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CERCOM - Development of an analytic software tool for the evaluation of innovative infrastructure maintenance methods in the move towards circularity

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ABSTRACT: Implementation of the circular economy and resource efficiency has the potential to significantly tackle the root causes of global challenges such as climate change, biodiversity loss and pollution whilst at the same time providing regenerative design for generations to come. The CEDR funded CERCOM project facilitates a move towards circular public procurement of national road infrastructure. A flexible and stable approach using ranked interpolation is used to generate KPI values for various criterion, where the user can specify the desired level of complexity based on scheme requirements and data available. The framework considers technical, economic, environmental and social criteria, as well as circularity, while assessing the change in risks in moving from a linear to a circular economy. National Road Authorities (NRAs) are at different maturity levels in relation to circularity. The developed framework caters for this, allowing flexibility for NRAs to tailor their application of the framework to suit their maturity level and the scheme under consideration. The outcome is a user-friendly intuitive tool with a step-by-step approach to enable informed decision making around adoption of the principles of circular economy in the maintenance of highway infrastructure.

1. INTRODUCTION

Implementation of the Circular Economy (CE) has the potential to play a significant role in limiting global climate change whilst providing regenerative design for generations to come. To achieve climate neutrality, synergies between CE and carbon reduction need to be established in the context of highway infrastructure. As highway construction and maintenance accounts for an extensive use of resources, road authorities must become more material and energy efficient, moving beyond recycling, to reuse, repair and minimizing use of materials. Research has shown that one of the most significant routes to embedding circularity is through the demonstration of innovative approaches which can also enhance Key Performance Indicators (KPIs) relating to life cycle cost and sustainability (Lamb et al, 2022a). However, the barrier to this seems to lie in the perception of risk and lack of standardisation related to new construction and maintenance approaches.

In 2020, the Conference of European Directors of Roads (CEDR) issued a call for research on Resource Efficiency and Circular Economy and commissioned the project (CEDR, 2020), 'Circular Economy in Road Construction & Maintenance' (CERCOM). The project is led by Research Driven Solutions (Ireland), with project partners of the Technical University of Delft (Netherlands), International Transport Experts Network (UK), the Danish Technological Institute (Denmark) and Hello My PA (UK). The project commenced on 1st September 2021 and runs for two years. The CERCOM project developed an innovative framework to facilitate the adoption of circular economy and Resource Efficiency (RE) principles in the procurement of highway infrastructure. A Software Tool developed around a Risk-Based Analysis Framework (RBAF) is presented, which utilizes a weighted sum incorporating risk, cost and a number of developed environmental and social KPIs to rank various construction strategies. The intuitive, user-friendly Software tool provides a means to assess the potential benefits of alternative solutions in the drive to increase circularity and reduce carbon emissions within the transport infrastructure sector, providing a means to quantify trade-offs between safety, cost, environmental and social factors to optimize potential scheme options, by consolidating all categories into a single weighted metric.

The Netherlands was the first European country to formalise the process for sustainable procurement, with the Dutch Government establishing clear goals as early as 2005 and embedding this further into their procurement processes. Rijkswaterstaat (the Department of Public Works of the Ministry of Infrastructure and the Environment) developed a methodology for infrastructure projects where the functional specification of the tender together with the quality input from the client ensure an innovative and high-quality solution. The criteria that formed the basis of assessing the sustainability attributes of tenders were CO_2 emissions and environmental impact (Lamb et al., 2022b). To facilitate this, the following two tools were developed to measure CO_2 emissions and environmental impacts, and are now mandated to be used by all tenderers:

- The CO_2 performance ladder – a certification system with which a tenderer can show the measures to be taken to limit CO_2 emissions within the company and in projects, as well as elsewhere in the supply chain.
- DuboCalc – 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.

One advantage of the CERCOM RBAF is the ability to integrate the results of these tools into the developed framework and build on advances already made in the move towards more circular sustainable options.

The aim of the RBAF is to facilitate procurement of circular solutions for road construction and maintenance while assessing the risk of doing so. As well as environmental, cost, circularity and social factors, the approach uses risk-based methods to evaluate the technical performance of the options. This allows uncertainties associated with novel methods or materials to be quantified.

The developed Software Tool provides a means to assess various innovative methods and materials with the goal of reducing material consumption and associated CO_2 emissions in highway construction, while also quantifying the potential risk associated with performance and functionality of more pioneering approaches. In addition, use of this approach provides a means to evaluate the impacts of certain measures and prioritize areas that require further research or investigation.

2. RISK BASED ANALYSIS FRAMEWORK

2.1. Framework Overview

The aim of the CERCOM framework is to build on risk-based methodologies and previous projects to facilitate procurement of circular solutions for road construction and maintenance (Khakzad et al., 2016). The steps involved in the generation of the RBAF are outlined in Figure 1 (Connolly et al., 2022).

Figure 1. CERCOM Risk-Based Analysis Framework

There are 5 steps within the risk assessment framework, as follows:

- Establish context - Includes 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, identifying the specific spatial and temporal boundaries of the assessment in question.
- Evaluate likelihoods - Includes details on likelihood of a “failure” event (P_f) or the probability of exceedance of a given damage state for given scenarios of hazard and action.
- Evaluate consequences – Includes direct and/or indirect consequences/costs associated a with failure event (Adey et al., 2003).
- Establish additional KPIs – Involves quantification of RE&CE, Cost, Environment and Social KPIs.
- Optimize – Involves optimization of various assessment criteria and KPIs.

2.2. Risk Analysis

For each potential construction or maintenance option, the risk associated with this strategy is calculated (Risk = P_f x Consequences of failure event). Within the RBAF, consequences are taken as the costs associated with a failure event (e.g., the direct and/or indirect costs associated with emergency resurfacing due to premature loss of skid resistance). Any number / type of consequence may be considered in this regard and the process should ideally consider the full range of potential outcomes. For each potential action, the risk associated with each strategy is calculated and used to generate the Risk Reduction Index (*RRI*), outlined in Eq. (1) (Yuan et al., 2015).

$$RRI_i = \frac{R - R_i}{R} \tag{1}$$

where $R =$ Risk associated with the “Do Nothing” option and $R_i =$ Risk associated with maintenance / construction option i. The *RRI* is then used within the optimization step.

“Do Nothing” is considered for the evaluation of risk to establish a baseline scenario. It is a hypothetical case rather than a viable maintenance option. The purpose is to evaluate the risk of carrying out minimal or no maintenance over the reference period, providing a means to quantify the reduction in risk associated with carrying out various maintenance options.

2.3. KPI Categories

For this project, it was essential to integrate circularity factors into procurement practices. However, when considering procurement, it is necessary to also consider more traditional criteria. As such, the RBAF was developed to take account of all these factors. The CERCOM framework considers 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, as outlined in Figure 2. The framework is applicable to all road infrastructure elements under the maintenance remit (e.g., road pavements, bridges, retaining walls, cuttings and embankments and roadside infrastructure).

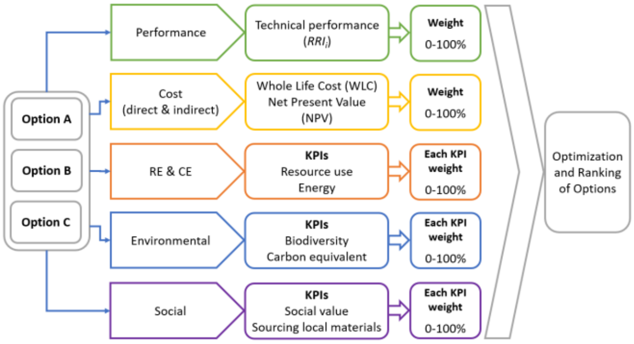

Figure 2. CERCOM Categories for assessment criteria and KPIs

2.4. Optimization

A weighted sum, the Net Risk Reduction Gain ($NRRG$) is incorporated into the CERCOM framework to allow scoring of various criteria to be considered and integrated into a single index for optimization purposes to rank various construction or maintenance solutions.

As with any tender evaluation, weight factors provided by the user are used to quantify priorities of each NRA for a specific project/scheme. The $NRRG$ is used to score the various potential maintenance strategies, amalgamating performance, cost, RE&CE, environmental and social factors using a weighted sum.

3. SOFTWARE TOOL

The objective of the Software Tool is to provide a user-friendly excel based tool to facilitate the procurement of RE&CE construction and maintenance options, while also considering costs, as well as the performance risk associated with more innovative methods/materials. The tool caters for the level of maturity of the NRA by allowing single or multiple entries of KPI under each category, and user defined numerical inputs or pre-set values to be selected for each criteria/KPI and each construction/maintenance option considered.

Firstly, for the Performance Category and the calculation of risk, the value of failure probability (P_f) must be a value between 0 and 1.0. Depending on the level of maturity, availability of sufficient data or expertise for the calculation of failure probability, the user has the option to input values directly (calculated using methods such as statistical analysis and/or probabilistic modelling) or use a pre-set scale. For options where the user selects to use the pre-set scale, two inputs are required and are selected by the user from a drop-down menu. One parameter relates to the performance characteristics of the construction/ maintenance option and the other is related to the level of uncertainty the user has in relation to the performance characteristics. This allows the user to account for uncertainty around the use of new or less proven materials or construction and production technologies. The selection is based on expert judgment or empirical data.

For performance the available options for selection are:

- Below average
- Average
- Above Average

For uncertainty the available options for selection are:

- Low
- Medium
- High

The two user inputs from the pre-set scale reference a matrix of values for the determination of the P_f value. Pre-set P_f values are approximate to give an indication of relative performance for a comparative analysis and should not be taken as absolute values for safety. It is important to note that all options must meet minimum safety standards outlined in the relevant design codes.

The developed additional KPIs 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.

A system of ranked interpolation is used to quantify KPIs. The first rank for each KPI is assigned a value of 0.0, and the final rank is assigned a value of 1.0. In the simplest case, a linear relationship is assumed between the first and final rank. Where a more subtle response is required, a multi-linear relationship may be determined between different KPI ranks. Ideally, KPIs should relate to existing targets and practices 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" or ranks of achievement of this goal. These "levels" can be related to KPI values and ranks for quantifying KPIs for potential schemes.

KPIs are utilized within the calculation of *NRRG* to integrate critical RE&CE, environmental and social factors. To calculate the additional KPIs, the user can input data directly to calculate KPIs or select pre-set KPI values from a drop-down menu. Within the tool, the KPI pre-set options are a range of values between 0 and 1 and are not KPI specific. The goal is to provide a broad range of values with generic descriptions to enable the user to provide an indication of the value of one scheme option over the other based on user experience, where more specific data to quantify these values is not available. Table 1 outlines the pre-set options available with an example of what these values could represent for an RE/CE KPI (Recycled Content of Solution).

Table 1. Pre-set KPI values with CE example

KPI Value	Description	Recycled Content Example
0	*No commitment to KPI ambition*	*No recycled content*
0.1	*Below minimum industry practice*	*5% recycled content*
0.25	*Minimum industry practice*	*10% recycled content*
0.5	*Exceed industry practice*	*40% recycled content*
0.75	*Far-exceeds industry practice*	*70% recycled content*
1	*KPI ambition achieved*	*100% recycled content*

If Numerical Input is selected for any of the scheme options, then input is required to carry out ranked interpolation to calculate the KPI value. The number of ranks, the unit of measurement for the data considered, the least favourable and most favourable threshold values must be entered, as well as a data value for each proposed construction/maintenance scheme option. When 2 ranks are chosen, a KPI value of 0.0 is assigned to the least favourable rank and a KPI value of 1.0 is assigned to the most favourable rank. A value for each scheme option is entered between these thresholds and linear interpolation is carried out to determine the KPI value. It is possible to select up to 4 ranks and use multi-linear interpolation, with a different slope between each rank. In this case, numerical values must be entered to quantify each rank using a data input value and a corresponding KPI value between 0 and 1, as illustrated in Figure 3.

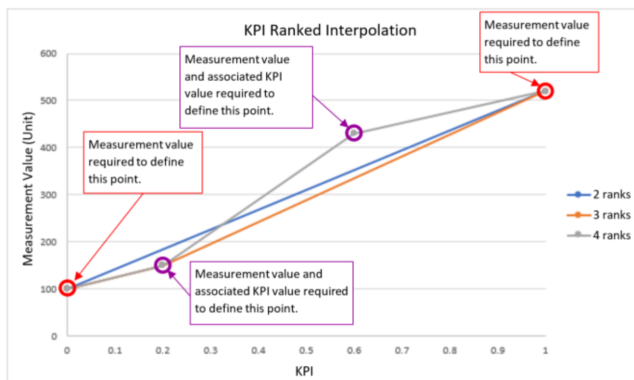

Figure 3. Ranked interpolation method

Unlike Figure 3, in some cases, the graph will have a negative slope depending on the characteristics of the KPI considered. For example, for carbon cost, a higher value of carbon will be least favourable (KPI of 0), and a lower value will be assigned to the most favourable rank (KPI of 1.0), leading to a graph with a negative slope. A KPI relating to recycled content, however, will have a positive slope.

Given the maturity level of most NRAs (Lamb et al., 2022a) and limited data currently available for various criteria, it is likely that two ranks will be sufficient in the short term to represent KPI relationships. However, over time as more data is collected, the more advanced options using 3 or 4 ranks may be utilized to more accurately reflect required response of KPIs to measured criteria.

A weight must be applied to each Criteria or KPI defined within the software tool. Different weights can be assigned for each maintenance option, but it is recommended that the same weights are used for each option for a meaningful, comparable output result. The sum of the weights for each option must equal to 1.0, otherwise an error will be displayed and results will not be presented.

The software tool calculates the weighted sum of the Criteria/KPI for each option and generates the $NRRG$. The construction/ maintenance options with the highest $NRRG$ value is considered the most advantageous option. The results are presented in the form of a graph and a table illustrating the contribution of each weighted criteria/KPI to the overall value of $NRRG$.

4. SAMPLE ANALYSIS

A sample application was generated and is presented for the purpose of demonstrating the application of the RBAF software tool. The data used within this analysis is notional to demonstrate functionality of the software developed and not intended to be representative of the actual values attributable to these maintenance scenarios.

For this example, a 1km section of dual carriageway is considered. The period of analysis is 42 years.

The following scenarios were considered:

- Option A – Two applications of preventative maintenance, once every 5 years to extend the life of an asphalt pavement. This is followed by standard reconstruction every 12 years.
- Option B – Standard resurfacing every 12 years over the lifetime considered.

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 maintenance is to improve the skid resistance, and as such, skid resistance was the chosen criteria under the performance category to assess risk.

Data was obtained from literature to relate crash rates to skid resistance over time as the pavement deteriorates between maintenance intervals (Silva, 2013; Vos et al., 2017). Over the analysed lifetime of 42 years, the probability of one collision or more occurring is 1.0 for both maintenance options and the “Do Nothing” scenario. The “Do Nothing” scenario assumes no maintenance over the lifetime with the purpose of providing a baseline reference for risk analysis.

For this analysis, the differentiation between both maintenance options in terms of risk comes down to the quantification of consequences. A yearly probability of collision is calculated based on the condition of the pavement each year (considering deterioration over time). The average proportion of collisions resulting in fatality, serious injury or minor injury is taken from the literature (SWOV, 2020). On this basis the consequence of failure (i.e., collisions) is calculated for each maintenance option over the lifetime considered. The calculated consequences are €400 million, €35 million, €40 million for the “Do Nothing” scenario, Option A and Option B, respectively.

Additional KPIs considered in the analysis are Net Present Value (NPV), circularity (CE), environmental and social. For the NPV KPI, the NPV for construction, maintenance, salvage value etc of the two options were calculated as €30,000 and €105,000 for Option A and Option B, respectively. Selecting 2 ranks, and assuming a least favourable rank of €150,000 based on experience of similar road schemes and most favourable rank of €0, the KPIs for Option A and B were calculated as 0.8 and 0.3, respectively.

The circularity associated with each option was determined considering factors such as material value added and end of life value. For preventative maintenance a circularity score was calculated as 5.6 and for standard maintenance a value of 15.4 was determined, with lower values indicating more circular solutions. Selecting 2 ranks, and assuming a least favourable rank of 20 and most favourable rank of 0, the KPIs for Option A and B were calculated as 0.72 and 0.23, respectively.

For the environmental KPI, given limited data available, empirical data was used to assign KPI values based on pre-set scales within the software. Given the reduced environmental burden from preventative maintenance, the KPI "0.50 – Exceed industry practice" was assigned to Option A. Option B was assigned KPI value of "0.25 – Minimum industry practice" to reflect the standard maintenance approach.

For social factors (such as average working hours, minimum wage, equality, local employment and supply chain). Pre-set options from the software were selected for the social KPI. With both options considered comparable in this case, and assuming standard social protocols, a KPI value of "0.25 – Minimum industry practice" was assigned for Option A and B.

The assigned weights for analysis are presented in Table 2. As per examples presented in the EC Public Procurement Guidance for Practitioners, 30% of the marks are allocated to cost (European Commission, 2018). As such, a weight of 0.3 is assigned to NPV KPI for this analysis. The remaining proportion of weight are divided between technical performance, CE, environment and social criteria (Table 2).

Table 2. Weight assigned to assessment criteria

Category	Name	Weight
Performance	*Skid resistance*	*0.3*
Cost	*NPV*	*0.3*
CE	*CE*	*0.15*
Environment	*Env*	*0.15*
Social	*Social*	*0.1*

The final step in the analysis is the calculation of the $NRRG$ for each scenario to select the most advantageous solution. The Net Risk Reduction Gain (*NRRG*) is the sum of the weighted KPIs, with the scenario with the highest *NRRG* being the most advantageous option. For this analysis, Option A, preventative maintenance has demonstrated to be the most optimal solution with a *NRRG* of 0.72. Option B results in a *NRRG* of 0.46. Figure 4 indicates the breakdown of the *NRRG* sum, where the product of the KPI and weight is provided for each category.

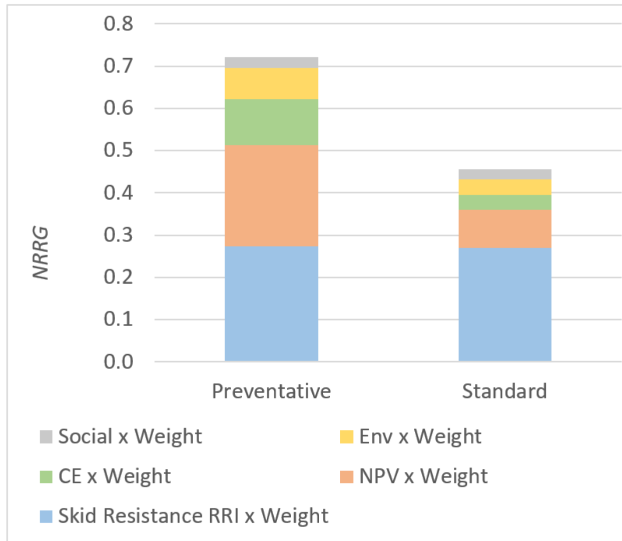

Figure 4. NRRG Results for Option A and Option B

The sample application provides a straightforward demonstration of the use and value of the developed framework and software tool. Figure 4 illustrates that for this case, much of the differentiation between maintenance options comes down to cost, with CE and environmental KPIs having a lesser effect. Technical performance and social factors have little or no impact on the optimal maintenance selection. This gives confidence that the increased risk associated with preventative maintenance rather than standard maintenance is minimal and illustrates other advantages of this approach.

5. CONCLUSIONS

The CERCOM Software Tool provides a user-friendly, versatile means for NRAs to assess the risk of using innovative circular construction and maintenance methods and materials along with additional criteria to facilitate optimum selection of scheme options and associated procurement practices. It is envisaged that all the tools and methods described will be updated and refined based on the practical experience gained from analysing various case studies within the final months of the project. This has the advantage of providing a tried and tested multi-faceted framework that will be extensively reviewed and verified by the end of the CERCOM project. It will then be available to CEDR NRAs to customise for use in procurement in the move towards a circular economy.

The developed tool provides sufficient flexibility to allow NRAs to decide on the level of engagement with the CE process, based on current CE maturity as well as future needs. 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 in the procurement process of construction and maintenance of road infrastructure.

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.

There is flexibility to include output results from independent Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA) into the developed software tool to provide additional functionality and complexity. This will be carried out and demonstrated later in the CERCOM project and is beyond the scope of this paper.

The fundamental limitation associated with the software tool is the availability of reliable data to assign values for criteria associated with alternative maintenance strategies and data to define thresholds for ranked interpolation. This framework and software tool facilitates the evaluation of sensitivities to evaluate the impacts of certain criteria and establishes areas that merit further investigation and data collection.

6. ACKNOWLEDGEMENTS

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