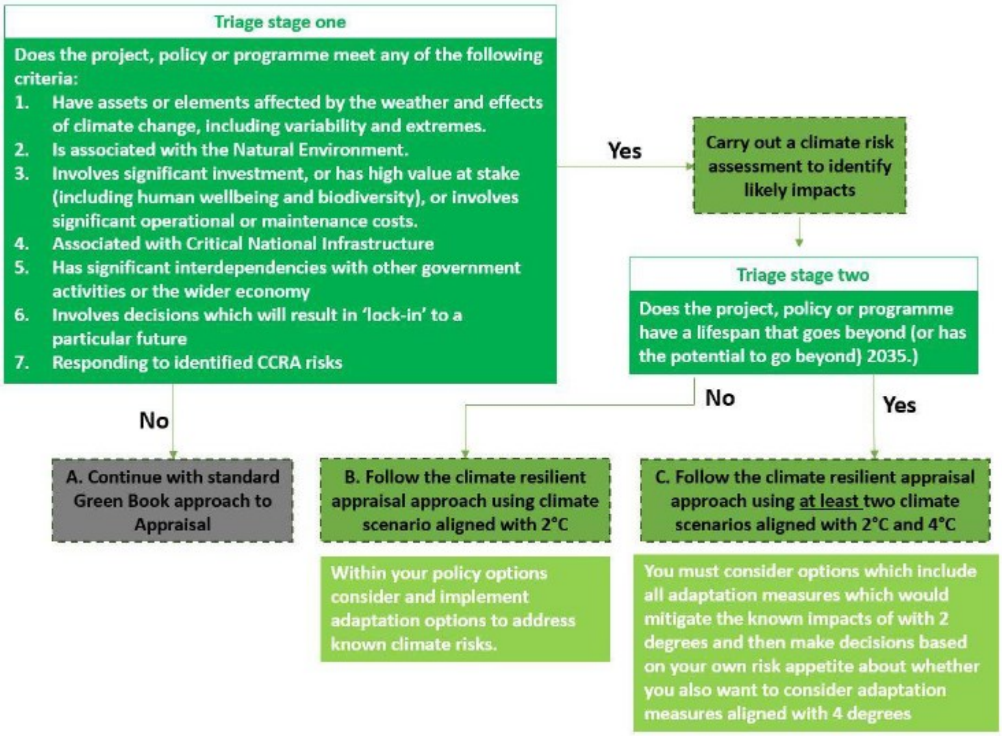
Supplementary to the Green Book, the Department for Environment Food & Rural Affairs (DEFRA) (2020) provided guidance for Accounting for the Effects of Climate Change. DEFRA provides guidelines of when a climate risk assessment is needed, climate change scenarios to adopt, and when to consider adaptation measures, as shown in Figure 2.12.

Where a project, policy or programme meets the criteria below, a climate risk assessment is required to identify likely impacts.

22 It is noted in TAG Uncertainty toolkit that real options can be employed to determine the value for flexibility but requires uncertainty be better characterised than its related DMDU approach EOA.

23 We note that Infrastructure Australia (2021) have adopted the earlier classification levels of uncertainty by Walker et al. (2010), which has since been expanded upon in Marchau, Walker, Pieters, et al. (2019).

Figure 2.12 DEFRA guidelines on accounting for effects of climate in appraisal



Source: DEFRA (2020)

DEFRA (2020) provides guidance on the monitoring process, suggesting, where possible, to quantify the weight and relative importance of flexibility using a value for money approach. Without specifying any particular approach to use, DEFRA (2020) highlights the important of timing, adaptation thresholds and adaptive pathways analysis for designing adaptation interventions.

With regard to methods for climate resilient appraisal economic decision making under uncertainty, DEFRA (2020) recommends ROA, RDM, portfolio analysis and rule-based decision making support.

2.4.2 Implementation

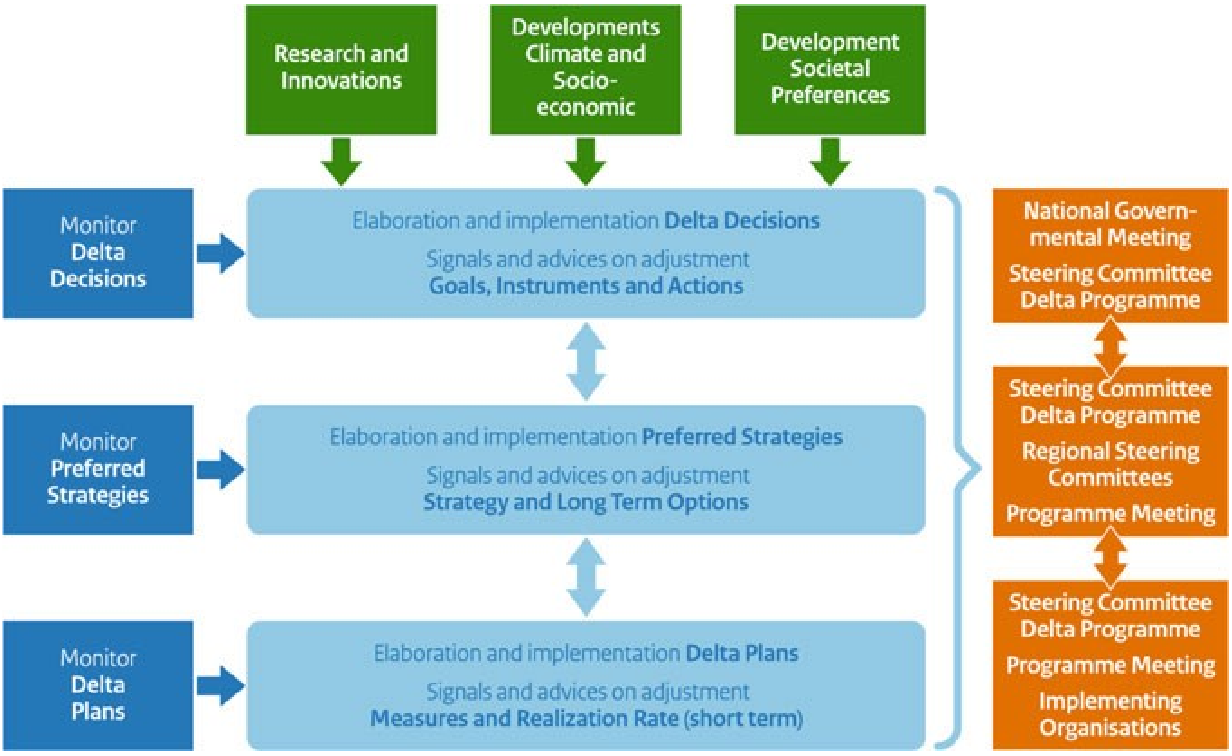
The Clifton to Tangoio Coal Hazards Strategy 2120 uses a hybrid approach based on DAPP, ROA) and multi-criteria decision analysis (MCDA) to decide on strategies for responding to the effects of coastal hazards in Hawke's Bay. The development of the strategy consisted of four parts: (1) definition of the problem, (2) framework for decisions, (3) developing actions and options, and (4) implementation. Steps 1 and 2 were undertaken by strategy consultants, Steps 3 and 4 by a technical advisory group and assessment panels (including wider community input) with MCDA used in Step 4 with modifications to pathway development. Eighteen possible adaption actions were identified, and six pathway sequences were identified for each coastal unit. Pathways were assessed using MCDA, with ROA used to assess their relative costs. Formal strategy reviews are planned to occur at 10-year intervals collecting data on beach profiles, wave climate, sediment movement, erosion losses, etc., including any new emerging research and relevant information. As the strategy is still in development, signals, triggers and thresholds for the adaptive pathways are under development (Bendall & Mitchell Daysh Ltd, 2018; Hawke's Bay Regional Council, 2022; Lawrence et al., 2019).

Auckland Council's (2020) Te Tāruke-ā-Tāwhiri: Climate Plan states that the Council uses dynamic adaptive policy pathways. At this stage of development, the plan has set up a range of monitoring variables across multiple domains including natural environment, built environment, transport, economy, community and coast, food and energy and industry. These indicators will be monitored over three years to measure progress in meeting current objectives and to establish baselines for determining future targets. We assume that this will include the development of triggers and tipping points, and adaptation pathways for each relevant domain as per the DAPP framework.

The UK Environment Agency (2012) adopted a *managed adaptive approach* (based on adaptive pathways approach) in response to the tidal flood risk in the Thames estuary, London. The risk of a storm tide is estimated at having a 1 in 1000 (0.1 percent) chance of occurring in any given year (Environment Agency, 2021). The Thames Estuary 2100 Plan (TE2100) monitors 10 indicators, including sea level, tide levels, river flows, infrastructure conditions, erosion, land use, and institutional/public attitudes. The plan is reviewed and updated every 10 years or if indicator values change significantly. Trigger values have also been identified for indicators, prompting adaptation actions included in the TE2100 plan. The strategy undertook its first monitoring review in 2016, five years after its implementation, and more recently its 10-year review in 2021 (Environment Agency, 2016, 2021).

The Dutch Delta Programme uses a planned adaptation approach for managing several domain goals of flood protection, freshwater supply and spatial adaptation. The programme has a planning horizon to 2100 and consists of multiple sub-programmes for each domain and related region that requires collaboration between national government, provinces, municipalities and regional water boards with inputs from social organisations, scientific and business communities. National and regional strategies are reviewed every six years and flood protection standards every 12 years. The Signal Group, consisting of domain experts, meets with other relevant experts, sub-groups and responsible authorities twice a year (Delta Programme, 2014, 2017; Pieters et al., 2019). Figure 2.13 shows the programme's multilevel monitoring, analysing and acting system to ensure the objectives of the Dutch Delta Programme are met.

Figure 2.13 Dutch Delta Programme – Monitoring, analysis and acting system



Source: Pieters et al. (2019)

3 Preferred methodology

In this section, we use our findings from the literature review to inform our recommendation on the preferred methodology for consideration of climate change uncertainties in transport appraisals.

3.1 The use of a probability-based approach

Keynes (1936, pp. 148–50, 161) suggested that some future consequences could have no probability ratios assigned to them. As a computational matter, mechanical use of formulas permits us to calculate a value for an arithmetic mean, standard deviation, etc., of any data set collected over time. However, the question is what meaning the values calculated in this way should carry in interpreting the past and in forecasting the future (Davidson, 1991; Schumpeter, 1936).

Recent studies further discuss the importance of using a scientific solution for assigning probabilities to future scenarios. This was mentioned by Marchau et al. (2019, pp. 2–3): “The question of assigning probabilities to future scenarios of climate change is particularly controversial. While many argue that scientific uncertainty about emissions simply does not allow us to derive reliable probability distributions for future climate states, others counter by saying that the lack of assigned probabilities gives non-experts free rein to assign their own, less well-informed probability estimates”. We will discuss this further in Section 3.4.

Deep uncertainty describes a situation where the full range of possible futures is unknown and no reliable probabilities can be attached to any future outcomes. Consequently, decision-making cannot be based on probability distributions for a bounded set of plausible futures with a reasonably reliable central tendency.

While long-term investment decisions are always associated with considerable risks, the emergence of climate change has added another dimension that has rendered previously used analytical approaches – used to support decision-making processes – inadequate. The type of analysis that is fit for purpose in the new environment must be considerably broader in order to reflect the complexity of decision-making under heightened uncertainty. As a result, such analyses can no longer be summarised by a simple set of numbers (such as cost–benefit ratios) that can be used as a basis for decision-making. Furthermore, investment strategies themselves must undergo considerable adaptation, which adds another layer of uncertainty to any evaluation of transport infrastructure. A prime consideration for any strategy in a highly uncertain environment will be the retention of an optimal degree of flexibility over time that offers the ability to make considerable adjustments in light of new information.

3.2 Standard evaluation method and uncertainty

Any valuation must first measure the level of uncertainty. One way to measure risk is to find the stochastic properties of the variables affected by the uncertainty. This can be done using stochastic methods, which allow for the values of the variable to change randomly. As Byett et al. (2017) noted, “There are many ways random effects might occur (e.g., a variable might transition to only one (unknown) state of two future possible states or it may potentially transition to many future states)”.

The standard tools in transport appraisals are the transport model and the CBA.

The transport models with a stochastic nature[24] provide information about the risk; that is, known unknowns. This limits their usefulness for considerations of deep uncertainty. However, the stochastic models provide useful information about likely outcomes of different scenario, when combined with other DMDU tools, such as DAPP.

The CBA method does not *transparently* summarise the benefit-cost and risk-reward trade-offs (Byett et al., 2017). This is because the common method for considerations of risks and uncertainty is to use lower and higher discount rates for sensitivity analysis. Byett et al. (2017) highlighted the importance of considering a risk premium: “The common method for factoring a risk premium into a valuation is to add a risk premium onto the discount rate, thus the discount rate is the sum of the risk-free rate and the risk premium. The (gross) discount rate then forms the denominator that discounts future expected cash flows. It is possible to instead apply a risk factor to the expected future cash flow directly and achieve the same result by discounting at the risk-free rate.”

Consistent with Byett et al. (2017), we suggest that the use of transport models and CBA will be improved through using robust planning and management processes, which we discuss in the next section. For the CBA and transport modelling to provide useful analyses, we suggest they need to:

1. Improve measurement accuracy to provide more accurate understanding of the impacts under different scenarios. This includes both the measurement of the variables and the accuracy of the estimated parameters.
2. Provide range estimates to account for underlying risks and variations in inputs. This can be done using stochastic methods and sensitivity analysis.

The considerations of different scenarios as defined during the planning process may be accompanied by technical assessments of interactions between the scenarios in transport modelling.

3.3 Criteria

Before laying out what we believe to be viable alternative methods to allow for deep uncertainty within a Waka Kotahi CBA, it is useful to specify criteria to apply when assessing the suitability of each approach. The following criteria were used to inform the recommendation of methods and measures. They are similar (but not the same) as the criteria set out by Beyazit (2011), Shiftan et al. (2021), and van Wee and Geurs (2011):

- Effectiveness in achieving objectives
- Simple to use
- Cost, time and technical feasibility of applying ADM in the context of Waka Kotahi’s procedures
- Be rigorous (quality assured), commensurate to the size and risk of the investment. A large-scale, high-risk investment may justify a complex and costly approach, while a small and/or low-risk investment may not.
- Fit of method with the IDMF, in particular MBCM.

24 As opposed to deterministic.

3.4 A practical solution

Acknowledging the difficulties with predicting the future in the case of deep uncertainties, we intend to provide a practical solution, with useful information provided for decision-makers. Within the world of DMDU, we attempt to provide a model/framework that is intended to be used not as a prediction tool, but as an engine for generating and examining possible futures (Marchau, Walker, Bloemen, et al., 2019).

There are many dimensions to consider when choosing a practical solution for ADM with deep uncertainty. As more judgemental input is required, it is important that decision-makers attempt to arrive at common understandings and interpretations about the full range of uncertainties impacting projects. A central tool for this is extensive scenario analysis, not with the primary intention of arriving at conclusions regarding relative plausibility and probabilities, but in order to gain a broad understanding of the implications of various uncertainties and the system's sensitivity to the change in assumptions.

The scenarios should examine a range of different paths for climate change progression and corresponding investment strategies. While scenario analysis involves the attachment of cost–benefit estimates to alternative pathways, it should not proceed to aggregation in order to reduce highly complex pathway systems to simple summary statistics.[25] In order to canvas a sufficient range of alternative futures, it may be necessary to move beyond the set of "plausible futures" – based on current knowledge – to the wider set of "possible futures".[26] Among wider insights, the analysis should provide information regarding the risks of over-investment and lock-in costs associated with particular pathways that reflect:

- A high degree of irreversible decisions
- Likely costs of modifications to investment projects over time, and
- Strategies for mitigation of costs associated with such changes

Based on comprehensive scenario analysis – and applying the usual caveats that relate to any decision-making based on assumptions about the future – it should be possible to ascertain whether there is a strong enough case to decide whether a particular investment project should be pursued or not. A sufficient set of scenarios would be required to show that there are suitable investment strategies that suggest a level of performance can be achieved in line with investment objectives.

An in-principal decision about proceeding with an investment needs to be followed by the identification of an optimal dynamic decision-making pathway. This involves an assessment of the appropriate magnitude of the initial investment tranche and the setting of effective future waypoints that enable adaptive decision-making in response to experience and new information that impacts the actual and likely future performance of the asset. Scenario analysis should enable the development of a robust investment strategy that, ex ante, performs well under a range of alternative futures. By definition, it would exhibit sufficient flexibility for adaptation to different types of changing circumstances.

In addition to the initial analytical assessments and investment decision processes, a practical ADM approach accounting for deep uncertainty will also place significant demands on ongoing asset management. Flexibility over time regarding the development paths and

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25 Otherwise, the lack of sufficient information would imply spurious accuracy.

26 The analytical framework referred to is the "cone of plausibility". For more information, see https://thevoroscope.com/2017/02/24/the-futures-cone-use-and-history/

modifications of assets requires re-evaluations at pre-set junctures, but possibly more frequently if sufficient critical new information emerges. Such re-assessments may confirm one of the initially identified potential pathways, or could suggest alternatives that have not previously been considered with a new set of future re-evaluation junctures. An example of this situation would be the decision to construct a road with stronger foundations than initially required in order to enable the subsequent elevation of the road in case of increasing incidence of flooding. However, when the decision to elevate the road is due to be made, the particular flooding patterns that have emerged suggest that it would be cheaper and more effective to invest in flood protection structures at a significant distance from the road. The new arrangement requires the adjustment of the timing of future decision points.

3.5 Evaluation of possible approaches

The methods identified in the previous chapter are not necessarily substitutable. Hence, in addition to the individual methods, we consider the reasonable combination of the methods to find a method that minimises the costs and maximises the usefulness. Accordingly, we identify the following methods:

1. Real options analysis
2. Scenario analysis
3. Dynamic adaptive policy pathways
4. Robust decision making or dynamic adaptive planning
5. DAPP and/or DAP/RDM and EOA (DAPP/DAP/RDM + ROA)
6. DAPP and/or DAP/RDM and SA (DAPP/DAP/RDM + SA)

Also, as discussed in the previous Chapter, EOA is more suitable for the consideration of deep uncertainty compared to ROA, but has not been implemented successfully due to its complex methodology – see Stanton and Roelich (2021). Hence, we do not consider EOA further. Another method that we discussed in the previous chapter was RDM, which provides a more simplified process than DAPP. The two approaches are complementary. Given the more complex/costly process of DAPP, we suggest that RDM could be used in the assessment of smaller size projects.

Table 3.1 shows the criteria for choosing the preferred methodology and the list of the identified methods. We have compared each method to the other methods and scored their suitability on a scale of low (1) to high (3). For example, if the cost of analysis for a method is assessed the highest amongst the available methods, then the score of that method will be low (1).

As illustrated, all methods apart from ROA and SA are ranked high in terms of effectiveness to achieving objectives. The reason for the relatively lower score of ROA is the difficulty in assigning likelihoods to different options. The SA is scored medium because of its potentially lower flexibility to be tailored for achieving multiple objectives. The effectiveness of ROA and SA methods could be improved by combining them with RDM, DAP and DAPP[27] – as shown in Columns 5 and 6 of the table.

27 As discussed, Robust Decision Making (RDM) is a process whereby deliberation is undertaken alongside analysis to iteratively generate and evaluate plausible scenarios to form robust strategies that protect against a range of plausible futures; Dynamic Adaptive Planning (DAP) focuses on implementing an initial prior plan before the resolution of all major uncertainties; Dynamic Adaptive Policy Pathway (DAPP) focuses on the timing of actions and provides an overview of alternative future paths based on adaptation topping points.

In terms of simplicity of use, ROA and SA scored lower than the other methods. This is because assigning likelihoods under deep uncertainty is difficult in ROA. Also, consideration of all scenarios within a SA is extremely difficult. RDM, on the other hand, has the highest score for simplicity, because of its simpler methodology compared to the other methods, which comes at a cost to its robustness (another criterion).

In terms of cost, time, and technical feasibility, the highest score is for RDM, followed by DAPP and DAPP/DAP/RDM+SA. However, RDM has scored lower in terms of technical feasibility because of the higher degree of judgement required by the analysts.

All methods are reasonably robust, if used in their relevant context and by acknowledging their caveats, as reviewed in the previous chapter. Amongst the identified methods, the highest rigour is for the combination of DAPP/RDM with SA and ROA.

In terms of fit with IDMF and MBCM, we suggest that ROA and SA are closely compatible with MBCM because they are already being recommended to be used within MBCM and the supplementary reports on uncertainty. We suggest that the combination of DAPP/DAP/RDM with ROA and SA also provide a high level of consistency with MBCM. The reason for the low score for DAPP and RDM in isolation is that they do not provide a summary number that could be incorporated into the MBCM.

Table 3.1 Criteria and methods

	(1)	(2)	(3)	(4)	(5)	(6)
Criteria	**ROA**	**Scenario Analysis (SA)**	**DAPP**	**DAP/RDM**	**DAPP/DAP/ RDM + ROA**	**DAPP/DAP/ RDM + SA**
Effectiveness	**Medium**	**Medium**	**High**	**High**	**High**	**High**
Simplicity	**Low**	**Low**	**Medium**	**High**	**Low**	**Medium**
Cost, time, technical feasibility	**Low, Low, Medium**	**Low, Low, Medium**	**Medium, Medium, High**	**High, High, Medium**	**Low, Low, Medium**	**Medium, Medium, High**
Rigour	**Medium**	**Medium**	**Medium**	**Low**	**High**	**High**
Fit with IDMF	**High**[28]	**High**	**Low**	**Low**	**High**	**High**

Source: Principal Economics

As discussed in our review, DAPP and RDM are complementary approaches. However, for a small-sized project, RDM in isolation could provide a useful framework for generating and evaluating plausible scenarios. Hence, we recommend using both approaches, depending on the size of the project and the exposure to uncertainty.

3.5.1 The consideration of longer analysis periods

Waka Kotahi's MBCM recommends a 40-year analysis period, which could be extended to 60 years for long-lived infrastructure activities:

28 Only when risk rather than uncertainty applies – which is rare.

“The analysis period, starting from time zero, is the period for which all costs and benefits are included in the BCR calculations. Analysis periods specified in this manual are designed to capture at least 90% of the present value of future costs and benefits. For a 4% discount rate, the standard analysis period remains 40 years. An increase of the analysis period to 60 years is permitted to ensure that the whole-of-life costs and benefits of long-lived infrastructure activities are captured.” (Waka Kotahi NZ Transport Agency, 2021, p. 21)

MBCM also noted that:

> “The time period used in economic evaluations must be sufficient to cover all costs and benefits that are significant in present value terms. [...] It is important to consider the useful lifespan of an activity and adjust the analysis period accordingly. For activities with short-lived assets, or activities where benefits dissipate quickly, it may only be necessary to assess the activity over a 5-to 10-year period. In these circumstances changes to the analysis period should be used as a sensitivity test.” (Waka Kotahi NZ Transport Agency, 2021, p. 21)

It is important to note that MBCM’s current recommendation suggests that, with an increase in the analysis period, the importance of demand forecasting increases:

> “An extension of the analysis period increases the importance of demand forecasting. Emphasis should be placed on developing a range of options and scenarios, and on reporting uncertainty in the business cases and economic evaluation, when the analysis period is extended.” (Waka Kotahi NZ Transport Agency, 2021, p. 21)

More importantly, a change in the timeframe of the analysis will require discounting over long time horizons, which implies lower interest rates, often referred to as intergenerational discounting or discounting future generations. Researchers have generally concluded that discount rates of 1.4–4.3 percent are likely to be appropriate (Goulder and Williams, 2012 as cited in the recent guidebook on accounting for low-frequency, high-impact events in CBA transport appraisals by Departments of Transport across the US – National Academies of Sciences, Engineering and Medicine (2020)).

3.5.2 Project-based and programme-level considerations of uncertainty

Waka Kotahi’s investment decisions are made on a project and programme basis. To understand the impacts of uncertainty at the programme level, valuations need to pay further attention to the distinction between “market” risk and “private” risk (or more literally, “risks and uncertainties”). As Byett et al. (2017) noted: “Market risks are unlikely to be diversifiable, e.g. national GDP growth will wax and wane and project benefits will do likewise. Conversely the private risks can typically be diversified, e.g. the risk of a cost over-run on one project could be offset by a cost under-run on other projects within the portfolio of all projects (assuming there is otherwise no bias towards management incompetence across the portfolio). When it comes to valuation, an undiversifiable risk requires inclusion of a risk factor in the valuation, effectively reducing the present value of any expected future benefits. Under certain circumstances, a diversifiable risk does not require a risk factor in the valuation and hence only a risk-free discount rate is applied to calculate present values” (Byett et al., 2017, p. 15).

Our review of the literature suggests that the available studies are mostly focused on projects. This limits our evaluation of the usefulness of the available methods for programme-level evaluations.

3.5.3 Generation of policy alternatives and scenarios

Defining the appropriate scenarios for consideration in the assessment of climate change uncertainties is beyond the scope of our study. In this section, we provide a brief description of the potential approaches for identifying the scenarios and suggest further investigation of the available methods in a future study.

Deep uncertainty tools such as RDM and EOA are methods that are explicit in how scenarios and policies are generated (and assisting in the decision-making and strategy development) using participatory methods and/or with computational methods. In RDM, scenarios are generated using an iterative participatory approach accompanied by computational model exploration to determine robust strategies. In EOA, scenarios (often thousands of them) are simulated based on sensitivity ranges and implicit consideration for potential follow-up responses to intermediate outcomes in the scenario. These are discussed in more detail in Sections 2.3.4 and 2.3.5.

Wiseman et al. (2011) outlined three approaches for climate change scenario analysis. Each approach corresponds with different outcomes sought by the assessment with different strengths and weakness under different situations.

1. The **off-the-shelf** approach relies on existing climate change scenario model outputs to define the context for developing strategies and decision making. The off-the-shelf approach is often the fastest approach and is most suited for adaptation challenges where uncertainty is relatively low. Examples include decisions that have relatively short timeframes (5–10 years) or where high-quality data and assumptions are well understood. For New Zealand, this would most likely source for off-the-shelf data are the climate change projections provided by MfE (2018).
2. **Tailored exploration** relies on contextual information to create multiple future scenarios in order to better understand climate change implications and adaptation options. In tailored exploration, climate change may be considered as just a “driver of change”. Tailored exploration is a participatory process that integrates diverse opinions and different forms of knowledge. Tailored exploration is best suited for circumstances where uncertainty and/or the potential impact of decisions and events are high. This can be particularly useful for strategy over long time frames, complex and ambiguous system interactions, and where unforeseen events must be acknowledged. The main disadvantage of the approach is that it can be both resource- and time-intensive.
3. **Tailored visioning** is an approach whereby workshop participants define a strategic direction based on a positive vision of a future state, relying on diverse perspectives and knowledge where participants agree on a single ideal vision. The approach does not require a detailed understanding of climate change science or complex system of interactions.

Table 3.2 Appropriateness of scenario development approach

Intention	Off-the-shelf	Tailored exploration	Tailored visioning
To define an ideal future and a pathway to get there	Low	Low	High
To produce scenarios that will act as communication tools	Low	Medium	High

To explore highly uncertain, catastrophic and non-linear events	Low	High	Low
That outputs be quantitative and 'definitive'	High	Medium	Low
To assign a level of probability to output scenarios	High	Low	Low
To use a process that relies on publicly accessible data	High	Medium	Medium
That the process is expert-driven	High	Medium	Low
That the process be participatory	Low	Medium	High
To communicate the potential impacts of climate change	High	High	Low
To incorporate diverse knowledge and opinions	Low	High	Medium
To emphasise learning from scenario process	Medium	High	High
To develop a clear strategic direction or decision recommendations	Medium	Medium	Medium
To avoid criticism for being unscientific	High	Low	Low
To get buy-in from traditional decision makers	High	Low	Low

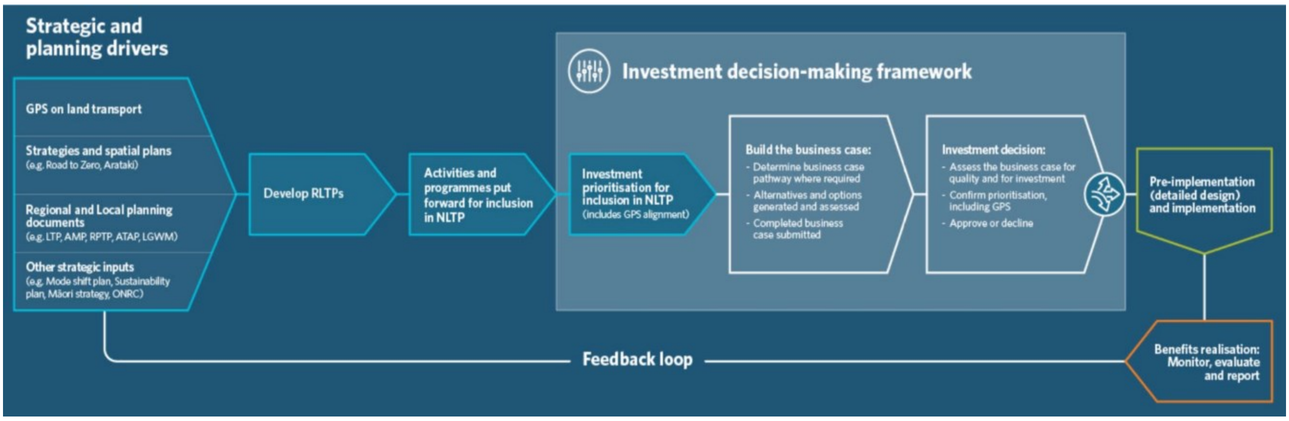
Source: Wiseman et al. (2011)

4 Fit with Waka Kotahi's IDMF

Our findings from the literature review suggested that a combination of Decision Making under Deep Uncertainty method with scenario analysis provides a useful approach for consideration of deep uncertainty. The list of DMDU methods includes DAPP, DAP and RDM. In this section we provide our recommendation for including ADM within Waka Kotahi's IDMF. The suggested changes/additions are presented in numbered paragraphs.

Figure 4.1 shows the end-to-end transport planning and investment system, which shows how the strategic and planning factors lead to the development of Regional Land Transport Plans and consequently the National Land Transport Programme. As shown, IDMF fits within this system, and consists of investment prioritisation for inclusion in NLTP, which includes the business case development, and the investment decision steps.

Figure 4.1 The end-to-end transport planning and investment system



Source: Waka Kotahi (2020)

The findings of our report have important implications for the Programme Business Case (PBC) and Single Stage Business Case (SSBC) development[29]. The process of business case development is in Figure 4.2, the steps required for the Strategic Case are show in Figure 4.3 and further details on the steps included in PBC and SSBC are shows in Figure 4.4.

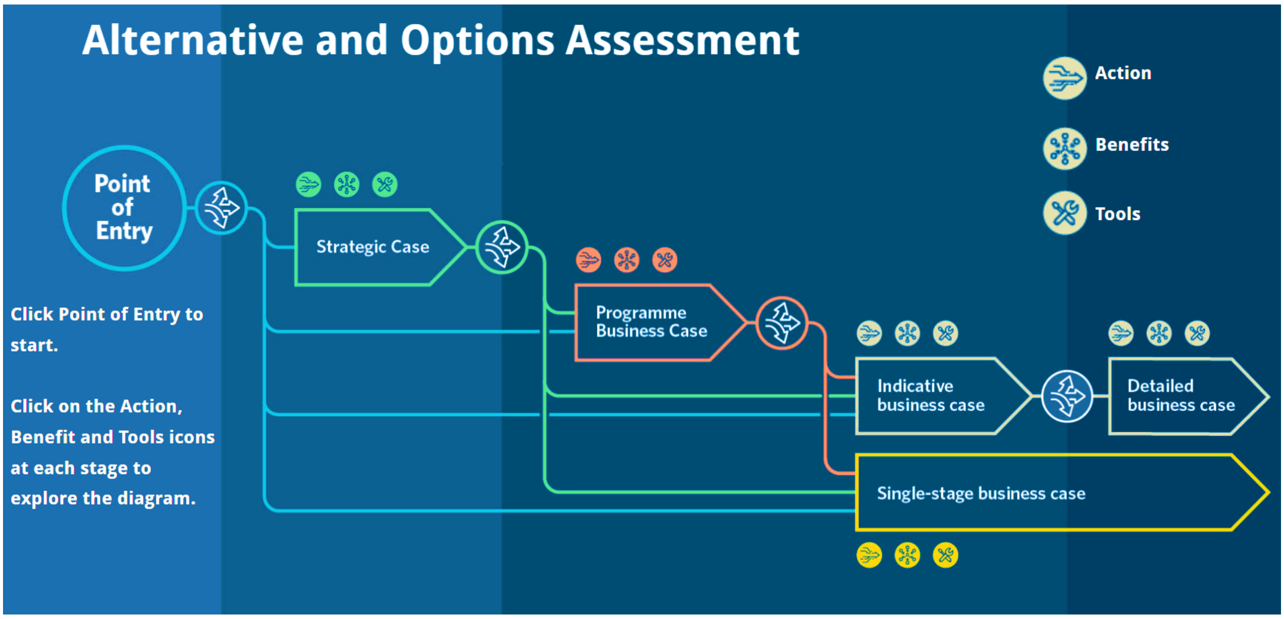
1. We suggest including the risks of climate change effects in early analysis and to consider whether a programme approach is more suited to address climate change uncertainties rather than a single project (e.g., a programme to address national investment into weight-restricted bridges (many of which will face higher flood risks from climate change)).
2. In the creation of the longlist, we recommend to include consideration of adaptive options. We also recommend to consider climate change uncertainties within the Strategic Case. Hence, we recommend adding row item to the steps included in Figure 4.3: "Identify major risk and uncertainties, including those pertaining to climate change". Similarly, we recommend adding this row to the guidelines provided for the 'Indicative business case actions' and the 'Detailed business case actions' – these are presented in slides 10 and 16 (out of 18) of the provided guidelines.

29 Business case approach is an evidence-based approach used for developing business cases for investment through the NLTP.

Adaptation is already being considered within Early long-list assessment (EAST)[30] and Multi-Criteria Analysis (MCA)[31], and therefore we do not suggest any changes.

In the next paragraphs, we provide further details on the fit of our recommended approach with the steps of PBC and SSBC.

Figure 4.2 Business Case development and benefits management



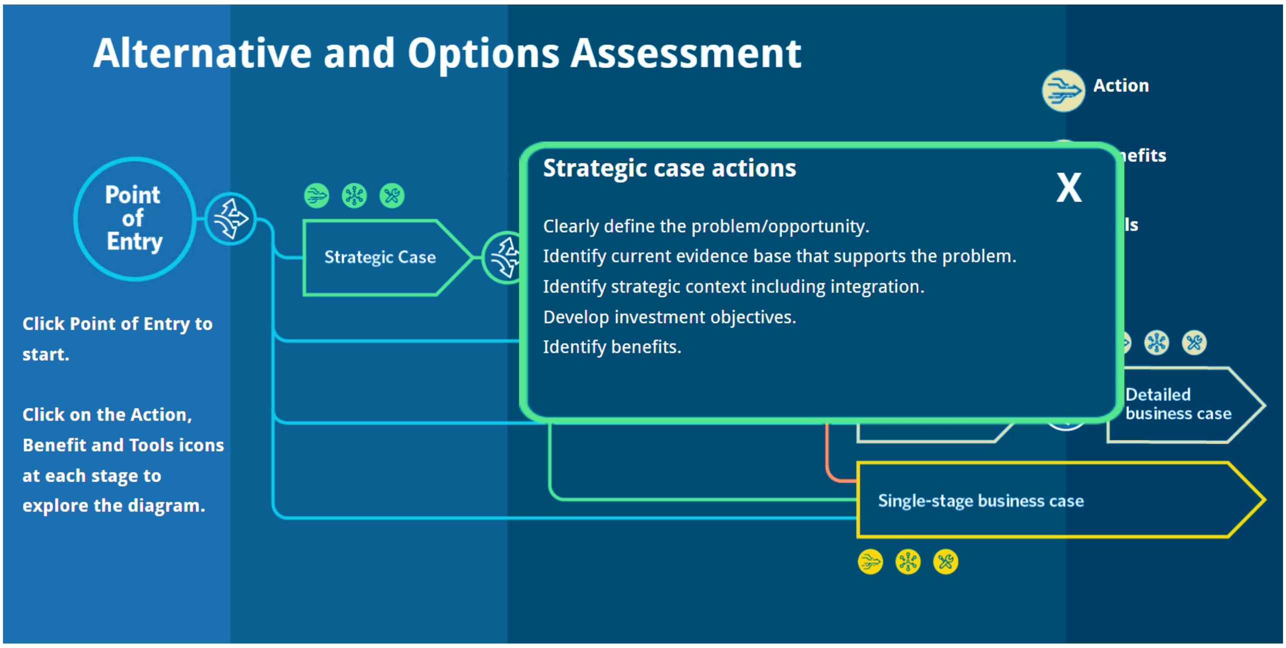
Source: Waka Kotahi (2020)[32]

30 Guidelines on Early assessment sifting tool are available here.

31 Multi-criteria Analysis guidelines are available here.

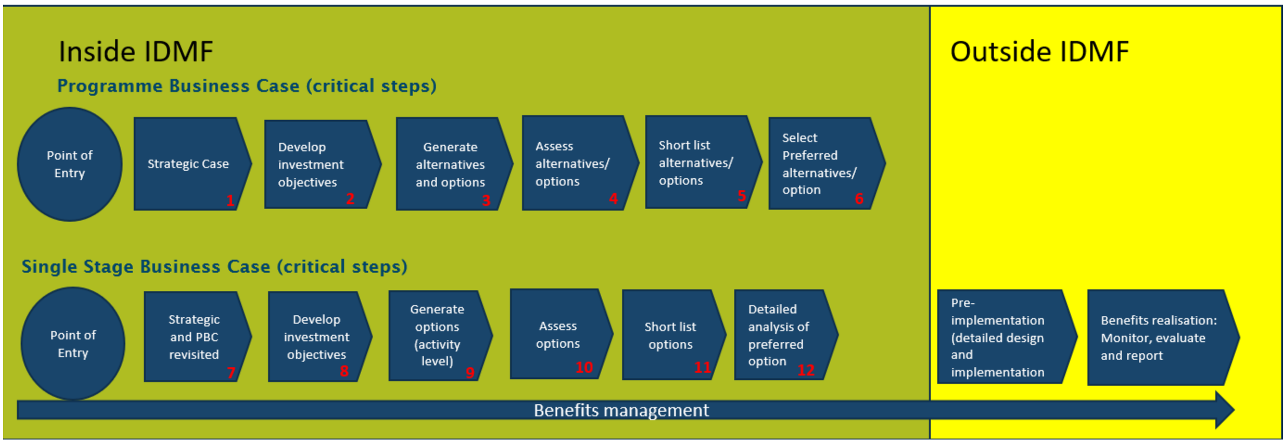
32 The picture is sourced from the Waka Kotahi's resources library – alternative and options assessment, available here.

Figure 4.3 Strategic case actions



Source: Waka Kotahi guidelines for developing alternatives and options – available here.

Figure 4.4 IDMF and business case development steps



Source: Waka Kotahi

The investigation of climate change scenarios (scenario planning) and potential pathways, need to be considered within the strategic case, in the development of business case – these fit within the PBC and SSBC as labelled by numbers 1 and 7 in Figure 4.4. This includes for example, the investigation of weather extremes, including sea level rise, flooding, and other 1 in 100-year events. The investigation of the scenarios needs to be informed using spatial planning and climate model outputs.[33]

3. For the investment objectives considered within PBC and SSBC (labelled by numbers 2 and 8 in Figure 4.4 Where relevant adaptation (and mitigation34) benefits should be

33 The use of a climate change model that shows regional impact variations for given levels of global warming is an essential input into comparative analysis. As most NZTA evaluations will be subject to such comparisons, the model outputs should be an integral part of scenario analyses for individual investments.

34 While mitigation is not within the scope of this report, we suggest it needs to be considered in the

incorporated into investment objectives. We suggest that adaptation needs to be added to the benefits framework.

4. For the generation of alternative and options within PBC (label number 3) and SSBC (label number 9), we suggest further investigation of the plausible scenarios and their different pathways. Our report recommends using a DMDU method for providing a clear consideration for different routes towards objectives. The DMDU methods we suggested included DAPP, DAP and RDM.
5. The process of developing scenario should be a logical sequence and can include a combination of options. Any uncertainties and assumptions need to be identified in this process and the reasoning for considering any identified pathway needs to be clarified. We suggest the current sifting approach for shortlisting the options (Waka Kotahi, 2021) provides a useful approach for shortlisting the identified scenarios (and their pathway)35. For the development of scenarios and pathways, the long-term investments need to consider a 100-year timeframe. Scenario planning process is beyond the scope of the current report, but we provided some high-level discussion in Section 3.5.3.

For the assessment of the identified scenarios (and pathways), as highlighted in numbers 4 and 10 in Figure 4.4, we suggested using ROA and SA. The current MBCM guidelines do not provide clear instructions for using ROA. An earlier Waka Kotahi research project (Byett et al., 2017) provides a comprehensive description for using ROA. SA is the other method that we suggested for quantifying the impacts of identified scenarios. Further guidelines on scenario analysis are provided in section 7 of MBCM. Next section provides further notes on our suggestions for inclusion in MBCM to provide further guidelines on the assessment of risk and uncertainty using ROA and SA.

6. We recommend adding a mandatory row to the Appraisal Summary Table (AST) under the 'Resilience and security" benefit and include the findings from the scenario testing of climate change.

4.1 Suggestions for inclusion within MBCM

Based on the discussion above, we recommend the following additions to the MBCM:

7. "1.5 Alternatives and options" to be changed to "1.5 Alternatives, options, and adaptive pathways"
8. To be appended to "1.5 Alternatives and options" at the end of the 'Options' section:

   Adaptation pathways describe adaptive policy options that can be taken under different environmental conditions (or possible futures). Adaptive pathways consist of a range of individual policy options across a range of different futures (leading to having options available under a range of different scenarios). The concept of adaptive pathways is important for assessing the impact of uncertainty."
9. In section "1.11 Sensitivity analysis", to revise the 'Risk and uncertainty' section: Replace the paragraph starting with "Uncertainties arise when [...]" with:

   "Uncertainties arise when it is impossible to define all possible outcomes or when the objective probabilities of outcomes occurring are unknown. The levels of uncertainty vary between two extreme levels of uncertainty (determinism and total ignorance).

35 While pathways are not currently mentioned in the provided guidelines, they could be considered in the recommended approach.

Deep uncertainty refers to the situations where the future is unknown. For example, climate change is commonly mentioned as a source of deep uncertainty. A low level of uncertainty presents in situations where there are a range of future possibilities. For example, while uncertain, it is possible to consider range of scenarios for the future population growth."

10. To be appended to section "1.11 Sensitivity analysis", at the end of the section:

    Decision Making Under Deep Uncertainty (DMDU) tools are useful for the analysis of deep uncertainty. DMDU approaches are more useful when:

    - The contextual uncertainties are deep, rather than well characterized
    - The set of policies has more rather than fewer degrees of freedom; uncertainties are well characterized and/or few degrees of decision freedom exist, DMDU approaches yield few benefits over traditional predict-then-act approaches
    - System complexity is a heuristic for how well experts know and/or disagree on the proper models, probabilities, and/or system outcomes.

    There are a range of DMDU methods available. The appropriate DMDU method for each project needs to be identified by providing reasoning for choosing that method. For more details on the pros and cons of each method and the most useful methods see Principal Economics (2022)."

11. To be added to section "1.6 Period of analysis" after the sentence "An increase of the analysis period to 60 years is permitted to ensure that the whole-of-life costs and benefits of long-lived infrastructure activities are captured.":

    "For the consideration of Climate change and low frequency-high impact events, particularly for major infrastructure projects, a 100-year time horizon needs to be considered."

12. Page 221 of 426, append at the end of "Scenario testing and demand estimate sensitivities" of Section "7. SENSITIVITY AND RISK ANALYSIS > 7.3 DEMAND ESTIMATION SENSITIVITY TESTS":

    "The situations of deep uncertainty and one in 100-year events require a combination of scenario testing with a Decision Making Under Deep Uncertainty tool, including Robust Decision Making (RDM), Dynamic Adaptive Planning (DAP) and Dynamic Adaptive Policy Pathway (DAPP). In situations that it is possible to allocate some likelihoods to different options, it is recommended to use Real Options Analysis (ROA). For further details see Principal Economics (2022)."

13. A section to be appended at end of "7.2 Sensitivity tests" follows:

    "The benefit estimation of an adaptive option requires account be taken of the option value inherent in the option. There is no prescriptive method available to make this calculation as the degree of uncertainty will vary. Suggest (a) require the analyst to describe the expected extra benefits and costs of adaptive option and (b) allow the analyst to provide an estimate of extra benefits as two sensitivity tests (one for a base scenario (e.g., +2.0°) and one for a warmer scenario (e.g., +4.0°) climate warming scenario)".

5 Conclusion

Background

Based on scientific studies and recent climate events in New Zealand, climate is beginning to exacerbate extreme "one-in-100-year" events. Higher temperatures mean more evaporation and moisture in the atmosphere and stronger storms, droughts and heat waves. Our knowledge of the likelihood of these large-impact events happening in shorter intervals is limited. For Waka Kotahi, the increasingly frequent weather events present a connected set of issues with potentially serious, costly impacts on infrastructure. Climate resilience means recognising that extremes are not necessarily extraordinary, and effective project evaluation methodologies are needed to support the ability to efficiently select between project alternatives, allowing Waka Kotahi to prepare, respond and recover quickly.

Purpose and scope

Waka Kotahi NZ Transport Agency commissioned Principal Economics to investigate how an adaptive decision-making approach to climate change can be incorporated into the Waka Kotahi Monetised benefit and cost manual (MBCM) for evaluating economic land transport activities in New Zealand. Accordingly, the scope of this report was to:

1. Identify the available methods for adaptive decision-making in climate change and their pros and cons
2. Update the consideration of risk and uncertainty for low-frequency/high-impact events
3. Recommend an approach that can be considered for incorporation into Waka Kotahi's processes and procedures, including the Investment Decision Making Framework (IDMF) and MBCM.

Methods, assumptions, and limitations

We used findings from our extensive literature review to identify a list of the available methods for adaptive decision-making and their pros & cons. In consultation with the project's Steering Group, we identified a range of criteria for evaluating the importance of the pros & cons of each method.

In our investigation of the preferred methodology, we identified the following limitations:

- Given the degree of uncertainty and the complexities of the analyses, decision-makers will need to rely on a high degree of qualitative assessments instead of numerical precision. Therefore, the usefulness of the identified approaches depends heavily on the scenario planning process.
- Scenario-based decision-making, strategy development and re-evaluation offer a pragmatic approach to arriving at suitable assessments for infrastructure investments under deep uncertainty. However, while the merit and investment dynamics of individual projects can be determined in that way, how to arrive at valid comparisons of competing projects is less clear.
- The use of a climate change model that shows regional impact variations for given levels of global warming is an essential input into comparative analysis. As most NZTA evaluations will be subject to such comparisons, the model outputs should be an integral part of scenario analyses for individual investments.

- Our review of the literature suggests that the available studies are mostly focused on projects. This limits our evaluation of the usefulness of the available methods for programme-level evaluations.

We recommend a range of Decision Making Under Deep Uncertainty (DMDU) methods to complement the current IDMF framework

We used findings from our extensive literature review to identify a list of the available methods for adaptive decision-making and their pros & cons. In consultation with the project's Steering Group, we identified a range of criteria for evaluating the importance of the pros & cons of each method. The preferred DMDU methods are as follows:

- Robust Decision Making (RDM): this is a process whereby deliberation is undertaken alongside analysis to iteratively generate and evaluate plausible scenarios to form robust strategies that protect against a range of plausible futures.
- Dynamic Adaptive Planning (DAP): this method focuses on implementing an initial prior plan before the resolution of all major uncertainties.
- Dynamic Adaptive Policy Pathway (DAPP): which focuses on the timing of actions and provides an overview of alternative future paths based on adaptation topping points.

Accordingly, to account for the climate change uncertainties, we suggest a combination of DAPP/DAP/RDM with the scenario testing method that is currently recommended within Waka Kotahi's Monetised Benefits and Costs Manual (MBCM).

The recommended DMDU method has implications for different steps in the IDMF

The findings of our report have important implications for the Programme Business Case (PBC) and Single Stage Business Case (SSBC) development. The investigation of climate change scenarios (scenario planning) and potential pathways, need to be considered within the strategic case, in the development of business case. Hence, we recommend the following considerations within PBC and SSBC:

- adaptation needs to be added to the benefits framework for the investment objectives considered
- the plausible scenarios and their different pathways need to be further investigated within the generation of alternative and options step
- Any uncertainties and assumptions need to be identified in the process of developing scenarios and the reasoning for considering any identified pathway needs to be clarified.
- For the development of scenarios and pathways, long-term investments need to consider a 100-year timeframe.
- For the assessment of the identified scenarios (and pathways), we recommend using Scenario Analysis (and Real Option Analysis (ROA) where appropriate).
- We suggest the current sifting approach for shortlisting the options (Waka Kotahi, 2021) provides a useful approach for shortlisting the identified scenarios (and their pathway).

Summary of other findings and recommendations

To account for deep uncertainty, we suggest further focus on the *programme level* analysis by accounting for the criticality of the assets.

The matter of intergenerational equity is becoming of increasing interest due to the potential damage from climate change effects. Intergenerational inequities are likely to occur when effects are long-lasting. The approach here, which is already consistent with the MBCM, is to account for long-lasting effects by applying a longer period of benefit assessment and a lower discount rate within a scenario.

For prioritisation of investments, it is important to compare apples with apples. We suggest considering an extra portfolio at the GPS level for ‘long-term investments’.

Implementation

To provide a useful guideline for the future analysis, it is critical to apply the methodologies identified in this report to a few case studies, with different features. The features of the identified projects with varying (low and high) lifespans, different levels of national significance and different exposure to uncertainty (or risk factors).

The implementation should highlight the process of scenario planning, and challenges with identifying uncertainties. Then, the implementation should provide further details on solutions used for addressing the identified challenges. The limitations of each case study need to be carefully discussed. It is particularly important to ensure robustness in the process of scenario planning.

6 Limitations and recommendations for future work

A critical element for decision-makers is to gain an understanding of the full range of uncertainties and vulnerabilities associated with an investment project over time. The climate-change-specific elements relate not only to the impact of changing natural conditions, but also to flow-on effects through economic and social responses. Given the degree of uncertainty and the complexities of the analyses, decision-makers will have to rely on a high degree of qualitative assessments instead of numerical precision.

Scenario-based decision-making, strategy development and re-evaluation offer a pragmatic approach to arriving at suitable assessments for infrastructure investments under deep uncertainty. However, while the merit and investment dynamics of individual projects can be determined in that way, how to arrive at valid comparisons of competing projects is less clear. Waka Kotahi operates in a resource-constrained setting where the ranking of potential projects is an important factor for the allocation of funding.

The literature does not provide a theoretical methodology that could be applied for comparative analysis. A high degree of judgement will again be a feature of a pragmatic approach to the issue. A central requirement is that the various projects that are being compared have been evaluated on the basis of consistent assumptions regarding the development of the underlying economic environment, as well as consistent assumptions about the impact of climate change. It is important to recognise that the latter does not mean, for example, the same incidence of bad weather events or coastal erosion for all regions. The use of a climate change model that shows regional impact variations for given levels of global warming is an essential input into comparative analysis. As most NZTA evaluations will be subject to such comparisons, the model outputs should be an integral part of scenario analyses for individual investments.

The usefulness of the DAPP and RDM approaches depends heavily on the scenario planning process. Defining the appropriate scenarios for consideration in the assessment of climate change uncertainties is beyond the scope of our study. We suggest further investigation of the available methods in a future study.

For prioritisation of investments, it is important to compare apples with apples. We suggest considering advocating for an extra portfolio at the GPS level for 'long-term investments'. We suggest that this is a major task with significant implications for prioritisation, which should be further investigated in a future study.

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Appendix A: Info-Gap decision theory (IG)

A.1.1.1 Definition

Info-Gap (IG) is a non-probabilistic decision theory for prioritising alternatives and making choices and decisions under deep uncertainty. An info-gap is the difference of what *is known,* and *what needs to be known* to make a responsible decision. The IG theory asserts that there is a trade-off between robustness and quality, and that immunity to an outcome increases as the quality of the outcome decreases. Under deep uncertainty IG theory reframes decision making process to ask the question of *What outcomes are critical and must be achieved?* It seeks satisficing outcomes that are acceptable over a wide range of unanticipated contingencies even if not necessarily optimal (Ben-Haim, 2006, 2010, 2019).

A.1.1.2 Description of the method

Ben-Haim (2019) suggests that when facing deep uncertainty attempting to optimise the outcomes based on zero-robustness prediction is not recommend. Instead, alternatives should be prioritised based on robustness for achieving critical outcomes, potentially supplemented by analysis of opportuneness.

In Ben-Haim & Demertzis (2016) the info-gap robust satisficing methodology is described as quantifying the trade-off between confidence (expressed as robustness to uncertainty) and performance (the decision maker's outcome requirements). The trade-off can be interpreted as the cost of robustness. In quantitative analysis using IG theory, this trade-off can be illustrated as a monotonic plotted of robustness versus performance requirements where the slope represents the cost of robustness, and the horizontal intercept reflects an error-free outcome. IG theory decomposes the decision-making processing into three components as illustrated in Table A.1.

Table A.1 Info-gap components

Components	Description
Uncertainty model	The uncertainty model expresses what we know and the unbounded horizon of uncertainty around our knowledge.
System model	The system model expresses what we known about the system or situation that must be influenced, its dynamics, evidence, environment and any other relevant knowledge.
Performance requirements	Performance requirements expresses the criteria for success. It answers the question of: *What do we need to know to achieve an acceptable outcome?*

Source: Ben-Haim (2006, 2010, 2019)

Info-gap decision functions

Using these three components two decision functions are formulated to support the choice in what actions to undertake. This is illustrated in Table A.2.

Table A.2 Info-gap decision functions

Decision functions	Description
Robustness function	Assess the greatest tolerable horizon of uncertainty. When operating under deep uncertainty determine which decisions guarantee that the desired outcome will be achievable.
Opportuneness function	Assess the lowest horizon of uncertainty which is necessary for better-than-anticipated outcomes to be possible (though not guaranteed). How wrong must we be for attractive but unexpected outcomes to be possible?

Source: Ben-Haim (2006, 2010, 2019)

Conceptual proxies for robustness

Ben-Haim & Demertzis (2016) provided a list of proxies for robustness relevant to decision making using IG theory - as shown in Table A.3.

Table A.3 Conceptual proxies for robustness

Proxies for robustness	Description
Resilience	An attribute of rapid recovery of critical functions. A policy is robust against uncertainty if it can rapidly recover from adverse surprise and achieve critical outcomes.
Redundancy	An attribute of providing multiple alternative solutions. A policy is robust against uncertainty if it can be achieved by having alternate policy responses available.
Flexibility	An attribute of rapid modification of tools and methods, often useful in recovering from surprise. A policy is robust if its implementation can be modified in real time.
Adaptiveness	An attribute of being able to adjust goals and methods in the mid- to long-term. A policy is robust if it can be adjusted as information and understanding changes. The emphasis is on a longer time range, distinct from on-the-spot flexibility.
Comprehensiveness	An attribute of having interdisciplinary system-wide coherence. A policy is robust if it integrates considerations from technology, organisational structure, capabilities, cultural attitudes and beliefs, historical context, economic mechanisms and forces, and other factors. A robust policy will address the multi-faceted nature of the problem.

Source: Adapted from Ben-Haim & Demertzis (2016) and Ben-Haim (2019)

This is similar to the 'most useful' definition of resilience identified by Money et al. (2017) that was adopted into the Waka Kotahi NZ Transport Agency Economic evaluation manual (EEM) (now superseded by the MBCM):

"Resilience is the ability of systems (including infrastructure, government, business and communities) to proactively resist, absorb, recover from, or adapt to, disruption within a timeframe which is tolerable from a social, economic, cultural and environmental perspective.” (Money et al., 2017, p. 5)

Appendix B: Real options analysis

B.1.1.1 Examples of different options in ROA

Options to *delay* some or all of an irreversible commitment to a project or part of project.

The emergence of desalination technologies made it viable, and safe, to delay committing to the costs of new facility that would not be needed should the drought break. The shorter lead times involved, and the greater certainty of supply enabled the delay, and so reduced the risk of overinvesting in capacity. The traditional approach to dealing with drought risk, building and filling dams ahead of the drought, afforded no such flexibility

***Information* options**

Information options provide access to information that may reduce key uncertainties which are constraining the value of the strategy. Additional information allows the project to be more tightly optimised around the way the future is actually going to be, rather than the way it was first assumed it would be.

- These can arise naturally out of delay options – for example delay in commissioning construction of a desalination plant has the potential to allow the drought to break and so enable commitment to the new plant to be avoided completely.
- They can also emerge from proactively commissioned investments which gain access to better information – for example, through mineral exploration, through commissioning of detailed studies of demographic trends near an area being considered for development, or through other forms of investment in R&D.

However, for the real options approach to add value to the decision-making process, either the information uncertainties must be resolvable prior to the investment being made or it must be possible to manage the investment so that it can adapt as uncertainties are resolved and outcomes emerge.

Options to *expand capacity or supply* rapidly or cost effectively in response to higher than expected demand

- Peaking power stations afford access to the capacity to ramp generation up rapidly, to respond to peaks in demand, allowing high value opportunities to be tapped to satisfy system demand.
- Making provision for transport corridors that allow for greater than expected future demand, for oversizing the pipes on gas or water infrastructure investments etc. can all enable lower cost future expansion in capacity.

Options to *reduce* supply **in response to a drop in demand or the value of marginal supply**

- Sydney's desalination plant can be scaled back, through switching off modules, or turned off entirely in the event that its dams fill and start to overflow, allowing wasteful operating costs and environmental impacts to be avoided.

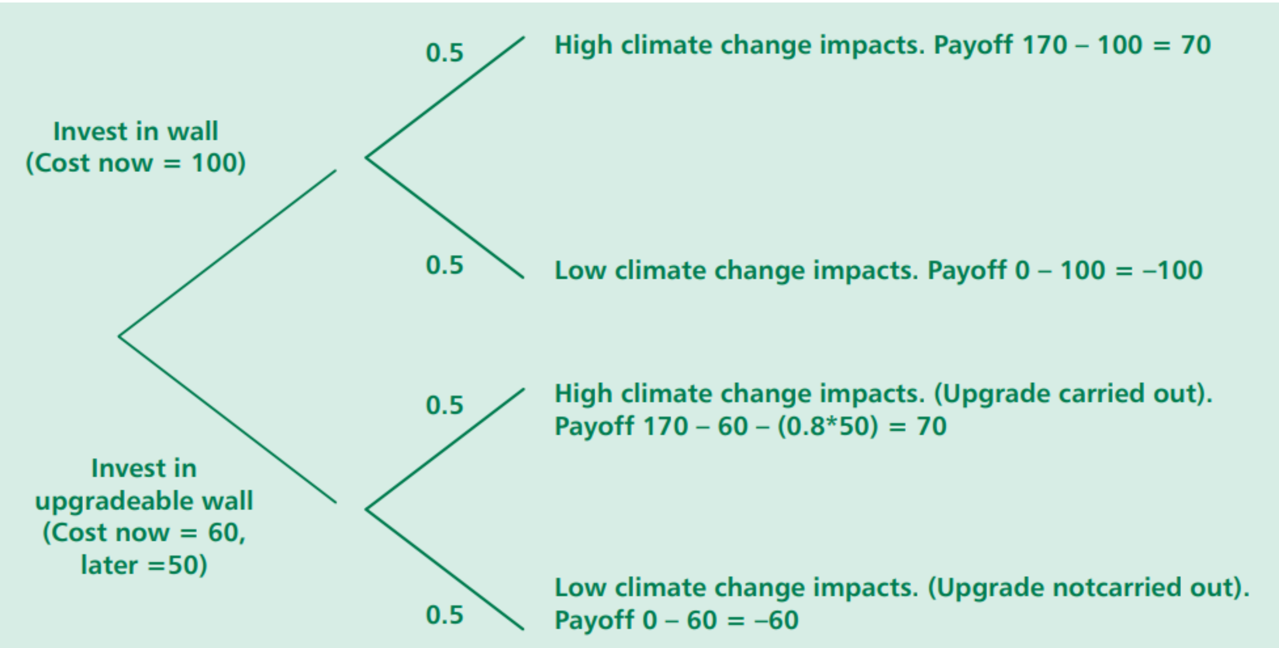
Options to switch the way a demand is met

- Dual petrol/LPG cars have options to switch between fuels to exploit shifts in relative prices or availability of fuels
- Options for dual fuel generating plant are more expensive, but allow advantage to be taken of future changes in relative fuel prices

B.1.1.2 Examples of ROA process

Consider a proposal for investing in infrastructure protecting against the impacts of river flooding due to climate change. Because of time required to build the infrastructure, this is best done in advance but there is uncertainty about future impacts. There are two options: invest in a wall, or invest in groundworks for a wall which has the option to be fully upgraded quickly in the future. There is an equal probability of high or low climate change impacts in the future. The standard wall costs 100, and has benefits of 170 from avoided flooding if high climate change impacts occur (zero otherwise). The groundworks for the upgradeable wall cost 60, the future upgrade costs 50 and the benefit is also 170 if high climate change impacts occur. The upgrade can however be put off until there is more certainty about climate change. The information can be set out in a decision tree:

Figure B.1 Example of ROA – using a decision tree



Source: Department for Environment, Food and Rural Affairs as cited by HM Treasury & Treasury (2020, p. 111)

Simplifying assumptions: residual damages under the "do not invest" strategies have been ignored; the discount factor for the future decision to upgrade or not is 0.8. The expected value of investing in the standard wall is a simple net present calculation, calculating the expected costs and benefits of the investment. The NPV is (0.5*70) + (0.5*-100) = -15. This suggests the investment should not proceed. Flexibility over the investment decision allows the possibility to upgrade in the future if the impacts of climate change are observed to be high. The expected value of this option can be calculated. If the impacts of climate change turn out to be high enough to warrant upgrading, then the value of the investment is 70 in net present value terms. If the impacts are low, no upgrade is carried out but the earlier groundworks are sunk costs, totalling 60. However, these sunk costs are lower than in the case of the "standard" wall and overall, the expected value of investing now with the option to upgrade in the future is (0.5*70) + (0.5*–60) = +5. Comparing the two approaches shows an NPV of -15 for the standard approach, and +5 for the Real Options approach. The Real Options approach also has an unmonetised benefit in allowing better views of the river for longer. Flexibility to upgrade in the future is reflected in the higher NPV, and switches the investment decision.

Appendix C: Dynamic adaptive planning (DAP)

Walker et al. (2019) outline five steps in undertaking DAP. We apply DAP at a high level to coastal flood hazards with the objective of residents and who live close to the shoreline to illustrate the approach.

Step 1 – Stage setting

Stage 1 sets the foundation of plan. Goals, and objectives important to planners and stakeholders are defined. Constraints are identified and a set of alternative actions to achieve the objectives are analysed.

Step 2 – Assembling an initial plan

Step 2 is to assemble the basic policy and the identification of conditions needed for the basic policy to succeed.

Step 3 – Robustness, vulnerabilities and opportunities of the initial plan and anticipatory actions

Step 3 identifies in advance the vulnerabilities and opportunities associated with the initial plan, and specific actions to be taken in anticipation or response to them. Vulnerabilities are developments that could adversely affect the performance of the initial plan and opportunities are developments that can increase the chance of success.

Kwakkel et al. (2010) identifies four types of actions that can be taken in anticipation of specific contingencies or expected effects of the initial plan, shown in Table C.1.

Table C.1 Actions

Contingent actions	Description
Mitigating actions (M)	actions to reduce adverse impacts from *certain* vulnerabilities
Hedging actions (H)	actions to spread or reduce risk from adverse impacts from *uncertain* vulnerabilities
Seizing actions (SZ)	actions taken take advantage of *certain (or very likely)* new developments that could make the plan more successful, or succeed sooner
Shaping actions (SH)	actions taken proactively to affect external events or conditions that either reduce the plan’s chance of failure or increase the plan’s chance of success

Source: Adapted from Kwakkel et al. (2010)

Step 4 – Set up a monitoring system

Step 4 is to develop a system to monitor the performance of the plan and inform decisionmakers on the actions that can be taken in response to new conditions. The monitoring program should include *signposts* indicating whether the initial plan is currently achieving its goals and/or whether vulnerabilities and opportunities are impeding the plan from achieving its objectives in the future.

Signposts specify the types of information and variables monitored. When a *signpost* level reaches a critical level or *trigger,* this signals that (contingent) actions should be taken to ensure the initial plan is on course to achieve its specified goals.

Step 5 – Prepare trigger responses

Trigger events and related actions are developed prior to implementation to adapt to new condition if a trigger event occurs over the life of the plan. These actions may require significant planning investment to ensure contingencies can be operational without jeopardising the initial goal.

Walker et al. (2013) describes four types of contingent actions that can be taken in response to triggers, shown in Table C.2.

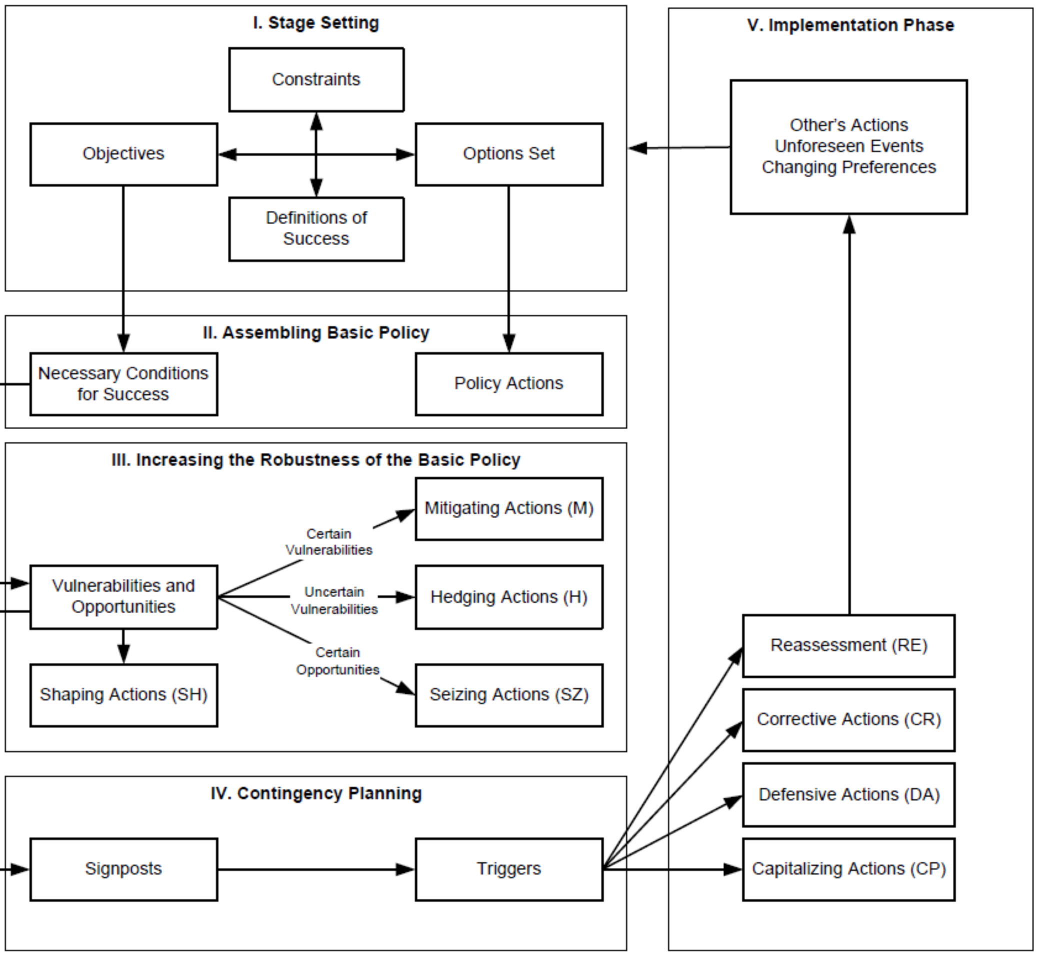
Table C.2 Contingent actions

Contingent actions	Description
Defensive actions (DA)	Responsive actions taken after implantation of the initial plan to clarify the plan, preserve its benefits, or meet outside challengers in response to specific triggers, but lead the initial plan unchanged
Corrective actions (CR)	Adjustments to the initial plan in response to specific triggers
Capitalising actions (CP)	Responsive actions taken after implantation of the initial plan to take advantage of opportunities that further improve its performance.
Reassessment	A process initiated when the analysis and assumptions critical to success have lost validity (i.e. when unforeseen events cause a shift in fundamental goals, objectives, and assumptions underlying the initial plan)

Source: Adapted from Walker et al. (2013)

The plan is then implemented with actions from Step 2 and 3 to be undertaken immediately and the monitoring system established. Policy making is suspended until a signpost reaches a trigger value prompting action or reassessment. Figure C.1illustrates the DAP development process.

Figure C.1 Designing a dynamic adaptive decision-making process



Source: Kwakkel et al. (2010) adapted from W. Walker et al. (2013)

C.1.1.1 Pros and cons and DAP

DAP's reduced dependence on the "predicted future" and adaptation to new information makes it more suitable for dealing with deep uncertainty (Singh et al., 2020). However, the qualitative nature of this approach has led to limited applications of it.

Appendix D: Further details on DAPP steps

Haasnoot *et al.* (2013, 2019) outlines the steps involved in implementing DAPP – as below.

1. Decision context
    a. Participatory problem framing
    b. Describe the system and its boundaries
    c. Specify objectives and outcome indicators
    d. Identify uncertainty or disagreements
2. Assess vulnerabilities and opportunities and identify tipping points
    a. Assess adaptation and opportunity tipping point conditions of present policy for relevant uncertainties
    b. Develop (transient) scenarios describing uncertainties
    c. Assess timing of tipping points with (transient) scenarios
3. Identify and evaluate options
    a. Assess efficacy of options, adaption and tipping point conditions, and timing of tipping points
    b. Reassess vulnerabilities and opportunities of options
4. Design and evaluate pathways
    a. Explore adaptation and development pathways
    b. Generate pathways map
    c. Evaluate pathways and illustrate trade-offs

Optionally, reassess options in light of new information from pathways map (Step 3).

1. Design adaptive plan
    a. Select preferred pathways
    b. Specify short-term actions and long-term options
    c. Specify preparatory actions to keep options open
    d. Design a monitoring plan for signals, including signposts and trigger values
2. Implement the plan
    a. Implement (short-term) actions
3. Monitor the plan
    a. Monitor for signals of change, new actions or breaking of assumptions
    b. Implement actions(s) if an adaptation tipping point is approaching
    c. Implement corrective and preparatory actions, or new signposts if needed to stay on track
    d. Reassess the plan if indicated by signals (e.g., unexpected developments or newly available actions) (Step 1).

    Reassess if needed (Step 1).