- CIRCUIT -

Holistic approach to foster CIRCUlar and resilient transport InfrasTructures and support the deployment of Green and Innovation Public Procurement and innovative engineering practices

– Deliverable 1.1–

Holistic circularity framework

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	Participant Legal Name	Country
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2	INFRA PLAN KONZALTING JDOO ZA USLUGE - INFRA PLAN	Croatia
3	INGEO BV – INGEO BV	The Netherlands
4	ANAS SPA – ANAS	Italy
5	ZAVOD ZA GRADBENISTVO SLOVENIJE – ZAG	Slovenia
6	EUROPEAN UNION ROAD FEDERATION – ERF	Belgium
7	ACCIONA CONSTRUCCION SA – ACCIONA	Spain
8	INSTITUTO ESPAÑOL DEL CEMENTO Y SUS APLICACIONES – IECA	Spain
9	BETON - LUCKO DOO ZA GRADITELJSTVO PROIZVODNJU TRANSPORT I TRGOVINU– BL	Croatia
10	Obcina Crna na Koroskem – CRNA	Slovenia
11	RIGHT-CLICK – RC	Spain
12	UNIVERSIDAD DE CANTABRIA – UC	Spain
13	DIGITALTWIN TECHNOLOGY GMBH – DTT	Germany
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Authors list		
Irina Stipanovic	Infra Plan	irina.stipanovic@infraplan.hr
Sandra Skaric Palic	Infra Plan	sandra.skaric@infraplan.hr
Daniel Rodik	Infra Plan	daniel.rodik@infraplan.hr
Irune Indacoechea Vega	UC	indacoecheai@unican.es
Pablo Pascual Muñoz	UC	pascualmp@unican.es
Carlos Martin-Portugues Montoliu	ACCIONA	Carlos.martinportugues.montoliu@acciona.com
César Bartolomé Muñoz	IECA	cbartolome@ieca.es
Rahul Tomar	DTT	rahul.tomar@digitaltwin.technology

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Executive Summary

The document, D1.1 – Report on CIRCUIT holistic framework with quantifiable KPIs for circular, smart, resilient, and sustainable transport infrastructure is a result of the Task 1.1, within which firstly thorough literature review for the CIRCUIT holistic framework development was performed. This has included overview of the European strategic and legal frameworks, previous works and EU projects (e.g. LCE4Roads, ASHVIN, FORESEE, etc.), actual sustainable frameworks and rating methodologies such as ENVISION or BREEAM Infrastructure and standards and other CEN documents dealing with sustainability of construction works (e.g. EN 17472, ISO 21929-1, CWA 17089), environmental product declarations (EN 15804), resilience (CWA 17819) and life cycle costing (ISO 15686).

Based on that and the co-creation process undertaken in Task 1.1 by involving the different organisations in the CIRCUIT consortium covering whole supply-value chain of transport infrastructures (from designers, construction materials and products producers, contractors, asset owners and researchers), a holistic circularity framework is proposed, with integrated methodology for resilience, economy, circularity, and environment impact assessment. Quantifiable KPI metrics is proposed, covering four aspects, social incl. resilience, economy, environment, and circularity, with digitalization as an additional aspect. The assessment of social performance differs from the assessment of economic and environmental aspects because it requires both quantitative and descriptive approaches.

CIRCUIT framework covers whole life cycle, from performance-based design, over construction, maintenance, and operation, to decommissioning and end-of-life of the transport infrastructure. Requirements for data integration into digital platform, visualization and analysis of KPIs will be developed within WP2.

The applicability and the capabilities of the developed holistic circularity framework will be demonstrated through the pilot projects in WP5.

Abbreviation list

Abbreviation	Definition
3DCP	3D Concrete Printing
ADP	Abiotic Depletion Potential
AEV	Annual Equivalent Value
AI	Artificial Intelligence
BIM	Building Information Modelling
BREEAM	Building research establishment environmental assessment method
CE	Circular Economy
CEN	Comité Européen de Normalisation
CFC	Chlorofluorocarbons
COP	Conference of the Parties
CPR	Construction Product Regulation
CTU	Comparative Toxic Units
CWA	CEN Workshop Agreement
DfA	Design for Assembly
DfD	Design for Disassembly
DPP	Digital Product Passport
DT	Digital Twin
EC	European Commission
EP	Eutrophication Potential
EPD	Environmental Product Declarations
FAI	Full Adaptive Installation
GPP	Green Public Procurement

Abbreviation	Definition
GRS	Geosynthetic Reinforced Soil
GWP	Global Warming Potential
IFC	Industry Foundation Classes
IPCC	Intergovernmental Panel on Climate Change
IPP	Innovative Public Procurement
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LULUC	Land Use and Land Use Changes
MEAT	Most Economically Advantageous Tender
NGO	Non-Governmental Organization
NPV	Net Present Value
PEF	Product Environmental Footprint
PCR	Product Category Rules
PI	Performance Indicators
RA	Recycled Aggregate
SME	Small and Medium Enterprise
SRM	Supplier Relationship Management
UAV	Unmanned Aerial Vehicle
WLC	Whole Life Cycle

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Glossary of terms

Annual Cost (AC) or Annual Equivalent Value (AEV)
A uniform annual amount that, when totalled over the period of analysis, equals the total net cost of the project taking into account the time value of money over the period.

Circularity
An economic concept (also: circular economy) meaning that a product, service or resource is renewed or regenerated, rather than wasted. Key principle of circularity is allowing materials and products to be used more than once in a value chain either processed (e.g. recycled) or unprocessed (e.g. reused).

Climate change vulnerability
The degree to which natural, built, and human systems are at risk of exposure to climate change impacts.

Design for Adaptability (DfA)
An approach to planning, designing, and constructing a building so it can be easily maintained, modified and used in different ways or for multiple purposes throughout its lifetime, extending its practical and economic life cycle.

Design for Disassembly (DfD)
Approach to the design of a product or constructed asset that facilitates disassembly at the end of its useful life in such a way that enables components, materials, and parts to be reused, recycled or, in some other way, diverted from the waste stream.

Externalities
Consequences due to activities in the whole life cycle of any work, product or service that have an impact on the society or environment, monetized as a cost. (e.g. additional travel time of road users, additional environmental pollution).

Life Cycle
Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

Life Cycle Assessment (LCA)
A methodology developed to assess the environmental impacts of a building, component, or material. The assessment compiles and evaluates the energy and material inputs and outputs of the material system throughout its life cycle and assesses the relevant environmental impact.

Life Cycle Cost Analysis (LCC)
An analysis of all the costs that will be incurred during the lifetime of the product, work or service. LCC may also include the cost of externalities such as environmental degradation or greenhouse gas emissions.

Material Circularity
The measure describing how much of the total material in the life cycle (%) is being directed back into the life cycle (e.g. recycled and cycled sourced materials vs. non-renewable and virgin material sourced).

Net Present Value (NPV)
The sum of the discounted future cash flows, both costs and benefits/revenues. Where only costs are included, this could be termed Net Present Cost (NPC).

Product system
Described by ISO 14040 as a "collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product."

Recovery
The process of systematically and intentionally collecting, salvaging and reusing materials from a building or construction site to extend their life cycle and reduce waste.

Recycling
Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes.

Resilience
The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.

Reusability
The measure describing how much of the existing structures could be used again at the end of life cycle.

Reuse
The repeated use of a product or component for its intended purpose without significant modification.

Upcycling
A form of recycling that repurposes waste, products or materials into a substance of higher value than the original.

Urban Mining
The process of recovering and reusing the raw materials that are already in the environment, cities or everyday products, in the resource cycle.

1 INTRODUCTION

1.1 Objectives

Over the past decade, the circular economy has been promoted across sectors to accelerate the shift towards more sustainable practices worldwide and tackle pressing problems such as climate change, resource depletion, waste and pollution (Gasparri et al., 2023). Boosting circularity can play an important role in the European Union's recovery from the adverse socio-economic and environment impacts, with a particular focus on resource intensive sectors and with clear goals set up by the Circular Economy Action Plan (EC, 2020). The new Construction Products Regulation (CPR) ensures the smooth functioning of the single market and the free movement of construction products in the EU harmonising technical specifications, which provide for a common technical language on how to test and communicate the performance of construction products (EC, 2011). The revised Regulation will offer digital solutions to reduce administrative burdens, particularly on SMEs, including a construction products database and a Digital Products Passport (DPPs). New product requirements will ensure that the design and manufacture of construction products is based on state of the art to make these more durable, repairable, recyclable, easier to re-manufacture. The construction works and any part of them shall be designed, constructed, used, maintained, and demolished in such a way that, throughout their life cycle, the use of natural resources is sustainable and ensures the following:

- Use of raw and secondary materials of high environmental sustainability and thus with a low environmental footprint, minimizing the overall amount of raw materials used;
- Minimizing the overall amount of embodied energy;
- Minimizing the overall use of drinking and brown water;
- Reusability or recyclability of the construction works, parts of them and their materials after demolition.

The overall objective of CIRCUIT project is to develop a holistic approach and associated digital solutions and guidelines to foster circular, smart, and resilient transport infrastructures proposing modifications in actual engineering and procurement processes and practices and to promote novel governance and procurement models to limit the overall emissions from construction, maintenance, operation and decommissioning of infrastructures. As one of the first steps, within Task 1.1, the aim is to co-create CIRCUIT holistic framework for circular, smart, resilient, and sustainable transport infrastructure management, and to define Key Performance Indicators for Resilience, Circularity, Economy, Sustainability, etc. and the contribution to the digital transformation and innovative and green procurement.

To achieve these, firstly the baseline for the CIRCUIT holistic framework development was established, which included thorough literature review of the previous works and EU projects, actual sustainable frameworks and rating methodologies, standards and other CEN documents dealing with sustainability of construction works, environmental product declarations, resilience, and life cycle costing. Based on that and the co-creation process undertaken in Task 1.1 by involving the different organisations in the CIRCUIT consortium covering whole supply-value chain of transport infrastructures (from designers, construction materials and products producers, contractors, asset owners and researchers), a holistic circularity framework is proposed, with integrated methodology for resilience, economy, and circularity impact assessment.

1.2 PURPOSE OF THE DOCUMENT

The work included in this report contributes to the fabrication of a set of newly developed circularity KPIs (assessment of recyclability, reusability, and end-of-life value of the existing assets) together with the social, economy and environmental KPIs used to measure performance of the selected solution. The project considered various pilot use cases and employed a bottom-up methodology to identify performance indicators that will eventually transform into key performance indicators (KPIs).

KPIs consider sustainability requirements and the resilience on different levels, from a material level over element, structure to the system level, such as multi adaptability, lifespan extension options, high value solutions to improve circular economy targets, reduce costs, energy consumption, environmental and social impacts. Quantitative methods to verify these KPIs will be developed in further project activities and together with the defined metrics will be integrated into the Digital Twin platform, allowing a visualization on its dedicated interface. The developed KPIs will be validated and enhanced in close collaboration with other project partners in other WPs and subjected to validation through five pilot projects, in WP5.

KPIs have been classified into four primary categories, namely circularity, economy, environmental, and social. The hierarchy of the analysis begins with the assessment of circular potential through circularity KPIs followed by impact assessment through LCA and LCC. The emphasis is placed on measurable metrics that can be converted into performance indicators (PIs). Incorporating performance indicators into a unified KPI results in a more structured and comprehensive assessment providing data-based evidence of the benefits of the circular, smart and resilientapproach. The assessment of social performance differs from the assessment of economic and environmental aspects because it requires both quantitative and descriptive approaches.

1.3 SETTING UP THE SCOPE

CIRCUIT project provides knowledge and technical solutions to consider properly the whole life cycle of transport infrastructure, limiting the overall emissions and energy consumption associated to construction, maintenance, operation and decommissioning of infrastructures, by exploiting the potential of four strategic pillars: Digitalisation, Recycle, Reuse and Energy, as shown in **Error! Reference source not found.**.

Digitalisation pillar aims to provide and validate the required digital tools and solutions to modify actual engineering practices considering the CIRCUIT principles, support decision making, boost circular business models and the green transition and introduce the required new elements for smart infrastructures.

Recycle pillar targets to extend the life cycle of transport infrastructures by restoring or boosting their properties at the end of their present useful life in order to contribute to sustainable transport infrastructure, favouring the transition from a linear economy to a circular and advancing in the decarbonization of the sector by upcycling construction and demolition waste.

Reuse pillar supports reusing strategies suitable for civil engineering purposes, taking into consideration the required design requirements and granting the accomplishment of actual regulations or proposing any necessary changes in standards or specifications. In this pillar two technologies will be included for bridges and foundations.

Energy pillar by validating different technologies will deliver a more efficient energy management on transport infrastructure operations providing the feasibility analysis required for the introduction of green energy sources and technologies to reduce energy consumptions associated to lighting and ventillation systems.

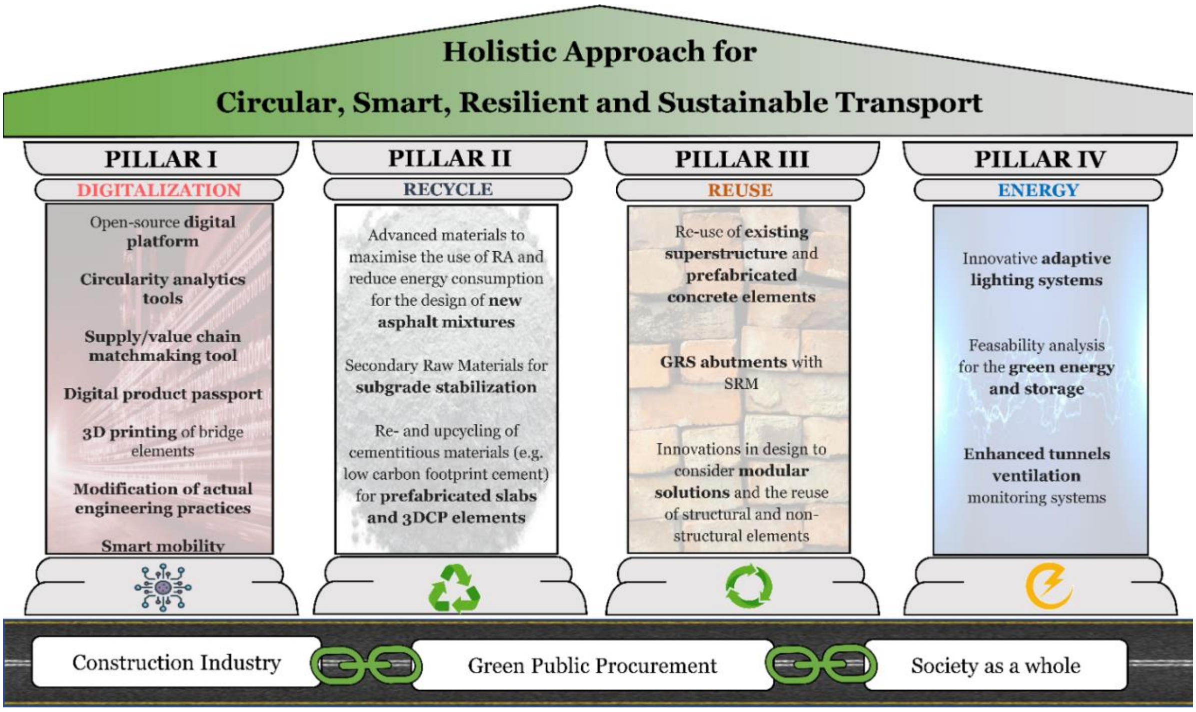


Figure 1 CIRCUIT concept with 4 pillars; digitalization, recycle, reuse and energy

Holistic CIRCUIT framework, on top of the four pillars in **Error! Reference source not found.**, has to provide methodology to assess the impacts of different design and technology solutions for transport infrastructure along the whole life cycle, as schematically presented in Figure 2. CIRCUIT framework is therefore including **four impact assessment categories** and digitalisation as a horizontal overall aspect:

- **Social impact:** which is considering the transport infrastructure system as a whole and its resilience in the societal context.
- **Economic impact:** which is considering costs related to the activities and products, along the whole life cycle of the infrastructure.
- **Environmental impact:** which is considering impacts on the environment of all activities and materials used in the transport infrastructure,
- **Circularity:** which assesses the level of circular economy principles implementation, assessed at product or material level Environmental and economy elements are assessed at project or life cycle level and society element is assessed at infrastructure surroundings level using more complex indicators such as resilience, accessibility, health, wellbeing, etc.

- **Digitalisation:** as horizontal aspect will be used to assess the level of the digitalisation of the infrastructure and will define the requirements (from data to result representation) for the implementation into digital platform.

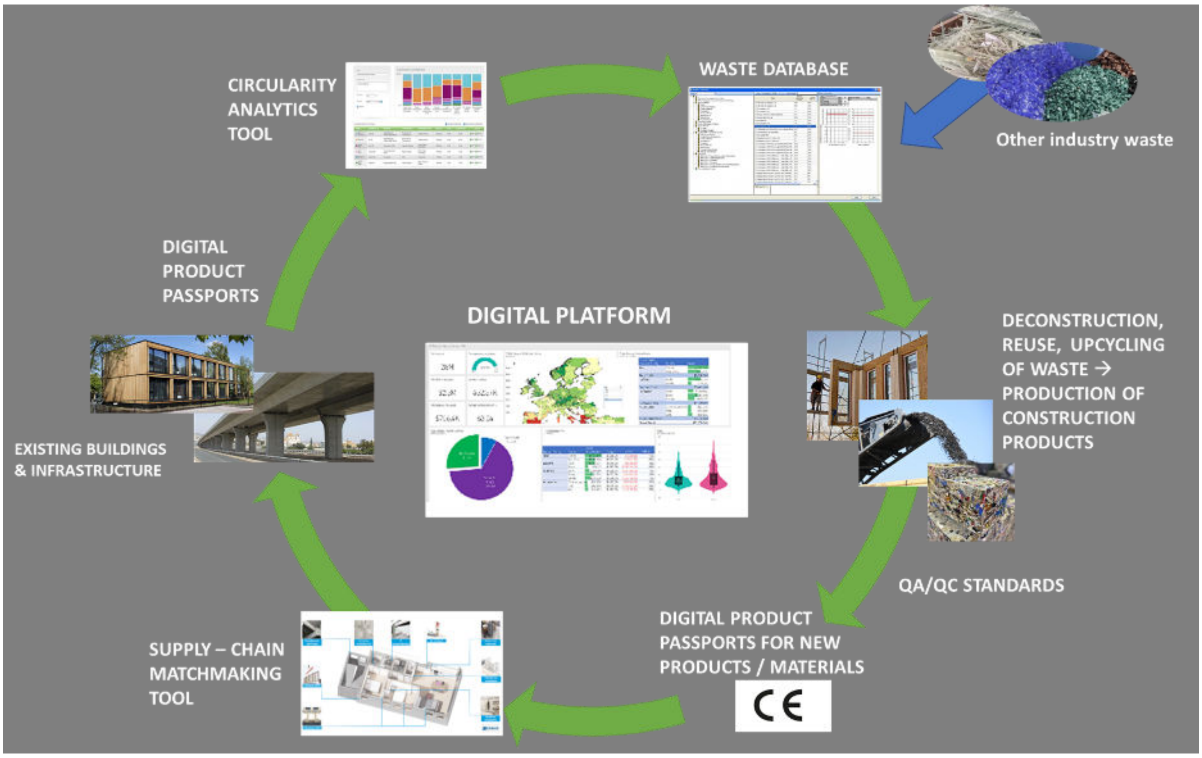


Figure 2 Overall CIRCUIT approach evolving around digital platform introducing innovative engineering practices in the construction supply/value chain

This report includes in Chapter 2 the overview of actual legal framework in EU, current standardisation and labelling approaches applied to construction products and of research projects related to sustainability (carbon footprint, pollution, resource depletion), roads, building materials and the built environment and technologies and business models relevant for CIRCUIT pilots. Based on that, a holistic circularity framework was co-created, by involving different organizations in the whole supply-value chain of transport infrastructures, from designers, construction materials and products producers, contractors, owners to standards developers and researchers. In order to implement CIRCUIT holistic approach in the practice and enable qualification and quantification of circularity potential embedded in the transport infrastructure, novel KPIs are proposed and described in Chapter 3 together with a compilation of widely accepted KPIs to assess environmental, economic and social aspects (e.g. those included in EN 17472). In Chapter 4 five pilot projects are briefly described with an overview of the applicability of the framework and KPIs. Finally, in Chapter 5 conclusions and description of the next steps are provided.

2 EXISTING STRATEGIC AND LEGAL FRAMEWORKS

2.1 Relevant European strategic frameworks

European Union strategic policy framework is a complex, broad, and dynamic policy process that should enable suitable life conditions for every citizen, setting the vision, goals, rights and obligations for private persons, business organisations or public bodies. The European Green Deal (EC, 2020), the NextGenerationEU (EC, 2020), the Circular Economy Action Plan (EC, 2020), Sustainable and Smart Mobility Strategy (EC, 2020) and the REPowerEU Plan (EC, 2022) provide a clear roadmap towards a more sustainable and resilient transport system with reduced greenhouse gas emissions, boosting energy efficiency, the uptake of CE principles and accelerating the use of clean energies. EU Taxonomy (Regulation EU 2020/852 of the European Parliament and of the Council of the European Union), Green Public Procurement (GPP) and Innovative public procurement (IPP) are major instruments to foster the transformation towards a green and digital economy. However, the level of deployment in the EU is lower than expected with a recent study reporting that most countries only apply GPP to procure less than 5% of their contracts in the period 2006-2017 (Rosell, 2021).

Therefore, CIRCUIT project is proposing holistic framework which will support fulfilment of EU Green Deal and EU Taxonomy objectives which will enable analysis of direct and indirect environmental and social performance indicators to measure emissions, pollution, and social inequity but also positive impacts to climate and environmental objectives. Additionally, the CIRCUIT project aims to make the digital transition of transport infrastructure in line with EU digital strategy, while helping to achieve its target of a climate-neutral Europe by 2050. (EC, 2021)

CIRCUIT project aims to support transformation of transport infrastructure into digital, resilient, smart, circular and sustainable project, and will:

- Contribute to the competitiveness of Europe's net-zero industry and accelerate the transition to climate neutrality using sustainability and circularity benchmarks;
- Unleash full potential of data leading to smart mobility and transport infrastructures;
- Improve the implementation of Green and innovative public procurement criteria in road construction and maintenance sector.

CIRCUIT framework will be integrated in the digital tools for circularity analysis and digital twin platform to assess the environmental, economic and social impacts of construction projects and of life cycle maintenance and repair activities of transport infrastructure with the aim of mitigating and seeking their adaptation to climate change.

This will support the decision making during the different lifecycle stages of infrastructures to facilitate the desired green and digital transition.

CIRCUIT promotes also transparent disclosure of information regarding its economic activities within its project developments, in accordance with sustainable regulations at the European level. In this regard, the traceability-oriented developments and the introduction of Digital product passports is a clear example of a link between EU Taxonomy and CIRCUIT. The CIRCUIT developments will favour the integration of advanced technologies into infrastructures such as roads, transportation systems, among others, to enhance their efficiency, sustainability, safety, and responsiveness to the changing needs of society. Smart infrastructure, through resources like sensors, connected devices, data analysis, and other technologies, will enable real-time data collection, facilitating informed decision-making for each case under study.

2.2 Relevant standards and guideline documents

2.2.1 EN 17472:2022 Sustainability of construction works – Sustainability assessment of civil engineering works – Calculation methods

The standard EN 17472:2022 provides rules for the assessment of the sustainability of civil engineering works including environmental, economic, and social aspects. The evaluation of technical and functional performance is beyond the scope of this standard but is considered by reference to the functional equivalent.

Key elements and indicators:

The assessment of environmental and economic performances of a civil engineering works is based on Life Cycle Assessment (LCA), Life Cycle Cost (LCC), Whole-Life Cost (WLC). The assessment of social performance differs from the assessment of economic and environmental aspects because it requires both quantitative and descriptive approaches.

Environmental assessment:

- Indicators, impacts, and aspects expressed according to EN 15804
- Others not considered in EN 15804:
  - Water use (Non consumptive use of fresh water and Water pollution)
  - Land occupation (Permanent and Temporary land occupation and Land use changes)
  - Use of material resources (the total amount of materials is separate information from the use and depletion of natural resources. The use of material resources, either virgin or recycled, shall be described in a disaggregated form)
  - Pollution/emissions to soil
  - Pollution/emissions to air
  - Biodiversity change
  - Ecological connectivity
  - Level of noise and other disturbances

Economic performance

- Whole-life costing (WLC) according to ISO 15686-5.

  The indicators should be expressed in terms of Net Present Value NPV) and/or Annual Equivalent Value (AEV) as defined in EN 16627:2015 Sustainability of construction works – Assessment of economic performance of buildings – Calculation method.

Social performance:

The assessment of social performance differs from the assessment of economic and environmental aspects because it requires both quantitative and descriptive approaches.

- Accessibility (Access for relevant users and for people with specific needs; access to services provided by the asset and connectivity)
- Adaptability (technical changes, change of use, complementary uses and external events)
- Connectivity
- Population distribution
- Health and wellbeing
- *Maintenance and maintainability: Safety for users and neighbours during maintenance.*
- Safety/security for workers, users and neighbours
- Resilience (Structural stability; Resilience against the consequences of climate change as a result of exceptional events such as: criminality, disruptions of utility supply or current and future loadings from rain, heavy wind, sand and dust storms, hail, snow, floods, temperature variations, droughts, sea level, waves and coastal effects, glacier, geological impacts and changes to permafrost, wild fires, earthquakes, landslides, etc.; Resistance to accidental actions (e.g. earthquakes, explosions, fire and traffic impacts); security against intruders, vandalism and terrorism; provisions in case of interruptions of supply of utilities).
- Sourcing of materials and services (materials' production; safety performance from start to finish of the materials' production; human rights; traceability; quality management/control; safety performance from start to finish of the service supplied; compliance with social responsibilities; environmental management/control)
- Stakeholders engagement
- Jobs creation
- Cultural heritage elements

For the assessment of the three aspects (environmental, economic and social), the same reference study period is used.

The functional equivalent of a civil engineering works or one of its parts shall include, but is not limited to, information on the following aspects:

- Civil engineering works type (e.g. road from A to B or harbour);
- Relevant technical and functional requirements (e.g. capacity for X number of vehicles, capacity of N containers per year);
- Pattern of use (e.g. number of expected vehicles per year, quantity of containers expected);
- Required service life.

To provide the complete description of the object of assessment, geographic and time-related characteristics of the civil engineering works need to be added to its physical description. This requires the development and use of appropriate scenarios describing the assumptions that can be applied to models for construction, use, and end-of-life stages of the object of assessment. The different stages of civil engineering works are properly considered as described in Figure 3, that illustrates the organization of the different information modules used for reporting the assessment of the civil engineering works.

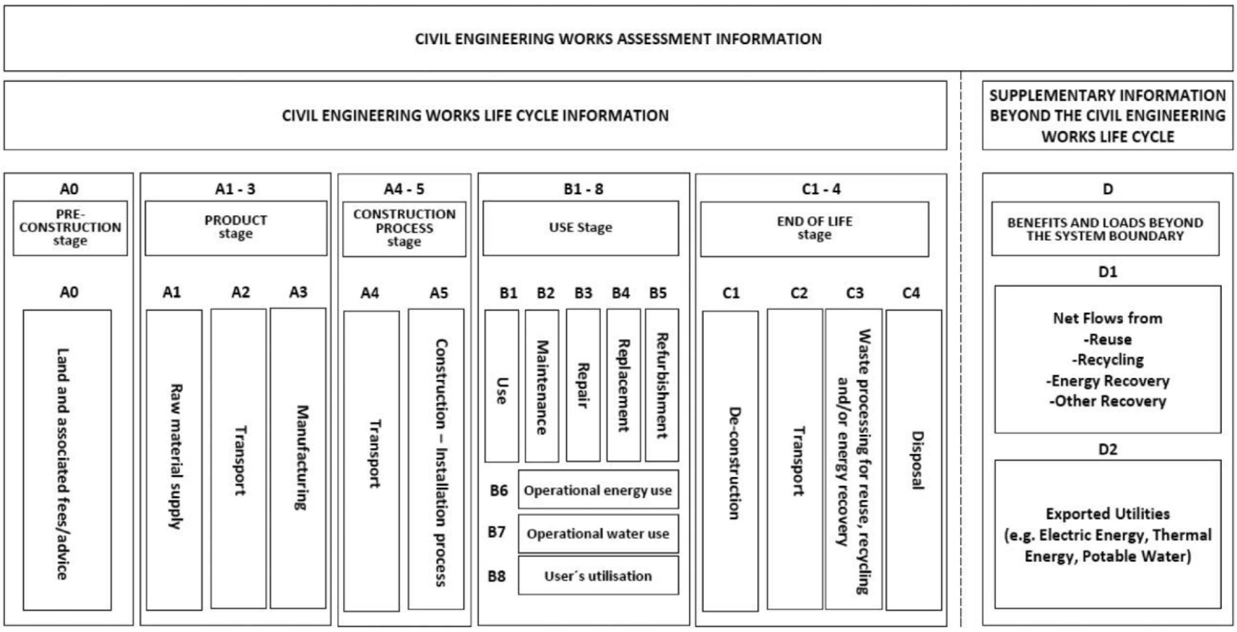


Figure 3 Display of modular information for the different stages of civil engineering works' assessment (Source: EN 17472:2022)

2.2.2 EN 15804 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products

This norm provides core product category rules for all construction products and services, ensuring that all Environmental Product Declarations (EPD) of construction products, construction services and construction processes are derived, verified and presented in a harmonised way including the indicators to be declared, the stages of a product's life cycle considered, rules for the inventory, LCA and reporting. In 2019, some of the main methodological elements of EN 15804: A1-2013 were harmonized with PEF (EU Product Environmental Footprint), and it was approved to define in the new EN 15804+A2: 2020 that amended previous standard as follows:

- It now accounts for the benefits of end-of-life recycling.
- EPDs are required to now include more life stages: All construction products now must declare modules A1-A3, as well as C1-C4, and module D.
- Biogenic carbon reporting: The revised version places more attention on biogenic carbon (including carbon offsetting). This means that the biogenic carbon mass in

the product and packaging now needs to be declared and biogenic carbon in construction products now needs to be included in EPDs.
The previous single Global Warming Potential category is no longer provided. The new categories include Climate change 1) total, 2) fossil, 3) biogenic and 4) LULUC (land use and land use changes).

- Data must also be available in ILCD format.
- Several new environmental and resource indicators were introduced: 19 Environmental impact categories and 17 other reporting categories are now required. (see chapter 2.4.3 Information given by an EPD).

Figure 4 shows the framework for the creation of EPDs and their connections to PCRs and LCAs. First, PCRs for the product are found or generated (reviewed by public comment and experts panel); then, a cradle-to-grave LCA must be carried out (and reviewed by an expert); and finally, an EPD is generated, verified and published (as reviewed by a Program Operator) as a more accessible version of the LCA.

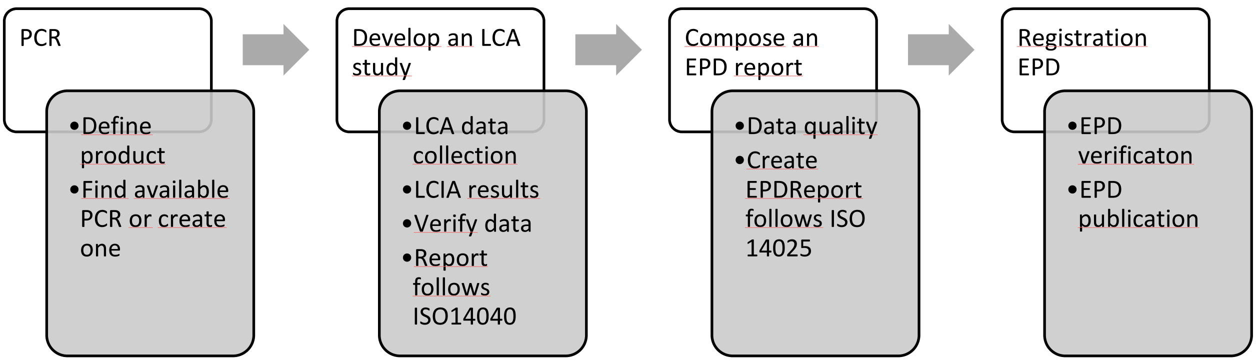


Figure 4 Framework for the development of EPDs

The advantage of EPD is that it is a third-party verified document which gives the information credibility and therefore is very suitable for procurement. Moreover, they also can be used to help procure lower impact construction materials as actually there are PCR and EPDs already registered for cement products, concrete, asphalt concrete, bitumen, precast elements and other construction products. Disadvantage is the amount of information they need to provide and how understandable it is by the market. The indicators included in an EPD are divided into core indicators (mandatory to be declared) and additional indicators (volunteer), resulting in a large number of categories which can be considered as a disadvantage for the following reasons, i.e. users of EPDs do not understand the real meaning of many of the indicators declared; many of the indicators included do not provide relevant information to the user; same impact, for example energy, are declared by many indicators that make information confusing and indicators related to circularity are not clear for the user. Therefore, it can be concluded that EPDs are a powerful tool to step forward in the task of assessing sustainability of infrastructures and civil works, but simplification is necessary, at least, for the CIRCUIT project.

In addition to the EN 15804:2012 standard, the ISO 21930:2017 "Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services" provides principles, specifications and requirements to develop an EPD for construction products and services, construction elements and integrated technical systems used in any type of construction works. This standard is thus to be considered the core PCR document for such products, services, elements and systems.

2.2.3 ISO 15686-5:2017 Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing.

This international standard provides requirements and guidelines for performing life-cycle cost (LCC) analyses of buildings and constructed assets and their parts, whether new or existing.
LCC considers cost or cash flows, i.e. relevant costs (and income and externalities if included in the agreed scope) arising from acquisition through operation to disposal. It typically includes a comparison between alternatives or an estimate of future costs at portfolio, project or component level. Life-cycle costing is performed over an agreed period of analysis, clearly identifying whether the analysis is for only part of or for the entire life cycle of the constructed asset.
It is well known and accepted evaluation method for comparison of different project alternatives. It will be also used in CIRCUIT project for the evaluation of innovations implementation across pilot projects.

2.2.4 CWA 17089:2016 Indicators for the sustainability assessment of roads

As one of the main outputs from the EU FP7 research project LCE4ROADS: Life Cycle Engineering approach to develop a novel EU-harmonized sustainability certification system for cost-effective, safer and greener road infrastructures, CEN Workshop Agreement (CWA) 17089 provides a recommended common set of indicators that can be used for sustainability assessment of roads and a suggested deployment procedure. The set includes environmental and economic indicators mentioned in EN 17472 (EN 15804 indicators and Whole life costing) and other interesting elements for the social pillar such as the link with safety audits and the comfort index.

Comfort index (for road projects)

Comfort is the subjective feeling of a vehicle driver or passenger while driving along a road, as this depends on multiple factors (vehicle type, traffic, speed, weather, road geometry, pavement, surface course, etc.). Comfort index is a performance indicator dependent on parameters such as those identified in the COST 354 model (longitudinal and transverse evenness, texture, surface defects and cracking).

Safety audits

The Directive (EU) 2019/1936 of the European Parliament and of the Council of 23 October 2019 amending Directive 2008/96/EC on road infrastructure safety management, establishes procedures relating to road safety assessments, audits and inspections. This indicator can be linked to the Smart Infrastructures concepts that might arise within CIRCUIT.

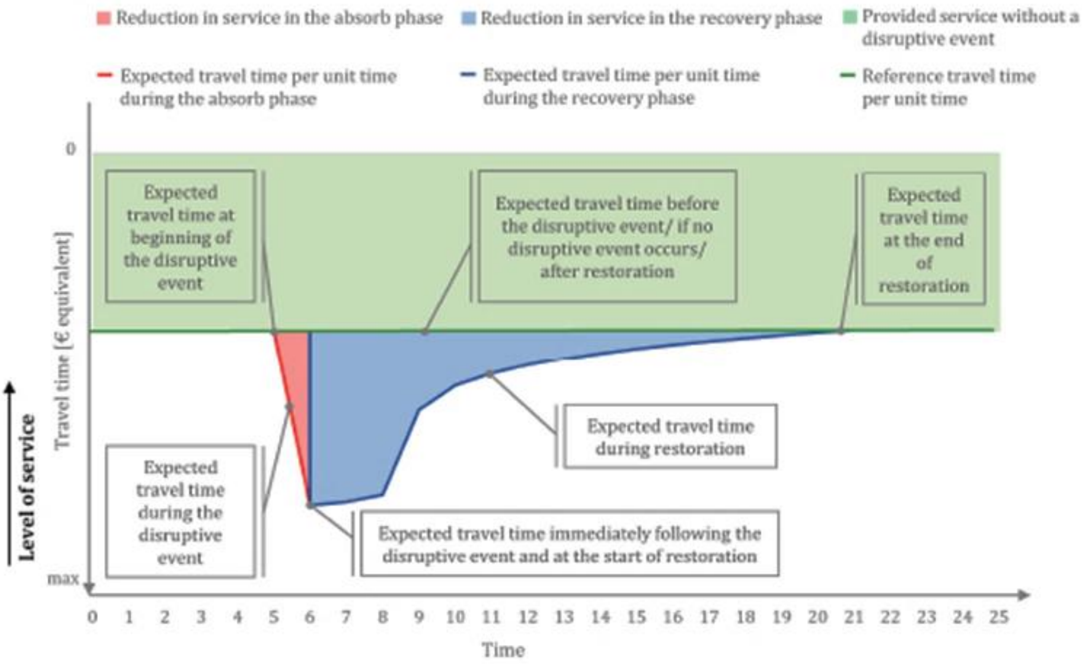
The link with CIRCUIT can be the introduction of the Comfort index as a performance indicator that links both long-term performance of the asset and social impact for users in the case of roads projects, and a not on safety audits can complement how safety is covered.

2.2.5 CWA 17819:2021 Guidelines for the assessment of resilience of transport infrastructure to potentially disruptive events

This CEN and CENELEC Workshop Agreement CWA 17819:2021 is a result of the activities carried out under the FORESEE project[1]. This document provides a guide for measuring service and resilience for different scales (i.e. a tunnel, 100km of a road or the total road network), considering different type of events (i.e. earthquakes, manmade events, extreme rainfall), times and available data, experience or resources.

The guideline provides the steps not only for measuring service and resilience but also to set targets and help the infrastructure manager to identify adequate interventions to improve resilience. However, it does not provide guidance on how to model the transport system or the interconnection between its components although such modelling is necessary for the implementation of the proposed steps.

Here, service is defined as the safe and sustainable mobility of people and goods; and resilience as the ability to keep providing the service in the event of a disruption. Thus, resilience can be measured as the cumulative difference between the service provide by the infrastructure if no disruptive event occurs and the service provided during the absorb and restoration phases when a disruptive event takes place; and between the intervention costs if no event occurs and intervention costs if a disruptive event occurs (Figure 5 and Figure 6).



[1] https://www.cencenelec.eu/news-and-events/news/2021/eninthespotlight/2021-11-22-infrastructure-systems-resilience/

Figure 5 Illustration of transport infrastructure resilience using the "travel time" measure of service (CWA 17189:2021)

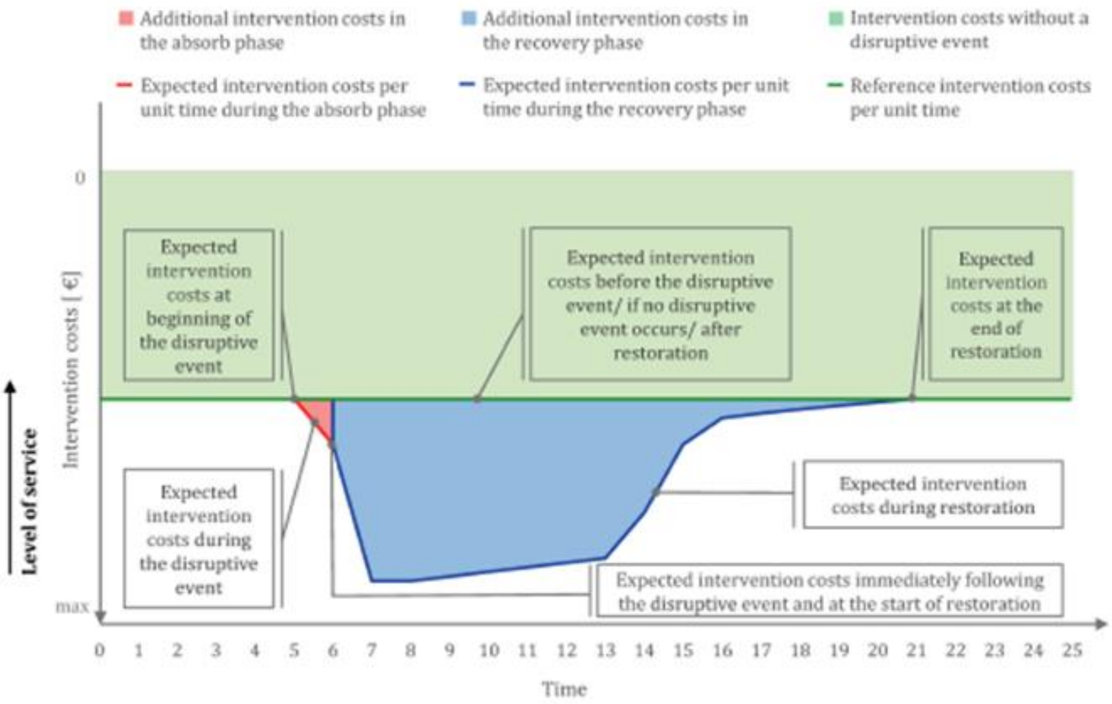


Figure 6 Illustration of transport infrastructure resilience using intervention costs (CWA 17189:2021)

Before measuring the service provided by the infrastructure and its resilience, the different parts of the **transport system** to be considered in the evaluation need to be defined and classified in:

- Infrastructure: the physical assets that are necessary to provide the service and that are under the control of the organization.
- Environment: the physical environment, affecting the provision of the service, in which are located both, the infrastructure and the organizational environment to which the infrastructure management organization belongs. This is outside the control of the organization.
- Organization: the responsible organization to guarantee that the infrastructure provides the service and is under the control of the organization.

To measure the service, it is necessary to decide how it is going to be measured, by simulation or by using indicators. If indicators are going to be used, which indicators will be used and how often the values will be collected and whether rough or more precise estimates will be used, depending on the available resources.

After the service is measured, **resilience can be measured** using three different levels, depending on its accuracy:

1. By simulation. This is the most accurate but the one that requires the highest effort. It is done by modelling the service reductions and the additional intervention costs if no disruptive event occurs and if a disruptive event occurs. These evaluations

result in clear measures of resilience and clear views of what can be done to improve it.
2. Using indicators with differentiated weights. This is the second most accurate and second most effort-intensive way to measure resilience. It requires the estimation of service reductions for each service measure and the additional intervention costs due to the values of each indicator. Indicators with differentiated weights consider the maximum and minimum possible service reductions and the additional intervention costs due to the values of each indicator.
3. Using indicators with equal weights. It only requires estimating service reductions for each service measure and additional intervention costs. It is assumed that variations in each indicator affect each service and intervention costs equally.

Examples of indicators and their possible values are included in this document and can be used as reference for resilience assessment.

2.2.6 Relevance for CIRCUIT project

CIRCUIT holistic framework is strongly aligned with forementioned standards developed for industry and being applied to improve sustainability of construction works.

The reference standard for CIRCUIT will be *EN 17472:2022 Sustainability of Construction works-Sustainability assessment of civil engineering works* as it is well aligned with the project principles and framework described in Chapter 1.

Other standards key for the project development will be *EN 15804 Environmental product declarations* and *ISO 15686-5 Life-cycle costing* respectively.

As complementary documentation, CEN Workshops Agreements will be considered to identify additional information, criteria and indicators that might be needed to complement the CIRCUIT holistic approach, in particular:

- CEN CWA 17089 Indicators for the sustainability assessment of roads
- CEN CWA 17819: Guidelines for the assessment of resilience of transport infrastructure to potentially disruptive events

2.3 Building up on previous / existing projects or initiatives- overview of frameworks / KPIs

The European Union has been actively promoting circular economy principles across various sectors, including construction sector. In the following chapter several European projects focusing on circular economy in the building and road infrastructure projects are presented. Key performance indicators or other metrics developed in those projects and initiatives, which are relevant for the CIRCUIT framework are briefly described in Table 1.

Table 1 Overview of existing EU projects/initiatives

Project/initiative	Focus/assets	Indicators used/developed
BEEYONDERS – Breakthrough European technologies yielding construction sovereignty, diversity & efficiency of resources (https://beeyonders.eu/)	Building construction, maritime construction, road construction, tunnels construction and road maintenance	• Environmental performance (LCA impact categories) • Economy (LCC) • Technical (productivity, autonomy, efficiency, reliability) • Social (inclusiveness, workers health and safety, technology acceptance)
ASHVIN – Assistants for Healthy, Safe, and Productive Virtual Construction Design, Operation & Maintenance using a Digital Twin (https://www.ashvin.eu/)	Airport runway, high-speed railway bridges, multi-family building, logistics hall, office building, footbridge, sport stadium roof, quay walls	• Structural mechanical • Costs • Sustainability & resource efficiency (LCA impact categories, energy consumption, material use, fresh water use • Health and safety • "Baukultur" (Aestetics, Upvaluation of surrounding area,…) • Level of Digitalization (Data, BIM/DT, Monitoring systems)
BAMB – Buildings As Material Banks (https://www.bamb2020.eu/)	Building materials	Physical properties • Dimensions, weight • Density • Building physics • Resistance and rigidity • Actively beneficial functions … Chemical properties • Life Cycle Assessment • Life Cycle Costing • Health and safety • Reuse and Recycling • Social Life Cycle Assessment … Biological properties • Renewable/non-renewable • Untreated/treated • Decomposability …
CIRCUIT – Circular Construction in Regenerative Cities (https://www.circuit-project.eu/)	Built environment	• Urban Mining Index (UMI) • Lifespan Index (LI) • Circularity Index (CI)
Platform CB'23 – The Dutch circular construction platform (https://platformcb23.nl/english/)	Construction sector	• Quantity of input materials used to produce and repair or refurbish the object or sub-object. • Quantity of output materials available for a subsequent cycle, (e.g. reused or recycled)

Project/initiative	Focus/assets	Indicators used/developed
		• Quantity of output materials lost for the next cycle, (e.g flows incinerated, and flow sent to landfill) • Environmental protection • Environmental Cost Indicator • Value retention • Functional value at the end of the life cycle • Economic value at the end of the life cycle
SUNRA – Sustainability for National Road Authorities (Sowerby et al., 2014)	Road infrastructure	• Accessibility • Air quality • Climate change adaptation • CO2 emissions • Cultural heritage • Economic viability • Ecosystems • Equity/equal mobility • Global partnership • Good governance • Innovation • Job creation& training • Modal split • Noise • Prosperity • Public Heath • Renewable energy • Resource consumption & waste • Road condition • Safety • Security • System efficiency • User satisfaction • Water quality
Pavement LCM – Life Cycle Management of Green Asphalt Mixtures and Road Pavements (Lo Presti et al., 2021)	Road pavements	• Environmental performance (LCA impact categories) • Economy performance (LCC) • Technical and functional requirements (Tyre-pavement noise, durability, …)
EDGAR – Evaluation and Decision Process for Greener Asphalt Roads CEDR Call 2013: Energy Efficiency (Wayman et al., 2014)	Road pavements	• Global warming potential (GWP) Depletion of resources • Air pollution • Acidification potential • Leaching potential • Noise reduction potential Recyclability • Skid resistance • Responsible sourcing • Life cycle cost • Traffic congestion cost • Performance (Durability)
LCE4ROADS – Life Cycle Engineering approach to	Road infrastructures	Sustainability performance indicators • LCA impact categories

Project/initiative	Focus/assets	Indicators used/developed
develop a novel EU-harmonized sustainability certification system for cost-effective, safer and greener road infrastructures (https://www.lce4roads.eu/Overview)		• LCC • Social (comfort, safety, Resilient, Noise, Sources, Congestion)
Sustainable Pavements & Railway Initial Training Network (https://cordis.europa.eu/project/id/607524/reporting/it)	Road pavements	Environmental indicators • Global warming • Energy demand • Secondary materials consumption • Materials to be reused or recycled • Water consumption • Acidification indicator of soil and water • Eutrophication indicator • Stratospheric ozone depletion indicator • Particulate matter indicator • Social indicators • Safety audits & safety inspections • User comfort (based on PSI or IRI) • Noise reduction • Traffic congestion • Economic indicators • Life cycle highway agency costs • Life cycle road user costs
CERCOM – Circular Economy in Road Construction (https://cercom.project.cedr.eu/)	Road infrastructure	• Technical performance • Cost (Whole life cost, Net present value) • RE&CE (KPIs – Resource use, Energy) • Environmental (KPIs – Biodiversity, Carbon equivalent) • Social value (KPIs Social value, Sourcing local materials)
PCDS – Product Circularity Data Sheet (https://pcds.lu/)	Products, materials	• Composition/Information on product constituents (chemical composition, chem. Substance threshold, hazard statements, recycled content, sourcing statements, • Design for better use (Designed for maintenance & repair, safe operation, actively positive impacts • Design for disassembly (demounting, disassembling, dismantling) • Design for re-use (Circularity pathways/scenarios,

2.3.1 Relevance for CIRCUIT project

Most of the indicators used/developed to assess environmental, economic or social aspects are included in the updated standards mentioned as reference for CIRCUIT (e.g.

EN 17472), so they can be considered as already included. However, concerning circularity, the indicators used/developed in PCDS will be taken into consideration to define the CIRCUIT KPIs.

2.4 CURRENT ENGINEERING AND MARKET PRACTICES

Sustainable approach, life cycle thinking, resource conservation, waste reduction and recycling practices together with the use of sustainable materials and environmentally friendly designs are becoming regular practices in certain areas of civil engineering. Innovative procurement practices such as Green Public Procurement (GPP), Most Economically Advantageous Tender (MEAT directive) and Best Value Procurement (BVP) are pushing the industry and procurers to foster sustainable engineering (COM/2008/400, EU, 2014/24; MnDOT, 2012).

To promote sustainable solutions public bodies in several European countries are including the evaluation and certification of the project as a part of procurement process, following one of the existing sustainability frameworks and rating systems. Level(s), BREEAM and LEED frameworks are utilized in Europe to evaluate and communicate the environmental performance of buildings and provide a standardized approach for assessing sustainability. A similar trend is emerging in civil engineering works with sustainable frameworks and rating systems like ENVISION or BREEAM Infrastructure(formerly CEEQUAL). The following sub-sections summarise the good practices mentioned to increase sustainability in construction works and relevance for the CIRCUIT project.

2.4.1 Procurement processes

The EU is providing framework for public procurement, in accordance with the provisions of the Treaty on the Functioning of the European Union. Furthermore, the EU Procurement Directives stipulate the main obligations and provide the basis for the European Commission's public procurement strategy, which are then transposed into national law. As a part of EU Procurement Directives (2014/23/EU, 2014/24/EU, 2014/25/EU) the Most Economically Advantageous Tender (MEAT) method was introduced, which includes additional criteria for the assessment, such as quality, price or cost using a cost-effectiveness approach, technical merit, aesthetic and functional characteristics, accessibility, social characteristics, environmental characteristics, innovative characteristics, after-sales service and technical assistance, delivery conditions such as date, process, and period.

The EU is also promoting the use of Green Public Procurement. A handbook document (EC, 2016) was published in 2011, which introduces the concept of GPP and summarises the key EU and national policies in this area, with the examples, outcomes and benefits of GPP, based on the approaches being implemented by public authorities throughout the EU. The legal and value-for-money aspects of GPP are also presented (EC, 2011).

CIRCUIT D4.1 Manual for a successful deployment of GPP in CIRCUIT pilots, provides a detailed analysis of procurement strategies and the approach to be followed in the project.

2.4.2 Sustainability frameworks and rating systems

2.4.2.1 Level(s) common framework

Level(s) is the first-ever European Commission framework for improving the sustainability of buildings, living by the values of flexibility, resource efficiency, and circularity. It started being developed in 2015, while it was officially launched on 15 October 2020 (Ferrari et al. 2022, Dodd et al., 2020). The framework targets three main project actors: project design teams, clients and investors, and public policy makers and procurers, offering potential advantages to each group. LEVEL(s) framework is based on six macro-objectives, as presented in Table 2. The common framework is organized in three levels representing the stages in the execution of a construction project (Level 1: Conceptual design, Level 2: Detailed design and construction performance and Level 3: Performance once built and in use).

Table 2 Overview of macro-objectives and indicators in Level(s) (Dodd et al. 2020)

Thematic areas	Macro objectives	Indicators			
Resource use and environmental performance	1.GHG emissions along a building's life cycle	1.1 Use stage energy performance (kWh/m²/yr)	1.2 Life cycle GWP (CO_2 eq./m²/yr)		
	2. Resource efficient and circular material life cycles	2.1 Bill of quantities, materials, and lifespans	2.2 C&D waste management	2.3 Design for adaptability and renovation	2.4 Design for de-construction
	3. Efficient use of water resources	3.1 Use stage water consumption (m³/occupant/yr)			
Health and comfort	4. Healthy and comfortable spaces	4.1 Indoor air quality	4.2 Time out of thermal comfort range	4.3 Lighting and visual comfort	4.4 Acoustics and protection against noise
Cost, value, and risk	5. Adaption and resilience to climate change	5.1 Life cycle tools: scenarios for projected future climatic conditions	5.2 Increased risk of extreme weather events	5.3 Increased risk of flood events	
	6. Optimized life cycle cost and value	6.1 Life cycle costs (€/m²/yr)	6.2 Value creation and risk factors		

2.4.2.2 Building research establishment environmental assessment method (BREEAM) Infrastructure

BREEAM Infrastructure (formerly CEEQUAL) is a sustainability assessment, rating, and awards program for civil engineering, infrastructure, landscaping, and public realm projects worldwide. It applies to various projects like roads, railways, ports, wind farms, flood alleviation schemes, and more. BREEAM Infrastructure focuses on strategy, design, and construction phases, excluding operation and maintenance assessments. It offers different assessment types for certification (BRE, 2020).

The categories and requirements that are assessed at each stage, with the respective weighting and credits, for the assessment are provided in the Guidelines (BRE, 2020) and are shown in the Table 3.

Table 3 Categories and weighting in BREEAM Infrastructure (BRE, 2020)

Category	Category weighting %	Credits available (max)
Management	11	550
Resilience	12	600
Communities and stakeholders	11	550
Land use and ecology	12	600
Landscape and historic environment	9	450
Pollution	8	400
Resources		
Materials, incl. waste	16	800
Energy and carbon (operational)	4	200
Energy and carbon (construction)	5	250
Water use	4	200
Transport	8	400
Total	**100**	**5000**
Innovation		500

Each of the category has defined assessment issues, as presented in Table 4.

Table 4 Assessment issues per category according to BREEAM Infrastructure (BRE, 2020)

	Category	Assessment issues
1	Management	1.1 Sustainability leadership 1.2 Environmental management 1.3 Responsible construction management 1.4 Staff and supply chain social governance 1.5 Whole life costing
2	Resilience	2.1 Risk assessment and mitigation 2.2 Flooding and surface water run-off 2.3 Future needs
3	Communities and stakeholders	3.1 Consultation and engagement 3.2 Wider social benefits 3.3 Wider economic benefits

	Category	Assessment issues
4	Land use and ecology	4.1 Land use and value 4.2 Land contamination and remediation 4.3 Protection and biodiversity 4.4 Change and enhancement of biodiversity 4.5 Long-term management of biodiversity
5	Landscape and historic environment	5.1 Landscape and visual impact 5.2 Heritage assets
6	Pollution	6.1 Water pollution 6.2 Air, noise and light pollution
7	Resources	7.1 Strategy for resource efficiency 7.2 Reducing whole life carbon emissions 7.3 Environmental impact of construction products 7.4 Circular use of construction products 7.5 Responsible sourcing of construction products 7.6 Construction waste management 7.7 Energy use 7.8 Water use
8	Transport	8.1 Transport networks 8.2 Construction logistics
	Innovation	Exemplary level of performance in existing issues Approved innovations

2.4.2.3 Sustainable infrastructure framework ENVISION

Envision is a framework that provides the guidance needed to initiate this systemic change in the planning, design and delivery of sustainable and resilient infrastructure. It is a decision-making guide, not a set of prescriptive measures, which provides industry-wide sustainability metrics for all types and sizes of infrastructure to help users assess and measure the extent to which their project contributes to conditions of sustainability across the full range of social, economic, and environmental indicators. Furthermore, the Envision framework recognizes that these sustainability factors are variable across a project's life cycle. As such, Envision helps users optimize project resilience for both short-term and long-term impacts. Projects can opt for two verification pathways: Path A for design and post-construction assessment, or Path B for post-construction only. The ENVISION framework consists of 64 sustainability indicators, called credits, that cover all dimensions of infrastructure sustainability, as shown in Figure 7 (ISI, 2018).

Category	Subcategory	Credit	Improved	Enhanced	Superior	Conserving	Restorative	Maximum Points
Quality of Life	Wellbeing	QL1.1 Improve Community Quality of Life	2	5	10	20	26	200
		QL1.2 Enhance Public Health & Safety	2	7	12	16	20	
		QL1.3 Improve Construction Safety	2	5	10	14	—	
		QL1.4 Minimize Noise & Vibration	1	3	6	10	12	
		QL1.5 Minimize Light Pollution	1	3	6	10	12	
		QL1.6 Minimize Construction Impacts	1	2	4	8	—	
	Mobility	QL2.1 Improve Community Mobility	1	3	7	11	14	
		QL2.2 Encourage Sustainable Transportation	—	5	8	12	16	
		QL2.3 Improve Access & Wayfinding	1	5	9	14	—	
	Community	QL3.1 Advance Equity & Social Justice	3	6	10	14	18	
		QL3.2 Preserve Historic & Cultural Resources	—	2	7	12	18	
		QL3.3 Enhance Views & Local Character	1	3	7	11	14	
		QL3.4 Enhance Public Space & Amenities	1	3	7	11	14	
Leadership	Collaboration	LD1.1 Provide Effective Leadership & Commitment	2	5	12	18	—	182
		LD1.2 Foster Collaboration & Teamwork	2	5	12	18	—	
		LD1.3 Provide for Stakeholder Involvement	3	6	9	14	18	
		LD1.4 Pursue Byproduct Synergies	3	6	12	14	18	
	Planning	LD2.1 Establish a Sustainability Management Plan	4	7	12	18	—	
		LD2.2 Plan for Sustainable Communities	4	6	9	12	16	
		LD2.3 Plan for Long-Term Monitoring & Maintenance	2	5	8	12	—	
		LD2.4 Plan for End-of-Life	2	5	8	14	—	
	Economy	LD3.1 Stimulate Economic Prosperity & Development	3	6	12	20	—	
		LD3.2 Develop Local Skills & Capabilities	2	4	8	12	16	
		LD3.3 Conduct a Life-Cycle Economic Evaluation	5	7	10	12	14	
Resource Allocation	Materials	RA1.1 Support Sustainable Procurement Practices	3	6	9	12	—	196
		RA1.2 Use Recycled Materials	4	6	9	16	—	
		RA1.3 Reduce Operational Waste	4	7	10	14	—	
		RA1.4 Reduce Construction Waste	4	7	10	16	—	
		RA1.5 Balance Earthwork On Site	2	4	6	8	—	
	Energy	RA2.1 Reduce Operational Energy Consumption	6	12	18	26	—	
		RA2.2 Reduce Construction Energy Consumption	1	4	8	12	—	
		RA2.3 Use Renewable Energy	5	10	15	20	24	
		RA2.4 Commission & Monitor Energy Systems	3	6	12	14	—	
	Water	RA3.1 Preserve Water Resources	3	5	7	9	12	
		RA3.2 Reduce Operational Water Consumption	4	9	13	17	22	
		RA3.3 Reduce Construction Water Consumption	1	3	5	8	—	
		RA3.4 Monitor Water Systems	1	3	6	12	—	
Natural World	Siting	NW1.1 Preserve Sites of High Ecological Value	2	6	12	16	22	232
		NW1.2 Provide Wetland & Surface Water Buffers	2	5	10	16	20	
		NW1.3 Preserve Prime Farmland	—	2	8	12	16	
		NW1.4 Preserve Undeveloped Land	3	8	12	18	24	
	Conservation	NW2.1 Reclaim Brownfields	11	13	16	19	22	
		NW2.2 Manage Stormwater	2	4	9	17	24	
		NW2.3 Reduce Pesticide & Fertilizer Impacts	1	2	5	9	12	
		NW2.4 Protect Surface & Groundwater Quality	2	5	9	14	20	
	Ecology	NW3.1 Enhance Functional Habitats	2	5	9	15	18	
		NW3.2 Enhance Wetland & Surface Water Functions	3	7	12	18	20	
		NW3.3 Maintain Floodplain Functions	1	3	7	11	14	
		NW3.4 Control Invasive Species	1	2	6	9	12	
		NW3.5 Protect Soil Health	—	3	4	6	8	
Climate and Resilience	Emissions	CR1.1 Reduce Net Embodied Carbon	5	10	15	20	—	190
		CR1.2 Reduce Greenhouse Gas Emissions	8	13	18	22	26	
		CR1.3 Reduce Air Pollutant Emissions	2	4	9	14	18	
	Resilience	CR2.1 Avoid Unsuitable Development	3	6	8	12	16	
		CR2.2 Assess Climate Change Vulnerability	8	14	18	20	—	
		CR2.3 Evaluate Risk and Resilience	11	18	24	26	—	
		CR2.4 Establish Resilience Goals and Strategies	—	8	14	20	—	
		CR2.5 Maximize Resilience	11	15	20	26	—	
		CR2.6 Improve Infrastructure Integration	2	5	9	13	18	
						Maximum TOTAL Points		1,000

Figure 7 Categories and assessment issues in ENVISION (ISI, 2018)

2.4.3 Impact assessment digital tools used by industry

Industry uses a diverse range of tools to quantify the impact of its activity. Within the construction industry, EPDs (as exposed in previous Section 2.2.2) support carbon emission reduction by making it possible to compare the impacts of different materials and products in order to select the most sustainable option. Architects, engineers and designers are able to choose the most sustainable option for their project and manufacturers are able to optimize the impact of their products and market their carbon transparency

LCA tools are becoming widely used by the construction industry to produce EPDs to quantify environmental impacts, but also to measure circularity. E.g:

- One Click LCA software offers a building circularity score to quantify material circularity in designs and allows comparison of different design scenarios to identify the most circular approach.
- The GaBi Circularity Toolkit quantifies, benchmark and communicates the circularity of your products with the GaBi Circularity Toolkit. The toolkit allows you to implement the Material Circularity Indicator (MCI) within conventional GaBi LCA models

The Material Circularity Indicator (MCI) was developed by the Ellen McArthur Foundation (Circularity Indicators 2019) and focuses on the restoration of material flows at product and company levels and is based on the following six principles:

1. Sourcing biological materials from sustained sources
2. Using feedstock from reused or recycled sources
3. Keeping products in use longer (e.g., by reuse/redistribution/increase durability)
4. Reusing components or recycling materials after the use of the product
5. Making more intensive use of products (e.g. via service, sharing or performance models)
6. Ensuring biological materials remain uncontaminated and biologically accessible

MCI is defined by considering the Linear Flow Index of the product (which measures the proportion of material flowing in a linear fashion, that is, sourced from virgin materials and ending up as unrecoverable waste) and a factor $F(X)$, built as a function F of the utility X that determines the influence of the product's utility on its MCI (accounting for the length of the product's use phase (lifetime) and another for the intensity of use (functional units).

2.4.4 Relevance for CIRCUIT project

As presented in Chapters 2.3 and 2.4, there are obviously numerous methodologies (standards, guideline documents and engineering practices) for the quantification of economy, social and environmental aspects of construction products. CIRCUIT project is building on top of them unique holistic framework for life cycle management of transport infrastructure. Proposed framework will use KPIs for four main categories, namely circularity, economy, environment and social aspects, similar to the categories in Levels, BREEAM Infrastructure and ENVISION. However, CIRCUIT is focusing on circularity aspect and digitalization, namely the integration of all KPIs into digital platform which will enable decision making process along the whole life cycle. Where methods and approaches leading to a quantitative result are not available for assessment criteria and indicators (e.g. social indicators), a checklist method is adopted based on civil engineering works-specific features and characteristics. For this reason, and to facilitate deployment, additional information and guidance from actual sustainable frameworks and rating methodologies (e.g., ENVISION and BREEAM Infrastructure) were considered as relevant to support the assessment within CIRCUIT.

3 8CIRCUIT FRAMEWORK AND HOLISTIC APPROACH

3.1 Pilot projects

The project considers various pilot projects and employs a bottom-up methodology to identify performance indicators that transform into key performance indicators (KPIs) which will be used for circularity and sustainability assessment, especially for the existing assets and their potential for reuse and recycling.

The five pilot projects present different operational environments, in different EU countries, covering different lifecycle stages of infrastructure as defined in EN 15643- Sustainability of Construction Works. These range from A0 – Pre-construction stage, through Use stage B1 to B8 to End of Life C4, as shown in **Error! Reference source not found.**. The pilot projects were broken down to facilitate the easy comprehension of system boundaries, engineering processes and circular objectives of each pilot.

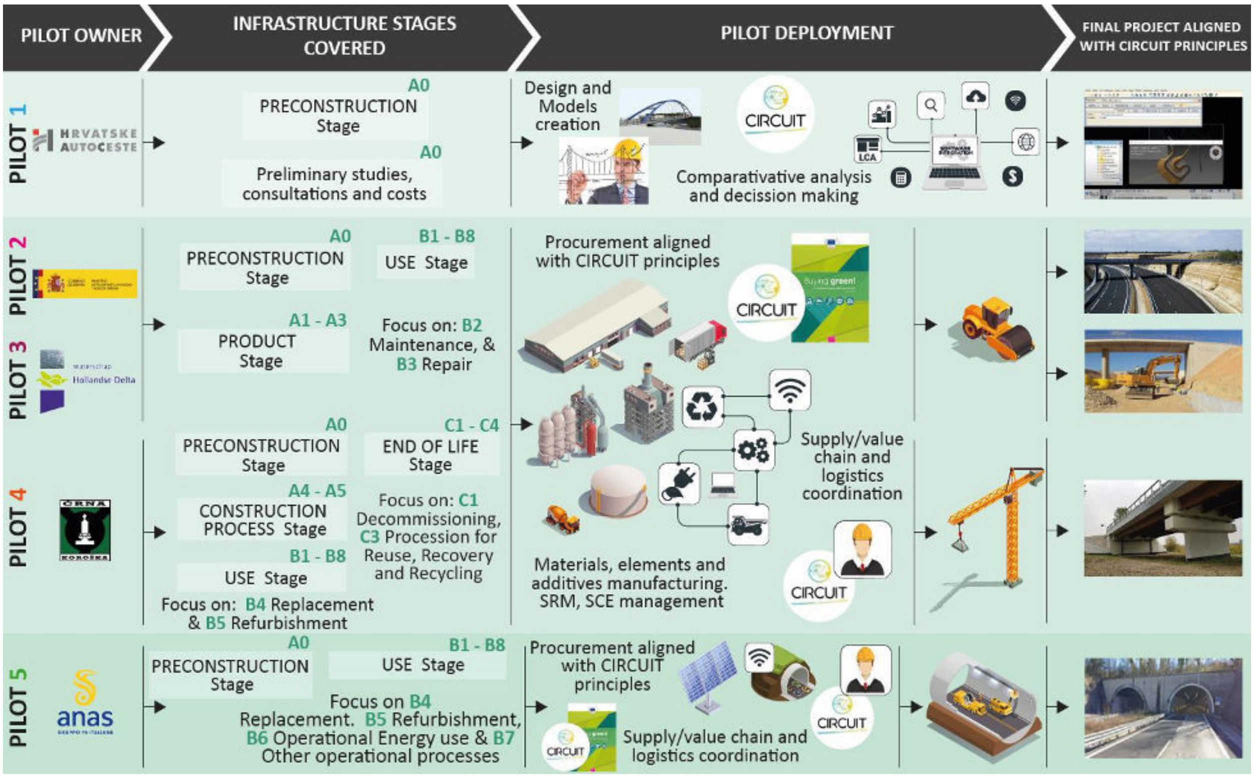


Figure 9 CIRCUIT pilot projects summary

3.2 LIFE CYCLE DECISION FLOW

The aim is to define, derive and apply data, performance indicators (PI) and key performance indicators (KPI) for planning, assessing and implementing different circular solutions, ranging from supply chain logistic planning and resource allocation to decision making process of transport infrastructures design, through life operation and maintenance and route planning. The overall CIRCUIT framework with CIRCUIT tools and KPIs implemented in the life cycle decision flow is shown in Figure 10.

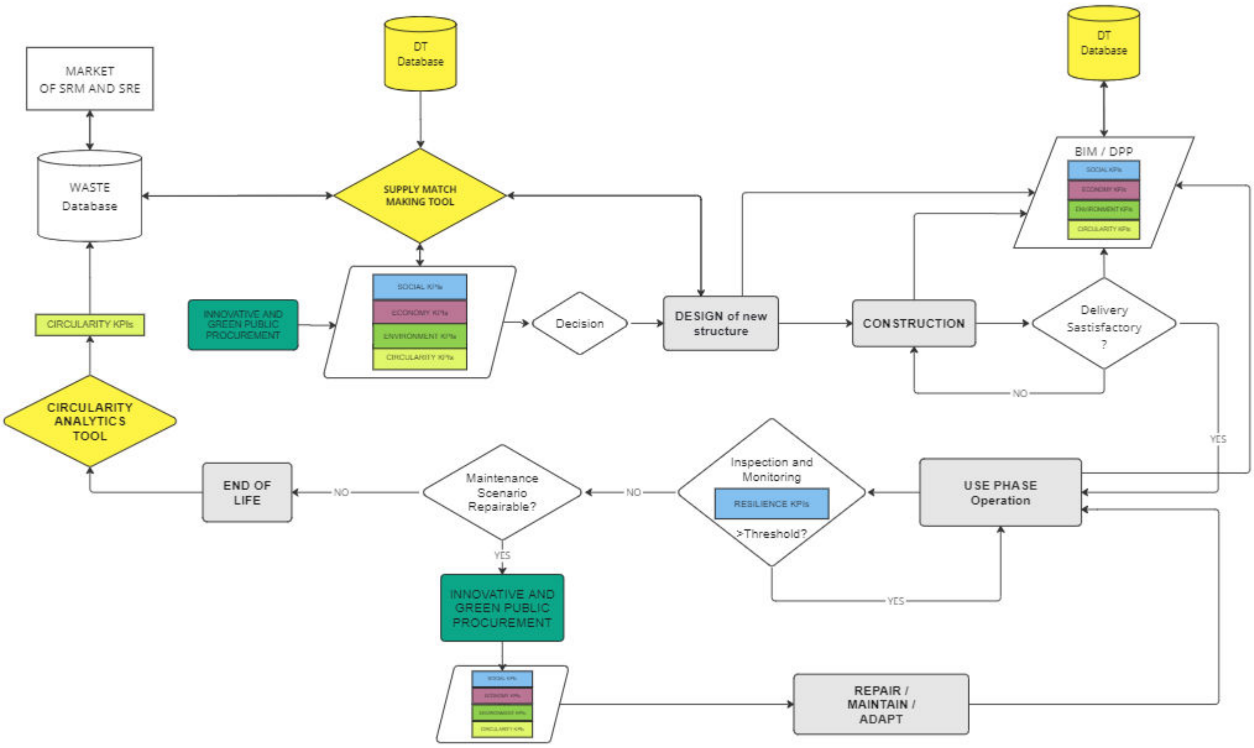


Figure 10 Proposed CIRCUIT framework in life cycle decision flow process

The decision flow proposed can be briefly described as follows including insights of the tools under development both in WP1 and WP2. For implementation of circularity principles into management of transport infrastructure it is important to understand key phases in the life cycle which are as follows:

- Initiation phase - involves identifying the need for a transport infrastructure project and defining its objectives. It includes preliminary feasibility studies, stakeholder engagement, and establishing the project's scope, budget, and timeline.
- Planning and Design phase - detailed planning and design work including environmental impact assessments, engineering design, obtaining necessary permits and approvals, and developing a detailed project plan.
- Procurement and Construction – upon the completion of the planning and design, the project moves into the procurement phase, where contractors are selected

through a bidding process. Construction begins once contracts are awarded, and the physical infrastructure is built according to the approved designs.

- Operation and Maintenance – upon the completion of construction, the infrastructure enters its operational phase. This involves managing day-to-day operations, providing services to users, and conducting routine maintenance to ensure the infrastructure remains safe and functional. Throughout the life cycle of the infrastructure, monitoring and evaluation are essential to assess performance, identify issues, and make necessary adjustments. This involves collecting data on factors such as traffic volume, safety incidents, and maintenance needs. Over time, transport infrastructure degrades due to wear and tear, environmental factors, or changing usage patterns. This phase involves renewing and rehabilitating the infrastructure to extend its lifespan and maintain its functionality.
- Decommissioning or Removal - eventually, the infrastructure reaches the end of its useful life or becomes obsolete. In this phase, the infrastructure is decommissioned, removed from service, and potentially replaced with newer infrastructure or repurposed for other uses.

Effective whole life cycle planning requires the accuracy and completeness of data to make informed cost-effective and sustainable decisions. With the multiple types of transport infrastructure assets having targeted performance goals (in terms of circularity, economy, society, and environment) and numerous data sources, it is intractable for infrastructure managers to systematically decide about the multiple aspects of through life (A: pre-construction/product/construction stage, B: use stage, C: end of life stage, D: beyond stage) planning based on implicit reasoning and judgments. Transportation agencies continuously collect and manage large amount of all kind of data from assets birth certificates, through life performance data to operational and maintenance data. The asset management data can be used to quantify the multiple performance objectives, where the multi-criteria methods can help to manage their conflicting nature. KPIs structuring around four key aspects social, economy, environment and circularity allow for quantitative, comprehensive and transparent (followable) assessment of each aspect separately. Various data, often already available to transport infrastructure managers, is translated into performance indicators and combined into KPIs surpassing the limitations of judgment-based decision making and ultimately reaching circularity goals.

The limitations of judgment-based decision making, inaccessibility of huge amount of data, and theoretical underpinning of single-objective methods emphasizes the need to improve the decision-making process in managing transport infrastructure. Digitalization of asset information enables on demand data access and analysis, continuous data collection and storage, and information-based management of infrastructure assets through their life cycle. Multi-criteria decision-analysis provide support to systematically accommodate the multiple performance objectives and produce an optimal through life network level management plan. This type of analysis enables experts to execute numerous planning scenarios under various performance requirements with budget, environmental and social limitations (Allah Bukhsh, 2019).

3.3 DIGITAL PLATFORM AND ASSOCIATED COMMUNICATION SYSTEMS AND TOOLS

The Trimble-Dodge Construction Network remarks that digital workflows facilitate the identification and causes of delays and error during both pre-construction and construction processes. As construction projects data grew in complexity and size, especially with the maturity of BIM / digital twin and the need for the building-centric semantic data models and formats, it became apparent that a new kind of interoperability is required. This has been started taking care of by buildingSMART community since 1994 which led to the introduction of IFC into the industry. Since then, many updates have been done by the community partners for the data exchange like introducing IoT into IFC. Data generated by these new systems has not been yet connected to the existing data exchange interface. Structured vocabularies are important to define and structure the meaning of concepts and terms used in the construction industry to ensure their consistent use by all stakeholders over the life cycle of a construction. Due to the recent advancement of the technology, there are only a few widely accessible architecture, engineering, construction, and operations (AECO) Object Type Libraries (OTLs) and data dictionaries.

The **open-source digital platform** will be developed in WP2 and together with the training materials created in WP6 facilitate the uptake of CIRCUIT principles into the design, construction, maintenance and decommissioning of transport infrastructure. The whole CIRCUIT digitalization process is taking into consideration actual existing barriers, ensuring consistency along the construction supply/value chain and using open-source models such as IFCs to facilitate interoperability. The platform is developed as an online service that acts as a data dictionary in the AECO industry in connection with other existing like bSDD. CIRCUIT allows linking all the database content by providing a standardised workflow to guarantee data quality and information consistency. The CIRCUIT online platform is configured to facilitate searches where stakeholder can search the terms and get the result in a more tree graphical mode for the relation of the searched term to the complete notation. To reduce complexity and filter information relevant to a particular use case, the notion of "contexts" makes it possible to scope associated codes and concept hierarchies to a particular local standard. The CIRCUIT project approach goes beyond the current way of data generation which is introducing traffic simulation and environment monitoring during the maintenance and operation of road infrastructures.

A graph database (a type of database that uses graph structures for semantic queries with nodes, relationships, and properties to represent and store data) including information from the technologies and systems developed in CIRCUIT and data from other sources such as relevant innovations identified for the different CIRCUIT pillars, datasets of SRM, SCE, NBS, etc., open databases including climate change adaptation measures (e.g. climate-ADAPT from the partnership between the European Commission and the European Environment Agency), EPDs of construction materials and projects (e.g. EPD international).

Apart from those datasets, data from the developments in CIRCUIT on Digital Passports for products and materials/Introduction of blockchain technologies (WP2) will be also integrated in the DT Database.

Increasing the rate of materials to be recycled and reused as SRMs by the construction industry requires the traceability of materials and components and their properties from the production phase until the recycling and reusing as SRMs.

Here, the **Digital Product Passport (DPP)** plays a key role because it is meant to digitally register a wealth of data about a product describing its characteristics, location, history, ownership status, etc., in a varying level of detail (e.g., material, product, and building). Gaps: i) DPPs are static, not fed by information from material production processes and not updated when materials and components are recycled /reused, ii) Materials and components cannot be traced throughout the entire construction value chain yet, iii) DPP data need to be correct and verifiable. There are first examples of application and usage of DPPs in construction as follows. The EU-funded project BAMB developed more than 300 passports at three detail levels: product, building and instance. The Madaster online platform[2] automatically generates passports for buildings containing information about the quality, origins and location of materials and products. Recently published report provides guidance on Materials Passports, which offer an opportunity to gather and organise data about materials contained within a building, which in turn enable material reuse (Costa & Hoolahan 2024).
CIRCUIT addresses the drawbacks of current, static DPPs and has the ambition to enable dynamic DPPs that allow the transparent and reliable traceability of materials and components from the extraction and production phase until the end-of-use and recycling phase, and further in subsequent use cycles. A blueprint for DPPs that give construction products a unique identification and that are registered on a blockchain-based platform are developed allowing all value chain partners to trace the life cycle material and component data. The developed platform is decentralized with a blockchain-based solution in which all the relevant DPP data are available to and traceable for value chain partners.

A wide variety of different methods and tools is currently available to inform decision-makers about certain design and construction impacts. These methods typically focus on one specific topic and use independent tools (i.e., life-cycle costing: LCC; finite elements tools (i.e. PLAXIS); LCA or carbon footprint tools; etc). Recently published Revision of Construction Product Regulation (EC, 2022) requires enhancements in the use of natural resources, energy and water, an increase of the use of secondary materials and those with a low environmental footprint and facilitating reuse or recyclability of the construction works, parts of them and their materials after demolition. To enable this, it is necessary to provide digital tools for the circularity and sustainability assessment, especially for the existing assets and their potential for reuse and recycling. Methods to measure all aspects linked to circularity, sustainability and resilience are still being conceptualized though and are, accordingly, not yet digitized in interoperable environments. It is also necessary to enrich actual libraries with innovations for construction aligned with these concepts: creating new datasets for SRM, SCE, NBS, biobased and low carbon construction materials, etc.

Recovered materials and components vary among each other on environmental, economic and supply chain aspects. Designers need to be informed better about such complex (multi-criteria) trade-offs. CIRCUIT is developing an analytics tool that provides

[2] https://madaster.com/material-passport/

designers integrated insights into such aspects (e.g., CO_2 figures, cost, performance, durability, construction/upgrading time, etc.) to perform a reliable comparative analysis, facilitating the decision-making process. This tool will be able to compare also different maintenance and operation scenarios, integrating several types of impact assessment with multi-criteria optimization methods in a user-friendly tool. It includes information about objects, infrastructure elements, their composition, etc. Digital Product Passport is used to enhance actual classification and the properties included in the description of each infrastructure element/object/material to be included in the IFC model (including IFC.js and Dynamo open-source models and tools and design considerations). In CIRCUIT an alternative to Dynamo[3] is developed with IFC.jc as open source, free and web-based. This allows stakeholders to create their own 3D BIM applications for web, desktop and mobile with visual programming. The platform will enable the data integration from different tools, like LCA (e.g., openLCA), LCC, BIM, digital twin platforms/tools, traffic simulation tools (e.g., SUMO) etc.

The **BIM-based matchmaking tool** will assist sustainable decision-making regarding the supply of reusable deconstruction products. Designers first need to become more aware about the available SRM, SCE, NBS, etc. The ambition of CIRCUIT is to foster that awareness with a matchmaking method that allows for scenario-based predictions of recoverable materials low environmental impact materials. By using owner's database and other public records, project aims to develop algorithms that can estimate the reuse potential of materials in a certain area and period. This helps the designers in selecting and integrating deconstruction products in their planned (re)designs. For reuse to occur, recovered components and materials need to find a 'match' with a new destination. To facilitate this, a digital BIM-based tool is developed for organizing and utilizing building data of donor structures and infrastructures. This tool informs decision-makers about different alternatives for the usage of SRM and SCEs and long-term performance design and emissions. It should therefore be able to import (re)created BIM models in an interoperable file format (IFC) for further analysis. An existing digital collaborative environment is extended, with a new, standalone and platform-independent module that assists the matchmaking of reusable building components. It helps the users in selecting an appropriate end-of-life strategy depending on a project's specific resources available for materials and waste management.

The CIRCUIT project perceives a circular transport infrastructure as an industry that replaces the linear value chain model with a model that creates value by reducing, reusing, recycling and recovering construction materials and components throughout the whole life cycle. It re-values the existing infrastructure stock as a resource of secondary raw materials and structural elements. The notion of 'buildings as material banks' - promoted in a Horizon 2020 research project with the same name - draws attention to the valuable resources that are locked in existing constructions (CIRCuIT, 2019-2023). These elements can be recovered for reuse or recycling processes during (selective) demolition, which will be enabled through the developed holistic framework

[3] https://dynamobim.org

and digital platform which will support decision along the whole life cycle of transport infrastructure.

3.4 Key Performance Indicators

KPIs proposed in CIRCUIT framework will be applied to different dimensions of construction product or work. The integration of social and sustainability aspects in civil construction projects is essential to ensure that not only technical and economic objectives are met, but also to promote human well-being and minimize environmental impact.

For example, construction of the bridge with used/recycled elements may result in the decreased GHG emissions compared to building of a new structure, expressed in a bridge LCA, but also may have social impact on a broad scale creating new jobs, involvement of local firms, etc.

The PIs are harmonized with existing practices and standards:

- **EN 15643:2021 Sustainability of construction works** – Framework for assessment of buildings and civil engineering works.
- **EN 17472:2022: Sustainability of construction works –** Sustainability assessment of civil engineering works – Calculation methods,

EN 17472:2022 was considered as reference for the selection of PIs to assess the environmental and economic performances of civil engineering works. EN 17472 is based on Life Cycle Assessment (LCA), Life Cycle Cost (LCC), Whole-Life Cost (WLC) and other quantified environmental and economic information. The approach to the assessment covers all stages of the civil engineering works life cycle and includes all civil engineering works related construction products, processes, and services, used over its life cycle.

This standard was also considered for the selection of KPIs impacts and categories for the assessment of the social performance of the civil engineering works. Social performance includes quantitative and qualitative indicators in diverse categories, including accessibility and connectivity, distribution of population, health, and wellbeing (both linked to workforce and community/users), safety and security, stakeholders' engagement, economic prosperity and development and resilience.

To assess resilience, the EC Technical guidance on the climate proofing of infrastructure in the period 2021-2027 was also considered to include the methodological approach and guidance provided.

Where methods and approaches leading to a quantitative result are not available for assessment criteria and indicators, a checklist method is adopted based on civil engineering works-specific features and characteristics. For this reason, and to facilitate deployment, **additional information and guidance from actual sustainable frameworks and rating methodologies (e.g., ENVISION and BREEAM Infrastructure) were considered as relevant to support the assessment.**

Concerning Circularity, analysed system is perceived in a form that the assets within the systems are donors or recipients of reusable structural elements, products or recyclable materials depending on the life cycle stage of the asset. An asset approaching the end of life cycle becomes a donor for the repairable assets in the system. Also, materials outside the system such as wastes from other industries are introduced into the system. Circularity PIs are formed to enable qualification and quantification of circling of elements and materials and will be implemented and validated on 5 five pilots. A thorough literature review was performed which served as a basis for circularity PIs structuring (CIRCuIT, 2023; ISI, 2018; Dodd et al., 2020; BREEAM, 2020; Ferrari, 2020). In general, the most important criteria used for the final selection of indicators have been: simplicity, ease of measurement, universality, comparability relevance and pertinence.

In order to support deployment and facilitating the understanding of each of the indicators select, Indicators cards will be created as guidance.

3.4.1 Explanation of Performance Indicators cards

A combination of Performance Indicators is used to define each selected key performance indicator. PI cards are produced containing the essential information for later analysis. The cards concisely summarize information's of Performance Indicators (PIs) used to track and measure the performance of specific CIRCUIT performance aspects. Each card includes various components that provide a comprehensive understanding of the PI. The following components are included in a PI card:

- Description/definition provides a brief explanation of the PI, including its purpose, significance, and the rationale behind its selection. It helps users understand why the PI is important and how it contributes to overall objective. It also contains the definition of what is measured and its structure.
- Relevant standard for PIs that are defined through a certain standard.
- Quantification method section presents the mathematical formula or algorithm used to compute the PI. It outlines the variables and data inputs involved in the calculation process. For certain number of PIs no calculation formula is provided since they can only be used for qualitative analysis. Some PIs are calculated with different model methodologies such as LCA or climate change models.
- Unit of measure specifies the unit of measure in which the PI is expressed. It provides a standardized format for reporting and analysing the PI across different use cases or technologies.
- Pilot project applicability outlines the specific scenarios or pilot use cases where the PI is most relevant and applicable. It helps users understand when and where to use the PI to gain valuable insights into performance.
- Data requirements outlines the specific data requirements needed to calculate the PI accurately. It includes the data sources, data elements, and any transformations or aggregations necessary for the calculation.
- Expected data source identifies the system, database, or application from which the required data for the PI can be sourced. It helps users locate and access the relevant data to ensure the availability of accurate inputs for the PI calculation. This can also contain collection interval which indicates how frequently the data for the PI should be collected. It defines the time intervals at which the PI data is captured to ensure accurate and timely measurement. Collection interval can vary from continuous to once in the whole lifespan of a structure.

Aspects assessed (Social PIs only) lists and describes what elements and information are taken into account when the specific PI is assessed. The information gathered could be quantitative (e.g. number of heavy floods occurred) and qualitative (e.g. satisfaction of users and other affected parties) and it is used to perform specific PI assessment.The following chapters detail the PIs selected for the CIRCUIT holistic approach. Criteria and guidance will be included in D6.4 CIRCUIT Guidelines and replication strategy.

3.4.2 Circularity KPIs

The current economic system thrives on production and sales of goods and services where buying products leads to an increased demand, which stimulates production, which creates jobs and businesses. This induces creation of value (and hence money), which increases capacity to buy. In theory, this cycle is endless, leading to a never-ending growth and increase of wealth. Except the increase of wealth, the consequence of current linear economic growth is rapid depletion of mineral resources, some of them exhaustible and predicted to be running out within the coming few decades. (K.Hund, D. La Porta, T. P. Fabregas, T. Laing, J. Drexhage, 2020).

Beside depletion of resources this kind of economy, often referred as "linear economy", generates waste as a useless component in production value chain and burdens the environment. Direct consequence is pollution of natural elements such as air, soil, waters, and oceans, and the quality of life is reduced both locally and globally. Circularity, as a measure, is based on circular economy concept striving that the entropy of the current system should be decreased. Key principle of circularity is recycling of construction materials and products allowing it to be used more than once in a value chain. Still various strategies are identified within the value chain such as reuse, repurpose or up-cycle.
In the CIRCUIT project circularity is analysed on a network level including several types of structures. A comprehensive assessment of the existing transport infrastructure network is performed to identify areas where circularity principles can be applied. Structures chosen for validation of each pilot should be defined with regard to its location, type of use, type of structural system and various original design features. In the platform digital twin models will be analysed and enriched with newly develop circularity KPIs (assessment of recyclability, reusability and end-of-life value of the existing assets).

The CIRCUIT project perceives a circular transport infrastructure as an industry that replaces the linear value chain model with a model that creates value by reducing, reusing, recycling and recovering construction materials and components throughout the whole life cycle. The project re-values the existing infrastructure stock as a resource of secondary raw materials and structural elements.

3.4.2.1 Overview

PIs listed in the

Table 5 will be used to measure the circularity of materials and products used for construction, but also in the operation and maintenance phase. Circularity PIs will be integrated into BIM models and digital platform with the objective to enable implementation of circular economy into decision making processes.

Table 5 List of Circularity KPIs

KPI	ID No.	PI	PI/Description	UNIT / MEASURE	Relevant Standard/ Source
CIRCULARITY	Cir 1	REUSABILITY	Reused content - The percentage (by mass) of system/structure/element which can be/is reused at the end of the life cycle	%	
	Cir 2	RECYCLABILITY	Recycled content - The percentage (by mass) of material of system/structure/element which can be/is recycled at the end of the life cycle	%	
	Cir 3	LOSS OF MATERIAL/WASTE GENERATION	Materials & wastes going to landfilling, incineration or lost - The percentage (by mass) or total mass of material of system/structure/element which goes to landfill, incineration or lost at the end of the life cycle	% or kg, t	
	Cir4	SECONDARY MATERIALS	Waste from other industries - The percentage of waste from other industries in overall used material or total amount of waste used	% or kg, t	
	Cir5	DISASSEMBLY POTENTIAL	The extent to which the connections between structural elements can be broken, so that an object can retain its function and high-quality reuse can be achieved.	Grades	DGBC circularity program, (Vliet et al., 20219
	Cir6	PREFABRICATION LEVEL	Degree of structures or structural elements readiness when delivered to the site to be assembled. It can refer to a single structure and its elements or a group/network of structures (number of the same/similar type of structures).	Grades or %	(Lu et al., 2016; Hong et al. 2016; Gibb, 2001; Steinhardt et al., 2014)

KPI	ID No.	PI	PI/Description	UNIT / MEASURE	Relevant Standard/ Source
	Cir7	TRANSPORTABILITY	Depending on the geometry and weight of the element it can or cannot be transported in a certain type of mode of transport. It also refers to the accessibility of areas, availability and type of transport network to be used for transport of elements/materials.	Yes/No or €/km	

3.4.2.2 KPI cards

Cir1	Reusability	Circularity
Description/Definition	Reusability refers to the ability of an object or component to be used multiple times for various purposes without losing their function and without significant degradation in quality or performance. In essence, it involves extending the lifespan and utility of a resource beyond its initial intended use. Components or parts of larger systems can be designed and manufactured for reuse in multiple products or applications. Modular design principles often facilitate component reusability, allowing for easy integration and replacement within different systems.	
Relevant standard	N/A	
Quantification method/model	Qualitative assessment, Numerical modelling of load bearing capacity	
Unit of measure	The percentage (by mass) of system/structure/element which can be/is reused at the end of the life cycle	
Pilot project applicability		
Data requirements	Inventory lists or databases that catalogue reusable assets and their characteristics, historic data on condition and performance of reusable items throughout their lifecycle	
Expected data source	Asset management systems, Technical documentation, Supply Chain and Inventory Records	

Pilot project applicability:

Pilot	1	2	3	4	5
KPI applicable	+		+		
LC stage	A0		A0, A4-A5, B4, B5, C1, C3		

<table>
<tr><th>Cir2</th><th>Recyclability</th><th>Circularity</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Recyclability refers to the ability to reclaim, recover, or repurpose materials and components at the end of their useful life. Recyclable material is collected, sorted, processed or converted into new materials or products and used again after its initial use.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">N/A</td></tr>
<tr><td>Quantification method/model</td><td colspan="2">Recycling Rate – Calculation of the percentage of materials or products that are recycled compared to the total amount generated or used. This metric provides a measure of the overall effectiveness of recycling efforts and the extent to which materials are diverted landfills or incineration.

Recyclable Content – Calculation of proportion of recycled content in materials or products. This involves quantifying the amount of recycled materials incorporated into new products or construction materials, such as recycled aggregates in concrete or wastes from other industries used in production of construction materials.</td></tr>
<tr><td>Unit of measure</td><td colspan="2">The percentage (by mass) of material of system/structure/element which can be/is recycled at the end of the life cycle or
The percentage (by mass) of material of system/structure/element containing recycled material</td></tr>
<tr><td>Pilot project applicability</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>KPI applicable</td><td>+</td><td>+</td><td>+</td><td>+</td><td></td></tr><tr><td>LC stage</td><td>A0</td><td>A0, B2-B7</td><td>B2, B3</td><td>A0, A4-A5, B4, B5, C1, C3</td><td></td></tr></table></td></tr>
<tr><td>Data requirements</td><td colspan="2">Inventory lists or databases that catalogue recyclable materials and their characteristics, historic data on condition and performance of assets containing recyclable materials throughout their lifecycle</td></tr>
<tr><td>Expected data source</td><td colspan="2">Technical documentation (information on the types of materials (e.g., concrete, steel, wood, plastics), their quantities, and their recyclability characteristics (e.g., recyclable, non-recyclable, recyclable with limitations))</td></tr>
</table>

Cir3	Loss of material/waste generation					Circularity
Description/Definition	Materials & wastes going to landfilling, incineration or lost at the end of life cycle or during life cycle of a system/structure/element. Loss of material refers to any reduction or depletion of resources during the construction, operation, or maintenance of transport infrastructure. Excess materials that are discarded or unused during construction activities, such as excavation, concrete pouring, or paving. Deterioration or degradation of materials over time due to environmental factors, wear and tear, or inadequate maintenance practices. Waste generation refers to the creation of unwanted or unusable materials during the life cycle of transport infrastructure projects. Generated during the construction, operation and maintenance phase, including excess materials, demolition debris and waste from maintenance activities. Waste generated when infrastructure reaches the end of its useful life and is decommissioned or demolished.					
Relevant standard	N/A					
Quantification method/model	Depending on the type of material or structure. Generally, it is measured through material flow analysis by quantifying flow of materials within the system including inputs, outputs and stocks. The flow can be tracked from extraction and production to construction, operation, and end-of-life stages.					
Unit of measure	The percentage (by mass) or total mass (kg, t) of material of system/structure/element which goes to landfill, incineration or lost at the end of the life cycle					
Pilot project applicability	Pilot	1	2	3	4	5
	KPI applicable		+	+	+	
	LC stage		A0, B2-B7	B2, B3	A0, A4-A5, B4, B5, C1, C3	
Data requirements	Material properties, Quantity of materials used					
Expected data source	Technical documentation					

Cir4	Secondary materials	Circularity
Description/Definition	Utilization of waste materials from other industries to reduce the demand for virgin materials, minimize waste generation, and lower costs.	
Relevant standard		
Quantification method/model	Depending on the type of material or structure. Generally, it is measured through material flow analysis by quantifying flow of materials within the system including inputs, outputs and stocks. The flow can be tracked from extraction and production to construction, operation, and end-of-life stages.	
Unit of measure	Total mass (kg, t) or The percentage of waste from other industries in overall used material or total amount of waste used	
Pilot project applicability	see table below	
Data requirements	Material properties, Quantity of materials used	
Expected data source	Technical documentation	

Pilot	1	2	3	4	5
KPI applicable		+	+	+	
LC stage		B2-B5	B2, B3	B4, B5	

Cir5	Dissassembly potential	Circularity
Description/Definition	Indicator that allows assessment of level of capacity of a product/system/structure or built asset to be disassembled at the end of its useful life so that parts and components can be recycled, repurposed, or used in other ways to be diverted from the waste stream. The indicator can be applied to design of new structures or repair and maintenance of existing structures, and to asses level of dissassemblability of existing structures. The assessment of the PI refers to establishing the extent to which the connections between structural elements can be broken, so that an object can retain its function and high-quality reuse of structural elements can be achieved.	
Relevant standard	N/A	
Quantification method/model	A grading system based on combination of qualitative and quantitative method requiring detailed understanding of the products/structures design and all its constituent parts. Expert judgment and structure engineer knowledge is required for performing this type of analysis. It may require going into numerical modelling of the structure. All products and elements of the structure need to be determined together with the connections between them for establishing disassembly potential.	
Unit of measure	System, structure, element, material is designed to be easily disassembled and used elsewhere rating system from 0–1 (based on the percentage of the structure that can be disassembled at end of life), with 1 being 100%dissassemblable system/structure	
Pilot project applicability	see table below	

Pilot	1	2	3	4	5
KPI applicable	+			+	

	LC stage	A0			A0, A4-A5, C1, C3	
Data requirements	Type of structure, inspection and monitoring data, fastening and structure joints					
Expected data source	Technical documentation					

Cir6	Prefabrication level					Circularity
Description/Definition	Degree of structures or structural elements readiness when delivered to the site to be assembled. It can refer to a single structure and its elements or a group/network of structures (number of the same/similar type of structures).					
Relevant standard	N/A					
Quantification method/model	Quantitative assessments might provide a clear, index style picture of how much of a building is prefabricated. It may also serve as an independent variable to generate the quantitative relationships between other construction-related variables, such as the amount of energy that may be saved when prefabrication is used to a given degree (Hong et al., 2016). But generally, for assessing the prefabrication level, the qualitative approach: "degree of product readiness when delivered to the site", is preferable. A grading system with a level taxonomy where Levels go from no prefabrication to prefabricated trusses and beams, prefabricated structural panels, specialized pods, modules, and fully completed structures delivered to site respectively.					
Unit of measure	A grading system e.g. a five-level taxonomy of prefabrication adoption: Level 0 - a project does not use any form of prefabrication at all, e.g. fully cast-in situ; Level 1 - Component and sub-assembly (e.g. lintels); Level 2 - Non-volumetric assembly (e.g. 2-dimensional precast concrete elements such as walls or slabs); Level 3 – Volumetric assembly; Level 4 - Modular building (e.g. 3-dimensional modules) (Gibb, 2001),					
Pilot project applicability	Pilot	1	2	3	4	5
	KPI applicable	+			+	
	LC stage	A0			A0, A4-A5, C1, C3	
Data requirements	Type of structure, structural capacity, historic data on structural performance, inspection and monitoring data					
Expected data source	Technical documentation					

<table>
<tr><th>Cir7</th><th colspan="6">Transportability</th><th>Circularity</th></tr>
<tr><td>Description/Definition</td><td colspan="7">Refers to ability of structural components or materials to be moved or transferred between different locations. Depending on the geometry and weight of the element it can or cannot be transported in a certain type of mode of transport. It also refers to the accessibility of areas from which or to which elements or materials are transported. The analysis of the area includes determining the availability and type of transport network to be used for transport of elements/materials.</td></tr>
<tr><td>Relevant standard</td><td colspan="7">N/A</td></tr>
<tr><td>Quantification method/model</td><td colspan="7">Combination of qualitative and quantitative method. It requires detailed assessment of structures technical documentation. For example, if an existing structure is modular, which involve prefabricated components then the elements are transportable. Modular components can be transported efficiently to multiple sites, allowing for rapid deployment and scalability of infrastructure projects. For other types of structures technical documentation needs to be analysed and numerical modelling may be required. For the area analysis a feasibility study for the specific case study needs to be performed.</td></tr>
<tr><td>Unit of measure</td><td colspan="7">Price/km which can be derived through feasibility study or Yes/No if components/elements/materials can or cannot be transported</td></tr>
<tr><td rowspan="3">Pilot project applicability</td><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td colspan="2">5</td></tr>
<tr><td>KPI applicable</td><td>+</td><td>+</td><td>+</td><td></td><td colspan="2"></td></tr>
<tr><td>LC stage</td><td>A0</td><td>A0, B2-B5</td><td>B2, B3</td><td>A0, A4, A5, B4, B5, C1, C3</td><td colspan="2"></td></tr>
<tr><td>Data requirements</td><td colspan="7">Dimensions of the element to be transported, distance and route for transport, type of vehicles for transport, transport network in the area with data about capacity (road load limits, rad weight/height limits) of the transport network.</td></tr>
<tr><td>Expected data source</td><td colspan="7">Technical documentation</td></tr>
</table>

3.4.3 Environmental KPIs

3.4.3.1 Overview

A number of standards, methodologies, research projects and certification systems such as BREAAM or ENVISION have been considered and their indicators compared and analysed to propose a succinct list of environmental indicators aligned with the CIRCUIT framework. As it can be seen in Table 6, most of the indicators here selected are those designated in the EN 15804, which are aligned with the Product Environmental Footprint (PEF) requisites (i.e., those indicators are aligned with the ones developed within the EF method).

Life Cycle Assessment-related indicators and others such as those involving land use, land contamination or biodiversity have been analysed and a refined selection provided, see

Table 6. As with the social indicators, the most important criteria considered for this final selection of environmental KPIs have been: simplicity, universality, comparability, relevance, ease of measurement and pertinence.

Table 6 List of Environmental KPIs

KPI	ID No.	PI	PI/description	UNIT	Relevant Standard
ENVIRONMENT	Env1	CLIMATE CHANGE	Global Warming Potential TOTAL (GWP-Total)	kg CO2 eq.	EN 15804 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products
			Global Warming Potential fossil fuels (GWP-fossil)	kg CO2 eq.	
			Global Warming Potential biogenic (GWP-biogenic)	kg CO2 eq.	
			Global Warming Potential land use and land use change (GWP-LULUC)	kg CO2 eq.	
	Env2	OZONE DEPLETION	Depletion potential of the stratospheric ozone layer due to emissions of ozone depleting gases.	kg CFC 11 eq.	
	Env3	EUTROPHICATION	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-freshwater)	kg PO4 eq.	
			Eutrophication potential, fraction of nutrients reaching marine end compartment (EP-marine)	kg N eq.	
			Eutrophication potential, Accumulated Exceedance (EP-terrestrial)	mol N eq.	
	Env4	PHOTOCHEMICAL OZONE FORMATION	Formation potential of tropospheric ozone (POCP);	kg NMVOC eq.	EN 15804 Sustainability of construction works
	Env5	DEPLETION OF ABIOTIC RESOURCES	Abiotic depletion potential for non fossil resources (ADP minerals& metals)	kg Sb eq.	
			Abiotic depletion for fossil resources potential (ADP-fossil)	MJ, net calorific value	

KPI	ID No.	PI	PI/description	UNIT	Relevant Standard
	Env6	WATER USE	Water (user) deprivation potential, deprivation-weighted water consumption (WDP)	m3 world eq. Deprived	
	Env7	PARTICULATE MATTER EMISSIONS	Potential incidence of disease due to PM emissions (PM)	Disease incidence	
	Env8	IONIZING RADIATION, HUMAN HEALTH	Potential Human exposure efficiency relative to U235 (IRP)	kBq U235 eq.	
	Env9	ECO-TOXICITY (FRESHWATER)	Potential Comparative Toxic Unit for ecosystems (ETP-fw)	CTUe	
	Env10	HUMAN TOXICITY, CANCER	Potential Comparative Toxic Unit for humans (HTP-c)	CTUh	
	Env11	HUMAN TOXICITY, NON-CANCER EFFECTS	Potential Comparative Toxic Unit for humans (HTP-nc)	CTUh	
	Env12	LAND USE RELATED IMPACTS	Potential soil quality index (SQP)		
			Use of land of high ecological value	m2	EN 17472:2022 Sustainability of construction works - Sustainability assessment of civil engineering works - Calculation methods
			Ecological connectivity	no. wild passages per km	
			Noise and other perturbations	m2 land impacted by noise	

3.4.3.2 KPI cards

<table>
<tr><th>Env1</th><th>Climate change</th><th>Environment</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Climate change is declared as global warming potential expressed as the sum of three sub-categories.
Performance Indicators:
• Global Warming Potential fossil fuels (GWP-fossil)
• Global Warming Potential biogenic (GWP-biogenic)
• Global Warming Potential land use and land use change (GWP-LULUC)
Details per indicator definition can be found in EN 15804.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">EN 15804 + A2 (2019), Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products
ISO/TS 14067 Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification</td></tr>
<tr><td>Quantification method/model</td><td colspan="2">Baseline model of 100 years of the IPCC based on IPCC 2013.
Sum of all direct and indirect GHG emissions and removals.
Direct emissions of all GHGs calculated using GWP values and emission factors (IPCC) for fossil and biogenic fuel combustion and respective CO_2 emissions.
Indirect emissions (e.g. due to consumption electricity or heat) using national or local emission factors.
Calculation rules for GWP-luluc shall follow the latest available version of PEF guidance document.
Based on Life Cycle Impact Assessment (LCIA)</td></tr>
<tr><td>Unit of measure</td><td colspan="2">kg CO_2 eq.</td></tr>
<tr><td>Pilot project applicability per information modules/stages in LCI</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>Modules /stages</td><td>A0</td><td>A0, A1-A3, B1-B8</td><td>A0, A1-A3, B1-B8</td><td>A4-A5,B1-B8,C1-C4</td><td>A0,B1-B8</td></tr></table></td></tr>
<tr><td>Data requirements</td><td colspan="2">Fossil and non-fossile fuel consumption, direct measurements of GHG emissions (CO_2, CH_4, N_2O, HFCs, PFCs), electricity and heat consumption, land use and changes in land use associated with product system.</td></tr>
<tr><td>Expected data source</td><td colspan="2">Owner, LCA, LCA databases, EPDs</td></tr>
</table>

<table>
<tr><th>Env2</th><th>Ozone depletion</th><th>Environment</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Ozone Depletion Potential (ODP)
Indicator of emissions to air causing the depletion of the stratospheric ozone layer expressed as depletion potential of the stratospheric ozone layer due to emissions of ozone depleting gases.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">EN 15804 + A2 (2019)</td></tr>
<tr><td>Quantification method/model</td><td colspan="2">Steady-state ODPs, developed by the World Meteorological Organization (WMO, 2014)
Sum of all ozone depletion gasses emitted expressed as ozone depletion potential in the steady state (ODP steady state) for each emission (kg CFC -11 eq. / kg emission)
Based on Life Cycle Impact Assessment (LCIA)</td></tr>
<tr><td>Unit of measure</td><td colspan="2">kg CFC 11 eq.</td></tr>
<tr><td>Pilot project applicability per information modules/stages in LCA</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>Modules /stages</td><td>A0</td><td>A0, A1-A3, B1-B8</td><td>A0, A1-A3, B1-B8</td><td>A4-A5,B1-B8,C1-C4</td><td>A0,B1-B8</td></tr></table></td></tr>
<tr><td>Data requirements</td><td colspan="2">Inventory of ozone depleting gases used and emitted in product system</td></tr>
<tr><td>Expected data source</td><td colspan="2">Owner, LCA, LCA databases, EPDs</td></tr>
</table>

<table>
<tr><th>Env3</th><th>Acidification</th><th>Environment</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Acidification potential
Indicator of the potential acidification of soils and water due to emissions of acidifying gases such as nitrogen oxides and sulphur oxides.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">EN 15804 + A2 (2019)</td></tr>
<tr><td>Quantification method/model</td><td colspan="2">Accumulated Exceedance, Seppälä et al. 2006, Posch et al., 2008 based on Life Cycle Impact Assessment (LCIA)</td></tr>
<tr><td>Unit of measure</td><td colspan="2">mol H+ eq.</td></tr>
<tr><td>Pilot project applicability per information modules/stages in LCA</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>Modules /stages</td><td>A0</td><td>A0, A1-A3, B1-B8</td><td>A0, A1-A3, B1-B8</td><td>A4-A5,B1-B8,C1-C4</td><td>A0,B1-B8</td></tr></table></td></tr>
<tr><td>Data requirements</td><td colspan="2">Inventory of acidifying gasses used and emitted (SO_2, NO_x, etc..) in product system</td></tr>
<tr><td>Expected data source</td><td colspan="2">Owner, LCA, LCA databases, EPDs</td></tr>
</table>

Env4	Eutrophication	Environment
Description/Definition	Eutrophication (also known as nutrification) includes the enrichment of the freshwater marine and terrestrial ecosystems, due to excessive levels of macro-nutrients containing nitrogen and phosphorous caused by emissions of nutrients to air, water, and soil in the environment. **Performance Indicators:** **EP-freshwater (**Eutrophication potential, fraction of nutrients reaching freshwater end compartment) **EP-marine (**Eutrophication potential, fraction of nutrients reaching marine end compartment) **EP-terrestrial (**Eutrophication potential, Accumulated Exceedance)	
Relevant standard	EN 15804 + A2 (2019)	
Quantification method/model	The stoichiometric procedure which identifies the equivalence between N and P for both terrestrial and aquatic systems. EUTREND model, Struijs et al., 2009b, as implemented in ReCiPe Based on Life Cycle Impact Assessment (LCIA)	
Unit of measure	**EP-freshwater** kg PO_4 eq. **EP-marine** kg N eq. **EP-terrestrial** mol N eq.	
Pilot project applicability per information modules/stages in LCA	Pilot: 1 | 2 | 3 | 4 | 5 Modules /stages: A0 | A0, A1-A3, B1-B8 | A0, A1-A3, B1-B8 | A4-A5,B1-B8,C1-C4 | A0,B1-B8	
Data requirements	Inventory of nutrients used and emitted in product system	
Expected data source	Owner, LCA, LCA databases, EPDs	

Env5	Photochemical ozone formation	Environment
Description/Definition	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.	
Relevant standard	EN 15804 + A2 (2019)	
Quantification method/model	Formation potential of tropospheric ozone (POCP); LOTOS-EUROS ,Van Zelm et al., 2008, as applied in ReCiPe Based on Life Cycle Impact Assessment (LCIA)	
Unit of measure	kg NMVOC eq.	
Pilot project applicability per information modules/stages in LCA	Pilot: 1 | 2 | 3 | 4 | 5 Modules /stages: A0 | A0, A1-A3, B1-B8 | A0, A1-A3, B1-B8 | A4-A5,B1-B8,C1-C4 | A0,B1-B8	
Data requirements	Inventory of gases used in product system that affect the creation of photochemical ozone in the lower atmosphere	
Expected data source	Owner, LCA, LCA databases	

<table>
<tr><th>Env6</th><th>Depletion of abiotic resources</th><th>Environment</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Indicators of the depletion of natural non-fossil and fossil resources.
• Abiotic depletion potential for non-fossil resources (ADP minerals &metals), extraction of resources, expressed as useful material.
• Abiotic depletion potential for fossil resources (ADP-fossil) expressed as extraction of resources of different fossil fuels.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">EN 15804 + A2 (2019)</td></tr>
<tr><td>Quantification method/model</td><td colspan="2">CML 2002, Guinée et al., 2002, and van
Oers et al. 2002.
Based on Life Cycle Impact Assessment (LCIA)</td></tr>
<tr><td>Unit of measure</td><td colspan="2">ADP minerals & metals - kg Sb eq.
ADP-fossil - MJ, net calorific value</td></tr>
<tr><td>Pilot project applicability per information modules/stages in LCA</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>Modules /stages</td><td>A0</td><td>A0, A1-A3, B1-B8</td><td>A0, A1-A3, B1-B8</td><td>A4-A5,B1-B8,C1-C4</td><td>A0,B1-B8</td></tr></table></td></tr>
<tr><td>Data requirements</td><td colspan="2">• Inventory of minerals, metals, and fossil resources
• Use of renewable primary energy
• Use of renewable primary energy resources used as raw materials
• Use of non-renewable primary energy
• Use of non-renewable primary energy resources used as raw materials
• Use of secondary material
• Use of renewable secondary fuels
• Use of non-renewable secondary fuels</td></tr>
<tr><td>Expected data source</td><td colspan="2">Owner (Bill of quantities), LCA, LCA databases, EPDs</td></tr>
</table>

<table>
<tr><th>Env7</th><th>Water use</th><th>Environment</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Water (user) deprivation potential, deprivation-weighted water consumption (WDP)
Indicator of the relative amount of water used, based on regionalized water scarcity factors.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">EN 15804 + A2 (2019)</td></tr>
<tr><td>Quantification method/model</td><td colspan="2">Sum of total water consumption weighted with regional water scarcity factors
Available WAter REmaining (AWARE) Boulay et al., 2016
Based on Life Cycle Impact Assessment (LCIA)</td></tr>
<tr><td>Unit of measure</td><td colspan="2">m3 world eq. deprived</td></tr>
<tr><td>Pilot project applicability per information modules/stages in LCA</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>Modules /stages</td><td>A0</td><td>A0, A1-A3, B1-B8</td><td>A0, A1-A3, B1-B8</td><td>A4-A5,B1-B8,C1-C4</td><td>A0,B1-B8</td></tr></table></td></tr>
<tr><td>Data requirements</td><td colspan="2">Inventory of total water consumption, regional water scarcity factors</td></tr>
<tr><td>Expected data source</td><td colspan="2">Owner, LCA, LCA databases, EPDs</td></tr>
</table>

Env8	Particulate Matter emissions	Environment
Description/Definition	Indicator of the potential incidence of disease due to particulate matter emissions	
Relevant standard	EN 15804 + A2 (2019)	
Quantification method/model	SETAC-UNEP, Fantke et al. 2016 Based on Life Cycle Impact Assessment (LCIA)	
Unit of measure	Potential incidence of disease due to PM emissions	
Pilot project applicability per information modules/stages in LCA	Pilot: 1 – Modules /stages: A0; 2 – A0, A1-A3, B1-B8; 3 – A0, A1-A3, B1-B8; 4 – A4-A5,B1-B8,C1-C4; 5 – A0,B1-B8	
Data requirements	Inventory of PM emissions	
Expected data source	Owner, LCA, LCA databases, EPDs and/or direct measurements	

Pilot	1	2	3	4	5
Modules /stages	A0	A0, A1-A3, B1-B8	A0, A1-A3, B1-B8	A4-A5,B1-B8,C1-C4	A0,B1-B8

Env9	Ionizing radiation, human health	Environment
Description/Definition	Indicator of damage to human health and ecosystems linked to the emissions of radionuclides. Potential Human exposure efficiency relative to U235 (IRP)	
Relevant standard	EN 15804 + A2 (2019)	
Quantification method/model	Human health effect model as developed by Dreicer et al. 1995 update by Frischknecht et al., 2000 Based on Life Cycle Impact Assessment (LCIA)	
Unit of measure	kBq U235 eq.	
Pilot project applicability per information modules/stages in LCA	Pilot: 1 – Modules /stages: A0; 2 – A0, A1-A3, B1-B8; 3 – A0, A1-A3, B1-B8; 4 – A4-A5,B1-B8,C1-C4; 5 – A0,B1-B8	
Data requirements	Inventory of direct ionizing radiation	
Expected data source	Owner, LCA, LCA databases, EPDs and/or direct measurements	

Pilot	1	2	3	4	5
Modules /stages	A0	A0, A1-A3, B1-B8	A0, A1-A3, B1-B8	A4-A5,B1-B8,C1-C4	A0,B1-B8

Env10	Eco-toxicity (freshwater)	Environment
Description/Definition	Impact on freshwater organisms of toxic substances emitted to the environment. Potential Comparative Toxic Unit for ecosystems (ETP-fw)	
Relevant standard	EN 15804 + A2 (2019)	
Quantification method/model	Usetox version 2 until the modified USEtox model is available from EC-JRC Based on Life Cycle Impact Assessment (LCIA)	
Unit of measure	CTUh	
Pilot project applicability per information modules/stages in LCA	Pilot: 1 – A0; 2 – A0, A1-A3, B1-B8; 3 – A0, A1-A3, B1-B8; 4 – A4-A5,B1-B8,C1-C4; 5 – A0,B1-B8 (Modules /stages)	
Data requirements	Inventory of toxic substances used and emitted	
Expected data source	Owner, LCA, LCA databases, EPDs	

Pilot	1	2	3	4	5
Modules /stages	A0	A0, A1-A3, B1-B8	A0, A1-A3, B1-B8	A4-A5,B1-B8,C1-C4	A0,B1-B8

Env11	Human toxicity, cancer	Environment
Description/Definition	Impact on humans of toxic substances emitted to the environment. Divided into cancer-related toxic substances and non-cancer. Potential Comparative Toxic Unit for humans (HTP-c) Potential Comparative Toxic Unit for humans (HTP-nc)	
Relevant standard	EN 15804 + A2 (2019)	
Quantification method/model	Usetox version 2 until the modified USEtox model is available from EC-JRC Based on Life Cycle Impact Assessment (LCIA)	
Unit of measure	CTUh	
Pilot project applicability per information modules/stages in LCA	(see table below)	
Data requirements	Inventory of toxic substances used	
Expected data source	Owner, LCA, LCA databases, EPDs	

Pilot	1	2	3	4	5
Modules /stages	A0	A0, A1-A3, B1-B8	A0, A1-A3, B1-B8	A4-A5,B1-B8,C1-C4	A0,B1-B8

<table>
<tr><th>Env12</th><th>Land use related impacts</th><th>Environment</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Measure of the changes in soil quality[4] (Biotic production, Erosion resistance, Mechanical filtration).
Performance Indicators:
Potential soil quality index (SQP)
Other potential (non- mandatory) indicators:
Use of land of high ecological value
Ecological connectivity - no. wild passages per km
Noise and other perturbations - m^2 land impacted by noise</td></tr>
<tr><td>Relevant standard</td><td colspan="2">EN 15804 + A2 (2019)</td></tr>
<tr><td>Quantification method/model</td><td colspan="2">Soil quality index based on LANCA model (LANd use indicator value Calculation)
Based on Life Cycle Impact Assessment (LCIA)</td></tr>
<tr><td>Unit of measure</td><td colspan="2">m^2</td></tr>
<tr><td>Pilot project applicability per information modules/stages in LCA</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>Modules /stages</td><td>A0</td><td>A0, A1-A3, B1-B8</td><td>A0, A1-A3, B1-B8</td><td>A4-A5,B1-B8,C1-C4</td><td>A0,B1-B8</td></tr></table></td></tr>
<tr><td>Data requirements</td><td colspan="2">Land use maps, time of land occupation, area of occupied land</td></tr>
<tr><td>Expected data source</td><td colspan="2">Owner, LCA, LCA databases, EPDs</td></tr>
</table>

3.4.4 Economy KPIs

3.4.4.1 Overview

Economy Key performance Indicators (

[4] Soil quality is defined as the "capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health" (Doran, 2002).

Table 7) for the specific infrastructure project are used to quantify the costs and incomes occurred in whole life cycle and are in line with the standard *ISO 15686-5:2017 Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing.* Life cycle presents consecutive and interlinked stages of the object under consideration. The life cycle comprises all stages from construction, operation, and maintenance to end-of-life, including decommissioning, deconstruction and disposal. As set in the standard: "The purpose of life-cycle costing should be to quantify the life-cycle cost (LCC) for input into a decision-making or evaluation process, and should usually also include inputs from other evaluations (e.g. environmental assessment, design assessment, safety assessment, functionality assessment and regulatory compliance assessment). The quantification should be to the level of detail that is required for key project stages. The scope of costs included/excluded from an LCC analysis should be defined and agreed with the client at the outset."

Table 7 List of Economy KPIs

KPI	ID No.	PI	PI/Description	UNIT/MEASURE	Relevant Standard/ Source
ECONOMY	Econ1	WHOLE LIFE CYCLE COST (WLCC)	Costs including all construction, operational, maintenance, repair and end of life activities during whole life.	€/functional unit	ISO 15686-5:2017 Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing.
	Econ2	INITIAL CONSTRUCTION COST (ICC)	Total capital costs needed for construction.	€/functional unit	
	Econ 3	MAINTENANCE COST	Total cost due to maintenance and repairs of the asset (it includes cost of repairs and regular maintenance costs).	€/functional unit	
	Econ 4	OPERATIONAL COST	Costs due to the regular operation Components or PIs: material costs, utility costs, services costs including transports, labour costs, taxes and fees (cost or benefits), rental costs or benefits, external costs and benefits.	€/functional unit	
	Econ 5	END OF LIFE COST	Net cost or fee for disposing of an asset at the end of its service life or interest period. Components may be Disposal inspection, Disposal and demolition.	€/functional unit	
	Econ 6	ENVIRON-MENTAL COSTS	Monetized environmental impacts according to LCA (e.g. shadow pricing).	€/functional unit	
	Econ 7	USER DELAY COSTS	User delay costs calculated based on the extra time and distance that users need to travel due to the disruptions (e.g. maintenance works)	€	
	Econ 8	ACCIDENT COSTS	Costs of accidents on the transport networks (including injuries and deaths)	€	

3.4.4.2 KPI cards

Econ1	WLCC - Whole Life Cycle Cost	Economy
Description/Definition	WLCC covers a defined list of costs over the physical, technical, economic or functional life of a constructed asset, over a defined period of analysis. The purpose of life-cycle costing should be to quantify the life-cycle cost (LCC) for input into a decision-making or evaluation process, and should usually also include inputs from other evaluations (e.g. environmental assessment, design assessment, safety assessment, functionality assessment and regulatory compliance assessment). The quantification should be to the level of detail that is required for key project stages.	
Relevant standard	ISO 15686-5:2017(E)	
Quantification method/model	LCC analysis	
Unit of measure	€/functional unit	
Pilot project applicability per information modules/stages in LCA	Pilot: 1 – Modules /stages: A0; 2 – A0, A1-A3, B1-B8; 3 – A0, A1-A3, B1-B8; 4 – A4-A5,B1-B8,C1-C4; 5 – A0,B1-B8	
Data requirements	• Material costs • Site costs • Energy costs (fuels, utilities) • Services costs including transports • Labour costs • Taxes and fees • Waste and excess material management • Costs including purchase or rental costs • Professional fees for planning and engineering • External costs and benefits • Subsidies and incentives • Disposal inspection costs • Disposal and demolition	
Expected data source	• Bill of quantities for initial construction cost • Construction logbook • Construction management project • Service life for nominal maintenance cost • Average and recorded historic discount rates • Payroll records • Degradation curves for timing of maintenance activities • Consumption records for machinery and equipment • Load specific energy usage details • Accounting records • Equipment maintenance logs • Vendor and/or manufacturer documentation • Repair and maintenance costs, • Bill of quantities from maintenance design project • Recyclability, and reusability study for end-of-life cost • Compliance tracking records, Regulatory documentation • Third-party audits • Incident reports, etc.	

Pilot project applicability (detail):

Pilot	1	2	3	4	5
Modules /stages	A0	A0, A1-A3, B1-B8	A0, A1-A3, B1-B8	A4-A5,B1-B8,C1-C4	A0,B1-B8

Econ2	Initial construction cost (ICC)	Economy
Description/Definition	Total capital costs needed for construction. Components or PIs can be the same as in LCC category.	
Relevant standard	ISO 15686-5:2017	
Quantification method/model	$$ICC = \sum_{i=n}^{m} CUC_i \times Cq_i \times (1+\chi)$$ wherein ICC = initial construction costs (€) i = construction element n until element m CUC_i = construction unit cost of element I (€/unit) Cq_i = the quantity of construction element i present in the design (unit) x = an additional percentage to cover unassigned, indirect, engineering and other costs.	
Unit of measure	€/functional unit	
Pilot project applicability per information modules/stages in LCA	(see table below)	

Pilot	1	2	3	4	5
Modules /stages	A0	A0, A1-A3, B1-B8	A0, A1-A3, B1-B8	A4-A5,B1-B8,C1-C4	A0,B1-B8

Data requirements	The same as in LCC category	
Expected data source	The same as in LCC category	

Econ3	Maintenance cost	Economy
Description/Definition	Total cost due to maintenance and repairs of the asset (it includes cost of repairs and regular maintenance costs). Maintenance cost can be taken into consideration in one moment in time to compare two different solutions according to its cost. In this case maintenance cost does not need to be discounted. If maintenance costs are taken into consideration throughout the life cycle of the structure, by analysing different through life scenarios, they are discounted with a discount rate.	
Relevant standard	ISO 15686-5:2017	
Quantification method/model	$$MC_{t,nom} = \sum_{i=n}^{m} AUC_i \times Aq_i$$ Where: $MC_{t,\,nom}$ = nominal maintenance costs for year t (€) i = activity n until m AUC = activity unit cost of activity I (€/unit) Aq_i = quantity of units for activity i in year t (unit) $$\sum_{t=0}^{T} \frac{MC_{t,nom}}{(1+r)^t} \times (1+\chi)$$ $MC_{tot,\,disc}$ = the total maintenance costs during the life cycle of the object (€) $MC_{t,\,nom}$ = maintenance costs for year t (€) *t* = year in life cycle from 0 until end of life cycle T	

<table>
<tr><td></td><td>r = the discount rate (%)
χ = an additional percentage to cover unassigned, indirect, engineering, and other costs (Stipanovic et al., 2017; Skaric Palic and Stipanovic, 2019)</td></tr>
<tr><td>Unit of measure</td><td>€/functional unit</td></tr>
<tr><td>Pilot project applicability per information modules/stages in LCA</td><td><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>Modules /stages</td><td>A0</td><td>A0, A1-A3, B1-B8</td><td>A0, A1-A3, B1-B8</td><td>A4-A5,B1-B8,C1-C4</td><td>A0,B1-B8</td></tr></table></td></tr>
<tr><td>Data requirements</td><td>The same as in LCC category</td></tr>
<tr><td>Expected data source</td><td>The same as in LCC category</td></tr>
</table>

<table>
<tr><th>Econ4</th><th>Operational cost</th><th>Economy</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Costs due to the regular operation. Components or PIs: material costs, utility costs, services costs including transports, labour costs, taxes and fees (cost or benefits), rental costs or benefits, external costs and benefits.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">ISO 15686-5:2017</td></tr>
<tr><td>Quantification method/model</td><td colspan="2">$$OC_{tot,disc} = \sum_{t=0}^{T} \frac{OC_{t,nom}}{(1+r)^{t}} \times (1+\chi)$$
Where:
OC_{tot} = the total operational costs during the life cycle of the object (€)
$OC_{t,\,nom}$ = operational costs for year t (€)
t = year in life cycle from 0 until end of life cycle T
r = the discount factor (%)
x = an additional percentage to cover unassigned, indirect, engineering and other costs</td></tr>
<tr><td>Unit of measure</td><td colspan="2">€/functional unit</td></tr>
<tr><td>Pilot project applicability per information modules/stages in LCA</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>Modules /stages</td><td>A0</td><td>A0, A1-A3, B1-B8</td><td>A0, A1-A3, B1-B8</td><td>A4-A5,B1-B8,C1-C4</td><td>A0,B1-B8</td></tr></table></td></tr>
<tr><td>Data requirements</td><td colspan="2">The same as in LCC category</td></tr>
<tr><td>Expected data source</td><td colspan="2">The same as in LCC category</td></tr>
</table>

<table>
<tr><th>Econ5</th><th>End of life cost</th><th>Economy</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Net cost or fee for disposing of an asset at the end of its service life or interest period. Components or PIs: Disposal inspection, Disposal and demolition. Because the end-of-life costs take place at the end of the life cycle of the object the costs will have to be discounted.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">ISO 15686-5:2017</td></tr>
<tr><td>Quantification method/model</td><td colspan="2">$$EoLC_{nom} = \sum_{i=n}^{m} DUC_i \times Cq_i$$
Where:
$EoLC_{nom}$ = nominal end-of-life costs (€)
i = construction element n until element m
DUC_i = demolition and disposal unit cost for element I (€/unit)
Cq_i = the quantity of construction element i present in the design (unit)
$$EoLC_{disc} = \frac{EoLC_{T,nom}}{(1+r)^T}$$
Where:
$EoLC_{disc}$ = are the discounted end-of-life costs (€)
$EoLC_{T,nom}$ = are the nominal end-of-life costs at the end of the life cycle (€)
T = year in which life cycle ends
r = discount factor (%)</td></tr>
<tr><td>Unit of measure</td><td colspan="2">€/functional unit</td></tr>
<tr><td>Pilot project applicability per information modules/stages in LCA</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>Modules /stages</td><td>A0</td><td>A0, A1-A3, B1-B8</td><td>A0, A1-A3, B1-B8</td><td>A4-A5,B1-B8,C1-C4</td><td>A0,B1-B8</td></tr></table></td></tr>
<tr><td>Data requirements</td><td colspan="2">The same as in LCC category</td></tr>
<tr><td>Expected data source</td><td colspan="2">The same as in LCC category</td></tr>
</table>

<table>
<tr><th>Econ6</th><th>Indirect environmental costs</th><th>Economy</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Monetized environmental impacts according to LCA (e.g. shadow pricing). Introducing environmental shadow prices provides a way of monetizing environmental effects which enables incorporation of these effects with all other monetary costs into analysis.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">ISO 15686-5:2017</td></tr>
<tr><td>Quantification method/model</td><td colspan="2">

$$EC = \sum_{i=n}^{m} EE_i \times ECI_i$$

where
EC = environmental costs
EEi = environmental effects for impact category i (kg of impact category equivalent (ICeq)/functional unit
ECIi = the environmental cost indicator for environmental effect category i (€/kg of ICeq)
i = environmental impact category n until m
The environmental effects per impact category can be determined using Equation:

$$EE_i = \sum_{j=n}^{m} EE_{i,j} \times Mq_j$$

Where:
EE_i = environmental effects for impact category *i* (kg of impact category equivalent (kg IC_{eq})/functional unit (one bridge))
$EE_{i,j}$ = environmental effect for impact category *i* per kg of material *j* (kg ICeq/kg material)
M_{qj} = material quantity per functional unit for material *j* (kg material/functional unit)
j = the different materials n until m</td></tr>
<tr><td>Unit of measure</td><td colspan="2">€/functional unit, €/kg, €/m2 or €/total</td></tr>
<tr><td>Pilot project applicability per information modules/stages in LCA</td><td colspan="2">
<table>
<tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Modules /stages</td><td>A0</td><td>A0, A1-A3, B1-B8</td><td>A0, A1-A3, B1-B8</td><td>A4-A5,B1-B8,C1-C4</td><td>A0,B1-B8</td></tr>
</table>
</td></tr>
<tr><td>Data requirements</td><td colspan="2">All data needed for LCA</td></tr>
<tr><td>Expected data source</td><td colspan="2">LCA, ECOINVENT database, Environmental Cost Indicators</td></tr>
</table>

3.4.5 Social KPIs

3.4.5.1 Overview

The social dimension of the CIRCUIT project aims to consider the impact on individuals and communities involved in the construction works life cycle, as well as the active participation of various stakeholders in the technological proposals to be developed throughout the project.

The information provided by the previously studied documents, sustainable frameworks, and rating methodologies, was considered to select scope, methodological framework and the most suitable social indicators as aligned with the CIRCUIT principles.

EN 17472:2022 has been considered as a reference since it addresses the evaluation of social impact, using tools and criteria to assess the social impact of a civil work on local communities, workers, and other stakeholder groups. Specifically, the indicators selected are split into two groups after literature review analysis and discussion:

- Resilience - assessed in a form of structural resilience and the resilience of the area surrounding the system that is analysed.
- Other social indicators

Integrated as other social indicator, smart infrastructures indicators can be included as they consider several factors linked to social aspects such as:

1. **User Benefits:** This includes metrics like travel time reduction, improved public transport reliability, and enhanced safety.
2. **Economic Viability:** This considers cost savings through optimized traffic flow, reduced fuel consumption, and improved infrastructure lifespan.
3. **Environmental Impact:** This focuses on factors like reduced air and noise pollution, and promoting sustainable transportation modes.
4. **Technological Advancement:** This assesses the level of technological integration in the infrastructure, such as intelligent traffic management systems, connected vehicles, and data analytics capabilities.

There isn't a single, universally accepted "perfect" indicator for smart transport infrastructures. As a result and as considered for other social indicators where methods and approaches leading to a quantitative result are not available, a checklist method is adopted based on civil engineering works-specific features and characteristics. For this reason, and to facilitate deployment, additional information and guidance from actual sustainable frameworks and rating methodologies (e.g., Mobility credit of the ENVISION framework, which includes elements to improve Community Mobility, Access and Wayfinding and encourage Sustainable Transportation) were considered as relevant to support the assessment within CIRCUIT.

3.4.5.1.1 Resilience

The concept of resilience refers to the ability of a material, mechanism, or system to return to its initial state once the disturbance to which it had been subjected has ceased. Infrastructure resilience involves the timely and efficient prevention, absorption, recovery, and adaptation of the essential structures and functions of infrastructure that have been exposed to hazards.

CIRCUIT relies on the *United Nations Office for Disaster Risk Reduction* definition of *resilience (UNDRR, 2009)*, recognizing that construction of resilient infrastructure requires both building capacity for each phase of risk management (screening and detailed analysis) and acknowledging:

1) the changing nature of risks and uncertainties.
2) the increasingly challenging nature of multiple risks;
3) the need to employ transdisciplinary and systemic methods that consider both the national infrastructure life cycle and its interdependent, multisectoral character.

The Technical guidance on the climate proofing of infrastructure in the period 2021-2027 is also a valuable element to cover resilience properly and adapt it to the EU strategies.

Structural resilience is defined through numerical values that indicate structural capacity on two levels, a single structure level and its elements. The capacity can be in a form of residual capacity at the end of life of a structure/element or the initial capacity at the beginning of structure/element life. Performance indicators that can be used for definition of structural resilience are condition index, reliability index.

Inspection of structures are generally carried out on the component level and often are divided subsystem groups depending on the type of structure, (bridges – substructure, superstructure, bridge equipment, pavement; tunnels – pavement, tunnel lining, tunnel drainage, equipment; road; road drainage, pavement). Through inspections a number of PIs are collected and analysed (processed), in order to determine the aggregated KPI at the structure level. Those PIs are usually related to the technical aspects mostly defined as structural performance or reliability. This requires collection of data which can be done with a conventional visual inspection, SHM and investigation works but also through application of new technologies (UAVs, digitalization, AI, etc.).

The overall assessment based on the collected data is usually done based on the condition indices per element, finally delivering an aggregated condition index e.g. Bridge Condition Index (BCI), Pavement Condition Index (PCI) or Tunnel Condition Index (TCI). Historical records of condition indices help track the general system condition over time and can provide basis for development of performance/degradation curves. This enable better prediction of future performance enabling development of life cycle scenarios, as well as planning for reuse and recycle of structures, elements and materials.

Area resilience presents information on how much impact does a single climate hazard including future climate changes, or any other change on the surrounding area have on the infrastructure asset from the beginning of the asset's usage until the projected end of the asset's lifetime. The exposure analysis shows which climate hazard are relevant for the analysed area. The exposure analysis is a two-step analysis exposure to current climate conditions and exposure to future climate conditions. Historical and current climate data for the area can be used to estimate current and past climate exposure. Projections based on climate models can provide a better overview of changes in exposure levels in the future. Special attention should be paid to changes in the frequency and intensity of extreme weather conditions and occurring hazards.

The table below shows the classification of climate related hazards according to EU taxonomy in Table 8. The list of social KPIs (resilience) selected is presented in

Table 9.

Table 8 Classification of climate-related hazards

	Temperature-related	Wind-related	Water-related	Solid mass-related
Chronic	• Changing temperature (air, freshwater, marine water) • Heat stress • Temperature variability • Permafrost thawing	• Changing wind patterns	• Changing precipitation patterns and types (rain, hail, snow/ice) • Precipitation or hydrological variability • Ocean acidification • Saline intrusion • Sea level rise • Water stress	• Coastal erosion • Soil degradation • Soil erosion • Solifluction
Acute	• Heat wave • Cold wave/frost • Wildfire	• Cyclone, hurricane, typhoon • Storm (including blizzards, dust and sandstorms) • Tornado	• Drought • Heavy precipitation (rain, hail, snow/ice) • Flood (coastal, fluvial, pluvial, ground water) • Glacial lake outburst	• Avalanche • Landslide • Subsidence

Table 9 List of Social KPIs- Resilience

KPI	ID No.	PI	PI/Description	UNIT/MEASURE	Relevant Standard
SOCIAL	Res1	STRUCTURAL RESILIENCE	Condition index – material/element/system level condition assessment	Rating system	
			Reliability index	ULS SLS Probability of failure €	Eurocodes
	Res2	AREA RESILIENCE	Natural hazards	Yes/No	
			Climate change impact	Rating system	EN17472 + “Technical guidance on the climate proofing of infrastructure in the period 2021-2027 (2021/C 373/01)”

3.4.5.1.2 Other social indicators

The assessment of social performance differs from the assessment of economic and environmental aspects because it requires both quantitative and descriptive approaches. This involves managing potential social risks, promoting equity and inclusion, and maintaining open and transparent communication with all stakeholders. In the table below other social performance indicators are listed (excluding resilience).

Table 10 List of Social KPIs - Other

ELEMENT	ID No.	KPI	PI/Description	Relevant Standard
SOCIAL	Soc1	ACCESSIBILITY	Accessibility assesses the provisions included in the civil engineering works to facilitate access to and use of its facilities and services.	EN 17472
	Soc2	CONNECTIVITY	Connectivity is used to assess the ability to transit across and around the infrastructure.	
	Soc3	POPULATION DISTRIBUTION	Population distribution changes and changes in the use and economic value of the land/properties due to civil engineering works.	
	Soc4	HEALTH AND WELLBEING	Indicator describes health and comfort (thermal comfort, indoor air quality, acoustic comfort, visual comfort, and spatial characteristics), for employees, users, and the general public. The assessment should consider the provision of sanitary and rest facilities, impacts from noise, air quality, solar radiation effects, shocks and vibration for workers during construction, maintenance, repair and refurbishment and deconstruction.	
	Soc5	IMPACTS ON NEIGHBOURHOOD	The following aspects shall be assessed: visual impact, glare/overshadowing, noise, shocks and vibration; emissions to outdoor air, soil and water, changes to microclimate, other impacts.	
	Soc6	SAFETY/SECURITY	This indicator expresses the measures adopted to avoid injuries or to increase the security and safety of workers, users and neighbours.	
	Soc7	SOURCING OF MATERIALS AND SERVICES	Information concerning responsible sourcing of materials and services.	
	Soc8	STAKEHOLDERS ENGAGEMENT	The assessment of engagement with relevant stakeholders as part of efficient and responsible management.	
	Soc9	JOB CREATION	The short- and long-term employment effects as a result of a civil engineering works.	
	Soc10	CULTURAL HERITAGE ELEMENTS	Indicators that report the number of cultural heritage elements affected due to the civil engineering works.	

3.4.5.2 KPIs cards

3.4.5.2.1 Resilience KPIs

<table>
<tr><th>Res1</th><th colspan="5">Structural resilience</th><th>Social</th></tr>
<tr><td>Description/Definition</td><td colspan="6">Numerical values that indicate structural capacity on two levels, a single structure level and its elements. The capacity can be in a form of residual capacity at the end of life of a structure/element or the initial capacity at the beginning of structure/element life.
Performance indicators that can be used for definition of structural resilience are condition index, reliability index.</td></tr>
<tr><td>Relevant standard</td><td colspan="6">Eurocodes</td></tr>
<tr><td>Quantification method/model</td><td colspan="6">Condition rating is used in order to evaluate the structure's current condition compared to its condition at the time of construction. Calculation of condition index takes into account different damages per type of structure and different coefficients that allow various attributes, such as importance of an element in the structure or importance of a structure in the whole network, taken into consideration.
Long-term performance of various types of structures is evaluated through the reliability-based method. It is based on two premises, the first of which is that the structures performance degrades over time when subjected to environmental and structural loads (ULS). The second premise describes concept of failure that occurs when the structure or a system can no longer support the demands and loads that it was designed for (SLS).</td></tr>
<tr><td>Unit of measure</td><td colspan="6">Condition index, Reliability index (ULS, SLS, p_f)</td></tr>
<tr><td rowspan="3">Pilot project applicability</td><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>KPI applicable</td><td>+</td><td>+</td><td>+</td><td>+</td><td></td></tr>
<tr><td>LC stage</td><td>A0</td><td>A0, B2-B5</td><td>B2, B3</td><td>A0, A4, A5, B4, B5, C1, C3</td><td></td></tr>
<tr><td>Expected data source</td><td colspan="6">Technical documentation, Inspection and monitoring data, Degradation propagation prediction data</td></tr>
</table>

<table>
<tr><th>Res2</th><th>Area resilience</th><th>Circularity</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Presents information on how much impact does a single/multi natural or climate hazard including future climate changes or any other change on the surrounding area have on the infrastructure asset from the beginning of the asset's usage until the projected end of the asset's lifetime.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">EN17472 + "Technical guidance on the climate proofing of infrastructure in the period 2021-2027 (2021/C 373/01)"</td></tr>
<tr><td>Quantification method/model</td><td colspan="2">Comprehensive climate change vulnerability area assessment developed considering the lifespan of the asset designed.
Comprehensive, multi hazard risk and resilience area evaluation conducted.
Assessment of future changes.
Assessment of future needs (BREEAM Infrastructure sustainability assessment and rating methodology).</td></tr>
<tr><td>Unit of measure</td><td colspan="2">Yes/No & Specific section in the climate resilience proofing documentation</td></tr>
<tr><td>Pilot project applicability</td><td colspan="2"><table>
<tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>KPI applicable</td><td>+</td><td>+</td><td></td><td>+</td><td></td></tr>
<tr><td>LC stage</td><td>A0</td><td>A0</td><td></td><td>A0</td><td></td></tr>
</table></td></tr>
<tr><td>Expected data source</td><td colspan="2">Technical documentation, Climate models - Copernicus Climate Change Services (C3S) Climate Data Store, Global Framework for Climate Services (GFCS), Historical data, Urban plans data</td></tr>
</table>

3.4.5.2.2 Other social KPIs

<table>
<tr><th>Soc1</th><th>Accessibility</th><th>Social</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Accessibility assesses the provisions included in the civil engineering works to facilitate access to and use of its facilities and services (e.g. electrical systems – switches, circuit breakers, access of passengers to a ship in a harbour, payment systems on toll bridges and motorways, etc., where relevant) as much for users as for employees.
Accessibility to facilities and services particularly applies to civil engineering works where public access is required for people with specific needs, e.g. persons with disabilities, elderly people, parents with small children.
Performance indicators
Accessibility
Inclusive access
Access to basic supplies</td></tr>
<tr><td>Relevant standard</td><td colspan="2">EN 17472:2022</td></tr>
<tr><td>Pilot project applicability</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>KPI applicable</td><td></td><td></td><td></td><td>+</td><td></td></tr></table></td></tr>
<tr><td>Aspects assessed/data requirements</td><td colspan="2">Accessibility
access for relevant users.
access for people with specific needs
access to services provided by the asset; and connectivity
Inclusive access
design features incorporated that enable access for all relevant users (such as % of bicycle lanes incorporated to the road, or surface for pedestrians);
the inclusion of points allowing safe and easy access to, from, and around the civil engineering works, with appropriate signage.
design features incorporated that enable access for all users and employees with specific needs (such as provision of appropriate tactile, visual and audio wayfinding systems
the number and proportion of allocated car-parking for users with specific needs relative to the total number of parking places provided
the number of kerb ramps to facilitate the use of asset
Access to basic supplies
Net change in the utility supply (measured by comparing the number of inhabitants that have access to each relevant basic supply before and after the construction of the civil engineering works)</td></tr>
<tr><td>Expected data source</td><td colspan="2">Technical documentation</td></tr>
</table>

Soc2	Connectivity	Social
Description/Definition	Connectivity is used to assess the ability to transit across and around the infrastructure. Civil engineering works are usually large projects that imply land take, temporarily as well as permanently. Obstruction or hindering of access to nature and recreational areas, to existing and proposed routes for pedestrians, cyclists and other relevant users, or to other nearby populations can occur. Civil engineering works can become a barrier for the population in order to access nature or other areas, or to communicate social groups.	
Relevant standard	EN 17472:2022	
Pilot project applicability	Pilot: 1 / 2 / 3 / 4 / 5 KPI applicable: 1: – / 2: + / 3: – / 4: + / 5: –	
Aspects assessed/data requirements	• Design features incorporated that enable transit for all relevant users (such as % pedestrian over/under passes); • Inclusion of points allowing safe and easy access around or across the civil engineering works, with appropriate signage; • The 'travel time' from a defined "source" to a defined "target".	
Expected data source	Technical documentation	

Pilot	1	2	3	4	5
KPI applicable		+		+	

Soc3	Population distribution	Social
Description/Definition	The indicators should evaluate the changes in the way the land is used, due to the civil engineering works. These changes can lead either to a revaluation or to a depreciation of the land's economic value, which consequently affects the population living in the areas of influence of the civil engineering works. Potential impacts can also include changes of productive land, changes of employment and income, changes of housing, changes of access to common resources and public services, and social fragmentation or integration.	
Relevant standard	EN 17472:2022	
Pilot project applicability	Pilot: 1 / 2 / 3 / 4 / 5 KPI applicable: 1: – / 2: – / 3: – / 4: + / 5: –	
Aspects assessed/data requirements	• Involuntary resettlement refers both to physical displacement (relocation or changes of shelter) and to economic displacement (changes of assets or access to assets that leads to changes of income sources or means of livelihood as a result of project related land acquisition). • Voluntary resettlement refers both to physical displacement (relocation or changes of shelter) and to economic displacement	
Expected data source	The data can be obtained from time series, statistics, aerial photographs, land use maps, databases with interpretations of urban extent, transportation routes, water features and other important land uses, social surveys, land and properties market or local and national Administrations.	

Pilot	1	2	3	4	5
KPI applicable				+	

<table>
<tr><th>Soc4</th><th colspan="5">Health and wellbeing</th><th>Social</th></tr>
<tr><td>Description/Definition</td><td colspan="6">For indoor environments that are part of civil engineering works, the health and comfort (thermal comfort, indoor air quality, acoustic comfort, visual comfort and spatial characteristics), for employees, users, and the general public (where appropriate) shall be assessed according to the requirements of EN 16309.

For the outdoor environment and for workers during construction, maintenance repair and refurbishment and deconstruction, the assessment should consider the provision (number and quality) of sanitary and rest facilities, impacts from noise, air quality (pollutants such as CO, CO2, NOx and SOx, VOCs and particulates), effects solar radiation, shocks and vibration.</td></tr>
<tr><td>Relevant standard</td><td colspan="6">EN 17472:2022</td></tr>
<tr><td rowspan="2">Pilot project applicability</td><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>KPI applicable</td><td>+</td><td>+</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td>Aspects assessed/data requirements</td><td colspan="6">Worker's health and comfort
• the provision (number and quality) of sanitary and rest facilities;
• protection against potential adverse effects such as those coming from: solar radiation, extreme heat and/or cold, other radiation effects in the outdoor environment (e.g. radon in tunnelling), construction processes or working conditions;
• design of the civil engineering works in order to allow a more comfortable construction and maintenance.
Characteristics of air quality
• The measurement of concentration of recognized pollutants (such as ozone, CO, NO_x and SO_x and particulates PM10 and PM2.5) that are regulated and/or stated in the clients brief;
The assessment may be by simulation (before construction) or monitoring (during construction, use and deconstruction).
• the values of those concentrations;
• measures to protect against the adverse effects of the above.
Acoustic characteristics
• sound insulation and other measures adopted against impact and airborne sounds from inside the construction works [dB(A)];
• sound insulation from airborne sounds from outside the construction works and other measures adopted (e.g. from traffic, airplanes or adjacent construction works)
Characteristics of visual comfort
• when used, the amount (coverage) and quality of artificial light for lighting (e.g. in tunnels, on station platforms, quaysides) and floodlighting (e.g. for car parks, sports facilities and outdoor activity centres);
• protection from glare for users.</td></tr>
<tr><td>Expected data source</td><td colspan="6">Direct measurements</td></tr>
</table>

<table>
<tr><th>Soc5</th><th>Impacts on neighbourhood</th><th>Social</th></tr>
<tr><td>Description/Definition</td><td colspan="2">For the assessment of the category impacts on the neighbourhood, the following aspects shall be assessed: visual impact, glare/overshadowing, noise, shocks and vibration; emissions to outdoor air, soil and water (dust and smoke, odours) changes to microclimate, other impacts.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">EN 17472:2022</td></tr>
<tr><td>Pilot project applicability</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>KPI applicable</td><td></td><td>+</td><td>+</td><td>+</td><td>+</td></tr></table></td></tr>
<tr><td>Aspects assessed/data requirements</td><td colspan="2">Visual impact
• Visibility (“zone of visual influence” or “zone of visual intrusion”); Visual intrusion; Obstruction of viewpoints
Glare and overshadowing:
• The projection and illuminance (lux) from the object of assessment at night and whether it is continuous or intermittent.
• The presence of (e.g. blinking, flashing, coloured) lighting causing irritation, loss of concentration, etc.
• Glare emitted during the civil engineering works use (e.g. lights coming from vehicles circulating in the opposite direction).
• Sun glare
• Overshadowing
Noise
• Emitted noise pressure level [measured in Leq dB(A)] and its evolution during the service life term.
• Peaks of noise [measured in L10 dB(A)] and their evolution during the service life term.
• Noise pressure levels at the receiver’s side.
• Internal sound insulation (on the source itself).
• Acoustic characteristics of the materials or the design.
• External noise barriers.
Shocks and vibration
• Vibrations emitted from the object of assessment
Emissions
• Dust: Levels of dust and measures against it.
• Smoke: Levels of smoke and measures against it.
Odours:
• Is there an emission of an odour? Yes/no.
• Number of persons impacted.
• Systems for controllability of the emission on civil engineering works level.
Changes of microclimate
• Impact on local temperature.
• Changes in precipitation (rain and snow).
• Changes in wind (speed and direction).
• Urban heat islands effects.
Other Impact on the neighbourhood</td></tr>
<tr><td>Expected data source</td><td colspan="2">GIS-based analysis, direct measurements, social surveys.</td></tr>
</table>

<table>
<tr><th>Soc6</th><th>Safety/security</th><th>Social</th></tr>
<tr><td>Description/Definition</td><td colspan="2">This indicator expresses the measures adopted in order to avoid injuries or to increase the security and safety of workers, users and neighbours.</td></tr>
<tr><td>Relevant standard</td><td colspan="2">EN 17472:2022</td></tr>
<tr><td>Pilot project applicability</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>KPI applicable</td><td>+</td><td>+</td><td>+</td><td>+</td><td>+</td></tr></table></td></tr>
<tr><td>Aspects assessed/data requirements</td><td colspan="2">For workers the indicator expresses the additional measures over the regulation that increase the personal safety and decreases the possibility of accidents.
For users, this indicator relates to the secure use of the infrastructure by the users.
For neighbours it is related to the level of possible injuries and accidents related to the infrastructure during construction, in use or because the asset itself.</td></tr>
<tr><td>Expected data source</td><td colspan="2">Safety documentation</td></tr>
</table>

<table>
<tr><th>Soc7</th><th>Sourcing of materials and services</th><th>Social</th></tr>
<tr><td>Description/Definition</td><td colspan="2">Information concerning responsible sourcing of materials:
a) Materials´ production
b) Safety performance from start to finish of the materials' production
c) Human rights
d) Traceability
e) Quality management/control

Sourcing of services:
a) Safety performance from start to finish of the service supplied:
b) Compliance with social responsibilities
c) Traceability.
d) Management procedures ensuring the traceability of the services supplied.
e) Quality management/control
f) Environmental management/control:</td></tr>
<tr><td>Relevant standard</td><td colspan="2">EN 17472:2022</td></tr>
<tr><td>Pilot project applicability</td><td colspan="2"><table><tr><td>Pilot</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>KPI applicable</td><td></td><td>+</td><td>+</td><td>+</td><td>+</td></tr></table></td></tr>
<tr><td>Aspects assessed/data requirements</td><td colspan="2">Raw material origin from the point of extraction or harvest of the raw
Implementation of occupational health and safety management systems (e.g. ISO 45001)
Compliance with social responsibilities (e.g. ILO declaration on fundamental principles and rights at work, ISO 26000 related to the human resources): Legal situation of the company, employees, contractors and subcontracted personnel; Social conditions applying to the workplace.</td></tr>
</table>

	• Management procedures ensuring the traceability of materials supplied and respective characteristics. • Implementation of quality management systems (e.g. ISO 9001) and factory production control. • Implementation of environmental management systems (e.g. ISO 14001).
Expected data source	Technical documentation, safety documentation, quality management systems documentation

Soc8	**Stakeholders engagement**					**Social**
Description/Definition	This aspect covers the assessment of engagement with relevant stakeholders as part of efficient and responsible management on any relevant environmental, social or economic aspect.					
Relevant standard	EN 17472:2022					
Pilot project applicability	Pilot	1	2	3	4	5
	KPI applicable	+	+	+	+	+
Aspects assessed/data requirements	• involvement of users and consideration of their needs • involvement of other interested parties • management and resolution of contradictions or conflicts among the opinions of the interested parties • satisfaction of users and other affected parties • improvement actions and lessons learned for future projects.					
Expected data source	Social surveys,...					

Soc9	Job creation					Social
Description/Definition	The short- and long-term employment effects as a result of a civil engineering works should be demonstrated by indicators such as the proportion of workers, suppliers or subcontractors employed directly or indirectly by the civil engineering works, the type and number of jobs influenced as a result of a better or worst access, etc. It includes the provision of employment by the civil engineering works and considers employment structure: working population in the areas of influence of the civil engineering works and their composition.					
Relevant standard	EN 17472:2022					
Pilot project applicability	Pilot	1	2	3	4	5
	KPI applicable	+	+	+	+	+
Aspects assessed/data requirements	• the number of people to be employed; • the original living place of employees (local or not local); • the number of local disadvantaged people to be employed.					
Expected data source	Cost Benefit Analysis, socio-economic researches, etc.					

Soc10	Cultural heritage elements					Social
Description/Definition	This aspect should include indicators that report the number of cultural heritage elements affected due to the civil engineering works. Both the level of effect from the civil engineering works on the cultural or historic element, and its protection category should be considered.					
Relevant standard	EN 17472:2022					
Pilot project applicability	Pilot	1	2	3	4	5
	KPI applicable			+	+	
Aspects assessed/data requirements	• tangible cultural heritage: architectural works, works of monumental sculpture and painting, elements • or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features, • which are of outstanding universal value from the point of view of history, art or science.					
Expected data source	Cultural and natural heritage reports					

3.4.6 Impact assessment

Impact assessment based on developed KPIs framework is performed through developed scenarios representing different management strategies, policies or interventions. The scenarios chosen for the analysis have to contain interpretation of the predefined performance goals set by the decision makers. Within asset management, physical assets are to be considered in relation with all other activities of the organization to deliver the required performance. For physical assets such as bridges, roads or tunnels this means single asset management is to be part of the management of the network, and the single asset performance levels must fulfil the network performance requirements.

Impact assessment is performed as comparative meaning that different scenarios are compared through the developed KPIs framework. Example of scenarios which set different performance priorities into focus is comparison of scenario of current management practices without specific circularity-focused initiatives and scenario which introduces circular economy principles such as material reuse, recycling, and resource efficiency into infrastructure management. Going further to the structure level current methodology that would usually be applied is replacement of structure/element with a new structure/element while the other scenario presents circular solution with reuse and recycle of structure/element/material.

Multiple asset performance aspects widen the scope of management planning where a number of related performance goals other than e.g. minimizing owner cost must be considered. The example of such performance aspects is the structural performance of the structure, safety and comfort of users, environmental impact, economic impact on the users, and incorporation of circularity. In addition to various aspects, these related

performance goals can have a conflicting nature e.g., higher initial investment for circular solution vs. long term savings and environmental benefits, or circular material flows vs already established supply chain efficiency. Considering the large number of assets on the transport network, it is intractable for an infrastructure manager to quantify the performance goals for each asset and systematically perform the trade-offs among them to select the solution that optimize the various performance goals. Moreover, at times, an infrastructure manager is uncertain of his preferences due to incomplete or unavailable data and due to lack of experience. So, the need to optimize multiple conflicting performance goals based on the preference uncertainty marks transport infrastructure management planning a complex decision-making problem.

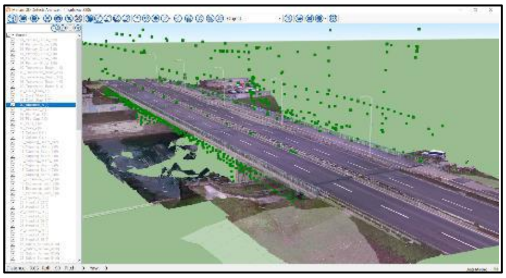
There are different MCDA Multi-Criteria Decision Analysis methods when dealing with analysis of such complex issues. Multi-Attribute Utility Theory (MAUT) has proved to be useful for network level management planning where multiple performance goals, defined as objectives, can be optimized (Allah Bukhsh, 2019).

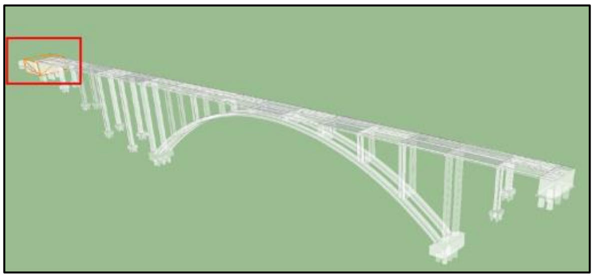
4 PILOT PROJECTS

CIRCUIT pilots have been configured to validate in an operational environment the technologies proposed for each of the CIRCUIT pillar, and will cover different EU countries, and the different lifecycle stages of infrastructures (from Pre-construction stage A0 to End of Life C1-C4 as described in EN 15643- Sustainability of Construction Works), counting on CIRCUIT partners as authorities and pilot managers.

System boundaries regarding spatial asset distribution from network level to material level and also time span from preconstruction stage to end of life are set vary between different pilots. The following chapters focuses on the technical requirements of each pilot to define functionality, features and the purpose regarding focus pillars. The analysis of each pilot use case is adjusted to suit unique characteristics of each and used for development of KPIs framework in the final chapter.

4.1 ASSET MANAGEMENT PILOT 1 – CROATIA





Strategic pillars:	**Digitalisation, recycling, reuse**
Focus pillar:	Digitalisation
Locations:	Project to be assessed to be defined with HAC
Infrastructures included:	Road, bridge, tunnel
Pilot owner:	Hrvatske autoceste d.o.o (HAC)
Problem/current scenario	Accurate information from **inspection and monitoring** is crucial to take the right decisions on maintenance and safety. The transition from the current practice, based on visual inspection, and corrective and time-based maintenance approaches, towards a **data informed, condition-based, risk-based and finally circular approach** leads not only to higher reliability and availability of the infrastructure but also to a more sustainable and cost-effective asset management.
Objectives per strategic pillar	To demonstrate the integration of the digital platform with the CIRCUIT holistic approach and the application of new technologies (UAVs, digitalization, AI, etc.) and new functionalities (circularity, decision-matrix, digital twin, etc.) on the existing cross-asset management system in Croatia.
Description of the proposed solution	The digitalization pilot will include the implementation of the **Digital platform and interoperability** with the engineering tools and existing Asset Management platform. One section on the Croatian Motorways network, which contains a number of engineering structures (bridges and tunnels) and road section will be inspected with UAVs for the purpose of scanning, inspection and development of digital twin models. **CIRCUIT KPIs** will be determined and implemented in the **Asset Management system**, with the aim to implement **circular management and supply-demand matchmaking tool.**
Innovation technologies implemented	**Digital platform** using **CIRCUIT KPIs** and **DPPs** Assessment of recycling and reusability potential

4.2 ROAD PAVEMENT PILOT 2 – SPAIN

Strategic pillars covered:	All
Focus pillar:	Recycle pillar
Locations:	Revilla de Camargo N623 national road and A8 motorway (Hoz Tunnel), Cantabria
Infrastructures included:	Road, tunnel
Pilot owner:	Ministerio de Transportes, Movilidad y Agenda Urbana (MITMA)
Problem/current scenario	Tunnels are currently the most demanding assets in terms of energy consumption during its operation (lighting, signalling, ventilation, etc.). Similarly, the construction and maintenance of road pavements also requires a significant amount of resources, including materials, energy and manpower.
Objectives per strategic pillar	**Recycling pillar:** Validation of 2 of the 3 technologies developed in task T3.1 aimed at maximizing the use of RAP and reducing the environmental impact of asphalt mixtures. **Energy pillar:** To validate the Full Adaptive Lighting System, and the remote control for tunnel ventilation systems designed or developed in T3.1. All these solutions aiming at reducing the overall energy consumption of the Hoz tunnel in A8. **Digitalization pillar:** To validate the smart dynamic traffic management system developed in task 2.5 with the objective to optimize traffic management and reduce accidents.
Description of the proposed solution	The technologies of the **Recycling pillar** will be implemented in a section from the N-623 road. Two of the three alternative binders developed will be selected and upscaled. Concerning the **Energy pillar**, the adaptive lighting and the remote control for tunnel ventilation systems from task 3.1 will be replicated in the Hoz Tunnel in the motorway A8. The capacity to reduce the energy consumption of the tunnel will be evaluated. As for the **Digitalization pillar**, a smart dynamic traffic management system will be deployed in a freeway section placed in the A-8 motorway in Cantabria.

Innovation technologies implemented	**Sulfur based low-carbon organic polymer binder** including industrial and agricultural by-products. This material does not require external heat during application and allows the recycling of wider array of waste materials and high rates of RA. **Biobinder from crude tall oil**, including the development of Hot Mix Asphalt, Warm Mix Asphalt and Half-Warm Mix Asphalt incorporating 50% RA. **Novel highly polymer modified bitumen** to improve the performance of asphalt mixtures with high RA content. **Full adaptative lighting system** will be designed. The design of the FAI system requires collating ambient data for at least six months before defining the regulation rules. The implementation of the system involves the development of the algorithms to manage the FAI system, as well as the design of the control system, where unavailable. **Remote-control ventilation system** will be designed, which will deliver real-time information of key variables such as alarms, vibrations, fan speed, temperatures and air flow. **Smart dynamic traffic management system** including opposite direction vehicles detection and advise system, dynamic signalling in traffic merging and on-ramp sections and traffic monitoring and real time information based on the network macroscopic diagram.

4.3 SUBSTRUCTURE PILOT 3 – NETHERLANDS

Focus pillar:	**Recycling** pillar
Locations:	South Holland Rotterdam region
Infrastructures included:	Roads and embankments
Pilot owner:	Waterschap Hollandse Delta (WSHD)
Problem/current scenario	The densely populated and highly industrialised Western Netherlands is underlain by highly compressible soft clay and peat deposits. Sea-level rise is a challenge for most low-lying countries. However, because of the softsoils the landmass in this area of the Netherlands is subsiding at a faster rate than the sea-level is rising. The subsidence is caused by ground water pumping used to control the water level, this results in consolidation settlement in the soft clay and oxidation of the peat. Roads, railways, waterways and flood defences are predominantly built on embankments/dykes which cover thousands of kms. Ongoing settlement of these critical infrastructure elements is a major problem in the region.
Objectives per strategic pillar	**Recycling pillar**: The aim of this pilot is to validate the optimized solution developed in task 3.1 to stabilize the soil in which industrial by-produced are used.
Description of the proposed solution	To implement SRM mixing in place to increase the strength and stiffness of the soft clay and peat deposits. The steps are: 1. **Soil samples** will be obtained from the critical areas and the ability of a range of candidate **by-products** to increase strength and stiffness will be assessed in the **laboratory**. 2. The impact of the most effective and lowest **life-cycle stabilisation solution** will be assessed in a numerical model to assess the increase in safety level and the impact of subsidence over the entire lifetime of the structure. 3. The solution will be **implemented at a demonstration site**. The treated area will be at least 4m square. The development of strength and stiffness over time will be assessed through the use of penetrometer and shear wave stiffness measurements.
Innovation technologies	**Soil stabilization with industrial by-products**

4.4 BRIDGE PILOT 4 – SLOVENIA

Focus pillar:	**Reuse pillar** Other pillars covered: **Recycling and Digitalisation**.
Locations:	Bistra Creek
Infrastructures included:	Local roads, Bridges and Geotechnical structures.
Pilot owner:	Občina Crna na Koroškem (CRNA)
Problem/current scenario	The rural council of Črna na Koroškem passed the mobility strategy in 2018. By implementing this strategy, they are shifting from the current car-oriented to people-oriented traffic solutions. In its five pillars, the strategy is encouraging walking and cycling and is aiming at optimizing road traffic. The latter is especially challenging due to a wide network of local roads connecting remote farms and serving logging operations. These roads frequently cross torrential creeks which in periods of heavy rain damage the bridges. Municipality Črna was heavily affected with the extreme flood event in August 2023, with several bridges collapsing. Therefore the objective is to increase the resilience of existing bridges and to reuse and recycle available SRM and SCE, potentially also from debris and failed structures.
Objectives per strategic pillar	**Recycling pillar:** Validation in a real environment of structural components implementing either recycled materials or low-carbon footprint cement in concrete for 3D printed safety wall and prefabricated slabs. **Reusing pillar:** Validation in a real environment of **GRS abutments** with reutilized infill and **modular bridge superstructure** with reclaimed girders. Infill for GRS abutments reutilizes gravel or crushed rock from road or railway structures. Modular bridge superstructure consists of **reused concrete girders** and **prefabricated slabs designed for disassembly and adaptability**.
Description of the proposed solution	A bridge will be replaced on a local road in Črna na Koroškem. The **abutments: innovative GRS system** which reduces erosion so classic anti-erosion measures are no longer necessary. The **modular superstructure** will be designed according to **DfA and DfD principles** and will comprise reused girder and prefabricated concrete slabs. The **safety wall** will be constructed of interlocking **3DCP segments** formed with parametric and/or generative design methods to reduce material consumption. Concrete for prefabricated slabs and for 3DCP safety wall will incorporate either **recycled materials** or **low carbon footprint cement**.
Innovation technologies	**Reused girder and prefabricated concrete slabs with Low carbon footprint cement, 3DCP safety guard, GRS abutments**

4.5 TUNNEL PILOT 5 – ITALY

 	
Focus pillar:	**Energy** pillar
Locations:	Umbria Region. State Road SS3bis, part of the European Itinerary E45. Colle Capretto tunnel.
Infrastructures included:	Roads and Tunnels
Pilot owner:	ANAS Spa
Problem/current scenario	In the EU GPP criteria for road lighting and traffic signals, it is highlighted the importance to address the key environmental impacts associated with the design, installation and operation of these systems. For road lighting, the criteria are broadly split into three parts: energy consumption, light pollution and durability aspects. From an LCA perspective, the main environmental impact is related to energy consumption during the operational phase, especially in tunnels, which are indeed the most demanding energy assets for the road transport sector.
Objectives per strategic pillar	**Energy pillar**. The objective is to validate in a real environment: 1) real-time control for the lighting and ventilation systems and 2) lighting poles equipped with photovoltaic and mini-wind generators to provide energy for their operation.
Description of the proposed solution	• **Full Adaptive Installation (FAI) lighting systems** to reduce the energy consumption as a function of ambient conditions: weather, traffic, and luminance. FAI involves the regulation of lighting systems according to a series of environmental conditions, such as external lighting, weather, and traffic. • **Lighting poles equipped with photovoltaic and mini-wind generators** to provide the necessary energy for their operation and drastically reduce their dependence from the energy providers; • **Real-time fan control system** to monitor and actuate the ventilation plant integrated with the full asset management system to identify inefficiencies, peaks of energy consumption and facilitate a good maintenance of tunnels ventilation systems. The combination of the renewable generators with the adaptive lighting system is estimated to provide a reduction of energy consumption close to 100% (daily energy balance).
Innovation technologies	FAI lighting systems Photovoltaic and mini-wind generators

5 CONCLUSIONS AND NEXT STEPS

This report provides literature review relevant for the CIRCUIT holistic framework development, which included overview of the European strategic and legal frameworks, previous works and EU projects, actual sustainable frameworks and rating methodologies such as ENVISION or BREEAM Infrastructure, standards and other CEN documents dealing with sustainability of construction works, environmental product declarations, resilience and life cycle costing. The reference standard for CIRCUIT is *EN 17472:2022 Sustainability of Construction works-Sustainability assessment of civil engineering works* as it is well aligned with the project principles and framework. Other standards key for the project development are *EN 15804 Environmental product declarations* and *ISO 15686-5 Life-cycle costing* respectively. As complementary documentation, CEN Workshops Agreements have been also considered to identify additional information, criteria and indicators that might be needed to complement the CIRCUIT holistic approach, in particular CEN CWA 17089 Indicators for the sustainability assessment of roads and CEN CWA 17819: Guidelines for the assessment of resilience of transport infrastructure to potentially disruptive events. Additional information and guidance from actual sustainable frameworks and rating methodologies (e.g., ENVISION and BREEAM Infrastructure) were considered as relevant to support the assessment. CIRCUIT holistic framework is strongly aligned with forementioned standards developed for industry and being applied to improve sustainability of construction works.

Since CIRCUIT project aims to support transformation of transport infrastructure into digital, resilient, smart, circular and sustainable project, a holistic circularity framework is proposed, with integrated methodology for resilience, economy, circularity, and environment impact assessment. Quantifiable KPI metrics is proposed, covering four aspects, social incl. resilience, economy, environment, and circularity, with digitalization as an additional aspect. Where methods and approaches leading to a quantitative result are not available for assessment criteria and indicators (e.g. social indicators), a checklist method is adopted based on civil engineering works-specific features and characteristics.

The hierarchy of the analysis begins with the assessment of circular potential through circularity KPIs followed by impact assessment through LCA and LCC. The emphasis is placed on measurable metrics that can be converted into performance indicators (PIs). Incorporating performance indicators into a unified KPI results in a more structured and comprehensive assessment providing data-based evidence of the benefits of the circular approach. Concerning Circularity, analysed system is perceived in a form that the assets within the systems are donors or recipients of reusable structural elements, products or recyclable materials depending on the life cycle stage of the asset. An asset approaching the end of service life becomes a donor for the repairable assets in the system. Also, materials outside the system such as wastes from other industries are introduced into the system. Circularity PIs are formed to enable qualification and quantification of circling of elements and materials and will be implemented and validated on 5 five pilots. A thorough literature review was performed which served as a basis for circularity PIs. In general, the most important criteria used for the final selection of indicators have been: simplicity, ease of measurement, universality, comparability relevance and pertinence.

CIRCUIT framework will be integrated into the digital tools for circularity analysis and digital twin platform that will assess the environmental impacts of life cycle maintenance and repair activities of transport infrastructure with the aim of mitigating and seeking their adaptation to climate change. Digital tools will promote also transparent disclosure of information by introducing Digital product passports, which will be direct link between KPIs and digital twin models. KPIs proposed in CIRCUIT framework will be applied to different dimensions of construction products or works, which will enable the integration of social and sustainability aspects in civil construction projects and ensure that not only technical and economic objectives are met, but also to promote human well-being and minimize environmental impact.

Next steps

- Based on the proposed KPIs, development of the Circularity analytics tool (CAT) is done. CAT will be integrated in the digital platform through the usage of Graph Database.
- Development of data requirements for data integration into digital platform, visualization and analysis of KPIs will be developed jointly with WP2.
- Collection of data with pilot owners for relevant KPIs per pilot will be performed. The applicability and the capabilities of the developed holistic circularity framework will be demonstrated through the pilot projects in WP5.
- Preparation of database for development of Digital Product passport prototype. DPP will be used to enhance actual classification and the properties included in the description of each infrastructure element/object/material to be included in the IFC model (including IFC.js and Dynamo open-source models and tools and design considerations). The platform will enable the data integration from different tools, like LCA (e.g., openLCA), LCC, BIM, digital twin platforms/tools, traffic simulation tools (e.g., SUMO) etc.

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