Conférence Européenne des Directeurs des Routes
Conference of European Directors of Roads

ICARUS

Improve the uptake of Climate change Adaptation in the decision making processes of Road Authorities

Current evidence-base of using cost-benefit analysis for assessing road infrastructure projects within the climate adaptation regime

Deliverable D3.1, Final version

30 November 2022

ICARUS

Improve the uptake of Climate change Adaptation in the decision making processes of Road Authorities

CEDR
Conférence Européenne des Directeurs des Routes
Conference of European Directors of Roads

CEDR call 2022: Climate Change Resilience

Deliverable D3.1 Final version

Current evidence-base of using cost-benefit analysis for assessing road infrastructure projects within the climate adaptation regime

30 November 2022

Alvaro Fonseca, Juliette Aplin, Ida B. Gregersen, Gonzalo Fuentes, Maria F. Asmussen, Mathilde Smith

Deltares
tecnalia MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE
RAMBOLL
RDS RESEARCH DRIVEN SOLUTIONS
Maple Consulting

Summary

The ICARUS project, framed within the CEDR Transnational Road Research Programme, aims at developing knowledge products for the integration of climate resilience into decision-making processes, as well as implementing existing resilience thinking and research into practice within the NRAs (National Road Authorities). The expected outcomes of the project are linked to the reduction of disruptive impacts of climate hazards on existing (and planned) road infrastructure.

It is within this context that this report studies economic appraisal/evaluation methods grouped under three major streams: traditional economic decision support; uncertainty framing; and economic decision-making under uncertainty. Specifically, the report focuses on Cost-Benefit Analysis (CBA) as a dominating tool supporting decision-making in the road infrastructure sector. Other approaches such as Multi-Criteria Analysis (MCA) are also analyzed.

This report identifies key knowledge and implementation gaps on the links between CBA, climate resilience and road infrastructure, based on a state-of-the-art literature review and a state of practice assessment, including insights collected through participatory workshops with NRAs. The key gaps identified can be summarized as:

- The use of economic appraisal methods dealing with climate uncertainty within NRAs is limited.
- It is uncertain to which extent NRAs are making use of 'hybrid' approaches combining CBA and MCA, and how this enables inclusion of the three key adaptation themes outlined in this report (uncertainty, valuation, and equity), as well as inclusion of co-benefits.
- Life-Cycle Costing (LCC), or variations of LCC, seem to be preferred by NRAs to a certain extent, as it's considered an easy and straightforward method to apply, especially when quantifying costs and linking the results to development of policies. The state-of-art (SoA) and state-of-practice (SoP), however, do not show this, with CBA and MCA being more predominant.
- It is not clear how NRAs are dealing with co-benefits when developing CBA. The report outlines specific adaptation-related valuation methods which help in capturing those intangible benefits, but it is uncertain to which extent the NRAs are working with this.
- The dynamics of decision-making within the NRAs need to be properly understood, to better tailor the development and outputs of ICARUS. The literature review did not reveal particularly strong decision-making levels within transportation agencies or road organisations. Moreover, the workshops did not give a clear picture either, and the interface between asset and operational level was not clear.
- Inclusion of and engagement with stakeholders as part of the decision-making process of the NRAs needs to be looked at in more detail.

These gaps will be addressed in the upcoming work in ICARUS. Specifically, more conversations with NRAs are needed to understand how climate uncertainties are accounted for in decision-making, especially the links with CBA, and how CBA and co-benefits are considered. It should be noted that, as the project evolves and more knowledge is collected and assessed, and as the understanding of the State of Practice is expanded (through e.g., case studies and deeper interactions with NRAs), the insights presented in this report will consequently be fine-tuned and consolidated. The results of this baseline assessment are used as a starting point for Work Package 3 within the ICARUS project.

Table of Contents

1 INTRODUCTION

1.1 Setting the context

The appraisal of climate change adaptation measures, being physical (infrastructure) or non-physical (policies) is linked directly to the results of technical assessments coupled with socio-economic evaluation of different options or solutions aiming at an overall reduction of current and/or future climate risks compared to a baseline scenario, i.e., a starting point. Appraising adaptation measures can likewise occur at different decision-making levels, from policy making to detailing design of infrastructure, with each level and context posing different challenges and opportunities to achieve the main objective of building climate change resilience across sectors, ultimately creating societal transformation and more resilient communities and infrastructure.

Incorporating climate change and resilience thinking in decision-making processes is, to paraphrase the ICARUS project summary, a balancing exercise whereby new approaches and technologies, well-proven and straightforward practices, information needs, data availability and quality, expected/demanded service levels and infrastructure investments, must all co-exist and complement each other. At the backbone of this difficult balance lies the crucial need for decision-makers to make sound, informed, forward-thinking, holistic, and cost-effective decisions.

The ICARUS project, framed within the CEDR Transnational Road Research Programme, aims at developing knowledge products for the integration of climate resilience into decision-making processes, as well as implementing existing resilience thinking and research into practice within the NRAs. The expected outcomes of the project are linked to the reduction of disruptive impacts of climate hazards on existing (and planned) road infrastructure. In this manner, ICARUS is ultimately expected to contribute to the development of a sustainable European transportation network.

It is within this context that this report studies economic appraisal/evaluation methods grouped under three major streams: traditional economic decision support; uncertainty framing; and economic decision-making under uncertainty. Specifically, the report focuses on Multi-Criteria Analysis (MCA) and Cost-Benefit Analysis (CBA), as tools supporting decision-making in the road infrastructure sector. Overall, socio-economic analysis can help organisations assess and prioritize adaptation options by outlining the potential long-term costs and benefits of alternative adaptation strategies. A socio-economic analysis measures those costs and benefits in a way that allows comparability among options, as well as with current policies and practices. Moreover, application of a socio-economic evaluation can become part of a systematic framework to organize vulnerability information on assets, compare alternative approaches that reduce the vulnerability, evaluate the benefits and costs of each solution, and inform decisions on which alternative or strategy to pursue (Filosa, Plovnick, Stahl, Miller, & Pickrell, 2017).

It should also be mentioned that this report is part of a series of baseline reports withing the ICARUS project:

- D1.1: Baseline report on determining impacts and risk due to climate change
- D2.1: Baseline report on minimum service levels and resilience evaluation

All baseline reports have been produced at the start of the ICARUS research, and although a common effort has been put in place to align terminologies and cross-cutting approaches, it is very likely that content narratives and approaches will change as the project moves forward and more knowledge and insights are developed.

1.2 Short introduction to CBA

Cost-benefit analysis (CBA) is a method to undertake socio-economic evaluation to assess the economic viability of proposed investments by examining the extent to which their benefits outweigh their costs. At its core, CBA is a decision-supporting tool involving estimation of overall costs and benefits, including monetization of benefits and co-benefits (i.e., non-tangible benefits or externalities). In the context of climate change adaptation projects, it enables decision-makers to understand the nature and scale of climate impacts which may be avoided if a particular intervention or solution is developed, allowing for the comparison of interventions/solutions that provide diverse benefits which otherwise may not be directly comparable.

In terms of flood resilience, CBA considers the impacts of a present-day flood situation (the base case or 'do-nothing' scenario) against a proposed solution to reduce risk and/or increase resilience. In this regard, the prioritised solution (or adaptation project) is that one which yields the highest net benefit (benefits minus costs) against the base case. Sections 3 and 4 provide details regarding the calculation of benefits and co-benefits. Figure 1 shows the general process followed when conducting a CBA.

Figure 1. General CBA process

Once the base case and the potential interventions/solutions have been defined, the CBA first estimates the total impacts under the base case without the solution. Following the same example on flood resilience, this process would be based on the results of a Flood Exposure Analysis. It would consider categories of impacts, including direct, indirect, and intangible along with impacts to relevant infrastructure, e.g., roads. A conceptual illustration is provided in the figure below.

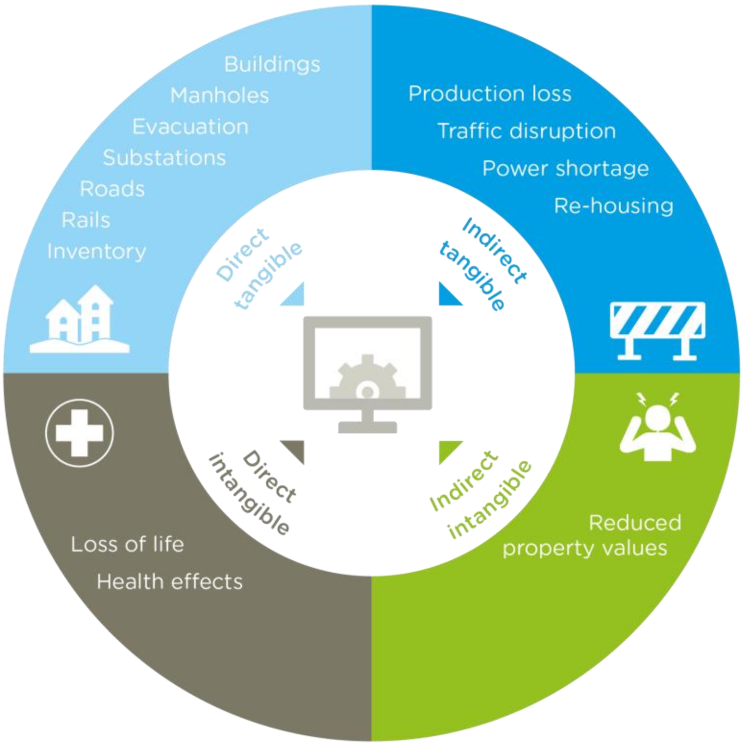

Figure 2. Conceptual illustration of types of impacts considered in the cost estimation of a CBA

Figure 2 also provides an overview of impacts (e.g., categories of damage) considered when performing a CBA. The calculation of the 'do-nothing' impacts should be done as early in the process as possible and use this information to support the development of the solutions proposed. In simple terms, damage avoided by implementing a solution is calculated as the difference between damages under the base case and the damages which would remain even with the solution in place. CBA results (benefits and costs) are typically presented in their present-day values (see section 3.2.3).

In addition to direct benefits (i.e., avoided damages), the CBA will consider and quantify where possible the co-benefits provided by the adaptation solution which are additional to those associated with the primary benefit, e.g., flood avoidance/reduction. These may include (but are not limited to):

- Biodiversity and habitat restoration
- Recreational and eco-based tourism opportunities
- Carbon sequestration and air quality benefits
- Embodied carbon in infrastructural works
- Water quality
- Health impacts for flora, fauna, and people
- Increased business opportunities and livelihood improvement

Valuation of material co-benefits (i.e., added values) is important for a full understanding of the wider societal impacts (positive and negative) associated with climate adaptation solutions, thus enabling a comparison of the trade-offs across options, and the selection of the optimal alternative. Valuation can be conducted using a range of environmental economic and social valuation techniques, including amongst others market data, hedonic pricing, or benefit transfer approaches (Alida, Berry, Zoran, Zoran, & Arlex, 2019).

Once benefits have been estimated, the overall costs of the solution are incorporated in the CBA calculation. These include initial/upfront costs (such as capital, construction, land and property, and contingency costs) and operation and maintenance costs (such as capital replacement, refurbishment, annual operating and maintenance, and contingency costs). Estimation of these costs is typically done in close collaboration with engineers and technical experts.

1.3 Structure of the report

This report is built using a simple and straightforward methodology, outlined in section 2. The literature review of the state of the art is described in section 3 while the state of practice is outlined in section 4. The identification and analysis of gaps is described in section 5, while section 6 provides a summary of findings. Section 7 offers a table of key concepts used in this report. The bibliography can be found in section 0.

2 METHODOLOGY

The methodology followed in this report is illustrated in the figure below.

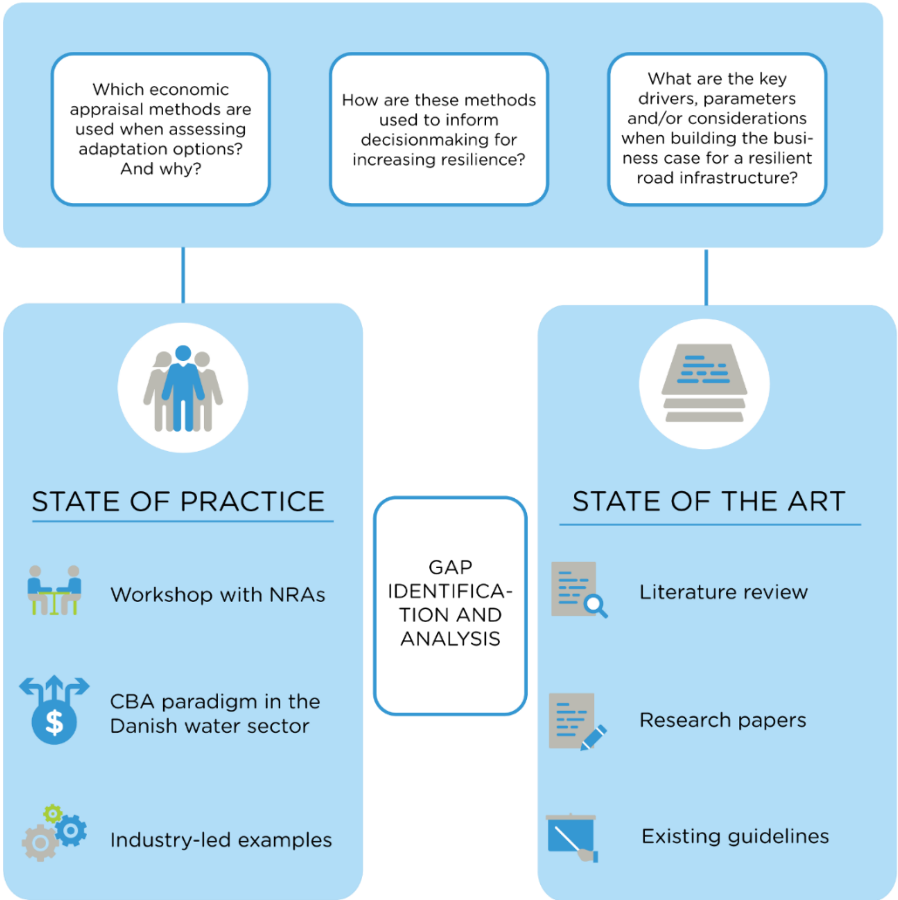

Figure 3. Methodology used in the development of this baseline assessment and gap analysis

The report follows two steps: a state-of-the-art (SoA) literature review, and a state of practice (SoP) analysis. Both steps aim at answering and provide insights into three overall topics/questions:

1. Which economic evaluation/appraisal methods are used when assessing adaptation options? And why?
2. How are these methods used to inform decision-making for increasing resilience?
3. What are the key drivers, parameters and/or considerations when building the business case for a resilient road infrastructure?

The identification of gaps is done qualitatively by comparing the findings of the SoA and SoP. Gaps in this case are framed primarily as knowledge and/or implementation gaps and provide a direction to follow in the upcoming work to be done withing the ICARUS project. Discussion and validation of the gaps will also be needed after delivery of this baseline report, as the project evolves and more knowledge is collected, especially through interacting more closely with NRAs.

3 BASELINE ASSESSMENT: STATE OF THE ART

In proceeding to map the current state of the art in this report, an in-depth literature review has been performed. The literature review comprises detailed assessment of more than 30 different documents, ranging from scientific articles, knowledge publications, guidelines/standards, handbooks/manuals, technical reports, book chapters, etc. This section summarizes what is considered to be the most updated basis forming the current state of the art within the topics of study in this report.

The following keywords were used in the literature review: CBA requirements; CBA boundaries; CBA methods; CBA criteria; resilient road infrastructure; decision-making; business case for resilience; adaptation measures; adaptation co-benefits; cost-effective measures; economic valuation.

3.1 Economic Appraisal Methods

There is a wide number of general economic appraisal methods, also sometimes referred to as economic evaluation methods, that are not necessarily linked to climate adaptation. These are methods or approaches typically used in general economic or financial assessments, where climate change impacts, climate variability and uncertainties are not included. The economic assessment of adaptation measures differs from a standard economic appraisal, in that the focus of analysis is centered within the management of (climate) uncertainties and risks. The methods therefore account for different timescales, complex systemic relationships and dynamics, and multiple sources of uncertainties, among other things (Tröltzsch, et al., 2016).

An overview of the main economic tools is given in the figures below.

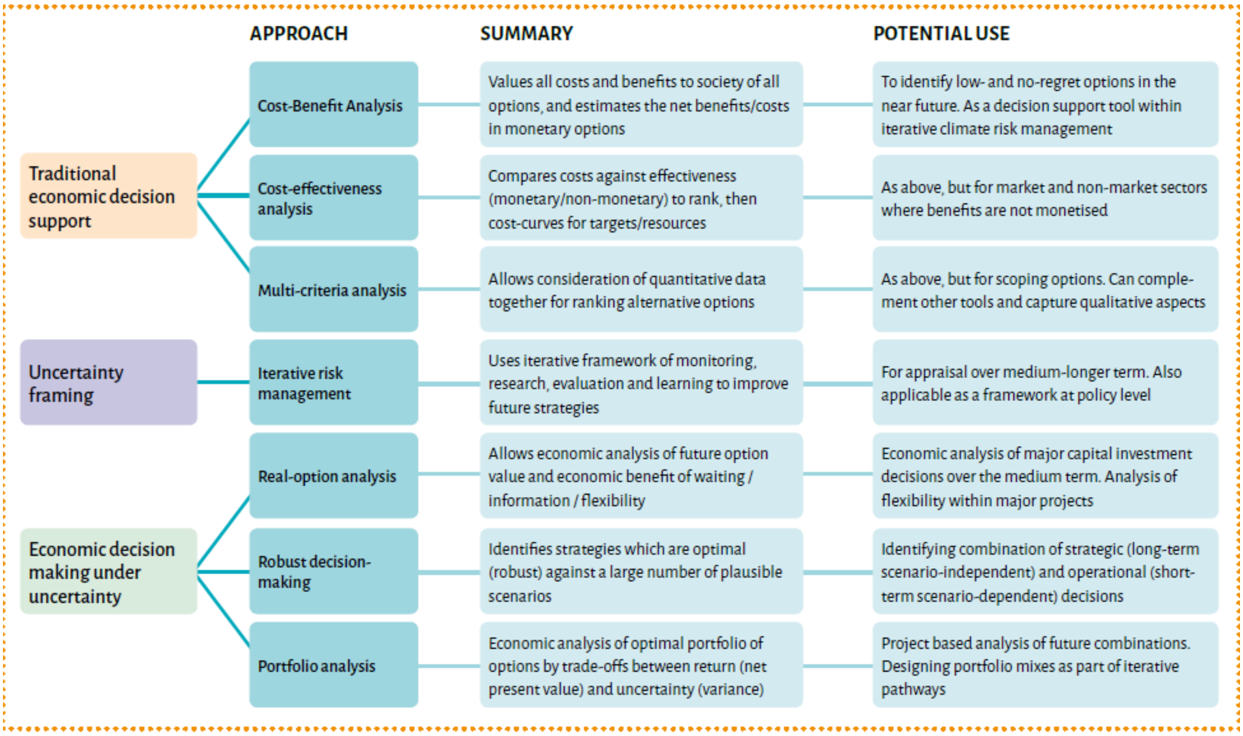

Figure 4. Main groups of methods in adaptation economics and their potential use (Tröltzsch, et al., 2016).

METHOD	STRENGTHS	CHALLENGES	DEALING WITH UNCERTAINTY
Cost-benefit analysis	Most useful when climate risk probabilities are known and sensitivity is small. Also where clear market values can be used	Valuation of non-market sectors / non-technical options. Uncertainty limited to probabilistic risks / sensitivity testing	Does not explicitly deal with uncertainty, but can be combined with sensitivity testing and probabilistic modelling
Cost-effectiveness analysis	As above, but for non-monetary sectors and where pre-defined objectives must be achieved	Single headline metric difficult to identify and less suitable for complex or cross-sectoral risks. Low consideration of uncertainty	Does not explicitly deal with uncertainty, but can be combined with sensitivity testing and probabilistic modelling
Multi-criteria analysis	When there is a mix of quantitative and qualitative data	Relies on expert judgement or stakeholders, and is subjective, including analysis of uncertainty	Can integrate uncertainty as an assessment criterion, however usually relies on subjective expert judgement or stakeholder opinion
Iterative risk management	Useful where long-term and uncertain challenges, especially when clear risk thresholds	Challenging when multiple risks acting together and thresholds are not always easy to identify	Deals explicitly with uncertainty by promoting iterative analysis, monitoring, evaluation and learning
Real-option analysis	Large irreversible decisions, where information is available on climate risk probabilities	Requires economic valuation (see CBA), probabilities and clear decision points	Deals explicitly with uncertainty by analysing the performance of adaptation for different potential futures
Robust decision-making	When uncertainty and risk are large. Can use a mix of quantitative and qualitative information	Requires high computational analysis and large number of runs	Explicitly incorporates uncertainties and risks, in particular, systemic dependent risks, to derive robust solutions
Portfolio analysis	When number of complementary adaptation actions and good information	Requires economic data and probabilities. Issues of interdependence	Deals explicitly with uncertainty by examining the complementarity of adaptation options for dealing with future climates

Figure 5. Main strengths and limitations of economic tools to support adaptation decision-making (Tröltzsch, et al., 2016).

ECONOADAPT (Tröltzsch, et al., 2016) outlines three overall groups of tools when talking about the economics of adaptation: traditional economic decision support; uncertainty framing; and economic decision-making under uncertainty. However, it should be noted that even if the tools are presented individually, they are not mutually exclusive and can be applied in combination with each other depending on the particular objectives of any given study. Due to their complexity, practical application of these tools is usually limited to large investment decisions or major risks.

The CEDR-funded WATCH project (Tucker, Corbally, & O'Connor, 2018) developed a Socio-Economic Analysis Framework, intended to be used by primary stakeholders in the decision-making process tackling the design, maintenance, and adaptation measures of drainage systems for effective water management within the context of climate change. The framework is shown in the figure below.

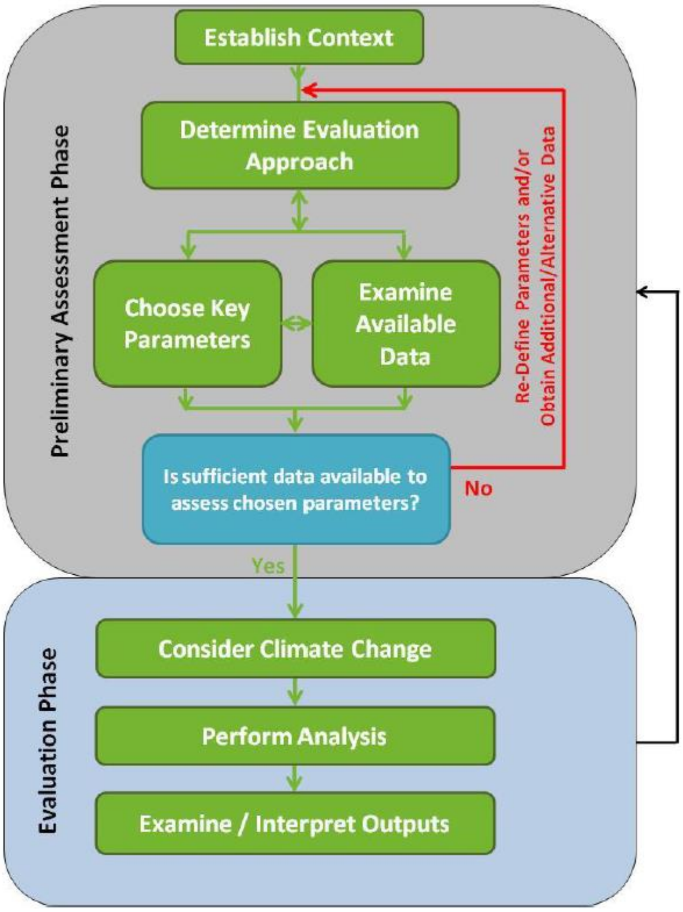

Figure 6. Socio-Economic Analysis Framework developed under the WATCH project (Tucker, Corbally, & O'Connor, 2018).

The framework consists of two main phases; a preliminary assessment where the context of the analysis is defined, incl. parameters, data constraints and evaluation approach. The second phase is the evaluation phase where climate change scenarios are brought in to guide the analysis. The framework was produced following a review of key literature and international best practices within climate change adaptation for water management in the road sector, and targets primary stakeholders with decision-making capabilities at NRAs. (Tucker, Corbally, & O'Connor, 2018).

The CEDR framework describes four economic evaluation methods used in the road sector: Multi-Criteria Analysis (MCA), Life-Cycle Costing (LCC), Cost-Effective Analysis (CEA), and Cost-Benefit Analysis (CBA). The choice of method largely depends on two key factors: the particular needs and the data availability and data quality to be used in the assessment. In the CEDR framework, these two overall factors ultimately determine the type of socio-economic method used. The figure below illustrates the relationships between MCA, CEA, and CBA.

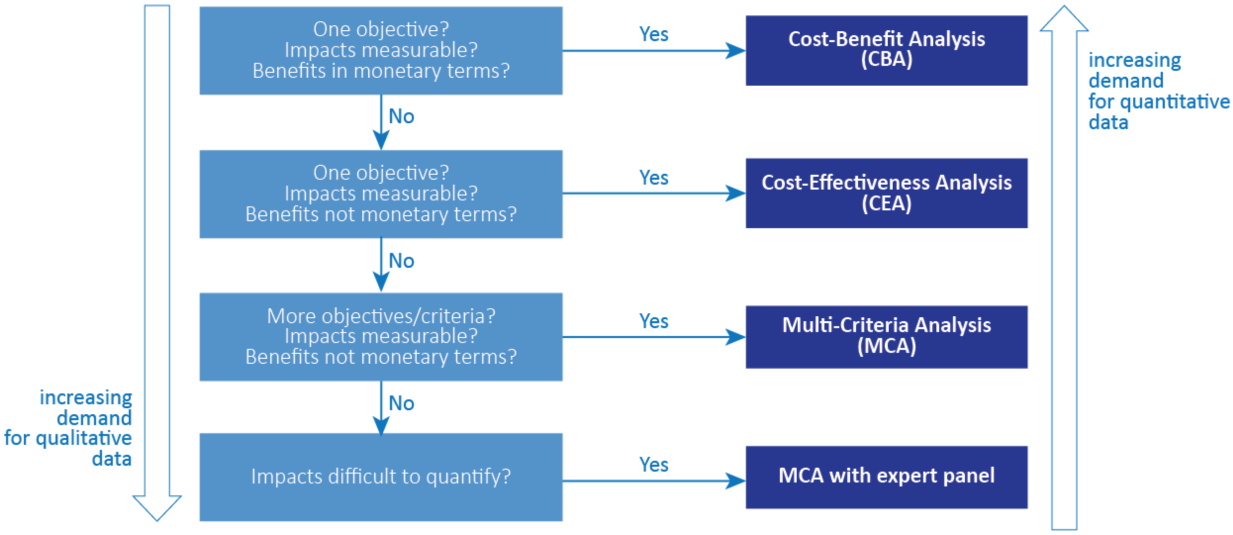

Figure 7. Links and dependencies between three economic evaluation methods: MCA, CBA, and CEA. Adapted from (UNFCCC, 2011)

The degree of available quantitative and qualitative data determines the suitability of applying MCA (more suited when qualitative data is predominant) or CBA (more suited when quantitative data is predominant), with CEA being in the middle of the scale of data demands (i.e., semi-quantitative). The other important element is the needs assessment that is required to determine the objective(s), the type of adaptation impacts and the nature of the benefits. The CEDR framework (Tucker, Corbally, & O'Connor, 2018) does not include the other methods analyzed by ECONOADAPT (Tröltzsch, et al., 2016) grouped within uncertainty framing and economic decision-making under uncertainty.

LCC, also called Life-cycle cost analysis (LCCA) is an approach commonly used to evaluate the differential costs of alternative designs or initial investment levels for transportation infrastructure. This method is less intensive than CBA as it's less experimental and does not consider external costs and benefits of adaptation options, i.e., ESG impacts or co-benefits to tourism (Gina Filosa, Amy Plovnick, Leslie Stahl, Rawlings Miller, Don Pickrell, 2017).

3.1.1 Application in the transportation sector

An example of implementation of Robust Decision-Making (RDM) is given by the recently launched Resilience and Disaster Recovery (RDR) Tool Suite (Badgley, et al., 2022) from the United States, which includes RDM to address future scenarios that are highly uncertain by:

1. Ranking projects based on economic return on investment (ROI) using Cost-Benefit analysis (CBA), CBA under Uncertainty/Regret Analysis, or Breakeven Analysis, depending on user data.
2. Including benefits of reduced repair cost, faster recovery time, and improved roadway network connectivity.
3. Allowing the use of default values or customized benefit and cost calculations based on agency data and knowledge.

The RDR Tool Suite includes cutting-edge knowledge readily available for National Road Authorities and thereby highly relevant within the purposes of ICARUS. The tool enables the assessment of transportation resilience return on investment (ROI) for specific transportation assets over a range of potential future conditions and hazard scenarios. The outputs can then be used in a decision-making process for prioritization of investments (Badgley, et al., 2022). See figure below.

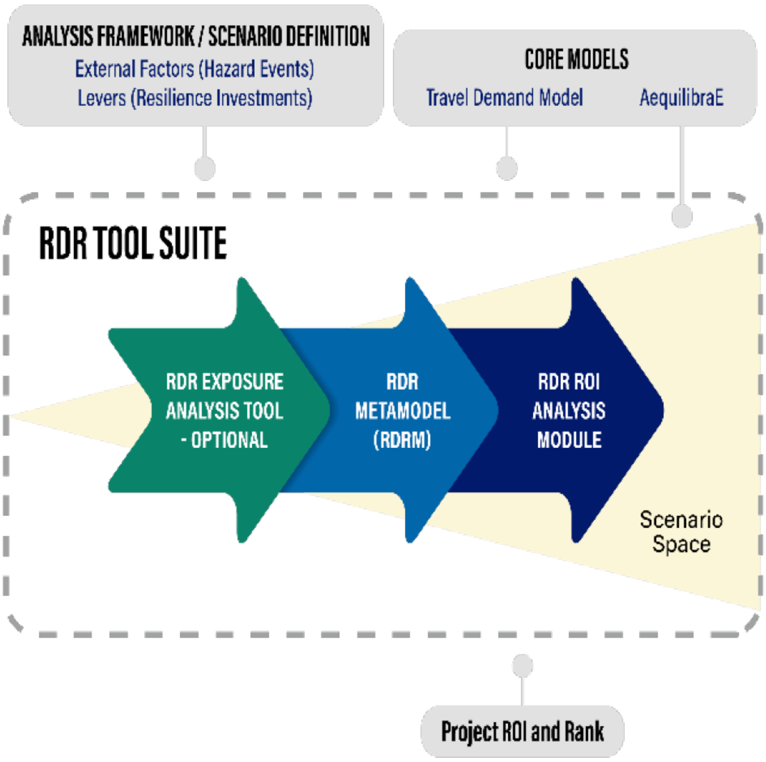

Figure 8. Resilience and Disaster Recovery Tool Suite. The scenario space is defined as the range of conditions over which the resilience investment performance is estimated. It therefore increases as more potential hazard severities, durations, recovery periods, and resilience investments are assessed. RDRM: Resilience and Disaster Recovery Metamodel (Badgley, et al., 2022).

There are also examples of more 'hybrid' approaches where CBA and MCA are combined to support the implementation of transport policies when prioritizing road infrastructure investment projects. One of these examples is given by (Gühnemann, Laird, & Pearman, 2012), where CBA results are incorporated into an MCA framework. Following this approach allows retaining the strengths of each method while offering decision makers a clear pathway to create an initial ranking of investment projects where the connections between all potential investments and the pursued policy goals are clear.

When aiming at combining CBA and MCA, there are four common issues that must be tackled (Gühnemann, Laird, & Pearman, 2012):

- The analysis needs to account for existing CBA and/or MCA procedures as much as possible, so as not to insert a specific bias while simultaneously ensuring adequate compatibility between the two approaches. In the end, the outcome of the analysis should be tangible and meaningful.

- Validation of the analysis is critical. To do this, the already chosen assessment criteria measurement scales, monetary values and/or multi-criteria weights needs to be properly outlined and included. Comparing the results of the assessment with previous results is highly recommended for validation purposes.

- Handling of uncertainties is also critical. The sources of uncertainties for both methods must be outlined and understood. These can be uncertainties related to impact levels and MCA weights. In the majority of cases, a full-scale study of uncertainties is not possible to do, and this needs to be properly accounted for in the assessment.

- The decision-maker entity (or individual) making use of the results of the analysis needs to be able to understand the robustness of the rankings (results of the analysis), to be able to communicate them properly and to make more informed decisions.

The 'hybrid' approach combining CBA and MCA could follow the process chart illustrated in the figure below, adapted from (Gühnemann, Laird, & Pearman, 2012).

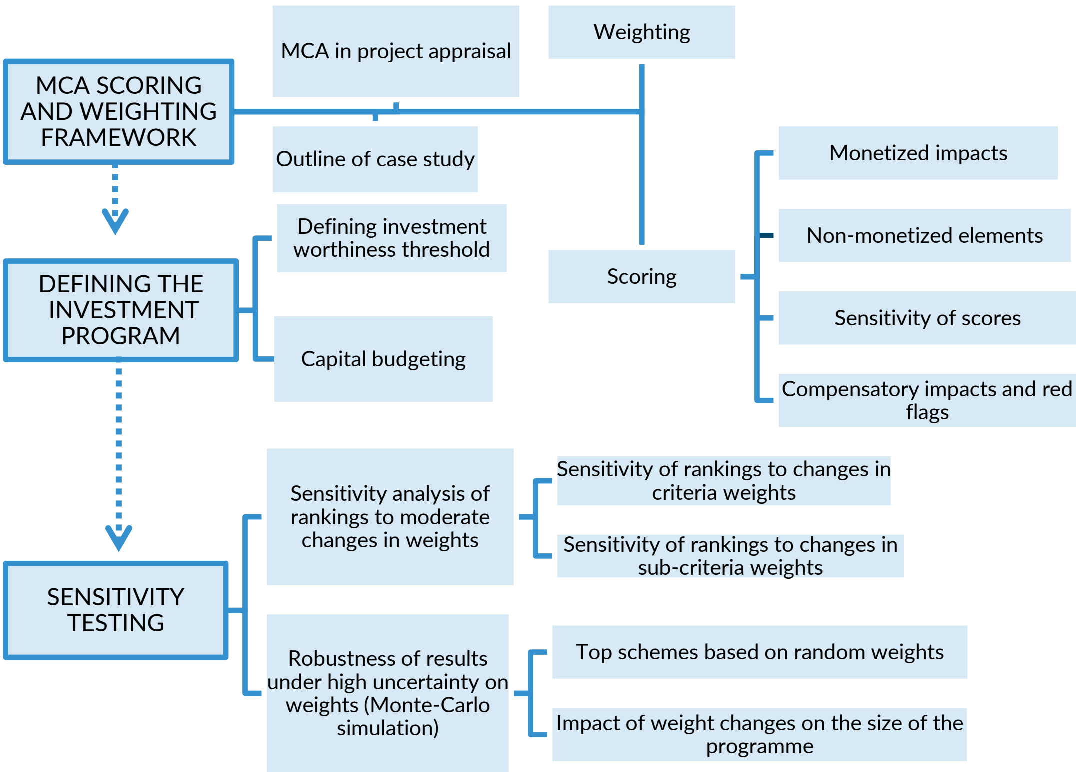

Figure 9. Development of MCA scoring and weighting framework including CBA elements, adapted from (Gühnemann, Laird, & Pearman, 2012)

The approach described above starts by defining the MCA scoring and weighting framework, through discussions with stakeholders and expert knowledge. The scoring is used to define the overall MCA in the project appraisal as well as outlining the case study. The second step is defining the investment programme, which entails defining the thresholds the different options must comply with as well as the definition of the capital budgeting available. The last step is then implementing a sensitivity analysis to address uncertainties related to the rankings (from the MCA) and the impact of weight changes on the previously defined investment programme.

Application of this methodology relies on the ability to transform monetary results (i.e., monetized impacts) from CBA into MCA scores by defining a benefit-cost ratio (BCR) threshold for projects or investments that are considered highly positive or desirable (i.e., 'investment worthiness threshold'). The methodology also proposes an incremental analysis to decide between mutually exclusive projects, introducing a 'value for money threshold' in determining the size of the investment program (Gühnemann, Laird, & Pearman, 2012). This process followed on transport sector investments has clear links to the road infrastructure sector and could be adapted to fit NRA decision-making processes.

A more recent attempt to combine CBA and MCA was carried out by (Henke, Carteni, & Francesco, 2020) where a methodology for a sustainable evaluation of transport sector investments was developed. See Figure 10.

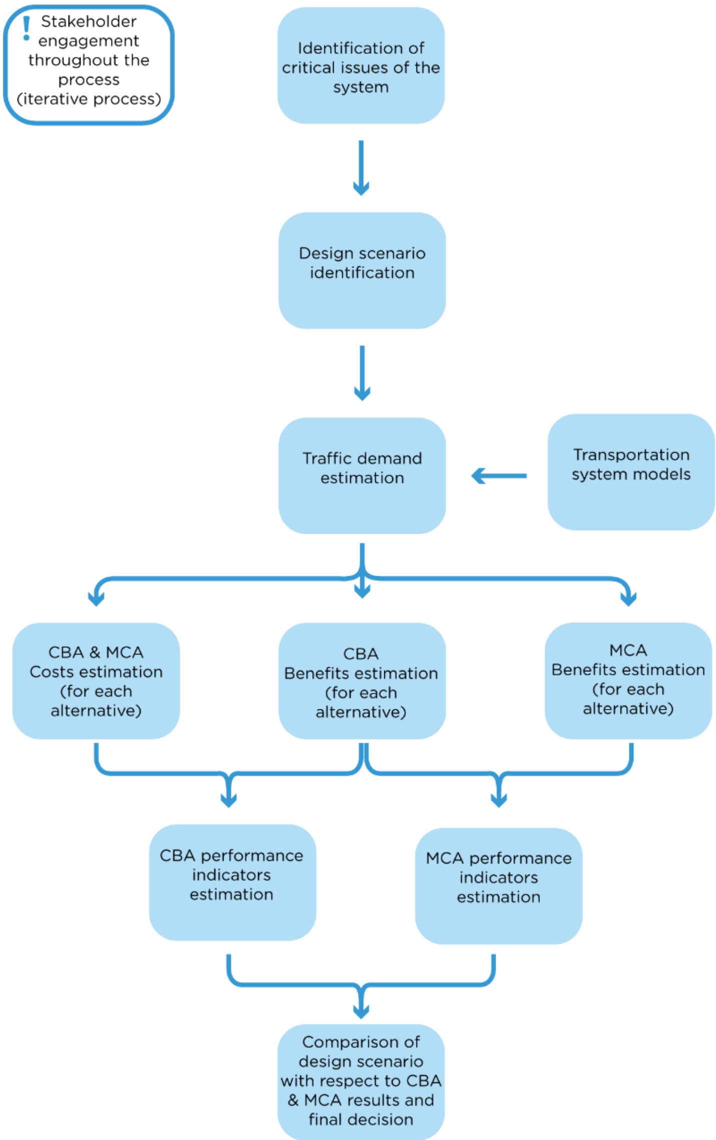

Figure 10. Proposed methodology for sustainable evaluation of investments in the transport sector through a combination of CBA and MCA (Henke, Carteni, & Francesco, 2020).

Even in contexts where CBA is a well-established decision-support tool, several research papers show that investment decisions are often strongly influenced by other political preferences (Eliasson and Lundberg, 2012; Quinet, 2011) or that decision-makers take an approach whereby criteria is handled through non-monetized ways despite those criteria being included in the CBA (Odeck, 2010). Hence, there's an indication that a 'hybrid' approach combining CBA and MCA can help in making decision-makers' preferences more transparent and streamlined by explicitly including all decision factors and thus establishing a strong link between policy objectives and appraisal results while still providing information for cost-efficient investment decisions (Gühnemann, Laird, & Pearman, 2012).

3.2 Cost-Benefit Analysis (CBA)

Application of CBA is, in general, fairly straightforward as the method has a consistent approach and methodology that can be applied to all (road) projects, thus enabling projects or project elements to be mutually comparable. CBA applies monetary values to a project to ensure a robust measure of the economic costs and benefits. This creates a degree of transparency and comparability, which are valuable elements for decision-makers when considering competing alternatives for funding (Government, 2011).

The following subsections provide an overview of key considerations and best practice when applying CBA as a method for assessing road infrastructure projects within the context of climate adaptation. The following themes are explored:

- Framing the cost and benefits of adaptation
- Use of CBA by National Road Agencies (NRAs)
- Key parameters (including discount rates, NPV, categories of damage)
- Incorporating resilience and service levels
- Co-benefits
- Data requirements
- Stakeholder involvement

3.2.1 Framing the costs and benefits of adaptation

Underpinning the application of CBA as a widely used economic appraisal method to assess climate change adaptation measures, is the need to tackle three key themes: uncertainty, equity and valuation (UNFCCC, 2011; Tröltzsch, et al., 2016). These overlapping themes are illustrated in the figure below.

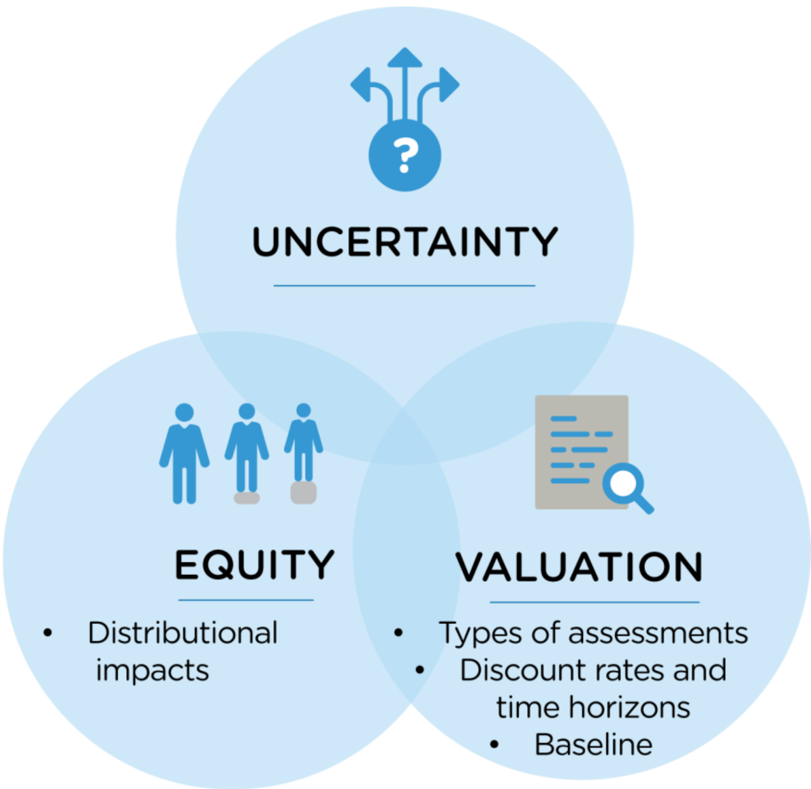

Figure 11. Main methodological themes concerning costs and benefits of adaptation (UNFCCC, 2011)

The issues surrounding proper handling of uncertainties is also highlighted by (Tröltzsch, et al., 2016), by recommending developing a risk framework to deal with climate uncertainties. A climate-driven risk framework should be seen as an overall strategy to account for major risks linked to climate change, in opposition to the traditional economic understanding of risk, which is typically defined as the potential, when the outcome is uncertain, for adverse consequences on lives, livelihoods, health, ecosystems, economic, social, and cultural assets, services, and infrastructure. Instead, and from a climate change and/or climate resilience perspective, major risks lie in the failure to adapt to changes in the environment, leading to instability and insecurity of economic system(s) threatening adequate level of societal welfare. The table below outlines the links between CBA and these three key adaptation themes.

Table 1. The link between CBA and key adaptation themes

Theme	Definition	Adaptation and CBA links
Uncertainty	Uncertainties are related to climate variability and uncertainty in future climate change scenarios and impacts. An uncertain future poses challenges to present decision-making as the range of possible impacts can be very large and difficult to account for. Uncertainties are typically grouped into three categories (Tröltzsch, et al., 2016): - *Epistemic uncertainty*: lack of information or knowledge for characterizing phenomena. - *Normative uncertainty*: absence of prior agreement on framing of problems and ways to scientifically investigate them. - *Translational uncertainty*: incomplete or conflicting scientific findings.	Uncertainties related to costs and benefits of infrastructure resilience directly affect the calculation of the benefit-cost ratio, i.e., the overall conclusion of the benefits and costs of strengthening exposed infrastructure assets. To tackle this uncertainty, the dominating approach seems to be the inclusion of several scenarios combining uncertainties in all parameters of the analysis (Hallegatte, Rozenberg, Rentschler, Nicolas, & Fox, 2019) (Mcginley, 2021). This is also the thinking behind the application of the RDR Tool Suite (see Figure 8). Also going beyond uncertainties related to climate change and climate variability. Sensitivity testing is also a way to cope with uncertainties (see Figure 9). Sensitivity analysis variables that might affect the overall CBA result could be traffic growth rate, effectiveness of the solutions, baseline traffic or travel time, adaptation costs, and hazard probability.
Valuation	Valuation refers to market and non-market goods and services, captured and transacted using monetary instruments and monetary information. Traditional market-based methods include averting behavior, replacement/restoration, and production factor method, etc. (Abdullah, Markandya, & Nunes, 2011). Adaptation-related valuation methods aim at capturing those intangible benefits, which typically don't have a market value and are associated with significant uncertainty (Skrydstrup, 2021).	Inclusion of non-market costs and benefits is necessary to assess adaptation options, i.e., those costs and benefits that are difficult to quantify in monetary terms because they are not traded on markets (e.g., human health and ecosystem services). This, however, requires that costs and benefits be readily quantified and valuated, which can be difficult as many of the benefits derived from adaptation solutions (e.g., nature-based solutions) are non-market goods, which requires special valuation techniques associated with high uncertainties (Skrydstrup, 2021). An example of non-market valuation methods is given by the Green Infrastructure Valuation Toolkit (The Mersey Forest, et al., 2010/2018). The Transport Analysis Guidance on Environmental Impact Appraisal (UK Department for Transport, 2022) is another example, providing monetary valuation of changes in noise levels and air pollution. Key parameters linked to valuation in CBA are outlined in section 3.2.3.
Equity	Equity refers to the distributional aspects of net adaptation benefits in the light of climate change impacts affecting vulnerable populations in a disproportionately way (UNFCCC, 2011).	To account for this type of 'equity bias' on CBA, it is recommended to assign weights to different costs and benefits on the basis of who receives the benefits and who bears the costs, i.e., for instance using MCA, but this can turn into a highly subjective assessment (UNFCCC, 2011). Another way to account for equity is through a criticality assessment including equity effects, e.g., distribution of disruption impacts across socially and economically vulnerable populations under a scenario of transportation disruption (National Academies of Sciences, 2021)

3.2.2 Use of CBA by National Road Authorities (NRAs)

The use of CBA as a tool supporting decision-making has also been looked in detail by CEDR through the development of the WATCH project's country comparison report, with focus on NRA's resilience approaches to water management (Bles, et al., 2018). The study makes use of

CBA within the context of adaptation and maintenance approaches for water management and drainage on national roads, and particularly points to the differences in performing CBAs at different decision-making levels within NRAs.

At the strategic level, no (major European) country in the study performed CBA to determine requirements for water management systems, even though the criticality or vulnerability of roads were linked to the design return periods of the assets. Despite of this, no CBA was used to support decision-making.

At the operational (project-specific) level, the use of CBA was deemed a standard practice for the selection of appropriate solutions. However, CBA was not used to determine the choices for specific infrastructure design requirements. The use of CBA was going more to the appraisal of an entire project and not only looking at one specific component, e.g., drainage.

The above clearly indicates that CBA were, back in 2018, mainly used for identifying the best solutions on a project level within participating NRAs, but without focusing on specific project components and rather looking at projects as a whole. The use and link of CBA to support decision-making linked to climate change adaptation measures was not visible. However, The Netherlands was planning to use CBAs for decision-making on whether climate adaptation and/or mitigation measures should be included (Bles, et al., 2018). Though these analyses have actually been undertaken in the past years in the Netherlands, resulting in benefit cost ratios for various adaptation measures on the asset level of the entire road network, it has not yet led to strategic decisions on possible changes of design and maintenance guidelines.

3.2.3 Key concepts

When performing CBA, there are a number of key parameters that need to be accounted for. Many of them are mentioned and defined in different places in this report. This section deals with the key concepts which are obligatory to include when performing a CBA, that is: discount rates, net present value and categories of damage.

3.2.3.1 Discount Rates

Probably the most discussed concept is the choice of the discount rate. Discounting is an economic method for determining the time value or opportunity cost of an investment, generally equal to the economic return that could be earned on the invested resources in their next best alternative use. An economic analysis uses a discount rate to convert anticipated future costs and benefits to present values, so different alternatives and time horizons can be directly compared. Discount rates are particular important when evaluating and comparing adaptation options, as the associated benefits (or avoided costs) are likely not realized for many decades (Gina Filosa, Amy Plovnick, Leslie Stahl, Rawlings Miller, Don Pickrell, 2017).

Many governments and businesses tend to use discount rates that put a substantially lower value on the future (i.e., a conservative approach), providing typically a bias towards established, engineering measures with well-defined, short-term benefits, over ‘soft’ and green measures that have less clear, longer-term benefits and costs. A recommended good practice is to use the official rates adopted by the implementing private or public agency, supplemented with sensitivity analysis based around different configurations of the Social Time Preference Rate (STPR) (Tröltzsch, et al., 2016). However, and directly related to the three key adaptation themes (see Figure 7), selecting an appropriate discount rate to use in the face of uncertainty is one of the biggest challenges when performing CBA (McGinley, 2021).

The discount rate is therefore a highly important parameter affecting decision-making. Adaptation projects typically have their costs concentrated upfront, in the early years of project implementation, while the benefits follow through later on; that is, the benefits will increase in the future due to more avoided impacts. This means that for adaptation projects, raising the discount rate tends to artificially lower the NPV of the resilience option, causing the future benefits of resilient infrastructure to be ignored. On the other hand, low or close to zero discount rates have the tendency to increase the NPV of resilience options compared to the 'do nothing' scenario (Gina Filosa, Amy Plovnick, Leslie Stahl, Rawlings Miller, Don Pickrell, 2017).

The following table summarises the discount rates currently being used for public sector projects across Europe.

Table 2. Overview of different discount rates (adapted from (OECD, 2018))

Country	Risk-Free Discount Rate	Overall Discount Rate	Long-Term Discount Rate
UK (The National Archives(UK), 2022)	3.5%	For all projects and regulatory analysis: 3.5% 1.5% per annum applies where there is risk to health and life.	The discount rate declines gradually to 1% after 300 years
Ireland *(Transport Infrastructure Ireland, 2016)*	5%	All road projects: 5%	-
Netherlands (de Jong, 2013)	2.5%	All projects and regulatory analysis: risk premium of 3% on all, so 5.5% total.	Discussions to introduce declining discount rates for climate (adaptation)-related investments are in progress.
Norway (Mouter, 2018)	2.5%	Risky projects and regulatory analysis: 1.5% risk premium + 2.5% risk free	Risk-free rate declining to 1% after 100 years. 0- 40 years: 4% 41-75 years: 3% 75-100 years: 2% 100 + years: 1 %
Sweden (Mouter, 2018) *ASEK Guidelines*	3.5%	All investments: 3.5%	
Denmark (Mouter, 2018) *Minister of Finance*	3%	All projects and regulatory analysis: 1% risk premium, so 4%	Declining discount rates after 35 years and 70 years. Declining risk premium is used
Finland (Hanssen, Helo, Solvoll, & Westin, 2020)	3.5%		
United States	3% with sensitivity up to 7%	3-7% 7% is a risky rate of return, but not project specific risk premium	OMB (2003) recommends lower rate for 'intergenerational' projects, US EPA (2010) recommends 2.5%
European Commission[1]	4%		

There seems to be no consensus on discount rates in the context of climate resilience. A common recommendation is to perform trial-and-error using sensitivity analysis with different discount rates.

[1] https://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf

A review of the 2021 UK's Green Book (HM Treasury, 2021) scrutinised current guidance on environmental valuation and investigating the case for using the same discount rate (1.5%) as currently applied to the valuation of life and health effects. The review concluded[2] not to lower the discount rate for environmental impacts.

Another choice is to use a variable discount rate, i.e., changing over the forecast horizon. In the Post Hurricane Sandy Transportation Resilience Study, a decreasing discount rate was applied to calculate the effect that disruption of a specific transportation asset would have on the regional economy over the forecast horizon. The analysis assumed a 3% real discount rate from 2010 through 2034, 2% for 2035–2084, and 1% for 2085–2100 (Filosa, G.; Plovnick, A.; Stahl, L.; Miller, R.; Pickrell, D., 2017) .

In the United States, guidelines from the federal Office of Management and Budget have recommended a real discount rate of 7% since 1992. Over the past 20 years, real rates of return on fixed income assets (such as Treasury bonds) have fallen substantially, calling into question the continuing validity of 7% as an appropriate long-term discount rate (National Academies of Sciences, 2021). However, latest research confirms there is still a debate on adjustment to discount rates in relation to climate risks. This is anchored in the fact that, as an asset becomes more resilient through incremental investments and/or the implementation of non-structural measures, its cost of equity should theoretically be reduced (CCRI, 2022). In other words, the rate of time preference becomes an intergenerational trade-off. When the benefits and costs are experienced by different generations, it raises questions as to whether an individual's rate of time preference is valid as a measure of how a society should trade off future versus present benefits and costs (National Academies of Sciences, 2021).

As a result, some argue that a lower discount rate, perhaps 3%, is appropriate for discounting future benefits and costs that involve intergenerational trade-offs. Methodological approaches for CBA have recommended the use of declining discount rates over time to capture the issue of intergenerational equity. In this regard, the Green Book, which is used widely in project appraisals in the United Kingdom, recommends an initial discount rate of 3.5% followed by a declining rate schedule for projects with long-term duration (National Academies of Sciences, 2021).

In The Netherlands, declining discount rates are not used, but discussions are held on introducing this, especially for climate (adaptation) related investments. Moreover, a 7% real interest rate would make the investment financially attractive for private financing, although revenue generation is in general difficult for public services.

3.2.3.2 Net Present Value (NPV)

Another central term when preforming a CBA is the Net Present Value (NPV). This quantifies the present value of the benefits, minus the present value of operating costs. The NPV can be used in all decision contexts and should be reported for all evaluations, especially when comparing mutually exclusive project options. Hence, the discussion provided above on discount rates is likewise relevant for net present value. NPV measures the actual or real net economic benefit of any given project. While the Benefit-Cost ratio (BCR) provides a ratio of benefits to costs, NPV

---

[2] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1014758/20210817_-_Environmental_discount_rate_review_conclusion.pdf

measures the absolute net economic gain and is connected to the discount rate as it is calculated by subtracting the discounted costs from the discounted benefits (Government, 2011).

3.2.3.3 Categories of damage

Within a CBA the benefit - in the form of avoided damage - is often categorized as being 'direct' or 'indirect' and 'tangible' or 'non-tangible' (Figure 12). The direct, tangible damage costs are the most obvious to include and are often relatively straightforward to monetize. Ideally, all types of avoided damage should be captured, to strengthen the business case.

Figure 12 gives a series of examples of direct and indirect costs, organized per tangible and non-tangible damage categories, within the context of flood resilience.

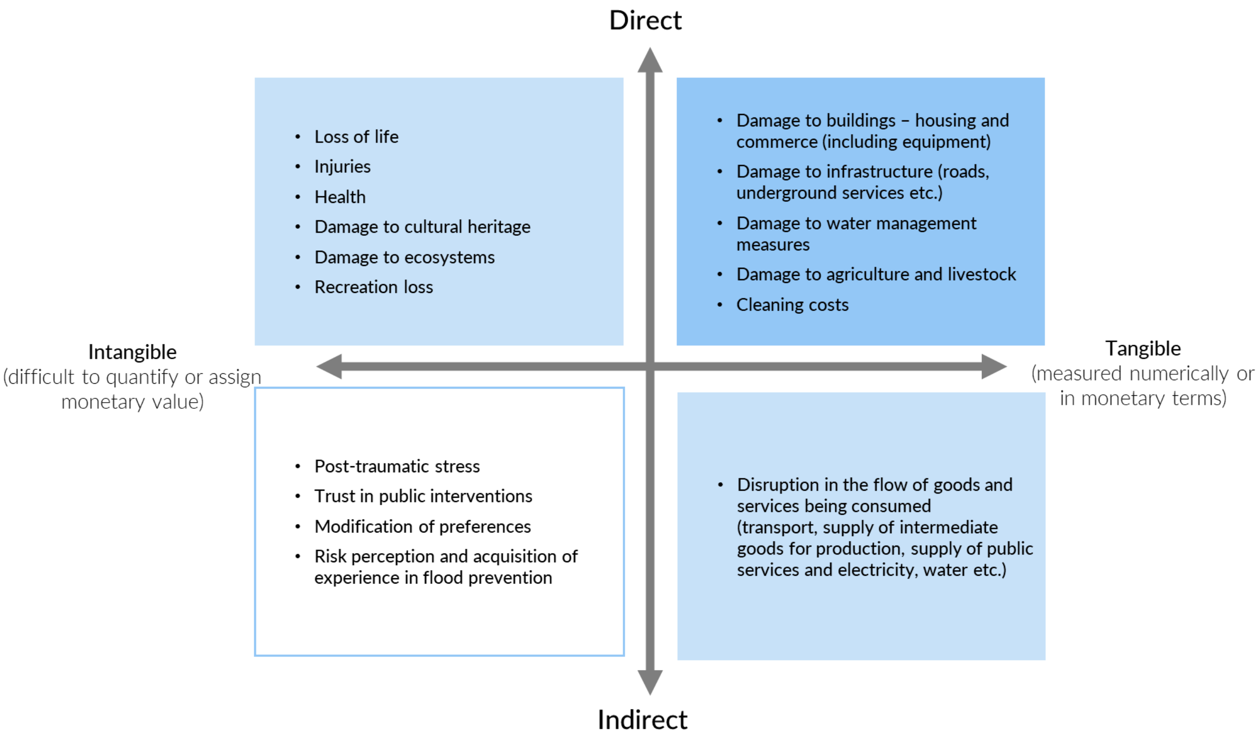

Figure 12: Types of damages, based on flooding (Scussolini, et al., 2016)

3.2.4 Incorporating resilience and service levels

The use of CBA to assess proposed road projects is not new; it's been a practice for many years. Hence, using CBA for climate adaptation planning is mainly about adapting a familiar tool to incorporate resilience targets and metrics. Moreover, the integration of resilience criteria in transportation decision-making processes has been increasing significantly in the past decade, including the development, piloting and use of innovative tools addressing resilience metrics, evaluation methods and prioritization of investments (National Academies of Sciences, 2021).

There have been, and continue being, many efforts in defining the concept of resilience across disciplines, i.e., from ecology, risk management, infrastructure design, etc. Deliverable D2.1 (Baseline report on minimum service levels and resilience evaluation) includes an in-depth discussion of resilience (section 3.1.1) from many angles and perspectives. This report focuses on CBA as a predominant socio-economic evaluation method, where a study of resilience per say is not included. For an appraisal of resilience definitions, the reader is referred to Deliverable D2.1 of the ICARUS project.

The following sections present three examples from practice which highlight different approaches to incorporating resilience and service levels into CBA and economic evaluation methods.

3.2.4.1 FORESEE Horizon 2020, resilience targets & service levels

The Horizon 2020 project, FORESEE, outlines the key links between CBA, services levels, and resilience targets (CEN, 2021). It highlights the importance for transport infrastructure managers to clearly understand:

1) the service provided by infrastructure; and
2) how the resilience of this infrastructure is affected by disruptive events.

To achieve the overall goal of risk reduction, infrastructure managers need to be able to *measure* or *quantify* the service provided by the transport infrastructure and the resilience during disruptive events. Depending on data availability and quality, analysis should aim to quantify the impacts of different types of hazards, at different scales (asset, connections, network).

The figures below illustrate the concept of resilience with three different measures of service: expected yearly travel time costs, injuries and fatalities costs, and intervention costs (see footnote 3). The figures are a conceptual representation of these three services measures, as units to measure the resilience of infrastructure. The scenario assumes a single disruptive event occurs, and that the infrastructure is restored back to its original condition, providing the same level of service as before the disruptive event.

- The green field represents the service and expected cost without a disruptive event.
- The red area and line represent the reduction in service in the absorb phase. It indicates how the expected cost increases from the moment a disruptive event beings to the moment when the disruption event ends.
- The blue area represents the reduction of service in the recovery phase. The blue lines indicate the expected costs from the moment the disruptive event ends until service is restored.
  The blue area also represents the total accumulated expected costs during the restoration phase (CEN, 2021).

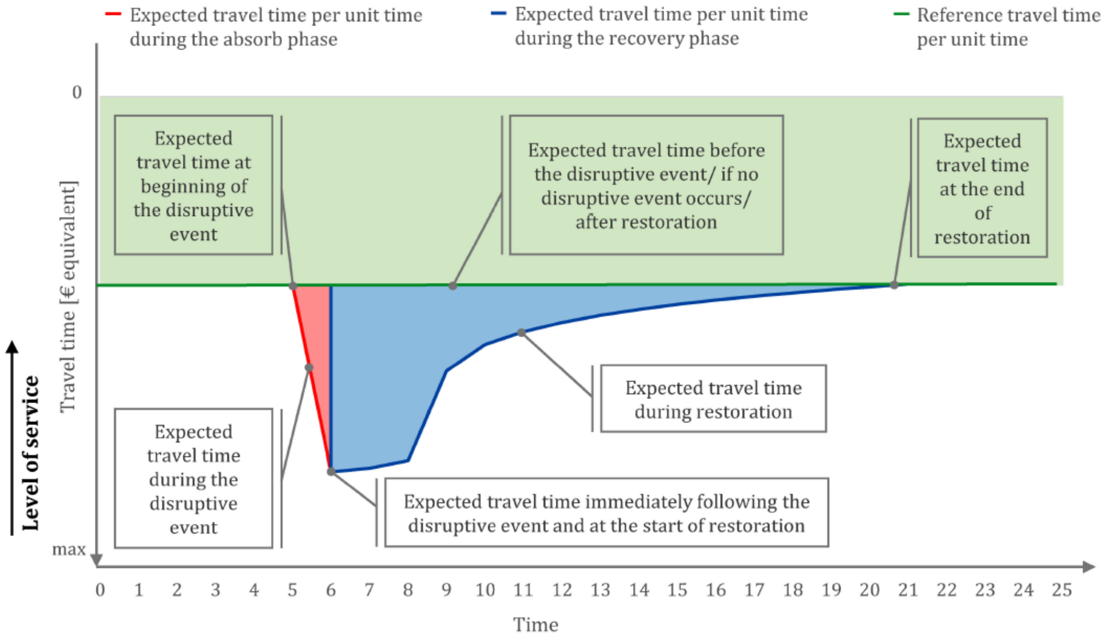

*Figure 13. Conceptual representation of transport infrastructure resilience using "**travel time**" as a measure of service (CEN, 2021)*

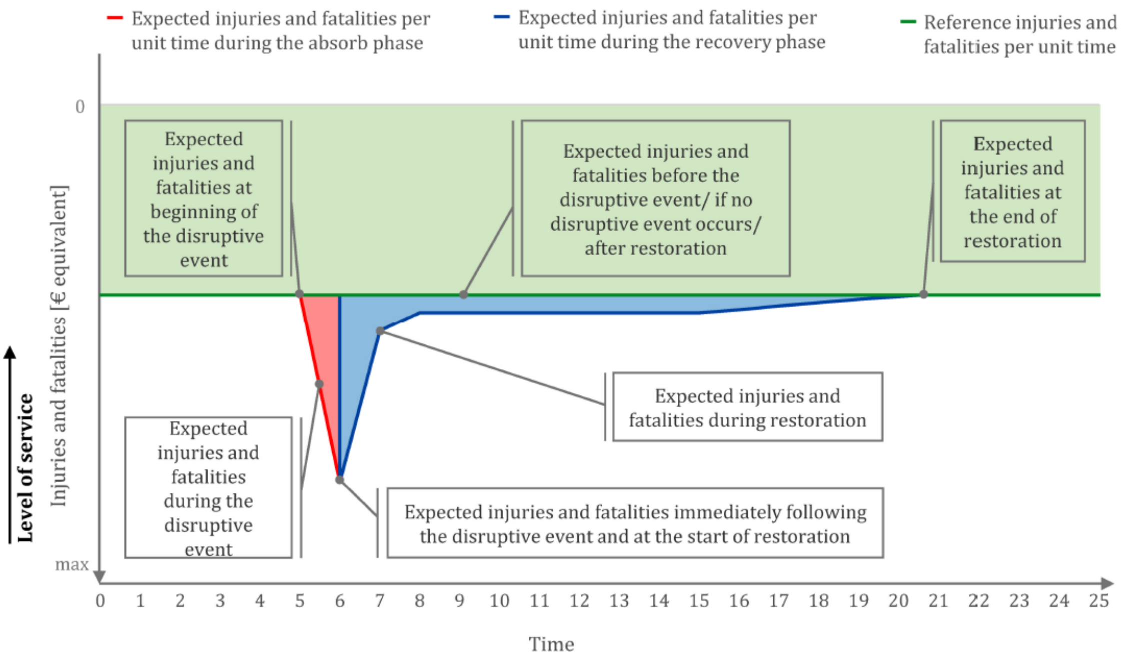

*Figure 14. Conceptual representation of transport infrastructure resilience using "**injuries and fatalities**" as a measure of service (CEN, 2021)*

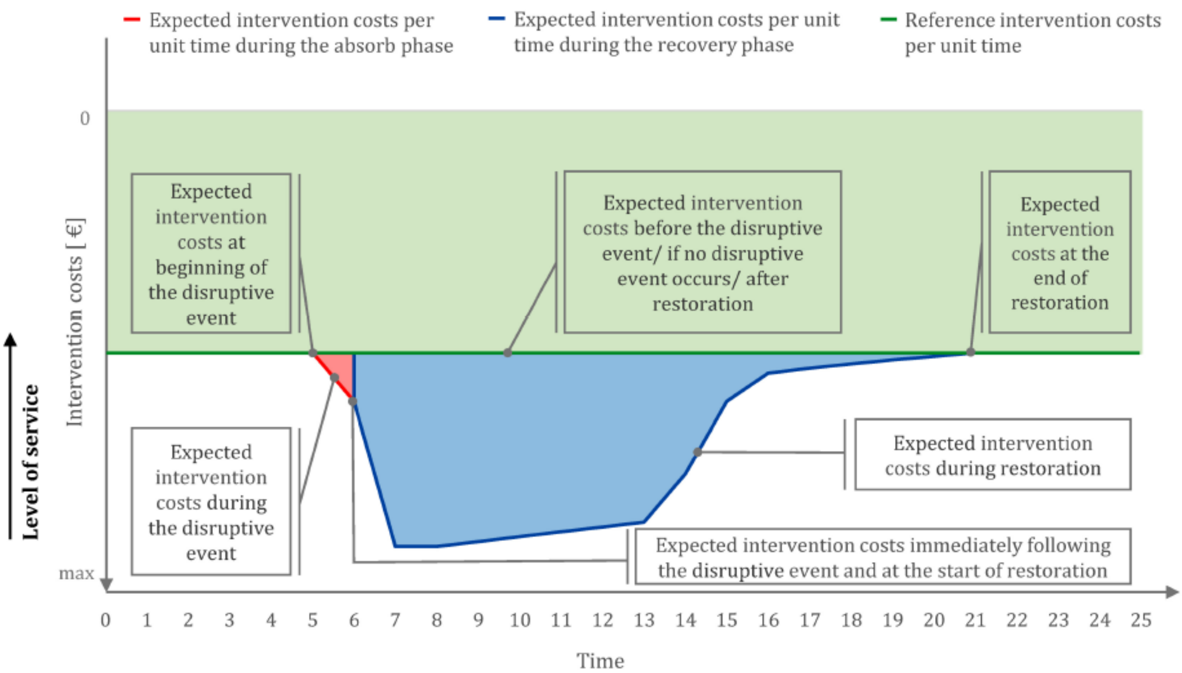

*Figure 15. Conceptual representation of transport infrastructure resilience using "**intervention costs**"[3] as a measure of service (CEN, 2021)*

This conceptualization enables service and resilience targets to be defined on the basis of two overarching goals: i) limiting the maximum reduction in service during the disruptive event and/or ii) accelerating the restoration of the service to the expected level.

Targets can then be set for: i) intervention costs (see footnote 3) or a measure of service; ii) combinations of intervention costs and measures of service; and iii) multiple disruptive events. Once targets have been defined, the benefits and the costs of achieving those targets can be explicitly estimated (CEN, 2021). An example for the context of flood resilience is given below.

Table 3. Example service and resilience target types for a 100-year flood event (CEN, 2021). Note: the CEN defines the intervention costs as "all costs incurred by the infrastructure manager" while an intervention in this report is defined as being equivalent to an adaptation solution or a measure to increase resilience.

Restoration intervention costs or measure of service	Target type	Description
Restoration intervention costs	Maximum increase in restoration intervention costs	The amount of money required to finance the activities of the emergency response team
	Maximum total restoration intervention costs or reductions in service	The total amount of money spent on interventions from the beginning of the disruptive event until the users can once again travel as they could prior to the disruptive event
Travel time	Maximum decrease in service	The maximum increase of travel time per day following a 100-year flood

[3] The CEN defines the intervention costs as "all costs incurred by the infrastructure manager" while an intervention in this report is defined as being equivalent to an adaptation solution or a measure to increase resilience.

	Restoration curve shape	The way in which travel time returns to normal following a 100-year flood
	Restoration time	The total amount of time from onset of the 100-year flood until users can once again travel as they could prior to the disruptive event

For road infrastructure to continue providing the target service level, NRAs could draw inspiration from the cost quantification scheme outlined in the table below.

Table 4. General description of intervention costs (CEN, 2021). Note: the CEN defines the intervention costs as "all costs incurred by the infrastructure manager" while an intervention in this report is defined as being equivalent to an adaptation solution or a measure to increase resilience.

Level 1	Level 2		
Measure	*Type*	*Description*	*It can be estimated using:*
Impact of executing interventions	Labour	Economic impact of people performing tasks	Cost of labour required for the execution of interventions
	Material	Economic impact of people ensuring that materials are available for use	Cost of material required for the execution of interventions
	Equipment	Economic impact of people ensuring that equipment is available for use	Cost of equipment required for the execution of interventions
Impact of accident during the execution of interventions	Infrastructure property damage	Economic impact of repairing damages caused due to the execution of interventions	Cost of replacing the damaged property or as part of the fatality of injury costs
	Workforce injury	Societal impact due to injury at workplace	Willingness to pay to avoid workforce injury
	Workforce fatality	Societal impact due to death at workplace	Willingness to pay to avoid workforce injury

3.2.4.2 USA Office of the Secretary of Transportation, integrating climate resilience into CBA decision making

In the Unites States of America, the Office of the Secretary of Transportation promotes the use of CBA for project justifications that include resilience benefits. As in FORESEE (CEN, 2021), resilience metrics for different scenarios are defined as by capturing different aspects of the system functionality during a disruptive event and recovery. While the direct link between service levels, intervention costs and resilience is missing, this case study gives specific examples on benefits to include in the CBA (Figure 16) and discusses the importance of including costs over the entire life-cycle. These costs should cover construction, operations, and maintenance (National Academies of Sciences, 2021)

Infrastructure Owner-Operators—Costs Reduced, Avoided
- Emergency operations
- Recovery and restoration
- Reconstruction

Users (freight)—Costs Reduced, Avoided
- Trip delay costs
- Rerouting costs
- Canceled trip costs
- Inventory costs

Users (personal travel)—Costs Reduced, Avoided
- Trip delay costs
- Rerouting costs
- Canceled trip costs
- Trip reliability

Communities—Costs Reduced, Avoided
- Business, tourism sales lost, deferred
- Workdays lost, furloughs, jobs lost
- Injuries and deaths
- Delayed shipment costs (e.g., stockouts, supply chain disruptions)
- Canceled shipment costs (e.g., stockouts, supply chain disruptions)
- Environmental damage costs
- Reductions in damage costs for non-transportation facilities and activities

Communities—Positive Changes
- Jobs gained in restoration, new construction

Figure 16 Types of benefits of resilience investments (National Academies of Sciences, 2021)

The following decision-making framework and metrics illustrate good practice within CBA. Figure 16 presents a proposed multi-step analytical framework used to estimate risks, benefits and costs to guide decision making. Figure 17 presents examples of decision-making metrics that can be developed within CBA.

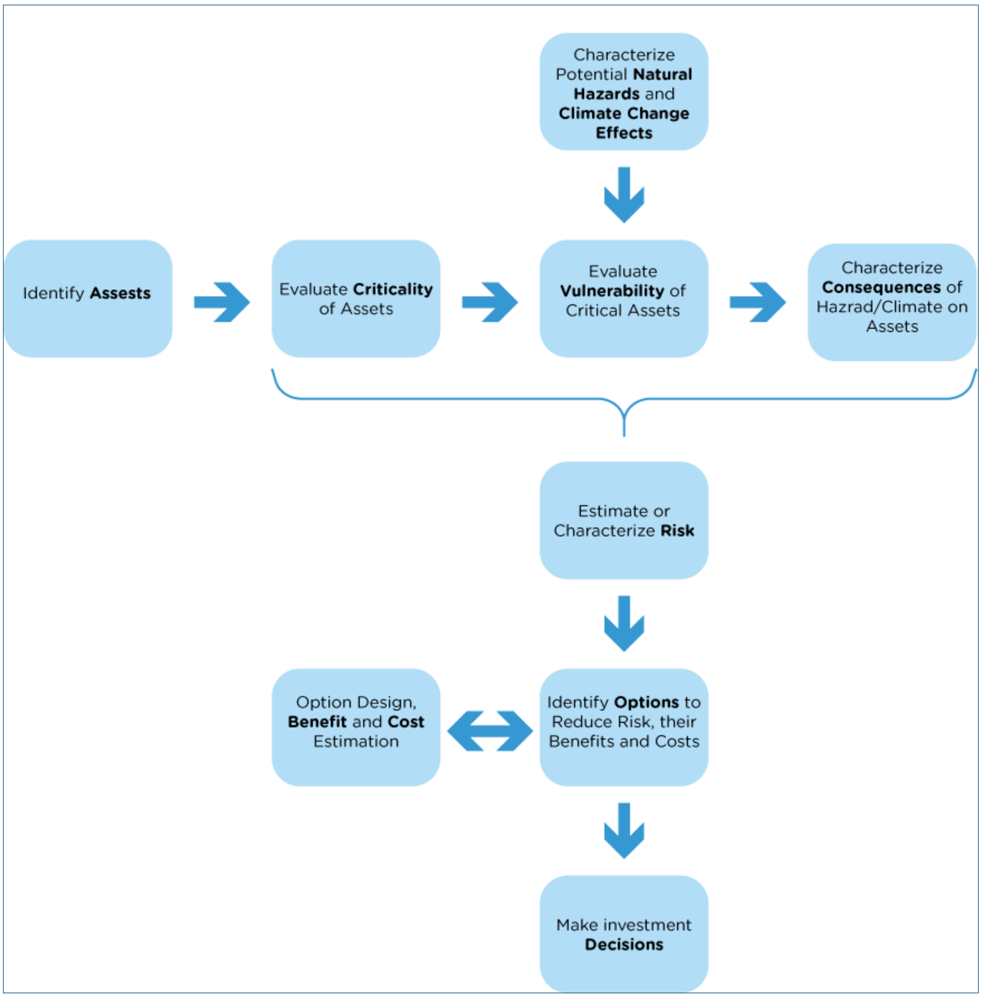

Figure 17. Multi-step decision support framework (National Academies of Sciences, 2021)

- Benefit-cost ratio
- Return on investment
- Net present value
- Costs avoided
  - Infrastructure damage
  - Incremental transportation costs—time and money
  - Economic disruption costs (due to blocked or delayed flows, late or failed deliveries, product spoilage, etc.)
  - Social disruption costs—social connections, impacts to vulnerable communities, health care, education activities delayed or prevented
- Equity of distributional effects
  - Inequities in the distribution of negative impacts across economic and social groups and on vulnerable populations

Figure 18. Examples of investment decision-making metrics derived from CBA (National Academies of Sciences, 2021)

3.2.4.3 Physical Climate Risk Assessment Methodology, integrating resilience in infrastructure investment appraisals.

The Coalition for Climate Resilient Investment has developed a Physical Climate Risk Assessment Methodology (PCRAM), that provides guidelines for Integrating Physical Climate Risks in Infrastructure Investment Appraisal (CCRI, 2022). This approach highlights the importance of making asset investment decisions based on a robust understanding of future Physical Climate Risks, under various scenarios. This approach identifies three parameters within infrastructure asset delivery decisions that guide the decision-making process (CCRI, 2022):

1. Decision-makers (incl. policymakers) tend to be driven by the wish to minimize capital expenditures and operating expenses (CAPEX and OPEX, respectively), as well as trying to comply with usually stringent timelines (all of this whilst trying not to pose a risk on lives/community wellbeing)

2. Decisions or changes should not compromise the assets functionality and durability. This means disruptions to the existing situation, regardless of their form, should be preferably non-present or very limited.

3. Infrastructure assets are governed by regulated environments, so any decision-making process must be anchored within the corresponding regulatory frameworks and design codes. In practice, having this in mind from the start can result in some specific measures or options being non-viable.

The PCRAM methodology is meant to facilitate a shift in the resilience narrative, so that resilience is no longer perceived as exclusive downside-minimisation exercises, often carried out ex-post, i.e., after an event. PCRAM seeks to make resilience a core component of an innovative strategic decision-making process, where a rigorous integration of climate risks becomes a pro-positive force, enabling stakeholders to become more strategic and competitive (CCRI, 2022). The PCRAM methodology is shown and explained below.

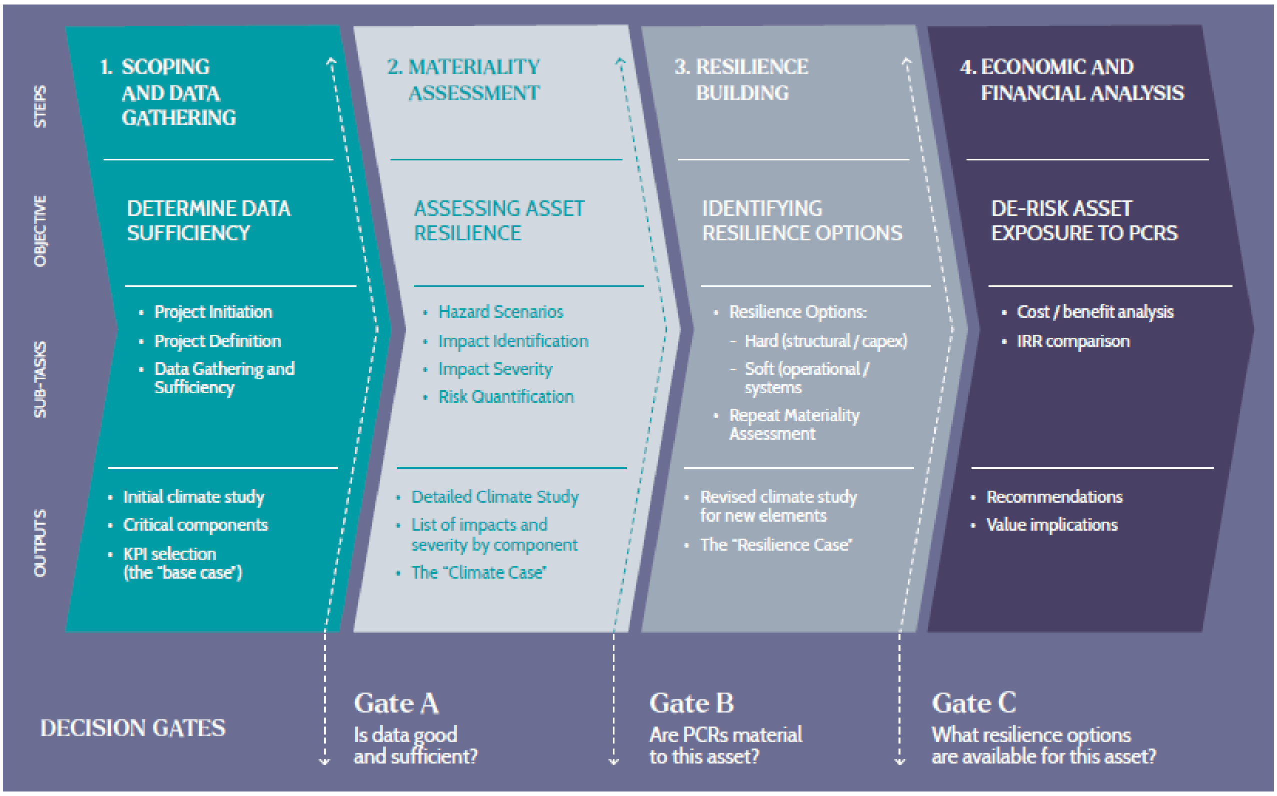

Figure 19. Physical Climate Risk Assessment Methodology, PCRAM, composed of four steps and three gates (CCRI, 2022)

In Step 1 (Scoping and data gathering), baseline data is collected, and an initial climate study is implemented, resulting in the 'base case', a list of commercial and financial key performance indicators (KPI). The methodology includes decision gates in every step, and if the data and results of step 1 are not good enough to proceed to step 2 (Materiality assessment), further scoping and data gathering work needs to be done. In this way, these feedback loops are similar to the socio-economic framework proposed by CEDR, see

Figure 6 (Tucker, Corbally, & O'Connor, 2018).

KPIs can be framed within a financial, commercial and/or ESG context, and they ultimately depend on the financial and commercial scope of the study, as they will be used will be used to measure the impact of PCRs from a financial and commercial perspective. A list of potential KPIs is given below.

Table 5. Sample of commercial/financial/ESG indicators, adapted from (CCRI, 2022)

Category/Type	KPI
Financial metrics	DSCR[4]: Debt-Service Coverage Ratio
	IRR: Internal Rate of Return
	NPV: Net-present Value
	ROI: Return of Investment
Commercial penalties or liquidated damages	Case-dependent
Socio-environmental metrics	CO_2 emissions
Socio-economic metrics	Job creation/loss

[4] Indicator used to measure the ability of an entity to pay debt obligations. Source: https://winrock.org/wp-content/uploads/2022/07/PIER-Policy-Brief-Infrastructure.pdf

In step 2 of the PCRAM methodology, the 'climate case' is developed by undertaking a detailed climate study taking the data from step 1 and assessing the severity of climate impacts to the infrastructure based on a hazard assessment and using the KPIs to quantify the risk. At the end of step 2 a decision needs to be made on whether PCRs are material to the asset being studied. This is, in essence, an exercise of risk quantification, whereby a range of scenarios are developed with the purpose of linking causes (climate change hazard) and effects (loss, increased maintenance, temporary or permanent downtime or a reduction in productivity). Hence, the 'climate case' incorporates the impacts of PCRs on forecasted cash flows. The effect or impact is quantified as a function of the KPIs. On the other hand, if PCRs are not material, the assessment is deemed complete and risk quantification is not needed.

These resilience options are taken through step 2 (Materiality Assessment) to measure projected benefits against the CAPEX and OPEX cost of the options. Moreover, depending on the specific conditions of the study, multiple climate cases might arise as the materiality[5] assessment can be done for a range of time horizons and RCP scenarios. Regardless, climate cases should also include the costs linked to commercial penalties (i.e., connected to the disruption of a mandatory service level), decrease in performance and other impacts of the "do nothing" scenario.

In step 3, the 'resilience case' is developed in collaboration between climate practitioners, engineers, and asset managers, by generating a list of options to improve resilience of the asset. Resilience Cases in the PCRAM methodology are composed of feasible resilience options (hard and soft options) that may reduce the severity of impacts. Comparison of KPIs developed in step 1 and 2 is done to quantify the impact of climate change. At the end of Step 3, a decision is taken on whether there are resilience options available to reduce the severity of impacts.

The objective of step 4, Economic and Financial Analysis, is to ultimately determine if there is a case for investment in resilience. This is done by comparing the 'climate cases' and 'resilience cases' through CBA and IRR calculations, and also looking at other KPIs including total life cycle costs (see also Table 5). Life cycle costs include all capital and operating costs linked to an asset during its entire lifetime, from construction to operation and decommissioning. This economic and financial analysis is undertaken to de-risk an asset exposure to PCRs and outline recommendations for resilience options, incl. also the use of sensitivity analysis where deemed needed to confirm the selected KPIs.

3.2.5 Co-benefits

Co-benefits form an important element of the overall climate resilience business case. Co-benefits can be defined as benefits obtained through adaptation measures, which are not always easy or possible to quantify or monetize. Co-benefits are also referred to as non-tangible benefits or indirect effects, linked to the improvement of resilience. These indirect effects can be environmental and social and represent an important category of benefits that result from redesigning or relocating transportation facilities or investing in protective features to improve resilience, for example through implementing Nature-based Solutions (NbS). Although co-benefits

[5] Materiality: effects on the financial, commercial, or other performance KPIs, e.g., damage costs, downtime, loss of service, socio-economic losses, i.e., what might be lost (CCRI, 2022).

can be difficult to value in economic terms, examples are related to air and water pollution, GHG emissions, access to recreational areas, all of which nowadays routinely valued in the economic analyses of government regulations and proposed infrastructure investments (Filosa, Plovnick, Stahl, Miller, & Pickrell, 2017).

The figure below illustrates potential co-benefits related to NbS in the context of climate resilience.

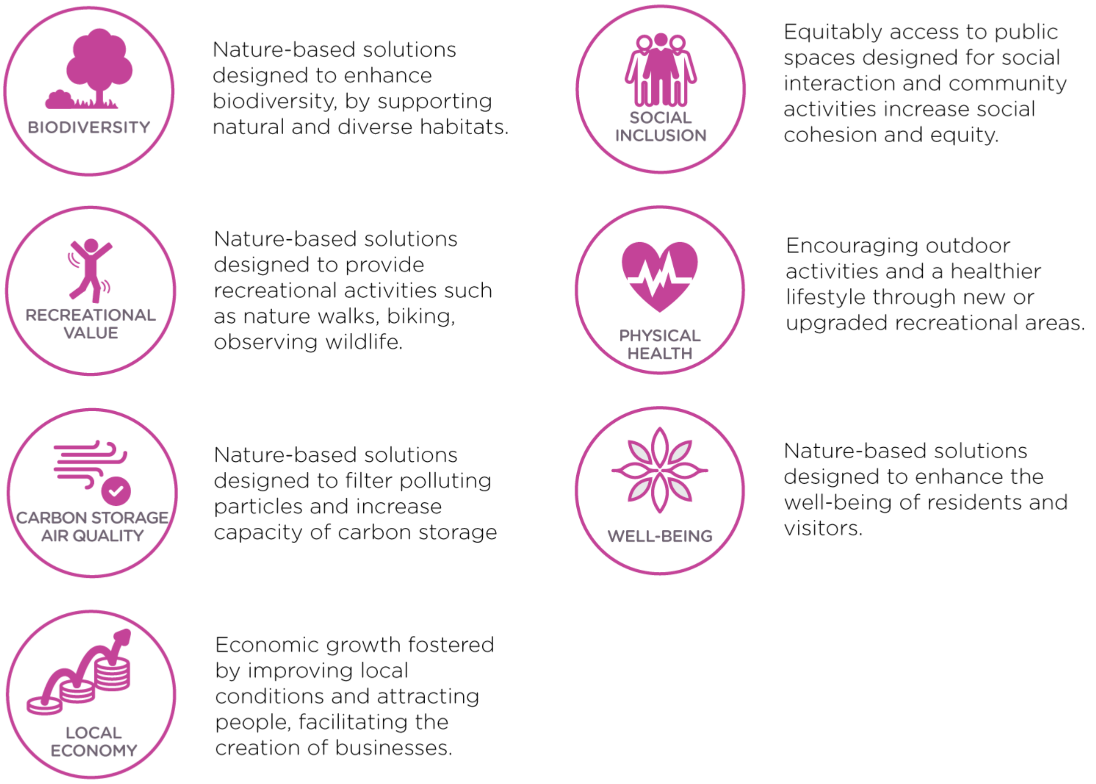

Figure 20. Potential co-benefits related to NbS in the context of climate resilience

The incorporation and valuation of co-benefits is also referred to as incorporating externalities by estimating their monetary value, which is the financial cost that would be incurred by those that benefit from the externality, to compensate those that incur the impact of the externality. For transport-related evaluation, the preferred treatment for externalities is to internalize these costs by calculating a monetary value expressed per VKT (vehicle km travelled) for inclusion in CBA calculations (Government, 2011).

Co-benefits are important in estimating the total benefits and costs of adaptation projects. In general, costs and benefits related to market goods and services are estimated using market prices. For wider social and environmental costs and benefits (i.e., co-benefits) for which no market price is available, specialised non-market valuation techniques may be applied. Some of the methods include (The Mersey Forest, et al., 2010/2018):

- Contingent valuation (CV): a survey method which aims to capture individual preferences for a change in the provision of a good or service through assessing their willingness to pay (WTP) or willingness to accept (WTA) compensation. It is important to ensure surveys are well designed to minimise all sources of bias. The contingent valuation approach is widely used for generating option and existence values - for example in protecting biodiversity.

- Hedonic pricing: this method relates the price of a marketed good to a non-marketed good, the most common of which are property and labour. The property value (PV) approach is the most common use. It consists of observing differences in the values of property between locations and isolating the effect of ambient environmental quality on those values. The approach is typically used to assess the impact of green infrastructure on residential property prices.

- Travel cost method: this takes the cost of getting to a site as the value attributed to the good or service. The value people place on a good environmental space is inferred from the time and cost they incur in travelling to it. This method is applied mainly to public recreation sites with free or minimal admission charges - for example coastal footpaths or a nature reserve - where it is argued that the cost of travel is a good proxy for the entry price.

- Effect on production: this measures the effect a project may have on the output, cost, or profitability of producers through its effect on their environment and the welfare of consumers. An example might be reservoirs creating new fisheries, or beekeepers benefiting neighbouring gardens. This method is often used to assess negative impacts associated with an investment.

- Preventative expenditure: this is typically used when comparing the benefits provided by green infrastructure to the costs of providing engineering solutions – for example protection from flood risk - and/or replacement cost approaches.

- Benefit transfer: effectively adopts or adapts information from valuation studies undertaken elsewhere - using a variety of the above techniques -and applies them in a new context. A more sophisticated use of benefit transfer is called the transfer function approach. This adapts the results from one study to make it more suitable to another context – for example adjusting for the socio-economic context or the location.

- Specific values: depend on the context, the most significant being the 'social cost of carbon' or 'shadow price of carbon'. This value is effectively a shadow price set by government - it is a requirement to adopt the value in public sector CBA.

3.2.6 Data requirements

To carry out resilience benefit assessments, transportation agencies or NRAs need to have access to high-quality data and analytic tools, in particular (National Academies of Sciences, 2021):

- Characteristics of natural hazards and their probability of occurrence at the location of existing and planned assets.
- Updated projections on future climate impacts at the same location(s).
- Asset management programs including vulnerability assessment and estimation of functional values (i.e., criticality).
- Mode-specific data and modelling tools to estimate the direct and indirect consequences of asset damage and functional losses.
- Data and modelling tools that can reveal the economic and social importance of the asset to different users, incl. directly affected communities and the broader region.

Required data can be obtained from the results of literature reviews and the local socio-economic and environmental context. Crucially, data should be gathered from local stakeholders including relevant provincial and regency agencies. Direct damage data may be available locally, or benchmarking information may have to be gathered from elsewhere. Also, data on the different asset types is important to gather. This may be sources from local or regional data sources. Table 6 presents a list of general potential indicators with associated data requirements.

Table 6. General data requirements

Costs	Unit capex costs of interventions over service life	Capital, construction, land and property acquisition, non-structural measures, and contingency costs	Engineering team
	Unit opex costs of interventions over service life	Capital replacement, refurbishment, annual operating and maintenance, non-structural measures, and contingency costs	Engineering team
Core benefits	Avoided damages	Data from flood risk analysis (yielding damage costs), for base case and interventions cases. These will be linked to the various asset classes; their location, condition, doorsteps etc. Plus, in terms of critical infrastructure, information on use may include revenue levels, visitor levels, use levels etc.	Flood risk analysis team, Local literature, and data sources
	Travel time savings	• Kilometers of road at risk of disruptive flooding • Average number of vehicles per day, by mode • Average travel time	Local literature and data sources (e.g., policy documents, surveys, databases)
Co-benefits *(includes disbenefits)*	Biodiversity and habitat restoration	Type of habitat and state/condition in area of influence	Local literature and data sources (e.g., policy documents, surveys, databases)
	Recreational and eco-based tourism opportunities	Average visitors per day to key tourism, recreational assets	Local literature and data sources (e.g., policy documents, surveys, databases)
	Carbon sequestration and air quality benefits	Extent of green space / number of trees planted or removed	Local literature and data sources (e.g., policy documents, surveys, databases)
	Embodied carbon in infrastructural works	Quantities of key construction materials (e.g., concrete, asphalt)	Engineering team
	Water quality	• Water quality survey results • Number of patients with water-related illnesses (e.g., dysentery) • Health costs associated with treating water-related illnesses • Insurance coverage	Local literature and data sources (e.g., policy documents, surveys, databases)
	Increased business opportunities and livelihood improvement	• Poverty rate (number of people below poverty line) • Number/% of people employed by gender (and economic sector if possible) • Average wage • Average customer spend in area of influence (retail, restaurants) • Average number of customers at local retail businesses in area of influence • Number and diversity of land uses/economic activities within area of influence e.g., x% manufacturing vs y% construction • Gross value add (GVA) in area of influence, by economic activity	Local literature and data sources (e.g., policy documents, surveys, databases)

3.2.7 Stakeholder involvement

When working with CBA within the road infrastructure sector and climate resilience, it is inevitable to engage actively with stakeholders throughout all stages of development. Stakeholders can be directly or indirectly affected by the adaptation measure and are vital to speak to and involve in the entire planning and implementation of adaptation projects. Stakeholders can take many forms and shapes: policymakers, project beneficiaries, project owners, asset managers, regulators, politicians, financiers, community organisations, government officials, technical experts, economists, lawmakers, etc. Looking at road stakeholder specifically, the table below provides an overview.

Table 7. Road stakeholder groups (CEN, 2021)

Stakeholder group	Definition	Examples
Owner/manager	Entity responsible for decisions with respect to physically modifying the infrastructure	A road authority, a concessionaire
Users	Persons who are using the roads	A person being transported on a road, a person transporting something on a road
Directly affected public	Persons who are in the vicinity of the road but are not using it	A person in a house next to the road that hear vehicles driving on the road, a person working at a gas station near a road
Indirectly affected public	Persons who are not in the vicinity of the road but are affected by its use	A person in a house far away from the road that do not hear vehicles driving on the road, but are affected by a changing climate due to the emissions produced by vechicles using the road

The table above describes the road owner as one stakeholder. However, in reality, many different people/stakeholders are involved at the strategic, tactical, and operational levels within an NRA. This is to ensure that objectives at a strategic level (primarily focussing on performance objectives for the entire road network), can be translated to use at a tactical level (for identification of hotspots for adaptation within a certain time frame) and further down to the operational level (allowing to gain an understanding of what needs to be done and how, on an asset or road stretch level).

In more general terms, the key components of pro-active and good stakeholder engagement can be seen in Figure 21. Moreover, stakeholders are particularly important when looking at vulnerability and risk assessments, as a cross-disciplinary team is often needed to effectively address the range of issues included in the assessment. In addition, some transportation agencies choose to form an interdisciplinary technical advisory committee with individuals either internal or external to the agency to provide input to the team conducting the vulnerability assessment at different stages of the process (CEN, 2021).

Engaging stakeholders and the public in general also involve effective communication of the process and results of the vulnerability assessment. Previous examples when communicating adaptation issues and concepts to internal and external stakeholders are framed by (CEN, 2021):

- Adaptation is about taking responsibility for risk management and holistic planning.
- Adaptation saves money. Preventing impacts is almost always less expensive than cleaning up and rebuilding after an extreme weather event.
- Past events, such as severe flooding event or a heat wave, help communicate what climate projections tangibly mean for communities.
- Impacts and adaptation issues can be referred to as “extreme events,” “all-hazard planning,” and “resilience.”

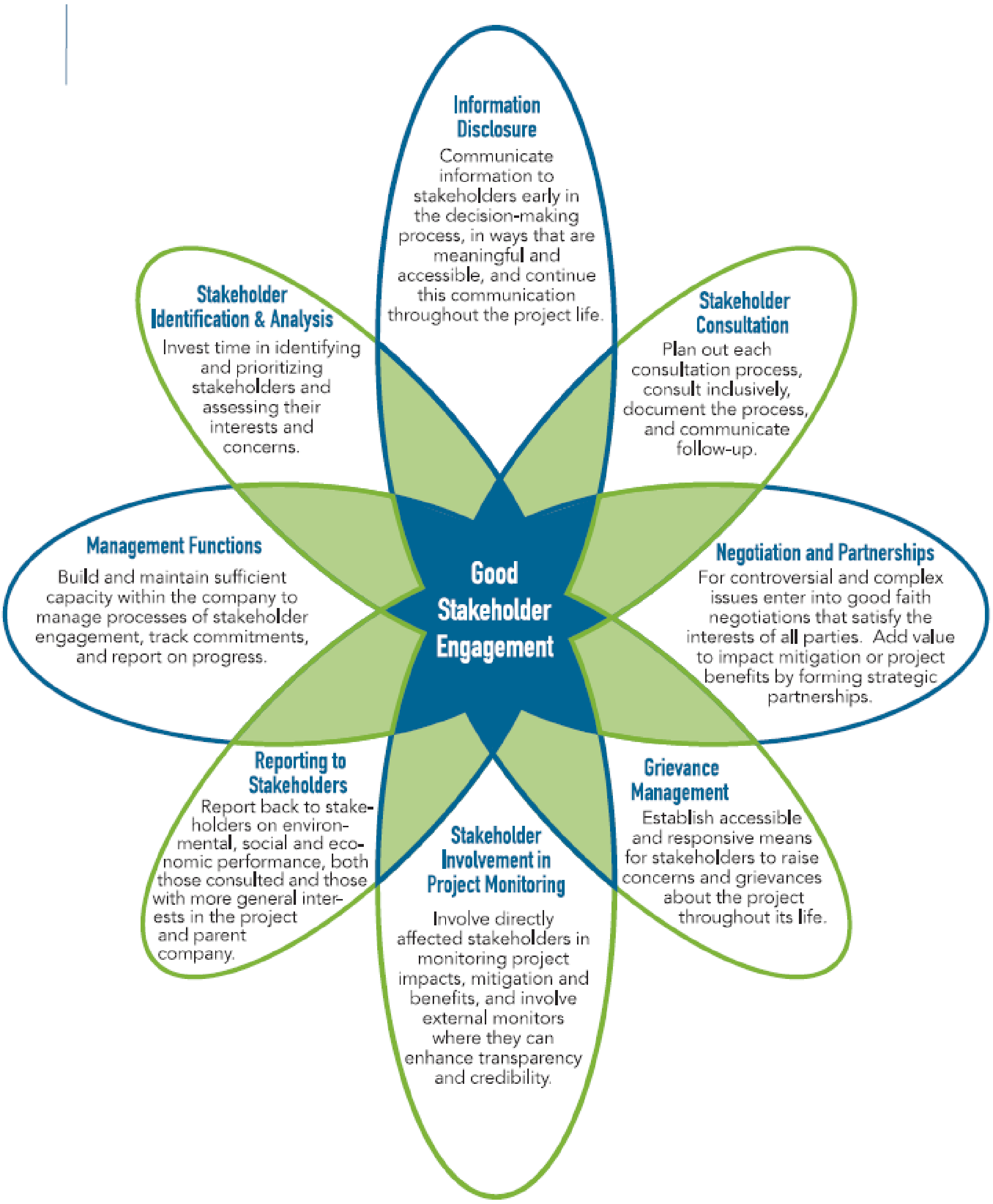

Figure 21. Key components of stakeholder engagement (IFC, 2007)

4 BASELINE ASSESSMENT: STATE OF PRACTICE

This section of the baseline report outlines our current understanding of the State of Practice in economic evaluation for assessing adaptation options. That is, it reflects the way the State of the Art (outlined in the previous section) has been implemented in practice so far.

The State of Practice is structured into three topics (as outlined in Figure 3):

- i) the key outputs and takeaway messages from three stakeholder workshops with National Road Authorities that took place in September 2022;
- ii) a collection of industry-led examples on the framing and use of CBA; and
- iii) a case study of the CBA paradigm implemented in the Danish water sector

Understanding the State of Practice is a key topic underpinning the success of ICARUS and will be continued throughout the remainder of the research. A case study portal and further workshops will be organized as part of the remainder of the project. These will both improve our understanding of the state of practice.

4.1 Outputs from the workshops with NRAs

In September 2022, the ICARUS team facilitated three workshops with stakeholders, with a total of 25 attendees from 9 different countries and various organisations including National Road Authorities (NRAs), rail authorities, government agencies such as Ministries or Departments of Transport, as well as local authorities. The countries represented were Austria, England, Finland, Iceland, Ireland, Italy, the Netherlands, Spain, and Wales.

The workshops were organized in two sessions, with the first session dedicated to Resilience and Service Levels (see deliverable D2.1), while the second session (which is described in this report) was targeted an appraisal and discussion of adaptation measures, economic evaluation methods and CBA. Three key topics/questions were discussed, in relation to participants' understanding of the concept of CBA, decision-making processes, economic evaluation, resilient business case, co-benefits and how CBA contributes to increase resilience in the road infrastructure sector.

4.1.1 Socio-Economic evaluation methods for planning/designing roads

To set the scene, economic evaluation was presented as having the overall purpose of determining the value of a policy, project, or program, dependent on the pursued objectives, considering key components like costs, benefits, drivers, boundaries, criteria, conditions, etc. The socio-economic analysis framework developed under the WATCH project was also discussed (Tucker, Corbally, & O'Connor, 2018).

As shown in Figure 22, the two most familiar socio-economic evaluation methods by participants were CBA and MCA, closely followed by LCC. CEA is the method that participants were the least familiar with. In general, participants demonstrated a high level of familiarity with each of the methods presented, even when not used by their organisation. It was also concluded that more than 80% of the organisations represented by participants are using CBA, whereas a bit over 20% are using CEA. MCA was also the second most used method.

One participant responded that no socio-economic evaluation method was used to determine service levels in his/her organisation.

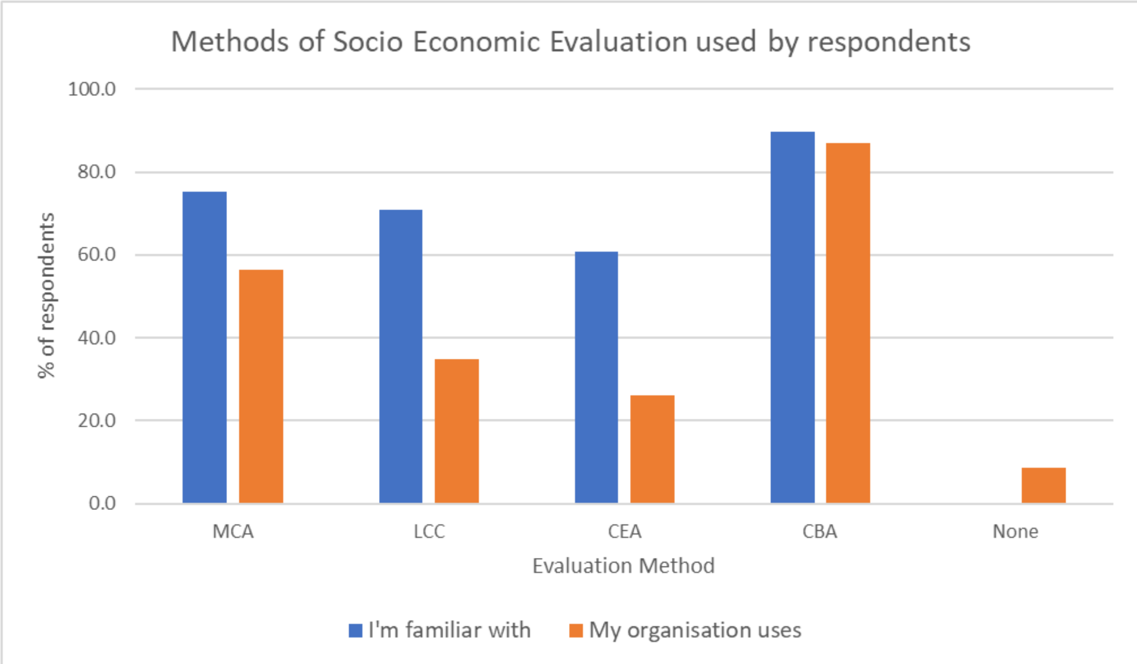

Figure 22. Socio Economic Evaluation Methods Used by organisations to plan and/or design roads

4.1.2 Using socio-economic evaluation methods to increase resilience

A similar question was then proposed, as to what degree the socio-economic evaluation methods are used to increase resilience levels in their organisations at the three decision-making levels; Strategic, Tactical and Operational. CBA was found to be the most frequently used method at all levels, with CEA the least frequently used method at Strategic and Tactical levels, and MCA the least frequently used method at operational level, as shown in Figure 23.

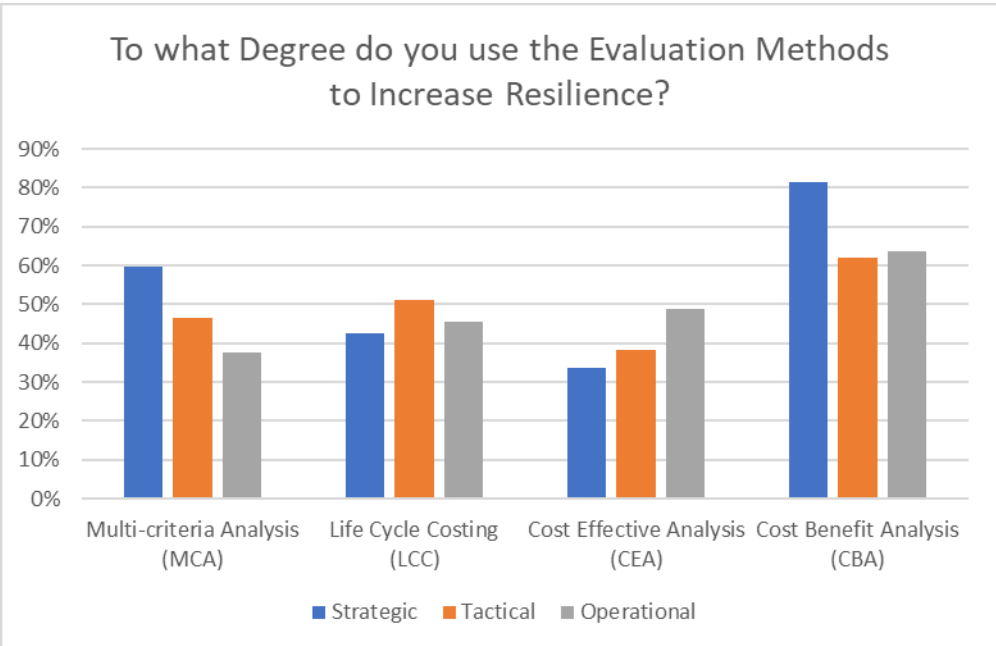

Figure 23. Evaluation Methods used to Increase Resilience at Strategic, Tactical and Operational Levels

The three levels of decision-making were introduced in the workshops using the following conceptual figure.

	Strategical	Tactical	Operational
Time scale	Long-term	Medium to long-term	Understanding of what needs to be done and how
Primary focus	Performance objectives for the entire road network – holistic assessment	Steps and actions to fulfil the strategy – more concrete	Application of actions in much more detail
Activities	Setting goals and direction	Identification of hotspots for adaptation within a certain time frame	Focus on operation and maintenance
Level of assessment	Network-level thinking	Connections-level thinking	Individual-level thinking (i.e. specific road assets or road stretches)

Figure 24. Conceptual outline of the three levels of decision-making (at the top) against a set of characteristics and the three levels of assessment (at the bottom). We have prepared this figure inspired by the two WATCH reports reviewed in this assessment.

4.1.3 Building the business case for a resilient road infrastructure

90% (19 of 21) of participants responded that co-benefits were a driver when building business cases. When we look further into the co-benefits, there are a number of reasons for considering co-benefits in building cases. For most participants, co-benefits were a driver due to mandatory regulations and were most frequently used at a strategic level (62% of respondents). Details shown in Table 8.

Table 8. Consideration of Co-Benefits when Building Business Cases

	Number of Responses	% of Responses
Co-benefits are included in regulations/guidelines you must follow	16	76%
Your organisation has pro-actively decided to include them	10	48%
On a strategic level	13	62%
On a tactical level	9	43%
On an operational level	7	33%
Number of respondents	21	100%

Participants for whom co-benefits were not a driver when building a business case responded that monetising the co-benefits could enrich the assessment; however, this can be difficult to implement in practical terms. Finally, participants were asked to rank the co-benefits according to their relevance for the development of business cases for increasing resilience in their organisations. Results may be seen in Figure 25.

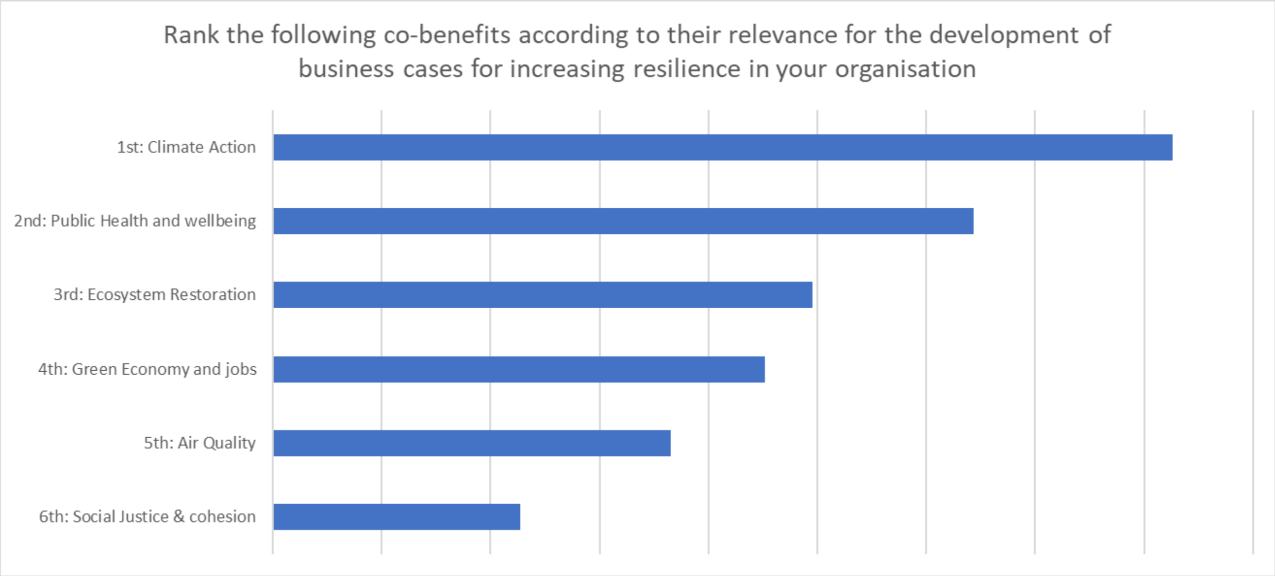

Figure 25. Ranking of Co-benefits

4.1.4 Takeaway messages

Most workshop participants were aware that some service levels exist within their organisation, with the majority of these pertaining to assets rather than connections or networks. However, there seems to be a lack of clarity on how they are defined and there also seem to be many barriers to their implementation in practice, such as lack of information, lack of funding and uncertainty on how to measure service levels with changing climate conditions. These barriers were common across representatives from all organisations, even those which would be considered at an advanced stage of maturity such as the Netherlands and Finland.

Correlations between country and responses such as understanding of the concept of resilience, and resilience assessment within the organisation were investigated, however, no significant correlations were noted. This is deemed to be due to the small sample number of participants per country and high variability of implementation of resilience assessment within each organisation. Therefore, all the below analysis was performed with results from all participants unless noted otherwise.

4 out of 5 participants from the Netherlands and Finland stated that they were completely comfortable with the concept of resilience, compared to none of the three participants from Italy. However, once more detail was requested in the workshop, there were various levels of personal and organisational understanding of the concept of resilience and implementation of service levels across all participants, regardless of country or organisation type.

Representatives from Highways England, who responded that they currently use Service Levels, stated that they are used at asset level, as well as at network level. However, that one of the barriers was "*trying to understand how much the existing weather-related service level metrics relate to climate / environmental metrics*".

Similarly, a Dutch representative stated that they don't want new service metrics, however, would like "*to know what actions they need to take and would like to stick with the metrics they have and understand how they can be adopted for Climate Change*".

Overall, it appears that some consistency is required in addition to more guidance on how to measure service levels, and perform resilience assessments of asset, connections, and networks.

In terms of the second session targeted an appraisal and discussion of adaptation measures, economic evaluation methods and CBA, the key takeaway messages from all workshops can be summarized as:

- LCC, despite not being the most used method by participants, captured many discussions and was highlighted as being easy and straightforward to apply, especially when quantifying costs and linking the results to development of policies.
- Following on the above, LCC showed to be used for Carbon Appraisal assessments at strategic level, expanding the original scope to something more in the direction of Life Cycle Carbon Analysis throughout the entire supply chain of a railway authority in the UK, effectively linking Resilience and Decarbonization. Issues like whole-life carbon and embodied carbon were mentioned.
- The divisions by level seemed not to be as cemented as expected. Especially the interface between asset and operational level was somewhat blurry.
- One particular comment during the discussions was that the size of the investment (overall) determines the type of economic evaluation method used, by large.

4.2 Industry-led examples on the framing and use of CBA for climate adaptation

This sub-section provides a few illustrative examples from across the transport, built environment and water utilities industry on the use of CBA to support decision-making. The examples have been selected from a variety of contexts to give a good overview of how CBA is being used for commercial and non-commercial purposes.

Table 9. Oregon Department of Transport

Oregon Department of Transport: Vulnerability Assessment for Highway Infrastructure (Filosa, Plovnick, Stahl, Miller, & Pickrell, 2017)	
Scope	The Oregon Department of Transport (ODOT) team engaged maintenance and technical staff and utilized asset data to assess the vulnerability of highway infrastructure in two coastal counties to extreme weather events and higher sea levels.
CBA Approach	Based on the results of the vulnerability assessment, the pilot conducted further analysis of specific adaptation sites, options, and benefits and costs for five priority storm and landslide hazard areas. Options analyzed ranged from "do nothing" scenarios to options for increased operations and maintenance and options with significant construction and engineering requirements
Outcome	Nearly all the designated "Lifeline Routes" in the study area, which are essential for emergency response and economic connectivity, were found to be vulnerable to projected climate impacts. ODOT developed a list of adaptation options for highly vulnerable sites. However, they found that implementing adaptation strategies would not be cost-effective at the two sites they performed cost-benefit analyses for, due to availability of detour routes and low traffic volumes, and other factors. This suggests adaptation may be more appropriate at a corridor-level in Oregon. ODOT also identified many parallels between adaptation planning work and seismic resilience planning work and is looking for ways to enhance that collaboration.

Table 10: Buzzard Point Blue-Green Masterplan for Climate Resilience

Buzzard Point Blue-Green Masterplan for Climate Resilience, Washington D.C. (Ramboll, 2019)	
Scope	A cost-benefit analysis was used to assess the profitability of the blue-green masterplan for climate resilience. The "Resiliency Concept Plan" was designed, and concepts and levels for storm surge and inland flood protection were integrated into the existing "Vision and Implementation Plan" for Buzzard Point. Two different levels of protection (a 100-year storm surge level in 2017 and a 500-year storm surge level in 2100) were evaluated. Implementation costs for both levels and avoided risks compared to a baseline scenario were estimated. Furthermore, the analysis also investigated the co-benefits of implementing nature-based and liveable solutions as part of the protection designs (see Figure 26).
CBA Approach	A 4-step approach, illustrated in Figure 26. was developed as an iterative process, with a main focus on identifying with the client co-benefits to be included in the CBA. Based on socio-economic studies the CBA for the project included increase in real estate values, improved health benefits, improved recreational and aesthetic value, and increased carbon sequestration. Eventually two cost-benefit ratios were estimated to determine the most profitable design scenario.

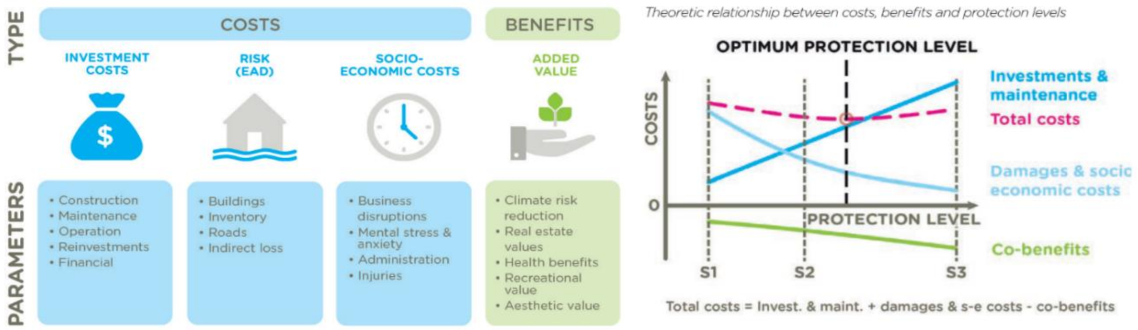

Figure 265. Inputs considered for CBA, and conceptual relationship between cost, benefits, and protection levels

Stakeholder Involvement	Stakeholder involvement was key in building a comprehensive cost-benefit analysis and ensuring all relevant costs and benefits were accounted for. There can be many direct and indirect costs and benefits of a major infrastructure project like this. Identifying and prioritizing the costs and benefits through local knowledge and a broad range of project stakeholders is therefore essential. Quantifying and monetising some of aspects of CBA analysis (particularly co-benefits) can be challenging, time-consuming and pose many uncertainties. As such it is important to prioritise resources on what project stakeholders and specialists find to be most important for the project. This approach was adopted in the Blue-Green Masterplan CBA to ensure the analysis was comprehensive enough for decision-making but avoided spending unnecessary time on identifying and monetising aspects that were not relevant to the project or unnecessary from the stakeholders' point of view.
Outcome	The example from Buzzard Point helped in showing the enormous potential for climate adaptation to build better cities and infrastructure, alternative financing models, and undo historic injustices. This potential is, however, lost when costs and benefits are not properly examined and documented. Too often protection levels are randomly selected. This project clearly showed the power of a solid

business case in advancing climate resilience, not as a cost but as an opportunity and a benefit.

Figure 27. Resilience Planning Approach: an iterative process takes place between the design of Blue-Green Infrastructure (BGI), appraisal of costs, benefits, and co-benefits, leading to a range of investment statements that can guide the decision-making process (Ramboll, 2019).

Table 11 Use of CBA in all water utilities sector climate adapation projects, Denmark

Use of CBA in all water utilities sector climate adaptation projects, Denmark (Danish Ministry of Climate, 2021) (Ministry of Environment of Denmark, 2021)	
Scope	In 2021 a new regulation was introduced in Denmark to regulate and optimise the expenditures of water utility companies in relation to their climate adaptation projects. Prior regulations had already been in place for optimising co-funding of climate adaptation projects between utilities and municipalities, but more detailed regulations were introduced to streamline the many different approaches taken across the many utilities across Denmark working with climate adaptation. As climate adaptations projects deliver many benefits, the use of monetary terms not only sets the common language to communicate the project to different stakeholders and drive the decision-making process, but also helps build the business case for optimum resiliency planning.
CBA Approach	In the planning phase of climate adaptation projects, utilities companies are required to evaluate between two and five adaptation options (more options must be evaluated when the investment costs are higher), all designed with the same purpose. They are required to choose the most economically viable solution of the evaluated designs. A four-step analysis approach is used: - First, hydraulic modelling and flood risk analyses were performed for the status situation - Second, different solution strategies were designed, and investment, maintenance and re-investment costs calculated for each strategy. - Third, based on the designs, new hydraulic models were run, and flood risks analysed.

	- Finally, the results come together in a simplified cost-benefit analysis where avoided damage costs were compared to the costs of design implementation. If none of the designs have a positive benefit-cost ratio, none of the designs that lift the service level above standard regulations can be approved. If the project area does not already meet standard regulations for service level, the most cost-efficient solutions must be chosen for the area to meet the standard levels, but no added service/protection can be financed by the utility companies This methodology, regulating service levels, ensures that utility companies only finance projects that are cost-effective and implement cost appropriate service levels. As avoided flood risks are the primary benefit of the projects from the utilities' point of view, the utilities are not allowed to include other benefits than avoided flood risk costs in their cost-benefit analyses (according to the service level regulation). Municipalities in Denmark on the other hand have a wider range of benefits they can include when building the business case for infrastructure investments. Climate adaptation investments will often contribute with many other benefits to society (known as co-benefits) than just avoided damages. These can include improved traffic conditions, higher real estate prices, improved air, and water quality, and added recreational values. There are, however, added uncertainties when estimating these co-benefits as the benefits are more intangible and sometimes indirect and as such harder to identify and evaluate in monetary terms.
Outcome	As the regulation has only recently been introduced in the time of writing this report, not many examples of implementation are publicly available. However, earlier projects have followed the described methodology and an example of application can be found in the city of Hørsholm, north of Copenhagen. The utility company in the area, Novafos, implemented the methodology to find the most profitable strategy for sewer separation and rainwater management for 10 separate catchments in the area (Krüger Veolia, 2020). For each catchment three or four solutions were tested and compared. Each comparison followed the same approach.

Table 12. Combined CBA and MCA analysis for robust decision makking: New Highway in northern Italy

Combined CBA and MCA analysis for robust decision making : New Highway in northern Italy (Henke, Carteni, & Francesco, 2020)	
Scope	A robust and sustainable evaluation process was developed to support decision making for investment into a new highway in Northern Italy. This approach aimed to standardize procedures followed by decision-makers; estimate the effects of new investment through quantitative methods; and enlarge consensus to reach shared choices among stakeholders.
CBA Approach	To propose a sustainable evaluation process for investments in the transport sector, based on the combined use of both CBA and MCA analysis and a stakeholders' engagement.
Outcome	The estimations performed underline that the CBA analysis significantly underestimated the non-users' benefits, while the opposite occurred for the MCA analysis. The incidence of the non-users' benefits is only the 14% of the total for the CBA, while it reaches more than the 79% for the MCA. This result is very relevant underling how, for a decision-making process aimed in comparing different design alternatives for which non-users' impacts are expected as relevant against the users' ones, the unique application of the most consolidated CBA analyses is not always adequate, while the joint use of the two evaluation methods ensures robust and rational choices for a sustainable development.

4.3 Combination of CBA and MCA

From a practical perspective, the appraisal of an economic evaluation is seldom following a linear path. Many times, what occurs is that a combination of different methods needs to be selected following the specific constraints applicable to the area of study or the context. In this regard, the combination of CBA and MCA is something that is being increasingly used, as it allows obtaining the many advantages of the CBA while also providing the method the embedded flexibility of an MCA. The figure below shows a simplified methodological approach to flood risk mitigation projects based on a combination of CBA and MCA, used by Ramboll in many projects around the globe.

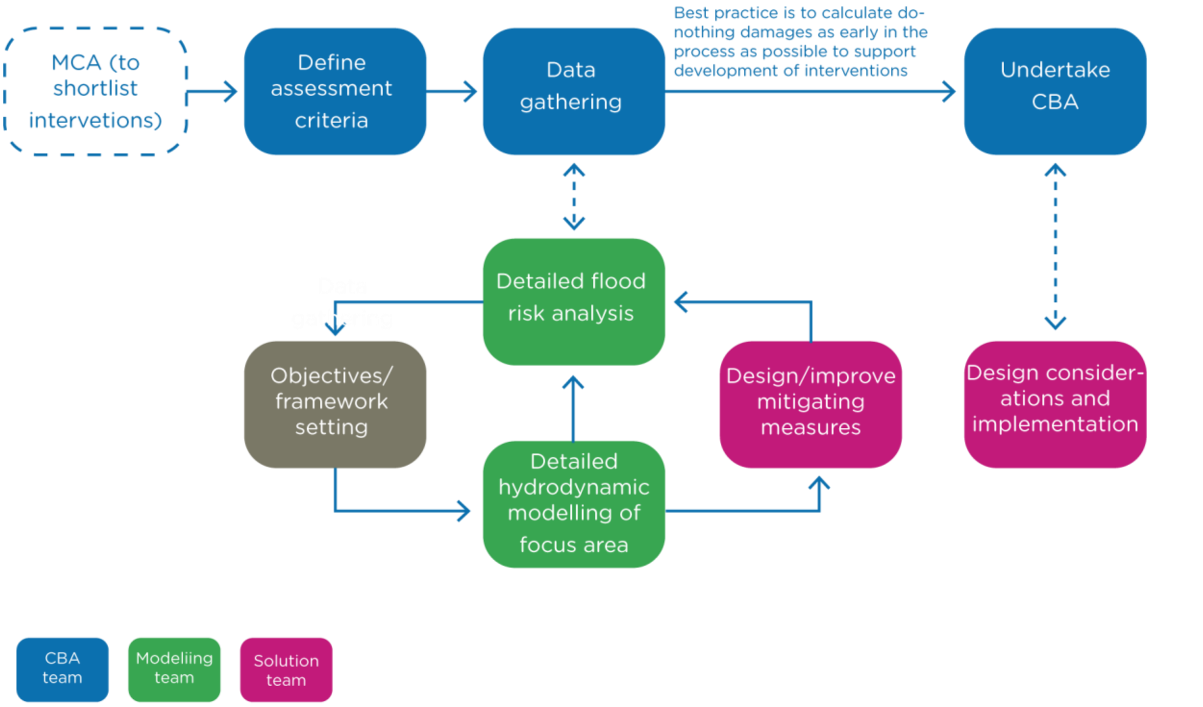

Figure 28: Simplified flood risk mitigation project methodology developed and used by Ramboll, combining MCA and CBA

The figure above is somewhat similar to the methodology presented in Figure 10 for sustainable evaluation of investments in the transport sector. The key differences rely in that the figure above is an approach that has been applied throughout several flood risk projects around the globe and continues therefore to be refined through feedback from stakeholders. It should also be noted the outlining of three inter-disciplinary teams: the CBA team, typically composed of environmental economists; the modeling team, typically formed by engineers, modelling experts, planners, and resilience specialists; and the solution team, which is formed by resilience experts, detail design engineers, hydrogeologists, etc.

To ensure the CBA contributes meaningfully to the decision-making process of a project, it is critical that the CBA team be involved early and consistently throughout the project process. This will enable the CBA team to contribute to key strategic and design considerations from a broader socio-economic and environmental perspective. It will also allow data requirements to be flagged early on and ensure that the CBA assessment is as comprehensive and accurate as possible. The early involvement of experts brings increased value to the project and should ensure that ultimately the CBA reflects the decision making that has been made within the project development process.

5 GAP ASSESSMENT

This section aims at identifying the key knowledge and implementation gaps coming from comparing the state-of-the-art and state of practice sections in this report. In identifying the gaps, a critical eye and experience are brought in so as to make the gaps as clear as possible, with corresponding actions to address them outlined as recommendations. A simple format is used to present the gaps, which are also linked to specific sections in the report. See the table below.

Table 13. Knowledge and Implementation Gaps identified in this report

No.	Section	Topic	Description of Gap	Action
1	3.1 and 4.1	Economic Appraisal Methods targeting climate uncertainty	There seems to be a limited number of economic appraisal methods used by NRAs, compared to the large number of methods documented in the literature. This is specifically relevant when looking at the methods dealing with climate uncertainty: uncertainty framing (Iterative Risk Management); and economic decision-making under uncertainty (Real-option Analysis, Robust Decision Making, and Portfolio Analysis).	Discuss further with NRAs to understand better how they are dealing with uncertainty when undertaking economic assessments. Specifically, discuss the use of CBA and climate uncertainty. This will be looked at in the development of Task 3.2 in ICARUS, related to methodologies for measure evaluation of climate resilience measures, with focus on best practices for quantifying and valuing co-benefits, which will likewise include a deeper analysis of economic appraisal methods in general.
2	3.1, 4.1 and 4.3.1	'Hybrid' approach combining CBA and MCA	The combination of CBA and MCA is clearly something that is increasingly being looked at in the literature, with several cases and frameworks proposing different ways of integrating these two methods. It is also a well-defined approach in the state of practice. However, during the workshops with the NRAs, no one mentioned this and all economic evaluation methods were treated separately. A potential bias could be playing a role here, in that questions on methods were also asked separately.	Discuss further with NRAs to understand if such a 'hybrid' approach is being used and to what degree. It'd also be relevant to investigate inclusion of co-benefits, which typically starts through an MCA. Also, consult with NRAs as to their view in implementing this approach as a way of combining the strengths of both methods. Similar to the gap described above, this gap will also be looked at in the development of Task 3.2, related to methodologies for measure evaluation of climate resilience measures, with focus on best practices for quantifying and valuing co-benefits, where this 'hybrid' approach is particularly suitable to address externalities.
3	3.1 and 4.1.4	The use of LCC as economic appraisal method within NRAs	During the workshops, LCC (or variations of LCC) were highlighted as being easy and straightforward to apply, especially when quantifying costs and linking the results to development of policies. But during the state-of-the-art, LCC was not predominant in the literature, with CBA and MCA being more visible.	More dedicated research needs to be done on the use and depth of LCC as a method within NRAs. It might be needed to undertake interviews with relevant experts. This gap will also be directly addressed when developing Task 3.2, related to methodologies for measure evaluation of climate resilience measures.
4	3.2, 3.3.1 and 4.1	Valuation of non-market goods and services, linked to monetization of co-benefits.	As explained in the report, adaptation-related valuation methods aim at capturing those intangible benefits, which typically don't have a market value and are associated with significant uncertainty. Section 3.2.5 describes several methods for doing this, and Figure 27 outlines an industry-led application case in Buzzard Point, Washington D.C., through	More conversations with NRAs are needed to better understand where the co-benefits are in the organisations. Given the increasingly relevancy in considering these intangible benefits, or externalities, it'd be important to know how to incorporate them into decision-making processes, and hence in development of business cases for resilience. Section 3.2.5 outlines a list of potential co-benefits

No.	Section	Topic	Description of Gap	Action
			application of a Resilience Planning Approach. Co-benefits were indeed introduced at the workshops with NRAs, and a ranking of some co-benefits was done (see Figure 25).	linked to NbS which could be discussed directly with NRAs, also on the basis of the report to be prepared in ICARUS, namely D4.2 Report on Nature Based Solutions. Moreover, co-benefits will also be looked in detail when addressing milestone M3.1 Definition of the central co-benefits critical to minimum service level estimation.
5	3.2.2 and 4.1	Levels of decision-making within NRAs	The literature review did not reveal particularly strong decision-making levels within transportation agencies or road organisations. Moreover, the workshops did not give a clear picture either, and the interface between asset and operational level was somewhat blurry.	Address specifically how ICARUS will deal with the levels of decision-making, as well as verification with the PEB, so that a coherent narrative in the project is achieved. This gap will be addressed through joint activities in WP2 and WP3, specifically related to the development of guidelines (D2.2 and D2.3) where a deep understanding and collaboration with NRAs is expected to take place.
6	3.3.3	Stakeholder engagement	Section 3.2.7 outlined the key Road stakeholder groups and provided the key components of stakeholder engagement, but this topic was not discussed during the workshops.	Obtain feedback from NRAs regarding how they approach stakeholders, to inform the development of guidelines in ICARUS. This gap will also be addressed through joint activities in WP2 and WP3, specifically related to the development of guidelines (D2.2 and D2.3).

6 CONCLUSION

This report has aimed at answering three key questions:

1. Which economic evaluation/appraisal methods are used (by NRAs) when assessing adaptation options? And why?
2. How are these methods used to inform decision-making for increasing resilience?
3. What are the key drivers, parameters and/or considerations when building the business case for a resilient road infrastructure?

To address these questions, the report introduces a state-of-the-art (SoA) literature review and a state of practice (SoP) assessment, covering review of research papers, handbooks, guidelines, etc., while also outlining key implementation examples showcasing best practices and/or lessons learned.

6.1 State of the Art

From the different socio-economic appraisal methods outlined in this report, what dominates the scientific literature is primarily the development of CBA studies and frameworks, but with different variations/additions to a traditional CBA, incl. a 'hybrid' approach combining MCA and CBA and an increasing trend to account for climate uncertainties and equity considerations. Using MCA and CBA allows inferring high flexibility to the process, which is very positive especially when considering uncertainties and context-led constraints through multiple and different stakeholders.

Even in contexts where CBA is a well-established decision-support tool, investment decisions are often strongly influenced by other political preferences or decision-makers take an approach whereby criteria is handled through non-monetized ways despite those criteria being included in the CBA. Hence, there's an indication that a 'hybrid' approach combining CBA and MCA can help in making decision-makers' preferences more transparent and streamlined by explicitly including all decision factors and thus establishing a strong link between policy objectives and appraisal results while still providing information for cost-efficient investment decisions.

The use and link of CBA to support decision-making linked to climate change adaptation measures has increased notably in the last 3-4 years. However, the line does not seem to be straight. For example, the use of CBAs for decision-making on climate adaptation and/or mitigation measures has been considered in The Netherlands for a few years now. However, although these analyses have actually been undertaken in the past years, resulting in benefit-cost ratios for various adaptation measures on the asset level of the entire road network, it has not yet led to strategic decisions on possible changes of design and maintenance guidelines. This exemplifies likewise the importance, documented in this report, of considering the level at which decision-making takes place within a NRA, as it affects the practical implementation of business case development and CBA particularly.

The most important parameter affecting decision-making when performing a CBA is the discount rate. Adaptation projects typically have their costs concentrated upfront, in the early years of project implementation, while the benefits follow through later on; that is, the benefits will increase in the future due to more avoided impacts. This means that for adaptation projects, raising the discount rate tends to artificially lower the NPV of the resilience option, causing the future benefits of resilient infrastructure to be ignored. On the other hand, low or close to zero discount rates have the tendency to increase the NPV of resilience options compared to the 'do nothing' scenario. A review of discount rates included in this report shows that, in Europe, the risk-free discount rates vary from 2.5-5%, and in the United States it goes up to 7%, whereas the overall discount rate in Europe varies from 1-4%. On the other hand, the review of long-term discount rates shows a clear tendency to include declining rates (i.e., variable downwards in time) to capture the issue of intergenerational equity.

The report also offers an overview of a few holistic frameworks recently developed to address the business case for resilience, linking CBA and resilience in more depth and addressing key issues like climate risks, uncertainties, data, asset management, KPIs and sensitivity analysis. The Horizon 2020 project, FORESEE, directly aims at providing transport infrastructure managers with knowledge and frameworks to clearly understand the service the infrastructure is providing, and the resilience of the infrastructure affected by disruptive events. It does this by defining three measures of service: expected yearly travel time costs, injuries and fatalities costs, and intervention costs[6]. This conceptualization allows defining service and resilience targets on the basis of two overarching goals: limiting the maximum decrease in service during the disruptive event and/or accelerating the restoration of the service to the expected level. Targets can then be set for: i) intervention costs (see footnote 6) or a measure of service; ii) combinations of intervention costs and measures of service; and iii) multiple disruptive events. Once targets have been defined, the benefits and the costs of achieving those targets can be explicitly estimated. FORESEE provides detailed costs to be included in the CBA.

Another recently developed framework is the Physical Climate Risk Assessment Methodology (PCRAM), which highlights the importance of making decisions on the basis of a robust understanding of future Physical Climate Risks (PCR) under various scenarios, especially regarding asset delivery and management. The PCRAM methodology aims at shifting the resilience narrative, so that resilience is no longer perceived as exclusive downside-minimisation exercises, often carried out ex-post, i.e., after an event. PCRAM seeks to make resilience a core component of an innovative strategic decision-making process, where a rigorous integration of climate risks becomes a pro-positive force, enabling stakeholders to become more strategic and competitive.

One of the innovative components of PCRAM is given through the development of the Economic and Financial Analysis, which aims at determining *if* there is a case for investment in resilience. This is done by comparing the ‘climate cases’ and ‘resilience cases’ through CBA and IRR calculations, and also looking at other KPIs including total life cycle costs (see also Table 5). Life cycle costs include all capital and operating costs linked to an asset during its entire lifetime, from construction to operation and decommissioning. This economic and financial analysis is undertaken to de-risk an asset exposure to PCRs and outline recommendations for resilience options, incl. also the use of sensitivity analysis where deemed needed to confirm the selected KPIs.

The report also provides a description of the non-tangible, indirect benefits of adaptation measures, i.e., the co-benefits (also referred to as externalities) that provide an added value beyond the primary value given by an adaptation solution. Co-benefits are important drivers linked to the improvement of resilience but are not always easy or possible to quantify or monetize. These indirect effects can be environmental and social and represent an important category of benefits that result from redesigning or relocating transportation facilities or investing in protective features to improve resilience, for example through implementing Nature-based Solutions. As there is no market price available for estimation of these wider social and environmental, specialised non-market valuation techniques may be applied, some of which are contingent valuation, benefit transfer, etc.

[6] FORESEE defines the intervention costs as “all costs incurred by the infrastructure manager”.

For transport-related evaluation, a way to deal with co-benefits is to internalize their financial costs by calculating a monetary value expressed per VKT (vehicle km travelled) for inclusion in CBA calculations.

6.2 State of Practice

The SoP presented in this report builds on three pillars: i) the key outputs and takeaway messages from three stakeholder workshops with National Road Authorities; ii) a collection of industry-led examples on the framing and use of CBA; and iii) a brief overview of the practice of combining CBA and MCA methods.

The key takeaway messages from the stakeholder workshops with NRAs are:

- LCC, despite not being the most used method by participants, captured many discussions and was highlighted as being easy and straightforward to apply, especially when quantifying costs and linking the results to development of policies.
- Following on the above, LCC showed to be used for Carbon Appraisal assessments at strategic level, expanding the original scope to something more in the direction of Life Cycle Carbon Analysis throughout the entire supply chain of a railway authority in the UK, effectively linking Resilience and Decarbonization. Issues like whole-life carbon and embodied carbon were mentioned.
- The divisions by level seemed not to be as cemented as expected. Especially the interface between asset and operational level was somewhat blurry.
- One comment during the discussions was that the size of the investment (overall) determines the type of economic evaluation method used, by large.

The various case studies offer examples of how CBA is being used to support decision making within the transport, built environment and water utilities sectors.

- The DoT Oregon case demonstrates why cost-benefit analyses are better in building the business case for climate adaptation compared to an evaluation of cost-effectiveness
- The use of CBA analysis within the Buzzard Point masterplan highlights the importance of incorporating co-benefits into the CBA
- The example of CBA use within the Danish water utilities sector details the approach by which utility companies ensure only cost-effective projects providing appropriate service levels receive investment.
- The use of both CBA and MCA analysis in the case of investment decision making in a new highway in northern Italy highlights the differences in outcomes with each method and promotes the use of a combined method to ensure robust and rational choices for highway development.
- The overview of the combined CBA and MCA approach outlines the inter-disciplinary expertise required in climate adaptation (and specifically flood risk) CBA analysis. It also highlights best practice in involving the CBA team early on and consistently throughout out the design and evaluation process.

6.3 Gap assessment

The main gaps found in this report through a qualitative assessment combining the SoA and SoP, together with the experience from the authors, are presented on Table . The report also outlines corresponding actions and an overall connection to how the gaps and actions fit within the remaining tasks to be implemented in the ICARUS project. All of this is expected to be discussed in detail with

CEDR, so as to validate the gaps and tailor the actions as the project evolves and more knowledge is collected, especially through interacting more closely with NRAs.

7 ABBREVIATIONS

Acronym/Concept	Definition
AAD	Average Annual Damages
BCR	Benefit-Cost Ratio
CAPEX	Capital Expenditure
CBA	Cost-benefit analysis
CEA	Cost-Effective Analysis
CEDR	Conference of European Directors of Roads
CV	Contingent valuation
EAD	Expected Annual Damages
ESG	Environmental, Social and Governance
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
LCC	Life-Cycle Costing
LCCA	Life-cycle cost analysis
MCA	Multi-Criteria Analysis
NPV	Net Present Value
NbS	Nature Based Solutions
NRAs	National Road Authorities
ODOT	Oregon Department of Transport
OPEX	Operating Expenses
PCR	Physical Climate Risks
PV	Property value
RCP	Representative Concentration Pathway
RDM	Robust Decision-Making
RDR	Resilience and Disaster Recovery
ROI	Return on Investment
SEA	Socio-Economic Analysis
SoA	State-of-the-art
STPR	Social Time Preference Rate
SoP	State of practice
VKT	Vehicle km travelled
WP3	Work package 3

8 BIBLIOGRAPHY

Bles, T., de Lange, D., Foucher, L., Axelsen, C., Leahy, C., & Rooney, J. P. (2018). WATer management for road authorities in the face of climate CHange. *CEDR TRANSNATIONAL ROAD RESEARCH PROGRAMMECall 2015*.

Abdullah, S., Markandya, A., & Nunes, P. A. (2011). *Introduction to Economic Valuation Methods.* ResearchGate.

Alida, A., Berry, G., Zoran, K., Zoran, V., & Arlex, S. (2019, June). Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. *Journal of Environmental Management, 239*, 244-254. Retrieved from https://doi.org/10.1016/j.jenvman.2019.03.036

Badgley, J., Flynn, D., Gillham, O., Gilmore, M., Lewis, K. C., Oberg, A., . . . Zhang, K. (2022). *The Resilience and Disaster Recovery Tool Suite: User Guide Version 2022.1.1.* U.S. Department of Transportation.

Brill, G., Shiao, T., Kammeyer, C., & Diringer, S. (2021). *Benefit Accounting of Nature-Based Solutions for Watersheds.* Oakland, California: Guide United Nations CEO Water Mandate and Pacific Institute.

CCRI. (2022). *Guidelines for Integrating Physical Climate Risks in Infrastructure I 8 nvestment Appraisal.* Coalition for Climate Resilient Investment. Retrieved from https://resilientinvestment.org/

CEN. (2021). *Guidelines For The Assessment Of Resilience Of Transport Infrastructure To Potentially Disruptive Events.* Brussels: CEN-CENELEC Management Centre. Retrieved from https://www.cencenelec.eu/media/CEN-CENELEC/CWAs/RI/cwa17819_2021.pdf

Danish Ministry of Climate, E. a. (2021). *The cost and expense declaration for climate adaptation projects in the Danish Water Utility Sector.* Retrieved from "Omkostningsbekendtgørelsen": https://www.retsinformation.dk/eli/lta/2020/2275

de Jong, G. (2013). *International Comparison of Transport.* University of Leeds.

Deliverable D5.5. (2022). *Report describing the potential for implementation of large scale NBS in Europe.* Ramboll.

DeTECToR. (2019). *Decision-support Tools for Embedding Climate Change Thinking on Roads.* DeTECToR.

Filosa, G., Plovnick, A., Stahl, L., Miller, R., & Pickrell, D. (2017). *Vulnerability Assessment and Adaptation Framework.* Washington DC.: U.S. Department of Transportation.

Filosa, G.; Plovnick, A.; Stahl, L.; Miller, R.; Pickrell, D. (2017). *Vulnerability Assessment & Adaptation Framework, Third Edition.* U.S. Department of Transportation. Cambridge, MA: Federal Highway Administration, Office of Planning, Environment & Realty. Retrieved from https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/

Government, Q. (2011). *Cost-benefit Analysis Manual.*

Gühnemann, A., Laird, J. J., & Pearman, D. A. (2012). Combining cost-benefit and multi-criteria analysis to prioritise a national road infrastructure programme. *Transport Policy*, 15-24.

Hallegatte, S., Rozenberg, J., Rentschler, J., Nicolas, C., & Fox, C. (2019). *Strengthening New Infrastructure AssetsA Cost-Benefit Analysis.* World Bank Group.

Hanssen, T.-E. S., Helo, P., Solvoll, G., & Westin, L. (2020). *Dissimilarities between the national cost/benefit models of road projects: Comparing appraisals in Nordic countries.* Elsevier.

Henke, I., Carteni, A., & Francesco, L. D. (2020). A Sustainable Evaluation Processes for Investmentsin the Transport Sector: A Combined Multi-Criteriaand Cost–Benefit Analysis for a New Highway in Italy. *Sustainability*.

HM Treasury. (2021). *Environmental Discount Rate Review Conclusion.* Crown copuright .

IFC. (2007). *Stakeholder Engagement: A Good Practice Handbook for Companies Doing Business in Emerging Markets.* Washington, D.C.: International Finance Corporation.

Krüger Veolia. (2020). *Områdeplaner Hørsholm.* Hørsholm: Krüger A/S –Veolia Water Technologies.

Mcginley, L. (2021). *Evaluating Cost Effectiveness of Climate Adaptation Measures.* NCHRP RESEARCH REPORT 938.

McGinley, L. (2021). *Evaluating Cost Effectiveness of Climate Adaptation Measures.* TR News (NCHRP Research Report 938).

Ministry of Environment of Denmark. (2021). *The Service Level Declaration for climate adaptation projects in the Danish Water Utility Sector.* Retrieved from ”Serviceniveaubekendtgørelsen”: https://www.retsinformation.dk/eli/lta/2020/2276

Mouter, N. (2018). A critical assessment of discounting policies for transport Cost-Benefit Analysis in five European practices. *TUDelft*.

National Academies of Sciences, E. a. (2021). *Investing in Transportation Resilience: AFramework for Informed Choices.* Washington, DC: Scofer, J L; Bocchini, P; DesRoches, S E; Heil, A; Knatz, G; Miller-Hooks, E; Ramirez-Marquez, J E; Rivas, V; Wilson, S. Retrieved from https://doi.org/10.17226/26292.

Nordic Development Fund. (n.d.). *Climate Resilient Roads.*

OECD. (2018). *Cost-Benefit Analysis and the Environment Further Developments and Policy Use.* Paris: OECD Publishing.

Ramboll. (2017). *Cloudburst resiliency in New York City.* Ramboll A/S.

Ramboll. (2019). *BUSINESS CASE FOR LIVEABLE SHORELINES IN BUZZARD POINT.* Ramboll A/S.

Scussolini, P., Kulk, O., Veldkamp, T., Hudson, P., de Murieta, E. S., Galarraga , I., . . . Christensen, O. L. (2016). *The economic appraisal of adaptation investments under uncertainties:Policy recommendations,lessons learnt and guidance.* ECONADAPT.

Skrydstrup, J. (2021). *Integrating strategic planning of nature-based solutions into urban planning.* DTU.

The Mersey Forest, Natural Economy Northwest, CABE, Natural England, Yorkshire Forward, The Northern Way, . . . Genecon LLP. (2010/2018). *The green infrastructure valuation toolkit.* GI-Val.

The National Archives(UK). (2022). *The Green Book.* HM Treasury.

Tröltzsch, J., Rouillard, J., Tarpey, J., Lago, M., Watkiss, P., & Hunt, A. (2016). *The economics of climate change adaption.* Econadapt.

Tucker, M., Corbally, R., & O'Connor, A. (2018). *WATCH WATer management for road authorities in the face of climate CHange.* CEDR Transnational Road Research Programme Call 2015.

UNFCCC. (2011). *ASSESSING THE COSTS AND BENEFITS OF ADAPTATION OPTIONS AN OVERVIEW OF APPROACHES.* UNFCCC.

United Nations. (2021). Business models for the road sector/TEM Network:considerations and recommendations. *UNECE*.

Viti, M., Lowe, R., Sørup, H. J., Rasmussen, M., Arnbjerg-Nielsen, K., & McKnight, U. S. (2022). *Knowledge gaps and future research needs for assessing the non-market benefits of Nature-Based Solutions and Nature-Based Solution-like strategies.* Science of The Total Environment.