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CERCOM
Circular Economy in Road COnstruction and Maintenance

Guideline Detailing Roadmap to Implementation

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CEDR Call 2021: Transnational Road Research Programme

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Executive summary

This report describes the progress of Work Package 3 (WP3) of the CERCOM project funded through the CEDR Call 2020 Resource Efficiency and Circular Economy. The aim of WP3 – Risk-Based Analysis Framework (RBAF) is to facilitate procurement considering Resource Efficiency (RE) & Circular Economy (CE) for road construction and maintenance while assessing the risk of doing so.

Identifying the fundamental characteristics of risk analysis enabled the development of a risk-based approach NRAs can integrate into their procurement processes, from preparation phase right through to tender evaluation. A review of relevant past research in the area of risk assessment provided the basis for the CERCOM RBAF. The literature is summarised in the context of the CERCOM approach and adapted to demonstrate how this risk analysis is further developed to consider Resource Efficiency (RE) & Circular Economy (CE).

Through engagement within the CERCOM consortium, relevant external stakeholders and input from other work-packages, the system boundaries are established and the RBAF is finalised, along with a methodology for proposing and calculating new Key Performance Indicators (KPIs). The RBAF provides NRAs with a facility to rank various maintenance strategies in terms of risk, cost, RE & CE. The framework has its basis in standard risk assessment approaches. First the context is established, followed by an evaluation of the risk in terms of likelihoods and consequences. RE and CE may be considered along with Multi-Life Cycle Analysis (MLCA) either through robust calculation or incorporation of KPIs. Attributes relating to performance, cost, RE/CE and social aspects may be weighted according to each NRA's requirements as a function of their maturity level. A sample application of the CERCOM approach demonstrates the capabilities and robustness of the RBAF and how it can be implemented by NRAs in their procurement process.

The process of integrating the RBAF into existing public procurement procedures is described. NRAs are at different maturity levels in relation to circularity. The framework outlined in this document caters for this, allowing flexibility for NRAs to tailor their application of the framework to suit their maturity level and the scheme under consideration. Variations in risk can be considered as well as the detail in which the analysis is performed in terms of KPI application and cost estimation. The outcome is a user-friendly intuitive software tool with a step-by-step approach to allow NRAs to assess the risk associated with different materials and methodologies in the move towards a circular economy. The final chapter of this report appraises current European procurement processes in order to define the roadmap for implementation of the RBAF.

The development of the RBAF gives NRAs the ability to assess the implications and advantages of using innovative maintenance methods and materials, with the ability to quantify the CE and RE impacts as well as the potential risks of using novel approaches. This will be further advanced with the development of multi-LCA, developed as part of Task 3.4 and presented in Deliverable 3.2.

1 Introduction

The CERCOM project aims to deliver an innovative risk-based framework and management tool to facilitate a step change in the adoption of Resource Efficiency (RE) and Circular Economy (CE) principles in procurement and multi-life cycle management by NRAs across Europe. This report describes Deliverable 3.1 of the project. CERCOM Work Package 3 is focused on the development of a risk-based framework to facilitate robust evaluation of RE & CE construction and maintenance options in the management of highway infrastructure. Overall, the framework will enable rational decisions to be made around the adoption of RE & CE approaches, with the principles of risk assessment at its core.

Deliverable 3.1 encompasses the work performed as part of CERCOM Tasks 3.1 – 3.3 and delivers a roadmap to the application of the work carried out as part of these work packages. As such, this document details the stages involved in developing the Risk Based Analysis Framework (RBAF) as well as guidance on the application of the framework within current public procurement practices. A key part of this work is the development of KPIs used within the RBAF to aid the move from a linear to circular economy.

2 Scope

To develop the Risk-Based Analysis Framework (RBAF) and establish the system boundaries, risk-based decision analysis was first reviewed to establish current good practice. An overview is provided in Section 3 of this report. A literature review of risk-based approaches from previous research projects was completed in Section 4. To develop the risk-based analysis framework for considering technical, economic, environmental and social criteria, as well as RE & CE, these previous frameworks for assessment of transport infrastructure were reviewed to facilitate identification of a starting point for the CERCOM approach. This review was the primary output of Task 3.2. For reference, the breakdown of tasks in WP3 are outlined in Figure 1 below.

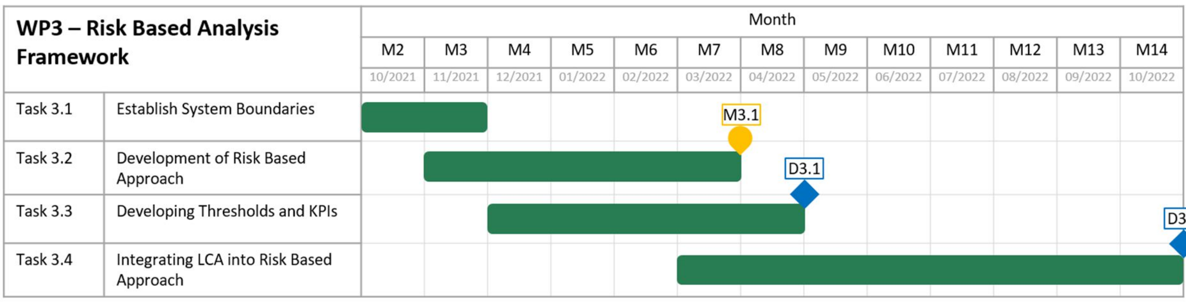

Figure 1. Outline of tasks in WP3

In Section 5, the CERCOM RBAF is developed from the initial basis of the previous frameworks reviewed. The system boundaries were established (Task 3.1) before fine tuning the RBAF procedure (Task 3.2).

To develop the RBAF considering RE & CE and allowing for integration of this methodology within NRA procurement processes, a system of KPIs was developed with appropriate and consistent methodologies to calculate values and thresholds. This was developed as part of Task 3.3 and is presented in Section 5.3 of this report. The proposed methodology takes account of the varying levels of maturity of NRAs in relation to RE & CE. The concept of maturity of NRAs is developed further within WP2 of the CERCOM project.

To demonstrate the functionality and capabilities of the RBAF, a sample application is presented in Section 5.4 of this report, following a user-friendly step by step approach. The optimization of alternative maintenance strategies using the RBAF is presented, as well as sensitivity studies to highlight its robustness. This provides a tool that will enable informed decision making around adoption of principles of circular economy in the maintenance of highway infrastructure. An Excel based prototype software will be presented in Deliverable 3.2, which will integrate outputs from Life Cycle Analysis (Task 3.4) into the RBAF.

Finally, Section 6 of this report outlines the multiple pathways to implementation of the RBAF within the NRA procurement processes and demonstrates the flexibly of the developed framework to account for varying levels of RE/CE maturity.

3 Risk Analysis Overview

Design and maintenance of road networks aims to meet the required performance standards while also limiting the risk to road users and the infrastructure itself. In procurement of any design or maintenance strategy, consideration of risk is paramount in deciding upon the most appropriate solution for the scheme. That is, the solution which maximises safety and ensures the desired level of functionality while minimising cost. With the move towards a circular economy, there is an added objective to ensure RE & CE factors are integrated within this assessment.

The aim of CERCOM Task 3.1 is to identify the fundamental characteristics of a risk-based framework to make it applicable to NRAs in their procurement processes. Risk based approaches are used by NRAs in the management of networks, so ensuring consistency with these will mitigate barriers to implementation. As such, an overview of risk-based decision analysis will be presented in this section.

While NRAs rely on their own risk management process, these processes should all follow standard approaches, which provide an understanding of what may go wrong, the probability of this happening and the associated consequences. By following such processes an infrastructure manager will be better equipped to make decisions on how to improve their infrastructure network. Risk management processes are seen as an integral part of how infrastructure is managed and should be used to complement other processes, including strategic planning and change management. Since things can “*go wrong*” in many different ways, there is a vast amount of literature from a variety of disciplines. The primary source for the current work is ISO 31000:2018 *Risk management — Guidelines*. The prescribed risk management process involves the systematic application of policies, procedures and practices to the activities of communicating and consulting, establishing the context and assessing, treating, monitoring, reviewing, recording and reporting risk. This process is illustrated in Figure 2 and each of the headings outlined in the figure are discussed in the sections below. In this section, standard risk management processes are discussed. These methods don’t directly relate to circularity, and as such, the aim of CERCOM is to examine risk analysis and further develop the functionality of existing approaches to integrate CE and RE into a RBAF for the maintenance of road infrastructure. This will be discussed in further detail in Section 5.

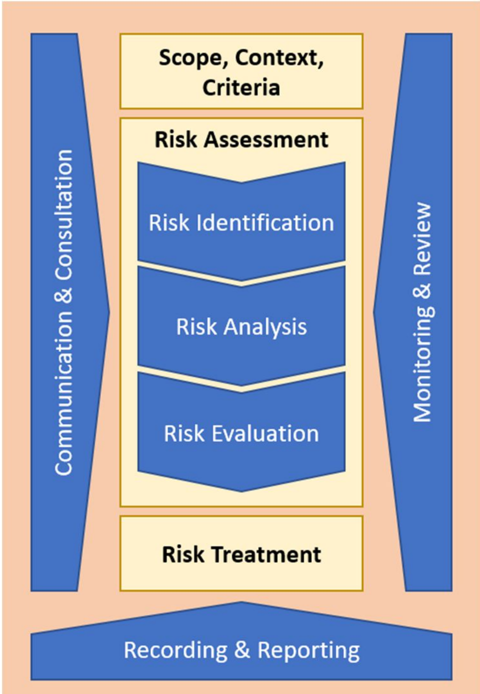

Figure 2: Risk Management Process (ISO 31000: 2018)

3.1 Communication and Consultation

It is essential that relevant stakeholders understand the risks, the basis on which decisions are made and the reasons why specific actions are required. For these reasons, communication is an integral part of the process. Equally, consultation allows feedback from stakeholders to impact decision-making. These are therefore implemented throughout the risk management procedure to ensure that different views are expressed and addressed throughout risk definition and evaluation phases.

In the context of risk assessment for road maintenance, it will be essential to include all actors in the process, including both contractors and engineering personnel, and also procurement personnel. Environment and circularity should be given appropriate voice throughout the process, ensuring the framework is in line with the environmental targets of the organisation.

3.2 Scope, Context and Criteria

The scope of risk assessment should reflect the objective for carrying out a risk analysis. This should also define the expected outcomes and include the steps to be taken in the process. The context of the risk assessment should consider both internal and external factors, which should be established from an understanding of the external and internal environments in which the organisation operates and be specific to the activity to which the risk management process is to be applied. Risk criteria should also specify the level of risk an organisation is prepared to accept. This will assist in defining the significance of risk for the specific objective of the analysis in question.

In the context of the CERCOM project, The Scope, Context and Criteria form aspects of the system boundaries, as discussed further in Section 5.1 of this report, where boundaries of the RBAF are outlined.

3.3 Risk Assessment

Risk assessment is the overall process of risk identification, risk analysis and risk evaluation. It should be noted that in all stages of the CERCOM project, risk is defined as the product of hazard probability and consequences for a given scenario, as discussed in Section 4.3.

3.3.1 Risk Identification

The risk identification stage seeks to find, recognise and describe risks that prevent an organisation achieving its objectives. This involves the identification of hazards, vulnerable assets and consequences of relevance. Specific hazards related to road maintenance may include flooding, exceedance of live load capacity etc. Vulnerability would then include items which describe the infrastructure's ability to perform as required (e.g. excessive bridge scour leading to bridge failure, requiring major repair). Finally, the consequences consider the realm of economic, environmental, RE & CE, reputational and other impacts felt by the NRA.

3.3.2 Risk Analysis

The purpose of risk analysis is to describe and understand the nature of the risk and its characteristics. Risk analysis requires a detailed consideration of uncertainties, risk sources, consequences, vulnerabilities, likelihood, events, scenarios, controls and their effectiveness. An event can have multiple causes and consequences and can affect different parts of the road system. These types of cascading and multi-component scenario analyses greatly add to the complexity of the analysis.

Risk analysis can be undertaken with varying degrees of detail and complexity, depending on the purpose of the analysis, the availability and reliability of data and the resources available. Analysis techniques can be qualitative, quantitative or a combination of these, depending on the circumstances and intended use. In the context of the CERCOM risk analysis framework, an effort shall be made to identify how NRAs of varying maturity can exploit the process.

3.3.3 Risk Evaluation

The final process within the Risk Assessment phase is the evaluation of risk within the considered context to support decisions. Risk evaluation involves comparing the results of the risk analysis with the established risk criteria (Section 3.2) to determine where additional action is required.

3.4 Risk Treatment

The risk treatment phase selects and implements the most appropriate actions to treat, mitigate and address the risk. These actions may be integral parts of an organisation's existing maintenance actions or form new actions, depending on the risk assessment analysis carried out. Risk treatment involves a balancing of potential benefits derived from each scenario. For highway maintenance, all treatment scenarios are necessarily mutually exclusive, and some scenarios may not be suitable for reasons outside the risk assessment calculation. The risk treatment should therefore not only minimise the risk, but also consider the organisations various other obligations (environmental, organisational etc.) and should be performed in accordance with the organisations risk criteria and available resources. Risk treatments may not produce the expected outcomes and can produce unintended consequences. Monitoring and review are therefore an integral part of the risk treatment process, giving assurances that the different forms of treatment become and remain effective. The risk treatment plan should therefore be based upon the results of the risk analysis process, which should be consulted when designing maintenance / risk mitigation plans.

3.5 Monitoring and Review

As mentioned under risk treatment, due to uncertainty, risk events may not occur in practice and risk treatments may not produce expected outcomes. For this reason, monitoring and review of the risk should be planned into the initial process and carried out at various stages, even after risk treatment. This allows for refinement of the associated risk calculation where variations in the norm occur.

3.6 Recording and Reporting

The entire Risk Management Process should be recorded and reported throughout the process using appropriate measures. This includes reporting of quantitative information used to develop the risk calculation, bearing in mind sensitivities related to data usage, commercially sensitive information and personal information. Reporting should consider the different users of the risk assessment and the varying levels of understanding and interest involved.

3.7 Application within CERCOM project

The ISO 31000 framework should be considered when developing risk assessment frameworks for any specific need, and as such forms the basis for the development of the CERCOM RBAF. The framework will enable rational decisions to be made around the adoption of RE & CE approaches, with the principles of risk assessment at its core.

Within the scope of CERCOM, the Scope Context and Criteria, Risk Assessment and Risk Treatment headings of ISO 31000 will be integrated directly into the core aspects of the RBAF which will be discussed further in Section 5. The other aspects of Communication and Consultation, Monitoring and Review and Recording and Reporting are continuous process ongoing throughout the project and fit well within all main phases of the public procurement process, which will be discussed further in Section 6.

In conclusion, Section 3 of this report has addressed the objectives of Task 3.1 to identify the fundamental characteristics of risk-based frameworks to ensure the CERCOM approach developed is applicable to NRAs and their procurement processes.

4 Risk Analysis Frameworks for Infrastructure: A Review

As discussed in the CERCOM Description of Work Task 3.2, the objective is to build upon risk-based assessment frameworks developed in the CEDR funded RE-GEN (Risk Assessment of Ageing Infrastructure) project (www.re-gen.net) as well as EU framework projects such as RAIN (Risk Analysis of Infrastructure Networks – www.rain-project.eu) and INFRARISK (Novel Indicators for Identifying Infrastructure at Risk – www.infrarisk-fp7.eu). Each of these projects involved the development of risk assessment frameworks. The aim of the INFRARISK framework was to assess risks with cascading impacts for the protection of existing infrastructure and robust planning of future critical infrastructure, while RAIN focused on the assessment of extreme weather events (such as flooding) on the EU critical infrastructure network, taking account of inter-related infrastructure issues. The objective of Re-Gen was to provide national road administrators with tools and methods to carry out risk assessments of critical infrastructure elements. Each of the projects will be outlined in more detail in the sub-sections below.

To develop the risk-based analysis framework for considering technical, economic, environmental and social criteria, as well as RE & CE, these previous frameworks for assessment of transport infrastructure will be reviewed to facilitate identification of good practice. These will subsequently be tailored to suit the CERCOM objectives. While numerous examples exist in the literature and were considered as part of the overall review, an overview is provided of these projects based on their relevance to the RBAF requirements.

4.1 INFRARISK

The INFRARISK project (www.infrarisk-fp7.eu/) aimed to develop reliable stress tests on European critical infrastructure using integrated modelling tools for decision-support. The project intention was to advance decision-making approaches leading to better protection of existing infrastructure while achieving more robust strategies for the planning of new infrastructure. INFRARISK proposed to expand existing stress test procedures and adapt them to critical land-based infrastructure which may be exposed to or threatened by natural hazards. Integrated risk mitigation scenarios and strategies were developed, using local, national and pan-European infrastructure risk analysis methodologies, taking into consideration multiple hazards and risks with cascading impact assessments. An operational framework with cascading hazards, impacts and dependent geospatial vulnerabilities was developed. INFRARISK also delivered a collaborative integrated platform where risk management professionals could access and share data, information and risk scenario results efficiently and intuitively.

In the context of CERCOM, INFRARISK is an excellent source of information for the development of the risk-based analysis framework. INFRARISK considered not only road infrastructure, but also railway and telecommunications. In this regard, the framework developed is flexible to various strategic objectives, lending a more robust platform that may be adopted by NRAs of varying maturity. Additionally, the consideration of multiple hazards and multiple infrastructures lends itself well to the wider systems approach required to achieve a truly Circular Economy approach.

To develop the INFRARISK Risk Assessment Framework, a two-phased approach was undertaken. A basic first effort was made to define the framework, having its basis in the universally accepted ISO 31000 Risk Management Process (discussed in Section 3 of this report). The Initial Framework is provided in Figure 3. A three-part process was proposed:

1. Establish the context
2. Risk Assessment
3. Risk Treatment

In order to establish the context of the risk assessment, the problem is first identified. This includes the generation of preliminary thoughts on the area to be investigated, the type of hazard that might occur (e.g., deterioration of surface layer leading to a loss in skid resistance) and if additional information may be required. Next, the system is defined. The system to be modelled includes all things required to assess risk, including the natural environment, e.g., amount of rain, amount of water in rivers, the physical infrastructure, the behaviour of a bridge when subjected to high water levels, and human behaviour, such as traffic patterns when a road bridge is no longer functioning. First, the system boundaries are defined, including the spatial boundaries (e.g., the extent of the transport network to be assessed) and the temporal boundaries (i.e., the time period over which the risk assessment will take place, and the subdivisions of this time period over which the risk will be analysed). The system elements must also be defined. In the INFRARISK project, these elements were linked to specific events that can occur, and were subdivided into source events (e.g., rainfall), hazard events (e.g., flooding), infrastructure events (e.g., various levels of road inundation), network events (e.g., how the network is affected by inundation) and societal events (e.g. loss of trade, delay etc.) These are standard items that should be considered in most risk assessments of transport infrastructure.

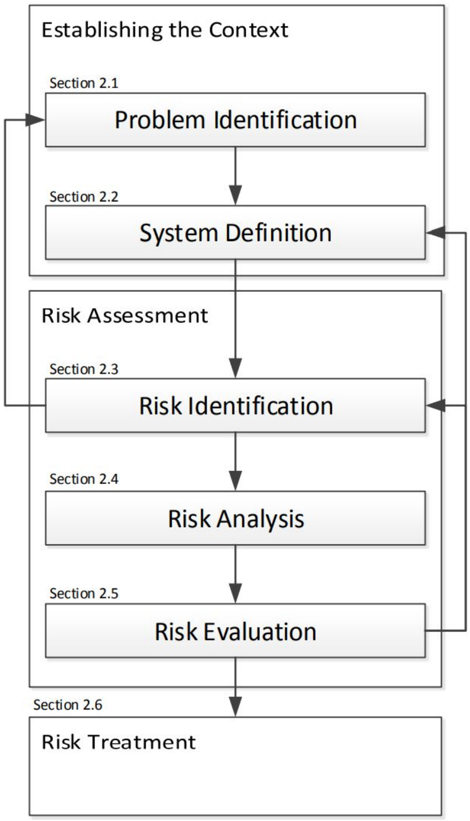

Figure 3: INFRARISK Initial Risk Assessment Framework

The Risk Assessment process was initiated with Risk Identification. While the system is outlined in the step above, this phase poses an initial decision on which parts of the system should be included in the risk assessment, what scenarios should be modelled and what interdependencies should be considered. The identification of the scenarios should be done in this step without an explicit estimation of their probability of occurrence or putting a value on the consequences. A basic sensitivity analysis supplemented with a description of the risk levels of the various hazards assist in this step.

The next step is the performance of the Risk Analysis. In the global sense, this involves calculation of various scenarios that can occur, as well as the consequences of these scenarios. The INFRARISK framework allowed for the application of various levels of risk assessment, from quantitative to qualitative approaches. The qualitative approach may be demonstrated by a risk matrix, with consideration of likelihood and consequences, but without formal quantification. Various methods of quantitative analysis were summarised including statistical analysis and probabilistic modelling (e.g., Monte Carlo Simulation, Bayesian Networks and Fault Trees). While the level of complexity should match the requirements of the risk assessment, the decision in this regard will often be influenced by data availability. In the context of the CERCOM approach, the level of complexity in the risk assessment process may be dynamic and vary depending on the maturity level of the NRA. These procedures can be applied to the hazard models, element models, network models and societal models. A final step in the process is the aggregation of risk. If different hazards are considered in the process, a system of aggregation will be needed to assess the global risk.

Risk Evaluation is required in order to evaluate the calculated risk in the context of the concerned organisation / stakeholders, as well as the process of the risk assessment itself. A large part of this is the consideration of how relevant people perceive the risk as opposed to the analyst's view from a technical perspective. One possible result of this step is that the risk analysis may need to be repeated with more detailed system representations, improved models and different values.

The final step in the process is Risk Treatment. In this case, one or more interventions are considered against the "do nothing" option to evaluate the best way to mitigate the risks. These interventions may be routine or operational maintenance, or may be new interventions which impact the initial risk assessment process. Where multiple interventions are considered, an optimization process is required to select the interventions which most effectively reduce the overall risk. The selection of the best way to modify the system involves balancing of the costs and effort of implementation against the benefits derived, taking into consideration constraints such as legal, regulatory, codified standards and other requirements (e.g. social responsibility and the protection of the natural environment). Costs here are not exclusively economic costs but all negative impacts associated with the execution of interventions, and benefits are not exclusively economic benefits but all positive impacts that can be achieved if interventions are executed (monetization of externalities).

This section of the INFRARISK framework is particularly relevant to the CERCOM approach. By integrating RE and CE KPIs into the risk treatment process, an organisation's goals with respect to CE and RE can be realised while optimizing safety, cost and organisation disruption.

The Initial INFRARISK Risk Assessment Framework had its basis in the global procedure of ISO 31000. This is key to any framework in order to keep the format in line with modern codes of practice. Through engagement within the INFRARISK consortium and discussion on the specific requirements, an updated Risk Assessment Framework was defined by the project, which provided a more flexible and open methodology which could be adapted to not only road and rail infrastructure networks, but all infrastructure networks, allowing for the inclusion of cascading events and interdependencies. The Framework is illustrated in Figure 3.

Figure 4: INFRARISK Final Risk Assessment Framework

The initial phase contains similar inputs to the "Context" phase of the initial framework. Again, spatial boundaries and temporal boundaries within the system should be considered. The step should also consist of an overview of how the assessment will be carried out. The levels of abstraction and the models and software to be used to determine if the infrastructure related risks are acceptable. This task takes a relatively short amount of time when compared to the expected amount of time for the entire process, around 10%. Effort should also be made at this stage to define what an acceptable level of risk may be in the context of the organisation. It is important that some thought is put into this before the risk assessment is conducted to provide context to the results.

The Conduct Risk Assessment phase again consists of analysing the system by simulating its behaviour in specific situations and estimating and evaluating the risk. The process may be considered similar to that described above. However, the INFRARISK approach recommends performing the assessment initially at a very high level of abstraction in order initially describe the process, followed by iteratively refining the level of abstraction until it is decided that the level of risk is either acceptable or not. The systems and models can be tested and benchmarked throughout the iteration process, and the level of detail in each model can be enhanced throughout each iteration. This saves time placing needless levels of detail on models that have a comparatively low impact on the risk. *This may be a useful step in the CERCOM context as the priorities and capabilities to perform risk analysis incorporating CE and RE aspects may vary significantly between NRAs.* The various sub tasks within this stage include (i) set up the risk assessment, (ii) determine approach, (iii) define system, including the definition/determination of the system boundaries, events, scenarios, relationships between events, and models, (iv) estimate risk, and (v) evaluate risk.

The Conduct Intervention Programme stage consists of developing measures to reduce the risk to an acceptable level and optimizing to choose the most advantageous action or combination of actions. The basic subtasks are (i) identify the possible interventions, (ii) identify the possible intervention programs, (iii) determine the risk reduction if each intervention program is implemented, (iv) identify the constraints, (v) identify synergies associated with each intervention program, (vi) determine the intervention program to be implemented taking into consideration the constraints and synergies. *While the INFRARISK approach to risk analysis is more complex than that which would be required for NRAs to adopt CE & RE solutions in the procurement process, there are certain aspects of the tools and framework that will prove to be of benefit, which are discussed in Section 5.*

4.2 RAIN

The RAIN project (http://rain-project.eu/) aimed to develop an analysis framework that identified critical infrastructure components impacted by extreme weather events and minimised the impact of these events on the EU infrastructure network. The project had a core focus on land-based infrastructure with a much wider consideration of the ancillary infrastructure network in order to identify cascading and inter-related infrastructure issues. A core component of the research considered the implications of climate change and the subsequent impacts that this may have on an already ageing and vulnerable infrastructure system.

The RAIN project is a particularly useful source for the development of the CERCOM approach in the development of quantitative tools which can be used for Risk analysis. The framework developed was fully probabilistic, with not only the hazards and impacts being modelled probabilistically, but also the consequences and “utility” of the associated impacts. As per the INFRARISK approach, while the methodology is complex and not directly applicable to the CERCOM objectives, many of the tools developed may be transferrable and as such, the RAIN risk assessment framework is reviewed here. The risk assessment framework developed is illustrated in Figure 5. The framework consisted of 5 steps, globally divided into two phases; the inference phase and the decision phase. The inference phase consists of an enumeration step, a quantification step, and a construction sub-step. The decision phase of the risk analysis framework in Figure 5 consists of a construction step and a maximization step.

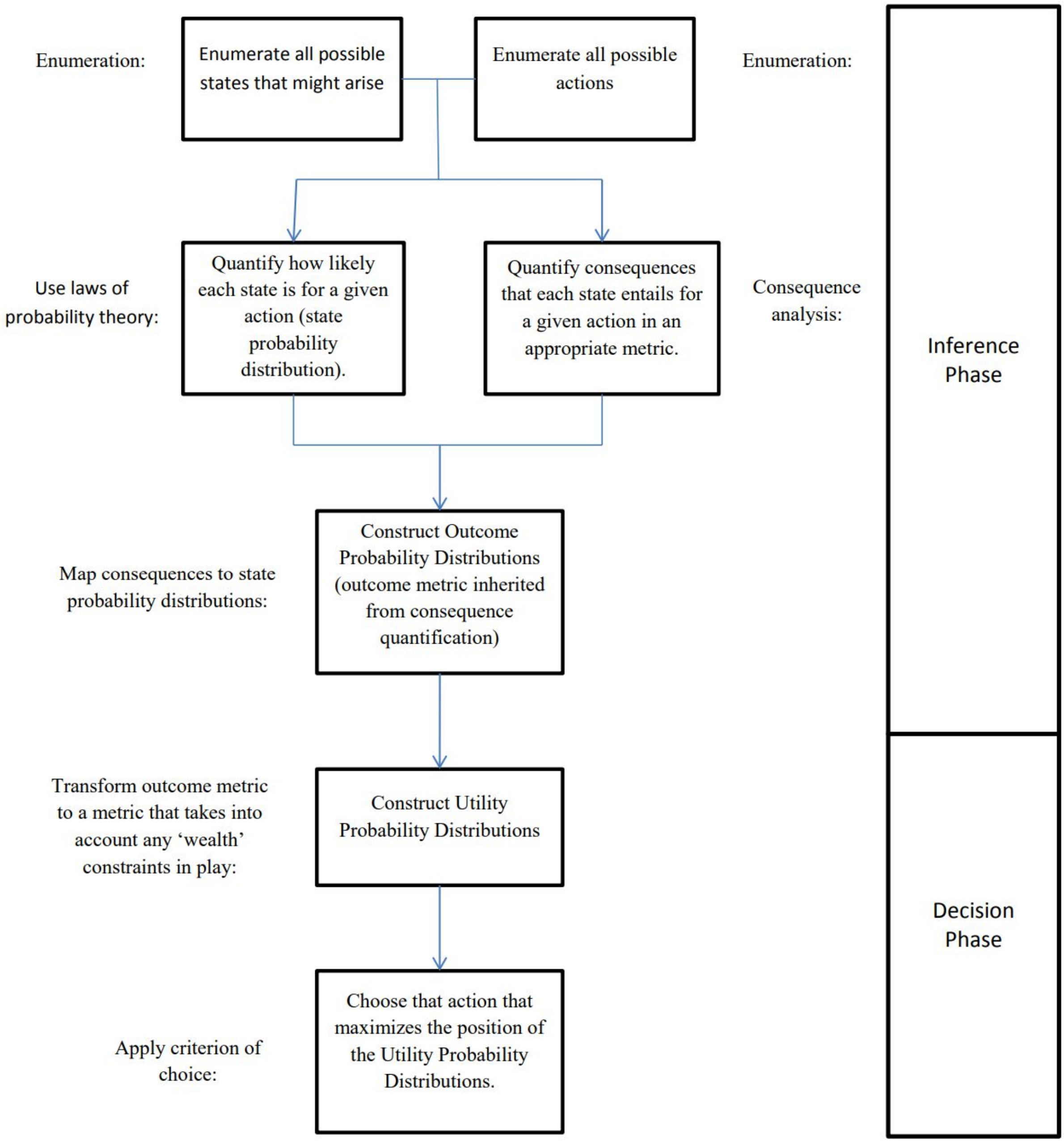

Figure 5: RAIN Quantitative Risk Analysis Framework

The first step of the inference phase, enumeration, consists of listing of all possible states that the infrastructure may be in (e.g.. various damage states associated with all hazards faced by a road network), as well as all the possible actions that can be taken to manage these states (e.g. drainage clearance to reduce flooding potential, resurfacing to repair damage etc.). This phase may be considered part of the "scope context and criteria" stage of the ISO 31000 risk management process. However, in the case of the RAIN project, the quantitative nature of the framework means that the definition of the state space should be sufficiently large to include as many potential hazard and action states as possible, even those which appear minimal at first. The RAIN project developed a probability sort algorithm capable of dismissing those states and actions which do not impact on the outcome probability distribution. This process allowed consideration of high uncertainty, low probability events which may not initially appear to impact the problem, and potential cascading hazards having comparatively higher consequences than anticipated. *In the context of the CERCOM project this computation of relevant states is not considered to be required, as the problem being addressed is already well defined, and infrastructure interdependencies are not of as high a relevance (i.e., only highways are considered).* These probabilistic quantitative methods may not be directly transferrable to the CERCOM requirements, considering potential difficulties with data availability. However, there may be scope to include a flexible approach whereby probabilistic tools may be employed where data is available in the future.

The second step in the inference phase is the quantification phase. In this step, the hazards and associated vulnerabilities of the infrastructure are modelled in order to describe the likelihood of each state occurring. The quantification of the likeliness of the possible states of the system under consideration gives us the state probability distributions. The probabilistic framework proposed in RAIN allows consideration of the uncertainty associated with each aspect of the system. The RAIN project provided guidance on the various tools available for probabilistic modelling including the basic probability theory, Bayesian statistics and Bayesian Network Modelling. The quantification step also contains the quantification of consequences of each state. This state consequence quantification is often based on historic data as well as estimates from key stakeholders. Consequences may be modelled probabilistically or deterministically. Various consequences may be built into the analysis. The most common and most easily quantifiable are economic / monetary consequences such as the cost of infrastructure repair. More complex metrics include the delay costs of users and the loss of confidence metric. Modelling exercises can be used to quantify these metrics, but it is often convenient to represent them in monetary terms. This will of course vary from stakeholder to stakeholder and should be based on the stakeholder's current practices. Another complex metric of consequence is the injury and loss of life metric. Whereas monetary costs are relatively easy to estimate deterministically, loss of life may have to be estimated probabilistically; seeing that more uncertainties are typically involved. So, for a given damage state a conditional probability distribution of loss of life may have to be constructed which is conditional on the specific damage state of the system. Additionally, the economic value of loss of life varies from country to country and has been the subject of much research in the past (Keller et al., 2021).

The final step in the inference phase is the construction of the outcome probability distribution. By mapping numerical consequences to the states of state probability distributions the outcome probability distributions are obtained. This involves multiplication of the consequences and likelihoods at each state in the system. The risk is represented by a random variable (i.e., it is probabilistic), representing the fact that the final risk is an uncertain value.

The first step in the decision phase is the construction of the "Utility" distribution. This is a distribution which describes the practicalities of a strategy in the context of the availability of budget to implement it. While the INFRARISK framework considered the utility of the stakeholder by quantifying levels of acceptable risk, the RAIN project required a more mathematical approach which could consider the available resources of the decision makers. An example of this may be presented by considering an NRA with an annual maintenance budget of €100 million. A risk representing a loss of €2 million will be felt less by this NRA than one with, say, an annual budget of €10 million. The RAIN framework needed to be able to consider this utility in its most basic form, so that decisions can be made based on available information. The RAIN project made use of Bernoulli's utility function (Bernoulli, 1738) to consider this phenomenon. These utility functions are then 'mapped' onto the outcome probability distributions so that the utility is inherently considered within the outcome. *While* *this approach may not be directly applicable to CERCOM, the idea of an inherent utility estimation within the risk metric is certainly of interest.*

The final step in the decision-making process is the choosing of a decision which maximises the ‘position’ of the outcome probability distribution. In this case, since the risk is not deterministic, that action which minimises the risk cannot easily be chosen, as each theoretical action may have various potential outcomes. A measure of the position of the probability distribution is therefore required which describes both the mean value and the uncertainty. The RAIN project proposed several ways of considering this decision metric. The final decision was to use the average of the expected value, the lower bound and upper bound confidence intervals. In this way, both the most likely theoretical scenario, and the potential realm of scenarios that could result from an action are considered. Choosing the action which optimizes the risk ‘position’ on this basis is therefore the final step in the process. *It is not envisaged that this level of probabilistic utility estimation will be required for CERCOM, and outcomes of the RBAF will need to be deterministic in order to be usable in the procurement process of most NRAs.*

The probabilistic quantitative framework developed in the RAIN project may not be directly transferrable to the CERCOM requirements, considering the amount of data required to perform the advanced probabilistic modelling. However, there may be scope to include a flexible approach whereby probabilistic tools may be employed where data becomes available. Nonetheless, the quantitative risk assessment tools developed in RAIN will be valuable resource to the CERCOM project, even if probabilistic modelling will be performed in a more simplistic way in CERCOM in order to make the framework operable. This will especially be the case when developing the Software Tool facilitating risk-based assessment of RE & CE approaches (D3.2) and the case studies of WP4.

4.3 Re-Gen

The primary objective of the CEDR funded Re-Gen Risk Assessment of Aging Infrastructure Networks (www.re-gen.net) was to provide Road Owners/Managers with best practice tools and methodologies for risk assessment of critical infrastructure elements such as bridges, retaining structures and steep embankments. The Re-Gen project sought to adopt a network-wide probabilistic risk-based approach to optimize lifecycle performance of the infrastructure, within the context of evolving traffic demands and climate change effects. The proposed framework considered the different types of risk faced by national road administrations such as safety risk, financial risk, operational risk, commercial risk and reputational risk. *While these approaches are of direct relevance to the CERCOM project, it is considered prudent that the CERCOM framework should be adaptable to a broad range of construction and maintenance options for all road infrastructure elements rather than just critical infrastructure elements.*

The Re-Gen project provided an extensive review of existing qualitative and quantitative risk assessment models in the safety science domain. Subsequently, a state-of-the-art literature review was provided on frameworks developed to address safety risks associated with climate change and traffic growth specifically. For the latter review, projects reviewed included the RIMAROCC project (Bles et al., 2012), WEATHER (Enei et al., 2012) and the UK Highways Agency (subsequently Highways England and now National Highways) climate change risk assessment (UK Highways Agency, 2009; 2011). The literature suggested that most of the risk frameworks are primarily qualitative or semi-quantitative. They often rank the risks on an ordinal scale and present the various levels of risk using risk matrices as a risk assessment tool. Methods such as fault tree (FT) and event tree (ET) analysis and Bayesian Belief Networks (BBNs) are core methods of quantitative risk assessment. Figure 5 illustrates a sample fault tree analysis for bridge failure. Bridge failure in this case may be representative of various damage states (e.g. collapse, serviceability failure, etc). BBNs are useful tools in making inferences about uncertain states when limited information is available. The Re-Gen project therefore suggested using quantitative risk assessment tools (e.g. fault trees or BBNs) to model the risk to road infrastructure in respect of climate change and long-term traffic growth. If historical data is not available to perform such analysis, Re-Gen recommended the application of structured expert judgment to provide quantitative data.

The Re-Gen project provided guidance on deterministic calculation of failure consequences, considering both direct and indirect costs. Rehabilitation costs C_{Reb}, vehicle detour / running costs C_{Run}, travel time costs C_{Trav} based on the average person wage and Accident costs C_{Acc}. The risk is then computed according to Equation 1:

$$R = P_f \times (C_{Reb} + C_{Run} + C_{Trav} + C_{Acc}) \quad (1)$$

Where P_f is the probability of a specific failure state occurring, computed from the fault tree analysis.

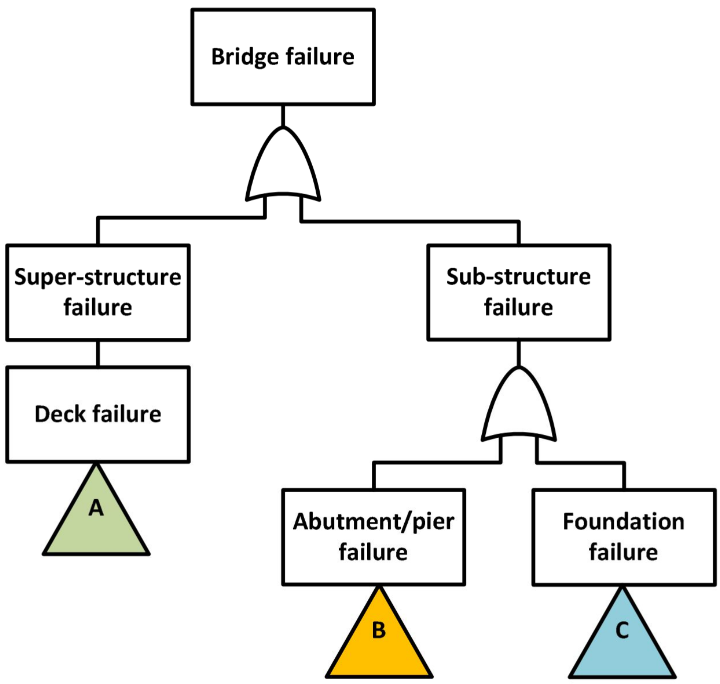

Figure 6: Re-Gen Fault Tree Analysis for Bridge Failure

Probabilities of failure and consequences can be scored qualitatively or quantitatively. Accordingly, the value of the respective risk would be estimated in the same manner. Figure 6 illustrates a qualitative risk analysis. The risk of a failure has consequences ranging from negligible (represented by 1) to very serious (represented by 4). Likewise, the probability of failure can be scored from very large (represented by 4) to negligible (represented by 1). Based on the combined likelihood and consequences the Risk can be ranked as low, medium or high.

		Consequence Severity			
		4	3	2	1
Likelihood	4	High	High	High	Medium
	3	High	High	Medium	Medium
	2	High	Medium	Medium	Low
	1	Medium	Medium	Low	Low

Figure 7: Example of a qualitative Risk Matrix

The Re-Gen project also proposed risk optimization techniques which will be of particular relevance to the CERCOM approach. To make effective decisions, the risk framework must be able to identify the action (or combinations of actions over time) which both minimise the risk and the required resources (expenditure). Re-Gen proposed Multi-Attribute Optimization for this task. An example was provided of potential interventions to prevent a risk (R) of bridge failure. It was assumed that after the implementation of the i_{th} intervention the value of the residual risk would be R_i. As such, a Risk Reduction Index (RRI) can be defined for each intervention as (Yuan et al., 2015):

$$RRI_i = \frac{R - R_i}{R} \tag{2}$$

The RRI lies in the interval 0.0 – 1.0 for feasible interventions. The cost of each intervention can be estimated as C_i and includes but is not limited to the cost of materials and labour. Having the total budget allocated for risk optimization B, a Cost Potential Index (CPI) can be defined for each intervention as (Yuan et al., 2015):

$$CPI = \frac{C_i}{B} \tag{3}$$

Finally, Net Risk Reduction Gain (NRRG) of the i_{th} intervention is defined in this work as:

$$NRRG_i = w_1 \times RRI_i + w_2 \times CPI_i \tag{4}$$

Where w_1 and w_2 are weighting factors, reflecting the preference of decision makers to either reduce the risk or to expend less money on interventions. It should be noted that w_1 + w_2 = 1.0, and CPI is considered negative in Equation (4), reducing the NRRG brought about by the intervention. The optimal intervention strategy is the one which maximizes the sum of $NRRG_i$; that is, the net gain of risk reduction should be the greatest after the application of the optimal intervention strategy under the constraint of the limited available budget.

Although the framework developed in Re-Gen had a different aim to the CERCOM project, the tools are a good starting point for evaluating risk while prioritising RE and CE uptake by NRAs in the procurement of road construction and/or maintenance activities. The flexibility to perform quantitative or qualitative risk assessment also lends itself well to CEDR NRAs of different maturity levels, while the multi-attribute optimization appears to be an excellent tool for building the prioritisation of environmental goals, RE and CE approaches. It is therefore suggested that a quantitative approach be developed in CERCOM with sufficient flexibility to be applicable across varying maturity levels.

5 CERCOM Risk-Based Analysis Framework

In this section, the CERCOM risk-based analysis framework is presented. By adapting and building on methodologies and previous projects outlined in Section 3 and Section 4, the risk-based analysis framework was developed and further refined through stakeholder engagement and internal CERCOM workshops. The framework aims to consider technical, economic, environmental and social criteria, as well as RE & CE, to assess the change in risks in moving from a linear to a circular economy.

In order to develop the basis of the framework, the system boundaries and general context were first established.

5.1 System Boundaries

In the context of developing the system boundaries of the CERCOM Risk-Based Assessment Framework, the following questions must be answered:

1. What is the goal and intended use of the framework?
2. Who are the intended users?
3. To what infrastructure elements and procedures can the framework be applied, and what combination of elements?
4. What are the spatial and temporal limitations of the framework?

The first point above may be addressed directly through the CERCOM Description of Work for this task. The aim is to enable rational decisions to be made around the procurement of maintenance solutions that take a more circular and resource efficient approach, with the principles of risk assessment at its core. However, the traditional aims of such a risk assessment framework will still be required when considering the CERCOM RBAF. For example:

- Optimize safety, technical performance and cost;
- Address socio-economic needs;
- Optimize asset management strategies to minimize/limit environmental impact and material use;
- Facilitate procurement process;
- Be applicable at all levels of CEDR NRA maturity.

The second question above, *"Who are the intended users?"*, is directly a function of the requirement of the CERCOM approach. That is, the intended users of the risk-based analysis framework are CEDR NRAs of any maturity level. It is important that the framework will be both user-friendly, and beneficial to NRAs when considering adoption of RE & CE. The framework will be discussed with key CEDR NRAs at promotion workshops in line with the CEDR dissemination plan (D6.1). This will provide an opportunity for feedback on the usability and usefulness of the tools for NRAs of all maturity levels.

The framework shall be applicable to all infrastructure elements under the maintenance remit of CEDR NRAs. This includes, but is not limited to:
- Road pavements
- Bridges
- Retaining walls
- Cuttings and embankments
- Tunnels

- Roadside Infrastructure (crash barriers, noise barriers, sign poles etc.)
- Drainage systems

The framework shall be:

- applicable at any level (i.e., network level or individual element / structure level),
- applicable to any combination of infrastructure elements,
- applied during procurement of construction and maintenance solutions for these elements / combinations of elements,
- adaptable to new construction and maintenance methodologies, lending itself to, for example, the evaluation of novel "green", circular and bio-based maintenance solutions, and
- a means by which the RE and CE ranking of different solutions shall be considered.

The final question, *"What are the spatial and temporal limitations of the framework?"*, relates to spatial and temporal boundaries. It is envisaged that the spatial boundaries are limited only by the jurisdiction of a CEDR NRA. That is, an NRA shall be able to apply the framework across their entire network or at an individual node in the network. It is not suggested that the framework for the current work be applied at a trans-European level, as the developed KPIs will need to be calibrated at a national level or lower. The framework will be applicable at scheme level initially. While the reuse of materials from other sectors may be considered within the framework, the CERCOM approach will consider assessment only in the context of the objectives of a single CEDR NRA.

The question of temporal boundaries is slightly more complex. It is envisaged that the risk framework may be applied over an assessment period in line with NRA requirements (e.g., 10-40 years). However, the framework must be capable of considering Multi-Life Cycle Analysis (Multi LCA) in order to evaluate the circularity of material use and solutions. Within the scope of CERCOM D3.1, a fixed assessment period will be considered. The capabilities of the RBAF will be extended within Task 3.4 (D3.2) to integrate outputs from Multi-Life Cycle Analysis.

5.2 Framework Overview

Bearing in mind the CERCOM objectives and the system boundaries described, the Risk-Based Analysis Framework is illustrated in Figure 8. This is initially developed for scheme level analysis and is reflective of the universally accepted ISO 31000 approach, with the "Scope, Context, Criteria", "Risk Assessment" and "Risk Treatment" integral within the 5 steps of the framework. Application of the approach within procurement of road construction and maintenance activities will be discussed further in Section 6.4. On the basis of the previous projects reviewed in Section 4, the RBAF is intended to further develop and enhance the capabilities of the Re-Gen methodology, as this is a tried and tested, agreed approach which can be adopted by CEDR NRAs. The Re-Gen project proposed the use of qualitative risk assessment tools, but where data is not available, recommended the application of structured expert judgement to provide qualitative data. This is relevant for the development of the CERCOM RBAF given the potential to include novel and innovative methods and materials, and to accommodate the varying maturities of NRAs, providing the flexibility to perform quantitative or qualitative risk assessment. The Re-Gen project also proposed the use of the Net Risk Reduction Gain optimisation technique to make effective decisions to minimize risk and required resources. The developed Re-Gen optimisation technique considered risk, cost and associated weighting factors providing an excellent starting point for further development to incorporate CE & RE factors into a multi-attribute optimization procedure. Establish context, evaluate likelihoods, evaluate consequences optimize are all steps carried out within the Re-Gen framework as part of the risk assessment and optimization. Additional development and further analysis is required for the CERCOM RBAF to establish additional KPIs related to RE & CE and other environmental and social factors. The INFRARISK approach recommends performing a high level assessment initially, followed iterative refinement of the analysis. While the INFRARISK approach to risk analysis is more complex than that required for the RBAF, this outlook is useful in the context of the RBAF, as the priorities and capabilities to perform risk analysis incorporating CE & RE aspects may vary significantly between NRAs.

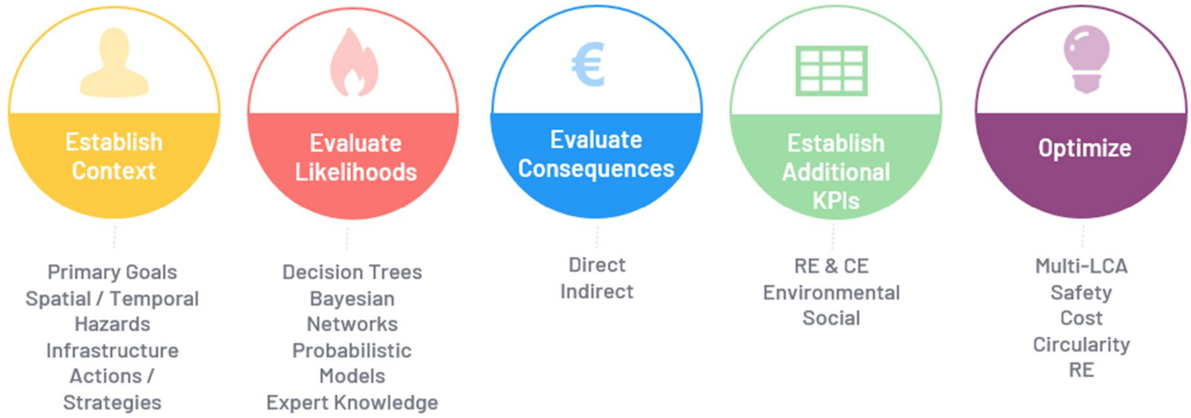

Figure 8: CERCOM Risk-Based Analysis Framework

There are two ways in which RE & CE can be included within this risk framework; the choice between them can be determined by each NRA depending on their maturity level, scheme type and access to suitable data:

- The risks associated with novel maintenance strategies that incorporate RE & CE approaches can be treated through a formal, quantified risk treatment that incorporates a multi-LCA. This is the preferred option in the long term. However, it requires substantial data and a relatively complex analysis, which is more suitable for NRAs at a higher level of maturity.
- Alternatively, where a detailed examination of certain costs isn't feasible, additional KPIs can be established within the framework to assess and quantify the implications with respect to various construction or maintenance options. This is likely to be a more practical method for many NRAs to incorporate RE & CE concepts alongside other factors in their selection of the most advantageous maintenance solution.

Each step of the framework outlined in in Figure 8 will be discussed in more detail below.

5.2.1 Establish Context

While the overall system boundaries to which the CERCOM RBAF have been identified in Section 5.1, the context of the specific Risk Assessment to be carried out must also be established. This includes an understanding of the primary goals of the assessment, the hazards involved, the potential actions to reduce risk, the consequences to be considered and how the hazards and consequences will be calculated (including the tools and data required). The context should identify the specific spatial and temporal boundaries of the assessment in question. The temporal context should identify the intended lifecycle of the solution and the analysis period should be defined. CERCOM proposes a qualitative approach to defining the context: expert judgement should be used to establish the nature of the assessment, the hazards, the actions which may be taken, the level of the analysis and the means of assessing RE & CE approaches (i.e., as KPIs or through quantitative cost representation).

5.2.2 Evaluate Likelihoods

CERCOM proposes that likelihoods shall be considered quantitatively within the RBAF, quantifying as accurately as possible, the probability of failure, or the probability of exceedance of a given damage state for given scenarios of hazard and action. This can be used to quantify possible increased risks associated with moving from linear to more circular materials and practices. An example may include quantifying the probability of a certain level of pavement wear for different products proposed as part of a resurfacing regime. By quantifying the probabilities associated with traditional methods and more innovative methods, the various risks associated with moving towards a circular economy can be assessed and optimized as part of the framework. Where data is not available to perform this quantification, quantification can be determined from expert judgement with input from Delphi panels. It is worth noting that there is a certain probability of failure/damage/wear associated with all methods of maintenance and construction. These are controlled and limited by following appropriate design standards where acceptable levels of failure are inherently incorporated for all limit states covered within the codes. It is important to highlight that the framework does not replace or override these minimum safety requirements set out in design standards, but rather, it aims to use the performance level associated with different methods to compare, rank, and optimize viable options.

To allow for increased capabilities within the analysis it is proposed that, where possible, quantitative probabilistic modelling is applied rather than deterministic modelling. While deterministic modelling assumes that all variables and input values to calculations have a distinct integer value, probabilistic modelling represents variables (such as material strengths, costs etc) as random variables, which can vary about some predefined mean value. This allows for uncertainties related to different materials and methods to be incorporated into the analysis. As innovative approaches are developed with the aim to increase circularity, the performance data associated with these approaches may be quite limited. Rather than just taking a single value to represent performance, a distribution can be applied and calibrated based on expert judgement, with the extent of the spread of this distribution taking account of the additional uncertainty associated with this novel material/method. The probability of failure/damage is indicated by assessing the portion of the distribution below a certain threshold. For simple illustrative purposes, Figure 9 indicates how the increased uncertainty associated with a more innovative option can influence the measure of performance and increase the portion of the distribution below a certain threshold. This illustrates the advantages of incorporating probabilistic modelling into the framework, as uncertainty is inherently considered in the risk.

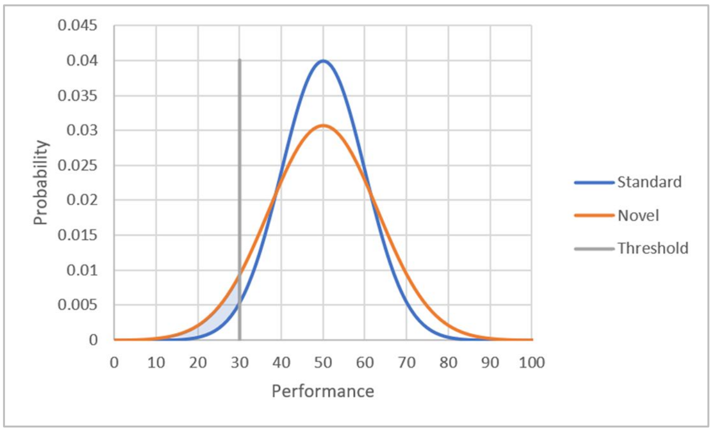

Figure 9: Example probability distributions of performance for standard and novel approaches

Probabilistic modelling can utilise Event Trees, Decision Trees and Bayesian Network Modelling to consider the complex interdependencies between different network elements. For NRAs of lower maturity who may not possess the level of data required to perform quantitative probabilistic modelling, Event Trees are also a useful tool to contextualise the problem and describe the processes leading to failure. Expert judgement can then be used rather than probabilistic modelling to input the likelihoods where required.

5.2.3 Evaluate Consequences

As discussed in Section 4.3 and outlined in Equation 1, consequences evaluated in a risk assessment are directly related to the specific failure states considered in evaluating likelihood. Probabilities and consequences are combined as part of the final optimization step of the process to calculate the Risk Reduction Index (*RRI*) associated with a proposed construction or maintenance scenario. It is proposed that consequences should be considered quantitatively, and expressed in monetary terms where possible. Probabilistic consequence modelling is not proposed in the CERCOM approach. Rather, deterministic values should be discerned based on prior available data and expert knowledge in order to simplify the process. The quantitative (monetary) consequences of road infrastructure failures include (i) direct costs of structural damage such as reconstruction, repair and maintenance, or damage to the life and properties of road users and (ii) indirect costs arising from the users' costs of traveling such as vehicle operating costs, travel time costs, and accident costs (Adey et al., 2003).

5.2.4 Establish Additional KPIs

In this step additional KPIs are established for the scheme in question and their values are quantified for each potential strategy. KPIs should be as orthogonal as possible to avoid double counting and should be determined in a collaborative way among all stakeholders. A range of scores are proposed for each KPI and values are assigned for each strategy. It is advised to use a similar scoring system for all KPIs where possible, with weights used to assign relative importance in the "Optimize" step. KPIs should have a value between 0.0 and 1.0, with 0.0 having the least beneficial impact on CE / RE and 1.0 having the most beneficial impact.

Within the developed framework, these additional KPIs are divided into 3 categories, RE & CE, Environmental and Social. The framework is flexible to include as many KPIs as necessary in order to capture individual NRA requirements. The CERCOM project does not propose to develop a complete list of KPIs for assessment as this will be scheme and location / organisation dependant. However, an initial discussion on the topic is provided in Section 5.3 below.

A key focus of the DoRN for this work was that a methodology is required for harmonised calculation of the proposed indicators across NRAs and sectors. The benefit of the proposed CERCOM approach to indicators is its specific field of application within procurement (as per Section 6). Additionally, the flexibility in the incorporation of semi-quantitative indictors calibrated by expert judgement in place of detailed calculation where data is insufficient, ensures a broad range of application across CEDR NRAs.

5.2.5 Optimize

To rank various construction or maintenance solutions, a metric is needed which is capable of scoring the various potential maintenance strategies. The Net Risk Reduction Gain (*NRRG*) discussed in Section 4.3 is incorporated into the CERCOM framework to allow performance, cost, RE&CE, environmental and social factors to be considered and integrated into a single index for optimization purposes.

For each potential action, the Risk associated with each strategy is calculated, as outlined in Equation 1 (Section 4.3). In terms of cost, the calculation of the Cost Potential Index (*CPI*) provides flexibility within the framework to allow NRAs to vary the level of complexity involved in the calculation of costs associated with each proposed strategy. This allows for maintenance and construction costs and/or Whole Life Costing/multi-LCA to be incorporated, and will be further developed in CERCOM Task 3.4. This is one method by which NRAs can choose to integrate areas of RE & CE into the framework. Alternatively, where a detailed examination of certain costs isn't feasible, cost-related circularity KPIs can be established within the framework to assess and quantify the implications with respect to various construction or maintenance options. KPIs are utilised within the calculation of *NRRG* to integrate critical RE&CE, environmental and social factors:

$$NRRG_i = w_1 \times RRI_i + w_2 \times CPI_i + w_3 \times KPI_{1,i} + w_4 \times KPI_{2,i} + \cdots \quad (5)$$

Where:

$$RRI_i = \frac{R - R_i}{R} \quad (6)$$

$$CPI_i = \frac{B - C_i}{B} \quad (7)$$

Note: CPI is considered as positive for the CERCOM RBAF.

R = Risk associated with the "do nothing" option;
R_i = Risk associated with maintenance / construction option i;
B = Budget available for maintenance / construction activity;
C_i = Cost associated with maintenance / construction option i;
$KPI_{3,4,5\ldots,i}$ = Values of each KPI associated with maintenance / construction option i;
$w_{1,2,3\ldots}$ = Values of weights for each KPI. Note that all weights must sum to 1.0

The developed additional KPIs should ensure that contractors can be rewarded for producing a scheme that will be long lasting, cost effective to maintain, use limited amounts of raw materials, designed for multiple lifecycles and/or can be readily repaired for (multi) life extension. The intention is to add components to the scheme design considering reuse, recycling, demountability, etc. pointing towards closing the loop. The KPIs should also be sympathetic to the various maturity levels across NRAs.

The development of RE & CE related KPIs forms part of CERCOM Task 3.3 (see Figure 1 for a breakdown of tasks in WP3). The high-level indicators provide a means to rank strategies taking account of resource efficiency, environmental and social factors within the framework, while allowing for quantification of risk and multiple lifecycle performance. While performance and cost are encompassed within the *RRI* and *CPI*, further KPIs are required for RE & CE, environmental and social considerations. It should be again noted that all weights should sum to 1.0, and the KPIs should be expressed in the interval of 0.0-1.0, with 1.0 being the maximum possible value achievable within each KPI. The minimum requirements of each KPI (as defined within the objectives and codified norms of the NRA) should be sustained for each option considered. KPIs should be developed and quantified within the risk assessment process in line with the broad divisions provided in Figure 10 below. Further guidance on KPIs within the divisions of Performance, Cost, RE & CE, Environmental and Social are provided in the next section, with a sample application outlined in Section 5.4.

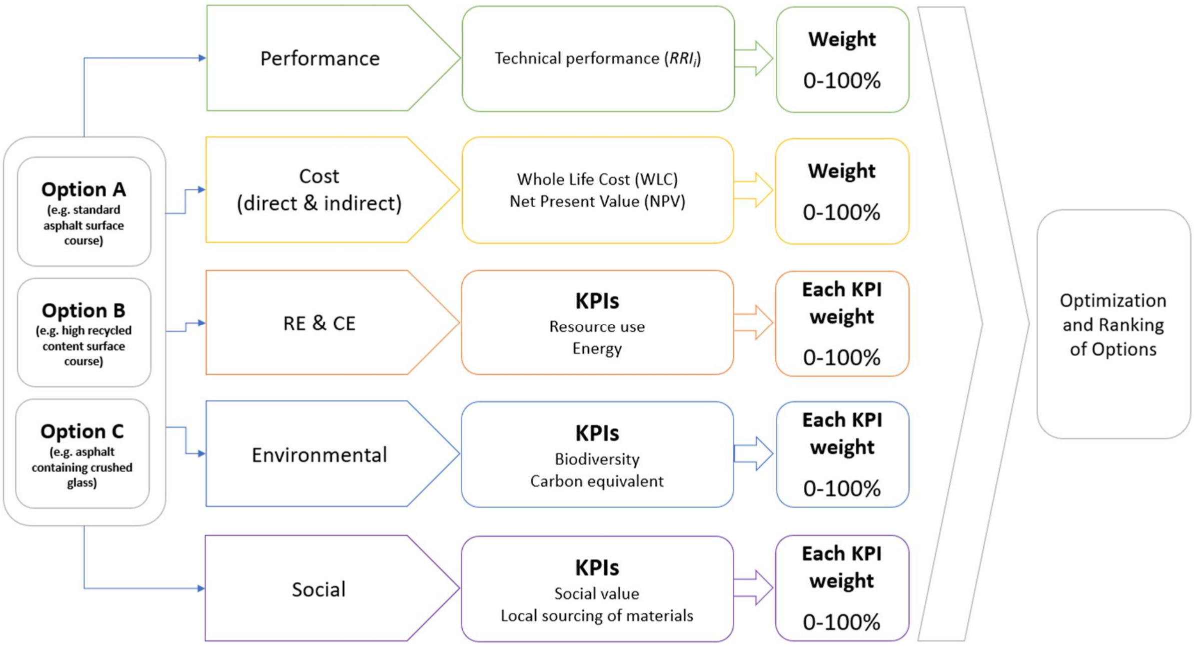

Figure 10: CERCOM Risk-Based Analysis Framework KPI division and weighting process

5.3 Performance, Cost and Additional KPIs

Any number of KPIs may be proposed within the overall context of the risk framework, but should be structured according to the divisions of Performance, Cost, RE & CE, Environmental and Social KPIs, as outlined in Figure 10. This section provides a discussion on some sample KPIs for consideration in the risk assessment process.

5.3.1 Performance KPIs,

The performance KPIs generally relate to the technical performance and durability implications of the scheme, and are represented by the Risk Reduction Index (RRI). The RRI only considers the risk in the context of the problem being addressed. For example, a scheme for road resurfacing where the primary reason for resurfacing is to improve skid resistance may only consider the skid resistance risk as a KPI, even though other indicators may impact on the safety / operational aspects of the road section (e.g., drainage clearance). Further examples of performance KPIs may include bearing capacity, texture, structural capacity etc.. This KPI aims to use the performance level associated with different methods to compare, rank, and optimize viable options. It does not undermine minimum safety requirements set out in design standards, and any strategies which do not satisfy these minimum requirements will not be considered within the framework. An exception is the consideration of the “do nothing” option. This is often considered within the risk analysis process in order to demonstrate the motivation for carrying out maintenance / rehabilitation activities and form an initial calculation of the system probabilities. In most cases, “do nothing” is not a realistic or viable maintenance option as statutory minimum requirements for safety must be complied with meaning that intervention always happens before the “do nothing” scenario is enacted. This consideration of the “do nothing” option is therefore common in academia but less so in industry practice, where the “do-minimum” is often evaluated as this scenario may be a viable maintenance option.

5.3.2 Cost KPIs

The Cost KPI should be quantified by the Cost Potential Index (CPI), which is normalised against the available budget for the scheme. This should include Whole Life Cost (made up of initial cost, maintenance cost and Residual Value). The cost should represent reuse of materials, through upcycling, downcycling or repurposing, with the ultimate aim of the NRA achieving zero waste/zero virgin material use. The "Residual Value" KPI provides a method to address multi-LCA by including in the analysis the monetary value that materials or assets have at the end of an assessment period. The monetary value is related to reuse or recycling within the same application or transferred for use in a different application.

Total costs (initial or life-cycle maintenance) are made up of direct (e.g., labour materials, equipment), indirect (e.g. transaction costs related to process activities that the NRA and contractors will need to carry out) and externalities. Transition to circular economy will introduce new ways of working and processes that will impact on the costs, e.g., revised procurement processes and Standards, greater and longer-term collaborative working with the supply chain, contractor responsibility at design stage for end of first life re-use, processing and storage of materials to reduce dependence on virgin materials etc. The size and scope of projects, the NRA maturity levels of transition and their priorities will all influence the relative impacts on direct and indirect costs. It would, therefore, be valuable, particularly during the transition from linear to circular economy, to collect detailed data on direct and indirect costs and give consideration to calculating individual Net Present Value (NPV) of direct and indirect costs, (where sufficient data is available) to represent cost KPIs. This will also help to better understand changes resulting from the move to circularity and greater resource efficiency.

5.3.3 RE & CE KPIs

Various measurable indicators may be used to quantify the RE & CE performance of construction and maintenance schemes. A number of performance measurements for assessing circularity from current literature will be outlined in CERCOM Deliverable 2.1. With reference to these studies, a sample of individual indicators are adopted here that are considered appropriate for the RBAF within NRA procurement processes. A description of possible KPIs are presented in Table 1 to provide an example of potential RE & CE factors that may be considered. The table is not an exhaustive list, as many KPIs will be scheme and/or maturity dependent.

Table 1: RE & CE KPIs

Name	Description
Energy Use	kWh of energy use per km throughout lifecycle of scheme
Recycled Content	Percentage of materials recycled against country minimum
Secondary Materials	Proportion of secondary materials used/reused against total
Virgin Material	Proportion of virgin material used against total
Waste Generation	Volume of material discarded/over ordered etc
Recyclability	Open loop / Closed loop or percentage recovery of materials for reprocessing, supported by relevant paperwork, licences etc
Haulage	Scale of works completed in situ, reducing haulage, local supply, maximising full loads (i.e., not part loads/orders)
Product Utilisation	Functional use achieved/industry average functional use

The list in Table 1 is not a comprehensive list of RE & CE KPIs to be considered in any scheme by an NRA. Relevant KPIs should be developed on a case-by-case basis in order to capture the unique characteristics of a scheme and the requirements of the NRA, although a number of pre-set KPIs will be integrated into the RBAF. The CERCOM RBAF has the flexibility to adopt various KPIs appropriate to a scheme, but care must be taken not to double count information and only consider KPIs which are relevant to the assessment in question. For example, KPIs like "Recycled Content", and "Secondary Materials" may be considered individually or together depending on the requirements of the NRA. It is clear that some NRAs will have internal targets with respect to some of these KPIs, and consideration should be given to building these targets into the KPI definition.

5.3.4 Environmental KPIs

Additional environmental indicators should be considered in this heading, for example, considering biodiversity, carbon emissions/carbon equivalent, noise pollution, air quality, ecology, water quality, etc. The list of KPIs with appropriate thresholds should be generated with knowledge of the scheme in question.

As discussed, care must be taken not to double count information and only consider KPIs which are relevant to the assessment in question. For example, there may be some crossover between a "Carbon Equivalent" KPI within the environmental heading and the "Energy Use" KPI listed in Table 1. An example of a scenario where it may be beneficial to consider each KPI would be where the construction and operation phases make provision for the use of more renewable energy sources which would not be picked up by a "carbon Equivalent" KPI.

5.3.5 Social KPIs

Social KPIs consider aspects of the value not covered under cost. Examples may include the use of local materials, employment (internal / contracted / local workforce and job creation) and availability of local supply chains. As above, KPIs can be normalised against some desirable value.

Again, care should be taken not to double count indicators across different categories. For example, the "Haulage" KPI in Section 5.3.4 may be considered under the environmental KPIs due to the impact on workload / emissions etc. However, the consideration of local supply, minimising freight traffic etc may have additional benefits on social indicators.

5.3.6 Quantifying KPIs for Risk Assessment

While technical performance and cost KPIs are quantified by the RRI and CPI in the CERCOM RBAF, additional RE & CE, environmental and social KPIs are also proposed to be quantified in order to allow separate weighting and consideration alongside risk and cost. A number of quantification methodologies were investigated, primarily consisting of direct formulae and / or a ranking system with interpolated values. When developing the methodology, a number of essential aspects relating to the KPIs must be born in mind:

1. KPIs must be quantified in the interval 0.0-1.0 in order to allow weighting alongside risk and cost;
2. The scale of the KPIs should be determined through normalisation against some constant / maximum value or range;
3. KPIs should be as orthogonal (statistically independent) as possible, and relate to each other in terms of quantity and impact on the risk calculation;
4. KPIs should be quantified in as impartial a way as possible, being solely outcomes of the system / maintenance scenario in question.

KPIs by Direct formulae

The CERCOM consortium considered the development of formulae for KPI quantification. The two examples below show how formulae may be constructed where the KPI is calibrated against a known point (e.g., the “do nothing” scenario) or against a possible range of options with a defined minimum and maximum. The first example is for the quantification of a carbon cost KPI for a maintenance scheme. The calculation may be of the form below:

$$KPI_{CC,i} = \frac{CC_{DN}}{CC_{DN} + CC_i} \tag{8}$$

Where CC_{DN} is the carbon cost associated with the “do nothing” scenario and CC_i are the additional carbon costs associated with each maintenance scenario. For many maintenance schemes, the carbon cost for the “do nothing” scenario will mostly consist of operational carbon, while the additional carbon associated with each maintenance scenario will consist mostly of the construction carbon. Similar formulae may be developed for other KPIs such as energy use. The second sample formula below may be used to quantify a KPI relating to recycled content of various maintenance schemes.

$$KPI_{RC,i} = \frac{RC_i - RC_{min}}{RC_{max} - RC_{min}} \tag{9}$$

Where RC_i is the recycled content used in each maintenance option, RC_{min} is the minimum allowable recycled content according to NRA specifications and RC_{max} is the maximum recycled content achievable while still providing sufficient structural integrity to provide a sufficiently low failure probability. Quantifying KPIs in this way allows for significant objectivity in the application, and satisfies KPI requirements 1, 2 and 4 in the list above. However, when considering an application of the KPIs, the quantities can be unrelated to each other. For example, the formula for the Carbon Cost KPI shown in Equation 8 is heavily influenced by operational carbon costs, which are often significantly higher than construction carbon costs. Using a similar approach for the Energy Use KPI, for instance, may produce a KPI of a very different value to the Carbon Cost KPI, despite the scenarios being comparable. This lack of stability would result in KPIs which either have no influence on the analysis, or too heavy of an influence. For this reason, the CERCOM consortium propose to quantify KPIs using a ranked interpolation approach.

KPIs by ranked interpolation

The procedure for quantifying KPIs by ranked interpolation is as follows, for each KPI:

1. Determine the number of ranks required to quantify the KPI;
2. Set the minimum rank to a value of 0.0, and the maximum rank to a value of 1.0;
3. Determine the mathematical relationship between each KPI rank;
4. Score the KPI for the scenario being evaluated, and interpolate according to the ranked relationship.

The first step is determining the number of ranks required. The minimum number of ranks is 2. There is no maximum number of ranks per se, but it is not recommended to exceed 5 as the interpolation may become unnecessarily cumbersome with more ranks. This should be sufficient to describe the nature of the KPI and how it impacts the risk. Ideally, the KPI should relate to existing targets and states of the KPI already defined by the overseeing NRA. For example, an NRA with a target to use more recycled content in maintenance schemes may already define different “levels” (ranks) of achievement of this goal. For example, 1 – 20% recycled content, 2 – 40% recycled content, 3 – 60% recycled content, 4 – 80% recycled content. The number of ranks required may also be influenced by the mathematical relationship between the first and last rank, as discussed below.

The first rank should always be assigned a value of 0.0, and the final rank should be assigned 1.0, to keep the KPIs commensurate with each other. In the simplest case, a linear relationship will be assumed between the first and final rank. In this case, only two ranks are necessary, and one can move straight to step 4.

Where a more subtle response is required, a multi-linear or quadratic relationship may be determined between different KPI ranks. The type of model may be developed for example where the benefit of increasing the rank raises the RE & CE, environmental or social value exponentially. In this case, linear interpolation should be carried out between each rank. With reference to Figure 11 an example of how ranks may be structured to reward innovation is outlined as follows:

- Rank 1 = minimum acceptable performance, KPI 0.0;
- Rank 2 = industry norm, established practice but not always applied, KPI 0.15;
- Rank 3 = industry leading performance, uncommon, KPI 0.6;
- Rank 4 = medium term goal, KPI 1.0.

There are certain circumstances where linear interpolation between each rank is insufficient to capture the modelled behaviour (as illustrated in Figure 11). In this case, cubic splines may be used to interpolate the modelled behaviour more accurately.

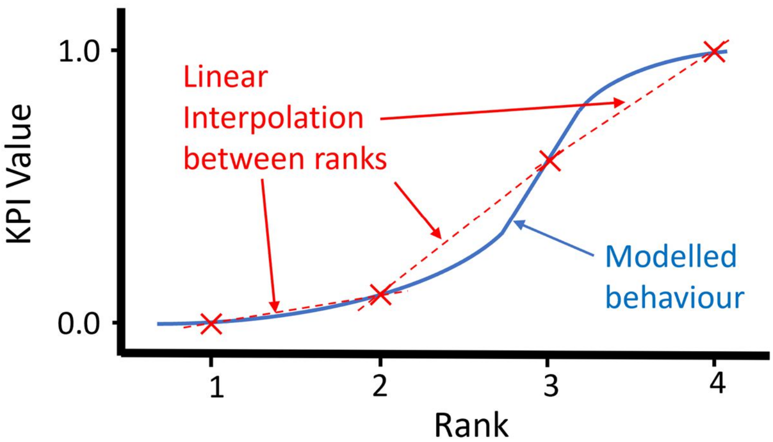

Figure 11: Interpolating KPI values

In the final step the KPI is scored according to the ranking and interpolation system developed.

5.4 Sample Application of Risk-Based Analysis Framework

In order to demonstrate the methodology, this section considers a sample application of a resurfacing scheme for a section of a road network. As well as the "do minimum" scenario, 3 resurfacing options will be considered:

- Scenario 1 - "Do minimum": put in place warning signs etc as necessary to mitigate potential increases in risk as a result of low skid resistance.
- Scenario 2 - Use of standard asphalt surface course with minimum recycled content in line with NRA requirements for surface course. This can be further recycled as a

surface course (at the same value) at the end of its life, or downcycled into binder / base course.
- Scenario 3 - Use of asphalt containing high-recycled content surface course (i.e., beyond that of local specification for a given NRA). Using recycled asphalt in rehabilitation and maintenance operations, enables materials to be reused locally, reducing CO_2 associated with transportation and maximising their value for future reuse.
- Scenario 4 - The use of asphalt containing 10% crushed glass and 20% reclaimed aggregate, jointly replacing 30% of the aggregate within the surface course to realise the potential value of materials from other industries. This reduces the extraction of raw materials and supports the maintenance of materials in use for longer as part of a circular approach.

These simple scenarios are chosen for the purpose of examining the approach of the RBAF to demonstrate its application, stability and robustness. The data used within this analysis is notional and not intended to be representative of the actual values attributable to these maintenance scenarios. It is acknowledged that many other maintenance scenarios may be of interest from a RE&CE perspective. These will be considered within CERCOM WP4.

5.4.1 Step 1 – Establish Context

The road section in question is a 150km section of dual carriageway. A maintenance budget of €20 million is assigned to the resurfacing scheme. The goal of the risk assessment is to evaluate and rank each of the resurfacing schemes listed above in terms of risk, RE & CE, environment and value over multiple lifecycles. It is important to note that in each step of the risk assessment, the “do minimum” case must also be evaluated for comparison. It is recognised that for safety reasons local measures may be put in place to limit the risk such as warning signs etc. However, this cost is likely to be minimal in relation to construction costs, and as such, the cost of the “do minimum” scenario is assumed to be zero for the purpose of this example. It is assumed that the cost of carrying out scenarios 2, 3 and 4 are €8 million, €7.5 million and €8.5 million, respectively.

In order to establish the risk-based approach, the purpose of the interventions must be ascertained in order to understand the risk. For this example, it is assumed that the key purpose of resurfacing is to improve the skid resistance. The scheme is expected to satisfy the minimum codified requirements in terms of skid resistance for a period of 20 years and as such, a 20-year assessment period will be analysed. It is noted that only scenarios that satisfy minimum safety standards outlined by design standards will be considered within the RBAF. The goal is to assess the relative risks associated with adopting the more resource-efficient maintenance scenarios through the application of the developed framework.

A minimum recycled material content of 20% will be assumed for the asphalt for all three scenarios due to minimum requirements of the NRA. 60% recycled material will be utilised for scenario 3, while 30% will be assumed for scenario 4 (consisting of 10% crushed glass and 20% of reclaimed aggregate).

5.4.2 Step 2 - Evaluate likelihoods

The likelihoods in this example refer to the probability of an early failure of the installed materials. Different methodologies / software may be employed in practice to establish these probabilities. For the current analysis, it will be assumed that likelihoods are calculated based on empirical evidence of the skid resistance offered by each asphalt type combined with engineering judgement. The probability of each scenario delivering insufficient skid resistance (P_f) over the 20-year lifespan of the road for each of the resurfacing scenarios is summarised in Table 2 below. It should be noted that these figures were chosen to represent reasonably varying levels of failure probability across maintenance approaches and are not representative of the relative durability / robustness of any of the strategies chosen.

Table 2: Event Probabilities for each Resurfacing Scenario

No.	Name	P_f	Justification
1	Do minimum	1.0	Current data demonstrates insufficient skid resistance and with expected traffic growth this is likely to worsen rather than improve.
2	Standard asphalt	0.1	Provision of standard asphalt provides skid resistance in line with codified norms with low risk of early failure on a dual carriageway section which is mainly straight.
3	Recycled asphalt	0.12	Use of recycled asphalt, based on empirical evidence may show a slightly higher risk of insufficient skid resistance than standard asphalt mixes.
4	Crushed glass	0.2	Use of crushed glass, based on empirical evidence may show a higher risk of insufficient skid resistance due to the polishing that may occur. In addition, increased uncertainty due to limited testing data increases modelled failure probability.

5.4.3 Step 3 - Evaluate Consequences

Consequences must be determined in order to evaluate the risk. In the current example, consequences primarily consist of the costs of emergency resurfacing due to premature breakdown in skid resistance below statutory minimum. Starting from the direct and indirect consequences from the Re-Gen project (as discussed in Section 4.3), the following consequences may be considered:

- Rehabilitation costs, C_{Reb};
- Vehicle detour / running costs, C_{Run};
- Travel time costs, C_{Trav}, based on the average person wage;
- Accident costs, C_{Acc}.

The Re-Gen project provided some guidance on calculation of these costs (Re-Gen, 2016). For the current example, detailed analysis is not provided.

C_{Reb} consists of cost to repair damaged or failed infrastructure. In the current example, it is envisaged that in the event of a breakdown in the surface quality to below the minimum requirement, the road will need to be resurfaced again with a minimum cost equal to €10 million. The cost in this case is higher than the option 2 maintenance scenario as resurfacing would need to be carried out quickly, with minimum planning and with significant disruption to traffic.

C_{Run}, C_{Trav} and C_{Acc} will be assumed to be minimal in comparison with the rehabilitation costs for the current example and will be ignored, leading to a total consequence of €10 million in the event of failure for all scenarios.

The consequences are assumed to be equal for all 4 scenarios (including the "do minimum" scenario). This may not always be the case but is assumed here for simplicity. Additional consequence categories may be included for other assessments such as loss of future business etc.

5.4.4 Step 4 - Establish and quantify additional KPIs

Any number of RE & CE, Environmental and Social related KPIs may be considered in the assessment. For the current assessment, the following RE & CE and environmental KPIs are considered:

- RE & CE KPIs
  - Energy Use (E)
  - Recycled Content (RC)
- Environmental KPIs
  - Carbon Cost (CC)

Energy Use

The Energy Use KPI (KPI_E) for each strategy will be evaluated according to Table 3 below. Intelligent Energy Europe (2010) provided extensive data on energy use from road construction projects. The report suggests evaluating energy use of a road project in terms of construction and operational costs, with construction costs being divided into machinery and embodied material energy use. Intelligent Energy Europe (2010) produced a piece of software called Joulesave which automatically calculates the energy implications of an alignment in terms of the energy required to construct the road and also the energy which would be used on that road over a 20-year lifetime, considering gradient, speed, traffic characteristics etc. This was evaluated and benchmarked against a number of past construction projects. Based on the data available, the construction energy use of a dual carriageways vary from 5.6-12.6 TJ/km, while the operational costs vary from 71-1291 TJ/km over 20 years. To produce a meaningful KPI, operational costs will be ignored for the energy use KPI. A fully linear relationship between the maximum and minimum rank will be assumed. However, a middle value of 2 is provided here to highlight that a linear relationship is assumed.

Table 3: Energy Use KPI Scoring System

Rank	KPI_E	Description
1	0	Construction energy use of over 13.0 TJ/km
2	0.5	Construction energy use of 9 TJ/km
3	1.0	Construction energy use of 5.0 TJ/km

For maintenance scenario 2, the construction costs will be assumed to be equal to 10 TJ/km which is equal to 1,500 TJ for the 150 km dual carriageway. For scenario 3, the construction material energy will be lower due to the lack of production and treating of raw material. This may be evaluated based on empirical data but for the purpose of this study, 1,200 TJ will be assumed for scenario 3. Finally, for scenario 4, an intermediate case of 1,400 TJ will be assumed. This yields a value of KPI_E equal to 0.375, 0.625 and 0.45 for scenarios 2, 3 and 4.

Recycled Content

The KPI associated with recycled content in the material use (KPI_{RC}) will be evaluated according to Table 4. Again, a linear relationship is assumed between the maximum and minimum rank, with the maximum rank of 100% recycled material being a theoretical boundary on the system.

Table 4: Recycled Content KPI Scoring System

Rank	KPI_{RV}	Description
1	0.0	0% recycled content in construction materials
2	0.5	50% recycled content in construction materials
3	1.0	100% recycled content in construction materials

A recycled content of 20%, 60% and 30% will be assumed for scenario 2, 3 and 4 yielding values of KPI_{RC} of 0.2, 0.6 and 0.3 for maintenance options 2, 3 and 4 respectively. Scenario 4 assumes 30% recycled content based on use of 10% recycled crushed glass and 20% reclaimed aggregate.

Carbon Cost

The Carbon Cost KPI (KPI_{CC}) for each strategy will be evaluated according to the scoring system in Table 5 below. The scoring system has been developed with consideration of construction carbon only, and does not consider the operational carbon associated with each strategy. This is due to the fact that the differences in operational carbon associated with each strategy will be negligible. The scoring system for this indicator may be modified to consider operational carbon where this is warranted due to significant savings in one scheme over another. The minimum rank of 1 (constituting a value of KPI_{CC} of 0.0) represents a construction cost of over 100 tCO_2e/km. Based on published research (Espinoza et al., 2019), it is considered unlikely that the construction carbon costs will exceed this value. Similarly, the maximum rank of 3 is assigned to a construction cost of under 25 tCO_2e/km.

Table 5: Carbon Cost KPI Scoring System (construction carbon only)

Rank	KPI_{CC}	Description
1	0.0	Construction carbon cost of over 100 tCO_2e / km
2	0.5	Construction carbon cost of 62.5 tCO_2e / km
3	1.0	Construction carbon cost of under 25 tCO_2e / km

It should be noted that advanced methodologies and bespoke software can be used to determine construction and operational carbon costs. Espinoza et al. (2019) provided carbon costs for road construction. Based on the information provided, a construction carbon cost of 8,000 tCO_2e (53 tCO_2e / km) will be assumed for scenario 2 in this study. Modest carbon savings associated with scenarios 3 and 4 are assumed since the locally available materials will reduce transport requirements. However, much of the construction carbon is associated with on-site machinery and labour which is the same for all the maintenance scenarios. 7,000 tCO2e will be assumed for scenario 3, equating to 47 tCO2e / km. 7,700 tCO_2e will be assumed for scenario 4, equating to 51 tCO_2e / km. These figures yield values of KPI_{CC} of 0.62, 0.71 and 0.65 for scenarios 2, 3 and 4 respectively.

5.4.5 Step 5 – Optimize

The final step in the framework is optimization, which involves calculation of the risk, costs and finally the weighted sum of all KPIs to calculate the *NRRG*.

Risk Reduction Index (RRI)

The RRIs for each scenario form one of the KPIs used to calculate the $NRRG$. Table 6 summarises the calculation of the risk and *RRI* for each scenario. This part of the framework allows NRAs to quantify and compare the risks associated with moving from a linear to a more circular economy.

Table 6: Risk Calculation for each scenario

No.	Name	P_f	Consequence	Risk	RRI
1	Do minimum	1.0	€10,000,000	€10,000,000	0
2	Standard asphalt	0.1	€10,000,000	€1,000,000	0.9
3	Recycled asphalt	0.12	€10,000,000	€1,200,000	0.88
4	Crushed glass	0.2	€10,000,000	€2,000,000	0.80

Cost

A simplified approach for cost is considered in this example. A more detailed approach considering multi-Life Cycle Analysis will be presented as part of CERCOM Deliverable 3.2. For this sample application, it is assumed that the cost of carrying out scenarios 2, 3 and 4 are €8 million, €7.5 million and €8.5 million, respectively. These costs are used to calculate *CPI* for each scenario, yielding values of 0.6, 0.63 and 0.58 for scenarios 2, 3 and 4.

In the full multi-Life Cycle Analysis, the value ascribed to the reuse of materials in successive lifecycles will be appropriately captured. Since this is lacking in this simplified treatment, an additional cost KPI for residual value is established. The Residual Value KPI (KPI_{RV}) will be assigned for each scenario based on a scoring system as shown in Table 7 in which each maintenance scenario is assessed based on the ability to re-use materials at the end of the 20-year lifecycle. This type of scoring system rewards the potential to re-use material which enhances the value at the end of the assessment period.

The maximum rank of 5 relates to a theoretical and currently unattainable level of residual value. This is advised in order to bound the problem within the confines of the other KPIs. KPIs may also be set in terms of the actual value of the asset at the end of the assessment period. This value can combine direct economic value in terms of reuse but may also include indirect value in terms of economic value of embodied carbon etc. This information may also be included within the *CPI* if sufficient data is available. Based on the system proposed in Table 7 scenario 2 is assigned to rank 3 (KPI_{RV} = 0.5), assuming that materials are fit for re-use with extensive processing required. Scenario 3 will be similar to scenario 2, but will require slightly more processing for reuse. As such, a value of KPI_{RV} = 0.45 will be assumed. Scenario 4 achieves a KPI_{RV} = 0.25, assuming that crushed glass will limit the options available for subsequent reuse in surface course material.

Table 7: Residual Value KPI Scoring System

Rank	KPI_{RV}	Description
1	0.0	Zero residual value or negative value associated with disposal etc
2	0.25	Positive value with re-usable materials (downcycling after processing)
3	0.5	Positive value with re-usable materials (maintains value at the same level but with extensive processing required)
4	0.75	Positive value with re-usable materials (maintains value at the same level with minimal processing)
5	1.0	Positive value at a higher level of application (with minimal processing)

Net Risk Reduction Gain (NRRG)

The final step in the analysis is the calculation of the $NRRG$ for each scenario to select the most advantageous solution. More detailed studies may use optimization techniques where various combinations of interventions are possible resulting in a large number of outcomes. For the current example, the $NRRG$ is calculated for each scenario. The scenario with the highest $NRRG$ is then selected as the most advantageous.

Table 8: NRRG Calculation

KPI		Scenario 2	Scenario 3	Scenario 4	KPI Weight
Risk Reduction Index		0.90	0.88	0.80	0.3
Cost	- Cost Potential Index	0.60	0.63	0.58	0.14
	- Residual Value	0.50	0.45	0.25	0.14
RE	- Energy Use	0.38	0.63	0.45	0.14
	- Recycled content	0.20	0.60	0.30	0.14
Environment	- Carbon Cost	0.62	0.71	0.65	0.14
Weighted Sum = NRRG:		**0.59**	**0.69**	**0.55**	1.00

Table 8 summarises the KPIs, weights and calculation of $NRRG$ for each scenario. Weights should be assigned to each KPI by the NRA according to priorities. For the current example, it is assumed that the NRA assigns almost twice as much importance to risk as each other KPI. The results show that scenario 3 is the most advantageous maintenance scenario. Additional sensitivities and scenarios will be discussed below.

"Do minimum" Scenario

The "do minimum" scenario is not considered in Table 8 as the associated failure probability makes it unrealistic in practice. However, it can be useful to present the findings of this case for reference against the different construction or maintenance options available. As discussed in Section 5.4.2, the probability of failure for the "do minimum" scenario is taken as 1.0 for a 20-year reference period, resulting in a *RRI* of 0, as no risk reduction has taken place. It is assumed that there is no cost associated with maintenance and *CPI* is assigned the maximum value of 1.0. In terms of the additional KPIs, values may also be assigned. For the purpose of this case study, the KPI_{CC} of 1.0 is appropriate for construction carbon cost under 25 tCO_2e / km. Similarly, since no construction work occurs for the "do minimum" scenario, KPI_E is assigned a value of 1.0 for construction energy use less than 5.0 TJ/km. There is zero recycled content used in construction or maintenance materials in this scenario and as such, KPI_{RC} is taken as 0. The Residual value associated with this option will be assumed to be equal to that of scenario 2 (KPI_{RV} = 0.5). Using these KPIs for the "do minimum" scenario and the weightings outlined in Table 8, the $NRRG$ is calculated as 0.49. This provides a reference value for comparison of proposed feasible scenarios. It is also acknowledged that the "do minimum" scenario may be the only possible option in some cases due to budget constraints.

KPI Weight

The weighting factors provide NRAs with a useful method to rank priorities when evaluating tender bids as part of the procurement process. This may also be a useful way for NRAs to tailor the RBAF to suit maturity, depending on the level of confidence in the calculated or assigned KPIs. However, it is acknowledged that the weights can have a significant impact on the outcomes of a risk-based analysis. A sensitivity study was carried out considering four combinations of KPI weights to highlight how these weights can impact the calculation of $NRRG$

and the optimization of maintenance scenarios, as well as to demonstrate the capabilities of the developed framework. Table 9 provides a breakdown of the weights assigned to each KPI for the purpose of this study.

Table 9: KPI Weights considered in sensitivity analysis

KPI	Weight A	Weight B	Weight C	Weight D
Risk Reduction Index	0.30	0.70	0.30	0.30
Cost - Cost Potential Index	0.14	0.30	0.30	0.30
- Residual Value	0.14	0.00	0.10	0.05
RE - Energy Use	0.14	0.00	0.10	0.05
- Recycled content	0.14	0.00	0.10	0.25
Environment - Carbon Cost	0.14	0.00	0.10	0.05
Sum:	1.00	1.00	1.00	1.00

For weight option A, the values from the case study outlined above are taken for reference. In construction, a typical procurement evaluation process tends to use weights for quality/technical and cost of approximately 0.7 and 0.3 respectively. Although sustainability aspects may be considered within the score for quality/technical, specific KPIs are not assigned to account for CE & RE or environmental factors. This scenario is represented in weight option B. To progress this to account for CE & RE and environmental KPIs in weight option C, the *CPI* weight remains at 0.3, but the *RRI* weight is reduced to 0.3, with a weight of 0.1 assigned for each additional KPI. In some cases, NRAs may have more confidence in the determination of certain KPIs related to CE & RE and wish to assign a higher weight to associated KPIs. Weight option D considers this as an example, placing a higher weight on the Residual Value KPI. The results of the analysis are presented in Figure 12.

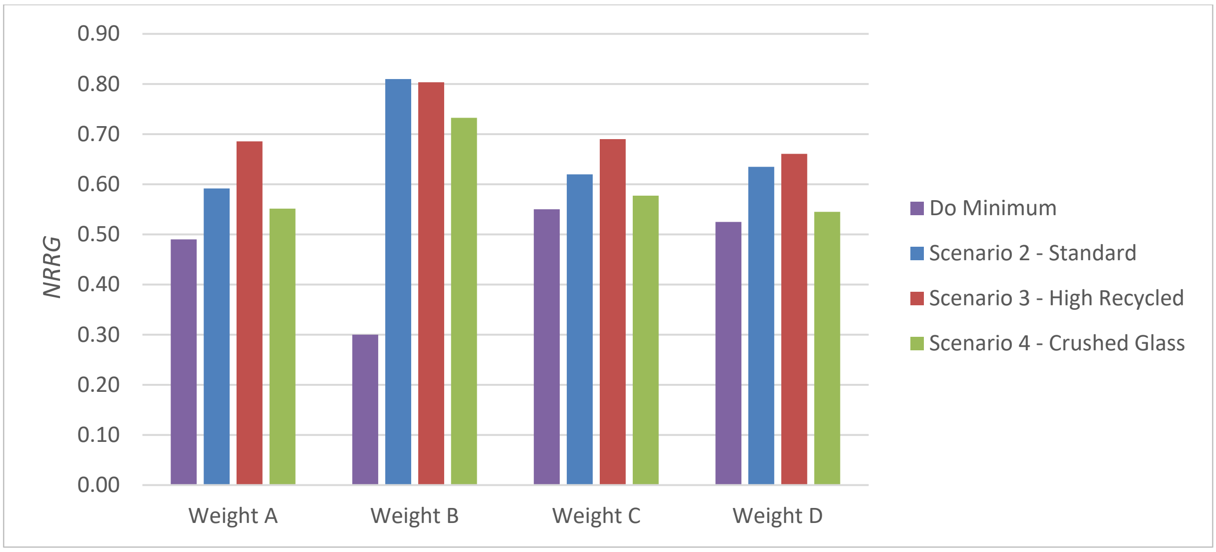

Figure 12: Effect of Weights on $NRRG$

It is clear from the results of this study that the weight assigned to each KPI can have a significant impact on the optimization stage of the RBAF. For weight option B, which is similar to a traditional evaluation, scenario 2 following a traditional maintenance solution emerges as the optimum solution. For weight option A, C and D where additional environmental and RE & CE KPIs are considered, scenario 3 (high recycled content) becomes optimal.

It is not surprising, but important to highlight, that the relative weight assigned to the various KPIs can influence the choice of construction or maintenance scenario, within the more circular options proposed. For illustration purposes, **Figure 13**, provides a breakdown of the weighted KPIs for scenario 4 for each weight option.

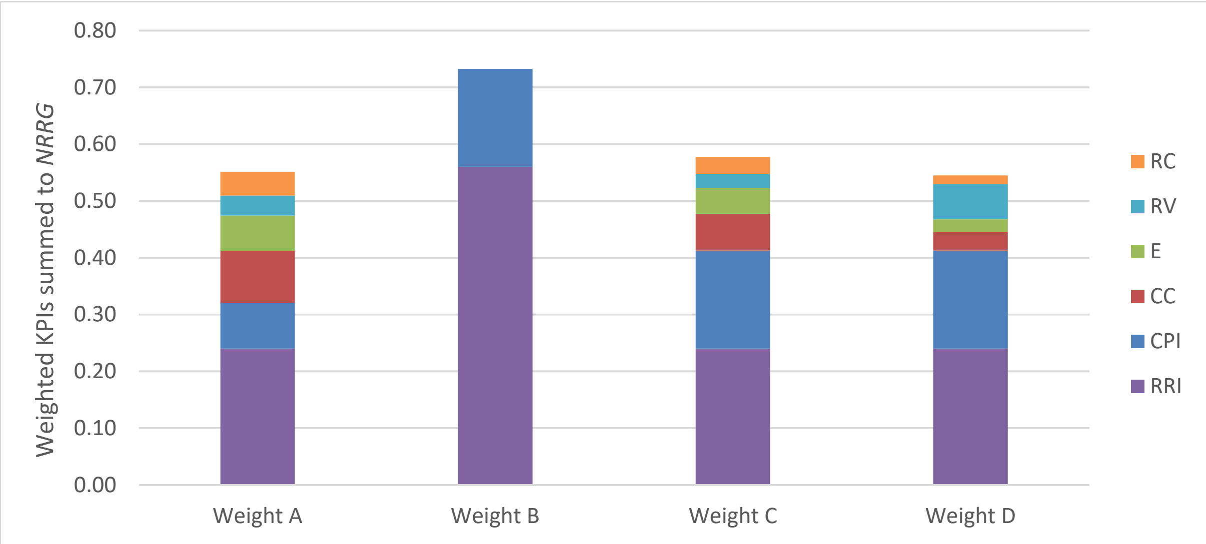

Figure 13: Effect of weights on Scenario 4 – KPIs and $NRRG$

Sensitivity

By performing sensitivity analysis, it is possible to see how the various input paraments can influence the results of the optimization process as well as to demonstrate the robustness of the developed process. This is useful for NRAs to gain insight into the sensitivity of the model and the implications of changing parameters or assumptions. Similar to the weights assigned to KPIs, it is important to have an indication of how the optimal construction or maintenance strategy can be affected by changes to the input parameters. Maintenance scenario 4 is selected for the purpose of this analysis. The sensitivity of the results of the RBAF to changes in the input values for probability of collision, construction cost, and KPI_{RV} are assessed.

Figure 14 indicates the sensitivity of *NRRG* to the probability of failure for Scenario 4. For crushed glass, there is less data supporting the effect of skid resistance over the 20-year lifespan of the road compared to traditional methods. On this basis, it is useful to vary the probability of collision between reasonable bounds to determine the effect of uncertainty on the optimal maintenance scenario. As discussed in Section 5.4.2, for the case study considered the probability of failure was assumed to be 0.2 for Scenario 4. Keeping all other inputs constant, varying the probability of failure for Scenario 4 demonstrates that the analysis is quite sensitive to failure probability for this particular example. The NRRG varies between being equal to that of scenario 2 and the “do minimum” option, when varying the failure probability from 0.1 to 0.4, as shown in Figure 14. It is noted that assigning a higher weight to performance (*RRI*) would increase this sensitivity.

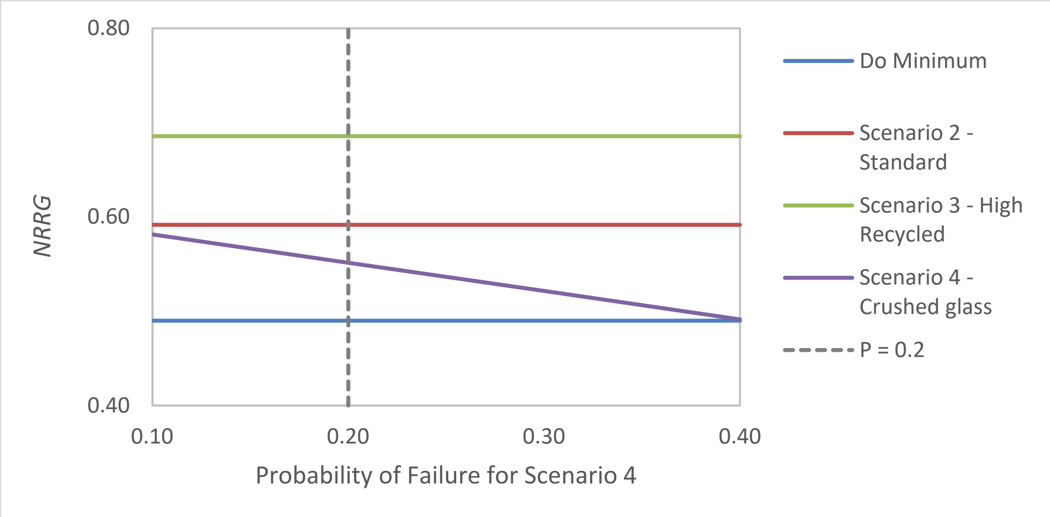

Figure 14: Sensitivity of $NRRG$ to P_f for Scenario 4

Similarly, the sensitivity to the construction cost of scenario 4 was investigated. As discussed in Section 5.4.1, the cost of carrying out maintenance scenario 4 was assumed to be €8.5 million. This cost was varied between €8 million and €14 million. The results show that while the analysis is reasonably sensitive to CPI, the variation in this figure does not change the ranking of maintenance scenario 4, as illustrated in Figure 15.

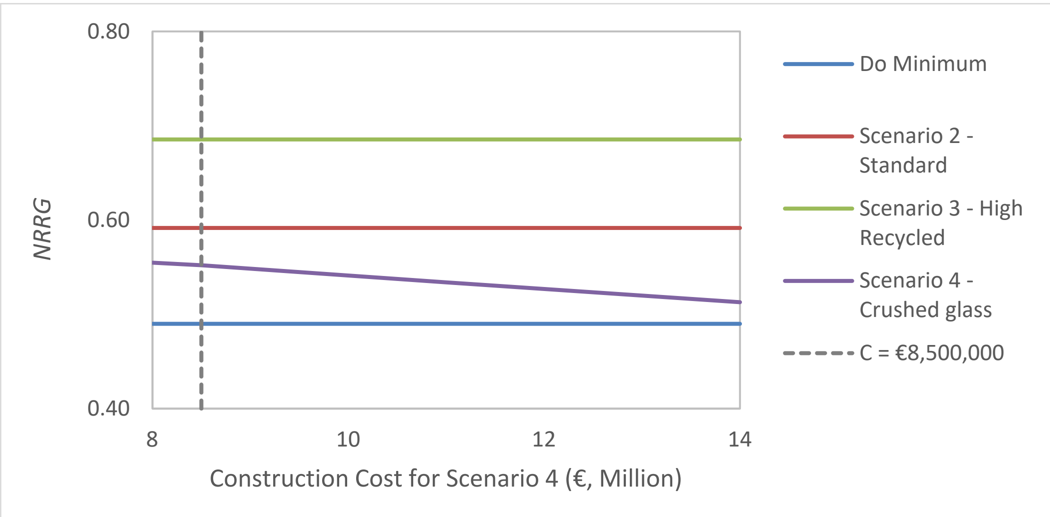

Figure 15: Sensitivity of $NRRG$ to Construction Cost for Scenario 4

In terms of circularity, understanding the sensitivity of the study to additional resource efficiency or KPIs indicative of multi-LCA will be of significant importance. Taking KPI_{RV} as an example, Figure 16 highlights the impact of the assumed rank for scenario 4 on the overall analysis of the RBAF. In the sample application of the analysis, rank 3 with a KPI_{RV} value of 0.25 was considered, assuming that the recycled glass scenario limits options for multiple use across various lifecycles. The sensitivity study indicates that if a higher level of residual value could be demonstrated for the end of life of scenario 4, it may be ranked higher than scenario 2 – standard asphalt.

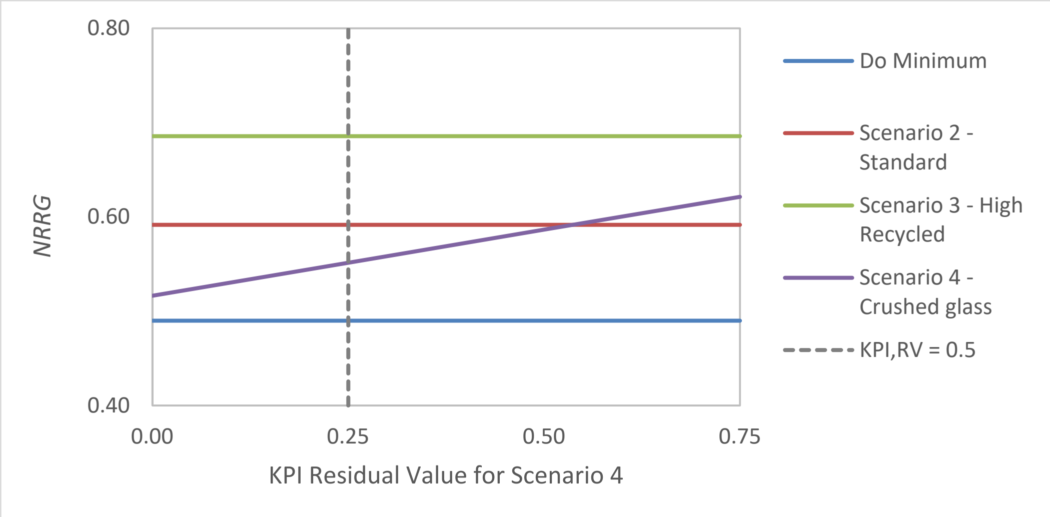

Figure 16: Sensitivity of $NRRG$ to KPI_{RV} for Scenario 4

The sensitivity studies carried out indicate the robustness of the analysis and provide confidence in the basis for the risk-based analysis framework. The ranked interpolation method to quantify KPIs provides a robust and stable means of integrating quantitative measures of RE & CE into the analysis for the evaluation of construction and maintenance scenarios in procurement. This results in an intuitive user-friendly framework for NRAs, providing trust and confidence in output results.

<u>Evolution of failure probability</u>

Over the design life of a pavement, the probability of loss of skid resistance may increase as the condition of the pavement deteriorates. In this example, three possible maintenance options are compared, as well as the "do minimum" option. To demonstrate the capabilities of the RBAF, the evolution of the probability of failure was assumed for each maintenance scenario, consistent with the values discussed in Table 6, and is illustrated in Figure 17.

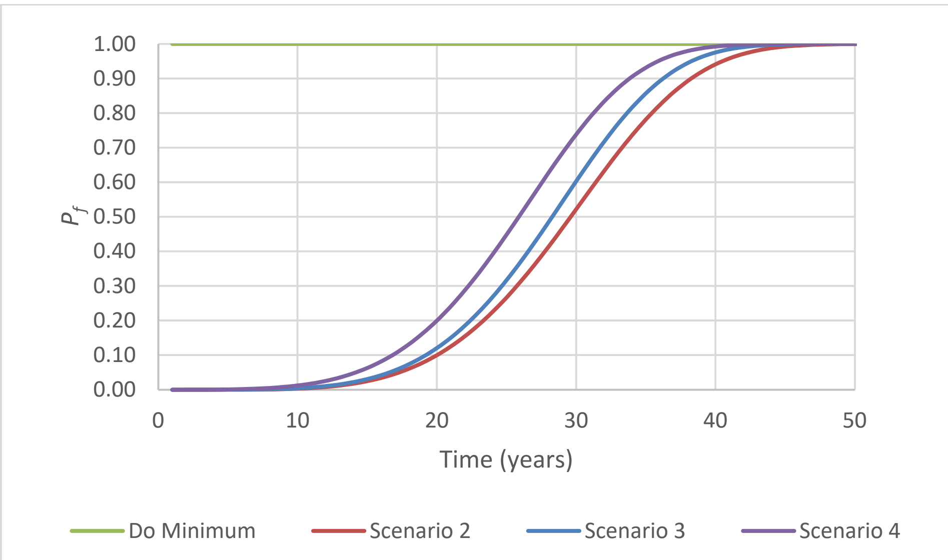

Figure 17. Evolution of probability of failure over time

The initial analysis examined a lifespan of 20 years. The evolution of *NRRG* between 10 and 30 years is illustrated in Figure 18. In this case study, maintenance scenario 3 remains the optimal option over the timescale considered, although the relative difference between the options reduces over time. Depending on the different options being considered and the evolution of probability of failure for each option over time, this framework provides NRAs with the ability to explore and optimize these possible maintenance scenarios at different points in the design life of the infrastructural element.

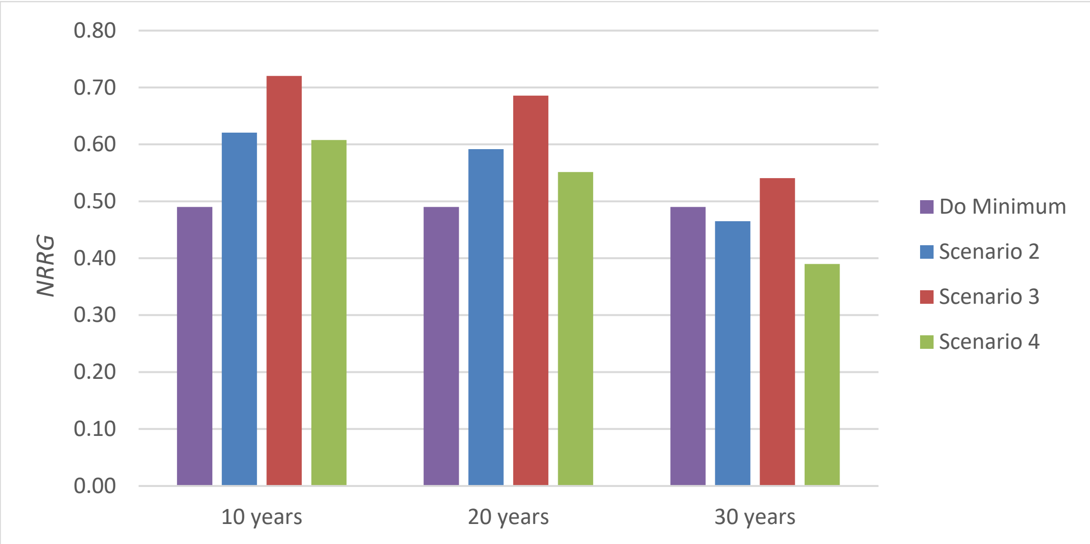

Figure 18. Evolution of NRRG for 10, 20 and 30 year lifespan

6 Roadmap to implementation

6.1 Introduction

This section outlines the roadmap to implementation of the CERCOM Risk Based Analysis Framework (RBAF) within the procurement of maintenance and construction schemes by NRAs. In this context, it is first investigated how risk is currently considered within procurement practices in NRAs, as well as EU guidance for procurement when projects are above EU thresholds. Following this, the roadmap detailing the integration of the RBAF into current procurement practice is outlined.

6.2 Current practice of NRAs in RA for procurement

The CERCOM team engaged with a number of CEDR NRAs to assess if and how risk is incorporated within procurement for maintenance and construction schemes. The purpose was to gain an understanding of the procurement process, particularly the consideration of risk. This allowed for seamless integration of the RBAF into the current procurement process without duplicating risks or contradicting current practices.

An in-depth meeting with the head of procurement in Transport Infrastructure Ireland (TII) provided valuable insight into the procurement life cycle process and how contract managers liaise with the central procurement team. There are many areas in the procurement process where risk is identified and managed. Internal TII Corporate Procurement Guidelines are followed to manage the risk and ensure a robust, auditable procurement process. This incorporates procedures documented in the National Transport Authority (NTA) *Guidelines for the Management of Public Transport Investment Projects*. It was highlighted that many of the national guidance documents that are used for the procurement process are based on strategies outlined in the European Commission's *Public Procurement Guidance for Practitioners*.

In Ireland, at present there is no formal consideration of CE & RE within the procurement process. Consideration is given to sustainability, energy efficiency and green procurement in generating the specification for tender documents. Currently, in some schemes environmental questions are posed in the tender documents, this is quite open ended and not specifically weighted as part of the tender evaluation process. A review is carried out on a pass/fail basis in terms of broad scope sustainability. In certain projects, the specification includes environmental factors to be considered as part of the contract (e.g., percentage of recycled goods, how and when they can be used). As part of the tender evaluation process, a weight of up to 10% can be assigned for environmental factors. Where specific environmental aspects are required as part of a contract, market consultation can be a useful stage of the design and procurement process to determine feasible options available on the market before publishing a tender. This allows for the addition of more specific achievable targets within the tender criteria to reduce the risk of any future legal challenges that may arise as part of the tender evaluation process.

Following discussions with CEDR NRAs, it was concluded that a risk register specifically related to the procurement process (rather than the complete scheme) is only completed for complex procurement procedures or if adverse consequences from the tender process may affect the operation or core services of the public body. It is created in the early stages and updated throughout the procurement life cycle. The risks generally considered are related to supply chain failure, aborted procurement processes, legal challenges in relation to the procurement procedure and the impact this may have on the organisation. They are independent of risks considered as part of the RBAF. This allows the flexibility to integrate the RBAF within in the procurement process to enhance the existing processes and policies without contradicting procurement practices that are already in place.

6.3 European Guidelines for Public Procurement

Figure 19 illustrates the life cycle of a typical procurement process as outlined in the Office of Government Procurement (OGP) Public Procurement Guidelines for Goods and Services. The figure is referenced from the European Court of Auditors and is in line with the European Commission's Public Procurement Guidance for Practitioners. The purpose of the guideline is to promote best practice and consistency in the application of public procurement. The purpose of this section is to provide a brief outline of these procurement procedures which are discussed further within the context of CERCOM in Section 6.4, where the integration of RBAF into procurement processes is outlined.

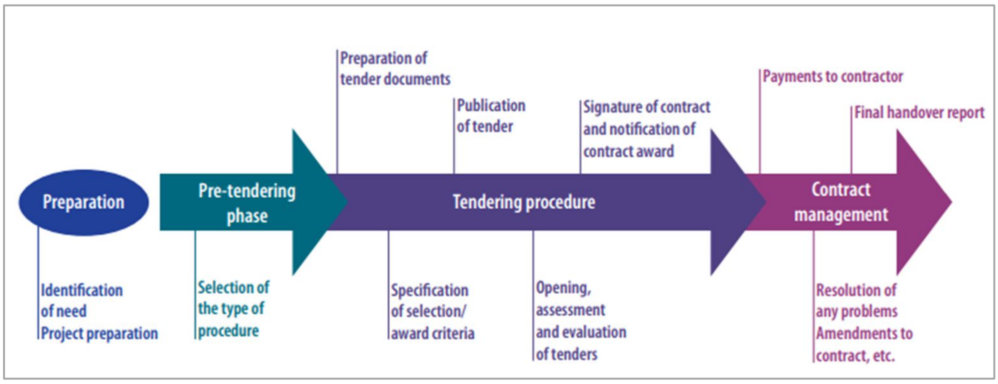

Figure 19 – Main phases in public procurement procedures (Office of Government Procurement, 2018)

The preliminary stage involves the preparation of a business case for the proposed scheme. The Pre-tendering phase can include a preliminary market consultation stage whereby the contracting authority may consult with leading suppliers in the market before beginning the tendering process. This facilitates the generation of improved specifications, reflecting the materials, methods and technologies available on the market. The capacity of the market to deliver works according to the requirements of the contracting authority and the risks involved can also be assessed. This aspect of the pre-tendering phase may encourage suppliers and tenderers use more innovative methods and materials if highlighted by contracting authorities at this early stage of the procurement process. It also has the potential to reduce procurement timescales and possibly remove the need for more costly formal processes, such as Competitive Dialogue, within the formal tendering procedures. In the next stage, the Tendering Procedure followed depends on whether national or EU rules apply. The threshold of works for public contracts by central government authorities is greater than €5.3 million. For a tendering procedure above EU thresholds, there are 6 forms of tendering procedures contracting authorities may use, as illustrated in Figure 20.

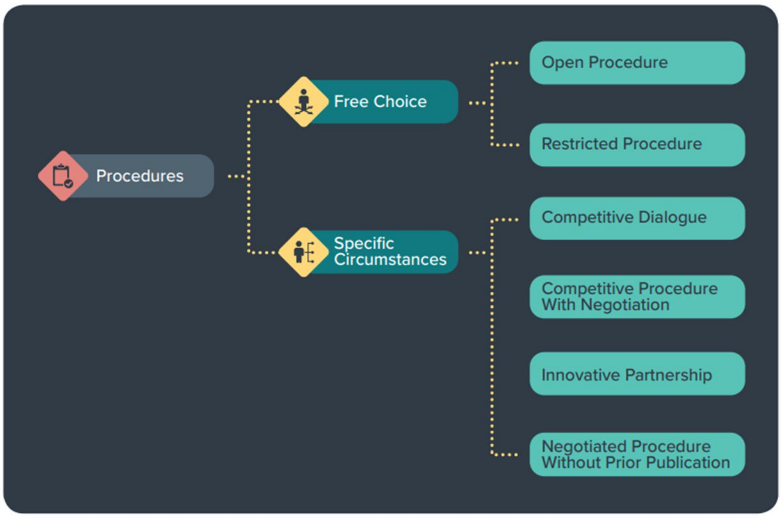

Figure 20 - 6 Award procedures for Public Contracts above EU thresholds (Office of Government Procurement, 2018)

These procedures are discussed briefly to outline the aspects of each, and which are most relevant to NRAs for the construction and maintenance of transport infrastructure. With the Open Procedure there is unlimited competition. It is the least complex and most common tendering procedure followed. The Restricted Procedure is a two stage process involving pre-qualification of suppliers. This is used to reduce tenders where the potential number of suppliers is very large or where the contracting authority wants to limit access to sensitive information. The Competitive Dialogue Procedure and the Competitive Procedure With Negotiation may be used, for example, when the contract includes design or innovative solutions or if a technical specification cannot be established with sufficient precision. They tend to be used for high value projects such as major transport infrastructure works and are therefore relevant within the CERCOM project. The Innovative Partnership and Negotiated Procedure Without Prior Publication are only utilised in very narrowly defined circumstances, and not considered appropriate for the scope of works in this framework.

For the evaluation of tenders, the criteria for assessment depends on the nature and complexity of the project and the tendering procedure. The assessment can be based on pass/fail criteria or a more complex numerical scoring methodology to rank tenderers. The contract should be awarded to the Most Economically Advantageous Tender (MEAT), taking into account one of the following approaches:

- Price only,
- cost effectiveness (e.g., life cycle costing), or
- best price/quality ratio taking account of qualitative social aspects.

The cost effectiveness approach allows for the consideration of the operational costs, end of life related costs and environmental costs, as well as the direct cost of works. For example, in the Netherlands, “DuboCalc” is a life-cycle analysis (LCA) based tool which calculates the sustainability value of a specific design based on the materials to be used. Bidders use DuboCalc to compare different design options for their submissions. The DuboCalc score of the preferred design is submitted with the tender price.

The criteria used to rank tenders must be clearly outlined in the tender documents. For the Competitive Dialogue procedure, the best price quality/ratio must be used. When this approach is applied, the award criteria and weighting must be included in the procurement documents by providing a scoring matrix or a clear evaluation procedure.

Following the selection of a successful tenderer, the Contract Award Notice is published by the contracting authority. The Contract Management phase of the procurement process begins to ensure adequate implementation of the works. The proposed methods to incorporate the RBAF into procurement procedures are discussed in the next section.

6.4 Implementation of RBAF within public procurement process

For CERCOM, the objective is to incorporate the RBAF into existing public procurement processes to introduce the quantification of RE & CE KPIs in the consideration of construction and maintenance strategies and life cycle analysis. It is proposed that the RBAF tool is primarily utilised by the NRAs as part of the preparation phase and the pre-tendering phase as an iterative process, as illustrated in Figure 21.

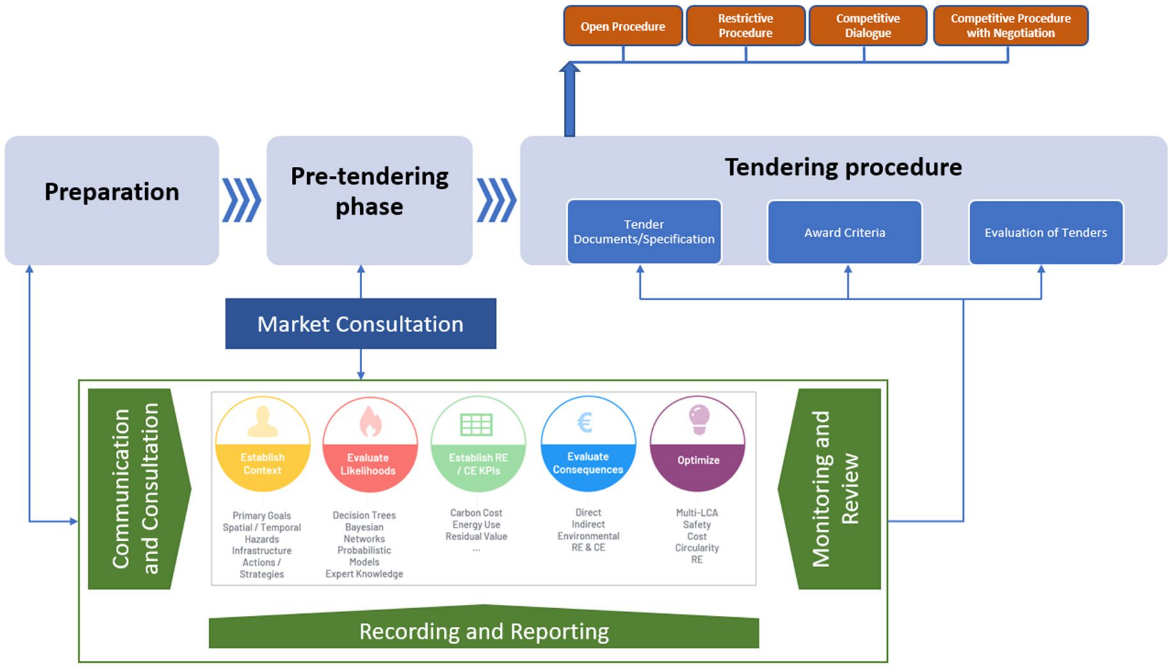

Figure 21 – Integration of CERCOM RBAF into Existing Procurement Practices

This gives the most flexibility for the incorporation of novel approaches early on in the procurement process, for example, by the development and incorporation of functional specifications to encourage circularity within construction and maintenance schemes. Functional specifications provide tenderers scope to suggest innovative solutions or materials, while also achieving minimum required technical performance. The novel and fundamental aspect of this framework is the ability to account for and quantify the risk associated with the various construction and maintenance scenarios available. This will provide the NRAs with a valuable tool in the initial stages of the procurement process to evaluate these risks and prioritise based on the objectives of the organisation and the scheme under consideration.

Initially, the framework can be used in early procurement preparation as a tool for NRAs to establish a baseline and set appropriate targets or goals before engaging in the pre-tendering phase. Allowing for a collaborative approach from the beginning, as part of the pre-tendering phase, conversations with market stakeholders may be insightful to gain knowledge of materials/methods/processes available on the market to aid the development of specifications to produce better outcomes and reduce time scales. As part of this process, the NRA can continually update and vary the input variables to the RBAF to assess different viable options. Following this analysis, the next stage in the procurement process is to translate information and experience gained into specific requirements and competition parameters. As part of this process, the RBAF will provide vital information for the generation of the specifications, selection/award criteria and the evaluation of tenders. Regardless of whether National or European rules are appropriate, the criteria for the assessment of tenders must be outlined within published tender documents. In this regard, any weights, KPIs, scoring matrix or evaluation metrics must be assessed and agreed on before publication of the tender. As such, the RBAF is most effective when utilised early on in the procurement process to allow for CE & RE factors to be considered and incorporated into the preparation of tender documents, specification of award criteria and in the evaluation of tenders, as illustrated in Figure 21.

As discussed in Sections 3 and 5.2, and illustrated in Figure 21, in accordance with ISO 31000 Risk Management Guidelines, Communication and Consultation, Monitoring and Review and Recording and Reporting will occur throughout procurement. The form and extent of engagement within each of these areas will be organisation and scheme dependent. Communication and Consultation is an integral part of the process as consultation and feedback from stakeholders can inform decision making, particularly in the early stages of the process. This allows for the discussion around inclusion of more circular innovative materials/methods and associated risks to be assessed within the framework. Monitoring and Review is planned in the initial stages and carried out at various stages throughout the process. This allows for refinement of the associated risk when/if more data/information becomes available. This may even occur at the end of the process to inform future decision making. Recording and Reporting is vital throughout the RBAF and procurement. The recording of information used in the calculation of risk, costs and KPIs used in the framework must be recorded and documented. Recording and reporting throughout the process should use appropriate measures depending on the function or use of the document. For example, a specific format will be required for the publication of tender documents/specification and award criteria.

6.5 Flexibility for different maturities / fostering change

The RBAF has varying levels of functionality and complexity to allow for the maturity of NRAs. There are specific key aspects within the framework where the level of maturity will impact the use and scope of the framework. Maturity levels of NRAs take account of many aspects and stages, and will be discussed in detail in CERCOM Deliverable 2.1. The aim of this RBAF is to allow NRAs to decide on the level and scope of analysis they wish to complete and provide a tool to do so taking account of the maturity level, as well as the scale and nature of the project.

Depending on maturity and the nature of the scheme, the RBAF may be used at one or multiple stages of the procurement process, as a single step or iteratively when refining the specifics of the scheme.

- Initial planning and preparation – NRAs can use the RBAF to identify the outcomes of possible construction and maintenance scenarios, assigning weight to particular RE & CE factors. This can be used to aid decision making when outlining the scope of the scheme.
- In the pre-tendering phase - the RBAF can be used to analyse different technologies or methodologies arising from conversations with market stakeholders.
- In the pre-tendering phase – when the scope of the scheme has been refined, the RBAF can be used to determine the sensitivity to KPIs and refine the weights to be assigned.
- As part of the formal tendering procedure - The results and metrics from the RBAF may be used in the development of functional and technical specifications, translating information and experience into specific requirements and award criteria. The criteria will need to be outlined clearly in the tender documents if used during the assessment and ranking of tenders.
- Multi-LCA – Multi-LCA will be developed and adopted within the RBAF as part of CERCOM Deliverable 3.2. For lower maturity, using a more simplistic approach, NRAs have the capability within the RBAF to include additional cost KPIs such as “Residual Value” to account for circularity.

The level of implementation of the RBAF at each stage in procurement will depend on the maturity of NRAs, staff training and awareness within different areas of the organisation, data and expertise available to develop or quantify KPIs.

Within the RBAF analysis interface, there are several areas providing flexibility to account for the maturity of the NRAs, as outlined below.

- KPIs – The number of KPIs and type of KPIs can be varied and altered for each scheme. For example, NRAs with low maturity may choose to include just a couple of RE & CE KPIs initially, based on methods or materials which are more commonly used in infrastructure. Values used to rank KPIs may be based on experience of personnel and empirical evidence. NRAs of more advanced maturity have the ability to include many KPIs with more advanced methods to determine the KPI values. This gives flexibility to include more innovative approaches to RE & CE.

- Weights – weights can be used by NRAs to prioritise specific elements of RE & CE that are appropriate for their organisation or the scheme under consideration, while still considering a range of other RE & CE KPIs that can be used to assess and rank various options available. For example, NRAs with lower maturity can choose to use lower weights for RE & CE KPIs, where there is less confidence or experience of the proposed option. NRAs with higher maturity across different areas have the capability to assign higher weights to different aspects of the analysis and the tender evaluation process.

- Probability of failure – in the calculation of the Risk Reduction Index (RRI), the probability of failure of each scenario considered is calculated and used in the optimization of the construction or maintenance scenarios. Depending on the data and experience associated with different options and the maturity of the NRA, the methods used to determine the probability of failure can be empirical or more complex. For lower maturity, the probability of failure may be based on empirical evidence and expert judgement. Whereas, for higher maturities, where there is more knowledge and data of RE & CE within the organisation, more complex probabilistic methods may be used to evaluate the probabilities associated with different scheme options. The strength of the approach is grounded within the probabilistic assessment process. Lack of data associated with new and innovative circular materials does not impact the robustness of the quantitative approach, as this impacts the uncertainty and in turn the failure probability, as outlined in section 5.2.2.

This RBAF achieves the objective to provide the NRAs with a user-friendly tool that can be used in procurement of maintenance and construction schemes and adapted to suit the maturity level of the NRA. It aims to support innovative use of new materials and methods to promote CE & RE while effectively managing associated risks.

7 Conclusion

At present, the maturity of many NRAs is on the lower level of the maturity matrix (discussed in detail in Deliverable 2.1), however, it is inevitable that this will increase in many aspects over time. As such, it was imperative that the developed RBAF provides sufficient flexibility to allow NRAs to decide on the level of engagement and is suitable for use within current practice as well as in the future. Within the developed framework, the functionality and capabilities can be adapted to suit the maturity of NRAs at any given time and can also be tailored to suit the scope and type of scheme under consideration. On this basis, the RBAF will prove to be a valuable tool in the move towards a circular approach to procurement in the construction and maintenance of road infrastructure.

The objective was to generate a user-friendly, intuitive framework that can be easily integrated into current procurement procedures to be used by NRAs with low maturity and also provide increased functionality for NRAs with higher maturity and provide scope for enhanced capability over time as maturity evolves over the coming years. As more data becomes available in terms of new materials and approaches, more advanced methods can be utilised to generate CE & RE KPIs. Engagement with stakeholders through the procurement process will encourage this knowledge gain and the move towards more innovative circular approaches.

In summary, the framework is constructed in such a way as to allow NRAs on different stages of the journey towards circularity to progress over time, building on successful strategies and engaging with more circular approaches.

The framework will be formalised in an Excel based prototype software tool as part of CERCOM Deliverable D3.2, which will be available to CEDR NRAs to customise for use in procurement in the move towards a circular economy. Appropriate training will be provided to different groups within NRAs as part of dissemination of CERCOM deliverables in WP5.

Annex A: References

Adey B, Hajdin R, Brühwiler E. Risk-based approach to the determination of optimal interventions for bridges affected by multiple hazards, Journal of Engineering structures, 2003; 25(7): 903-912.

Bernoulli D., (1738). "Exposition of a New Theory on the Measurement of Risk". Translated from Latin into English by Dr Louise Sommer from `Specimen Theoriae Novae de Mensura Sortis', Commentarii Academiae Scietiarum Imperialis Petropolitanas, Tomus V, 175-192, (1954).

Bles, T, Ennesser, Y, Fadeuilhe, J, Falemo, S, Lind, B, Mens, M, Ray, M., Sandersen, F (2012). Risk Management for Roads in a Changing Climate (RIMAROCC), Deltares report 1205568-000-GEO-0007, Version 2.

Enei, R., Doll, C., Klug, S., Partzsch, I., Sedlacek, N., Nesterova, N., Kiel, J., Rudzikaite, L., Papanikolaou, A., Mitsakis, V., (2012). Weather Extremes: Impacts on Transport Systems and Hazards for European Regions (WEATHER), European 7th RTD Framework Programme 2012 (http://www.weather-project.eu/weather/index.php)

Espinoza, M., Campos, N., Yang, R., Ozer, H., Aguiar-Moya, J.P., Baldi, A., Loría-Salazar, L.G. and Al-Qadi I.L., (2019), Carbon footprint estimation in road construction: La Abundancia–Florencia case study. Sustainability 11.8 (2019): 2276.

European Commission (2018), "Public Procurement Guidance for Practitioners"

Intelligent Energy Europe (2010), "Energy Conservation in Road Pavement Design, Maintenance and Utilisation" (ECRPD).

International Standards Organisation (2018), "ISO 31000:2018 Risk Management Guidelines"

Keller, E., Newman, J.E., Ortmann, A., Jorm, L.R. and Chambers, G.M., 2021. How Much Is a Human Life Worth? A Systematic Review. Value in Health.

Office of Government Procurement (OGP) (2019), "Public Procurement Guidelines for Goods and Services", Ireland.

National Transport Authority (NTA) (2010), "Guidelines for the Management of Public Transport Investment Projects", Ireland.

Re-Gen Deliverable 4.2 (2016), "Risk Optimization Road Infrastructure Elements", available at (https://www.re-gen.net/deliverables)

UK Highways Agency (2011), Highways Agency Climate Change Risk Assessment.

UK Highways Agency (2009), Climate change adaptation strategy and framework.

Yuan Z, Khakzad N, Khan F, Amyotte P. Risk-based optimal safety measure allocation for dust explosions. Safety Science, 2015; 74: 79-92.