CEDR Transnational Road Research Programme
Call 2020: Resource Efficiency and the Circular Economy

Funded by: Denmark, Ireland, Netherlands, Norway, Sweden, Switzerland and the United Kingdom

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

CERCOM
Circular Economy in Road COnstruction and Maintenance

Software Tool Facilitating Risk-Based Assessment of RE & CE Approaches

Deliverable No. D3.2
December 2022

Research Driven Solutions Ltd. (RDS), Ireland
Delft University of Technology (TUD), Netherlands
ITEN, United Kingdom
Danish Technological Institute (DTI), Denmark
Hello My PA, United Kingdom

CEDR Call 2021: Transnational Road Research Programme

CERCOM
Circular Economy in Road COnstruction and Maintenance

Software Tool Facilitating Risk-Based Assessment of RE & CE Approaches

Due date of deliverable: 31/10/2022
Actual submission date: 1/11/2022

Start date of project: 01/09/2021 End date of project: 31/08/2023

Author(s) this deliverable:
Dr. Emma Sheils, Research Driven Solutions, Ireland
Lorcan Connolly, Research Driven Solutions, Ireland
Prof. Alan O' Connor, Research Driven Solutions, Ireland
Daniel Berman, Danish Technological Institute, Denmark
Asger Alexander Wendt Karl, Danish Technological Institute, Denmark
Dr A. (Katerina) Varveri, Delft University of Technology, The Netherlands
Dr. Avishreshth Singh, Delft University of Technology, The Netherlands

Version: draft, V2, R1

Table of contents

Executive summary

This report provides a detailed description of the Risk-Based Analysis Framework (RBAF) Software Tool developed as part of CERCOM Work Package 3 and Deliverable 3.2. The aim of the framework is to facilitate procurement of circular solutions for road construction and maintenance while assessing the risk of doing so.

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 such as Performance, Cost, Environmental and Social factors. As such, the RBAF was developed to take account of all these factors. 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 Software Tool not only considers performance but also the uncertainty associated with performance given the use of new or less proven materials or construction and production technologies.

It was imperative that the developed RBAF provides sufficient flexibility to allow NRAs to decide on the level of engagement and be suitable for current levels of requirements 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 user manual within this report provides a step-by-step approach to guide users through the use of the RBAF Software Tool.

1 Introduction

This document is to accompany the Risk-Based Analysis Framework (RBAF) Software Tool developed as CERCOM Deliverable 3.2 with the objective to provide a user-friendly Software Tool which can used by NRAs to facilitate adequate and accurate consideration of RE & CE in procurement.

A brief outline of the RBAF process outlined in Deliverable 3.1 is provided, as well as a detailed description of the Life Cycle Analysis (LCA) and Life Cycle Cost Assessment (LCCA) methods that were developed as part of Task 3.4 to define and quantify key input parameters for the RBAF Software Tool. This is followed by a detailed description of the Software Tool, with a step-by-step user guide for each section of the spreadsheet.

2 Scope

The scope of Deliverable 3.2 is the development of a Software Tool, facilitating the use of the RBAF outlined in Deliverable 3.1, whilst integrating the outputs of the LCA and LCCA completed as part of Task 3.4 into this framework. While an LCA/LCCA methodology is discussed within this document to provide a complete tool for the project, the RBAF tool can also incorporate KPIs calculated using tools outside the proposed LCA/LCCA methodology (i.e., the RBAF can incorporate KPIs calculated using tools or software already utilised by NRAs).

Within the CERCOM project, the Software Tool will be used to assess the construction/maintenance options assessed as part of the case studies in Work Package 4 (WP4). The LCA and LCCA frameworks developed as part of Task 3.4, reflecting the multiple life cycles of materials and assets, will be used to generate input KPI values and thresholds for different options. RE/CE and Social KPIs will also be integrated into the tool and methods developed to calculate these KPIs will be outlined for the case studies in WP4. The process of integrating the KPIs into the RBAF for each of these categories is discussed in this report.

A user guide within the report outlines the step-by-step approach for using the Microsoft Excel based RBAF Software Tool, with screenshots and sample arbitrary data used to demonstrate the use of the tool and generate results.

The Software Tool is flexible and adaptable to account for the varying levels of NRA maturity and the complexity of the software can be tailored to suit the requirements of the scheme and the quantity/quality of data available.

Updates of the Software Tool will be carried out if required as the evaluation of the various case studies in WP4 progresses.

3 Risk-Based Analysis Framework (RBAF)

3.1 Outline of RBAF

The steps involved in the Risk-Based Analysis Framework as outlined in CERCOM Deliverable 3.1 are illustrated in Figure 1. Within the Software Tool, input is required from the user for each of these steps to ultimately perform optimisation of proposed options. An outline of data required by the user for each stage is summarised in Figure 2. More detail on specific user inputs required is provided in Section 6.

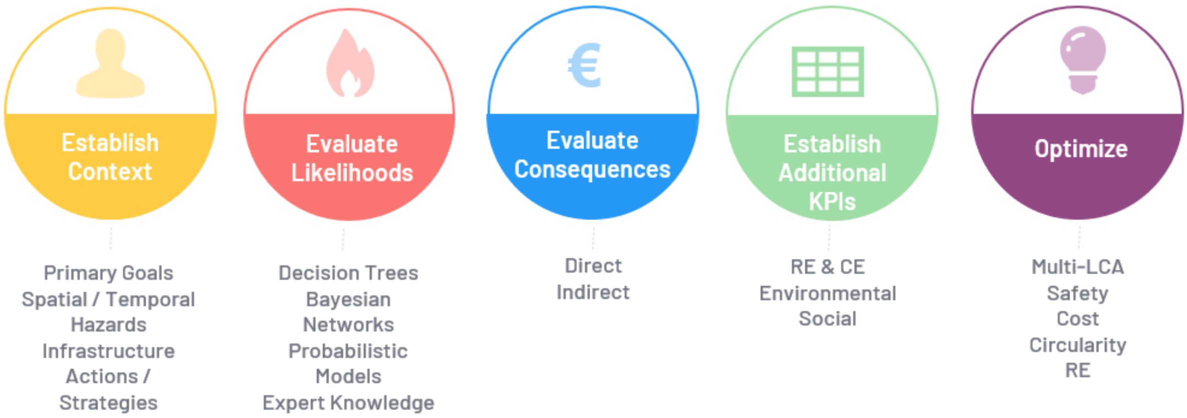


Figure 1. Outline of RBAF

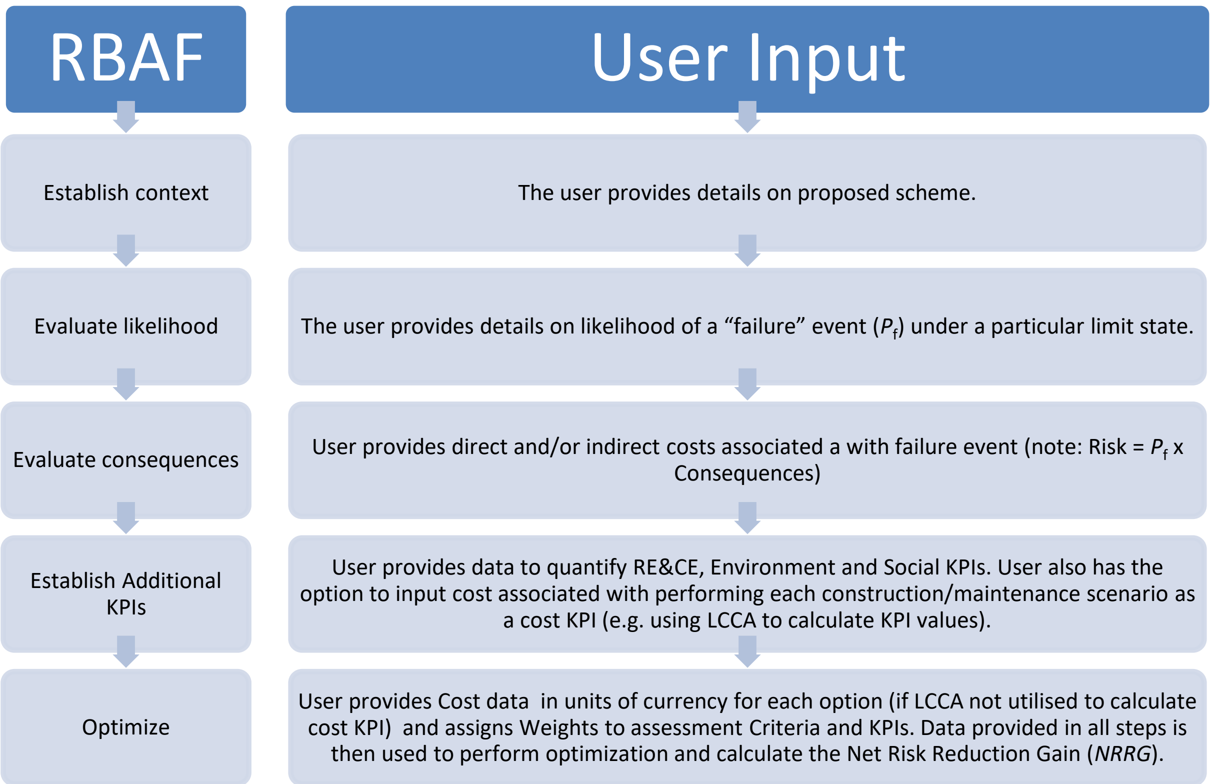


Figure 2. Outline of user inputs for each stage of RBAF

Note: The cost associated with performing each construction/maintenance scenario can be entered as a numerical value in units of currency (within the optimize step) or calculated using LCCA and inputted into the Software Tool as a cost KPI. Input options for cost data will be discussed further in Section 6 of this report.

3.2 Key Performance Indicator (KPI) Ranked Interpolation

As discussed in detail in Deliverable 3.1, the CERCOM consortium propose to quantify KPIs using a ranked interpolation approach. As well as RE&CE, Environmental and Social KPIs, cost KPIs can also be defined if required. This provides an alternative means to quantify cost associated with performance of each scenario, or to broadly quantify factors such as residual value, where more detailed cost data is not available. Figure 3 illustrates the categories under which criteria and KPIs for optimization are assigned.

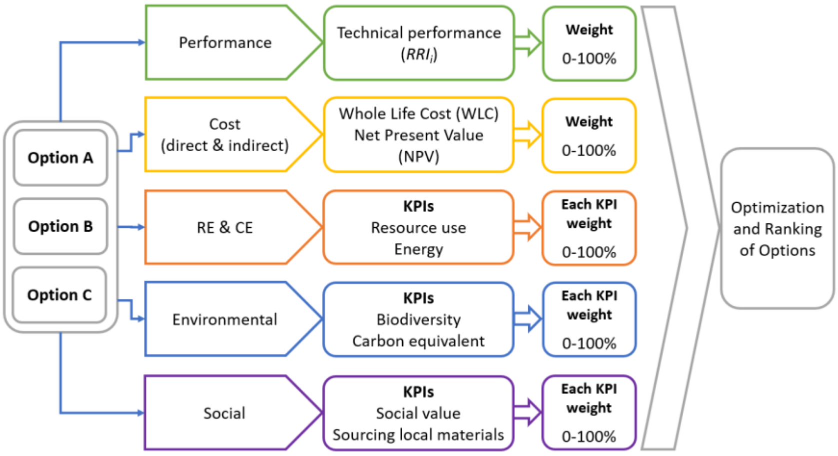


Figure 3. Categories defining criteria an KPIs for optimisation.

<u>*KPIs by ranked interpolation*</u>

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.

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 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.

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.

3.3 Net Risk Reduction Gain ($NRRG$)

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* ($NRRG$) 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, (note: Risk = P_f x Consequences of failure event). Within the RBAF, consequences are taken as the costs associated with a failure event, as entered by the user, in units of currency (e.g., the direct and/or indirect costs associated with emergency resurfacing due to premature loss of skid resistance).

In terms of costs associated with the performance of each maintenance/construction scenario, 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 to be incorporated in units of currency. Alternatively, cost related KPIs calculated using LCCA considering Net Present Value (NPV) can be calculated and integrated into the framework to assess and quantify cost implications with respect to various construction or maintenance options. It is recommended that costs are considered using either *CPI* **or** LCCA. If costs are calculated using *CPI* (e.g., considering only direct construction/maintenance costs), there is also an option to include additional cost KPIs along with this input to reflect other factors such as Residual Value. KPIs are utilised within the calculation of $NRRG$ to integrate critical RE&CE, environmental and social factors:

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

Where:

$$RRI_i = \frac{R - R_i}{R} \quad (2)$$

$$CPI_i = \frac{B - C_i}{B} \quad (3)$$

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

R = Risk associated with the “Do Minimum” 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 construction/maintenance options with the highest $NRRG$ is then selected as the most advantageous. Additional information on the factors involved in the calculation of $NRRG$ are provided in Deliverable 3.1.

4 Life Cycle Analysis (LCA)

4.1 Outline of LCA

The LCA tool will be comprised of three parts: An interface for the user to provide input; a library to provide data for the LCA impact calculations; as well as a dashboard to display results benchmarking the impacts of scenarios selected by the user against a selected reference scenario. The results calculated by the tool give a comprehensive account of severity of the environmental risks associated with carrying out road maintenance over the course of the user defined assessment period. When using the tool, the user will provide road and maintenance specifications for a specific proposed maintenance strategy through the interface. The interface will also include more generic predefined options, for instances where more specific data is unavailable. This will allow for more environmentally sound decisions. The environmental impacts accrued over multiple lifecycles of the road are captured by the tool through increasing the assessment period, for which maintenance of the road will be assessed.

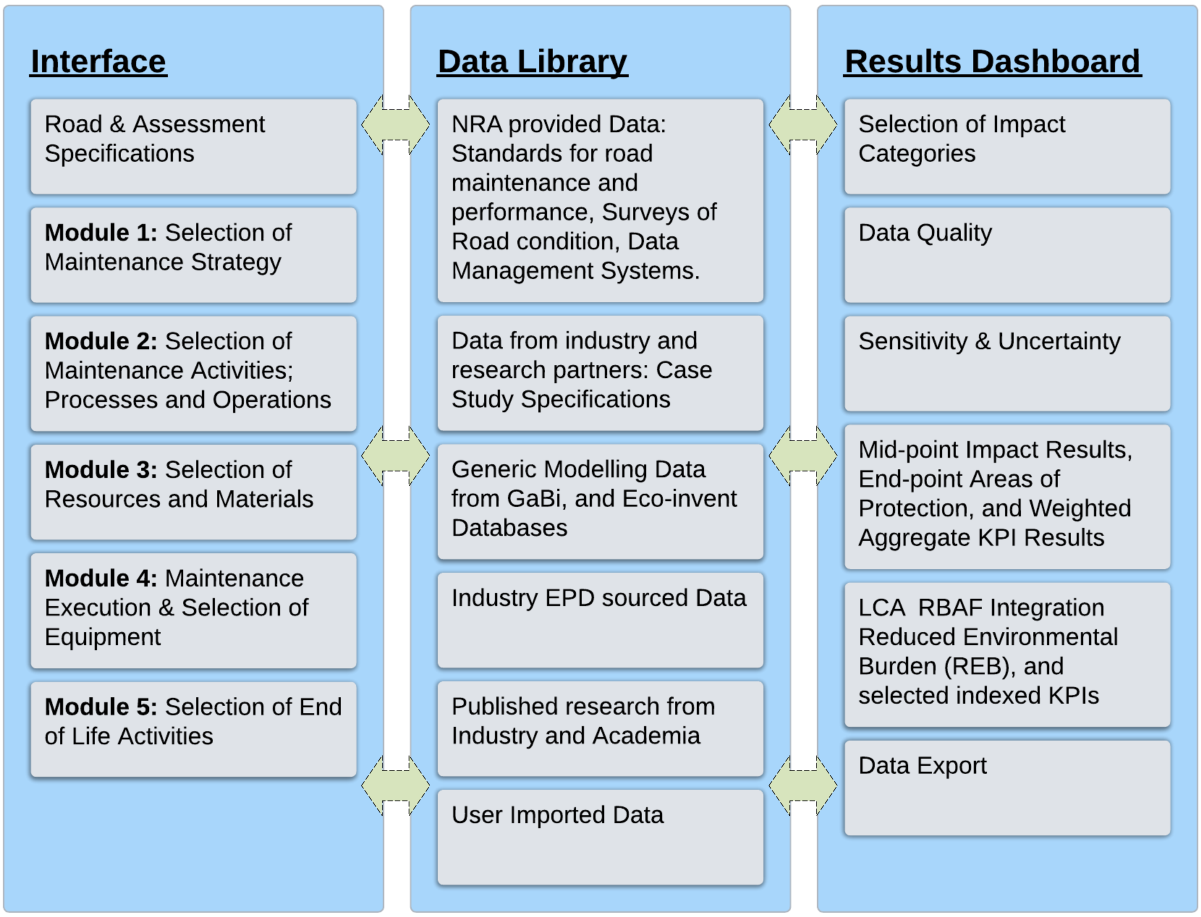


Figure 4: Overview of CERCOM LCA tool structure including interface, data library and results dashboard

A modular approach will be taken in structuring the LCA tool's sections, as outlined in Figure 4. First beginning with Road and Assessment Specifications, where site specific data supplied by NRAs will be used for defining the context of the maintenance applications to be compared.

Further modules include selection of maintenance strategies; unit processes; executions of maintenance; and lastly end-of-life treatment.

Data stored in the tools library are grouped into five classifications based on their source. Each maintenance method and its associated components (i.e., processes and operations, materials and resources, equipment and execution, and end-of-life (EoL) processes) are stored in the tool's library, and will draw on data sourced from NRAs, project research partners, generic LCA modelling data, EPD data, as well as data sourced from published research. By accessing the more advanced section of the tool's interface, the user will have the additional option to create and store custom entries in the tool's library where case specific data a can be added. The data will also be qualified based on its geographic, temporal, and technological representativeness, as defined in the EPD standard (EN 15804:2012+A2:2019). The selection of data in the tools' library is curated based on its relevance.

The Maintenance Strategy will be comprised of modules of maintenance activities, and EoL activities. The user will have the option to select from predefined strategies and activities as well as constructing individual activities to define customised strategies. Each activity will contain a bill of input materials, processes, as well as the transportation associated with each material, and process. EoL activities will in addition, include a bill of recovered materials and resources. The user will then define the years over the course of the assessment period for which each activity will occur. In the same fashion the user will also define the counterfactual reference strategy for which the assessed strategy will be benchmarked (Figure 5).

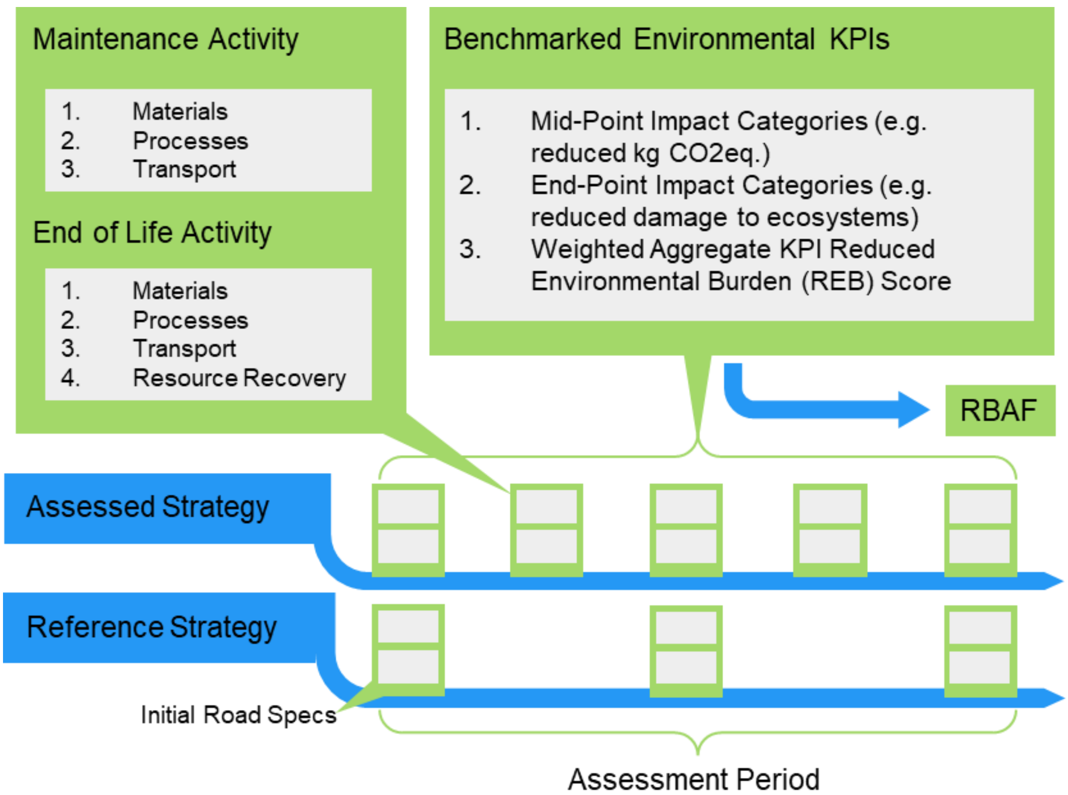


Figure 5: Structure of Maintenance Strategies in the LCA tool, and integration of environmental KPIs within the RBAF

The dashboard section of the tool will provide a visualization, benchmarking the assessed maintenance strategies against a baseline reference scenario. These results of the LCA will be quantified as mid-point impacts, and end-point impact categories. A weighting will then be applied to aggregate these impacts into a single end-point key performance indicator (KPI) representing a total environmental burden. This will allow for the subsequent integration of the environmental KPI into the RBAF.

4.2 Determination of KPI values

There are a few approaches for the life cycle impact assessment which can generate KPIs that could be integrated into the RBAF. This includes utilising mid-point impact categories, end-point impact categories, as well as a selection of mid-point or end-point impact categories aggregated according to an applied weighting.

ReCiPe 2016 was selected as the methodology for providing characterization and conversion factors for assessing the life cycle impacts of road maintenance in CERCOM. This choice was made as the methodology provides the functionality of calculating both mid-point and end-point impacts of scenarios for road maintenance. While end-point impact categories give more value in terms of quantifying effects on human health, in disability adjusted life years (DALY), ecosystem health, in species loss years, and reduced resource availability, in USD $, it is also important to consider the trade-off between these two approaches, being that end-point methodologies are inherently associated with a significantly higher degree of uncertainty when compared to midpoint impact indicators (Figure 6). It is also important to note that some indicators such as freshwater, marine, and terrestrial ecotoxicity carry high degrees of uncertainty as the damage pathways are poorly understood in comparison to climate change, acidification, and eutrophication indicators, which are based on a significantly larger amount of research.

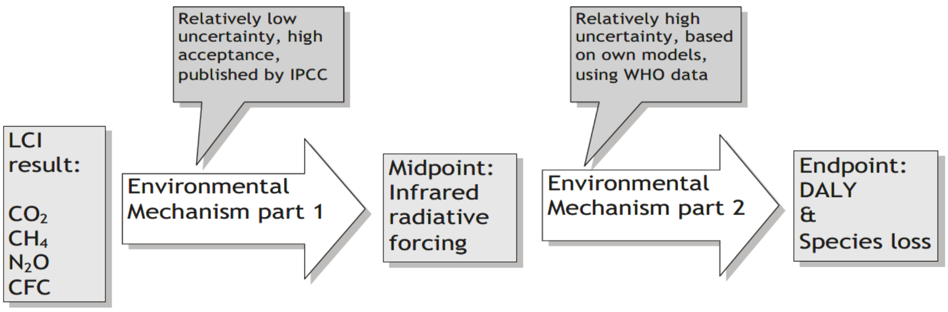


Figure 6: Example of how midpoint and endpoint impacts are derived for climate change (Goedkoop et al., 2013).

Another methodology developed by the European platform for LCA, environmental footprint 3.0, was also considered. However, this only includes midpoint impacts normalized to person, and global equivalents (European Commission, 2020), resulting in its exclusion.

The chosen Life Cycle Impact Assessment (LCIA) methodology defines the impact categories of which all the elementary flows of materials and resources for each scenario will contribute to. The amount a specific flow contributes to each impact category will be based on the characterization factors implemented by the LCIA method. The characterization factors, conversion factors, and weightings are stored in the tools data library. Once the user has defined the parameters of the maintenance strategies to be assessed, the tool will begin generating a series of results which will be visualised in the tool's results dashboard. The user will have the choice of selecting the specific impacts, be it mid-point impacts, end-point impacts, or the total weighted and aggregated score based on relevancy to the priorities of the user.

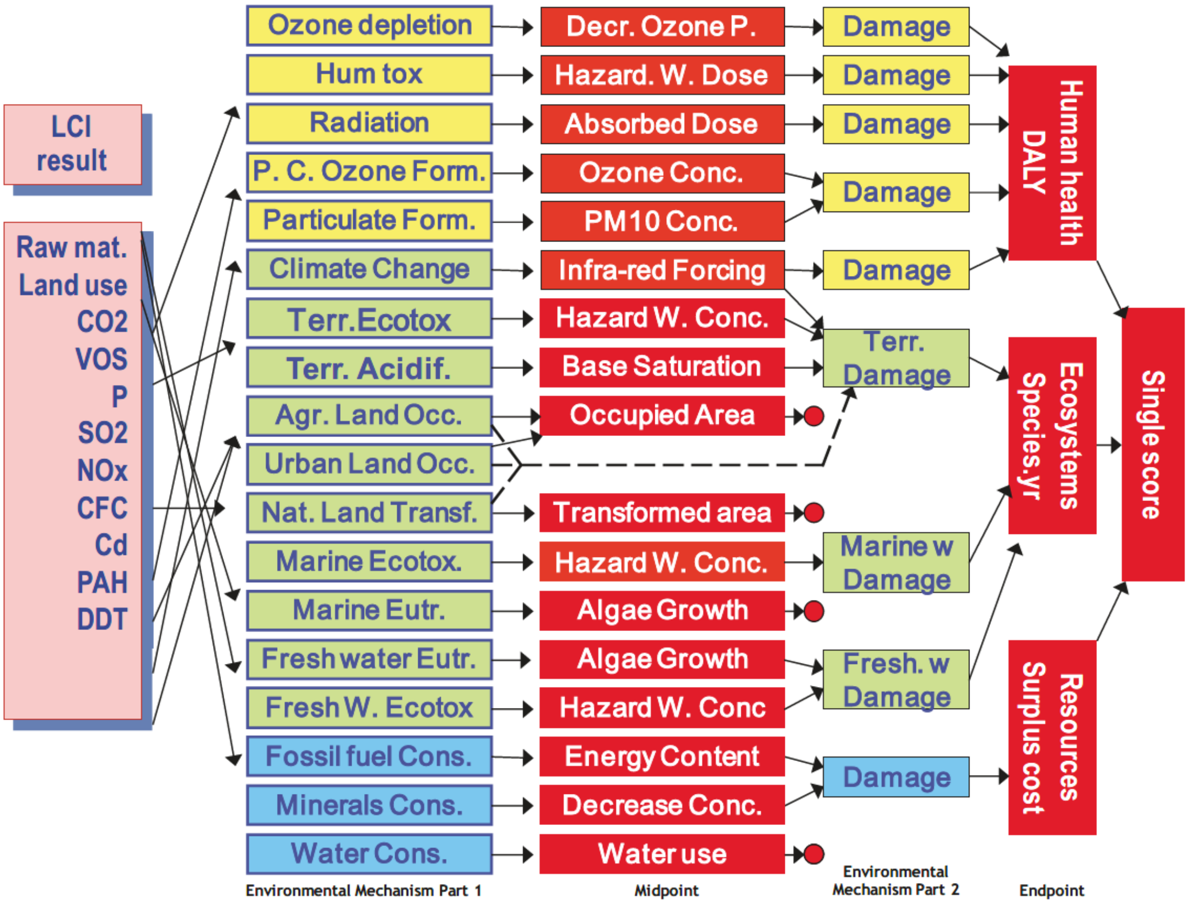


Figure 7: ReCiPe LCIA Model overview of LCA results, midpoint impact categories, environmental mechanisms, endpoint areas of protection, and the final aggregated single score KPI (Goedkoop et al., 2013).

LCIA methodology, including ReCiPe 2016, calculate mid-point impact indicators by multiplying the systems elementary flows by a characterization factor for each indicator. Elementary flows include all material and resource flows from the environment, such as resource extraction, and all flows emitted into the environment. These characterization factors are based on scientific research of how each flow contributes to each indicator, as in the ReCiPe 2016 methodology previously mentioned. Midpoint impacts can then be multiplied by a conversion factor representing the degree of damage to the three areas of protection, also known as endpoint impact indicators (Figure 7). ReCiPe also includes a weighting factor for each of the three end-point impact categories, which add up to 100, in order to aggregate the endpoints into a single score. This aggregated score represents the total environmental burden of the assessed maintenance strategy. The user will also have the option to apply their own weightings based on the contextual priorities of the assessment.

4.3 Integration of KPI values into RBAF

A weighting will be applied to the LCIA impact categories, either defined by the user or by ReCiPe 2016, in order to aggregate the results into one environmental burden score (Equation 4), for each assessed scenario defined by the user. This weighting will reflect the degree of importance of each impact category to be in alignment with the priorities of the NRA.

A KPI representing the reduced environmental burden (REB_n) will be calculated, based on the difference of the aggregated environmental burdens for each scenario (EB_n), in relation to the aggregated environmental burdens of the "Do Minimum" reference scenario (EB_{DM}).

$$REB_n = \frac{EB_{DM} - EB_n}{EB_{DM}} \tag{4}$$

The REB_n will then be incorporated as an Environmental KPI into the RBAF *Net Risk Reduction Gain* (*NGGR*) metric described in Section 3.3 of this document and Deliverable 3.1.

The same indexing principal applied in the Reduced Environmental Burden Score Equation 4 is also applied to the individual midpoint impact categories, as well as ReCiPe's areas of protection, or endpoint impact categories, in order to benchmark the assessed maintenance strategies against the corresponding counterfactual reference strategies. This ensures that the KPIs are indexed on a benchmark, between 0 and 1. This approach allows for subsequent integration of reduced environmental impacts into the CERCOM RBAF.

The output from the LCA is considered as an additional KPI within the Environmental category. The KPI name will be entered by the user into the spreadsheet. A weight within the context of the RBAF (Section 3.3) will be assigned by the user to this KPI. The data for this KPI will be inputted using the KPI Ranked Interpolation method within the spreadsheet, under the Environmental category, using 2 ranks with threshold values of 0 and 1. The KPI value outputted from the LCA for each option will then be entered directly into the spreadsheet. Further explanation of the use of the RBAF Software tool is provided in Section 6.3.

Example calculations of two road maintenance scenarios, and a reference maintenance for midpoint impacts, endpoint impacts, and the interpolated REB_n KPI are given in Annex B.1, B.2, and B.3 respectively. These examples are calculated on the basis of maintaining 1m^2 of asphalt pavement, over an assessment period of 15 years.

N.B. The flows and their respective quantities and midpoint impacts given in these examples are indicative for demonstration purposes do not represent figures of actual scenarios for road maintenance. Further applications will be outlined in the case studies presented as part of Work Package 4.

5 Life Cycle Cost Analysis (LCCA)

5.1 Outline of LCCA

The cost related KPIs will be calculated using a lifecycle cost assessment (LCCA) methodology. The net present value (NPV), which takes into account future maintenance and/or preservation cash flows (discounted to base year) and results in a single economic output that allows for comparison between distinct alternatives (Braham 2016; Chen et al. 2019; Diependaele 2018), is used as the lifecycle cost KPI.

5.2 Determination of LCCA Values

The different steps that will be undertaken to determine the NPV for the different maintenance/construction options are presented below (Braham 2016; Chen et al. 2019; Diependaele 2018; Federal Highway Administration (FHWA) 2002; Walls III and Smith 1998):

5.2.1 Identify alternative pavement scenarios

The first step of the LCCA methodology is to identify possible alternative pavement maintenance / rehabilitation / reconstruction strategies. In general, a minimum of two mutually exclusive scenarios are considered for the analysis and the component activities for each alternative strategy is detailed. Although the Federal Highway Administration (FHWA) recommends a minimum analysis period of 35 years (to account for at least one rehabilitation activity and reflect the long-term variations), the analysis period (shorter or longer) is selected based on project specific requirements. However, it is important to mention that all the strategies should be evaluated for equivalent pavement units and same time periods to allow for rational comparisons.

5.2.2 Determine activity and time periods

The information related to the type and duration of the scheduled maintenance/preservation/rehabilitation activities are gathered from the respective roadway agencies.

5.2.3 Compute the discount rates

Real discount rates are used to reflect the rate of change in economic value with the passage of time, while considering the fluctuations in both inflation rates and nominal interest rates (Braham 2016; Chen et al. 2019; Diependaele 2018; Rodríguez-Fernández et al. 2020). The real discount rate (enabling comparison as if the price of commodities does not change over time) is estimated using Equation 5. If the nominal interest rate exceeds the rate of inflation, the discount rate is expressed using Equation 6.

$$r = \frac{1+i_{int}}{1+i_{inf}} - 1 \quad (5)$$

$$r = i_{int} - i_{inf} \quad (6)$$

Where:

r = real discount rates (%),
i_{int} = nominal interest/market interest rate (%), and
i_{inf} = inflation rate (%).

It is recommended to use a reasonable discount rate to account for historical trends with the passage of time and estimate the current value of the future costs. Since 2018, the real discount rates for European countries have been found to vary between 1 and 3% with an average value of 2% (Diependaele 2018). However, precise discount rates should be collected from the respective NRAs or government agencies before the analysis. In addition, sensitivity tests will be performed to account for the effect of varying discount rates on the LCCA results.

5.2.4 Quantify the agency costs

The expenditure incurred by the agency comprises the following elements:

- Initial and future costs including preliminary engineering, contract administration, and construction supervision
- Initial cost of construction (materials and technology)
- Costs associated with routine as well as preventive maintenance (e.g., preservation), resurfacing, and rehabilitation
- Salvage value, and
- Reconstruction costs.

The costs that are common for the various considered pavement alternatives are excluded from the analysis. Further, the routine maintenance costs might be ignored (in case they are not available) as their contribution to the NPV is negligible (Diependaele 2018; Federal Highway Administration (FHWA) 2002; Walls III and Smith 1998). The salvage value (remaining value of the pavement alternative at the end of an analysis period) is incorporated as a negative cost in the LCCA comprising two components:

Residual value: refers to the net value of the pavement in the market after implementing a maintenance strategy, e.g., recycling, at the end-of-life and is expressed as the difference between the economic value of the recycled materials and the costs involved in the removal and recycling process.

Serviceable value: represents the differences in remaining service life between various pavement alternatives at the end of the analysis period and is expressed as the product of the percent of design life at the end of analysis period and the rehabilitation cost of the alternative.

5.2.5 Estimate the user costs

The expenditure incurred by the road users comprises vehicle operating costs (VOC), delay costs (DC), and crash costs (CC). For VOC, the data (pavement roughness, traffic flow, and speed) pertaining to the expenditures incurred by the road users associated with traversing a facility during the periods with and without a maintenance activity should be collected from the road agencies. The DC (price / person-hour) is based on factors namely, average wage, type of vehicle, travel type, and vehicle occupancy. Further, the CC (fatal, non-fatal, and property damage to the road users) is expressed as a function of the number of vehicle miles travelled, crash rates, and the unit cost per crash type.

5.2.6 Compute the net present value

Once all the scenarios, associated timings of the activities, and costs are established, the future costs are discounted to the base year and merged (added and subtracted) with the initial cost to ascertain the NPV as given in Equation 7.

$$NPV = IC + \sum_{k=1}^{n} MC_k \left[\frac{1}{(1+i)^{n_k}}\right] + \sum_{k=1}^{n} RC_k \left[\frac{1}{(1+i)^{n_k}}\right] - \left[\frac{SC}{(1+i)^k}\right] \quad (7)$$

Where:

IC = initial construction cost,
MC_k = maintenance cost of activity k,
RC_k = rehabilitation cost of activity k,
SC = salvage cost,
i = real discount rate (%),
n_k = year into the future of cash flow of activity k, and
$\frac{1}{(1+i)^k}$ = discount factor

5.3 Integration of LCCA into RBAF

The lifecycle cost KPI denoted as $LCCA_{NPV}$ is computed in relation to the "proposed maintenance" scenario and "Do Minimum" scenario using Equation 8.

$$LCCA_{NPV} = \frac{NPV_{DM} - NPV_i}{NPV_{DM}} \tag{8}$$

Where:

NPV_{DM} = net present value of reference "Do Minimum" scenario, and
NPV_i = net present value of i^{th} maintenance scenario.

An example is presented below to show the required inputs (Table 1) for computing the NPV. Scenarios A and B represent the corresponding proposed maintenance activity and the "Do Minimum" scenario. The NPV, shown in Table 2, is determined using Equation 7 and the inputs supplied in Table 1, while the KPI $LCCA_{NPV}$ was determined using Equation 8.

Note: The inputs and outputs supplied in Table 1 *and* Table 2 *are indicative for demonstration only and do not depict actual numbers.*

Table 1. Inputs for computation of the Net Present Value

Cost component	Inputs	Pavement maintenance alternatives	
		A	**B**
Generic information	Pavement type (1 km long, 3.5 m wide, and 0.5 m thickness)	Flexible	
	Year of construction	2010	2008
	Cost of pavement system (€)	33000	35000
Initial construction cost	Analysis period (years)	30	30
	Discount rate (%)	4	4
	Initial construction cost of surface layer (€)	10000	9000
	Material costs (bitumen, cement, aggregates, additives, etc.) (€)	2500	2400
Agency costs (maintenance and/or	Pavement condition assessment costs (E.g.: roughness) (€)	500	500
	Treated length of pavement (km)	1	

rehabilitation expenses)	Treated lane width (m)	3.5	
	Number of treated lanes	1	
	Treated surface thickness (m)	0.15	
	Routine maintenance costs such as cleaning (€)	500	500
	First maintenance cost (including duration per day, lane closures, materials, implementation, labour administrative, etc.) (€)	800	1500
	Life extension (years)	3	4
	Second maintenance cost (including lane closures, materials, labour, implementation, administrative, etc.) (€)	1200	7500
	Life extension (years)	4	5
Salvage value	Economic value of recycled materials (€/T)	10	8
	Costs involved in removal and recycling (€/T)	7	5
	Design life at the end of analysis period (years)	25	30
User costs (vehicle operating costs, delay costs, and crash costs)	Detour length (km)	3	1
	Average daily truck traffic (vehicles per day)	50	70
	Duration of maintenance (days)	2	2
	Average vehicle occupancy for cars and trucks (vehicles per day)	25	28
	Average detour speed (km/h)	15	20
	Average wage of road users (€/h)	10	12
	Average total compensation (€/h)	8	9
	Time value of goods transported in cargo (€/h)	15	17
	Number and severity of crashes (fatal, non-fatal, damage to property)	3	2
	Unit cost per crash type (€)	1000	480
	Pre-construction crash rate per million vehicle km travelled	12	10
	Vehicle miles travelled during workzone	50	44

Table 2. Outputs and Key Performance Indicator for Lifecycle Cost Analysis

Initial construction cost (surface layer)		**Discount factor $(1/(1+i)^{n}{}_{k})$ @ year 30**	**Maintenance costs**				**Salvage value**	
			Agency		User			
A	B		A	B	A	B	A	B
10000	9000	0.308	770	3000	1000	1800	200	50
Net present value; $NPV_A = 11570$, $NPV_B = 13750$ $LCCA_{NPV} = 0.16$								

The output from the LCCA is considered as the lifecycle cost KPI $LCCA_{NPV}$ (under the Cost category, Figure 3). The KPI name is entered into the spreadsheet by the user. A weight within the context of the RBAF (Section 3.3) is assigned by the user to this KPI. The data for this KPI are entered using the KPI Ranked Interpolation method within the spreadsheet, under the Cost category, using 2 ranks with threshold values of 0 and 1. The KPI value (LCCA output) for each option is then entered directly into the spreadsheet. Further explanation on the use of the RBAF Software tool is provided in Section 6.3.

6 Software Tool – User Manual

6.1 Introduction

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. It was important to include the functionality to incorporate additional environmental and social factors to allow NRAs to evaluate options considering a broad range of evaluation criteria. Using the tool, it is possible to assess the "Do Minimum" option as well as up to 3 possible alternative schemes.

As outlined in Figure 3, criteria and KPIs for optimization are considered under the following categories:

- Performance,
- Cost,
- RE&CE,
- Environmental,
- Social.

The Software Tool follows this general format.

The tool caters for the level of maturity of the NRA by allowing:

- Single or multiple entries of KPI under each category,
- User defined numerical inputs or pre-set values to be selected for each criteria/KPI and each construction/maintenance option considered,
- Environmental KPIs to be specified and quantified by the user or LCA to be used to generate global environmental KPI or specific individual environmental KPIs of interest,
- Costs to be defined by the user and inputted directly into the Software Tool in units of currency or LCCA can be used to evaluate costs and input into the software as a KPI,
- Weights to be specified by the user for each criteria/KPI,
- The complexity of the ranked interpolation to be tailored for each KPI by selecting the number of ranks.

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. Further information is provided in Section 6.3.5.

Currently up to 4 Criteria/KPIs can be added under the categories Cost, RE&CE, Environmental and Social in Figure 3. This may be extended if required by the WP4 case studies over the coming months.

6.2 Cover Sheet

The first tab of the Software Tool is the Cover Sheet, a screenshot of this worksheet is presented in Figure 8. This provides details of the current version of the model and a general description. It is envisaged that versions will be updated as the Software Tool is modified if required to suit the requirements of WP4 case studies.

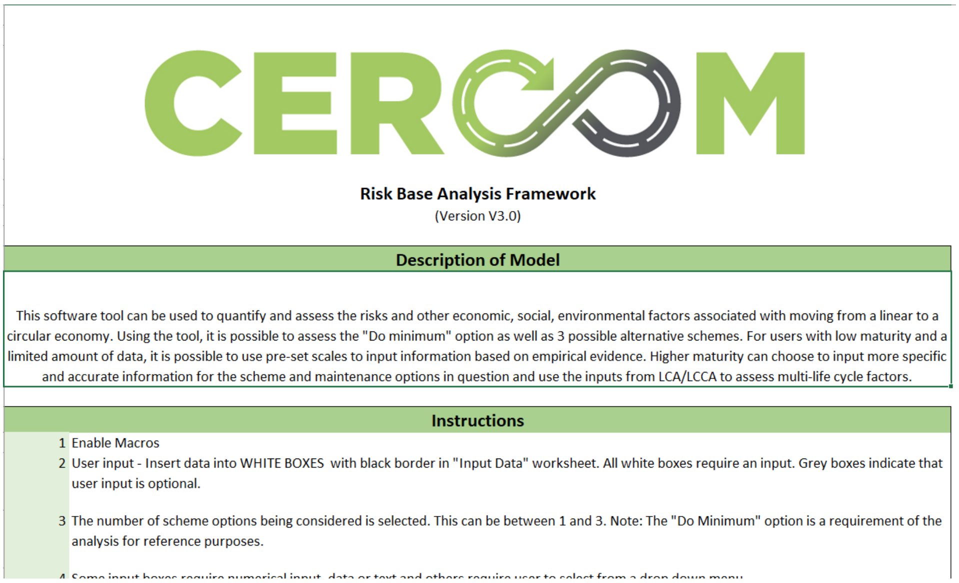


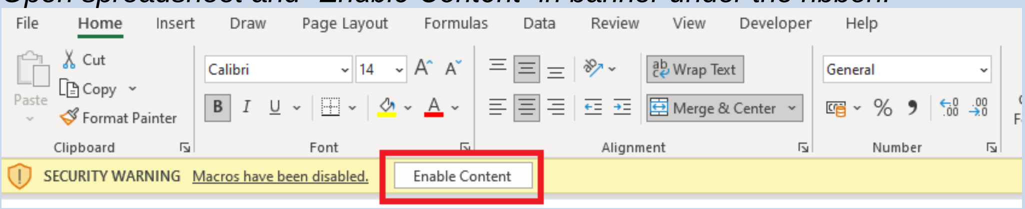
Figure 8. Screenshot of “Cover Sheet” worksheet of CERCOM Software Tool

A summary of the instructions for use are provided in this tab, although, a more detailed User Manual is provided within this document.

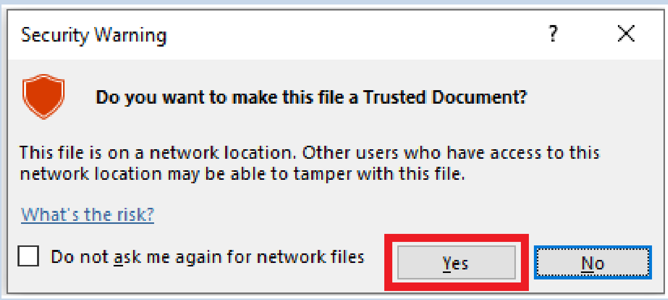
The steps to follow when opening the spreadsheet are outlined below.

The steps required for using the Software Tool are as follows:

1. *Open spreadsheet and “Enable Content” in banner under the ribbon.*



2. *Click “Yes” to confirm this is a trusted document.*



3. *Go to “Cover” tab and review Cover Sheet Instructions*
4. *Go to “Input data” tab and populate required input data. Check no error appears under “Select Weights” table.*
5. *Go to “Results Output” tab and click button “Press Button for Updated Results”*

6.3 *Input Data*

6.3.1 Introduction

There are areas within this worksheet that required different forms of user input. In general, white cells with a black border within the “Input Data" worksheet require user input. Each section of the worksheet and the data required will be described in more detail below.

6.3.2 General Scheme Information

Firstly, the Project Name, Project Number, Date and User Initials can be entered. This information should be entered for good practice but is not required to run the Software Tool. To provide a distinction between cells requiring an input (white), cells with optional inputs are filled with a light grey colour.

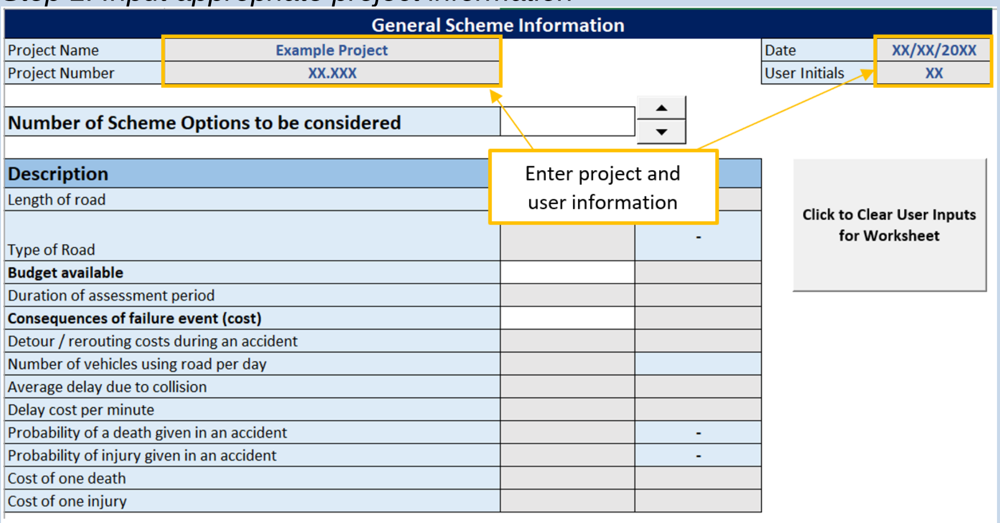
Next, the number of scheme options to be considered alongside the “Do Minimum” scenario must be selected using the toggle buttons. The options available are 1, 2 and 3.

Below this, various information can be provided on the scheme. The white cells require an input in units of currency (e.g., €, £). As well as the value, the associated unit should also be entered in the appropriate column. The cells filled with grey are optional user inputs, where input is not required to run the Software Tool. Within this section there is an option to enter additional scheme information as well as indirect costs associated with a failure event. If no values are entered, these indirect costs are taken as zero. With the exception of “Type of Road”, all data entered in the Value column must be a numerical value greater than or equal to zero.

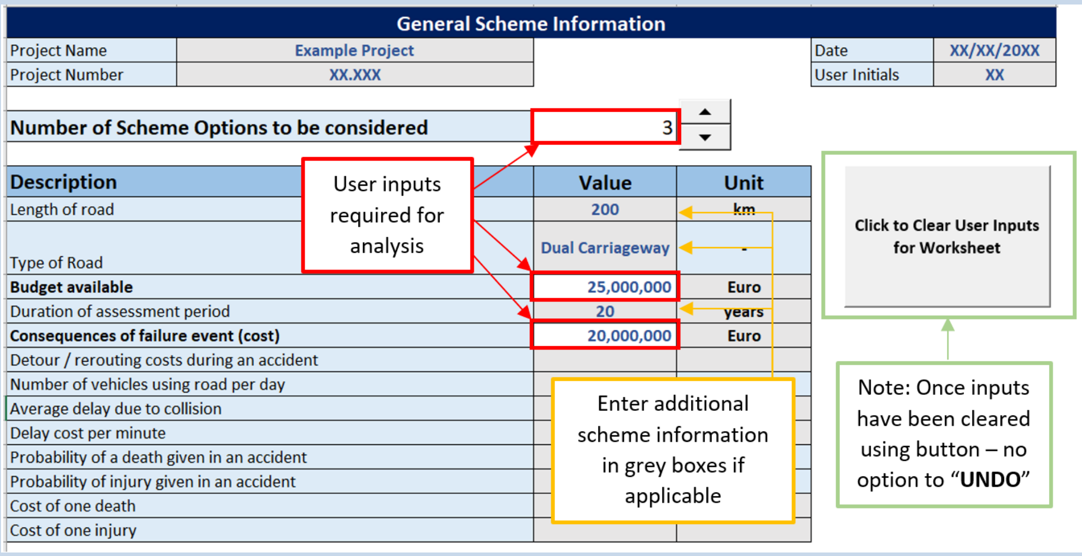
Assumption: the cost/consequences of a failure event are the same for the “Do Minimum” scenario and each of the construction/maintenance options considered.

To populate the **General Scheme Information** section of the spreadsheet, the following steps should be followed:

Step 1: Input appropriate project information



Step 2: Select number of scheme options to be considered alongside "Do Minimum" scenario. Input required cost data and any additional scheme data applicable.



*Note: There is an option to **clear all** user inputs within the "Input Data" worksheet to clear the worksheet of input data for use on a new scheme or project. Once the button is pressed, there is **no option to UNDO** this action. It is recommended to save project as a new spreadsheet before using this button.*

6.3.3 Input Categories and Select KPIs

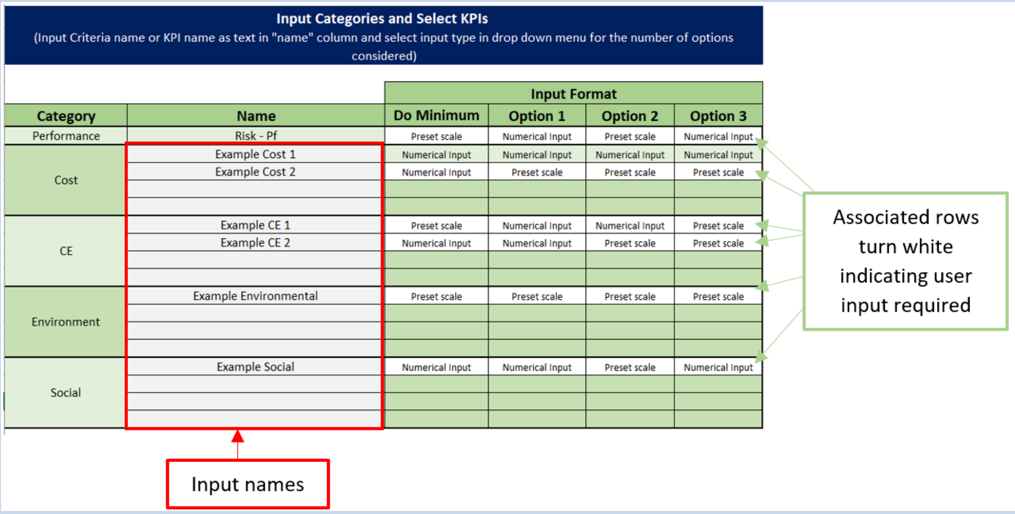
Within each of the categories outlined in Figure 3, input can be provided by the user on Criteria and KPIs to be considered when running the Software Tool. As this is a Risk Based Assessment Framework, risk associated with technical performance must be quantified in terms of probability of a particular failure event, as well as the associated consequences/cost (specified above in General Scheme Information). Values for Probability of Failure for the considered limit state must be provided for the "Do Minimum" scenario as well as each of the construction/maintenance options considered. The input format for each value can be selected by the user. The user can choose to input a Numerical Value or choose from a pre-set scale. Within this section, the user just selects the format of data to be entered. The data is entered by the user in a section further below, entitled **Scheme Options – Input Data**.

To calculate *CPI* (Equation 3), a cost associated with each scenario must be entered as a numerical value in units of currency. Therefore, for the first row within the cost category, numerical values are required as an input and cannot be changed to Pre-set Scale. The name and type of cost can be defined by the user (e.g., construction cost, whole life cost, etc.). The numerical values for each scenario and the unit of measurement are inputted in a section of the spreadsheet further below. As an alternative to inputting cost values for the calculation of *CPI*, the user can leave this first row blank and enter cost data as KPIs in the second and subsequent rows within the cost category. For example, the cost analysis for each option may be calculated using LCCA and inputted into the Software Tool as $LCCA_{NPV}$ (see Section 4 for detailed discussion of LCCA). The user should be familiar with the calculations of *CPI* and $LCCA_{NPV}$ to ensure certain costs are not considered twice within different criteria. It is recommended that costs are considered using either *CPI* **or** *LCCA*$_{NPV}$. If costs are calculated using *CPI*, for example, considering only direct construction/maintenance costs, there is an option to include additional cost KPIs along with this input to reflect other factors such as Residual Value.

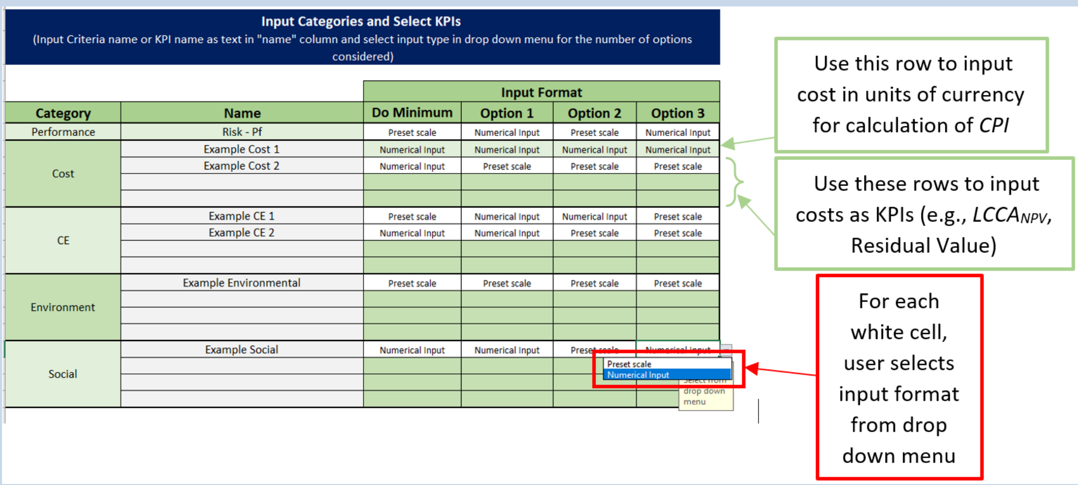
For additional Criteria/KPIs within the cost category and remaining categories, the Criteria name or KPI name can be inputted in the grey boxes. Once a name is inputted, the associated row turns from green to white indicating that user input is required to select the format of input data to be provided. Names of KPIs from LCA and LCCA can be entered here. The data is entered by the user in a section further below, entitled **Scheme Options – Input Data**.

To populate the **Input Categories and Select KPIs** section of the spreadsheet, the following steps should be followed:

Step 1: Input Criteria KPI Names.



Step 2: Select Input format for each scenario.



Note: If the input format is selected and the Criteria/KPI name is subsequently deleted, the shading of the associated row will turn from white to green, and the selected input format will remain, but will not be considered in the analysis.

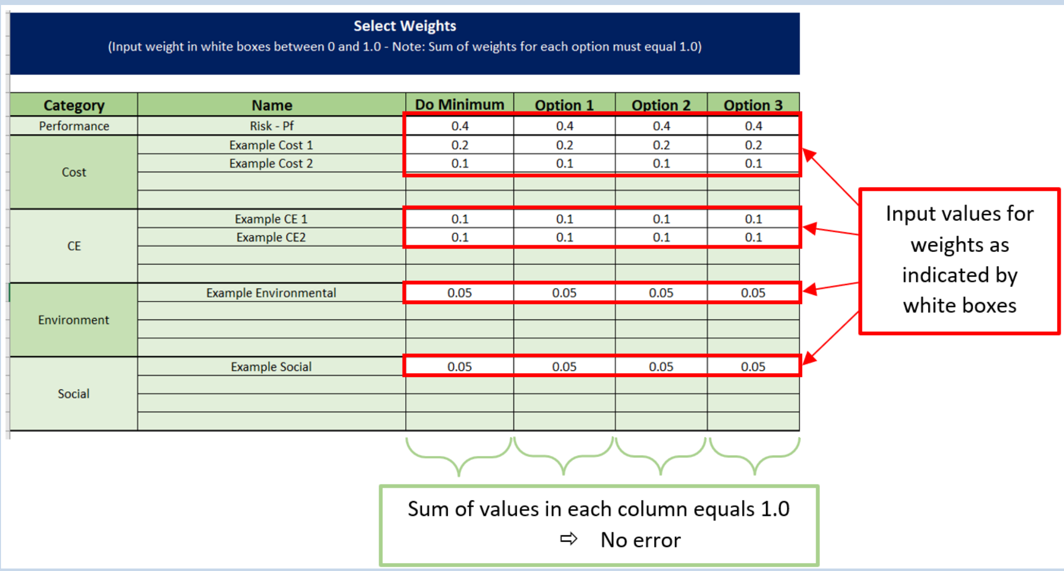
6.3.4 Select Weights

A weight must be applied to each Criteria/KPIs specified above. The names of the Criteria/ KPI specified above automatically appear in the table. Different weights can be assigned for each scenario, but it is recommended that the same weights are used for each option for a meaningful, comparable output result.

NB: The sum of the weights in each column of the table must equal to 1.0. An error will be displayed below the table if the sum is not equal to 1.0 for each of the scenarios considered, and results will not be displayed in the “Results Output” worksheet.

To populate the **Select Weights** section of the spreadsheet, the following steps should be followed:

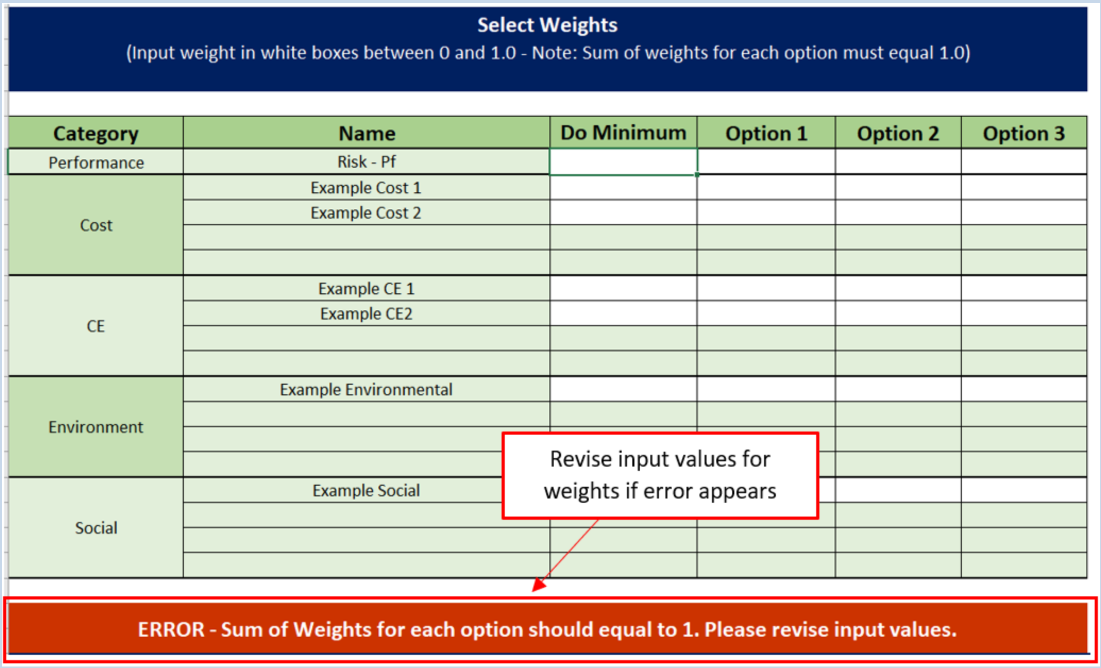
Step 1: Enter values between 0.0 and 1.0 for each white box in the table. Ensure the sum of weights for each column is equal to 1.0.



Select Weights
(Input weight in white boxes between 0 and 1.0 - Note: Sum of weights for each option must equal 1.0)

Category	Name	Do Minimum	Option 1	Option 2	Option 3
Performance	Risk - Pf	0.4	0.4	0.4	0.4
Cost	Example Cost 1	0.2	0.2	0.2	0.2
	Example Cost 2	0.1	0.1	0.1	0.1
CE	Example CE 1	0.1	0.1	0.1	0.1
	Example CE2	0.1	0.1	0.1	0.1
Environment	Example Environmental	0.05	0.05	0.05	0.05
Social	Example Social	0.05	0.05	0.05	0.05

Step 2: Check for errors.

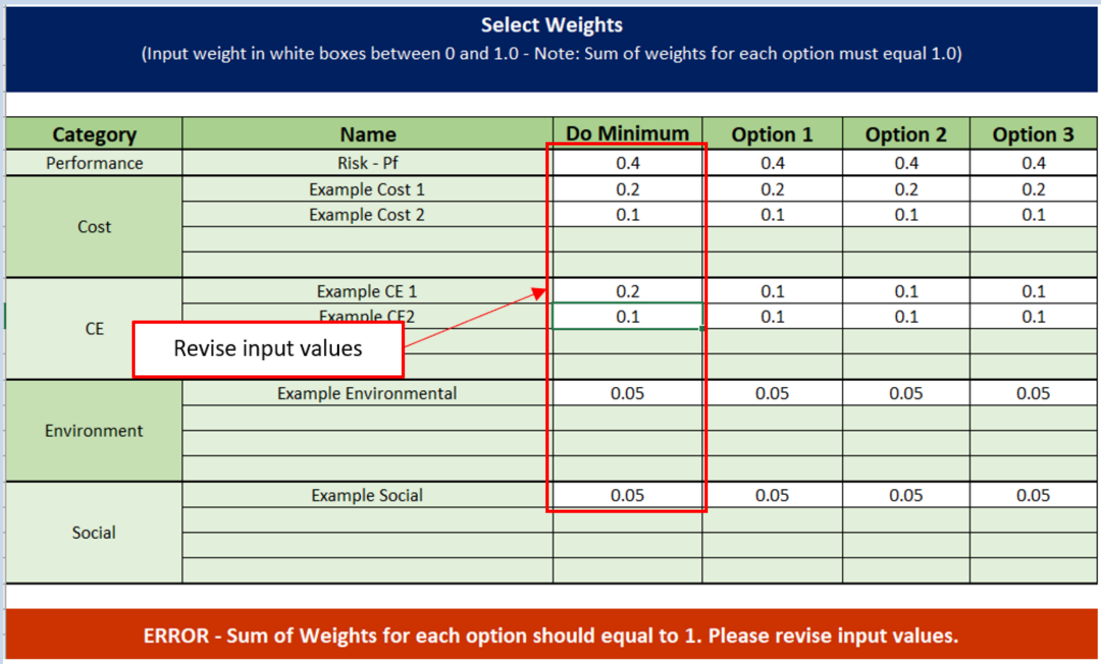


Select Weights
(Input weight in white boxes between 0 and 1.0 - Note: Sum of weights for each option must equal 1.0)

Category	Name	Do Minimum	Option 1	Option 2	Option 3
Performance	Risk - Pf				
Cost	Example Cost 1				
	Example Cost 2				
CE	Example CE 1				
	Example CE2				
Environment	Example Environmental				
Social	Example Social				

Revise input values for weights if error appears

ERROR - Sum of Weights for each option should equal to 1. Please revise input values.



Select Weights
(Input weight in white boxes between 0 and 1.0 - Note: Sum of weights for each option must equal 1.0)

Category	Name	Do Minimum	Option 1	Option 2	Option 3
Performance	Risk - Pf	0.4	0.4	0.4	0.4
Cost	Example Cost 1	0.2	0.2	0.2	0.2
	Example Cost 2	0.1	0.1	0.1	0.1
CE	Example CE 1	0.2	0.1	0.1	0.1
	Example CE2	0.1	0.1	0.1	0.1
Environment	Example Environmental	0.05	0.05	0.05	0.05
Social	Example Social	0.05	0.05	0.05	0.05

Revise input values

ERROR - Sum of Weights for each option should equal to 1. Please revise input values.

Note: Values in the unused cells (green) are not considered in the assessment and will not be included in the sum of weights for each column.

6.3.5 Scheme Options – Input Data

The formatting of the **Scheme Options – Input Data** section is automatically customised based on the information already inputted by the user.

Firstly, for the Performance Category, the value of failure probability (P_f) to calculate risk is a value between 0 and 1.0. Where the user has selected Numerical Input, the value between 0 and 1 should be entered as indicated by the white cells. For options where the user selected Pre-set scale, two inputs are required, as indicated by the white cells. Pre-set P_f values for the calculation of risk are based on two inputs selected by the user from a drop down menu, one related to the performance characteristics of the construction/ maintenance option and the other related to the level of uncertainty the user has in relation to the performance characteristics. For further information on the effect of uncertainty on the calculation of P_f, please refer to Section 5.2.2 of Deliverable 3.1.

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. For the purposes of this Software Tool, the pre-set values for P_f incorporated within the software are presented in Table 3 and Table 4. Current values in the tables are purely indicative for comparison purposes and it is likely that the values will be revised and updated as data becomes available for the case studies in WP4.

Table 3. Pre-set P_f values for “Do Minimum” Scenario

		Performance		
		Below Average	Average	Above Average
Uncertainty	Low	0.85	0.75	0.6
	Medium	0.9	0.85	0.75
	High	1	0.9	0.85

Table 4. Pre-set P_f values for Construction/Maintenance Options

		Performance		
		Below Average	Average	Above Average
Uncertainty	Low	0.15	0.1	0.05
	Medium	0.2	0.15	0.1
	High	0.25	0.2	0.15

Under the Cost heading, a numerical value for costs associated with each option can be inputted as required for the calculation of *CPI* (see Section 3.3 and/or Deliverable 3.1 for further information). The name entered in the first row of the cost category under “Input Categories and Select KPIs” above is automatically entered here. If this is blank, no cost input data is required. Where input is required, the unit of currency should be the same as the Input unit for "Budget available" in the General Scheme Information section above.

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, as selected above. Where pre-set scale is chosen, a drop down menu is provided for the user to select the appropriate KPI value from a pre-set list of values. This list provides a range of options between 0 and 1 with an associated generic description, as the pre-set options are not KPI specific. Table 5 outlines the pre-set options available, with two examples of what these values could represent for specific RE/CE and Social KPIs.

Table 5. Pre-set KPI values incorporated within RBAF and associated examples

KPI Value	Description	RE/CE - Recycled Content Example	Social - Working Hours Example
0	No commitment to KPI ambition	No recycled content	No policy or assessment of working hours
0.1	Below minimum industry practice	5% recycled content	Policy in place outlining appropriate working hours
0.25	Minimum industry practice	10% recycled content	Policy in place for monitoring working hours
0.5	Exceed industry practice	40% recycled content	Strategy for improving current practices
0.75	Far-exceeds industry practice	70% recycled content	Targets specified and steps taken to implement improvements
1	KPI ambition achieved	100% recycled content	Fully implemented – policy targets achieved

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. When the data is entered to perform the ranked interpolation method for each required option, a toggle button can be used on the graph in the spreadsheet to view the KPI Ranked Interpolation graph for each KPI considered. The location of each scheme option can be viewed on the graph (not including pre-set options).

Note: when entering data, least favourable and most favourable threshold values must be entered before intermediate ranks.

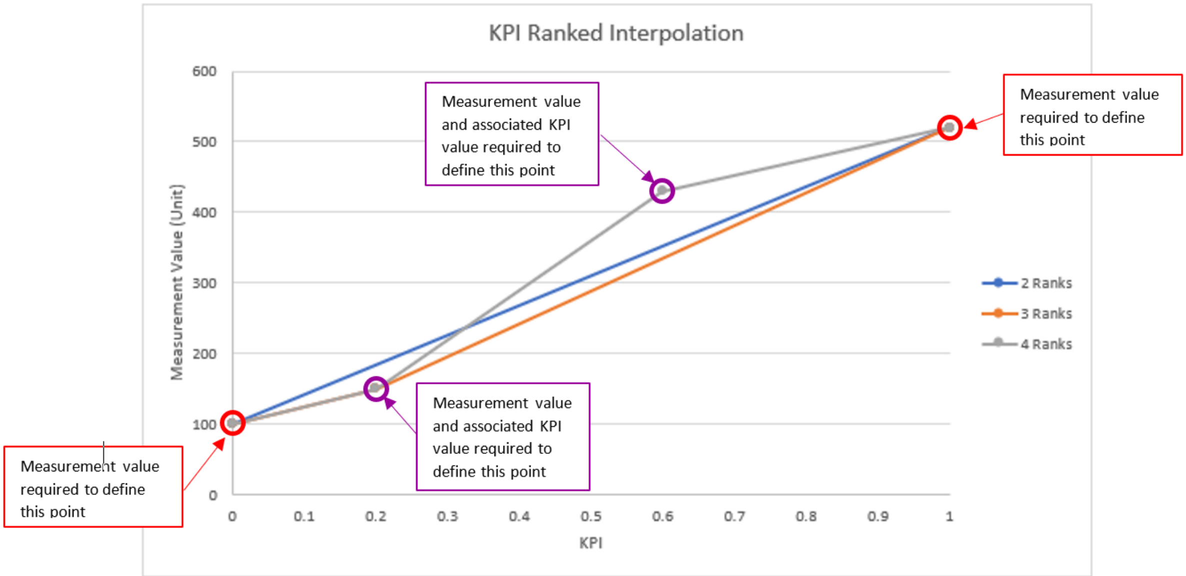
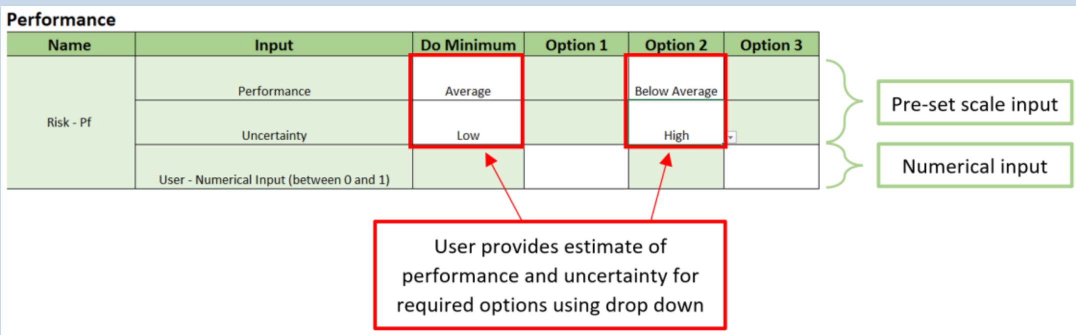


Figure 9. Data required to perform ranked interpolation.

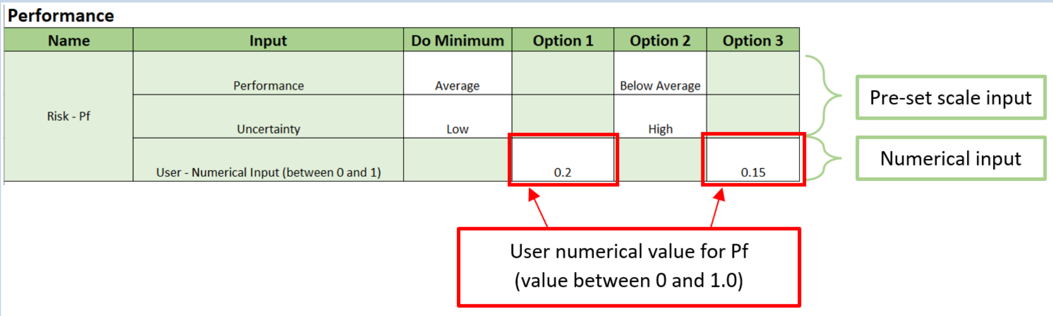
Unlike Figure 9, in some cases, the graph will have a negative slope depending on the characteristics of the KPI considered. For example, for carbon cost, a higher value of carbon will be least favourable (KPI of 0), and a lower value will be assigned to the most favourable rank (KPI of 1.0), leading to a graph with a negative slope. A KPI relating to recycled content, however, will have a positive slope.

To populate the **Scheme Options – Input Data** section of the spreadsheet, the following steps should be followed:

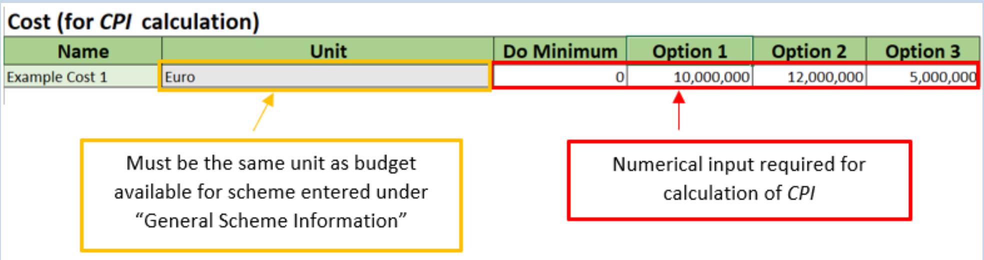
Step 1: For Pre-set scale input values for Risk – Pf, select options from drop down menu for Performance and Uncertainty. The cells requiring input will appear white.



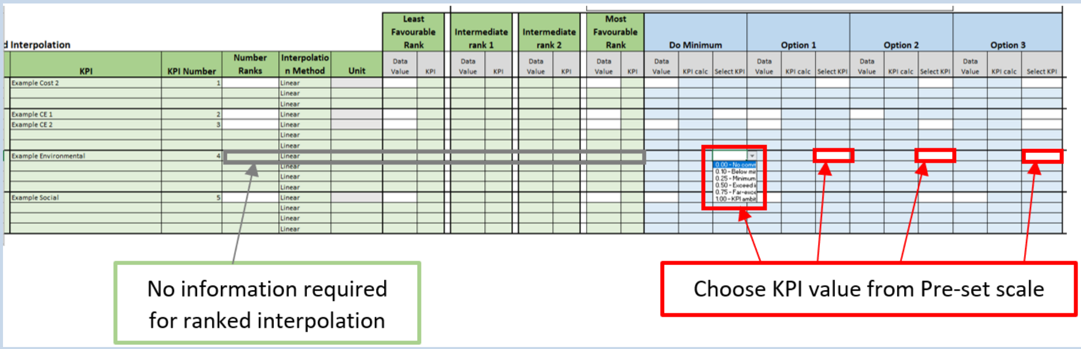
Step 2: For Numerical input for Risk – Pf, input values between 0 and 1 for each option required (white cells).



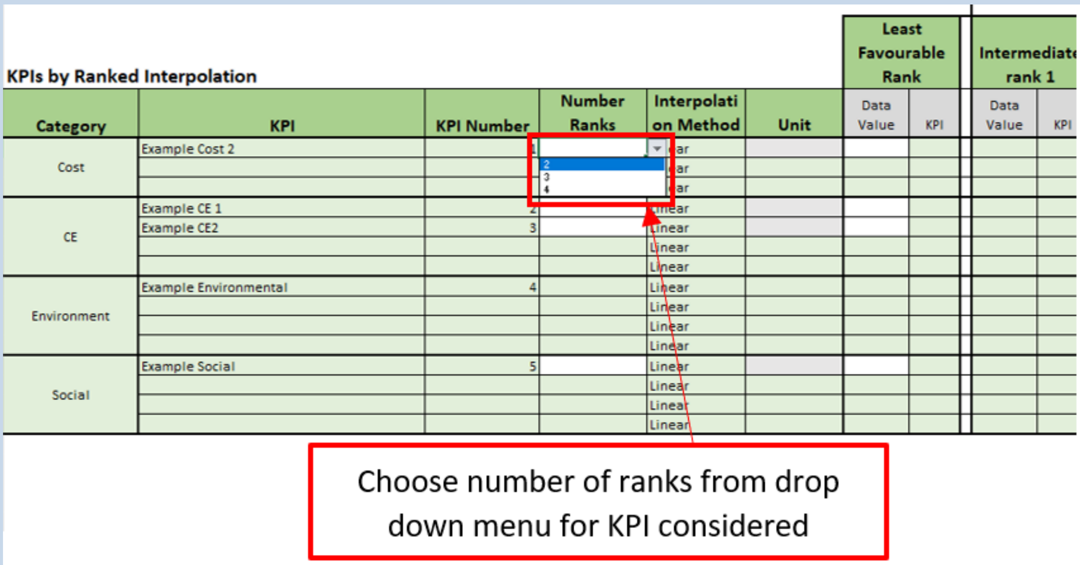
Step 3: Input numerical value costs associated with each option if required. The cost units should be the same as the Input unit for "Budget available" in the General Scheme Information section above.



*Step 4: Where Pre-set scale is chosen above for **ALL** scenarios, no data is required for Ranked Interpolation. A drop down menu is provided for the user to select the appropriate KPI value from a pre-set list of values.*

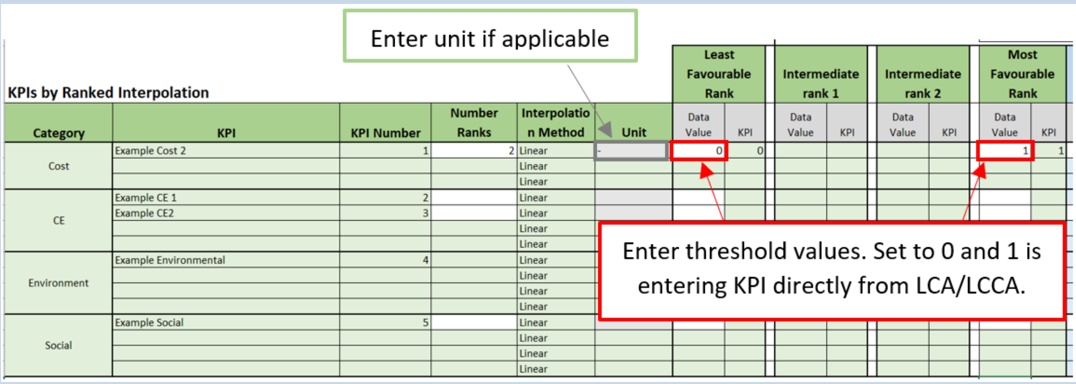


Step 5: Where Numerical Input is chosen for any scenario, information must be provided by the user to carry out ranked interpolation. Firstly, is it necessary to choose the number of ranks (options between 2, 3, 4 from drop down menu).

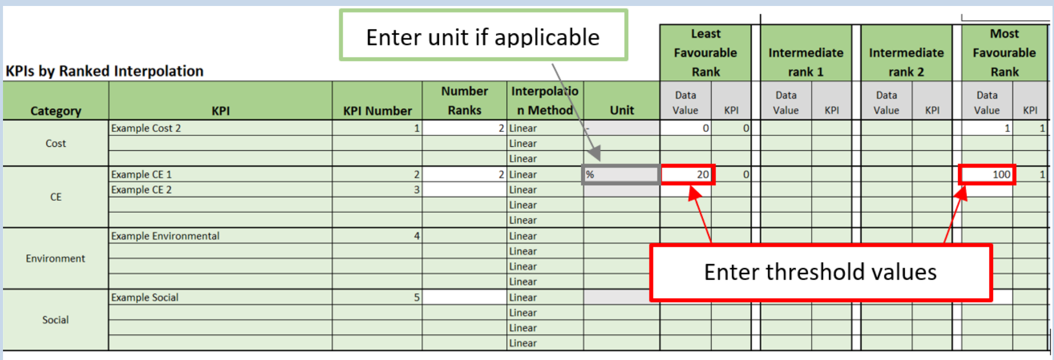


Step 6: Enter unit and threshold values for least favourable and most favourable ranks.

Note: Numerical values for Least favourable may be higher than most favourable.



Note: When inputting KPI values direct from the LCA or LCCA, select 2 ranks and threshold values of 0 and 1 (as indicated in the first row above). The KPI data value for each option can then be entered in Step 8.



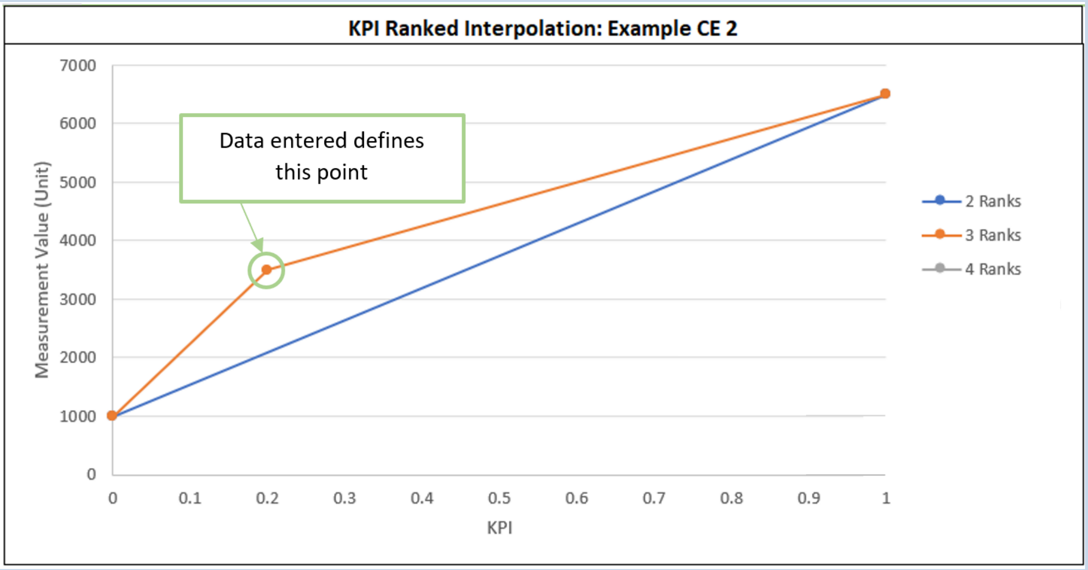
Step 7: Enter data value and KPI value for intermediate ranks (if number of ranks is greater than 2)

KPIs by Ranked Interpolation

						Least Favourable Rank		Intermediate rank 1		Intermediate rank 2		Most Favourable Rank	
Category	KPI	KPI Number	Number Ranks	Interpolation Method	Unit	Data Value	KPI	Data Value	KPI	Data Value	KPI	Data Value	KPI
Cost	Example Cost 2	1	2	Linear	-	0	0					1	1
				Linear									
				Linear									
CE	Example CE 1	2	2	Linear	%	20	0					100	1
	Example CE 2	3	3	Linear	Tons	1000	0	3500	0.2			6500	1
				Linear									
				Linear									
Environment	Example Environmental	4		Linear									
				Linear									
				Linear									
				Linear									
Social	Example Social	5	4	Linear									
				Linear									
				Linear									
				Linear									

3 or 4 Ranks: Enter data value between threshold values

3 or 4 Ranks: Enter KPI value between 0 and 1.0 corresponding to data vale

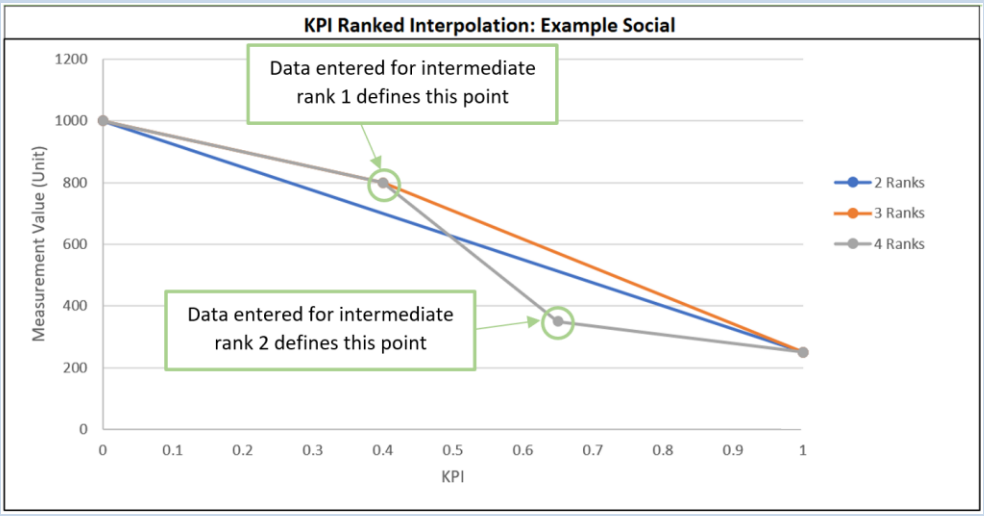


KPIs by Ranked Interpolation

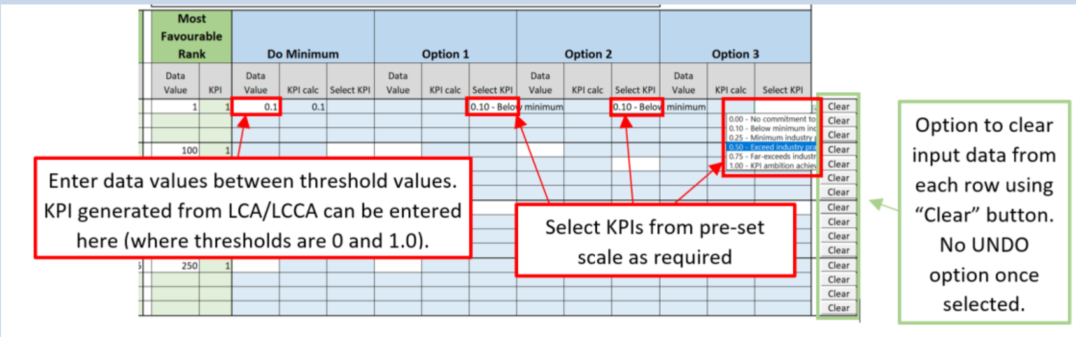
						Least Favourable Rank		Intermediate rank 1		Intermediate rank 2		Most Favourable Rank	
Category	KPI	KPI Number	Number Ranks	Interpolation Method	Unit	Data Value	KPI	Data Value	KPI	Data Value	KPI	Data Value	KPI
Cost	Example Cost 2	1	2	Linear	-	0	0					1	1
				Linear									
				Linear									
CE	Example CE 1	2	2	Linear	%	20	0					100	1
	Example CE 2	3	3	Linear	Tons	1000	0	3500	0.2			6500	1
				Linear									
				Linear									
Environment	Example Environmental	4		Linear									
				Linear									
				Linear									
				Linear									
Social	Example Social	5	4	Linear	km	1000	0	800	0.4	350	0.65	250	1
				Linear									
				Linear									
				Linear									

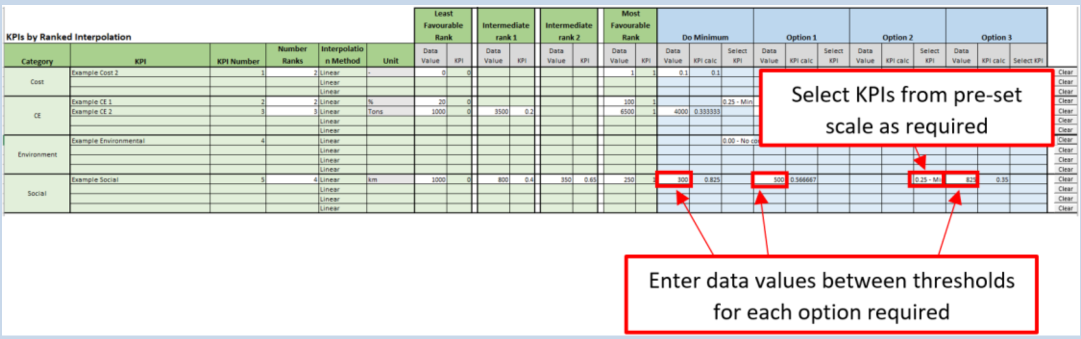
4 Ranks: Enter data value between Intermediate Rank 1 value and Most Favourable Rank value

4 Ranks: Enter KPI value between KPI Intermediate rank 1 and 1.0



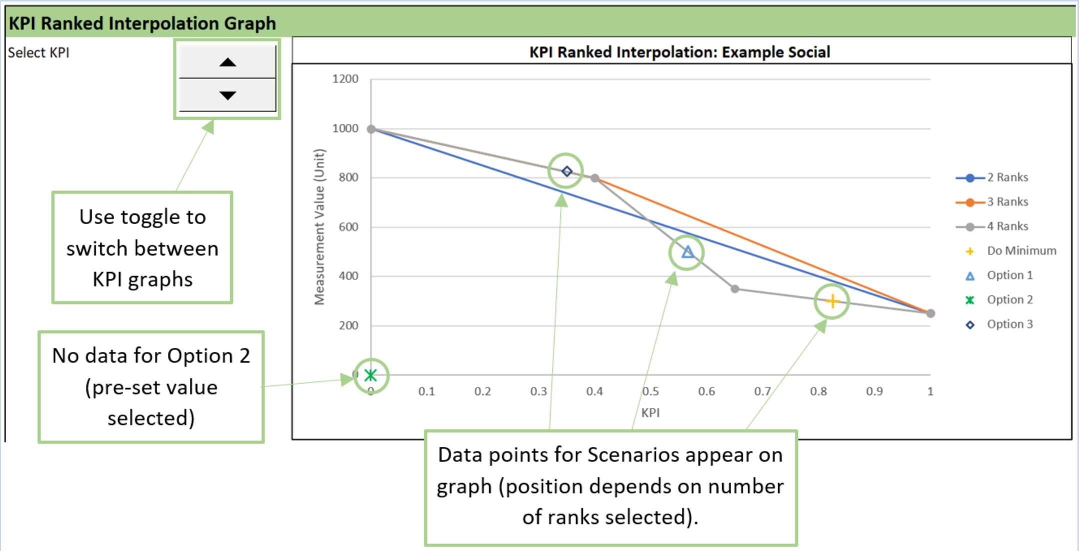
Step 8: Enter data value for "Do Minimum" scenario and each scheme option as required (data value entered must be between threshold values provided). KPI value is calculated automatically based on data provided. Select any pre-set options from the drop down menu.





Note: There is a button at the end of each row to clear user input data from that row. Once the data has been cleared, there is ***no option to undo*** *this action.*

Step 9: Toggle through graphs to view and check values inputted for ranked interpolation. Where more than 2 ranks are selected, the graph shows a plot of the data for the indicated number of ranks, as well as the equivalent plot if *less ranks were selected. (Note: pre-set values selected do not appear on the graph). There are 16 options within the toggle button corresponding to the number of potential KPIs. Rows populated with KPIs appear together and blank rows appear at the end (use down arrow of toggle button to skip from blank rows to populated rows).*

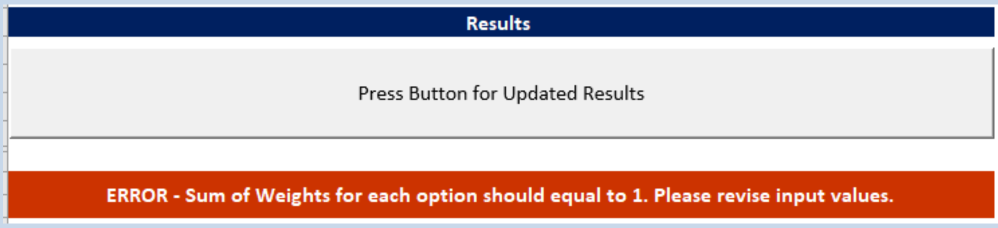


6.4 Results Output

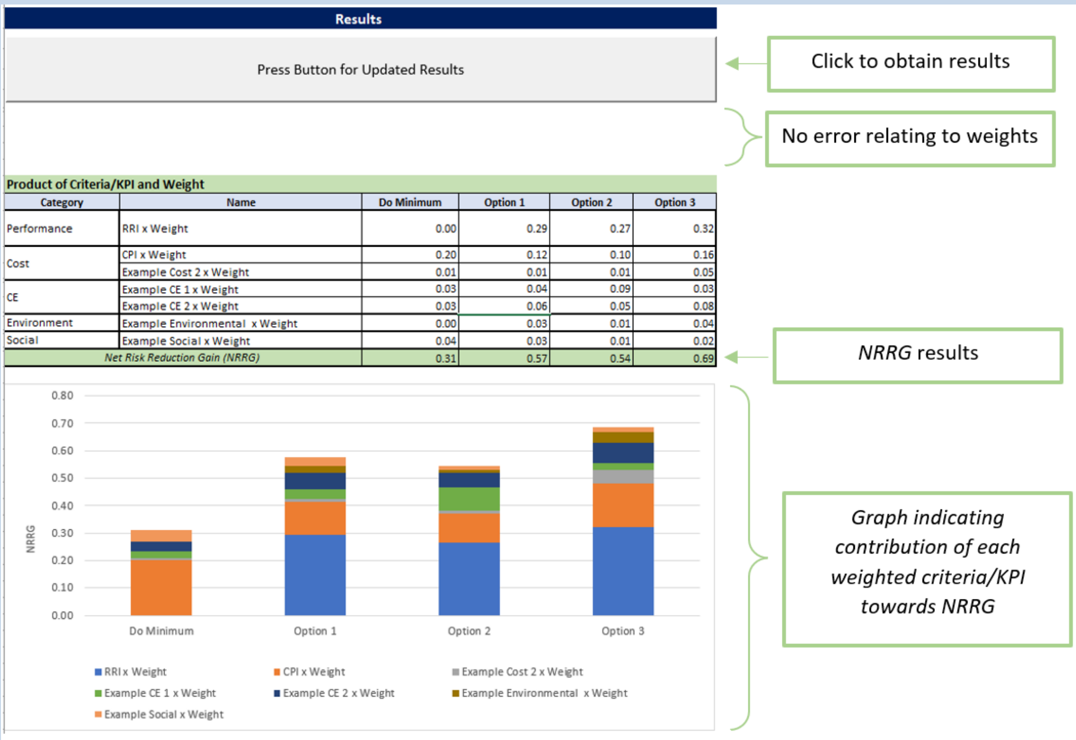
A table and bar chart are presented outlining the overall value of Net Risk Reduction Gain ($NRRG$) for the "Do Minimum" option and each scheme option considered. The construction/maintenance options with the highest $NRRG$ value is considered the most advantageous option. The product of Criteria/KPI value and assigned weight is also presented for each option to highlight the contribution of each Criteria/KPI type to the overall value of $NRRG$.

To view results in the **Results Output** worksheet, the following steps should be followed:

Step 1: Select the Results Output worksheet. Check if an error appears relating to the Sum of Weights. If error appears, please revise weights entered in Input Data worksheet.



Step 2: If no error is present, click “Press Button for Updated Results” to view results table and graph. The construction/maintenance options with the highest $NRRG$ is then selected as the most advantageous.



Category	Name	Do Minimum	Option 1	Option 2	Option 3
Performance	RRI x Weight	0.00	0.29	0.27	0.32
Cost	CPI x Weight	0.20	0.12	0.10	0.16
	Example Cost 2 x Weight	0.01	0.01	0.01	0.05
CE	Example CE 1 x Weight	0.03	0.04	0.09	0.03
	Example CE 2 x Weight	0.03	0.06	0.05	0.08
Environment	Example Environmental x Weight	0.00	0.03	0.01	0.04
Social	Example Social x Weight	0.04	0.03	0.01	0.02
	Net Risk Reduction Gain (NRRG)	0.31	0.57	0.54	0.69

Note: If errors appear in the table, please revise input values in Input Data worksheet. If changes are made to the Input Data worksheet, ensure button “Press Button for Updated Results” in the Results Output worksheet is clicked each time to view the updated results.

7 Conclusion

The CERCOM Software Tool provides a user-friendly, versatile means for NRAs to assess risk of using circular innovative methods and materials along with additional criteria to facilitate optimum selection of scheme options and associated procurement practices. The user manual provides a step-by-step guide on how to use the Software Tool, with background information on the RBAF as well as the LCA and LCCA methods adopted as part of the overall framework approach.

The user manual describes the best use of the tool but also the flexibility available within the software to allow the user to adapt it to suit the maturity of the NRA as well as the desired level of complexity. It is expected that in most cases, this will be dictated by the data available at the time of analysis.

The LCA and LCCA methods have been developed, as outlined in this report, and will be implemented as part of the case studies in Work Package 4. It is envisaged that all the tools and methods described will be updated and refined based on the practical experience gained from analysing the case studies. 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. This will be available to CEDR NRAs to customise for use in procurement in the move towards a circular economy.

Annex A: References

Braham, A. 2016. “Comparing Life-Cycle Cost Analysis of Full-Depth Reclamation Versus Traditional Pavement Maintenance and Rehabilitation Strategies:” *Transportation Research Record*, 2573 (1): 49–59. SAGE Publications Inc. https://doi.org/10.3141/2573-07.

Chen, J.-S., C. H. Yang, and C.-T. Lee. 2019. “Field evaluation of porous asphalt course for life-cycle cost analysis.” *Construction and Building Materials*, 221: 20–26. https://doi.org/10.1016/j.conbuildmat.2019.06.072.

Diependaele, M. 2018. *A guide on the basic principles of Life-Cycle Cost Analysis (LCCA) of pavements*. 38. Brussels, Belgium: EUPAVE.

European Commission. 2020. *European Platform on Life Cycle Assessment*. [online] Available at: <https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml>.

Federal Highway Administration (FHWA). 2002. *Life-Cycle Cost Analysis Primer*. Washington DC, United States: Federal Highway Administration.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A., Struijs, J. and van Zelm, R., 2013. *ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*. Report I: Characterisation v1.08. Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer.

Walls III, J., and M. R. Smith. 1998. *Life-Cycle Cost Analysis in Pavement Design - Interim Technical Bulletin*. 107. Washington DC, United States: Federal Highway Administration.

Annex B: LCA Calculation Examples

B.1: Midpoint Impact Indicators

Scenarios and Ref. Scenario for 1m2 of Road Maintenance for 15yrs	Flow	Flow Quantity (FQ) [kg]	Characterization Factors (CF)	SUM quantities per MP Impact indicator (∑CF*FQ)	Midpoint (MP) Impact Category (Unit)
Scenario 1 (e.g. Resurfacing with Aggregate Recycling) [n=1]	*Input Flow A*	30	*17 CFs per flow*	43	*Global Warming - (kg CO2 eq.)*
	Input Flow B	50	"-"	15	*Stratospheric ozone depletion - (kg CFC11 eq.)*
	Input Flow C	1	"-"	19	*Ionzing Radiation - (kBq Co-60 emitted to air eq.)*
	Input Flow D	10	"-"	35	*Fine particulate matter formation - (kg PM2.5 eq.)*
	Input Flow E	4	"-"	34	*Photochemical oxidant formation: Terrestrial Ecosystems (kg NOx eq.)*
	Output Flow A	2	"-"	14	*Photochemical oxidant formation: Human Health (kg NOx eq.)*
	Output Flow B	6	"-"	45	*Human Toxicity - (cancer) (kg 1,4-DCB emitted to urban air eq.)*
	Output Flow C	1	"-"	47	*Human Toxicity - (non-cancer) (kg 1,4-DCB emitted to urban air eq.)*
	Output Flow D	4	"-"	47	*Water consumption - (m3 consumed)*
	Recycled Flow E	-10	"-"	27	*Terrestrial Acidification - (kg SO2 eq.)*
				22	*Terrestrial Ecotoxicity - (kg 1,4-DBC emitted to industrial soil eq.)*
				37	*Land use - occupation and transformation (m2·annual crop eq)*
				35	*Freshwater Eutrophication - (kg P to freshwater eq.)*
				31	*Freshwater Ecotoxicity - (kg 1,4-DBC emitted to freshwater eq.)*
				15	*Marine Ecotoxicity - (kg 1,4-DBC emitted to sea water eq.)*
				42	*Mineral resource scarcity (kg CU eq.)*
				37	*Fossil resource scarcity (kg oil eq.)*
Scenario 2 (e.g. Rejuvenation) [n=2]	*Input Flow A*	50	"-"	13	*Global Warming - (kg CO2 eq.)*
	Input Flow B	20	"-"	18	*Stratospheric ozone depletion - (kg CFC11 eq.)*
	Output Flow A	6	"-"	11	*Ionzing Radiation - (kBq Co-60 emitted to air eq.)*
	Output Flow B	9	"-"	11	*Fine particulate matter formation - (kg PM2.5 eq.)*
	Output Flow C	10	"-"	4	*Photochemical oxidant formation: Terrestrial Ecosystems (kg NOx eq.)*
	Output Flow D	15	"-"	6	*Photochemical oxidant formation: Human Health (kg NOx eq.)*
				10	*Human Toxicity - (cancer) (kg 1,4-DCB emitted to urban air eq.)*
				20	*Human Toxicity - (non-cancer) (kg 1,4-DCB emitted to urban air eq.)*
				13	*Water consumption - (m3 consumed)*
				6	*Terrestrial Acidification - (kg SO2 eq.)*
				7	*Terrestrial Ecotoxicity - (kg 1,4-DBC emitted to industrial soil eq.)*
				20	*Land use - occupation and transformation (m2·annual crop eq)*
				7	*Freshwater Eutrophication - (kg P to freshwater eq.)*
				17	*Freshwater Ecotoxicity - (kg 1,4-DBC emitted to freshwater eq.)*
				19	*Marine Ecotoxicity - (kg 1,4-DBC emitted to sea water eq.)*
				12	*Mineral resource scarcity (kg CU eq.)*
				14	*Fossil resource scarcity (kg oil eq.)*
Ref. Scenario (e.g. Traditional Resurfacing) [rf]	*Input Flow A*	100	"-"	46	*Global Warming - (kg CO2 eq.)*
	Input Flow B	40	"-"	58	*Stratospheric ozone depletion - (kg CFC11 eq.)*
	Input Flow C	25	"-"	44	*Ionzing Radiation - (kBq Co-60 emitted to air eq.)*
	Input Flow D	10	"-"	20	*Fine particulate matter formation - (kg PM2.5 eq.)*
	Output Flow A	15	"-"	39	*Photochemical oxidant formation: Terrestrial Ecosystems (kg NOx eq.)*
	Output Flow B	25	"-"	39	*Photochemical oxidant formation: Human Health (kg NOx eq.)*
	Output Flow C	20	"-"	49	*Human Toxicity - (cancer) (kg 1,4-DCB emitted to urban air eq.)*
	Output Flow D	10	"-"	39	*Human Toxicity - (non-cancer) (kg 1,4-DCB emitted to urban air eq.)*
	Output Flow E	10	"-"	53	*Water consumption - (m3 consumed)*
				29	*Terrestrial Acidification - (kg SO2 eq.)*
				46	*Terrestrial Ecotoxicity - (kg 1,4-DBC emitted to industrial soil eq.)*
				19	*Land use - occupation and transformation (m2·annual crop eq)*
				46	*Freshwater Eutrophication - (kg P to freshwater eq.)*
				31	*Freshwater Ecotoxicity - (kg 1,4-DBC emitted to freshwater eq.)*
				46	*Marine Ecotoxicity - (kg 1,4-DBC emitted to sea water eq.)*
				52	*Mineral resource scarcity (kg CU eq.)*
				47	*Fossil resource scarcity (kg oil eq.)*

B.2: Endpoint Impact Indicators

Maintenance Scenarios and Ref. Scenari+A1:I64o for 1m2 of Road Maintenance	SUM of quantities for each MP Impact indicator (∑CF*FQ)	Midpoint (MP) Impact Categories [Unit]	MP to EP Conversion Factors (CoF)	Units	Endpoint (EP) impact categories	Enqpoint Values (EP) [CoF*MP]	SUM EP (Damage to human health, ecosystems, resource availability)	Unit
Scenario 1 (e.g. Resurfacing with Aggregate Recycling) [n=1]	43	*Global Warming - (kg CO2 eq.)*	9,28E-07	*DALY/kg CO2 eq.*	*Global Warming - Human health*	3,99E-05	3,03E-02	*DALY*
	15	*Stratospheric ozone depletion - (kg CFC11 eq.)*	5,31E-04	*DALY/kg CFC11 eq.*	*Stratospheric ozone depletion - Human health*	7,97E-03		
	19	*Ionzing Radiation - (kBq Co-60 emitted to air eq.)*	8,50E-09	*DALY/kBq Co-60 emitted to air eq.*	*Ionzing Radiation - Human health*	1,62E-07		
	35	*Fine particulate matter formation - (kg PM2.5 eq.)*	6,29E-04	*DALY/kg PM2.5 eq.*	*Fine particulate matter formation - Human health*	2,20E-02		
	34	*Photochemical oxidant formation: Terrestrial Ecosystems (kg NOx eq.)*	9,10E-07	*DALY/kg NOx eq.*	*Photochemical ozone formation - Human health*	1,27E-05		
	14	*Photochemical oxidant formation: Human Health (kg NOx eq.)*	3,32E-06	*DALY/kg 1,4-DCB emitted to urban air eq.*	*Toxicity - Human health (cancer)*	1,49E-04		
	45	*Human Toxicity - (cancer) (kg 1,4-DCB emitted to urban air eq.)*	2,28E-07	*DALY/kg 1,4-DCB emitted to urban air eq.*	*Toxicity - Human health (non-cancer)*	1,07E-05		
	47	*Human Toxicity - (non-cancer) (kg 1,4-DCB emitted to urban air eq.)*	2,22E-06	*DALY/m3 consumed*	*Water consumption - human health*	1,04E-04		
	47	*Water consumption - (m3 consumed)*	2,80E-09	*Species*yr/kg CO2 eq.*	*Global Warming - Terrestrial ecosystems*	1,20E-07	3,47E-05	*Species*yr*
	27	*Terrestrial Acidification - (kg SO2 eq.)*	1,29E-07	*Species*yr/kg NOx eq.*	*Photochemical ozone formation - Terrestrial ecosystems*	4,39E-06		
	22	*Terrestrial Ecotoxicity - (kg 1,4-DBC emitted to industrial soil eq.)*	2,12E-07	*Species*yr/kg SO2 eq.*	*Acidification - Terrestrial ecosystems*	5,72E-06		
	37	*Land use - occupation and transformation (m2·annual crop eq)*	1,14E-11	*species*yr/kg 1,4-DBC emitted to industrial soil eq.*	*Toxicity - Terrestrial ecosystems*	2,51E-10		
	35	*Freshwater Eutrophication - (kg P to freshwater eq.)*	1,35E-08	*Species*yr/m3 consumed*	*Water consumption - terrestrial ecosystems*	6,35E-07		
	31	*Freshwater Ecotoxicity - (kg 1,4-DBC emitted to freshwater eq.)*	8,88E-09	*Species*yr/(m2·annual crop eq)*	*Land use - occupation and transformation*	3,29E-07		
	15	*Marine Ecotoxicity - (kg 1,4-DBC emitted to sea water eq.)*	7,65E-14	*Species*yr/kg CO2 eq.*	*Global Warming - Freshwater ecosystems*	3,29E-12		
	42	*Mineral resource scarcity (kg CU eq.)*	6,71E-07	*Species*yr/kg P to freshwater eq.*	*Eutrophication - Freshwater ecosystems*	2,35E-05		
	37	*Fossil resource scarcity (kg oil eq.)*	6,95E-10	*species·yr/kg 1,4-DBC emitted to freshwater eq.*	*Toxicity - Freshwater ecosystems*	2,15E-08		
			6,04E-13	*Species*yr/m3 consumed*	*Water consumption -aquatic ecosystems*	2,84E-11		
			1,05E-10	*species·yr/kg 1,4-DBC emitted to sea water eq.*	*Toxicity - Marine ecosystems*	1,58E-09		
			2,31E-01	*USD2013/kg Cu*	*Mineral resource scarcity*	9,71E+00	2,66E+01	*$*
			4,57E-01	*USD2013/kg oil eq.*	*Fossil resource scarcity*	1,69E+01		
Scenario 2 (e.g. Rejuvenation) [n=2]	13	*Global Warming - (kg CO2 eq.)*	9,28E-07	*DALY/kg CO2 eq.*	*Global Warming - Human health*	1,21E-05	1,66E-02	*DALY*
	18	*Stratospheric ozone depletion - (kg CFC11 eq.)*	5,31E-04	*DALY/kg CFC11 eq.*	*Stratospheric ozone depletion - Human health*	9,56E-03		
	11	*Ionzing Radiation - (kBq Co-60 emitted to air eq.)*	8,50E-09	*DALY/kBq Co-60 emitted to air eq.*	*Ionzing Radiation - Human health*	9,35E-08		
	11	*Fine particulate matter formation - (kg PM2.5 eq.)*	6,29E-04	*DALY/kg PM2.5 eq.*	*Fine particulate matter formation - Human health*	6,92E-03		
	4	*Photochemical oxidant formation: Terrestrial Ecosystems (kg NOx eq.)*	9,10E-07	*DALY/kg NOx eq.*	*Photochemical ozone formation - Human health*	5,46E-06		
	6	*Photochemical oxidant formation: Human Health (kg NOx eq.)*	3,32E-06	*DALY/kg 1,4-DCB emitted to urban air eq.*	*Toxicity - Human health (cancer)*	3,32E-05		
	10	*Human Toxicity - (cancer) (kg 1,4-DCB emitted to urban air eq.)*	2,28E-07	*DALY/kg 1,4-DCB emitted to urban air eq.*	*Toxicity - Human health (non-cancer)*	4,56E-06		
	20	*Human Toxicity - (non-cancer) (kg 1,4-DCB emitted to urban air eq.)*	2,22E-06	*DALY/m3 consumed*	*Water consumption - human health*	2,89E-05		
	13	*Water consumption - (m3 consumed)*	2,80E-09	*Species*yr/kg CO2 eq.*	*Global Warming - Terrestrial ecosystems*	3,64E-08	6,89E-06	*Species*yr*
	6	*Terrestrial Acidification - (kg SO2 eq.)*	1,29E-07	*Species*yr/kg NOx eq.*	*Photochemical ozone formation - Terrestrial ecos*	5,16E-07		
	7	*Terrestrial Ecotoxicity - (kg 1,4-DBC emitted to industrial soil eq.)*	2,12E-07	*Species*yr/kg SO2 eq.*	*Acidification - Terrestrial ecosystems*	1,27E-06		
	20	*Land use - occupation and transformation (m2·annual crop eq)*	1,14E-11	*species*yr/kg 1,4-DBC emitted to industrial soil eq.*	*Toxicity - Terrestrial ecosystems*	7,98E-11		
	7	*Freshwater Eutrophication - (kg P to freshwater eq.)*	1,35E-08	*Species*yr/m3 consumed*	*Water consumption - terrestrial ecosystems*	1,76E-07		
	17	*Freshwater Ecotoxicity - (kg 1,4-DBC emitted to freshwater eq.)*	8,88E-09	*Species*yr/(m2·annual crop eq)*	*Land use - occupation and transformation*	1,78E-07		
	19	*Marine Ecotoxicity - (kg 1,4-DBC emitted to sea water eq.)*	7,65E-14	*Species*yr/kg CO2 eq.*	*Global Warming - Freshwater ecosystems*	9,95E-13		
	12	*Mineral resource scarcity (kg CU eq.)*	6,71E-07	*Species*yr/kg P to freshwater eq.*	*Eutrophication - Freshwater ecosystems*	4,70E-06		
	14	*Fossil resource scarcity (kg oil eq.)*	6,95E-10	*species·yr/kg 1,4-DBC emitted to freshwater eq.*	*Toxicity - Freshwater ecosystems*	1,18E-08		
			6,04E-13	*Species*yr/m3 consumed*	*Water consumption -aquatic ecosystems*	7,85E-12		
			1,05E-10	*species·yr/kg 1,4-DBC emitted to sea water eq.*	*Toxicity - Marine ecosystems*	2,00E-09		
			2,31E-01	*USD2013/kg Cu eq.*	*Mineral resource scarcity*	2,77E+00	9,16E+00	*$*
			4,57E-01	*USD2013/kg oil eq.*	*Fossil resource scarcity*	6,39E+00		
Ref. Scenario (e.g. Traditional Resurfacing) [rf]	46	*Global Warming - (kg CO2 eq.)*	9,28E-07	*DALY/kg CO2 eq.*	*Global Warming - Human health*	4,27E-05	4,37E-02	*DALY*
	58	*Stratospheric ozone depletion - (kg CFC11 eq.)*	5,31E-04	*DALY/kg CFC11 eq.*	*Stratospheric ozone depletion - Human health*	3,08E-02		
	44	*Ionzing Radiation - (kBq Co-60 emitted to air eq.)*	8,50E-09	*DALY/kBq Co-60 emitted to air eq.*	*Ionzing Radiation - Human health*	3,74E-07		
	20	*Fine particulate matter formation - (kg PM2.5 eq.)*	6,29E-04	*DALY/kg PM2.5 eq.*	*Fine particulate matter formation - Human health*	1,26E-02		
	39	*Photochemical oxidant formation: Terrestrial Ecosystems (kg NOx eq.)*	9,10E-07	*DALY/kg NOx eq.*	*Photochemical ozone formation - Human health*	3,55E-05		
	39	*Photochemical oxidant formation: Human Health (kg NOx eq.)*	3,32E-06	*DALY/kg 1,4-DCB emitted to urban air eq.*	*Toxicity - Human health (cancer)*	1,63E-04		
	49	*Human Toxicity - (cancer) (kg 1,4-DCB emitted to urban air eq.)*	2,28E-07	*DALY/kg 1,4-DCB emitted to urban air eq.*	*Toxicity - Human health (non-cancer)*	8,89E-06		
	39	*Human Toxicity - (non-cancer) (kg 1,4-DCB emitted to urban air eq.)*	2,22E-06	*DALY/m3 consumed*	*Water consumption - human health*	1,18E-04		
	53	*Water consumption - (m3 consumed)*	2,80E-09	*Species*yr/kg CO2 eq.*	*Global Warming - Terrestrial ecosystems*	1,29E-07	4,31E-05	*Species*yr*
	29	*Terrestrial Acidification - (kg SO2 eq.)*	1,29E-07	*Species*yr/kg NOx eq.*	*Photochemical ozone formation - Terrestrial ecosystems*	5,03E-06		
	46	*Terrestrial Ecotoxicity - (kg 1,4-DBC emitted to industrial soil eq.)*	2,12E-07	*Species*yr/kg SO2 eq.*	*Acidification - Terrestrial ecosystems*	6,15E-06		
	19	*Land use - occupation and transformation (m2·annual crop eq)*	1,14E-11	*species*yr/kg 1,4-DBC emitted to industrial soil eq.*	*Toxicity - Terrestrial ecosystems*	5,24E-10		
	46	*Freshwater Eutrophication - (kg P to freshwater eq.)*	1,35E-08	*Species*yr/m3 consumed*	*Water consumption - terrestrial ecosystems*	7,16E-07		
	31	*Freshwater Ecotoxicity - (kg 1,4-DBC emitted to freshwater eq.)*	8,88E-09	*Species*yr/(m2·annual crop eq)*	*Land use - occupation and transformation*	1,69E-07		
	46	*Marine Ecotoxicity - (kg 1,4-DBC emitted to sea water eq.)*	7,65E-14	*Species*yr/kg CO2 eq.*	*Global Warming - Freshwater ecosystems*	3,52E-12		
	52	*Mineral resource scarcity (kg CU eq.)*	6,71E-07	*Species*yr/kg P to freshwater eq.*	*Eutrophication - Freshwater ecosystems*	3,09E-05		
	47	*Fossil resource scarcity (kg oil eq.)*	6,95E-10	*species·yr/kg 1,4-DBC emitted to freshwater eq.*	*Toxicity - Freshwater ecosystems*	2,15E-08		
			6,04E-13	*Species*yr/m3 consumed*	*Water consumption -aquatic ecosystems*	3,20E-11		
			1,05E-10	*species·yr/kg 1,4-DBC emitted to sea water eq.*	*Toxicity - Marine ecosystems*	4,83E-09		
			2,31E-01	*USD2013/kg Cu eq.*	*Mineral resource scarcity*	1,20E+01	3,35E+01	*$*
			4,57E-01	*USD2013/kg oil eq.*	*Fossil resource scarcity*	2,15E+01		

B.3: Interpolated Reduced Environmental Burden (REB_n) KPI

Maintenance Scenarios and Ref. Scenario for 1m2 of Asphalt pavement over 15yrs	Agg. Endpoints (EP)	Endpoint Category [unit]	Weighting (W)	Aggregate Environment Burden Score (EB) [∑W*EP]	Reduced Environment Burden KPI [(EB_rf-EB_n)/EB_rf ; n= 1, 2]
Scenario 1 (e.g. Resurfacing with Aggregate Recycling) [n=1]	3,03E-02	*Damage to Human Health (DALY)*	40	533,18	0,21
	3,47E-05	*Damage to Ecosystems (Species*yr)*	40		
	2,66E+01	*Damage to Ressource Availability ($)*	20		
Scenario 2 (e.g. Rejuvenation) [n=2]	1,66E-02	*Damage to Human Health (DALY)*	40	183,96	0,73
	6,89E-06	*Damage to Ecosystems (Species*yr)*	40		
	9,16E+00	*Damage to Ressource Availability ($)*	20		
Ref. Scenario (e.g. Traditional Resurfacing) [rf]	4,37E-02	*Damage to Human Health (DALY)*	40	671,25	0,00
	4,31E-05	*Damage to Ecosystems (Species*yr)*	40		
	3,35E+01	*Damage to Ressource Availability ($)*	20		