Chapter 4. Managing climate change uncertainty in transport infrastructure design and network planning

Managing uncertainty is not a new aspect of transport policy – considerable climate change uncertainty surrounds future demand projections and the global trends that can impact flows of people and goods. There is also micro-level uncertainty on how specific parts of the transport networks may be affected by disruptions. Addressing these incidents and sources of uncertainty lies at the heart of transport decision making. This chapter looks at strategies including, but not limited to, cost-benefit analysis to address this "deep" uncertainty for transport infrastructure and services whose life-times extend well into the future.

Transport asset managers face a fundamentally uncertain future with respect to infrastructure and network vulnerability to climate change and future extreme weather events. Broad evidence supports the view that man-made emissions of greenhouse gases are changing the climate, yet considerable uncertainty remains over the exact scale, scope and regional impacts of climate change which complicates adaptation efforts. This uncertainty remains irrespective of the source of climate change (anthropogenic or natural) and is sensitive to our understanding of the physical processes that link observed increases in atmospheric greenhouse gas concentrations to changes in climate. Nonetheless, despite this uncertainty, decision-makers must still make investment decisions that maximise public welfare and deliver on public policy objectives. This section explores the nature of uncertainty linked to climate change adaptation efforts and explores principles and tools for decision making under these uncertainties.

Climate change uncertainty in the context of adaptation efforts

Normally, meteorological and climate factors fall into the range of manageable risks that asset managers must contend with. In fact, in many ways, they are one of the principal risks that asset owners must address because they have the potential to significantly, and sometimes suddenly, degrade assets and network performance. For this reason, historic climate and meteorological variables are embedded in both the siting of transport networks and the design specifications of specific assets. This ensures that infrastructure continues to operate under a range of expected meteorological conditions and weather phenomena. Even though the natural variability of extreme weather events may cause significant disruption, if asset owners have undertaken due diligence in both the planning and design phases of infrastructure deployment, these risks are generally well known and are more-or-less contained. This is may no longer be true since under a changing climate regime, both meteorological and climate parameters are changing in uncertain ways leading to difficult-to-predict end-states. Indeed, many infrastructure owners and managers already have to come to grips with the implications of climate change for the performance of their assets and networks. Here, the “embeddedness” of climate variables in transport infrastructure places assets and network service continuity at risk. – both at potentially significant costs.

Part of the difficulty facing asset owners and managers is that the decision-support mechanisms that were used to assess existing infrastructure are less and less adapted to assessing their replacements or, for that matter, understanding forward-going risks (Patt, Hinkel and Swart, 2011;Watkiss et al., 2012). That is because the science behind understanding future climate change impacts is based neither on observational data of future climate nor on experimental approaches but rather on models. While the models used for climate projections are informed by observational data, the models produce representations of future climates that extend well beyond the range of the climate in which the data that informs these representations were gathered (Patt, Hinkel and Swart, 2011). These models, as described in Chapter 1, assemble numerous uncertainties that cannot be reduced through observation. The cascading uncertainties include uncertainty on:

- the volume of greenhouse gases emitted over time
- the sequestration rate for these gases and thus their resultant atmospheric concentration
- the response rate of global temperatures to these evolving atmospheric concentrations
- the impacts these changes in temperature will have on hydro-meteorological phenomena at finer and finer spatial resolution
- how these changes in hydro-meteorological cycles (and sea level rise) will impact ecosystems, the built environment
- how humans will react and/or adapt to these impacts.

For all of these, the larger the range of uncertainty, the smaller the likelihood that the mean of the projected range will be near the actual future value. Thus, in the absence of explicit likelihood information for a particular variable, the range of uncertainty may provide some guidance to approximate likelihood. For some of the uncertainties listed above, the ranges of outcomes can be described in a quantitative manner while, given current knowledge, this may not be possible for many others. Walker et al. (2003) describes a gradient running from deterministic knowledge to indeterminacy (Figure 4.1) that helps frame uncertainty for decision making. In the context of climate change, statistical uncertainty may be associated with the observation of existing climate variables that may include some observational biases, scenario uncertainty may extend to knowledge about policy responses to (uncertain) levels of emissions and their efficacy, and recognised ignorance may describe the current state of knowledge on certain hydro-meteorological feedback cycles and which calls for competing models to provide a range of plausible future outcomes. Various alternate scenarios and analysis pathways may compensate for these three types of uncertainties – but there are some things that fall outside of the range of the deterministic – these are things we do not know we do not know – or complete indeterminacy (Walker et al., 2003). All of these types of uncertainty, and the latter one especially, matter for climate change adaptation policy and will require tools and approaches that help guide decision making despite imperfect knowledge about climate change.

Figure 4.1. **Knowledge-ignorance gradient for uncertainty management**

Statistical uncertainty	Scenario uncertainty	Recognised ignorance	Total ignorance
Determinism			Indeterminacy

Source: Walker et al., 2003.

A changing climate poses two fundamental challenges to infrastructure owners. The first is that they must ensure continued asset performance under sometimes significantly modified climate conditions – conditions which may decrease the present value of their networks or increase maintenance and refurbishment costs, or vice-versa. The second challenge is that authorities or private operators must design and build new or replacement assets in the context of these same changing and largely uncertain climate variables. Uncertainty regarding these variables runs the risk of over- or under-specification of infrastructure design standards. Over-specification of design standards results in stranded or non-productive investments whereas under-specification may lead to asset failure or network service degradation. These are important risks for public authorities who are tasked with delivering satisfactory and predictable transport services and for private operators who must realise expected returns for their investors.

Critical to this dual task is the ability for authorities or private entities to assess options, including capital investment options, to deliver transport services in spite of this uncertainty. A number of decision-support tools are available to undertake this appraisal, and the first among these is cost-benefit analysis (CBA). Other traditional transport appraisal techniques include cost-effectiveness analysis and multi-criteria analysis.

Traditional decision support tools

Cost-benefit analysis

Cost-benefit analysis (CBA) is one of the most widely used decision-support tools for guiding transport investments. CBA places a value on relevant costs and benefits to society of considered options and then estimates the net present value of these taking into account the life of the investment and a selected discount rate. It is up to the decision maker to select the time horizon of discounting and required returns on investment. For transport system investments the horizon varies according to the technical life span of the investment. For transport infrastructures, such as roads and railways, the horizon is typically 20-50 years. For some systems, such as traffic control systems which involve information and communication technologies, the life span of which is much shorter, usually not more than 10 years.

Cost-benefit calculus can be used for any investment or activity that marginally changes the behaviour or performance of the system under analysis. In transport infrastructure projects, it is the network that is changed and the aforementioned savings are pursued by the investment capital outlay.

The costs of crashes and environmental items are usually considered externalities, i.e. costs that are not borne within the system (users of the mobility system, infrastructure owners, etc.) but by third parties or society as a whole. Benefits can also be external, but these are difficult to capture and are often excluded from standard analysis. The boundaries of cost-benefit analysis must be decided on beforehand; as the externalities can extend indefinitely they cannot all be considered in practice.

Extreme weather and climate change risks (costs) represent a new type of externality which should be addressed in CBA. No standard procedure exists to do this, although some basic principles have been introduced in analytical format (see e.g. Frankhauser et al., 1999). Routine CBA may not be suited for assessing medium-term or long-lived investments in light of climate change. That is because CBA is an “Agree on Assumptions” approach that first seeks agreement on current and future conditions (e.g. either discretely as in the statistical value of life or through a probability distribution regarding future demand levels), analyses options and picks an optimal outcome. “Agree on Assumption” appraisal works best when stakeholders can agree on the quantification of impacts and how these impacts should be valued over time.

Where the probability of future climate impacts can be robustly assessed and where agreement can be found on both the quantification of non-monetised impacts and discount rates, CBA retains its usefulness. Risk-adjusted discount rates and providing decision makers with explicit assessments of climate-related uncertainties can help improve CBA (ITF, 2014). However, many climate change impacts are subject to deep and cascading uncertainty and cannot be assigned objective or subjective probabilities. Likewise, agreement on other inputs to CBA may be difficult to obtain in light of a changing climate. These shortcomings limit the usefulness of cost-benefit analysis as a stand-alone approach to guide transport investments for long-lived infrastructure in light of climate change.

The EWENT project identified three types of cost categories for CBA in the context of climate change and extreme weather: crash-related costs, time costs, and infrastructure-related costs. The latter comprised physical damages to infrastructure and increased maintenance costs (Nokkala et al., 2012). In the EWENT project framework, only crash-related costs were regarded as externalities, but even this can be debated as most crash-related costs are typically covered either by insurance or by users of the transport system themselves. Hence, in theory, most extreme weather costs should already be internalised, but they in fact are not. The reasons for this are multiple, and include the following:

- Extreme weather related crash costs appear in crash statistics and are hence accounted for in purely statistical sense. However, the marginal impact of extreme weather to crash incidence is not clear and measures that purely improve traffic safety might not have any material impact on weather-related crashes. In Kreuz et al. (2012) it was estimated that 10%-20% of all road crashes are more or less attributed to adverse weather conditions.

- Extreme weather-induced time delays of freight affect shippers' costs, amounting to significant cumulative annual figures (Nokkala et al., 2012). These costs are borne by actors outside the transport system and therefore they can be regarded as externalised.
- Increased maintenance costs are in many cases borne by private sector contractors, especially when road or other infrastructure managers have outsourced day-to-day maintenance services to private service providers. This has been done widely in some countries e.g. in Sweden and Finland, both at national level and municipality level. To win the fixed-period maintenance contracts, the contractors cannot or will not include extreme weather risk premiums in their contract prices and in the worst cases cover the negative cash flows themselves. These costs do not appear in any calculations. It is an outsourced risk from the perspective of infrastructure managers but a socio-economic loss as a whole.

Difference in policy and managerial decision tools

In most cases, extreme weather or climate change risks are not a part of the project appraisal methods and this reflects the difference in policy statements and tools put to work in practice. An example of this was pointed out in Leviäkangas and Hautala (2011) concerning environmental externalities in transport sector in Finland. The pricing regime (taxes on vehicles and fuels) and policy commitments forcefully favour greener transport, but when investments are made for example in road infrastructure, the standard appraisal method clearly prioritises efficiency-enhancing (i.e. time-saving) projects. Environmental benefits account approximately only 1% of the identified benefits of Finland's greenfield road projects. The analysis stated:

> Even if climate change could be challenged in many respects, there is a possibility, a risk, that the change is real. This should be reflected in price, as do the risks of future prospects in the prices of shares quoted in stock market. Hence, the unit cost values (prices) of emitted tons and persons exposed should be lifted to a level that corresponds to the policy targets when making public investments (Leviäkangas and Hautala, 2011).

This analysis underlines that policy objectives may be misaligned with the outcome of CBA especially when the latter assumes prices and weights that are not reflective of societal preferences and appetite for risk.

Extreme weather risks and time value of money

Standard CBA calculations are based on discounting future flows of cash or non-cash based costs and benefits, using two principal risk appraisal techniques: either by risk-adjusting the required return on investment (the discounting rate) or, or by including probabilistic risks (e.g. the expected costs) into the equation. Both methods work in principle, but are applicable to different contexts.

Risk-adjusting of discounting rates is a demanding exercise. Any risk can be argued to be valid for adjusting the rate, but not all risks should be incorporated into CBA. Adjusting can be done for uncertainty regarding to-be-realised costs or benefits (volatility), demand risk, technological risk, etc. The common denominator for all these risks is *time*, as "the nature of things" defines that all these risks are increasing as a function of time.

"Time risk" means that the longer the time period considered, the more uncertain are the states-of-the-world that lay the basis for future projections. In other words, the further to the future we aim, the greater the uncertainty of hitting the target. In strictly financial investments this logic is self-evident: it is riskier to invest one's money for 30 years than for three years. For transport investments, this issue has been analysed in the context of investments in intelligent transport systems (ITS). ITS investments have typically much shorter life span than conventional infrastructure investments and therefore there are grounds to risk-adjust the discounting rate downwards for ITS investments (see e.g. Leviäkangas and Lähesmaa, 2002), thus making ITS investments time-wise less risky than traditional infrastructure investments. For extreme weather and particularly climate change related analysis time risk is of relevance as the phenomena are not only uncertain but also perhaps far away in the future.

"Volatility risk" may be associated directly with time risk (for the far-away future) but it also may be associated with expected volatility of costs and/or benefits, which of course are uncertain just like most assumptions regarding the future. But the costs of extreme weather bear precisely this risk volatility: the costs can be more or less as expected or they can be completely out of the normal range of expectations, massive in scope and exceeding all expectations. Potential savings in these costs deserves attention in cost-benefit analysis. There are scientists that have analysed extreme events and some of the results suggest that our perception of weather extremes in fact underestimates their frequency (Makkonen, 2006; 2008), but there is no consensus among researchers regarding this finding.

The most pragmatic stakeholder group, which is also familiar with economic risk assessment, is the project finance community. Financiers, for the most part, approach risk operationalisation through adjusting their required returns according to risk-return theory, first introduced by Markowitz (1959). Public investors, such as transport agencies, face difficulty in changing the standard cost-benefit analysis procedures and are not familiar with risk-adjusting their discounting rates, though in principle this should be possible (Stiglitz, 1994). But in practice, public investors' required returns – the social discounting rates – are kept constant and applied as such thus disregarding the varying risk profiles of projects. In this context, public investors' alternative is to include the expected costs of extreme weather events as cost items in their cost-benefit calculations.

The selection of discounting rate is a managerial decision, and for social discounting rates to be used for public investments the situation is identical. Each country and their public body investors must decide on how much they require return for public investments. In Finland, for example, the discount rate has been set at 4% for all transport sector state investments across the modes (Finnish Transport Agency, 2011). The rate was lowered from 5% and residual values are estimated based on true expected technical life of the sub-asset after 30 years. Infrastructure projects are divided to sub-components, e.g. sub-structures, bridges, culverts, pavements. For instance, if the expected life of a bridge in a road project is 80 years and the cost estimate is EUR 20 million, the present residual value with 4% discounting rate of the bridge in cost-benefit calculus is EUR 20 million × (80-30) a / 80 a × 0.308 = EUR 3.85 million. This calculus is repeated across the sub-components of the project.

The changes made to the previous guidelines make long-term evaluation more feasible than previously. Also the unit values for crashes, time and environmental factors have been raised by 1.5% annually for the 30 year standard s period. The choice of discount rates and how to handle residual values are key parameters in the long-term appraisal of infrastructure projects using CBA. Keeping the rates low and including the residual values in the project appraisal gives an entirely different perspective with regard to life cycle management of the infrastructure.

ITF (2014) formulates two specific strategies for improving CBA in light of uncertainty surrounding climate change and extreme weather events. The first involves undertaking uncertainty assessments that evaluate both the range of scientific uncertainty on hazards and socio-economic uncertainty regarding impacts and exposure. Due to the nature of the uncertainties considered, these assessments cannot simply be slotted into existing CBA as quantitative inputs, but can qualify the results of CBA with guidance on confidence regarding the results of the exercise. In terms of addressing the selection of discount rates, the report points to two potential pathways for improving CBA in light of uncertainty: applying a risk premium to selected discount rates or applying a subjective probability distribution over the objective probability distribution for the discount rate in order to capture inherent uncertainty ranges. Neither of these approaches fully addresses challenges posed by deep uncertainty but they do help adapt traditional CBA to project appraisal in light of climate and extreme weather impacts.

Generally CBA is most useful for assessing adaptation options when climate probabilities are known, climate sensitivity is assumed to be small compared to costs and benefits, good quality data exists for the major cost-benefit categories and agreement is high on valuation scales for costs, benefits and discount rates (Watkiss et al., 2012)

Cost-effectiveness analysis

When achieving agreement on monetary evaluation is difficult or impossible, cost-effectiveness analysis (CEA) can provide a way to weigh the relative value of various options. CEA compares and ranks alternative for achieving similar outcomes. Typically, CEA allows options to be ranked along a single comparable metric – e.g. cost per unit of desired outcome. These marginal abatement curves are particularly helpful in charting the least-cost path to achieving a set of desired outcomes. CEA can also identify the highest impact options from a range of considered measures and thus can guide resources to where they deliver the biggest benefits at the lowest cost.

However, while suited for prioritising GHG mitigation options, among others, CEA is perhaps less well suited for assessing adaptation measures. This is partly due to the fact that its reductive focus on a single metric makes it difficult to account for regional and local specificities and leaves out a number of costs and benefits that cannot adequately be captured in a benefit per cost of unit approach. For instance, cost effectiveness metrics to measure reduction of flood risk or impacts from sea level rise or storm surge could include exposure metrics (cost to reduce the potentially flooded area, cost to reduce the percentage of the population exposed to flooding) or economic metrics (cost to reduce expected annual damages). Alternatively, the metric could focus on reducing impacts (cost per land area unit relative to the value of the protected land). Another possibility could include the cost to limit flooding to a pre-determined threshold. All of these metrics present challenges in assessing impacts, precisely due to the uncertainty of climate risk and some also include the added challenge of determining acceptable levels of risk and/or protection. Indeed, by relying on single cost curves based on central estimates for a single or a selection of emission scenarios, CEA fails to account for the fundamentally uncertain nature of many climate change impacts. Further, when looking across the broad range of potential climate change impacts, it becomes difficult to select and prioritise CEA metrics across impact vectors. While CEA has been used in some non-transport adaptation contexts (e.g. health impact metrics or acceptable levels of flood risk metrics) it is not clear that it is any better – or worse – suited for adaptation appraisal than CBA which enjoys wider use (Watkiss et al., 2012).

In addition to the contexts in which CBA is useful, CEA can be helpful for assessing adaptation when a high level of agreement exists on social objectives (e.g. broad acceptance of risk thresholds), when a reduced set of impact is being considered and when the timeframes or impacts being considered are less subject to deep uncertainty.

Multi-criteria analysis

Multi-criteria analysis (MCA) is particularly well suited for assessing options using both quantitative and qualitative information. MCA provides a systematic methodology for assessing and ranking options against a range of scoring criteria that may be expressed in monetary units or in qualitative weights. In many cases, MCA is used in conjunction with traditional CBA to capture impacts that are difficult to monetise. Because it allows the consideration of a much broader range of criteria than CBA or CEA, MCA can be useful for assessing options in the absence of a market or shadow prices. It also by its nature encourages consultation across a wide range of stakeholders. However, the scoring and weighting exercise always remains somewhat subjective even if an effort is made to make the process as transparent as possible. It can also be cumbersome to carry out due to the consultation process. In particular MCA may not be well suited for capturing uncertainty in any other than a subjective manner.

Tools and approaches for decision making under uncertainty

All three traditional decision-support tools discussed in the prior section, while familiar to many transport decision-makers and planners, are generally not well-suited to handling the deep uncertainty that characterises many climate change adaptation decisions. For this reason, there is growing interest in alternative appraisal frameworks that better capture this aspect of adaptation planning.

Table 4.1. **Traditional vs. adaptive attitudes for transport appraisal**

Decision making in predictable contexts	Decision making under uncertainty
Seek precise predictions	Uncover a range of possibilities
Build prediction from detailed understanding	Predict from experience with aggregate responses
Promote scientific consensus	Embrace alternatives
Minimise conflict among actors	Highlight difficult trade-offs
Emphasise short-term objectives	Promote long-term objectives
Presume certainty in seeking the best outcome	Account-for and evaluate future feedback and learning
Define best outcomes from a predictable set of alternatives	Seek outliers
Seek productive equilibrium	Expect and design for change

Source: Walters, 1986.

Walters (1986) describes the main features of the types of decision making frameworks that work well under predictable circumstances compared to those that are better able to handle deep uncertainty on impacts and inputs.

Table 4.2. **Summary of tools adapted to decision making under uncertainty**

Real-options analysis	Allows economic analysis of future option value and economic benefit of waiting, gathering more information and flexibility
Robust decision making	Identifies robust (rather than optimal) decisions under deep uncertainty, by stress testing a large number of scenarios
Portfolio analysis	Assessment of an optimal blend of portfolios of options by trade-off between return (net present value) and uncertainty (variance)
Iterative risk (adaptive) management	Uses monitoring, research, evaluation and learning to better adapt future strategies to scenarios and risk thresholds

Source: Watkiss et al., 2012.

In their comprehensive review, Watkiss et al. (2012) builds on earlier work by Hallegatte (2009) and others to map out "new" appraisal approaches that display better aptitude to handle climate uncertainty. They identify several potential approaches, four of which are outlined in Table 4.2 and summarised in Table 4.3. Two of these approaches, real-options analysis and robust decision making, seem well suited for transport-related adaptation appraisal.

Real-options analysis

Real-options analysis (ROA) is rooted in options-based approaches from financial markets. In the latter, an option gives investors the right, but not the obligation, to acquire an asset in the future. This serves to help buffer against market volatility and uncertainty regarding the value of assets over time. The flexibility in exercising the option is the source of the option's market value. Similarly, investments in physical assets may benefit from flexibility in light of future uncertainty. Because with time, society will gain better knowledge about the scale and scope of climate impacts, real-options analysis ("real" because it deals with physical as opposed to financial assets) incorporates this flexibility into decision making and may usefully serve to guide certain climate change adaptation efforts.

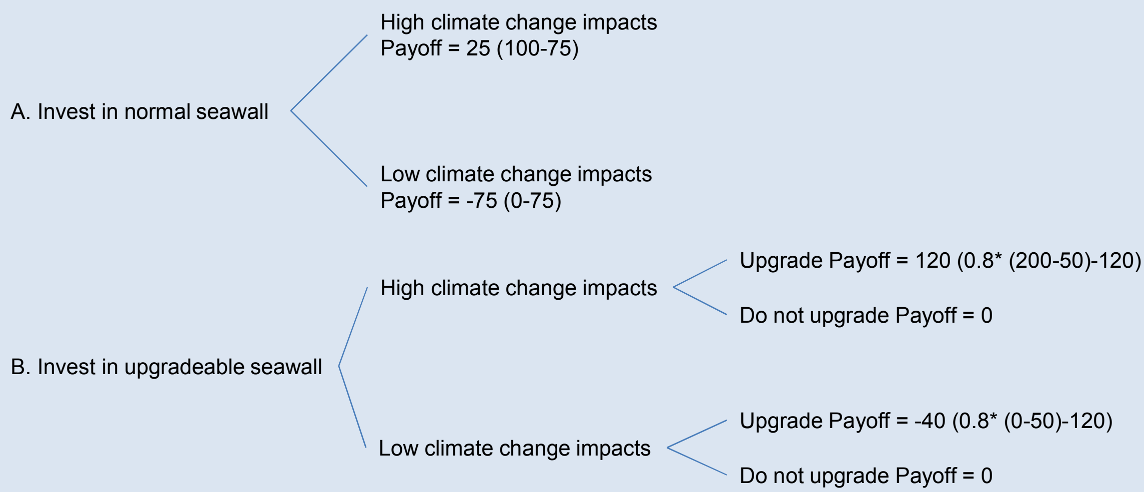
This flexibility refers both to the timing of the investment decision ("build now" vs. "build later") as well as to the ability for the infrastructure to adjust to changing conditions over time (e.g. "build for, but not with"). Accounting for this flexibility may yield different investment decisions than under traditional and deterministic economic appraisal techniques. ROA analysis may indicate that it makes sense to put off an investment until such time when better information about climate change impacts becomes available. It may also indicate that it is worth proceeding with the initial stages of a project (or phasing a project so that it may be deployed over several discrete stages) despite a weak traditional economic appraisal score in order to keep the option of further developing or completing the project alive. For instance, ROA analysis may support building a seawall such that it can be retrofitted at a later date to better account for rising sea level and increased incidences of storm surges. An upgradeable seawall will cost more upfront than a traditional seawall and this may cause this option to fail a standard CBA test. In the context of uncertainty, however, it may cost less to invest more upfront in this option (see Box 4.1).

The value of putting off an investment will be greater if the time to acquisition of new information is shorter and the higher the degree of uncertainty over outcomes. There is a cost to putting off an investment stemming from the delayed delivery of the services or other benefits the investment would have delivered. There is also an opportunity cost from over-investing in an initial phase of a project that must be weighed against the benefit of reduced investment at a future date should one uncertain option play itself out. These trade-offs can be captured with various computational decision-tree methods. Projects should proceed if ROA analysis indicates that the overall lost value from benefits during the waiting time is superior to the value of waiting or, alternatively, that that the option value derived from a series of optimal choices at multiple decision-points marking each phase in a multi-phase project is greater than the standard appraised value of average returns over the life of the project (Watkiss et al., 2012).

Real-options analysis is particularly suited for large, up-front and irreversible investments; it has been used in assessing investments in dikes and large-scale hydraulic projects. However, because probabilities must be assigned to specific outcomes, the formal application of ROA requires probabilistic inputs regarding climate impacts and therefore may be less suited to cases where deep uncertainty exists.

Box 4.1. **Appraisal using a real-options analysis**

Consider a proposal for investing in infrastructure protecting against the impacts of flooding due to climate change. There are two options: invest in a wall, or invest in a wall which has the option to upgrade in the future. There is an equal probability of high or low climate change impacts in the future. The standard wall costs 75, and has benefits of 100 from avoided flooding. The upgradeable wall costs 50, the upgrade costs 50 and would give benefits of 200 from avoided flooding. The discount rate is 0.8.



The expected value of investing in the standard wall is a simple net present value (NPV) calculation, calculating the expected costs and benefits of the investment. The NPV is (0.5*25) + (0.5*-75) = -25. 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 high. The expected value of this option can be calculated.

If the impacts of climate change are high enough to warrant upgrading, then the value of the investment is 120. If the impacts are low, then upgrading is not justified since the payoff is negative (-40). Since the investment costs of the upgrade are not realised in practice in the low outcome, they are therefore not incorporated into the NPV. The expected value of investing now with the option to upgrade in the future is (0.5*120) – 50 = +10.

Comparing the two approaches shows an NPV of -25 for the standard approach, and +10 for the real-options approach. Flexibility to upgrade in the future is reflected in the higher NPV and switches the investment decision.

Source: HM Treasury, 2009.

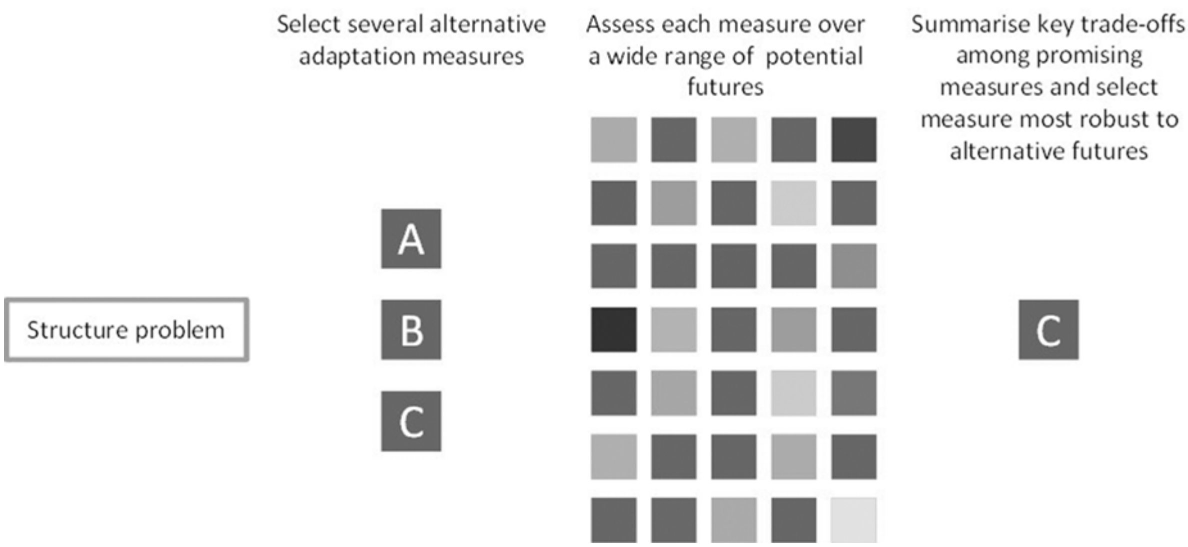
Robust decision making

Robust decision making (RDM) is an alternative approach that is adapted to situations where no probabilistic information exists regarding impacts or outcomes. RDM seeks to select those strategies and investments that are consistently robust under the widest range of plausible climate outcomes and impacts. RDM represents an alternative "agree on outcomes" approach to decision making where outcomes are selected first and then tested for robustness. In this way, it avoids having to find consensus on future climate change impacts which otherwise hampers "agree on assumption"-based approaches. Because RDM obviates the need to select probabilities of outcomes, it is especially well-suited to decisions characterised by deep uncertainty. Crucially, RDM may favour outcomes that are optimal in no single situation but that are good enough in most circumstances. RDM seeks to minimise regrets rather than optimise specific (but perhaps vulnerable) outcomes.

RDM is computationally heavy as multiple scenarios entailing complex decision outcomes must be modelled. This may be less of a constraint as even large-scale and complex calculations have been accelerated by parallelised processing and use of cloud-based servers. Nonetheless, RDM requires a high level of expert knowledge on potential outcomes of investment decisions under multiple contexts and their inter-relationships.

Methodologically, RDM iterates analysis of decision outcomes over multiple potential future scenarios based on a multi-step approach (see Figure 4.2).

Figure 4.2. **The process of robust decision making**



Source: Adapted from Groves et al., 2008.

RDM starts out by characterising the problem to be addressed (e.g. a climate change impact to be mitigated) and, rather than seek to establish a probabilistic range of future scenarios to which the decision on a strategy or measure must be adapted, it looks at describing a variety of potential measures. Each measure is then assessed over a wide range of computer-generated future scenarios. This “stress test” helps to determine which combination of uncertainty parameters are most important to the choices between strategies. Based on this exercise, one or several, measures can be selected that are best able to deliver desired outcomes across the widest range of possible futures. Selected outcomes may be optimal under no specific scenario but “good enough” under the widest range of futures. Because it enables insight to be gained from situations characterised by deep uncertainty, RDM is best suited for those situations where specific climate impacts are highly uncertain – like precipitation.

Though some cases exist, neither ROA nor RDM have worked their way into widespread project appraisal for transport infrastructure at this time. There are many reasons for this, including the regulatory structure governing appraisal and insurance requirements regarding risk assessment. Work therefore remains to understand how best these approaches can be integrated into transport investment appraisal.

Table 4.3. **Summary overview of decision support tools for the appraisal of climate change and extreme weather adaptation strategies**

Tool	Strengths	Weaknesses	Most useful when
Cost-benefit analysis	Provides direct analysis of economic, benefits, justification for action, and optimal solutions. Well known and widely applied.	Difficulty of monetary valuation for non-market sectors and non-technical options. Uncertainty usually limited to probabilistic risks.	Climate probabilities known. Climate sensitivity small compared to costs/benefits. Good data exists for major cost/benefit components.
Cost-effectiveness analysis	Benefits expressed in physical terms (not monetary) thus applicable to non-market sectors. Relatively simple to apply and easily understandable ranking and outputs. Use of cost curves can assess policy targets with least-cost optimisation. Used for mitigation, thus widely recognised and resonance with policy makers.	Benefits can be difficult to identify and single metric does not capture all costs and benefits. Less applicable cross-sectoral/complex risks. Works best with technical options, and often omits capacity building and soft measures. Sequential nature of cost curves ignores interlinkages and potential for portfolios. Does not lend itself to the consideration of uncertainty, as works with central tendency.	Same as CBA, but for nonmonetary metrics. Agreement on sectoral social objective (e.g. acceptable risks of flooding).
Multi-criteria analysis	Combines quantitative and qualitative data,; monetary and non-monetary units, thus applicable where quantification is challenging. Relatively simple and transparent, and relatively low cost/time requirement. Expert judgement can be used very efficiently, and involves stakeholders, thus can be based on local knowledge.	Results need further interpretation and elaboration in more detailed studies. Different experts may have different opinions, i.e. subjectivity involved. Stakeholders may lack knowledge and can miss important options. Analysis of uncertainty is often qualitative and subjective.	Mix of qualitative and quantification data.

Table 4.3. **Summary overview of decision support tools for the appraisal of climate change and extreme weather adaptation strategies (continued)**

Tool	Strengths	Weaknesses	Most useful when
Real-options analysis	Assesses value of flexibility and learning, in quantitative and economic terms. Decision trees conceptualise and visualise the concept of adaptive management.	Data and resource intensive, with high complexity and expert input. Data a potential barrier, (probabilistic climate, quantitative and economic information). Identification decision points often complex.	Large irreversible capital decisions. Climate risk probabilities known or good information. - Good quality data for major cost/benefit components.
Robust decision making	Assesses robustness rather than optimisation. Applicable where probabilistic information is low or missing, or climate uncertainty is high. Can work with physical or economic metrics, enhancing application across sectors.	Lack of quantitative probabilities can make more subjective, influenced by stakeholders. The formal application has a high demand for quantitative information, computing power, and requires a high degree of expert knowledge.	High uncertainty of climate change signal. Mix of quantitative and qualitative information. Non-market sectors (e.g. ecosystems, health).
Portfolio analysis	Assesses portfolios, which analysis of individual adaptation options not allow. Measures “returns” using various metrics, including physical or economic, thus broad applicability. Use of the efficiency frontier an effective way of visualising results and risk-return trade-offs.	Resource intensive and needs expert knowledge. Relies on the availability of quantitative data (effectiveness and variance/co-variance). Requires probabilistic climate information, or an assumption of likelihood equivalence. Issues of inter-dependence between options.	Adaptation actions likely to be complementary in reducing climate risks. Climate risk probabilities known or good information.

Table 4.3. **Summary overview of decision support tools for the appraisal of climate change and extreme weather adaptation strategies (continued)**

Tool	Strengths	Weaknesses	Most useful when
Adaptive management	Process of monitoring, research, evaluation and learning that avoids irreversible decisions and encourages learning to adjust decisions over time. Uses scenarios to delineate uncertainties not to predict the future. Is more policy orientated and flexible in objectives and appraisal methods Encourages discussion about (un)acceptable change and definition of critical indicators.	Challenging when multiple risks acting together, or indirect links to climate change. Thresholds are not always easy to identify, especially those that are poorly defined. Focuses on existing management objectives. Unknown impacts and new challenges may be overlooked/difficult. Loses simplicity for communication less well defined thresholds and multiple drivers./	High uncertainty. Clear risk thresholds and indicators. Mix of quantitative and qualitative information.

Source: Watkiss et al., 2012.

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