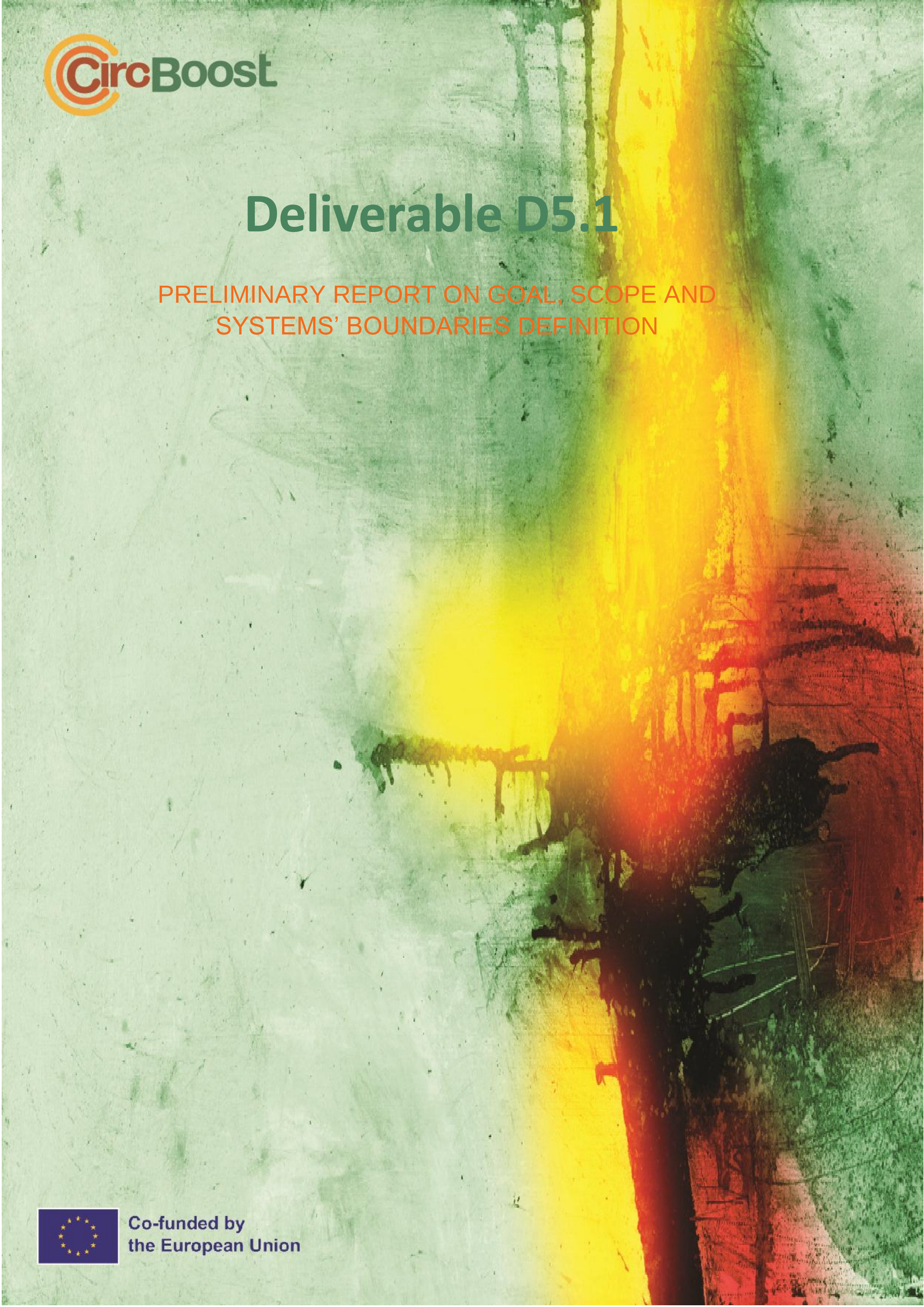

CircBoost

Deliverable D5.1

PRELIMINARY REPORT ON GOAL, SCOPE AND SYSTEMS' BOUNDARIES DEFINITION

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3R – Reduce, Reuse, and Recycle

CDW – Construction Demolition Waste

cLCC – Conventional Life Cycle Costing

DfD/R – Design for Deconstruction / Reuse

EC – European Commission

eLCC – Environmental Life Cycle Costing

EoL – End of Life

GA – Grant Agreement

ICS – Integrated Circular Solutions

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

NA – Natural Aggregate

NAC – Natural Aggregate Concrete

PCR – Product category rules

RA – Recycled Aggregate

RAC – Recycled Aggregate Concrete

SETAC – Society of Environmental Toxicology and Chemistry

S-LCA – Social Life Cycle Assessment

UNEP – United Nations Environment Programme

WP – Work Package

Executive summary

The construction sector faces significant challenges related to inefficient and unsustainable practices, like poor waste management, limited recycling and reuse of secondary materials, and a lack of integration of advanced digital tools to enhance resource efficiency. Additionally, there is often insufficient collaboration among stakeholders and a need for better education and training for the workforce to adopt new technologies. These issues hinder the construction sector's ability to move towards more sustainable and circular practices, further aggravating resource depletion, increasing emissions and generating more waste.

The Circ-Boost project aims to address these problems by promoting circular solutions, fostering collaboration, and integrating innovative digital and technical approaches. Specifically, it seeks to enable and demonstrate an increase in the large-scale uptake of integrated circular solutions (ICS) in European construction by enhancing the reuse, recycling, and valorization of construction and demolition waste (CDW) into new products, the development and deployment of both digital and technical solutions in building urban material databanks, and digital twins, while also boosting the commercial potential of these solutions through targeted exploitation measures. By leveraging existing networks and effective communication strategies, Circ-Boost aims to ensure widespread adoption of sustainable practices in the construction industry and promote industrial competitiveness and greater resource-use efficiency in buildings and the European construction sector. The project's core consists of five pilot projects across different European regions, demonstrating novel solutions for demolition, waste processing, management, and valorization. These solutions will be evaluated by DRAXIS in the framework of WP5, from an environmental, economic, and social perspective employing a threefold life-cycle sustainability assessment evaluation system, through environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) respectively.

The LCA methodology follows the principles, guidelines, and requirements of ISO 14040 and ISO 14044 standards, consisting of four main stages: 1) Goal and Scope Definition, 2) Lifecycle Data Inventory, 3) Impact assessment, and 4) Results interpretation. The methodology for carrying out the LCC study is based on the SETAC guidelines on Life Cycle Costing. An environmental LCC (eLCC) approach is selected to focus on the same stages of the value chain, as the LCA. The methodology for carrying out the S-LCA study is based on the UNEP/SETAC Guidelines for Social Life Cycle Assessment of Products and Organizations. The methodology foresees the identification of the relevant stakeholder groups (workers, local community, society, and value chain actors) and impact indicators. For each stakeholder group, a set of impact indicators will be identified based on a three-step approach including: a) screening of relevant published material, b) use of social impact databases and c) consultation with local key actors. The Reference Scale Approach for Life Cycle Impact Assessment is selected for assessing the social performance and risks of the studied system.

This deliverable D5.1 is an interim Life Cycle Sustainability Assessment report, presenting the methodology and the study’s basic approach to assess the proposed solutions and it focuses on the first stage of the LCA methodology, considering the same Goal & Scope (including functional unit and system boundaries) characteristics for all three aspects of the sustainability assessment. For this purpose, DRAXIS has established a continuous communication with the Spanish/French/Serbian/Norwegian/Czech pilot leader, to fill in the goal and scope template and outline the production process, specifying the supply chain stages and illustrating each stage with a process flow diagram. A baseline scenario, depicting the situation prior to the implementation of the solutions, has been defined to compare with the modified scenario incorporating the proposed solutions. The first stage of goal and scope definition has been completed for all pilots to ensure a fair comparison between the solutions and the business-as-usual scenario, alongside a hotspot analysis of the solutions. For Pilot 1 (UPC) and Pilot 3 (FCE), the focus of the goal and scope has been at the building level i.e. the concrete structure. Pilots 4 (MNORD) and 5 (SKA) focus on the material level, examining a concrete element, while Pilot 2 (CAP) examines the potential impacts of a digital and physical hub for secondary materials.

The upcoming steps of the study include data collection and building of the lifecycle inventory (LCI), modeling in LCA software, and deriving results and conclusions. These steps will be included in the final environmental sustainability assessment report (D5.2).

1. Introduction

In recent years, urbanization has accelerated globally at an extraordinary rate. Currently, 55% of the world's population lives in urban areas, a proportion that is expected to increase to 68% by 2050, placing additional stress on the built environment and the construction sector (United Nations, 2019).

The construction industry is alone responsible for a large portion of Europe's environmental footprint: 50% of natural raw materials use, 40% of total energy consumption (as the single largest consumer), 46% of total waste generated, and 36% of all greenhouse gas (GHG) emissions, exerting high pressures on the environment, society, and economy (Marinković et al., 2023). Particularly, the environmental impacts of activities such as raw material extraction, manufacturing/distribution of construction products, construction, use and management of infrastructure, and demolition and disposal of construction demolition waste (CDW), place construction as one of the largest polluters, consumers of natural resources and a significant waste generator.

To date, most advancements in the construction sector have focused on reducing "operational carbon" (the emissions generated from heating, cooling, and lighting buildings). These emissions are expected to decrease from 75% to 50% of the sector's total in the coming decades making buildings more energy efficient. However, efforts to reduce "embodied" carbon associated with building materials, construction and demolition of buildings have significantly lagged (UNEP & CEA Yale, 2023).

With regard to construction materials, the concrete industry plays a leading role in this process: concrete production is not especially harmful per unit of concrete; however, the global production and utilization of concrete is very high; roughly 25 billion tons of concrete are produced globally each year, or over 3.8 tons per person per year, while in developed countries, structural concrete (concrete utilized in reinforced concrete structures) constitutes over 50% of all concrete (Marinković et al., 2021).

With the global built-up area expected to exceed 415 billion m^2 by 2050 due to population growth (United Nations, 2019), it is of crucial importance to find ways of greening the concrete industry, that is, to decrease its impacts on the environment. A shift to a circular and more holistic life cycle analysis of buildings is necessary.

The Circ-Boost project (HORIZON EUROPE, GA no. 101082068) aims to become a central hub and interaction node for different emerging technologies to foster circularity in buildings and the construction sector. The project focuses on developing and deploying digital and technical solutions, such as urban material databanks and digital twins, as well as selective demolition, decontamination, recycling, and reuse of waste materials. Among the different strategies that the Circ-Boost project investigates to decrease such impacts are:

- Recycling of construction and demolition waste and usage in green concrete on the material level
- Promoting "design for disassembly and reuse – DfD/R" buildings for longer service life and waste mitigation on the structural level
- New supply-and-demand models that allow for the storing, preparation and maintenance of secondary materials, which can lead to a decrease of Construction & Demolition Waste (CDW) and GHG emissions and allow the reusability of materials later in the building cycle

The project's core consists of five pilot projects, deployed in different European regions, P1 (UPC) in Spain, P2 (CAP) in France, P3 (FCE) in Serbia, P4 (MNORD) in Norway, and P5 (SKANSKA) in Czech Republic, highlighting and demonstrating at large scale, novel and integrated solutions for demolition, construction waste processing, management, and valorization in new products. These solutions are assessed from a holistic sustainability perspective by sustainability provider DRAXIS through environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) respectively.

Life Cycle Assessment (LCA) is a state-of-the-art approach that assesses the environmental impacts of a product over its Lifecycle. LCA can be defined as the collection and estimation of resource inputs, outputs of a product system, including their processes and designs, throughout its life cycle and quantifies the environmental burdens associated with various stages. It provides a holistic and systematic approach to assess the environmental performance of materials and identify opportunities for improvement. LCA quantifies impacts such as carbon emissions, energy consumption, water usage, air pollution, waste generation and ecosystem depletion.

Goal and scope of the report

This deliverable (D5.1 – Preliminary Report on Goal, Scope, and Systems' Boundaries Definition) marks the first output under Task 5.1 of the Circ-Boost project, which operates within the broader framework of Work Package 5 (WP5 – EVALUATE). It lays the methodological groundwork for the Life Cycle Sustainability Assessment (LCSA) activities to follow, encompassing environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA). Developed in alignment with ISO 14040 and 14044 standards, the report focuses on the initial phase of the LCSA methodology—Goal and Scope Definition—without delving into impact results or inventory data, which remain confidential at this stage. Instead, it establishes a coherent and standardized framework to set the goal and scope and guide the subsequent data collection and analysis phases, ensuring methodological consistency across all sustainability dimensions.

The scope of D5.1 includes the identification of technologies and systems to be assessed within Circ-Boost along with their respective baseline technologies, the definition of system boundaries for LCA, LCC, and S-LCA, the specification of functional units and reference flows, and the clarification of assumptions, limitations, and intended use of results. It also outlines the methodological approach to be followed. This framework has been applied across five pilot cases, each representing distinct technological and socio-economic contexts. Pilot 1 (UPC, Barcelona) and Pilot 3 (FCE, Belgrade) focus on modular, reusable concrete structures designed for deconstruction and reuse. Pilot 2 (CAP, Paris) evaluates a physical platform for waste treatment and material reuse, comparing it against conventional demolition waste practices, while Pilot 4 (MNORD, Vesterålen, Norway) and Pilot 5 (SKA, Prague) assess the use of recycled aggregate concrete versus natural aggregate concrete in building elements.

Deliverable D5.1 thus serves as an interim report, presenting the conceptual and methodological foundation for the comprehensive sustainability assessments to be conducted in Deliverable D5.2. The final report, scheduled for Month 47, will include inventory data (where applicable) and the results of the environmental, economic, and social assessments. By establishing a unified structure and clearly defined scope, D5.1 ensures that the forthcoming evaluations will be consistent, transparent, and tailored to the specific characteristics of each pilot case.

Connection with other WPs

The threefold sustainability assessment and the execution of the LCA, LCC, and S-LCA are closely linked to other work packages within the Circ-Boost project. Notably, WP3 – PILOT: Deploy ICS in Operative Environments, is particularly relevant, as it oversees the implementation and validation of the five pilot cases. In particular, Deliverable D3.1 – Pilots Deployment Strategy provides supplementary insights that support the accurate simulation and evaluation of the technologies under assessment, alongside the pilot partners, who serve as the primary source of information regarding the layout, operational processes, and system-level input and output data (e.g., raw materials, energy, equipment, emissions) of the proposed solutions.

Simultaneously, the Social Life Cycle Assessment draws on insights from WP2 – CONNECT: Engage with All Relevant Stakeholders. Specifically, Task 2.2 – Construction Ecosystem Mapping, led by CAP, provides essential stakeholder identification at local, regional, and European levels. This mapping supports the social dimension of the assessment by ensuring that relevant actors and their roles are adequately considered in the evaluation of social impacts.

Structure of Report

The report is structured to support a clear and consistent presentation of the goal and scope definition for the upcoming sustainability assessments carried out within the Circ-Boost project. Chapter 1 introduces the scope and objectives of the deliverable, explaining how they are connected to the other work packages (WPs) of the program (namely WP2 and WP3).

Chapter 2 presents the methodological foundations for the threefold sustainability assessment—environmental (LCA), economic (LCC), and social (S-LCA)—including the relevant standards, tools, and software applied. The methodology and stages of the LCA, as defined by ISO standards, are thoroughly explained, along with a description of the system boundaries, the functional unit of analysis, and the selected impact categories. This chapter also outlines the approach to data confidentiality, which is particularly critical at this stage of the project.

Chapter 3 provides a detailed goal and scope definition for each of the five pilot cases. For every pilot, the chapter includes a technology overview, a description of the baseline conventional scenario, and the proposed solution. This is followed by a comprehensive definition of the goal and scope, the functional unit, and the system boundaries—addressing aspects such as multifunctionality and key assumptions. Each pilot case is structured into three dedicated subchapters, outlining the goal and scope for the environmental (LCA), economic (LCC), and social (S-LCA) assessments, ensuring methodological consistency while still adapting to the specific context of each pilot.

Finally, Chapter 4 summarizes the key findings and outlines the next steps, including compiling data inventories, modeling, and impact analysis, which will be presented in Deliverable D5.2.

2. Methodology, tools and relevant standards

This chapter describes the process to be followed to carry out the environmental, social and economic assessment of the Circ-Boost solutions proposed by the 5 pilots (UPC, CAP, FCE, MNORD, SKA) as these are described in Chapter 3. To perform the threefold sustainability assessment of the solutions, the methodologies of LCA, LCC and S-LCA are employed.

Initially, chapters 2.1, 2.2 and 2.3 present the methodologies for LCA, LCC, and S-LCA, respectively, along with the relevant standards and corresponding guidelines for each assessment. Subsequently, chapter 2.4 provides an overview of the methodological tools, particularly the software tools and the databases that will be used for the threefold analysis. These tools will support the main tasks of the next deliverable, including data processing, modeling, and impact analysis. (D5.2). In the final chapter, Chapter 2.5, a brief description of the data confidentiality and the agreements introduced to treat and protect those data are presented.

2.1 Life Cycle assessment methodology

Life Cycle Assessment is a structured, internationally standardized method for identifying and quantifying the inputs and outputs and the corresponding environmental and health impacts that are associated with products, processes and services throughout their lifecycle (James A. Fava, 1991). The core principle of the method is that the environmental impact is present at each process and stage of the value chain, from the extraction of raw materials to material processing, manufacturing, distribution, use, repair and maintenance, and finally disposal, reuse, or recycling. Any changes in conditions at these stages can lead to either positive or negative consequences.

Due to this quantification and thorough documentation, LCA helps to avoid resolving one environmental problem and creating another, the so-called “shifting of burdens”, while giving the insight to make more well-informed decisions (European Commission; JRC, 2011). The most important aspects of LCA are the identification of environmental hotspots in the life cycle of a product that can lead to optimization of processes, the analysis of the contribution of the life cycle stages to the overall environmental load, the comparison between products for internal or external communication that can point to the most burden-free alternatives among a set of options, as well as the identification of Key Performance Indicators used in companies for life cycle management and decision support.

To ensure the scientific robustness, standardization, and the validity of the results of the LCA studies, the International Organization for Standardization (ISO) has established guidelines for conducting Life Cycle Assessment (LCA) through standards ISO 14040:2006 and ISO 14044:2006 (International Organization for Standardization (ISO), 2006b, 2006a). These standards outline four major phases for any LCA which are the following:

1. Goal and scope definition
2. Life cycle inventory (LCI)
3. Life cycle impact assessment (LCIA)
4. Interpretation

These methodological phases, which are elaborated in the following sections, ensure that LCA studies are systematic, transparent, and consistent.

As shown in Figure 1, LCA is an iterative process which means that several assessment loops can be taken to move from more generic to more specific data and increase the level of detail of the study with each iteration. This iterative process allows the practitioner to go backwards and locate those processes, or those material and energy inputs that contribute more to each impact category and propose alternatives.

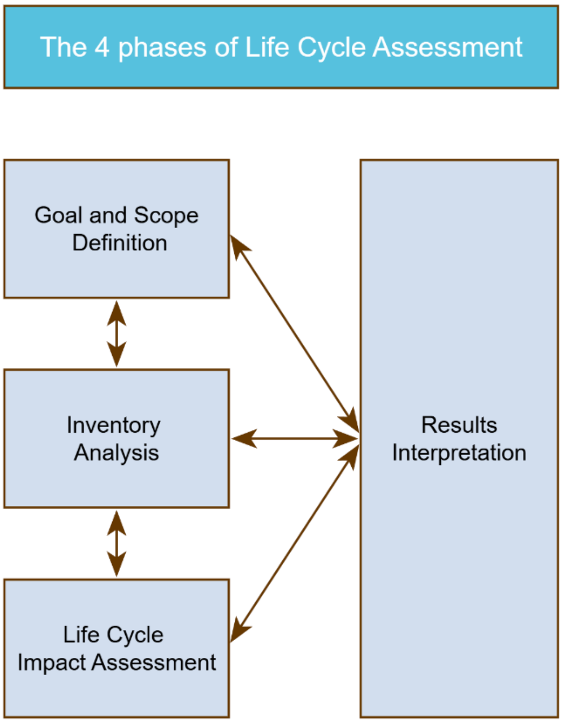


Figure 1. The life cycle assessment framework based on ISO 14040:2006 (ISO, 2006a).

2.1.1 Goal and scope definition

In this first phase of an LCA study, all key questions that will define the purpose of the study must be addressed to ensure that the results are both useful and valid. This phase of an LCA determines the intended purposes of performing the study, as well as the details of the product/process/technology system(s) to be addressed regarding their environmental impacts through the LCA lens.

Goal Definition

The goal definition is the starting point of an LCA and determines the purpose of the study in detail. This greatly influences the LCA because decisions made in later LCA phases must be consistent with the goal definition. The influence may also go the other way, for example, if unforeseen data limitations in the inventory analysis necessitate a revision of the goal definition. Such a revision is an example of the iterative nature of LCA. Main characteristics of goal are the intended application(s) of the LCA results, the reasons for carrying out the study as well as the target audience, and whether the results are intended to be used to support comparative assertions for public disclosure, are stated by the LCA practitioner.

Scope Definition

Afterwards, in the Scope of an LCA study, the product system and its functions are identified, as well as the functional unit, respective reference flow(s), the system boundaries and allocation procedures if applicable in the study. Moreover, this is the point where the relevant impact categories and the appropriate impact assessment method are selected and the potential data requirements, assumptions, and limitations are documented.

The study framework largely depends on the level of detail required for applying the results. In fact, the outcome of an LCA study primarily hinges on the accuracy of the input data (Haes et al., 2002). Additionally, the validity of LCA results depends heavily on the quality of the data. For each data point, general considerations should include accuracy, repeatability, temporal and geographical coverage, and its representativeness within the defined geographic and temporal context.

Taking all this into account, an LCA requires a quality graphical depiction of the life cycle processes of the system under study using a Process Flow Diagram. This flow diagram should include only those life cycle stages within the system boundaries. Special attention must be given to ensure all references relate to the functional unit to maintain mass and energy balances.

Functional Unit

According to ISO 14040:2006 standard, the functional unit is a characteristic measure of the value chain, typically a quantity of the final product, which serves as the reference point for quantifying the system's inputs and outputs, as well as its environmental impact (ISO, 2006a). The correct selection of the functional unit allows for a clear representation of the environmental impact expressed in terms of the product (material or non-material) under examination and ensures the possibility of comparing different production systems of the same unit/product, with the goal of selecting the most sustainable solutions. A functional unit defines the qualitative aspects and quantifies the quantitative aspects of the function, which generally involves answering the questions "what?", "how much?", "for how long/how many times?", "where" and "how well?" (Hauschild et al., 2018).

Multifunctionality

Multifunctionality in a system examined through LCA refers to the system's ability to deliver simultaneously multiple functions or provide various products and services besides the primary function or product. To accurately analyze the environmental impact of such a system, LCA often requires distinguishing or allocating environmental burdens across different functions.

Allocation procedures

When a system provides multiple functions or produces more than one product, the environmental impacts associated with the system's inputs and outputs must be correctly distributed. This allocation ensures that each function or product is assigned its share of the environmental impacts. Allocation procedures thus contribute to a more accurate representation of the system's overall footprint, allowing for fairer comparisons and more effective optimization of its environmental performance.

Assumptions and limitations

During the execution of an LCA, a large volume of data may be available, or there may be a lack of data, making the processing of such information a complex task. In cases where abundant data is available, it is possible to exclude stages that are proven not to affect the outcome. This can be done if data from previous studies are considered, which identify the inputs and outputs of specific stages that have negligible or even zero influence on the product's life cycle and, consequently, its environmental impacts. Stage exclusion can also be applied when comparing two products that involve identical processes throughout their life cycle. However, when there is a lack of data, the LCA should be based on the stages for which data is available. For other stages, a theoretical approach to the data is sometimes feasible, which should be based either on actual data or on prior studies with corresponding geographic and temporal coverage.

Cut-off criteria

During the execution of an LCA, there may be either a large volume of data or a lack of it, making data management a complex task. The application of cut-off criteria is an important step, determining which stages and processes in the life cycle of a product will be included or excluded, simplifying the analysis and facilitating data management.

Cut-off criteria should be systematic and transparent, considering data quality and the objectives of the analysis. Additionally, they must be limited to avoid incomplete data and uncertainty in the results. Typically, stages that do not significantly impact the outcome may be excluded based on previous studies. A commonly applied approach is the 3% cut-off rule, which allows for the exclusion of processes that have an impact smaller than 3% of the total impact of a system (European Commission; JRC, 2016). Stage exclusion can also apply when comparing two products that involve identical processes in their value chain.

For other stages, a theoretical approach to the data may be feasible, based on actual data or previous studies with corresponding geographic and temporal coverage. Other cut-off criteria may be more oriented toward the specific goal and scope of the comparative analysis, where certain processes with non-negligible impacts can be excluded if their inclusion hinders comparability between the systems examined or does not provide significant information and conclusions in the context of the comparison.

System boundaries

The system boundaries define the specific processes that will be included in the LCA. They can encompass all the processes in the value chain (cradle-to-grave) or a subset of them (cradle-to-gate, gate-to-gate, gate-to-grave). The selection of processes to be considered depends directly on the purpose and scope of the study. The "cradle-to-grave" model is suitable when the goal of the study is to calculate the total impact, such as for Environmental Product Declarations (EPDs). Other models allow for the strategic exclusion of processes, either to focus on specific impacts or to compare systems with shared components—simplifying both analysis and interpretation. The processes considered are organized into subsystems, which may consist of grouped or individual processes, depending on what best supports the assessment. In general, the most prominent types of LCA boundaries are the following:

- Cradle-to-Gate: This boundary starts from the extraction of resources from nature and continues until the product is ready at the factory gate.
- Cradle-to-Grave: This boundary extends from resource extraction through the entire life cycle of the product, including its end-of-life disposal.
- Cradle-to-Cradle: This boundary includes the recycling or reuse of the product, creating a closed-loop system.

Impact categories definition

The final stage in defining the goal and scope is the selection of impact categories to be examined. The categories are chosen before the data inventory step, determining the extent to which certain flows are necessary for the accuracy of the analysis, and to what extent the data inventory is considered complete and comprehensive. The categories are linked to specific, measurable indicators, which form the final product of the analysis. The selection of categories is largely flexible but typically aligns with the objectives of the analysis and the specific characteristics of the unit under examination. Typical examples of impact categories include climate change, acidification, eutrophication, and others.

2.1.2 Life cycle Inventory Analysis

This is the phase involving the compilation and quantification of inputs and outputs, for a given product system throughout its life cycle. This is an iterative process, where data on inputs of energy and materials flows, as well as data on outputs like products, co-products, emissions, and waste discharges are collected before impact assessment. The LCI phase also involves collecting data to allocate inputs to the products and co-products of a product system. This phase also includes validating the collected data and relating them to the reference flow of the functional unit. The inputs and outputs refer to:

- Material inputs, including main and ancillary flows
- Energy inputs, from fossil fuels, non-fossil fuels, electricity, or purchased thermal energy,
- Equipment inputs,
- Product and by-product outputs,
- Wastes for further treatment,
- Emissions to air,
- Discharges to water and soil

At the same time, during the inventory, qualitative information is collected to characterize the emissions, such as whether the flows are processed, unprocessed, recycled, or discarded. Other data may involve technical details, such as transportation processes within the system (method of transport, type and fuel consumption, distances, etc.).

2.1.3 Life Cycle Impact Assessment

This is the phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. In LCIA, the classification of the data of the LCI to the selected impact categories and related category indicators takes place, as well as the selection of the characterization model that allows the quantification of the environmental impacts. According to ISO, every LCA must at least include classification and characterization and can be optionally followed by normalization that allows the calculation relative to reference information and by weighting that displays an aggregation of results.

The environmental impacts of the Circ-Boost technologies will be assessed with the Environmental Footprint method (EF3.1), as it covers a wide range of environmental impacts (See Table 1). The EF is developed and promoted by the European Commission as part of the Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) initiatives.

Table 1. The EF 3.1 method (Andreasi Bassi et al., 2023).

EF Impact Category	Abbreviation	Characterization Unit	Normalization Factor (Crenna et al., 2019)	Weighting Factor (Sala et al., 2018)
Climate Change, total	CC	kg CO_2 eq.	7550	0.2106
Ozone depletion	ODP	kg CFC-11 eq.	0.0523	0.0631

Human toxicity, cancer	HTP-c	CTUh	1.73E-5	0.0213
Human toxicity, non-cancer	HTP-nc	CTUh	1.29E-4	0.0184
Particulate matter	PM	Disease incidence	5.95E-4	0.0896
Ionizing radiation, human health	IR-HH	kBq U235 eq	4220	0.0501
Photochemical ozone formation/human health	POCP-HH	kg NMVOC eq	40.9	0.0478
Acidification	AC	mol H+ eq.	55.6	0.062
Eutrophication, terrestrial	EuT	mol N eq.	177	0.0371
Eutrophication, freshwater	EuF	kg P eq.	1.61	0.028
Eutrophication, marine	EuM	kg N eq.	19.5	0.0296
Ecotoxicity, freshwater	EcF	CTUe	56700	0.0192
Land use	LU	Dimensionless (pt)	819000	0.0794
Water use	WU	m3 water eq. of deprived water	11500	0.0851
Resource use, minerals and metals	RUmm	Kg Sb eq.	0.0636	0.0755
Resource use, fossil fuels	Ruf	MJ	65000	0.0832

Three additional environmental impact categories assessed in the LCA studies of this deliverable are Climate Change – fossil (*CC – Fossil*), Climate Change – Biogenic (*CC – bio*) and Climate Change – Land Use and Land Use Change (*CC – luluc*), representing the climate change related impacts of the LCA systems under study due to the use of fossil fuel, the sequestration or emission of biogenic carbon and the occupation/change of land use type, respectively. These three impact categories sum up to the Climate Change (CC) impact category as shown in Equation 1:

$$C = CCfossil + CCbio + CCluluc$$

Equation 1. The formula of Climate Change.

According to ISO 14044 (ISO, 2006b), the selection of impact categories must be consistent with the goal and scope of the study and must comprehensively address the main environmental issues relevant to the system under analysis. To meet this requirement and ensure sectoral relevance, the indicators used in this study also draw from the set of standards developed by CEN/TC 350 for the sustainability assessment of construction works.

Specifically, the indicators defined in EN 15804 (CEN, 2019) at the product level and EN 15978 (CEN, 2011) at the building level are adopted. These standards ensure a life cycle perspective and provide harmonized indicators for assessing environmental performance from construction through end-of-life stages.

Importantly, there is a strong alignment between the impact categories defined in EF 3.1 and those specified in EN 15804 and EN 15978 (CEN, 2011, 2019). The latest revision of EN 15804 (A2:2019) has integrated characterization factors from the EF method, resulting in a high degree of methodological compatibility.

Selection of Impact Categories for Impact hotspot Assessment

As the EF3.1 method includes a substantial number of Impact Categories, it was deemed necessary to perform an initial identification of the most relevant impact categories for each LCA study, using the EF3.1 Normalization and Weighting method along with the 80% criterion (European Commission; JRC, 2021). The process involves the following steps:

1. **Normalization and Weighting:** The EF3.1 characterized impacts are normalized and weighted by applying the EF3.1 normalization and weighting factors presented in Table 1**Error! Reference source not found.**. This step enables the calculation of the weighted score for each Impact Category, as well as the total single score (the sum of all weighted impacts) for the LCA system. Normalization is an optional step under ISO 14044:2006 to support the interpretation of the impact profile from the characterization. Normalization means that indicator scores for all impact categories are expressed in a common metric, typically the annual contributions to total environmental impacts of an average person. This serves among others, the decision-makers to better understand the magnitude of characterized results by relating them to a common familiar and external reference (Hauschild et al., 2018).
2. **Ranking:** The weighted scores of each Impact Category are then ranked, from highest to lowest.
3. **Contribution Calculation:** The contribution of each Impact Category's weighted score to the total single score is calculated by dividing the weighted score of each category to the total single score.
4. **Selection:** The weighted scores of the Impact Categories are cumulatively summed, starting from the highest, until they account for ~80% of the total single score. The Impact Categories that, together, contribute to this 80% threshold are considered the most important for further (impact hotspot) assessment. The impact categories deemed as the most relevant from this initial identification procedure are further refined by setting additional selection criteria in each LCA study according to the relevant LCA goals. The additional criterion set in all LCA studies, is to focus only on impact categories that have a >10% weighted contribution to the total single score of the respective LCA systems, as to further refine the most relevant impact categories for these cases.

2.1.4 Interpretation

This is the last of the four steps in LCA and is the phase where the results of the LCIA are portrayed in a comprehensive manner and conclusions are drawn. Moreover, this is where the identification and evaluation of opportunities to achieve process improvements for the reduction of environmental impacts takes place, based on the results of the impact assessment.

2.1.5 Circ-Boost relevant standards

Depending on the purpose of the study and the specific context of the respective products and processes that are evaluated through LCA, additional documents, standards and platforms may apply influence in the specifics of the relevant studies. Therefore, to support the evaluation of the Circ-Boost solutions, standards developed specifically for the construction sector by the technical committee CEN/TC 350—focused on the sustainability of construction works within the European Committee for Standardization (CEN)—were employed, offering more targeted and sector-relevant guidance.

The evaluation of the Circ-Boost solutions is based on standards developed specifically for the construction sector by the technical committee CEN/TC 350, which focuses on the sustainability of construction works within the European Committee for Standardization (CEN). These standards provide targeted and sector-relevant guidance for conducting environmental impact assessments.

EN 15804 (CEN, 2019) establishes the core product category rules (PCR), setting out specific requirements and guidelines for all construction products and services. This ensures that life cycle assessments (LCAs) are conducted in a standardized manner, making it easier to compare the environmental performance of similar products within a category.

As concrete is the most important material in the Circ-Boost project, **EN 16757** (CEN, 2022) further refines these rules by providing material-specific rules specifically for concrete and concrete elements. It builds upon the general framework of EN 15804, addressing unique characteristics of concrete such as carbonation, mix design variability, and end-of-life recycling, thereby ensuring accurate and comparable LCAs and environmental product declarations (EPDs) for concrete products.

EN 15978 (CEN, 2011) complements EN 15804 by providing a framework for assessing the environmental performance of buildings at the whole-building level. It specifies calculation methods for evaluating impacts throughout the entire building life cycle, from construction to demolition. To ensure consistency between product-level and building-level assessments, EN 15978 uses the same indicators as EN 15804 (and, by extension, EN 16757 for concrete).

A modular concept was introduced by CEN TC350 standards, for the definition of the system boundaries of construction products and buildings, which is illustrated in Figure 2. According to this framework, the potential environmental impacts occurring over the life cycle of the building are allocated to the stage in which they occur, thus enabling full transparency of the results of the analysis. Hence, according to these standards, the system boundary of the analysis entails the stages of materials extraction and production (Modules A1 to A3), the construction stage (Modules A4 and A5), the use stage (Modules B1 to B7), the end-of-life stage (Modules C1 to C4) and Module D, which is the module where the benefits and loads due to recycling, recover or reuse of materials are allocated.

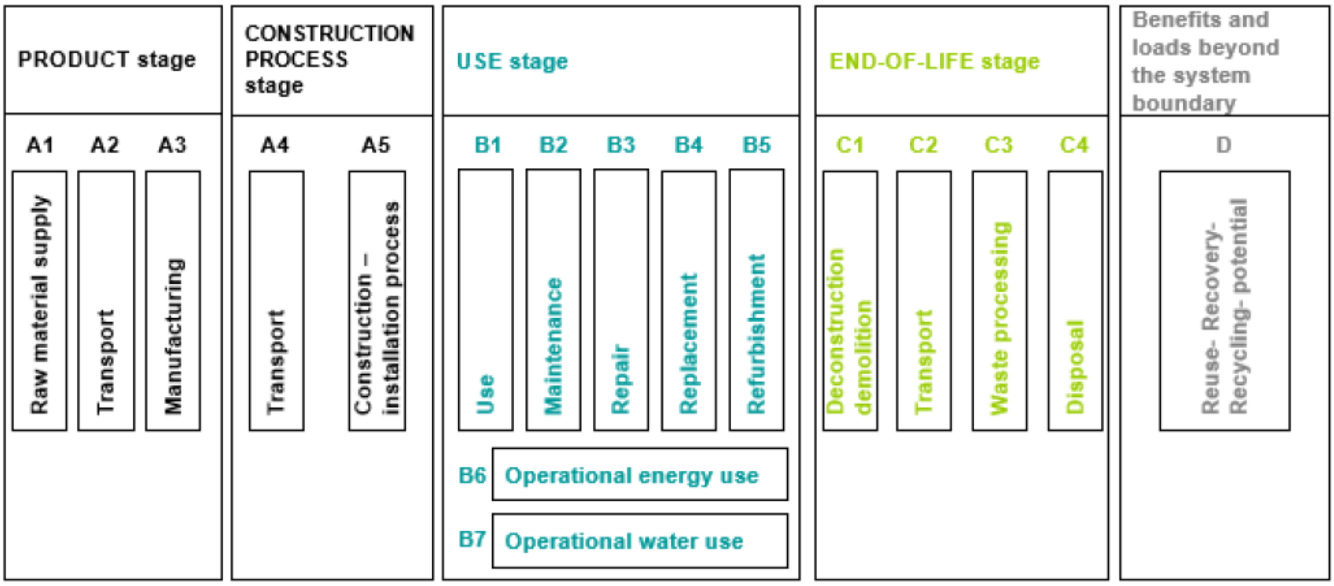


Figure 2. Scope of the LCA of buildings according to CEN TC350 standards EN15804 & EN15978.

2.2 Life Cycle Costing (LCC)

Overview

The idea of life cycle sustainability assessment (LCSA) builds on the so-called “three pillars” (or three dimensions) interpretation of sustainability, according to which sustainability is composed of an environmental, social and economic pillar (Hauschild et al., 2018) and LCA is expanded to also encompass social and economic aspects, in addition to environmental aspects of sustainability when analyzing product life cycles. In the current chapter, the concept of Economic Life Cycle Impact Assessment in terms of LCC and the respective standards used for the analysis is described.

Definition of LCC

Life Cycle Costing (LCC) is a comprehensive methodological approach used to assess the total costs incurred throughout the entire life cycle of a product, process, or service - from initial investment to end-of-life disposal. It functions as a strategic decision-support tool that enables the optimization of resource allocation and the evaluation of long-term financial performance by capturing both immediate and future cost implications. Within the context of sustainability-oriented research and practice, the literature distinguishes between three principal forms of LCC: Conventional Life Cycle Costing (cLCC), which focuses solely on direct economic costs incurred by the owner or operator; Environmental Life Cycle Costing (eLCC), which integrates environmental externalities monetized through impact assessments; and Societal Life Cycle Costing (sLCC), which extends the analysis to encompass broader societal costs and benefits, including those incurred by third parties or future generations (Rödger et al., 2017).

The economic assessment of the Circ-Boost pilots will be conducted through Environmental Life Cycle Costing (eLCC) analyses for each pilot case. In addition to internal costs, eLCC accounts for the environmental impact by converting it into monetary terms. By quantifying environmental impact in financial terms, eLCC provides a clearer understanding of the environmental effects, as all impact categories are expressed using a common unit of measurement. The methodology employed for the eLCC analyses is structured into the following ten steps:

- **System boundaries**
  The eLCC analysis follows the system boundaries already established by the LCA, unless cost-specific considerations require adjustments. Any changes are clearly documented and justified.
- **Functional unit**
  The eLCC analysis is typically aligned with the functional unit defined by LCA, unless a particular case dictates otherwise. Final calculations are carried out in functional unit terms.
- **Data collection**
  The initial phase of the eLCC analysis involves gathering relevant data within the defined system boundaries, consistent with those established in the LCA. The process begins with the development of the LCI for the eLCC, which is integrated into the LCA's LCI by adding additional rows and columns related to economic data. This inventory categorizes processes into various stages, each associated with specific cost categories, such as capital expenditures (CAPEX), operational expenditures (OPEX), and End-of-Life (EoL) costs. To ensure accurate data collection, the LCI is accompanied by detailed guidelines to assist pilot teams in understanding the specific data required, with additional support provided as necessary. Key information includes cost descriptions, unit prices, units of measure, sources of price information, and space for additional comments to support clarity and traceability.

  If pilots are unable to provide all the required information, desk research is conducted to obtain secondary data from reputable sources, such as scientific journals, industry reports, and other credible publications, and fill the remaining gaps. It is essential to verify the reliability and accuracy of these secondary data sources to maintain the integrity of the analysis.
- **Assumptions**
  To ensure consistency in the analysis, specific assumptions must be established. This includes selecting an appropriate discount rate for calculating Net Present Values, typically based on the real interest rate. The analysis period is also established, typically assumed to align with the overall project duration, and is aligned with the expected lifespan of capital investments, allowing for a simplified approach without the need to account for residual values.

  Additional assumptions cover end-of-life (EoL) costs, administrative expenses, and maintenance requirements, particularly in cases where direct data is unavailable. These assumptions are applied consistently throughout the analysis and documented to ensure transparency and reproducibility.
- **eLCC template development**
  The development of the Excel-based tool represents a critical preparatory phase preceding the execution of the eLCC calculations. Initiated following the system scoping and definition, the tool is constructed in alignment with the established system boundaries and is designed to systematically deconstruct the system into discrete processes and corresponding cost categories. This structured approach enables the comprehensive identification and classification of all relevant

cost elements associated with the project, thereby ensuring a robust and transparent analysis of the overall cost structure. To facilitate comparability and analytical consistency, cost data - often reported in aggregated formats such as annual expenditures - are normalized to the functional unit defined in the LCA. Standardized unit prices are assigned to each cost category using consistent measurement units, enhancing the reliability and reproducibility of the assessment.

- **eLCC calculation**
  Once the necessary data has been gathered and the eLCC template is prepared, the calculation process can commence. The first step involves calculating the total cost for one full year of operation, which serves as the foundation for extending the calculations across the entire analysis period. To estimate future costs, the real interest rate is applied as a discount rate, enabling the calculation of the Net Present Value (NPV). This discount rate adjusts future costs to their present value, reflecting the time value of money. Next, the average annual cost per functional unit is determined for each cost category and production stage. The total eLCC is then derived by summing these average annual costs across all cost categories, providing the average cost per functional unit over the analysis period.

  Subsequently, following the completion of the LCA study, its results are converted into monetary terms for the eLCC analysis. During this phase, all processes are iterated to facilitate the calculation of environmental costs for the entire project period, including the determination of their NPV. Finally, the average environmental cost per functional unit is calculated for the duration of the project.

- **Hotspot Analysis**
  Hotspot analysis is essential for evaluating the distribution of costs across various stages of the eLCC. This process involves a comprehensive review of cost categories at each production stage, considering both internal and external costs, and identifying the primary cost drivers at both the individual stage level and throughout the entire eLCC. By highlighting areas of concentrated costs, this analysis provides a foundation for optimizing future processes and improving cost efficiency.

- **Sensitivity Analysis**
  The sensitivity analysis aims to evaluate the robustness of the analysis results by examining the extent to which variations in the values of key cost categories, identified during the hotspot analysis, affect the overall outcome. This process involves systematically adjusting the values of these critical cost categories to assess the degree of impact on the final results. By exploring a range of potential scenarios, the sensitivity analysis helps to identify which cost factors most significantly influence the total eLCC, offering valuable insights into areas of high uncertainty and potential financial risk. This understanding enables more informed decision-making and enhances the reliability of the analysis. A one-at-a-time sensitivity analysis is conducted, using Excel, assuming usually a ±10% variation of the different input parameters aggregated for each project stage to observe the variation of the NPV.

- **Comparison**
  At this stage, the analysis results are systematically compared with those obtained from conventional production processes or products. Within the context of the Circ-Boost framework, the Circ-Boost solutions will be compared to conventional solutions. The comparison will be conducted within the same framework, using the same functional unit, to assess the financial viability of Circ-Boost's solutions. Additionally, this comparison will extend to external costs, providing a comprehensive overview of all aspects of the project.

- **Interpretation**
  Upon completion of all preceding steps, the results are thoroughly analyzed to derive meaningful conclusions. This process involves evaluating key findings, addressing uncertainties, and assessing the overall consistency of the analysis. If needed, refinements are made to improve accuracy. Ultimately, the insights gained from this analysis provide recommendations for future improvements and support informed decision-making.

These ten steps provide a structured framework for a comprehensive study, thoroughly examining all aspects of both Circ-Boost's solutions and conventional alternatives. Following these in-depth analyses and comparisons with the production costs of conventional products, a thorough and complete assessment will be achieved.

2.3 Social Life Cycle Assessment (S-LCA)

The Social Life Cycle Assessment (S-LCA) is a relatively new methodology for the socio-economic assessment of products and organizations. S-LCA provides information on social and socio-economic aspects for decision making, in the prospect of improving the performance of organizations and ultimately the wellbeing of the associated stakeholders (Benoît Norris et al., 2020). Guidelines for S-LCA have been developed in 2009 by the UNEP/SETAC Life Cycle Initiative and updated in 2020. The "Principles and Framework for Social Life Cycle Assessment" ISO 14075:2024 standard (International Organization for Standardization, 2024), establishes principles and framework, specifies requirements and gives guidance to practitioners for an efficient and credible development and implementation of practices for assessing social impacts.

The 2020 Guidelines for Social Life Cycle Assessment of Products and Organizations (hereinafter referred to as S-LCA Guidelines) provide a roadmap and a knowledge base to help stakeholders in the assessment of social and socio-economic impacts of products' life cycles, their related value chains, and organizations (Benoît Norris et al., 2020). This means that S-LCA focuses not only on the process that produces a product, but also on the social aspects related to all the associated processes, both upstream and downstream. The S-LCA Guidelines provide additional information and consensus-based guidance for each step of the S-LCA, expand the framework to cover new methodological and practical developments such as social organizational LCA (SO-LCA) and present the strengths and challenges to handle various concerns linked to the social sustainability of products and organizations, for instance to support measuring and assessing progress towards the UN Sustainable Development Goals (SDG).

The S-LCA methodology is in line with the LCA and the respective ISO Framework 14075:2024 (International Organization for Standardization (ISO), 2024), therefore it comprises the same four phases: (i). Goal and scope definition, (ii). Social Life Cycle Inventory Analysis (S-LCI), (iii). Social Life Cycle Impact Assessment (S-LCIA), and (iv) Interpretation. According to Benoît-Norris et al. (2020), these four phases are described in Figure 3 and are subsequently explained:

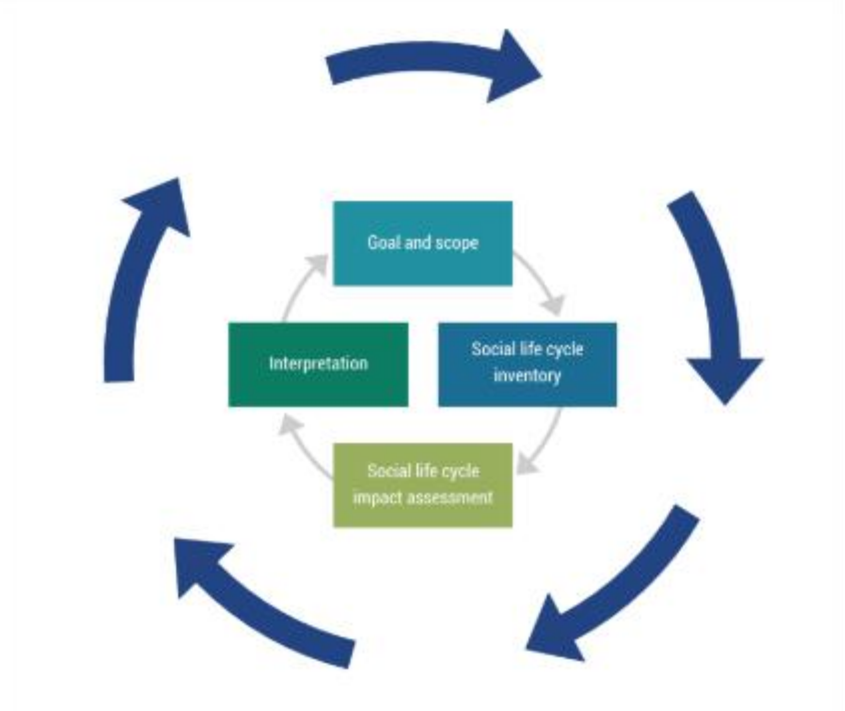


Figure 3. The four iterative phases of S-LCA (UNEP, 2020).

2.3.1 Goal and scope

This first phase aims to specify the purpose and the object of the study and determine the methodological framework. It is considered a key phase of a S-LCA, which has a significant impact on the conduction of the study and the results. In this phase the system boundaries, functional unit and the cutoff criteria should be described, as well as the methodological pathways regarding the selection of stakeholder groups and impact subcategories together with the impact assessment method.

S-LCA assesses social impacts in relation to various stakeholder groups, who will potentially be affected through the life cycle of products and services. The S-LCA Guidelines consider 6 stakeholder categories: Workers, Local community, Society, Value chain actors, Consumers and Children (Benoît Norris et al., 2020). However, depending on the system boundaries and sector specificities of the study, it is possible to add, exclude, differentiate, or define new stakeholder categories. For the present study, the foundational stakeholder categories considered are Workers, Local Community, Users, Value chain actors, Consumers and Society (Children are excluded), based on recommendations in the UNEP Guidelines (Benoît Norris et al., 2020) and the Handbook (Goedkoop et al., 2020).

These stakeholder categories are described as follows:

- **Workers:**
  These are individuals directly involved in the processes of the building's life cycle. This includes workers involved in raw material extraction, manufacturing of construction products, construction on-site, maintenance, repair, and demolition/deconstruction.
- **Local Communities:**
  This group refers to the people living in the geographical area directly affected by the activities throughout the building's life cycle (e.g., near manufacturing sites, construction sites, or the building's operational site).
- **Consumers (Users/Occupants):**
  These are the individuals who occupy or use the building during its operational phase.
- **Society (or Broader Society):**
  This category encompasses a wider range of social impacts that affect society at large, or specific vulnerable groups within society, not necessarily tied to a specific local community or direct use. This can also include impacts related to public policy, human rights, and broader economic development.
- **Value Chain Actors:**
  This category refers to other organizations or businesses within the building's supply and value chain. This includes suppliers of materials and services, distributors, and other partners.

The stakeholder groups are divided into subcategories which are assessed by means of inventory indicators. These indicators are classified though impact categories and subcategories, which may include one or more indicators and are directly related to a specific stakeholder group (See Figure 4):

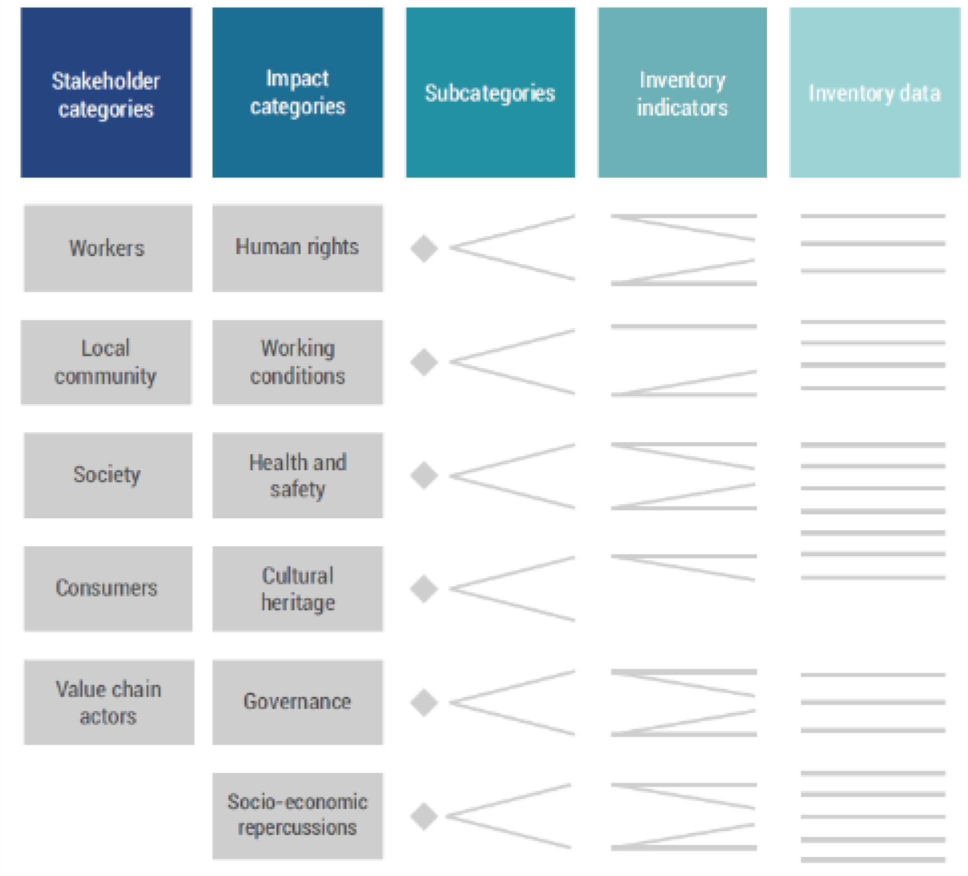


Figure 4. S-LCA assessment system (Benoît-Norris et al., 2020).

Functional unit

The functional unit is a crucial component of Life Cycle Assessment. In the case of E-LCA, defining the functional unit is typically straightforward. However, this task becomes more complex in S-LCA as it assesses social aspects that rely primarily on qualitative data and indicators (Arzoumanidis et al., 2020). Consequently, an S-LCA can be conducted without a defined functional unit, as demonstrated by (Azimi et al., 2020). This was further confirmed by Arzoumanidis et al. (2020), who reviewed this issue and found that approximately 25% of studies did not specify a functional unit. In the present study, the functional unit is aligned with the LCA and LCC studies. However, in contrast to LCA and LCC studies, impacts/effects are not expected to be quantitatively scaled to it. The final decision regarding this approach will be made during subsequent phases of the study, which are beyond the scope of the present deliverable.

2.3.2 Social Life Cycle Inventory (S-LCI): Impact categories and indicators selection

Impact categories and related indicators are the foundational components for the inventory building. In the inventory phase of a S-LCA, **impact categories** serve to define the broad areas of social concern relevant to the study's scope (e.g., "Health and Safety" or "Employment"). **Indicators**, which are specific, measurable variables (e.g., "Accidents" or "Jobs created"), are then essential for collecting and compiling the actual data within these defined impact categories. Therefore, both are critical: impact categories establish *what* social aspects are being examined, and indicators specify *how* the data for those aspects will be collected and organized within the inventory.

The selection of relevant impact categories and indicators is a crucial step for the inventory. The approach followed is based on established official documents and database, including UNEP/SETAC S-LCA Guidelines, Methodological Sheets and SHDB. These frameworks provide a solid foundation, while also offering the necessary flexibility to incorporate tailor-made indicators where specific project goals or unique social impacts necessitate a more bespoke measurement approach as stated in different parts of the documents:

“The sheets have been developed recognizing that data collection is the most labor-intensive activity when carrying out a Social LCA. Therefore, different indicators may be used depending on data availability and the goal and scope of the study. The sheets are meant to inspire S-LCA case studies based on the Guidelines rather than to represent a complete set of indicators that must be included and criteria that must be met.”

“It is foreseen and wanted, that the Methodological Sheets act as a living resource in the sense that that they evolve over time and that their content continues to be expanded as the field of S-LCA advances.”

“The choice of social inventory indicators will determine the data that ought to be collected. In S-LCA, indicators can be of qualitative, semiquantitative, or quantitative nature. They can also be company specific, site-specific, generic, primary, or secondary”.

Acknowledging the inherent flexibility articulated within the UNEP/SETAC S-LCA Guidelines and Methodological Sheets—which are presented as adaptable guidance rather than an exhaustive, prescriptive list of indicators, and are intended to evolve over time—they were adopted as the foundational framework. Building upon this, a strategy was implemented to include additional impact categories and indicators not explicitly detailed in the Methodological Sheets. This customization was deemed essential to precisely reflect the unique social dimensions pertinent to our project's specific context, as the generic indicators, while comprehensive, might not fully capture the nuanced social impacts relevant to our particular area of interest. This tailored approach ensures a more accurate and relevant assessment, consistent with the spirit of adaptability promoted by the S-LCA methodology itself.

Thus, the strategy adopted for indicators selection involved the following key steps:

- UNEP/SETAC S-LCA Guidelines: The foundational framework provided by the UNEP/SETAC guidelines was used to establish a solid methodological base.
- Social Hotspots Database (SHDB): The SHDB was consulted to identify potential social risks and opportunities relevant to pilot supply chains and operations.
- Tailor-Made Indicators: To capture the unique social impacts of our specific project, “tailor-made" indicators were defined that go beyond standard frameworks.
- CEN Standards: CEN (European Committee for Standardization) standards for construction, particularly through CEN/TC 350, address social aspects of sustainability in construction works. These standards provide a framework for assessing the social performance of buildings and civil engineering projects, alongside environmental and economic considerations.
- Literature Review: A thorough literature review was conducted to verify and validate the selected indicators, ensuring their relevance and appropriateness for the study's scope.

This multi-faceted strategy allowed us to create a highly relevant and detailed S-LCA, focusing on the social benefits and impacts most critical to our project and its stakeholders.

The following table presents the total indicators considered for the pilots under study and the source of each one of them:

Table 2. Comprehensive list of indicators selected and their source.

Impact Category	Indicator	Source of Indicator Definition / Concept
Health and Safety (accidents, exposure to hazardous substances or PM)	Accidents	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
	Exposure to hazardous substances	UNEP/SETAC S-LCA Guidelines; Methodological Sheets

Employment	Hours of Paid Employment	SHDB
	Jobs created or jobs lost	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
Labor Practices and Decent Work	Fair Salary	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
	Working Hours Compliance	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
	Social Security & Benefits Coverage	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
	Non-Discrimination	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
	Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
Contribution to Circular Economy and Resource Efficiency	Raw materials savings	Tailor-made (Direct link to Circular Economy concept)
Public health	Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
Climate Change Adaptation and Societal Resilience	Reduced Societal Vulnerability to Climate Change Impacts	Tailor-made (Emerging S-LCA area, linked to environmental impacts)
Knowledge & Innovation	Contribution to R&D and Knowledge Dissemination on Sustainable Concrete	Tailor-made (Reflects project-specific goals)
Economic growth/ Economic contribution	Factor tax payment	SHDB
	Revenues from material treatment / Volume of treated material	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
	Revenues from deconstruction/demolition activities	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
Human Capital Development	Skills Development and Job Enhancement in the Value Chain	UNEP/SETAC S-LCA Guidelines; Methodological Sheets
Innovation & Contribution to Sustainable Construction / Contribution to Industry Advancement and Sustainable Construction	Development and Commercialization of Sustainable Material Technologies	Tailor-made (Reflects project-specific innovation goals)
Contribution to Industry Advancement and Sustainable Construction	Development and Commercialization of	Tailor-made (Reflects project-specific innovation goals)

	Sustainable Construction Technologies	
Project execution speed	Project execution speed	Tailor-made (Reflects project-specific operational efficiency)
Affordability for users	Affordability for the first life cycle	UNEP/SETAC S-LCA Guidelines; LCC Frameworks
	Affordability for the second life cycle	UNEP/SETAC S-LCA Guidelines; LCC Frameworks
Adaptability	How well the building can be modified or adjusted to meet changing needs over time.	CEN, Tailor-made (Reflects specific building design features)
More sustainable Economic performance for public buildings	Life Cycle Cost Savings for Public Buildings	Tailor-made (Specific link to LCC for public sector)
Waste Diversion and Reduced Landfill Burden	Volume of waste avoided from landfill	Tailor-made (Direct link to Circular Economy concept, quantified by LCA)
	Alignment with CDW policy	Tailor-made (Reflects project-specific policy goals)
Socio-economic Performance/ Economic contribution	Total revenue (in currency) / Revenue from Waste Disposal / Total revenue (in currency) or volume of reused/recyclable materials sales	UNEP/SETAC S-LCA Guidelines; Methodological Sheets

For each pilot, a specific set of indicators was chosen from the abovementioned comprehensive list to match the distinct boundaries and involved stakeholders of that case. Social Life Cycle Assessment (s-LCA) is inherently an iterative process, and the final selection of indicators will be determined based on data availability during the assessment phase. As the project progresses, certain indicators may be added or removed to reflect the realities of data accessibility, stakeholder input, and contextual relevance.

2.3.3 Impact assessment approach

This phase aims at the determination and understanding of the potential social impacts of a system through its life cycle. The term “potential” is important as it reflects on the likely presence of the social impact, supported by a range of hypotheses and thus limitations. S-LCIA approaches are classified into two main groups:

- Reference Scale Assessment (“Type I” or RS S-LCIA) assesses the social performance or social risk
- Impact Pathway Assessment (“Type II” or IP S-LCIA) assess the consequential social impacts through characterizing the cause-effect chain.

Reference scale Assessment evaluates the social performance within a product system. Specifically, it assesses the social performance of organizational activities in the product system—such as the practices employed to manage social impacts—based on defined benchmarks of expected conduct, referred to as Performance Reference Points (PRPs). These assessments draw upon data, information, or expert judgment and yield results that focus primarily on the activities of companies within the product system. Typically, they offer an immediate evaluation (e.g., at the inventory indicator level), without further extrapolation of downstream effects. Consequently, reference scale approaches generally do not establish a direct connection between an activity and its potential long-term social impacts. Instead, they estimate the probable extent and relevance of such impacts based on the information available (Benoît Norris et al., 2020).

Impact pathway Assessment (S-LCIA) evaluates potential or actual social impacts by establishing causal or correlation/regression-based directional relationships between the activities of the product system or organizations and the resulting potential social impacts—a process referred to as characterization. This approach emphasizes the identification and analysis of the consequences of activities, potentially extending to long-term implications along a defined impact pathway. It aligns more closely with Environmental Life Cycle Assessment (E-LCA), wherein inputs (such as inventory data or collected metrics, e.g., CO_2 emissions) are connected to environmental issues (midpoint impacts, such as global warming), and subsequently to endpoint impacts, for example, effects on human health (Benoît Norris et al., 2020).

For the S-LCA studies, the Reference Scale Assessment (RS S-LCIA) will be applied. For the comparative analysis in this study, the baseline scenario representing current or conventional practices will serve as a key Performance Reference Point against which the pilot scenarios will be evaluated.

2.3.4 Interpretation of results

It consists of reviewing all the previous phases and conducting a thorough analysis of S-LCA results and covers among others the materiality assessment and the final conclusions, limitations, and recommendations on actions to take at the production site or regarding the supply chain. A materiality assessment is a process to select the most significant social issues regarding their impact on stakeholders or relevance to the business.

2.4 Methodological tools

2.4.1 LCA modelling software and databases

OpenLCA

OpenLCA is a free sustainability assessment software developed by GreenDelta (GreenDelta, 2023). It will be among the available options to be used for performing the LCA study that will be conducted and reported in the following deliverable D5.2, along with the Ecoinvent database (Wernet et al., 2016).

SimaPro

SimaPro is a commercially available LCA tool developed by PRé Sustainability (PRé Sustainability, 2023), and it will be used along with the ecoinvent and SHDB database for conducting the E-LCA and S-LCA of the 5 Circ-Boost pilots.

2.4.2 Databases

ecoinvent

The ecoinvent database is a commercially available database for simulating real-life processes and product systems in a LCA context (Wernet et al., 2016). It includes over 18000 datasets able to model a diverse set of socioeconomic processes that range from everyday human activities to more complex agricultural and industrial productive systems. The ecoinvent is used in the OpenLCA software for the provision of the datasets necessary for conducting the LCA studies.

Social Hotspot Database (SHDB)

The Social Hotspots Database (SHDB) is a tool that provides a comprehensive approach to assessing social issues in supply chains (Benoît Norris, 2022). It was launched in 2009 to provide transparent access to information about working conditions and other social impacts in global supply chains and through a risk mapping tool, and a license in combination with LCA software (such as OpenLCA and SimaPro), provides full access to information on social risks in 244 countries and territories and 57 sectors to supply chain managers, academics, policy-makers, development organizations, investors etc., through visualization and analysis tools. The SHDB is used in the SimaPro and OpenLCA software and will be extensively used for indicators screening in the following months.

2.5 Data Confidentiality

In the context of the Circ-Boost project, a structured procedure was established to safeguard the confidentiality of data throughout the implementation of activities related to the Life Cycle Assessment (LCA). This procedure included the following key elements:

Initial discussions were held via online meetings to define the scope of the LCA and communicate the relevant data needs to partners, particularly the pilots. Where concerns regarding confidentiality arose, further exchanges were initiated to clarify the type of data required and its intended use solely for the purpose of implementing the project and for the proper execution of the Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA), as well as for the preparation of the relevant deliverables.

Confidentiality obligations were formalized through Non-Disclosure Agreements (NDAs) signed between the parties involved, prior to any exchange of potentially sensitive information. Each data provider was asked to explicitly indicate which categories of data were considered “Confidential” or “Non-Confidential,” to ensure transparency and appropriate handling of information from the outset.

The public nature of the LCA-related deliverables was explicitly stated in the NDAs, to avoid ambiguity. It was emphasized that all data—whether confidential or not—would be used exclusively for the purposes defined within the project scope and in accordance with the contractual obligations of the parties.

It was clearly established that access to Confidential Information would be strictly limited to project personnel directly involved in the relevant tasks, on a strict need-to-know basis. Where confidential data was required for the preparation of public deliverables, assurances were provided to data providers that results would be presented respecting relevant applicable NDA clauses. This commitment aimed to prevent the disclosure of sensitive information and to ensure full compliance with the project’s dissemination obligations. All confidentiality measures taken were aligned with the terms of the Consortium Agreement, respecting its provisions and reflecting the restrictions or conditions outlined by the partners in the Background section of the Agreement. This procedure reflects the project’s commitment to responsible data handling and the protection of confidential information throughout its duration.

3. Goal and scope definition per pilot case

3.1 Pilot 1 (UPC): DfD/R modular prototype building (Barcelona, Spain)

3.1.1 Technology overview

Currently, many concrete buildings around the world are demolished to make way for new constructions, with the goal to maximize the construction speed, ignoring future deconstruction, transformation capacity and reuse even though the elements of these buildings often have the potential to last much longer. Despite the existence of the technical know-how on how to build durable buildings with long service lives, there are numerous cases of 30-40 year old buildings being demolished—often due to functional obsolescence or lack of adaptability—indicating poor exploitation of the concrete's durability potential (Eberhardt et al., 2019). With cement—the main ingredient in concrete—responsible for around 7-8% of global human-made CO_2 emissions, there is an urgent need to rethink how we design and manage concrete structures not just during construction, but across their entire life cycle.

Concrete buildings are typically constructed using two primary methods: **cast-in-situ** and **precast**. Cast-in-situ construction involves mixing, pouring, and curing concrete directly on-site within formwork. This method offers significant design flexibility and is well-suited for complex architectural forms, as it allows the structure to be shaped and adapted in real time during construction. Precast construction, on the other hand, involves manufacturing concrete elements in controlled factory environments and transporting them to the site. This process ensures high quality, consistency, and reduced material waste, while significantly shortening on-site construction time and minimizing labor—making it ideal for projects with tight schedules. However, both methods lack **reusability** potential, as even in precast construction, the concrete elements are not designed for disassembly and do not bear the necessary connectors that would enable reusability. As a result, these methods contribute to the prevailing linear "cradle-to-grave" model, where buildings are treated as disposable, perpetuating a linear economy.

In response to growing political and industrial interest in sustainable development, the construction sector is increasingly recognized as having high potential for adopting circular economy (CE) models. These models promote a shift from the traditional linear approach— "take, make, use, dispose"—to a circular one focused on reduce, reuse, and recycle. Central to this transition is the concept of design for disassembly and reuse **(DfD/R)**, which encourages the creation of buildings that can be adapted, deconstructed, and repurposed over time. This strategy not only extends the service life of building materials and components but can potentially reduce construction and demolition waste, resource extraction and CO_2 emissions by maximizing the use of existing materials.

In this context, P1 (Universitat Politècnica de Catalunya) proposes an innovative strategy for sustainable and durable buildings by optimizing the structural design for "deconstructable" prefabricated concrete elements, inspired by the work of TESIS srl (a member of the Circ-Boost consortium) and the DeConStRACtion project (Pepe et al., 2023). The solution proposed is a prototype structure which is meant to be demonstrated at the ACCIONA Demo-Park in Madrid and will be designed and modelled in BIM, integrating sustainability and circularity indicators. The structure is planned as a single-story structure with precast walls/façade modular panels and an optimized semi-precast deconstructable one-way slab system. In accordance with the experience of the DeConStRACtion approach, the structural members and panels will be realized through precast elements.

The key novelty compared to traditional precast elements, is the creation of a *modular, deconstructable concrete/connector* combination that can be used multiple times, thereby increasing reusability and enhancing sustainability. The project involves assembling precisely designed prefabricated panels using a prestressing system with the use of an innovative memory®-steel technique (See Figure 5). The target is highly modular buildings that support rapid construction and flexible reconfiguration of interior spaces.

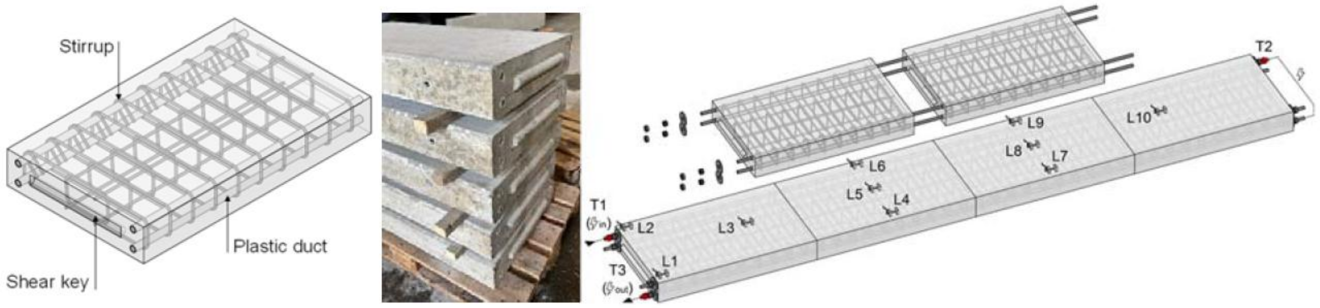


Figure 5. DfD/R precast concrete panel system with a prestressing technique previously developed by TESIS.

Following collaboration with the Italian design firm TESIS, the structural design of the deconstructable house was finalized as a single-story building with dimensions of 4.2 meters in length, 3.6 meters in width, and 3.4 meters in height (See Figure 6). The structure comprises 56 precast concrete panels. The gross floor area (GFA) is calculated as: GFA = L × W = 4.2 m × 3.6 m = 15.12 m^2.

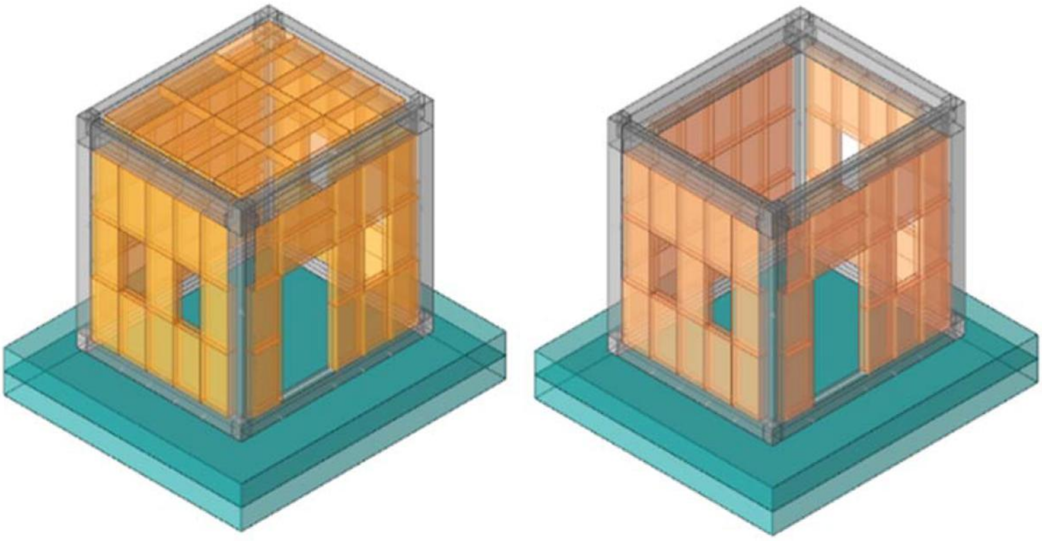


Figure 6. Layout of the prototype DfD/R structure.

To minimize transportation-related emissions and logistical complexity, the precast producer has been selected near Madrid, in close proximity to the ACCIONA Demo-Park construction site. The single-story modular structure will be assembled on-site, then disassembled and reassembled at the same location. During reassembly, the configuration of the precast panels will be altered—for instance, roof panels will be repositioned to serve as side walls, and vice versa—demonstrating the flexibility and adaptability of the design.

The reference scenario, against which the Pilot 1 proposed solution will be compared, has been chosen to be a cast-in-situ reinforced concrete structure with the same dimensions as the DfD/R structure. Although a building of such small size wouldn't typically be made from concrete, a concrete cast-in-situ is considered here as a prototype to simulate what could be replicated on a larger scale, aiming to be a system for entire buildings. To enable an equal comparison, the design company TESIS has designed models both for the DfD/R modular house and the reference cast-in-situ structure with the assumption that they both use concrete of the same type, quality and durability. Therefore, a commercial mix of natural aggregate concrete (NAC) is considered for both structures.

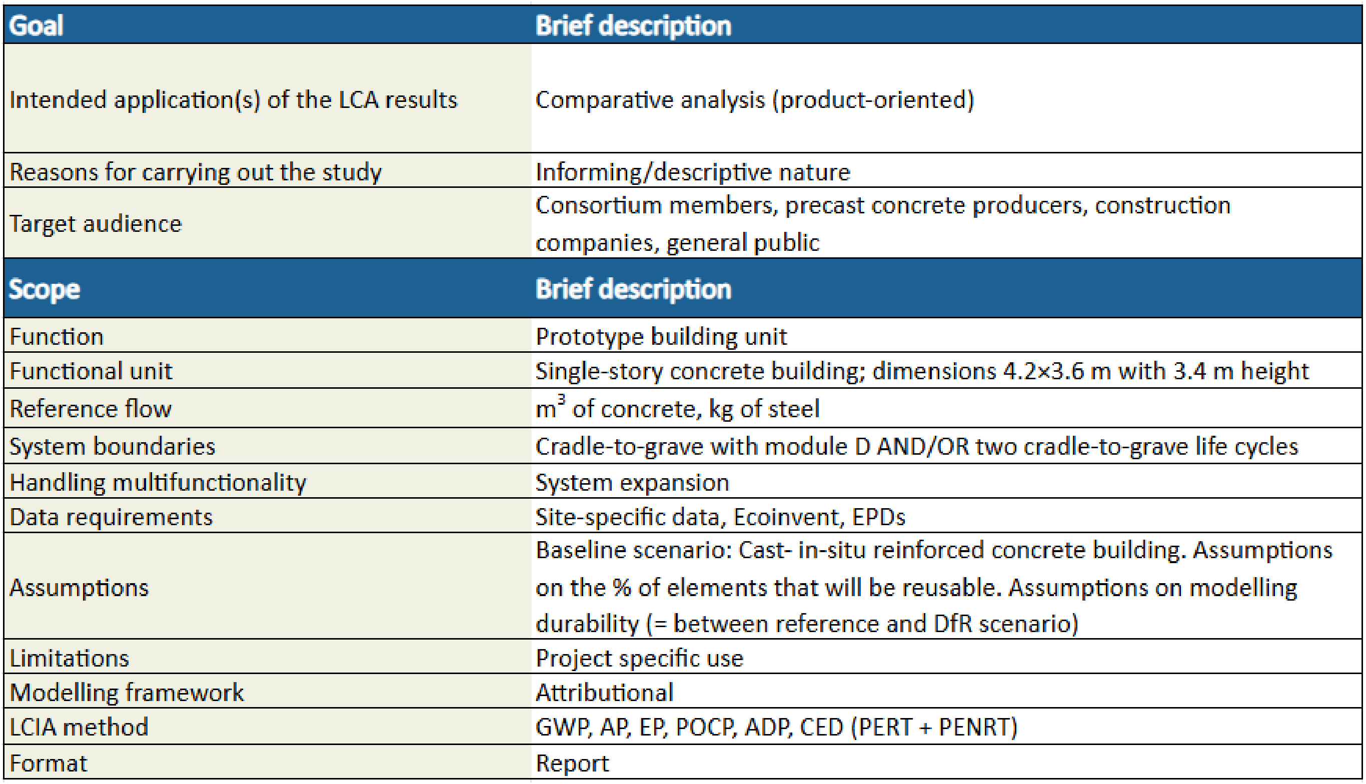
3.1.2 Life Cycle Assessment (LCA)

3.1.2.1 Goal and scope definition

The purpose of the study is to model and assess the environmental, economic and social impact of the Pilot 1 solution for the construction of 1 single-story modular deconstructable concrete structure, utilizing regular commercial natural aggregate concrete (NAC). The pilot will be assessed as a standalone technology through hotspot analysis, evaluating the impacts of constructing a modular and reusable DfD/R precast concrete structure. In addition, the study aims to provide insights into how the environmental, economic and social impacts compare to traditional construction of cast-in-situ building of the same dimensions, concrete type and durability. For this purpose, the goal and scope for both the current practice baseline and the solution introduced by Pilot 1 must be defined.

An initial meeting was held with the pilot team to assess the progress and key features of the implemented technology. Following a brief introduction to the Life Cycle Assessment (LCA) methodology and the definition of the study's goal and scope, a structured template was provided to the pilot leader for completion. A follow-up meeting was then conducted to review the filled-in template and to consolidate the core elements of the goal and scope definition. The finalized template is presented in the following table:

Table 3. Goal & Scope Template of Pilot 1 (UPC).



Goal	Brief description
Intended application(s) of the LCA results	Comparative analysis (product-oriented)
Reasons for carrying out the study	Informing/descriptive nature
Target audience	Consortium members, precast concrete producers, construction companies, general public
Scope	**Brief description**
Function	Prototype building unit
Functional unit	Single-story concrete building; dimensions 4.2×3.6 m with 3.4 m height
Reference flow	m^3 of concrete, kg of steel
System boundaries	Cradle-to-grave with module D AND/OR two cradle-to-grave life cycles
Handling multifunctionality	System expansion
Data requirements	Site-specific data, Ecoinvent, EPDs
Assumptions	Baseline scenario: Cast- in-situ reinforced concrete building. Assumptions on the % of elements that will be reusable. Assumptions on modelling durability (= between reference and DfR scenario)
Limitations	Project specific use
Modelling framework	Attributional
LCIA method	GWP, AP, EP, POCP, ADP, CED (PERT + PENRT)
Format	Report

Goal

Reasons for carrying out the study

The main objective of this analysis is to evaluate the performance of the proposed building structure from a life cycle perspective through a comprehensive sustainability assessment. This includes all three pillars of sustainability—environmental, economic, and social. The study aims to identify key impact hotspots of the P1 solution, across the life cycle stages using Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA). The purpose is primarily informative and descriptive: to highlight the most critical stages and processes over time, support decision-making, and guide improvements in future implementations.

Intended audiences

According to the declared applications of the study, the LCA study spanning across D5.1 and D5.2 is intended to be addressed to following audiences:

- The technology provider (ACC, SEN, TESIS)
- The local partner (UPC)
- The European Union, as the main funding institution of the Circ-Boost project
- The European Commission, as the main reviewing mechanism of the Circ-Boost project
- Circ-Boost Consortium members
- Civil engineers
- Designers
- Researchers
- Ready-mix and precast concrete producers
- Construction and demolition companies (e.g. CDE)
- Contractors
- The Spanish government and Barcelona municipality
- Policy makers
- Standardization bodies
- Local community
- General public

Comparative assertions

The LCA study that is initiated in D5.1 and will be concluded in D5.2, is partially intended to support comparative claims meant for public disclosure via the conduction firstly of an independent LCA and afterwards a comparative LCA against the baseline scenario which is the cast-in-situ reference structure in the geographical context of Spain. This intention does not stem from commercial competitive purposes, but purely from a scientific research point of view. Therefore, no external review (besides the review procedure prescribed by the project's Grant/Consortium Agreements) will be necessary for the Deliverables 5.1 and 5.2, according to ISO 14040:2006 and ISO 14044:2006.

Scope

Functional Unit

A functional unit in LCA is a quantified description of the performance of a product system, serving as a reference point for all inputs and outputs in the assessment. It ensures that comparisons between different products or systems are meaningful and consistent.

The functional unit of the analysis is a 1 single-story concrete building of gross floor area (GFA) of 15.12m^2 over a reference study period of 100 years in Madrid for both the baseline and the Circ-Boost solution, since they have the same dimensions.

While the functional unit is essential for quantifying environmental impacts in Life Cycle Assessment (LCA), it may not fully capture the comparability between systems that follow different life cycle strategies. According to EN 15978 (CEN, 2011), it is necessary to also define the functional equivalent to ensure transparent, fair, and meaningful comparisons in building-level LCA studies. The functional equivalent complements the functional unit by ensuring that the systems being compared serve the same purpose, operate under the same conditions, and deliver equivalent performance over the reference study period. This dual definition—functional unit for quantification and functional equivalent for comparability—is particularly important when comparing alternative building systems that differ in design strategies, such as end-of-life treatment or reuse potential, while still fulfilling the same overall function.

Thus, in accordance with EN 15978, the functional equivalent in this study is defined as, a structural building system with identical geometric dimensions (length, width, and height), constructed using the same type of concrete and designed to deliver equivalent structural performance and durability. Both systems are located in Madrid and assessed over a 100-year reference study period. The buildings are conceptual in nature and are not assigned specific occupancy patterns or thermal comfort requirements.

The reference flow that serves the functional unit is represented by the material inflows of concrete and steel since concrete is usually coupled with reinforcement steel to enhance its performance to tension forces. Steel reinforcement is used in both the traditional in-situ construction as well as the precast reusable panels. Thus, the reference flows of m^3 of concrete and kg of steel are considered.

The comparison includes two construction approaches:

- A conventional cast-in-situ system that is constructed, used for 50 years, demolished, constructed a-new, and used for an additional 50 years before final demolition.
- A Design for Disassembly and Reuse (DfD/R) system that is assembled, used for 50 years, disassembled, reassembled, and used for another 50 years before final disassembly.

System boundaries

The methodology adopted in this study follows the process-based LCA approach for both the baseline (cast-in-situ) and the DfD/R building alternative. Specifically, it adheres to the modular framework defined in EN15978, ensuring a consistent and transparent assessment of environmental impacts across all relevant life cycle stages. This framework is illustrated in Table 4 and includes stages A1–A5 (product and construction), C1–C3 (end-of-life), and D (benefits and loads beyond the system boundary). The final stage of disposal (C4) is excluded from both the reference case and DfD/R solution scenarios as it is assumed that all concrete waste is recycled and leveraged from a subsequent product system.

Moreover, as shown in Table 4, modules B1-B7, representing stages related to the use, maintenance, repair and refurbishment of the building, have not been included in this analysis as this study is focused on the impacts of the building materials throughout their lifecycle, excluding impacts from the building's operational stage. Since, A1-A3, A4-A5, C1-C3 and D modules are included in this study, this represents a "cradle-to-gate with options" system boundaries case as per EN 15978 (CEN, 2011).

Table 4. Stages included in the LCA analysis of Pilot 1 reference and solution based on EN15978.

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction / inst. process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse/recovery/recycling
x	x	x	x	x	-	-	-	-	-	-	-	x	x	x	-	x

To accurately reflect the construction, deconstruction and subsequent construction of the DfD/R (Design for Disassembly and Reuse) solution, its assessment is modeled through two consecutive "cradle-to-gate with options" lifecycles. In this scenario, the modular building is initially assembled, used for 50 years, and then disassembled. The disassembled components are subsequently reassembled into an identical structure, which undergoes another 50-year use phase before final disassembly—completing two full cycles.

For a fair comparison, the baseline in-situ structure is also assigned a design service life of 50 years. However, due to its non-reusable nature, and in order to match the total service life of 100 years of the

DfD/R house, it is assumed to be constructed and demolished after 50 years, followed by the construction of a new, identical structure to serve for another 50 years. This comparative lifecycle approach for the baseline and the DfD/R building is more effectively illustrated in Figure 7 and Figure 8 respectively and further elaborated in the following sub-sections for the baseline and Circ-Boost solution.

Baseline scenario

For the baseline scenario, the dual-lifecycle approach is illustrated in Figure 7. Specifically, modules A1_1 to C3_1 fall within the boundaries of the first lifecycle, representing the construction and end-of-life stages of the first cast-in-situ building. The second construction phase is captured by modules A1_2 to C3_2, which define the boundaries of the second lifecycle representing the construction and end-of-life of a new cast-in-situ building.

Module D lies outside the system boundaries, as it accounts for the environmental benefits and burdens associated with the use of by-products of this product system by subsequent systems. In this case, each lifecycle is followed by its own Module D, where the benefits of substituting primary materials and loads from further processing & transport are reported. This is primarily due to the path considered for the recycled materials after the demolition of both the first and second buildings and the assumptions made regarding their recycling. End-of-life processes are modeled in accordance with EN 15804 and EN 16757 (CEN, 2019, 2022), as explained earlier.

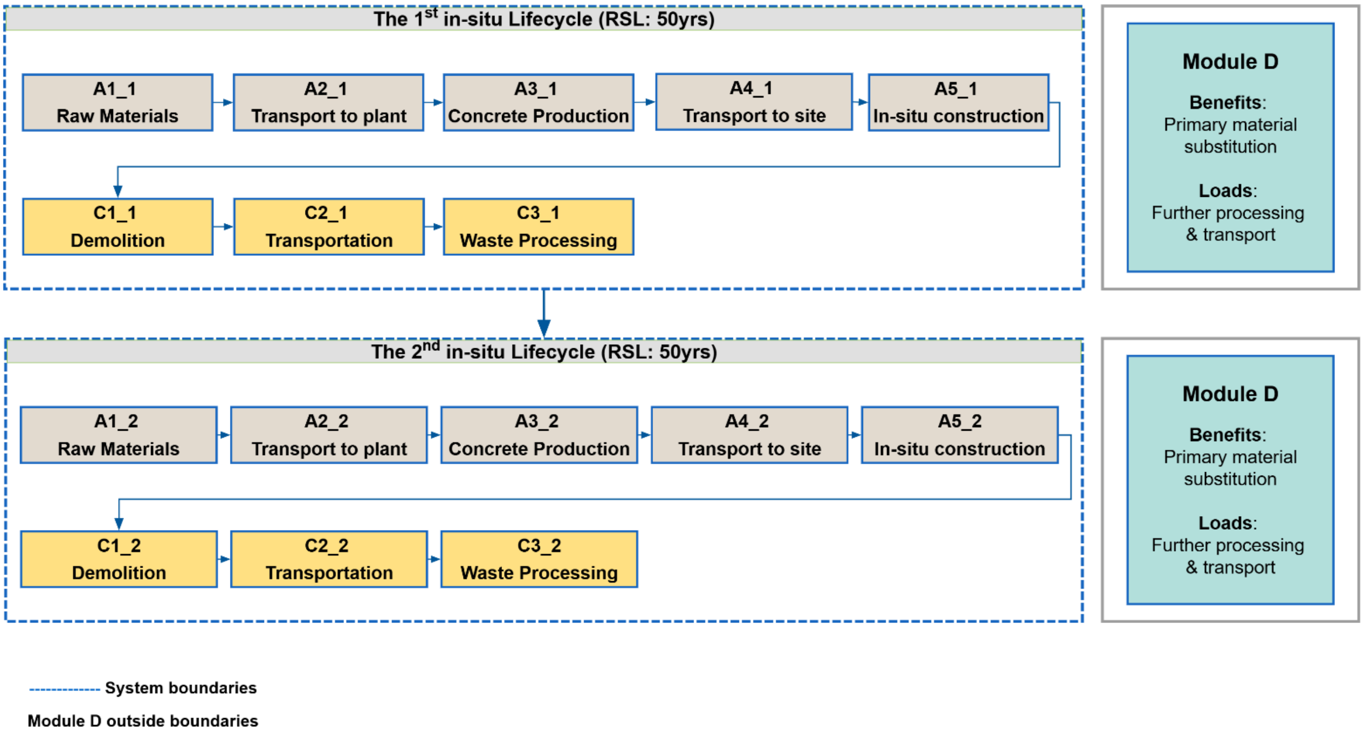


Figure 7. System boundaries of the dual lifecycle approach applied to the Pilot 1 baseline in-situ building.

The number following the underscore (e.g., "_1") indicates the number of life cycle. For instance, "_1" refers to the first life cycle, while "_2" would refer to the second. The processes included in each module LCA analysis of P1 for the reference cast-in-situ are briefly explained below. The following breakdown is identical for both lifecycles depicted in Figure 7.

- **Modules A1 – A3**: These modules include the extraction of raw materials (cement, NA, water, plasticizer, steel), transportation to concrete plant (A2) and production of all building materials (concrete batching in A3), until the gate of the factory.
- **Modules A4 – A5**: These stages refer to the transportation of the concrete mix and reinforcement to the construction site (A4) and the use of equipment/machinery for the construction of the building (A5). The preparation of the terrain for the construction of the building, the installation of auxiliary infrastructures and the construction of access to the construction site are not considered.
- **Modules C1 – C3**: These modules include all relevant data related to the end of life of the building and its materials. This includes the use of equipment and machinery for the demolition of the building (C1), transportation of demolition waste to the recycling plant (C2) and sorting, crushing and processing of materials (C3). The final stage of disposal (C4) is excluded from the reference case scenario of Pilot 1 as it is assumed that all concrete waste is recycled and leveraged from a subsequent product system.
- **Module D**: This module allocates net benefits and loads from the reuse, recycling and recovery of materials in the next product system. In this case, the benefits falling under primary material substitution include avoiding the production of natural aggregate by replacing it with recycled aggregate and avoiding pig iron production by using scrap steel. Additionally, the loads credited in Module D stem from two main activities: the additional sieving of recycled aggregate for use in fresh concrete, and the transportation of scrap steel to a steel production facility.

This above breakdown is identical for both lifecycles. Since the structure will be demolished and rebuilt on site, it is assumed that no transportation between the first and the second cycle is needed.

Circ-boost solution

Similarly, for the Design for Disassembly and Reuse (DfD/R) solution proposed by P1, the dual-lifecycle approach is illustrated in Figure 8. Modules A1_1 to C3_1 fall within the boundaries of the first lifecycle, representing the initial assembly and subsequent disassembly of the DfD/R house after 50 years. However, due to the reusability of the structural components, modules C2_1 to C3_1 (associated with the transportation and processing of demolition waste) are excluded for the **reusable** materials, because these are reintegrated into the second assembly.

Consequently, stages A1_2 to A4_2, which typically account for raw material extraction, transportation, production of new building elements and their transportation to the building site, are also excluded from the second lifecycle boundaries, reflecting the reuse of the concrete panels. By modelling in a dual-lifecycle approach and leaving out stages C2_1 to C3_1 in the first lifecycle and A1_2 to A4_2 in the second lifecycle, the environmental benefits from avoiding these stages, are counted directly within the system boundaries. This means the savings are included in the main lifecycle results, rather than being treated as future or external benefits.

Nevertheless, as previously discussed, a portion of the materials will not be reusable and will follow the conventional waste processing and disposal route. Accordingly, new materials must be introduced in the second lifecycle to compensate for the loss of these damaged components. This is represented by modules C2_1 and C3_1 for the non-reusable materials, and A1_2, A2_2, A3_2 and A4_2 for the production and delivery of the replacement materials, all highlighted in green in the diagram.

Once more, module D lies outside the system boundaries, as it accounts for the environmental benefits and burdens associated with the use of by-products from this product system by subsequent systems. In the DfD/R case, each lifecycle is followed by its own Module D. Similarly, since the structure will be demolished and rebuilt on site, it is assumed that no transportation between the first and the second cycle is needed.

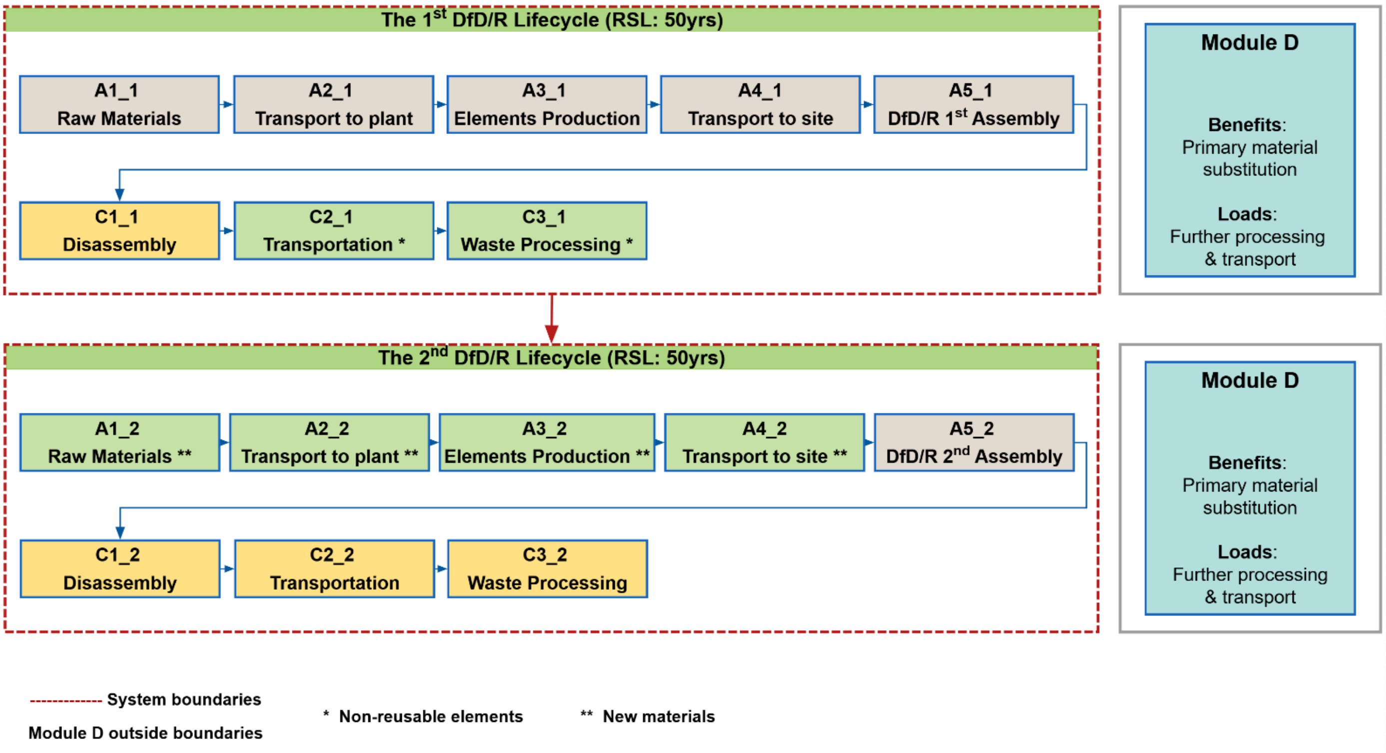


Figure 8. System boundaries of the dual lifecycle approach applied to the Pilot 1 DfD/R solution.

The processes included in each module of the LCA analysis of Pilot 1 for DfD/R are briefly explained below. The number following the underscore (e.g., "_1") indicates the number of life cycle. For instance, "_1" refers to the first life cycle, while "_2" would refer to the second.

- **Modules A1_1 – A3_1**: These modules include the raw material supply (cement, NA, water, plasticizer, steel), their transportation to the precast producer (A2_1) and production of all building elements (panels, slab, roof in A3_1), until the gate of the factory.
- **Modules A4_1 – A5_1**: These stages refer to the transportation of the DfD/R panels and active reinforcement to the construction site (A4_1) and the use of equipment/machinery for the construction of the building (A5_1). The preparation of the terrain for the construction of the building, the installation of auxiliary infrastructures and the construction of access to the construction site are not considered.
- **Modules C1_1 – C3_1**: These modules include all data relevant to the end of life of the building and its materials. These refer to the use of equipment and machinery for the deconstruction of the walls and roof (C1_1), transportation of damaged DfD/R panels and non-reusable concrete foundations to the recycling plant (C2_1) and sorting, crushing and processing of materials (C3_1). Stages C2_1 and C3_1 don’t apply to the reusable element, or those that are in a condition to be reused. Lastly, the final stage of disposal (C4) is excluded from the DfD/R scenario as it is assumed that all concrete waste is recycled and leveraged from a subsequent product system.
- **Module D_1**: This module allocates net benefits and loads from the reuse, recycling and recovery of materials in the next product system. In this case, the benefits include avoided natural aggregate production and avoided pig iron production while the loads stem from two main activities: the sieving of recycled aggregate for use in fresh concrete, and the transportation of scrap steel and unusable active reinforcement to a steel plant.

Subsequently, in the second lifecycle of the DfD/R building the following modules take place:

- **Modules A1_2 – A3_2**: These modules include the raw material supply (cement, NA, water, plasticizer, steel), their transportation to the precast producer (A2_2) and production of the new precast elements that substitute the destroyed elements (A3_2), until the gate of the factory. These stages apply mainly to the fraction of newly manufactured elements that substitute the unusable DfD/R panels and active reinforcement. These modules don't apply to reusable elements.
- **Modules A4_2 – A5_2**: These stages refer to the transportation of the newly manufactured DfD/R panels and active reinforcement to the construction site (A4_2) and the use of equipment/machinery for the 2nd assembly of the DfD/R building (A5_2). The A4_2 doesn't apply to the fraction of reusable elements. The preparation of the terrain for the construction of the building, the installation of auxiliary infrastructures and the construction of access to the construction site are not considered.
- **Modules C1_2 – C3_2**: These modules include all relevant data, ranging from the use of equipment and machinery for the 2nd disassembly of the DfD/R building (C1_2), transportation of all materials to the recycling plant (C2_2) and waste processing of all materials (C3_2).
- **Module D_2**: The benefits include avoided natural aggregate production and avoided pig iron production and the loads credited in Module D stem from two main activities: the sieving of recycled aggregate for use in fresh concrete, and the transportation of scrap steel and active reinforcement to a steel plant.

3.1.2.2 Multifunctionality

In Life Cycle Assessment (LCA), multifunctionality arises when a process or product system delivers more than one function or output that cannot be separated without applying an allocation procedure. This typically occurs in systems that produce co-products or serve multiple purposes simultaneously, requiring a methodological approach to distribute environmental impacts fairly among the outputs. In the context of this study, both the reference and DfD/R buildings are single-function products. Additionally, neither natural aggregates (NA) nor steel input flows are co-products of another process. Therefore, no multifunctionality is expected on the input side, and no allocation is necessary for their environmental impacts.

At the end-of-life stage, the waste generated from demolition or deconstruction follows the waste processing path (Module C3) for reuse as recycled aggregates (RA) in a subsequent system. This is a single waste stream, and as such, this scenario does not constitute multifunctionality, and allocation is again not required on the output side.

This study applies the Polluter Pays Principle (PPP), as outlined in EN 15804 (CEN, 2019), which assigns the environmental impacts of waste treatment to the system that generates the waste. As such, all impacts from demolition waste processing (e.g., crushing, sorting) are attributed to the original building system and modeled in Module C3.

In contrast, Module D captures the environmental benefits of using recycled materials by crediting the system for displacing primary materials (e.g., aggregates, steel) in future applications. To account for these avoided burdens, the study uses system expansion, in accordance with EN 15804 and EN 16757 (CEN, 2019, 2022), allowing the inclusion of benefits from material recovery beyond the system boundary. Additionally, loads from further processing of the materials to be deemed appropriate for reuse as well as transportation loads are also attributed to module D.

3.1.2.3 Assumptions and limitations

- Firstly, the same type, quality, and durability of concrete—namely, natural aggregate concrete (NAC)—is considered for both structures.
- For both the DfD/R and the reference building systems, it is assumed that materials recovered at the end of the first 50-year lifecycle are not reused as input materials in the second lifecycle. Instead, they are processed for use in external product systems beyond the scope of this study.
- It is assumed that not all components can be reused due to potential damage such as reinforcement corrosion, concrete spalling, or crushing during service life. The exact proportion of reusable panels—e.g., two-thirds out of 56 elements—will be determined through testing. Through parametric analysis, the environmental benefits from reuse may be scaled accordingly, rather than assuming full (100%) recovery.
- The same principle applies to structural loads: Since the objective is to replicate the original structure, some damaged or non-reusable elements must be newly produced. This results in additional environmental loads associated with the manufacturing of replacement panels which are declared in modules A1_2, A2_2, A3_2 and A4_2. A parametric analysis for the loads may be applied based on the results of the reuse assessment.
- At the end of the second life cycle of both the reference and DfD/R buildings, it is assumed that all materials are fully recycled, with none sent to landfill—thus contributing environmental benefits beyond the system boundary, as captured in Module D. In Stage C3, concrete and steel are processed into secondary materials that can substitute virgin resources. Recycled concrete is typically divided into 50% coarse and 50% fine aggregates. The coarse fraction, suitable for use in road subbases, drainage systems, and even concrete production (up to 20% in structural and 100% in non-structural applications), requires additional processing such as sieving and screening. These processing impacts are accounted for alongside the substitution benefits in Module D. In contrast, the fine fraction, commonly used for backfilling in road construction, requires no further treatment, and only its substitution benefits are reported. This approach aligns with EN 16757, which includes crushing, recycling, and stockpiling within Stage C3 as part of the producer's system.
- In the DfD/R solution, the foundation is considered the only non-reusable element. As a result, the main difference between the two lifecycles lies in the amount of concrete recycled and credited in Module D. In the first lifecycle, only the foundation and any damaged panels are recycled. In the second lifecycle, the entire house is dismantled and recycled, leading to a significantly higher amount of concrete being recovered and accounted for in Module D.
- Scrap will be accounted for, as in the reference cast-in-situ scenario, however it is necessary to determine the recycled content percentage of the steel used. In the DfD/R scenario, after the second lifecycle, a significant amount of high-strength steel bars is expected to be available for recycling, contributing to the overall material recovery and reducing the demand for primary steel production.
- Although the precast producer that produces the concrete mix and panels will be close to the Demo-Park, in the analysis some transport distances will be assumed.
- Waste generated during stages A3 (manufacturing) and A5 (construction) is negligible—estimated at around 5%—and therefore excluded from the system boundaries.

3.1.2.4 Cut-off criteria

A 1% cut-off criterion will be applied for excluding processes the impact of which contributes less than 1% of the total impact per selected impact category.

3.1.3 Life Cycle Costing (LCC)

During Task 5.1, the goal and scope of the Life Cycle Costing (LCC) assessment for Pilot 1 were clearly defined, ensuring full alignment with the framework conditions of the environmental Life Cycle Assessment (LCA). This alignment includes the use of consistent system boundaries and a shared functional unit, thereby guaranteeing coherence between environmental and economic evaluations.

The system boundaries for the LCC of Pilot 1 encompass modules A1-A3, A4-A5, C1-C3, and D, following a dual lifecycle approach that mirrors the structure of the environmental LCA framework. Similarly, C4 (Disposal in Landfill) is excluded.

Data collection for Pilot 1 is scheduled to begin in the coming months and will draw from both primary and secondary sources. The pilot will provide average cost estimates for key life cycle elements, including raw materials, transportation distances, construction and deconstruction activities, and replacement parts. Where pilot-specific data is not yet available, secondary sources—such as literature and price databases—will be used to fill gaps. All cost-related inputs will be gathered using a standardized LCC inventory template developed within the project.

Finally, the Life Cycle Costing analysis phase will commence after Month 30, with the launch of Task 5.3, and will continue until Month 47. This phase will incorporate both fixed and variable costs provided by the involved partners, as well as external costs—indirect social costs typically associated with environmental degradation and emissions. These externalities will be quantified and included in the final deliverable, D5.2.

3.1.4 Social Life Cycle Assessment (S-LCA)

The Social Life Cycle Assessment of the current study relies on the general framework described in section 2.3.1 which is adjusted to the pilot case's particular objectives. The following section presents the methodology's application to define the goal and scope for Pilot 1.

3.1.4.1 Goal and Scope

The goal of the study

This Social Life Cycle Assessment (S-LCA) study investigates the potential social benefits and impacts associated with applying the Design for Deconstruction and Reuse (DfD/R) modular construction method within the Spanish construction sector. The analysis compares a pilot scenario employing this innovative construction method against a baseline scenario based on conventional in-situ practices.

Focusing on the current product system and the geographic context of Barcelona, Spain, the study aims to uncover both positive and negative social implications for key stakeholder groups, including construction workers, material suppliers, local communities, and policymakers.

The results will be of particular interest to public authorities, construction and material production companies, recycling firms, sustainability consultants, circular economy practitioners, and academic researchers. Insights from this assessment will support future policy development, inform circular procurement strategies, and guide the design of socially responsible construction practices in Spain and beyond.

Functional unit

The functional unit for the specific S-LCA is consistent with the one used in the LCA and LCC studies. However, unlike LCA and LCC, the social impacts and effects in the S-LCA are not currently expected to be quantitatively scaled to the functional unit. Nevertheless, this decision will be addressed in the later stages of the Social LCA study. As outlined in the LCA goal and scope chapter of Pilot 1, chapter 3.1.2.1, the functional unit is defined as one single-story concrete building with a gross floor area (GFA) of 15.12 m^2, assessed over a reference study period of 100 years in Madrid, applicable to both the baseline and the Circ-Boost solution, as they share identical dimensions.

System boundaries

The system boundaries for this Social Life Cycle Assessment (S-LCA) are aligned with those defined in the LCA. To ensure a harmonized and transparent categorization of social impacts and enhance comparability, the boundaries follow the modular structure of EN 15804 and EN 15978 (CEN, 2011, 2019), encompassing all relevant activities within each examined stage.

These include raw material extraction (A1), transportation (A2, A4, C2), building materials production and processing (e.g., engineered precast panels) (A3), building construction and site operations (A5) and end-of-life treatment (C1-C3). The disposal stage (C4) is excluded from Pilot 1, as all demolished materials are fully processed and valorized within subsequent product systems, ensuring no waste is sent to landfill.

In contrast to the LCA and LCC studies, this assessment explicitly incorporates the use phase, driven by the potential social impacts directly affecting consumers and users during building operation. This means that Module B1 representing the use stage has been included, excluding though the rest of the B modules associated with maintenance, repair, and refurbishment of the building.

Additionally, Module D, which usually considers future reuse and recycling benefits beyond the current system, has been excluded from this Social Life Cycle Assessment. Including it would require assumptions about long-term scenarios that are difficult to predict and not directly linked to the people or social processes involved today. Since the focus of this study is on social impacts that are more immediate and observable—such as those affecting workers, users, and communities—the analysis stays within lifecycle stages where these interactions are clearer and more relevant.

Similarly to the LCA, this Social Life Cycle Assessment adopts a dual lifecycle approach for both the baseline and the Circ-Boost solution. This enables a comparative examination of the potential social benefits and impacts within the defined system boundaries, focusing on the current lifecycle stages of each construction scenario.

Consequently, the system boundaries for the S-LCA include Modules A1–A3 (product stage), A4–A5 (construction process stage), B1 (use stage), and C1–C3 (end-of-life stage), covering two consecutive life cycles. In Figure 9, the system boundaries are depicted using a single illustration for both the baseline and the Circ-Boost solution, for the sake of simplicity and visual clarity.

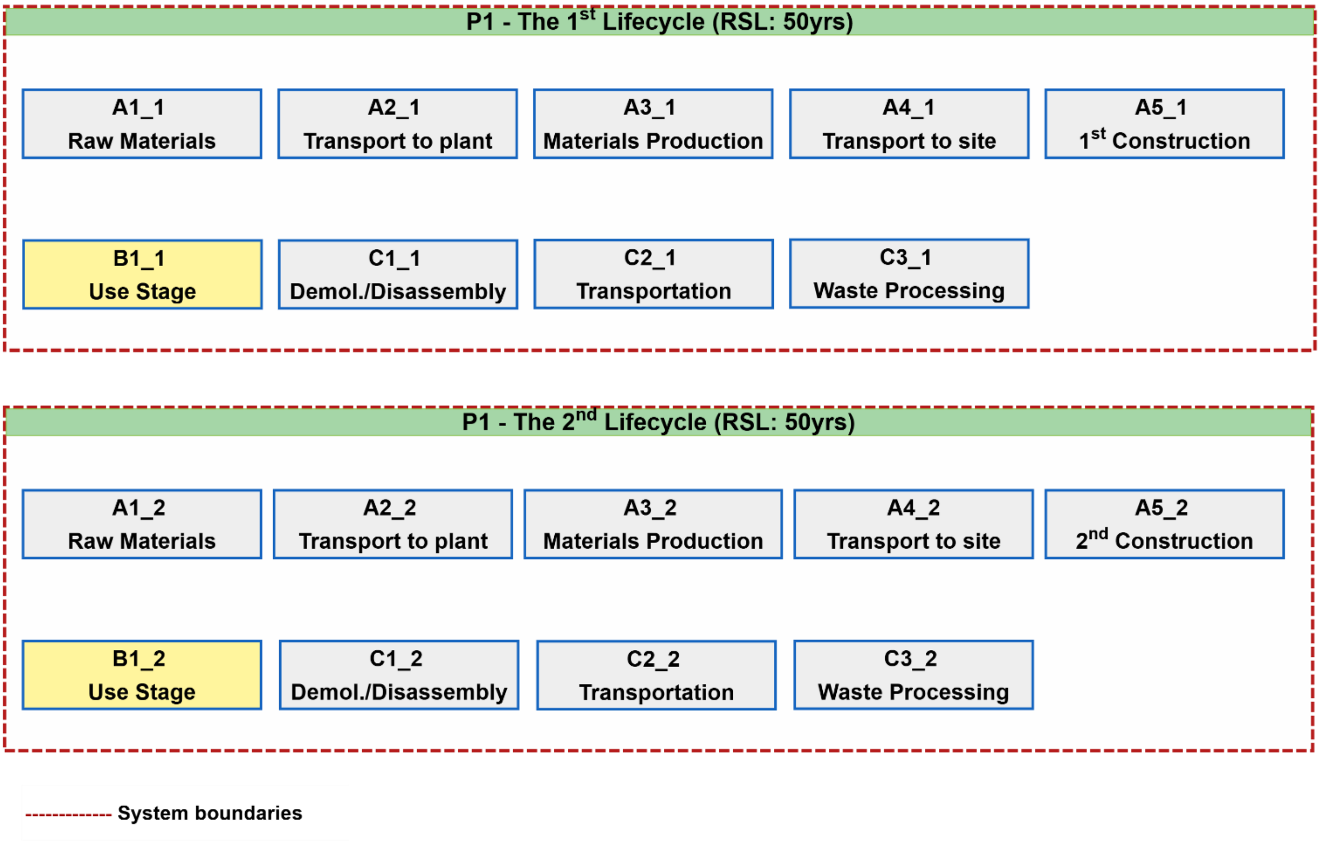


Figure 9. Social LCA system boundaries of Pilot 1, covering both the baseline and solution scenarios within the dual-lifecycle approach.

Stakeholders' selection

Stakeholder groups were identified separately for each life cycle stage, as defined by (Benoît Norris et al., 2020). These groups were then further categorized into subcategories, drawing on the stakeholder mapping conducted within Circ-Boost WP2 and Task 2.2 and incorporating input from pilot partners. This approach ensures that the stakeholder analysis is both methodologically robust and contextually relevant to the construction sector.

A definition of the selected stakeholders, along with their type of relationship to the system, is presented in Table 5 for both the Design for Disassembly/Reuse (DfD/R) and the conventional in-situ building of Pilot 1. Corresponding life cycle modules (in parentheses) indicate where each stakeholder group is involved.

Table 5. Definition of the stakeholder categories across S-LCA stages of Pilot 1's DfD/R and conventional in-situ building case, with corresponding life cycle modules indicated in parentheses.

Stakeholder group	Stakeholder Subcategory/Sub-Stakeholders	Definition	Type of relation
Workers	Primary material extraction workers: (NA, Cement, Steel) | [baseline+pilot] (A1)	Employees involved in the extraction and initial processing of raw materials used in the construction sector.	Affected – they are affected by the system's practices and decisions.
	Building material production workers: Building Panels/Concrete mix (A3)	Employees within the building material production sector, who work in precast concrete and concrete mix industry, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.

	Construction workers/Equipment operators (A5)	Employees working within the construction sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Deconstruction/Demolition Workers (C1)	Employees working within the building deconstruction/demolition sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Recycling workers (C3)	Employees working within the CDW processing and recycling sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Transportation workers (A2, A4, C2)	Employees working in the transportation sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
Society	Academic Research Institutions	Bodies that execute applied research to find/test new applications in sustainable construction and circular economy.	Concerned – they are concerned by the environmental, social and economic performance of available products/technologies in the market. They develop novel products and conduct research studies for technology progress purposes.
			Involved – they are involved in the decision-making process.
	General Population (A1-A3, A5, B1, C1-C4)	Citizens and communities indirectly affected by the environmental, economic and social impacts of raw material savings, building materials production, construction, end-of-life processes.	Affected – they are affected by the system's practices and decisions and by economic performance of public buildings.
	Not-for-profit association committed to advancing the technical, economic, aesthetic and environmental performances of concrete structures worldwide (A1-A3)	Organizations engaged in the promotion of ecofriendly, sustainable and climate-smart technologies/materials and innovations.	Concerned – they are concerned by the environmental, social and economic performance of available products/technologies in the market and influence the promotion of sustainable practices.
	Policy Makers (C1-C3)	Government officials and institutions responsible for creating policies and regulations related to construction, waste, and sustainability.	Directly involved – they shape the legislative and strategic environment that enables or constrains the adoption of new solutions.
Local community	Neighborhood near virgin raw material extraction [baseline & pilot] (A1)	Residents living in proximity to sites where virgin raw materials (e.g. natural aggregates, limestone, clay) are extracted.	Affected – their well-being and environment may be influenced by extraction activities and associated infrastructure.

	Neighborhood near concrete panel & concrete mix production facilities (A3)	Residents living close to facilities where building panels/components and concrete mix are manufactured.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
	Neighborhood near panel assembly facilities/construction site (A5)	Residents living near the location where DfD/R or in-situ buildings are assembled or constructed.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
	Neighborhood near deconstruction/demolition facilities (C1)	Residents close to sites where buildings are dismantled or demolished.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
	Neighborhood near waste processing/recycling plants (C3)	Residents living near facilities that process construction and demolition waste (CDW) for recycling.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
Value chain actors	Primary & secondary material supply companies (A1)	Companies that extract/receive construction materials intended for manufacture building components.	Directly involved – they respond to project requirements and influence material availability, quality and circularity.
	Building materials production companies (suppliers) (A3)	Companies that produce construction elements/materials, including panels and concrete mix.	Directly involved – they respond to project requirements and influence material availability, quality and circularity.
	Material technology development companies (A1-A3)	Firms engaged in R&D and innovation related to construction materials, including durability, recyclability, and performance.	Directly involved – they enable circular design through material innovation and life-cycle optimization.
	Equipment/machinery companies (A5)	Providers of machinery used in the construction/assembly of buildings.	Directly involved – they supply the tools necessary for efficient construction.
	Construction technology development companies (Architectural bureau/Design bureau/Investor) (A5)	Stakeholders involved in designing, planning, and financing of buildings.	Directly involved – they shape project execution through design choices and strategic direction.
	Deconstruction/Demolition companies (C1)	Companies specialized in dismantling buildings and recovering materials.	Directly involved – they execute end-of-life activities and influence reuse and recycling potential.
	Recycling companies (C3)	Entities responsible for processing and managing construction and demolition waste.	Affected – they are affected by variations of waste volumes and may need to adapt to changing material flows.

	Transportation companies (A2, A4, C2)	Entities responsible for transportation services of materials/waste.	Affected – they are affected by the system's practices and decisions regarding flow volumes of materials, products and waste and transportation distances.
Consumers	Private individuals as building buyers (private use)/Local and regional authorities or regulators as buyers (public use) (A5 & B1)	Individuals or entities purchasing buildings for private use.	Directly involved – they make purchasing decisions and influence market demand for the building sector. Affected - they are affected by economic performance of the building and the building construction processing time.

Impact categories and indicators

The stakeholder groups and subcategories were identified and mapped to each life cycle stage, following the modular structure of EN 15804. Each stakeholder subcategory was then linked to the most relevant social impact categories, which were subsequently connected to specific indicators. This structured and sequential approach ensures a consistent and traceable connection between stakeholders, potential social impacts, and the metrics used to assess them. This correlation is depicted in Table 6. It should be noted that Social Life Cycle Assessment (S-LCA) is inherently an iterative process, and the final selection of indicators will be determined based on data availability during the assessment phase. As the project progresses, certain indicators may be added or removed to reflect the realities of data accessibility, stakeholder input, and contextual relevance.

Table 6. Indicators selection for DfD/R and in-situ conventional building in Spain (P1-UPC).

Life Cycle Stage	**Stakeholder Group**	**Stakeholder Sub-Category**	**Impact Category**	**Indicator**
A1_Raw material extraction/supply **A2**_Transportation of materials to concrete plant **A3**_Production of building materials/elements (concrete mix/precast elements in concrete plant	**Workers**	Raw materials production (Primary material extraction workers **vs** Secondary recycled material receivers/pre-processers) (A1)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Hours of Paid Employment (for all employees)
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Building material production workers (concrete mix **vs** concrete panels) (A3)	Health and Safety	Accidents
				Exposure to hazardous substances

			Employment	Hours of Paid Employment (for all employees)
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Transportation workers (A2)	Employment	Jobs created or jobs lost
			Health and Safety	Accidents
				Exposure to hazardous substances
	Local Community	Neighborhood near to building material production facilities (concrete mix **vs** concrete panel) (A3)	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
	Society	General population	Contribution to Circular Economy and Resource Efficiency from potential raw material savings	Raw materials savings (from the second life cycle as panels are reused from the first cycle)
			Public health	Air Quality
			Climate Change Adaptation and Societal Resilience	Reduced Societal Vulnerability to Climate Change Impacts
		Academic Research Institutions	Knowledge & Innovation	Contribution to R&D and Knowledge Dissemination on Sustainable Construction of Buildings
		Not-for-profit association committed to advancing the technical, economic, aesthetic and environmental performances of concrete structures worldwide.	Knowledge & Innovation	Contribution to R&D and Knowledge Dissemination on Sustainable Construction of Buildings

	Value Chain Actors	Raw material companies	Economic growth/ Economic contribution	Factor Tax Payments
		Building materials production companies (suppliers)	Economic growth/ Economic contribution	Factor Tax Payments
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
		Material Technology development companies	Economic growth/ Economic contribution	Factor Tax Payments
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
			Innovation & Contribution to Sustainable Construction	Development and Commercialization of Sustainable Material Technologies
			Contribution to Industry Advancement and Sustainable Construction	Development and Commercialization of Sustainable Material Technologies
		Transportation companies (A2)	Economic growth/ development	Factor Tax Payments
A4 _Transportation of ready concrete mix/precast elements to construction site **A5** _Construction/Assembly of building	**Workers**	Construction workers / Equipment operators (A5)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Transportation workers (A4)	Employment	Jobs created or jobs lost
			Health and Safety	Accidents
				Exposure to hazardous substances
	Local Community	Neighborhood near to construction site	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits

				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
	Society	General population	Public health	Air Quality
			Climate Change Adaptation and Societal Resilience	Reduced Societal Vulnerability to Climate Change Impacts
	Value Chain Actors	Equipment/machinery companies	Economic growth/ development	Factor Tax Payments
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
		Construction technology development companies (Architectural bureau/Design bureau/Investor)	Economic growth/ Economic contribution	Factor Tax Payments
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
			Innovation & Contribution to Sustainable Construction	Development and Commercialization of Sustainable Material Technologies
			Contribution to Industry Advancement and Sustainable Construction	Development and Commercialization of Sustainable Material Technologies
		Transportation companies	Economic growth/ development	Factor Tax Payments
	Consumer	Private individuals as building buyers (private use) / Local and regional authorities or regulators as buyers (public use)	Project execution speed	Project execution speed
B1 _Use	**Consumer**	Private individuals as building buyers (private use) / Local and regional authorities or regulators as buyers (public use)	Affordability for users (Building buyers for private use, Local authority/regulator & user, Regional authority/regulator & user)	Affordability for the first life cycle
				Affordability for the second life cycle Cost savings (e.g., percentage reduction in material costs) achieved by using reused precast panels

			Adaptability	How well the building can be modified or adjusted to meet changing needs over time
	Society	General public	More sustainable Economic performance for public buildings	Life Cycle Cost Savings for Public Buildings
C1 _Demolition/Deconstruction of building **C2** _Transport of Construction and Demolition waste (CDW) to waste processing facility **C3** _Waste processing (sorting, crushing)	**Workers**	Demolition/Deconstruction workers (C1)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Hours of Paid Employment (for all employees)
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Recycling workers (C3)	Health and Safety (accidents, exposure to hazardous substances or PM)	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Transportation workers (C2)	Employment	Jobs created or jobs lost
			Health and Safety	Accidents
				Exposure to hazardous substances
	Local Community	Neighborhood near to Deconstruction/Demolition facilities	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of

				PM2.5/PM10 in ambient air)
		Neighborhood near to waste processing/recycling plants	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
	Society	Policy makers	Alignment with CDW policy	Alignment with CDW policy
	Value Chain Actors	Deconstruction/Demolition companies	Economic growth	Total revenue (in currency)
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
		Recycling companies	Economic growth / Revenues from reused/recyclable materials sales	Total revenue (in currency) (decreased due to less input material)
		Transportation companies	Economic growth/ development	Factor Tax Payments

3.2 Pilot 2 (CAP): Physical and Digital Platform (Paris, France)

3.2.1 Technology Overview

The French construction sector is one of the most resource-intensive industries in the country, accounting for approximately 50% of raw material consumption and 70% of total waste generation. In 2018, the sector used around 397 million tons (Mt) of mineral materials, of which 343 Mt consisted of gravel and sand. This massive extraction and consumption of resources has led to significant environmental pressures, particularly in urban regions such as Île-de-France, where land artificialization linked to raw material extraction and waste landfilling has more than doubled over the past 30 years (SDES, 2022).

In response to these challenges, France has progressively adopted a more circular approach to the building sector. Regulatory frameworks have evolved to promote resource efficiency, waste reduction, and material reuse. Notably, recent legislation asks for a diagnostic audit prior to the demolition or a significant renovation. This audit must detail the nature, quantity, and location of materials present, as well as their potential for reuse, recovery, or valorization. However, despite these promising advances, the sector still faces structural limitations: fragmented data, lack of traceability, and insufficient coordination between upstream and downstream actors limit the systematic recovery of construction and demolition waste (CDW).

To overcome these hardships, robust tools for monitoring material flows, matching supply and demand, and structuring reuse frameworks are urgently needed. These tools must not only ensure compliance with regulations but also enable stakeholders to go beyond minimum requirements and promote circularity as a strategic opportunity.

The Circ-Boost project aims to act as a European hub for emerging circular technologies in the construction sector. The main goal is to boost reuse, recycling, and valorization of CDW through digital and physical solutions. The French pilot (Pilot 2) contributes to this ambition by focusing on the creation of new material sources, the optimization of material flows, and the development of supply-demand models that support the storage, preparation, and maintenance of secondary materials.

This approach is expected to:

- Reduce the volume of CDW sent to landfill.
- Lower greenhouse gas (GHG) emissions associated with virgin material production.
- Extend the lifecycle of construction materials.
- Support the emergence of new business models for material reuse.

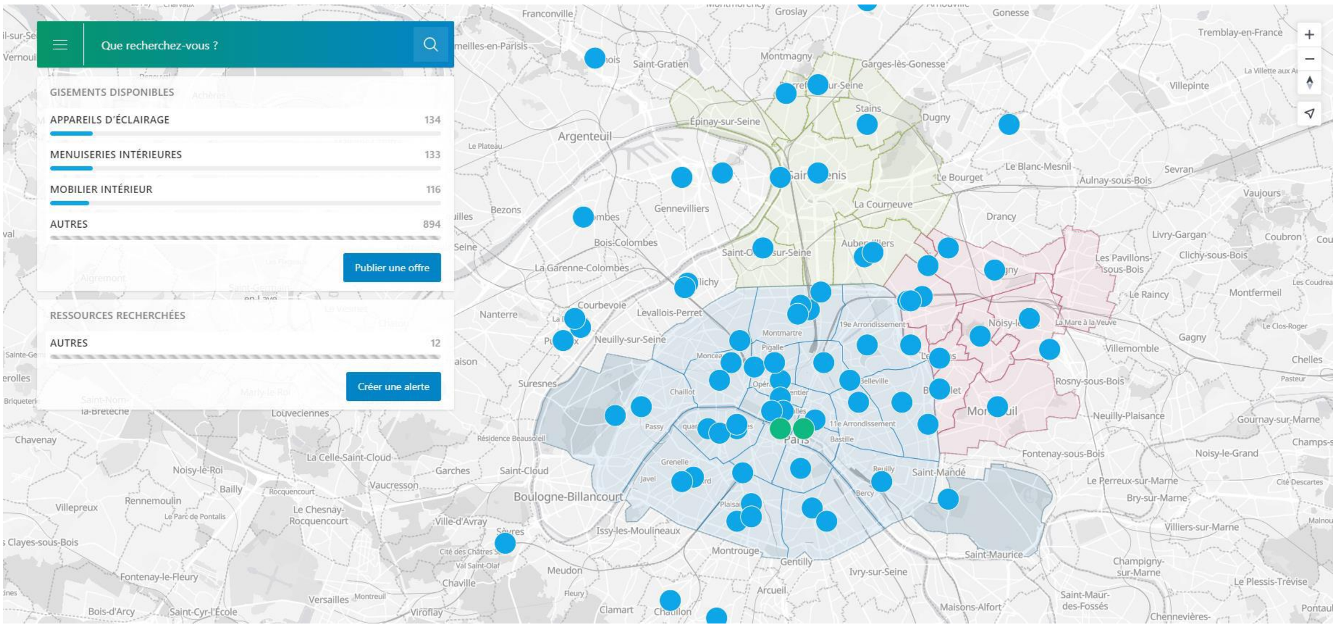
Within this framework, Pilot 2 is led by a consortium of eight French partners, including industrial actors, technology providers, and public authorities. This project aims to facilitate the matching of supply and demand for construction materials through the development of a digital and a physical platform. The objectives of the pilot are to:

i. develop a platform facilitating the matching between supply and demand for materials and waste, allowing for a better identification of construction waste deposits and regional needs.

ii. explore innovative construction processes that enhance the value of materials obtained from deconstruction.

iii. structure the materials and waste upcycling sectors resulting from the deconstruction of buildings.

A digital platform is designed to aggregate data on material deposits and waste flows. It integrates information from online marketplaces, physical platform catalogues, public databases, and user-generated listings. The platform aims to improve visibility, traceability, and matching efficiency between material supply and demand (See Figure 10).



GISEMENTS DISPONIBLES

APPAREILS D'ÉCLAIRAGE	134
MENUISERIES INTÉRIEURES	133
MOBILIER INTÉRIEUR	116
AUTRES	894

RESSOURCES RECHERCHÉES

AUTRES	12

Figure 10. Preview of the digital platform of Pilot 2.

On the other hand, a physical platform consists of a multi-site operation adapted to dense urban contexts. Physical platforms are smaller (maximum 1 ha) than traditional platforms (between 4 and 6 ha) and are characterized by mobile processing equipment, enabling flexible deployment and reduced logistical constraints. Two physical sites have been selected to support the deployment of Pilot 2:

- A products refurbishing site located in Île-Saint-Denis (Unibétonne site): operated by Demcy, this site serves as a showroom for reused materials but also as a workshop for refurbishing activities. The focus is on the reuse of raised flooring systems and skylights, which are dismantled, refurbished, and prepared for resale.
- An inert waste and soil management site, located in a 4500 m² site in Gennevilliers: managed by Eiffage, this site stores up to 30000 tons of inert waste annually (See Figure 11). The materials are then refurbished by Saint-Gobain and transformed into thermal inertia panels.

Figure 11. Preview of the Gennevilliers urban physical platform and other sites in Paris region.

Consequently, the physical platform as the solution proposed by Pilot 2 in the framework of Circ-Boost, will be compared against the baseline scenario. In particular:

- Baseline Scenario: Conventional waste treatment and disposal practices without targeted reuse or refurbishment of materials.
- Circ-Boost Solution: Deployment of a compact, mobile physical platform across two urban sites to enable the reuse and recycling of inert waste (into thermal inertia panels), raised flooring systems, and skylights.

The environmental evaluation of Pilot 2 is conducted using the Life Cycle Assessment (LCA) methodology, in accordance with the standards ISO 14040, ISO 14044 (ISO, 2006a, 2006b) and EN 15804 (CEN, 2019). LCA provides a standardized, quantitative, and multi-criteria framework for assessing environmental impacts across the entire life cycle of a system, from the raw material extraction to its End-of-Life (EoL) stage. It is widely recognized by researchers (Bjørn et al., 2018; Cerdas, 2022) as the most relevant tool for addressing Life Cycle Engineering (LCE) challenges, including those related to waste management in the construction sector.

3.2.2 Life Cycle Assessment (LCA)

3.2.2.1 Goal and Scope Definition

The primary objective of this environmental evaluation is to assess the life cycle environmental impacts associated with the implementation of Pilot 2 in France, with a specific focus on the physical platform for waste treatment and material reuse. This focus is justified by the current lack of data regarding the digital platform. Based on preliminary assessments and expert judgment, the environmental footprint of the digital platform is expected to be negligible compared to the physical platform. Nevertheless, a brief comparative analysis will be conducted to validate this assumption and ensure consistency during the final assessment.

To initiate the LCA process, a preliminary meeting was organized with the pilot stakeholders to review the scope and expected outcomes of the pilot. Following this, a structured Goal & Scope template, aligned with ISO 14040/44, ISO 15804 (CEN, 2019; (ISO), 2006a, 2006b), and the Circ-Boost methodology, was shared with the pilot leader for completion. This template aimed to capture key parameters such as functional unit, system boundaries, reference flows, and assumptions. A follow-up meeting was then held to review the completed template, clarify uncertainties, and consolidate the core elements of the study framework. The finalized version of the template is presented in the table below.

Table 7. Goal & Scope Template of Pilot 2 (CAP).

Goal	**Brief description**
Intended application(s) of the LCA results	Assess the environmental impacts of the CIRCBOOST waste treatment platform compared to conventionnal practices of waste treatment
Reasons for carrying out the study	Informing/Descriptive nature
Target audience	Circ-Boost consortium members, European Union and European Commission, technology providers, local partners, civil engineers, architects, and researchers, construction and demolition companies, contractors and public authorities, policy makers and standardization bodies, local communities and the general public
Scope	**Brief description**
Function	Treatment of inert waste and products refurbishing
Functional unit	The treatment of a material flow composed of 1 tonne of inert waste, 1 tonne of raised flooring system, and 1 tonne of skylight in Île-de-France.
Reference flow	tonnes of waste and products
System boundaries	gate-to-gate with options
Hundling multifunctionality	Subdivision of processes and system expansion to account for the avoided burden
Data requirements	Site-specific data, Ecoinvent, EPDs
Assumptions	Digital platform excluded ; Material reuse quality not accounted for ; Extended system boundaries to capture substitution benefits ; Conventional scenario based on generic assumptions ; Site-specific data used for the physical platform
Limitations	Project specific use
Modelling framework	Attributional
LCIA method	Environmental Footprint 3.1
Format	Report

Goal

Reasons for carrying out the study

The objective of this environmental evaluation is to assess the life cycle environmental impacts associated with the implementation of Pilot 2 in the Île-de-France region, with a specific focus on the physical platform. This platform is designed to facilitate the reuse and recycling of three key material flows:

- Inert waste, recycled into thermal inertia panels
- Raised flooring systems, refurbished for reuse
- Skylights, refurbished for reuse

The study aims to quantify the environmental benefits of these circular practices compared to a baseline scenario, and it also seeks to identify environmental hotspots and support decision-making for future replications of the pilot.

Intended audiences

The results of this LCA study are intended to inform a wide range of stakeholders, including:

- Circ-Boost consortium members
- The European Commission and relevant EU institutions
- Technology providers (Demcy, Eiffage, Saint-Gobain)
- The local partner (CAP)
- Civil engineers and architects
- Researchers
- Construction and demolition companies
- Contractors and public authorities
- Policy makers and standardization bodies
- Local communities and the general public

The results are expected to support decision-making, inform future pilot replications, and contribute to the broader objectives of the Circ-Boost project. It should be noted that the results may be subject to a degree of uncertainty due to the assumptions and data used in the analysis. Consequently, the conclusions derived from this analysis should be interpreted with a degree of caution.

Comparative assertions

This study supports comparative assertions between:

- A baseline scenario representing conventional waste treatment and disposal practices.
- The Circ-Boost scenario, representing the treatment and valorization of materials through the physical platform developed in Pilot 2.

The comparison aims at being science-based and informative, intended to support internal project evaluation and policy recommendations. It is not designed for commercial claims or public comparative marketing. Therefore, in accordance with ISO 14040:2006 and ISO 14044:2006, no external critical review (besides the review procedure prescribed by the project's Grant/Consortium Agreements) is required beyond the internal quality assurance procedures established within the Circ-Boost project.

This study is intended to support decision-making by providing a descriptive and comparative analysis of the platform developed in the project, compared to conventional treatments in the building sector. The results have the potential to provide valuable insights into the environmental performance of circular practices using LCA indicators. According to recent works (Mannan & Al-Ghamdi, 2022; Saidani et al., 2022), this approach that combines circular and LCA indicators, contributes to achieve a "better understanding of economic, social, and environmental sustainability".

Scope

Functional unit

The primary function of the systems under study is the waste treatment of construction and demolition waste for reuse or recycling within the Île-de-France region. Accordingly, the Functional Unit (FU) is defined as: The treatment of a material flow composed of 1 ton of inert waste, 1 ton of raised flooring system, and 1 ton of skylight in Île-de-France.

The unit provides a consistent basis for comparing the environmental performance of the pilot and baseline scenarios.

The reference flow corresponds to the amount of material (in tons of materials or products) required to provide the function and fairly compare the scenarios on common basis.

System boundaries

The scope of this study refers to the treatment of inert waste and the reuse of equipment in the Île-de-France region. The analysis is limited to a gate-to-gate perspective with options, as depicted in Table 8, based on the framework from ISO 15804, meaning it includes the collection and transport of waste materials (C2), the refurbishing of raised flooring systems and skylights, the recycling of inert waste into thermal inertia panels and the preparation of materials for reuse or resale (C3).

Table 8. Stages included in the LCA analysis of Pilot 2 baseline and solution based on EN15804.

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction/ inst. process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse/recovery/recycling
-	-	-	-	-	-	-	-	-	-	-	-	-	x	x	(x)	(x)

Therefore, this approach excludes raw material extraction, use phase and End-of-Life (EoL) of the final products, as shown in Table 8. Although a cradle-to-grave approach would offer a more comprehensive perspective, it would require numerous assumptions regarding the second life of the products, their performance, and end-of-life scenarios, which are currently unknown. To maintain methodological robustness and avoid speculative modelling, the study focuses on the waste processing stage only.

However, in a secondary analysis, the system boundaries will be expanded to assess the avoided environmental burdens associated with the substitution of virgin materials by secondary materials. This approach ensures that the quality and potential applications of the output streams are reflected in the assessment, in line with the principles of system expansion and circularity accounting.

The study adopts an attributional modelling framework, to assess the environmental impacts directly related to the scenarios under current conditions. A consequential approach could also be valuable for assessing the environmental implications of supplying higher-quality and greater quantities of waste streams.

Baseline scenario

The baseline scenario represents the conventional practices for treating CDW generated during building deconstruction. It serves as a reference point for evaluating the environmental performance of the Circ-Boost pilot. The scenario assumes average End-of-Life (EoL) pathways for a waste flow defined in the functional unit: inert waste, raised flooring systems, and skylights.

The system boundaries of the baseline scenario are illustrated in Figure 12.

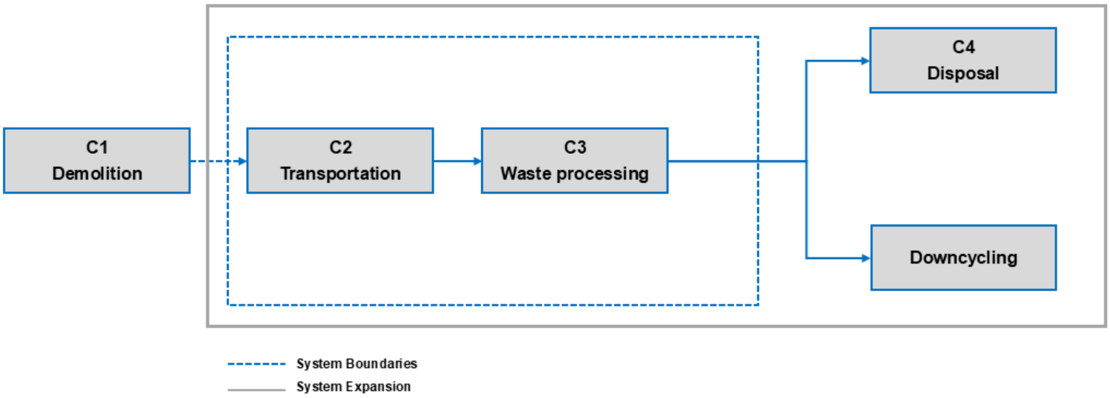


Figure 12 : System boundaries of the Pilot 2 baseline scenario.

- **Module C1:** This module captures the initial demolition activities that generate the waste flow. It includes the dismantling of building components and quantifies the resulting material streams: 1 ton of inert waste, 1 ton of raised flooring system, and 1 ton of skylight. As this module is common to both the baseline and pilot scenarios, and no specific data is available, it is excluded from the system boundaries.
- **Module C2:** Waste materials are then transported from the demolition site to conventional treatment facilities. Transport modes may include truck, boat, or train, depending on site accessibility. In the baseline scenario, these facilities are typically located far from urban demolition sites, resulting in longer transport distances. Regional averages for transport distances in Île-de-France will be used to model this stage.
- **Module C3**: Upon arrival, materials are unloaded, sorted, and processed according to standard EoL practices. These may include landfilling, low-grade recycling, or incineration, depending on the material type and local infrastructure. Raised flooring systems and skylights are generally not reused, and inert waste is often downcycled or disposed of.
- **Module D (System Expansion)**: Residual waste that cannot be valorized is sent to landfill or other final disposal routes (Module C4). In conventional practice, only a limited fraction of materials is recovered, and this recovery often corresponds to low-value applications, such as downcycled uses, resulting in minimal environmental benefits. For example, excavated materials and inert waste are frequently used as road sub-base layers or backfill. As a result, the net environmental benefits associated with conventional waste treatment are expected to be lower than those achieved through the Circ-Boost pilot. These benefits will be credited in module D, by applying system expansion in a future sensitivity analysis.

Circ-boost solution

The Circ-Boost scenario models the treatment of the same waste flow through the two innovative physical platforms developed in Pilot 2. These platforms facilitate the recycling and refurbishment of materials of significant value through the implementation of innovative and efficient waste treatment processes.

The system boundaries of the Circ-Boost scenario are illustrated in Figure 13.

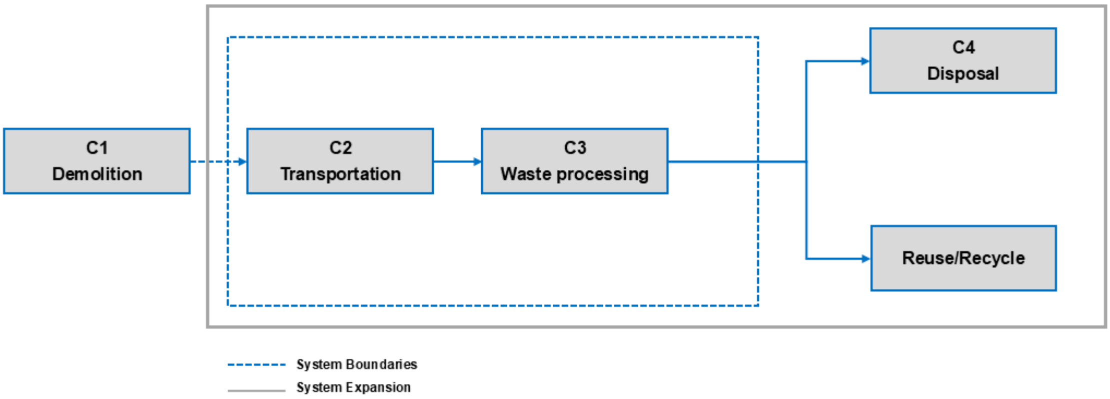


Figure 13 : System boundaries of the Pilot 2 physical platform of waste processing.

- **Module C1**: As in the baseline scenario, this module captures the generation of the waste flow during building demolition. It is excluded from the system boundaries due to a lack of specific data for each scenario.
- **Module C2**: Waste materials are transported to two dedicated treatment sites: Gennevilliers for inert waste processing and Île-Saint-Denis for refurbishing of raised flooring systems and skylights. These platforms are strategically located closer to demolition sites, reducing transport distances and associated impacts. Transport modes may include truck, boat, or train, depending on accessibility. Conducting a sensitivity analysis of these transportation distances and modes may provide valuable insights into their influence on the environmental outcomes.
- **Module C3**: Upon arrival, materials are sorted, stored, and treated using specialized processes. Inert waste is recycled into thermal inertia panels via a process developed by Saint-Gobain. Raised flooring systems and skylights are refurbished by Demcy, following technical protocols that ensure compliance with reuse standards.
- **Module D (System expansion)**: The Circ-Boost scenario generates substantial environmental benefits by substituting virgin materials with secondary products. Thanks to the specific refurbishing and recycling processes implemented on the physical platform, the volume of residual waste requiring final disposal is considerably reduced compared to conventional practices. Non-recoverable fractions are still sent to landfill or other disposal routes (Module C4), but their proportion is minimized through targeted interventions. Recovered materials are reintegrated into the construction value chain in the form of functional components (thermal inertia panels, refurbished flooring systems, and skylights) rather than being downcycled into low-value applications. These benefits are modelled in module D and include the avoided production of new thermal panels, the avoided manufacturing of new flooring systems and skylights, and the reduced extraction of raw materials and associated emissions.

3.2.2.2 Multifunctionality

In Life Cycle Assessment (LCA), multifunctionality occurs when a process or a product system delivers multiple outputs that cannot be clearly separated without applying an allocation procedure. This situation is common in End-of-Life (EoL) stages, where materials may be recovered in various forms. As recommended by ISO 15804+A2, allocation will be mostly avoided by dividing the whole waste process into sub-processes according to flow type (inert waste, raised flooring systems and skylights) during the modelling of Pilot 2. Should the situation demand it, the allocation of waste (masses or volumes) will be conducted using physical metrics (waste mass or volume).

In other cases, multifunctionality is addressed through the principle of system expansion, as recommended by EN 15804 (CEN, 2019). This approach allows the inclusion of environmental benefits resulting from the substitution of virgin materials by reused or recycled ones, such as inert waste, raised flooring systems, and skylights, in subsequent product systems. Rather than allocating impacts between co-products, system expansion models the avoided burdens beyond the system boundary, ensuring a fair and transparent comparison between scenarios.

3.2.2.3 Assumptions and limitations

The following assumptions and limitations are to be applied to the scope and modelling of the LCA:

- The digital platform is excluded from the core analysis due to limited data availability and its expected low environmental impact relative to the physical platform. However, a simplified assessment will be conducted to validate this assumption.
- The demolition stage (Module C1) is excluded from the scope of the study due to a lack of relevant data. Therefore, deconstruction scenarios are not to be considered as being distinct from demolition scenarios.
- Refurbished materials (flooring systems and skylights) are assumed to meet technical standards for reuse and to exhibit equivalent performance (e.g., safety, durability, functionality) compared to virgin materials and new products.
- The influence of material quality on the performance of reused products in their second life is not considered, due to insufficient data, and therefore the quality is considered to be identical. Consequently, reused components are assumed to exhibit the same technical performance, durability, maintenance and service life as their virgin counterparts.
- Transport distances are modelled using site-specific geographic data, based on the actual locations of demolition sites and treatment platforms. The results may therefore differ between regions, depending on the available land for platforms and the building density in the area considered, as these factors influence both the quantities and the distribution of wastes.
- For the baseline scenario, data will be sourced from French national averages (INIES) and generic LCA databases (ecoinvent).
- For the Circ-Boost scenario, data will be collected from project documentation, partner inputs, and expert discussions.
- As previously stated, several sensitivity analyses may be conducted in a subsequent stage to evaluate the influence of key parameters, such as transport distances and modes, as well as refurbishing efficiency and energy consumption, depending on the results of the hotspot analysis.
- A secondary analysis will extend the system boundaries capturing the environmental benefits of substituting virgin materials and products with secondary ones.
- The realization of the LCA will depend on the availability of the data collected from pilot project partners. If insufficient data is available, either generic datasets will be used, or the analysis will be discontinued.

3.2.2.4 Cut-off criteria

Processes contributing less than 1% to the total environmental impact per impact category may be excluded, provided they do not cumulatively exceed 5%. All relevant flows related to the three material types are included to ensure completeness.

3.2.3 Life Cycle Costing (LCC)

During Task 5.1, the goal and scope of the Life Cycle Costing (LCC) assessment for Pilot 2 were clearly defined, ensuring full alignment with the framework conditions of the environmental Life Cycle Assessment (LCA). This alignment includes the use of consistent system boundaries and a shared functional unit, thereby guaranteeing coherence between environmental and economic evaluations.

The system boundaries for the LCC of Pilot 2 encompass modules C2 related to waste transportation and C3 related to waste processing, refurbishment and preparation for reuse. In a secondary analysis, modules C4 and D could potentially be considered, following the results of the environmental LCA analysis.

Data collection for Pilot 2 is scheduled to begin in the coming months and will draw from both primary and secondary sources. The pilot will provide average cost estimates for key life cycle elements, including raw materials, transportation distances, construction and deconstruction activities, and replacement parts. Where pilot-specific data is not yet available, secondary sources—such as literature and price databases—will be used to fill gaps. All cost-related inputs will be gathered using a standardized LCC inventory template developed within the project.

Finally, the Life Cycle Costing analysis phase will commence after Month 30, with the launch of Task 5.3, and will continue until Month 47. This phase will incorporate both fixed and variable costs provided by the involved partners, as well as external costs—indirect social costs typically associated with environmental degradation and emissions. These externalities will be quantified and included in the final deliverable, D5.2.

3.2.4 Social Life Cycle Assessment

The Social Life Cycle Assessment of the current study relies on the general framework described in section 2.3.1, which is adjusted to the pilot case's particular objectives. The following section presents the methodology's application to define the goal and scope for Pilot 2.

3.2.4.1 Goal and Scope

The goal of the study

This Social Life Cycle Assessment (S-LCA) study investigates the potential social benefits and impacts associated with the deployment of an innovative physical platform for more efficient waste treatment and valorization of three flows of demolition materials in the Île-de-France region.

Focusing on the current product system and the geographic context of the Île-de-France region in Paris, France the study aims to uncover both positive and negative social implications for key stakeholder groups, including construction workers, material suppliers, local communities, and policymakers.

The results will be of particular interest to public authorities, construction and material production companies, recycling firms, sustainability consultants, circular economy practitioners, and academic researchers. Insights from this assessment will support future policy development, inform circular procurement strategies, and guide the design of socially responsible construction practices in France and beyond.

Functional unit

The functional unit for the specific S-LCA is consistent with the one used in the LCA and LCC studies. However, unlike LCA and LCC, the social impacts and effects in the S-LCA are not currently expected to be quantitatively scaled to the functional unit. Nevertheless, this decision will be addressed in the later stages of the Social LCA study. As outlined in the LCA goal and scope chapter of Pilot 2, chapter 3.2.2.1, the functional unit is defined as the treatment of a material flow composed of 1 ton of inert waste, 1 ton of raised flooring system, and 1 ton of skylight in Île-de-France, applicable to both the baseline and the Circ-Boost solution.

System boundaries

The system boundaries for this Social Life Cycle Assessment (S-LCA) are aligned with those defined in the LCA. To ensure a harmonized and transparent categorization of social impacts and enhance comparability, the boundaries follow the modular structure of EN 15804 and EN 15978 (CEN, 2011, 2019), encompassing all relevant activities within each examined stage.

The Social Life Cycle Assessment (S-LCA) for Pilot 2 focuses on the treatment of inert waste and the reuse of equipment within the Île-de-France region, following a gate-to-gate system boundary approach. The analysis includes activities such as the collection and transport of waste materials (Module C2), the refurbishing of raised flooring systems and skylights, the recycling of inert waste into thermal inertia panels, and the preparation of materials for reuse or resale (Module C3). On the contrary, Modules C4 (disposal) and D (benefits and loads beyond the system boundary) are excluded from the current assessment. Including Module D would require speculative assumptions about long-term scenarios that are difficult to predict and not directly linked to the current social processes or stakeholders involved. Furthermore, raw material extraction (A1-A3), the use phase (B), and the end-of-life (C1) of the final products are also excluded, in alignment with the boundaries defined in the corresponding environmental LCA and Life Cycle Costing (LCC) studies. This boundary definition allows the S-LCA to focus on immediate and observable social impacts within the scope of the pilot activities.

Consequently, the system boundaries for the S-LCA include Modules C2 and C3. In Figure 14, the system boundaries are depicted using a single illustration for both the baseline and the Circ-Boost solution, for the sake of simplicity and visual clarity.

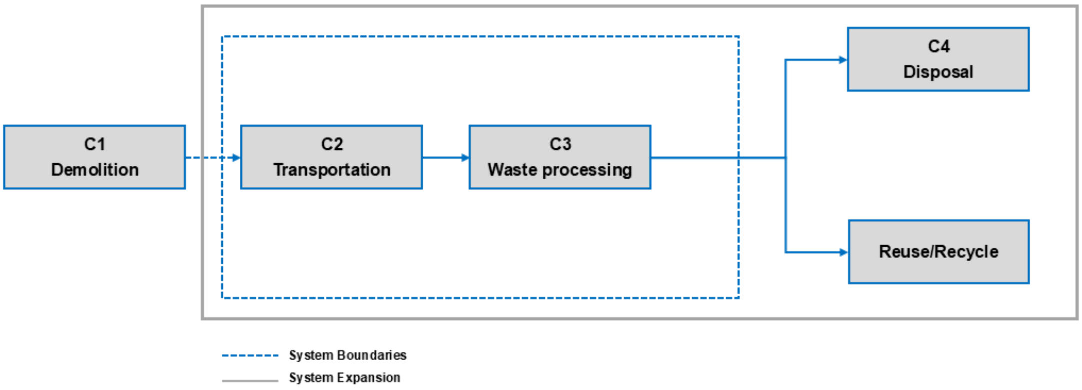


Figure 14. Social LCA system boundaries of Pilot 2 covering both the baseline and solution.

Stakeholders' selection

Stakeholder groups were identified separately for each life cycle stage, as defined by (Benoît Norris et al., 2020). These groups were then further categorized into subcategories, drawing on the stakeholder mapping conducted within Circ-Boost WP2 and Task 2.2 and incorporating input from pilot partners. This approach ensures that the stakeholder analysis is both methodologically robust and contextually relevant to the construction sector.

A definition of the selected stakeholders, along with their type of relationship to the system, is presented in Table 9 for both the innovative waste treatment via the newly introduced physical platform and the conventional waste treatment in the Île-de-France region of Paris. Corresponding life cycle modules (in parentheses) indicate where each stakeholder group is involved.

Table 9. Definition of the stakeholder categories across S-LCA stages of Pilot 2, with corresponding life cycle modules indicated in parentheses.

Stakeholder group	Stakeholder Subcategory/Sub-Stakeholders	Definition	Type of relation
Workers	Transportation workers (C2)	Employees working in the transportation sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.

	Recycling workers (C3)	Employees working within the CDW processing and recycling sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
Society	Academic Research Institutions	Bodies that execute applied research to find/test new applications in sustainable construction and circular economy.	Concerned – they are concerned by the environmental, social and economic performance of available products/technologies in the market. They develop novel products and conduct research studies for technology progress purposes.
			Involved – they are involved in the decision-making process.
	General Population (C2-C3)	Citizens and communities indirectly affected by the environmental, economic and social impacts of raw material savings, building materials production, construction, end-of-life processes.	Affected – they are affected by the system's practices and decisions and by economic performance of public buildings.
	Policy Makers (C1-C3)	Government officials and institutions responsible for creating policies and regulations related to construction, waste, and sustainability.	Directly involved – they shape the legislative and strategic environment that enables or constrains the adoption of new solutions.
Local Community	Neighborhood near waste processing/recycling plants (C3)	Residents living near facilities that process construction and demolition waste (CDW) for recycling.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
Value Chain Actors	Transportation companies (C2)	Entities responsible for transportation services of materials/waste.	Affected – they are affected by the system's practices and decisions regarding flow volumes of materials, products and waste and transportation distances.
	Recycling companies (C3)	Entities responsible for processing and managing construction and demolition waste.	Affected – they are affected by variations of waste volumes and may need to adapt to changing material flows.

Impact categories and indicators

The stakeholder groups and subcategories were identified and mapped to each life cycle stage, following the modular structure of EN 15804. Each stakeholder subcategory was then linked to the most relevant social impact categories, which were subsequently connected to specific indicators. This structured and sequential approach ensures a consistent and traceable connection between stakeholders, potential social impacts, and the metrics used to assess them. This correlation is depicted in Table 10. It should be noted that Social Life Cycle Assessment (s-LCA) is inherently an iterative process, and the final selection of indicators will be determined based on data availability during the assessment phase. As the project progresses, certain indicators may be added or removed to reflect the realities of data accessibility, stakeholder input, and contextual relevance.

Table 10. Indicators selection for demolition waste physical platform in France (P2-CAP).

Life Cycle Stage	Stakeholder Group	Stakeholder Sub-Category	Impact Category	Indicator
C2 _ Transport of Construction and Demolition waste (CDW) to Waste processing facility **C3** _ Waste processing (sorting, crushing)	**Workers**	Transportation workers (C2)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
		Recycling workers (C3)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
	Local Community	Neighborhood near to waste processing/recycling plants	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
	Society	General population	Waste Diversion and Reduced Landfill Burden	Volume of waste avoided from landfill
		Policy makers / Environmental NGOs	Alignment with CDW policy	Alignment with CDW policy
	Value Chain Actors	Transportation companies (C2)	Economic growth / Development	Factor Tax Payments
		Recycling companies (C3)	Economic growth / Economic contribution	Revenues from material treatment / Volume of treated material

3.3 Pilot 3 (FCE): DfD/R prototype 3R building (Belgrade, Serbia)

3.3.1 Technology overview

The construction industry is one of the most resource-intensive sectors globally, exerting a significant environmental impact due to its high consumption of raw materials, energy, and the vast amounts of waste it generates. Among its most impactful components is the concrete industry, which produces nearly 20 billion tons of concrete annually (UNEP & CEA Yale, 2023). A major contributor to this footprint is cement production, responsible for approximately 7–10% of global anthropogenic CO_2 emissions—primarily due to the energy-intensive process of producing clinker, the key ingredient in Portland cement.

In the Balkan region, the construction industry has experienced steady growth over the past decade. However, this expansion has largely followed traditional practices, with limited consideration for environmental sustainability. While innovative green solutions are being developed globally—and even within Serbian research institutions—their implementation in the regional market remains sporadic. This is largely due to a lack of practical experience, comprehensive guidelines, and standardized frameworks.

A critical opportunity lies in the use of locally sourced waste materials, which requires a systematic understanding of locally available resources and effective waste management. In Serbia alone, an estimated 1.5 –1.6 million tons of construction and demolition waste from residential buildings is generated annually (Marinković et al., 2023), with approximately 24% being concrete. This translates to 360,000–380,000 tons of potentially recyclable concrete. Yet, the current production of recycled concrete aggregate (RCA) stands at only 14,000 tons per year. The recent opening of Serbia's first recycling plant for construction and demolition waste in Vinča, near Belgrade—with a capacity of 200,000 tons per year—marks a significant step forward, but practical application of RCA remains limited. Despite existing technical standards allowing for 30–50% replacement of coarse RCA in structural elements, recycled aggregate concrete (RAC) has yet to be used in structural building components. Instead, RCA is primarily used for terrain levelling and filling—applications of lower value, representing a form of down-cycling.

Another pressing environmental issue in Serbia is the vast accumulation of fly ash (FA), a by-product of coal combustion in thermal power plants. Each year, around 7 million tons of FA are produced, with over 3 million tons of low-quality FA currently deposited across more than 1,500 hectares of fertile land. These deposits pose significant environmental and health risks to nearby communities. Despite its potential as a supplementary cementitious material—particularly as a partial replacement for clinker in cement production—only about 3% of FA is currently utilized. A promising and underused solution is the adoption of High-Volume Fly Ash Concrete (HVFAC), which can incorporate large quantities of FA into concrete mixtures. This approach not only helps reduce the environmental burden of FA landfills but also contributes to lowering carbon emissions in the construction sector by reducing clinker demand.

Traditionally, Serbia's construction industry relies on cast-in-situ and precast concrete methods (D Milinković, 2019). While these techniques are effective for residential and commercial projects, they lack reusability potential. Even precast elements are not designed for disassembly, meaning that once a building reaches the end of its life, its concrete components are typically demolished and discarded—contributing to landfill waste and necessitating the extraction of new raw materials. This approach not only depletes natural resources but also generates substantial carbon emissions during the production and transportation of new concrete.

To address these challenges, “Design for Disassembly and Reuse (DfD/R)” offers a transformative approach. By enabling the easy disassembly and repurposing of building components, DfD/R helps retain material value across extended life cycles—minimizing waste, conserving resources, and reducing emissions. When combined with locally sourced recycled materials such as RCA and FA, DfD/R buildings could potentially enhance circularity and environmental performance in the Balkan construction sector.

To demonstrate this approach in practice, the Faculty of Civil Engineering at the University of Belgrade will construct a single-story pilot house measuring 6 by 4 meters (24 m²), guided by the 3R principles—reduce, reuse, and recycle. This innovative demonstrator will showcase DfD/R as a transformative strategy to extend the service life of building materials and reduce construction and demolition waste. The building will incorporate locally sourced waste and by-product materials with high reuse potential (See Figure 15).

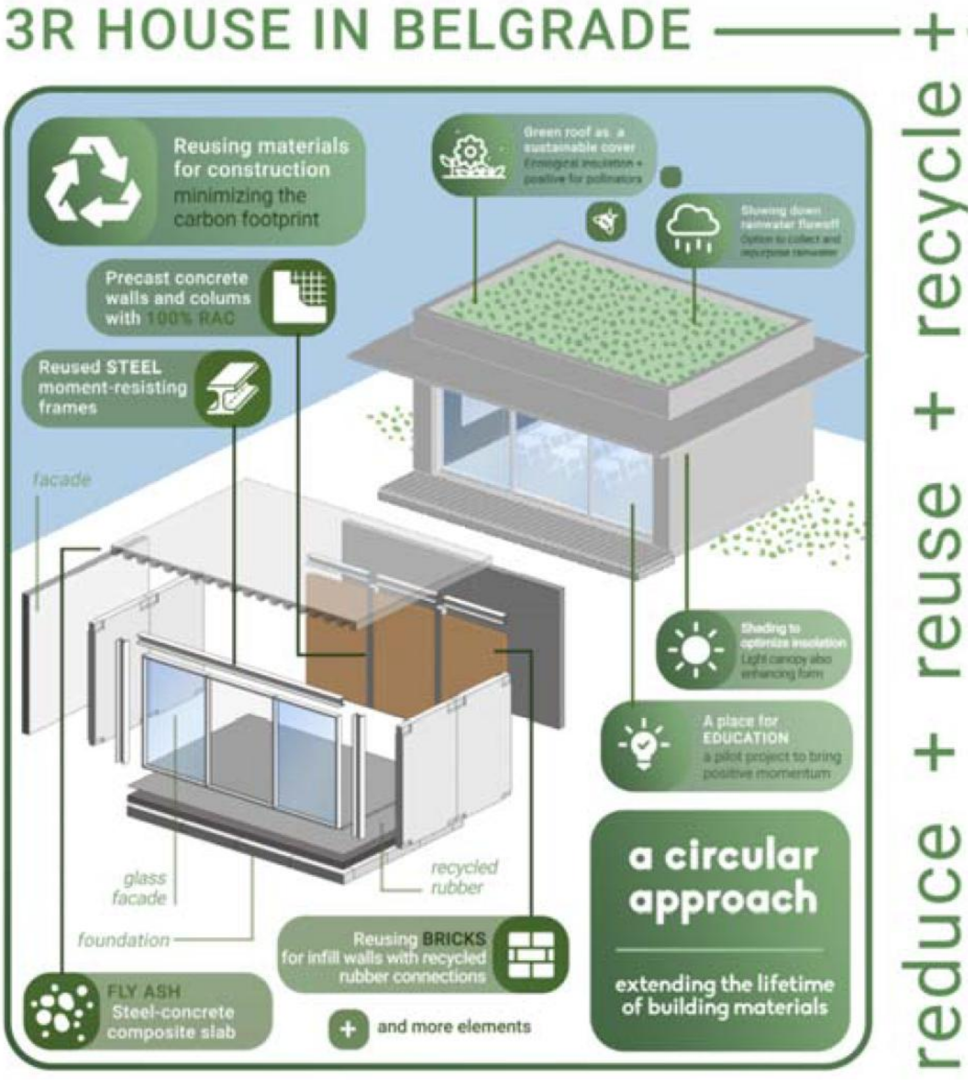


Figure 15. 3R Pilot house incorporating locally sourced secondary materials.

In Serbia, over 0.5 tons of construction and demolition waste (CDW) per capita are illegally dumped each year. This pilot aims to address that issue by integrating recycled CDW into concrete aggregates, reclaimed steel, and masonry bricks. Additionally, fly ash—a by-product of thermal power plants, with more than 300 million tons currently stockpiled in Serbia—will be used as a partial cement replacement, contributing to reduced emissions. Recycled tire rubber, sourced from newly established domestic tire factories, will also be used as a bonding material for masonry walls, further supporting the project's circular and low-carbon objectives. Two types of “green concrete” will be used in the production of this house: (i) Recycled aggregate concrete (RAC) with 100% of recycled concrete coarse aggregate (RCA) and (ii) Fly ash concrete (FAC) made with more than 40% of fly ash as a partial replacement of cement.

The precast foundations will be made with FAC, the precast concrete walls with RAC and a composite slab made with profiled steel sheet and both RAC and FAC concrete will be used as a roof slab. Combination and adaptation of existing connections available in the precast industry will be used to design easy assembly/disassembly connections between all precast elements.

To further enhance the structure's circularity, the steel frame will feature novel adjustable beam-to-column joints using high-strength bolts, along with adjustable connection systems between the composite slab, steel beams, and walls. This will allow for complete disassembly and reuse of the roof structure. Recycled tire rubber will be applied around masonry partition walls to decouple them from surrounding structural elements, improving earthquake resistance and reducing damage and waste. Importantly, any type of brick—regardless of age, strength, or shape—can be used for the masonry walls, including old bricks with reduced load-bearing capacity.

The primary objective of this project is to showcase the practical application of structural elements and solutions developed by the Faculty of Civil Engineering (FCE) in collaboration with industrial partners. By integrating required performance standards with the use of local waste materials, optimized design strategies, and precast construction methods, these innovations aim to promote sustainable and circular building practices across the Balkan region. The project envisions scaling these solutions both horizontally—from laboratory research to real-world implementation—and vertically, evolving from individual components to a fully functional modular house.

The single story 6x4m modular house will be assembled in the backyard of FCE in Belgrade. It will be fully pre-cast, demountable and modular, meaning that modules can be interconnected, creating forms and spaces that can serve larger capacities and more complex needs (See Figure 16).

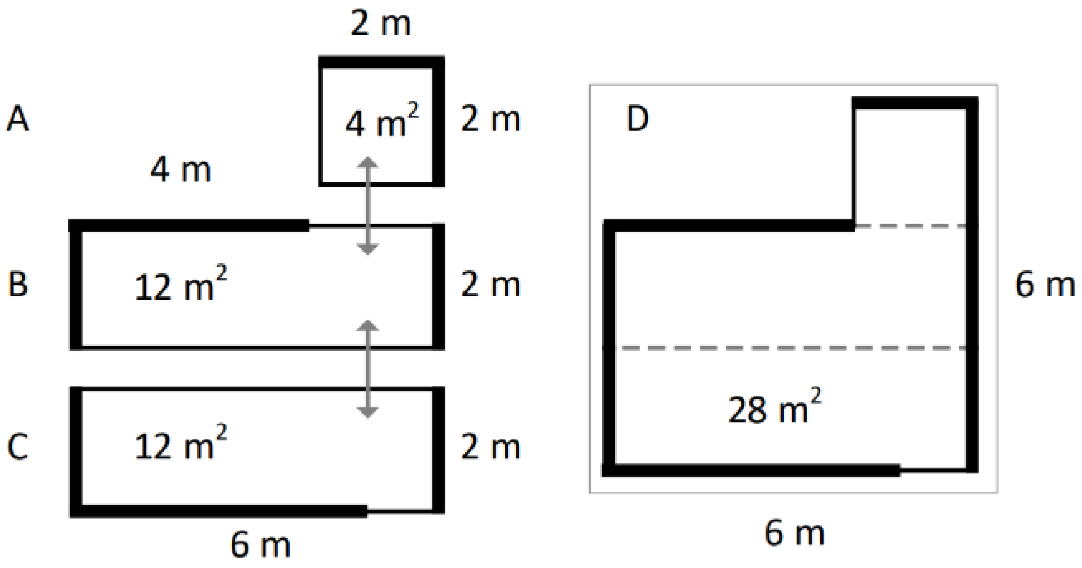


Figure 16. Example of the modularity of the 3R Pilot house in Belgrade.

Modularity of this pilot house will be achieved with all elements made as prefabricated ones with the dimensions that enable easy transport and construction. The circular solutions involved at the material level are:

- Recycled aggregate concrete (RAC) with locally sourced RCA
- Fly ash concrete (FAC) with locally sourced FAC
- Reused steel
- Reused bricks
- Recycled rubber sheets and screed.

After the successful house assembly, and a series of load-bearing tests, the house will be disassembled using the same mechanization as during the initial assembling stage and avoiding any destructive methods. After disassembling, the whole house will be assembled for a second time in the same manner ensuring no destructive techniques are applied during disassembly.

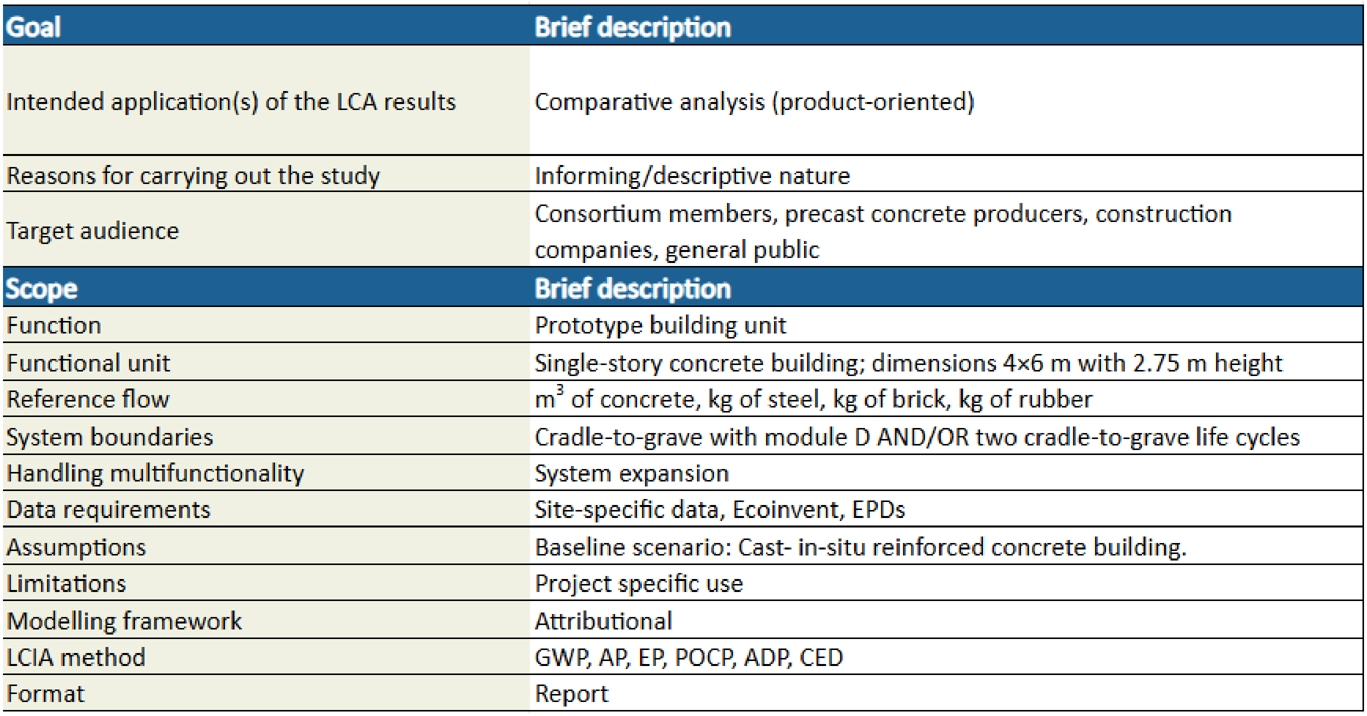
3.3.2 Life Cycle Assessment (LCA)

3.3.2.1 Goal and scope definition

The purpose of the study is to model and assess the environmental, economic and social impact of the pilot for the construction of a modular 3R (reduce, reuse, recycle), Design for Disassembly and Reuse building. The pilot will be assessed as a standalone technology, evaluating the impacts of using recycled concrete, recycled steel, recycled brick and rubber as replacement in the production of new virgin materials, through hotspot analysis as well as a comparison of the environmental impact between the newly introduced technology and the current baseline situation of cast-in-situ building construction in Serbia. For this purpose, the goal and scope for both the current practice baseline and the solution introduced by Pilot 3 must be defined.

An initial meeting was set with the pilot to examine the progress and characteristics of the technology introduced and after a brief introduction to the LCA methodology and goal and scope definition, a template was sent to the pilot leader for completion. Following this, a subsequent meeting was held to review the filled-in template and consolidate the goal and scope main characteristics. The finalized template is presented in the following table:

Table 11. Goal & Scope Template of Pilot 3 (FCE).



Goal	Brief description
Intended application(s) of the LCA results	Comparative analysis (product-oriented)
Reasons for carrying out the study	Informing/descriptive nature
Target audience	Consortium members, precast concrete producers, construction companies, general public
Scope	**Brief description**
Function	Prototype building unit
Functional unit	Single-story concrete building; dimensions 4×6 m with 2.75 m height
Reference flow	m^3 of concrete, kg of steel, kg of brick, kg of rubber
System boundaries	Cradle-to-grave with module D AND/OR two cradle-to-grave life cycles
Handling multifunctionality	System expansion
Data requirements	Site-specific data, Ecoinvent, EPDs
Assumptions	Baseline scenario: Cast- in-situ reinforced concrete building.
Limitations	Project specific use
Modelling framework	Attributional
LCIA method	GWP, AP, EP, POCP, ADP, CED
Format	Report

Goal

Reasons for carrying out the study

The main purpose for conducting this analysis is to assess the performance of the building structure, from a life cycle perspective, via a comprehensive sustainability assessment at all three pillars of sustainability (environmental, economic, social). The LCA study, along with the LCC and S-LCA studies aim at the identification of the respective environmental, economic and social impact hotspots within the different life cycle stages of the implementation of the FCE proposed solution through a hotspot analysis. The reasons for carrying out the study are of informing and descriptive nature.

Intended audiences

According to the declared applications of the study, the LCA study spanning across D5.1 and D5.2 is intended to be addressed to following audiences:

- The technology provider (Evrobrod-EBR, PENTA, SDA-engineering)
- The local partner (FCE)
- The European Union, as the main funding institution of the Circ-Boost project
- The European Commission, as the main reviewing mechanism of the Circ-Boost project
- Circ-Boost consortium members
- Civil engineers
- Architects
- Researchers
- Ready-mix concrete producers
- Precast concrete producers
- Construction and demolition companies
- Contractors
- The Serbian government and Belgrade municipality
- Policy makers,
- Standardization bodies
- Local community
- General public

Comparative assertions

The LCA study that is initiated in D5.1 and will be concluded in D5.2, is partially intended to support comparative claims meant for public disclosure via the conduction firstly of an independent LCA and afterwards a comparative LCA against the baseline scenario which is the cast-in-situ construction with traditional concrete in the geographical context of the Belgrade region. This intention does not stem from commercial competitive purposes, but purely from a scientific research point of view. Therefore, no external review (besides the review procedure prescribed by the project's Grant/Consortium Agreements) will be necessary for the Deliverables 5.1 and 5.2, according to ISO 14040:2006 and ISO 14044:2006.

Scope

Functional Unit

In the context of building life cycle assessment (LCA), the functional unit provides a consistent basis for comparing different construction solutions. In this case, the functional unit of the analysis is a 1 single-story concrete building of gross floor area (GFA) of 24m^2 and a reference study period of 100 years for both the baseline and the Circ-Boost solution, since they have the same dimensions. The total gross floor area (GFA) is calculated based on the dimensions L= 4m x W=5m of the designed buildings. The height H=4.4m is not included in the calculation.

At building level, *the functional equivalent* complements the functional unit by defining the material flows and structural requirements necessary to deliver the same physical performance over the reference period. In this study, the functional equivalent is defined as a single-story structural building system with a gross floor area of 24 m² (L = 4 m, W = 6 m, H = 4.4 m), designed to provide equivalent structural performance and durability over a total 100-year reference study period. Both systems—the conventional cast-in-situ concrete structure and the DfD/R (Design for Disassembly and Reuse) solution—are conceptual in nature and located in Belgrade, with no assigned occupancy, thermal comfort requirements, or specific utility functions.

To fulfill this functional equivalent, the reference flows represent the quantities of materials entering the system. These include concrete and steel—used together to meet both compressive and tensile performance requirements—as well as bricks for masonry and rubber for structural decoupling. In the P3 Circ-Boost solution, two types of concrete are used: recycled aggregate concrete (RAC), incorporating up to 100% recycled aggregate, and high-volume fly ash concrete (HVFAC), with over 40% fly ash replacing cement. Reused steel, reused bricks, and recycled rubber are also included. In contrast, the baseline scenario relies on natural aggregate concrete (NAC), conventional steel reinforcement, and standard bricks.

Thus, the reference flows for both buildings are expressed in cubic meters (m^3) of concrete and kilograms (kg) of steel, bricks, and rubber. These flows reflect the material inputs required to meet the functional equivalent and enable a consistent comparison with the traditional in-situ construction approach.

The comparison includes two construction approaches:

- A conventional cast-in-situ system that is constructed, used for 50 years, demolished, constructed a-new, and used for an additional 50 years before final demolition.
- A Design for Disassembly and Reuse (DfD/R) system that is assembled, used for 50 years, disassembled, reassembled, and used for another 50 years before final disassembly.

System boundaries

The methodology adopted in this study follows the process-based LCA approach for both the baseline (cast-in-situ) and the DfD/R building alternative. Specifically, it adheres to the modular framework defined in EN15978, ensuring a consistent and transparent assessment of environmental impacts across all relevant life cycle stages. This framework is illustrated in Table 12 and includes stages A1–A5 (production and construction), C1–C4 (end-of-life), and D (benefits and loads beyond the system boundary).

As shown in Table 12, modules B1-B7, representing stages related to the use, maintenance, repair and refurbishment of the building, have not been included in this analysis as this study is focused on the impacts of the building materials throughout their lifecycle, excluding impacts from the building's operational stage. Since, A1-A3, A4-A5, C1-C4, D modules are included in this study, this represents a "cradle-to-gate with options" system boundaries as per EN 15978 (CEN, 2011).

Table 12. Stages included in the LCA analysis of Pilot 3 reference and solution based on EN15978.

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction / inst. process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse/recovery/recycling
x	x	x	x	x	-	-	-	-	-	-	-	x	x	x	x	x

To accurately reflect the construction, deconstruction and subsequent construction of the DfD/R (Design for Disassembly and Reuse) solution, its assessment is modeled through two consecutive "cradle-to-gate with options" lifecycles. In this scenario, the modular building is initially assembled, used for 50 years, and then disassembled. The disassembled components are subsequently reassembled into an identical structure, which undergoes another 50-year use phase before final disassembly—completing two full cycles.

For a fair comparison, the baseline in-situ structure is also assigned a design service life of 50 years. However, due to its non-reusable nature, and in order to match the total service life of 100 years of the DfD/R house it is assumed to be constructed and demolished after 50 years, followed by the construction of a new, identical structure to serve for another 50 years. This comparative lifecycle approach for the baseline and the DfD/R building is more effectively illustrated in Figure 17 and Figure 18 respectively and further elaborated in the following sub-sections for the baseline and Circ-Boost solution.

Baseline scenario

For the baseline scenario, the dual-lifecycle approach and the processes taking place in each module is illustrated in Figure 17.

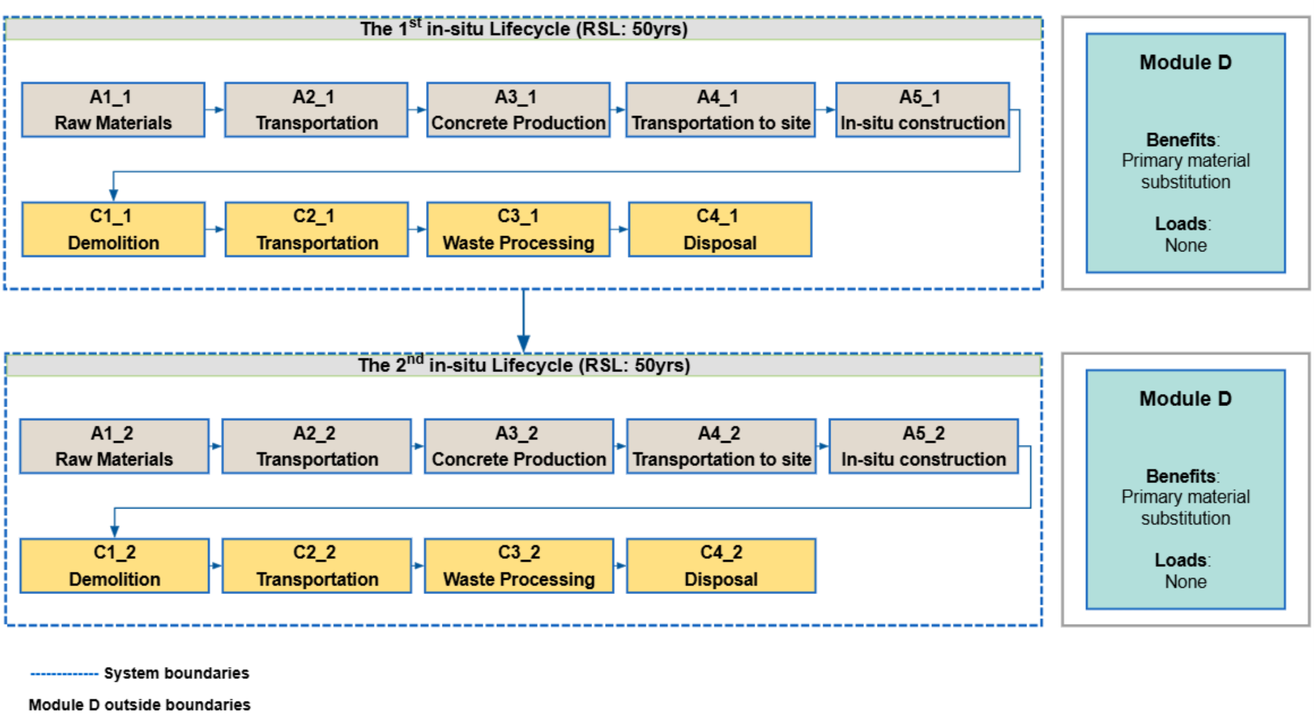


Figure 17. System boundaries of the dual-lifecycle approach applied to the Pilot 3 baseline in-situ structure.

Modules A1_1 to C4_1 represent the first lifecycle, encompassing the initial construction and end-of-life stages of the original cast-in-situ building. The second lifecycle, which involves reconstructing the same type of building, is captured by modules A1_2 to C4_2. Module D is outside the system boundaries of the life cycle assessment (LCA) because it accounts for future environmental impacts or benefits from the reuse, recycling, or energy recovery of materials after the product's end-of-life. It reflects how recovered materials might offset impacts in other systems, beyond the current product's life cycle.

The number following the underscore (e.g., "_1") indicates the number of the life cycle. For instance, "_1" refers to the first life cycle, while "_2" would refer to the second. The processes included in each module LCA analysis of P3 for the reference cast-in-situ are briefly explained below. The following breakdown is identical for both lifecycles depicted in Figure 17, therefore the modules are explained once.

- **Modules A1 – A3**: These modules include the supply and extraction of raw materials (cement, recycled aggregate, filler, water, plasticizer, reused steel, reused brick), transportation to plant (A2) and production of all building materials (concrete batching, reinforcement cutting/bending, brick manufacturing in A3), until the gate of the factory.
- **Modules A4 – A5**: These stages refer to the transportation of building materials (concrete mix, reinforcement, bricks, mortar) to the construction site (A4) and the use of equipment/machinery for the in-situ construction of the building (A5). The preparation of the terrain for the construction of the building, the installation of auxiliary infrastructures and the construction of access to the construction site are not considered.
- **Modules C1 – C4**: These modules include all relevant data, addressing the end-of-life of the building. This includes the use of equipment and machinery for the demolition of the building (C1), transportation of demolition waste to the recycling plant (C2) and sorting, crushing and processing of materials (C3) and final stage of disposal (C4). In the current business-as-usual recycling scenario, bricks and rubber are assumed to be disposed of until further information becomes available.
- **Module D**: After processing in C3, crushed concrete is typically split into 50% coarse and 50% fine aggregate. The coarse fraction, when used in road construction without further processing, is credited in Module D for substituting primary materials, with no additional environmental loads. The fine fraction currently has no practical application in Serbia and is sent to landfill, with its impact reported in Module C4. Additionally, steel is sent for scrap recycling, and the pig iron substitution is accounted for in the benefits reported under module D.

Circ-boost solution

For the Design for Disassembly and Reuse (DfD/R) solution proposed by P3, the dual-lifecycle approach is illustrated in Figure 18. The first lifecycle includes modules A1_1 to C4_1, which represent the initial construction and eventual disassembly of the modular and deconstructable house after 50 years. However, due to the reusability of structural components, modules C2_1 to C4_1—typically associated with the transport, processing, and disposal of demolition waste—are excluded for reusable materials, because these are reintegrated into the second construction cycle.

As a result, in the second lifecycle, modules A1_2 to A3_2, which typically account for raw material extraction, transportation, and the production of new building elements, are also excluded from the second lifecycle boundaries, reflecting the reuse of the previous building elements. By modelling in a dual-lifecycle approach and leaving out stages C2_1 to C4_1 in the first lifecycle and A1_2 to A3_2 in the second lifecycle, the environmental benefits from avoiding these stages, are counted directly within the system boundaries. This means the savings are included in the main lifecycle results, rather than being treated as future or external benefits.

Nevertheless, as previously discussed, a portion of the materials will not be reusable and will follow the conventional waste processing and disposal route. Accordingly, new materials must be introduced in the second lifecycle to count for the substitution of these non-reusable components. This is represented by modules C2_1, C3_1, and C4_1 for the non-reusable materials, and A1_2, A2_2, and A3_2 for the replacement materials, all highlighted in green in the diagram.

Once more, module D lies outside the system boundaries, as it accounts for the environmental benefits and burdens associated with the use of by-products from this product system by subsequent systems. In the DfD/R case, each lifecycle is followed by its own Module D. Similarly, since the structure will be disassembled and reassembled on site, it is assumed that no transportation between the first and the second cycle is needed.

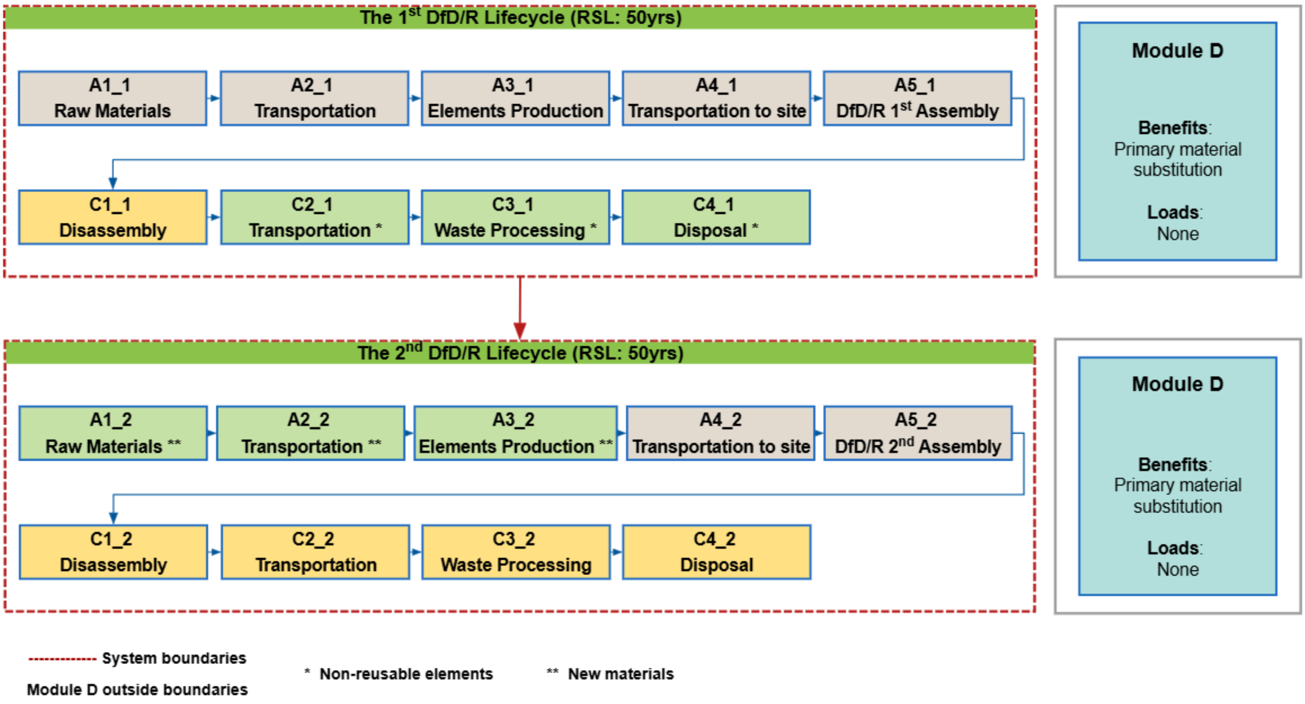


Figure 18. System boundaries of the dual-lifecycle approach applied to the Pilot 3 DfD/R structure.

The processes included in each module of the system boundaries of P3 for DfD/R are briefly explained below. The number following the underscore (e.g., "_1") indicates the number of the life cycle. For instance, "_1" refers to the first life cycle, while "_2" would refer to the second.

- **Modules A1_1 – A3_1**: These modules include the raw material supply (cement, recycled aggregate and brick and steel), their transportation to the precast producer (A2_1) and production of all building elements (foundations, walls, slab, roof in A3_1), until the gate of the factory.
- **Modules A4_1 – A5_1**: These stages refer to the transportation of the DfD/R building elements to the construction site (A4_1) and the use of equipment/machinery for the assembly of the building (A5_1). The preparation of the terrain for the construction of the building, the installation of auxiliary infrastructures and the construction of access to the construction site are not considered.
- **Modules C1_1 – C4_1**: These modules include all relevant data, related to the 1st end-of-life of the building. These refer to the use of equipment and machinery for the deconstruction of the walls, slab and roof (C1_1), transportation of non-reusable elements (e.g. concrete foundations, steel connectors) to the recycling plant (C2_1), sorting, crushing and processing of materials (C3_1) and C4_1 for final disposal. Stages C2_1, C3_1 and C4_1 apply only to the non-reusable elements and are omitted for the reusable ones. Specifically, 50% of fine recycled aggregate fraction after concrete crushing, cannot be reused or recycled, thus, it ends up in the landfill.
- **Module D_1**: This module allocates net benefits and loads from the reuse, recycling and recovery of materials in the next product system. In this case, the benefits include avoided natural aggregate production and avoided pig iron production. Regarding loads, since the 50% of useful coarse aggregate fraction is used without further processing, there are no loads credited in module D. In contrast, if recycled steel is produced through melting for use in a subsequent product system, the associated environmental loads will be accounted for in module D. However, this will be confirmed once more data becomes available.

The second cycle begins with raw material extraction for non-reusable components—specifically, new concrete for foundations and new steel for connectors. These initial phases (A1–A3) apply only to non-reusable elements. The reusable components, after disassembly, are transported to a new site (A4_2) and reassembled (A5_2). Following the use phase, the building is disassembled for a second time, and all building is then either recycled or landfilled. Module D in the second cycle reflects the same benefits and loads as in the first. The key difference between the two DfD/R cycles lies in the quantity of concrete recycled: in the first cycle, only the foundations and steel connectors are recycled, while in the second, the entire house is subject to recycling. In particular, in the second lifecycle of the DfD/R building the following modules take place:

- **Modules A1_2 – A3_2**: These modules include the inserting of new materials that replace the non-reusable elements (concrete, reinforcement steel), their transportation to the precast producer (A2_2) and production of the precast elements (concrete foundations, steel connectors) that substitute the non-reusable elements (A3_2), until the gate of the factory. These modules don't apply to reusable elements.
- **Modules A4_2 – A5_2**: These stages refer to the transportation of the newly manufactured DfD/R elements and the previous reusable elements to the construction site (A4_2) and the use of equipment/machinery for the 2nd assembly of the DfD/R building (A5_2). In this case, it is assumed that the 2nd assembly takes place in a new construction site, thus some distance is involved. Therefore, the A4_2 applies both to the transportation of both the reusable elements and newly manufactured materials to the new site. The preparation of the terrain for the construction of the building, the installation of auxiliary infrastructures and the construction of access to the construction site are not considered.
- **Modules C1_2 – C3_2**: These modules include all relevant data, related to the 2nd end-of-life of the building. These refer to the use of equipment and machinery for the deconstruction of the foundation, walls and roof (C1_2), transportation of all materials to the recycling plant (C2_2) and waste processing of all materials (C3_2), and disposal of the fraction of materials that are not reusable (e.g. fine aggregate fraction) in module C4_2.
- **Module D_2**: Similarly to the first cycle, since the useful fraction of concrete requires no further processing, no loads are credited in module D. Additionally, the benefits include avoided natural aggregate production and pig iron production.

3.3.2.2 Multifunctionality

In Life Cycle Assessment (LCA), multifunctionality occurs when a system delivers multiple outputs that require allocation of environmental impacts. However, in this study, both the reference and DfD/R buildings are single-function products, and inputs like natural aggregates and steel are not co-products—so no allocation is needed on the input side.

At end-of-life, waste can either be processed for reuse (Module C3) or landfilled (Module C4). These are alternative paths for the same waste stream, not co-products, so no output-side allocation is required. Each route is modeled separately with its own impacts.

This study follows the Polluter Pays Principle (PPP) per EN 15804 (CEN, 2019), assigning all waste treatment impacts—such as crushing and sorting—to the original building system, and modeling them in Module C3.

In contrast, Module D accounts for the environmental benefits of material recovery by crediting the system for displacing primary materials—such as aggregates and steel—in future applications. To capture these avoided burdens, the study applies system expansion in line with EN 15804 and EN 16757 (CEN, 2019, 2022)allowing the inclusion of benefits that occur beyond the system boundary. Additionally, any environmental loads associated with further processing of recovered materials and their transportation to the next user are also assigned to Module D.

3.3.2.3 Assumptions and limitations

- Firstly, both the reference in-situ scenario and the DfD/R building are assessed over two life cycles, with each cycle having a design service life of 50 years, resulting in a total assessment period of 100 years.
- Different type of concrete is used for the reference and the reusable structure. Natural aggregate concrete (NAC) is considered for the reference structure and two types of green recycled concrete for the DfD/R building (RAC and FAC). Also reused steel, recycled rubber and reused brick will be used in the DfD/R building, in conjunction with virgin materials used in the reference in-situ building.
- EN 16757 outlines two end-of-life scenarios for crushed concrete: (i) use in road construction without further processing, which yields environmental benefits and no loads credited in Module D; and (ii) use in fresh structural concrete, which requires additional processing and includes both benefits and associated loads in Module D. Crushed concrete is not currently used in Serbia for producing new structural concrete but is instead subject to downcycling, primarily for road construction thus no additional loads are considered in module D.
- The processed material is estimated to be separated into two fractions: approximately 50% coarse aggregate, which is reused in road subbase applications without further processing and credited in Module D, and 50% fine aggregate (<4 mm), which currently lacks practical application and is landfilled, with its environmental impacts reported in Module C4.
- In the absence of detailed data on end-of-life treatment for most building materials in Serbia's business-as-usual scenario, disposal is assumed for brick and rubber. Scrap steel is considered to be recycled; however, additional data are needed to confirm this assumption.
- For both the reference and the DfD/R building systems, it is assumed that within the dual lifecycle approach, materials recovered at the end of the first 50-year lifecycle are not reused as input materials in the second lifecycle. Instead, they are either processed for use in external product systems beyond the scope of this study or are directed to landfill.
- DfD/R: Foundations and steel connectors are considered non-reusable elements in the second lifecycle. In current Serbian practice, foundations are treated like any other concrete waste—transported to recycling facilities. Steel connectors, likely to be damaged during disassembly, are also assumed not to be reused. Therefore, Modules C2_1 to C4_1 account only for these non-reusable components. In Module D, of the first cycle, any benefits relate to the potential recycling of the foundations and possibly the steel, if such recycling aligns with business-as-usual practices in Serbia.
- DfD/R: Reusability is modelled within the system boundaries rather than in Module D, as it forms part of the second lifecycle and allows for meaningful comparison. Thus, benefits and loads of reusability are directly carried into the second cycle.
- DfD/R: All reusable elements are assumed to remain undamaged after the first lifecycle and will not be remanufactured. They are considered suitable for reuse in their original state for an additional 50-year lifecycle, without requiring any modification or repair.
- Reference in-situ: For the reference in-situ scenario, it is assumed that the second lifecycle is identical to the first, in terms of concrete. Although future technologies will likely differ from those used today over the next 50 and 100 years, in this study these changes are not considered for simplification and in order to maintain consistency across both cycles. This simplification may be addressed in future sensitivity or uncertainty analyses.
- DfD/R: This assumption about future technologies does not relate to the reusable house. Since components like columns are produced in the first cycle and reused in the second, they retain the environmental profile of their original production.

- DfD/R: It is reasonable to assume that a reusable house will not be reconstructed on the same site. As a result, transportation distance becomes a relevant factor influencing environmental impacts. A representative distance will be selected for the case study, with the potential for further analysis of different scenarios.

3.3.2.4 Cut-off criteria

A 1% cut-off criterion will be applied for excluding processes the impact of which contributes less than 1% of the total impact per selected impact category.

3.3.3 Life Cycle Costing (LCC)

During Task 5.1, the goal and scope of the Life Cycle Costing (LCC) assessment for Pilot 3 were clearly defined, ensuring full alignment with the framework conditions of the environmental Life Cycle Assessment (LCA). This alignment includes the use of consistent system boundaries and a shared functional unit, thereby guaranteeing coherence between environmental and economic evaluations.

The system boundaries for the LCC of Pilot 3 encompass modules A1-A3, A4-A5, C1-C4, and D, following a dual lifecycle approach that mirrors the structure of the environmental LCA framework.

Data collection for Pilot 3 is scheduled to begin in the coming months and will draw from both primary and secondary sources. The pilot will provide average cost estimates for key life cycle elements, including raw materials, transportation distances, construction and deconstruction activities, and replacement parts. Where pilot-specific data is not yet available, secondary sources—such as literature and price databases—will be used to fill gaps. All cost-related inputs will be gathered using a standardized LCC inventory template developed within the project.

Finally, the Life Cycle Costing analysis phase will commence after Month 30, with the launch of Task 5.3, and will continue until Month 47. This phase will incorporate both fixed and variable costs provided by the involved partners, as well as external costs—indirect social costs typically associated with environmental degradation and emissions. These externalities will be quantified and included in the final deliverable, D5.2.

3.3.4 Social Life Cycle Assessment (S-LCA)

The Social Life Cycle Assessment of the current study relies on the general framework described in section 2.3.1 adjusted to the pilot case's particular objectives. The following section presents the methodology's application to define the goal and scope for Pilot 3 (FCE).

3.3.4.1 1 Goal and Scope

The goal of the study

This Social Life Cycle Assessment (S-LCA) aims to identify and evaluate the potential social benefits and impacts associated with the use of recycled building materials—specifically reused recycled aggregate concrete (RAC), fly ash concrete (FAC), rubber, steel, and bricks—combined with the Design for Deconstruction and Reuse (DfD/R) approach in the Serbian construction sector. The analysis compares a pilot scenario incorporating these materials and techniques with a baseline scenario based on conventional construction practices and materials. In the pilot scenario, reused materials are partially integrated (e.g., 40% FA instead of cement) in block building components. By focusing on the current product system and geographic context of Serbia, the study explores both positive and negative social implications for stakeholders such as construction workers, material suppliers, local communities, and policymakers. The findings will be of interest to public authorities, construction and material production companies, recycling firms, sustainability consultants, circular economy practitioners, and academic researchers. Results will be used to inform future policy development, support circular procurement strategies, and guide the design of socially responsible construction practices in Serbia and beyond.

1.2 Functional unit

The functional unit for the specific S-LCA is consistent with the one used in the LCA and LCC studies. However, unlike LCA and LCC, the social impacts and effects in the S-LCA are not currently expected to be quantitatively scaled to the functional unit. Nevertheless, this decision will be addressed in the later stages of the Social LCA study. As outlined in the environmental LCA goal and scope chapter of Pilot 3, chapter 3.3.2.1, the functional unit is defined as 1 single-story concrete building of gross floor area (GFA) of 24m^2 and a reference study period of 100 years for both the baseline and the Circ-Boost solution, since they have the same dimensions.

System boundaries

The system boundaries for this Social Life Cycle Assessment (S-LCA) of Pilot 3 are aligned with those of the environmental LCA and defined in accordance with EN 15804 and EN 15978 (CEN, 2011, 2019) covering all relevant activities of the examined construction system. They encompass all relevant activities of the examined construction system over the span of a dual lifecycle.

These include raw material extraction (A1), transportation (A2, A4, C2), building materials production and processing (e.g., engineered precast panels) (A3), building construction and site operations (A5) and end-of-life treatment (C1-C4). The disposal stage (C4) is included in Pilot 3, because part of the demolished materials is not suitable for reuse, and it is sent to landfill.

In contrast to the LCA and LCC studies, this assessment explicitly incorporates the use phase, driven by the potential social impacts directly affecting consumers and users during building operation. This means that Module B1 representing the use stage has been included, excluding though the rest of the B modules associated with maintenance, repair, and refurbishment of the building.

Moreover, Module D—typically addressing future reuse and recycling benefits—is excluded due to its reliance on long-term assumptions and limited connection to current stakeholder impacts.

Finally, this S-LCA adopts a dual lifecycle approach for both the baseline and the Circ-Boost solution, enabling a comparative analysis of potential social impacts within the defined boundaries.

Consequently, the system boundaries for the S-LCA include Modules A1–A3 (product stage), A4–A5 (construction process stage), B1 (use stage), and C1–C4 (end-of-life stage), covering two consecutive life cycles. In Figure 19, the system boundaries are depicted using a single illustration for both the baseline and the Circ-Boost solution, for simplicity and visual clarity.

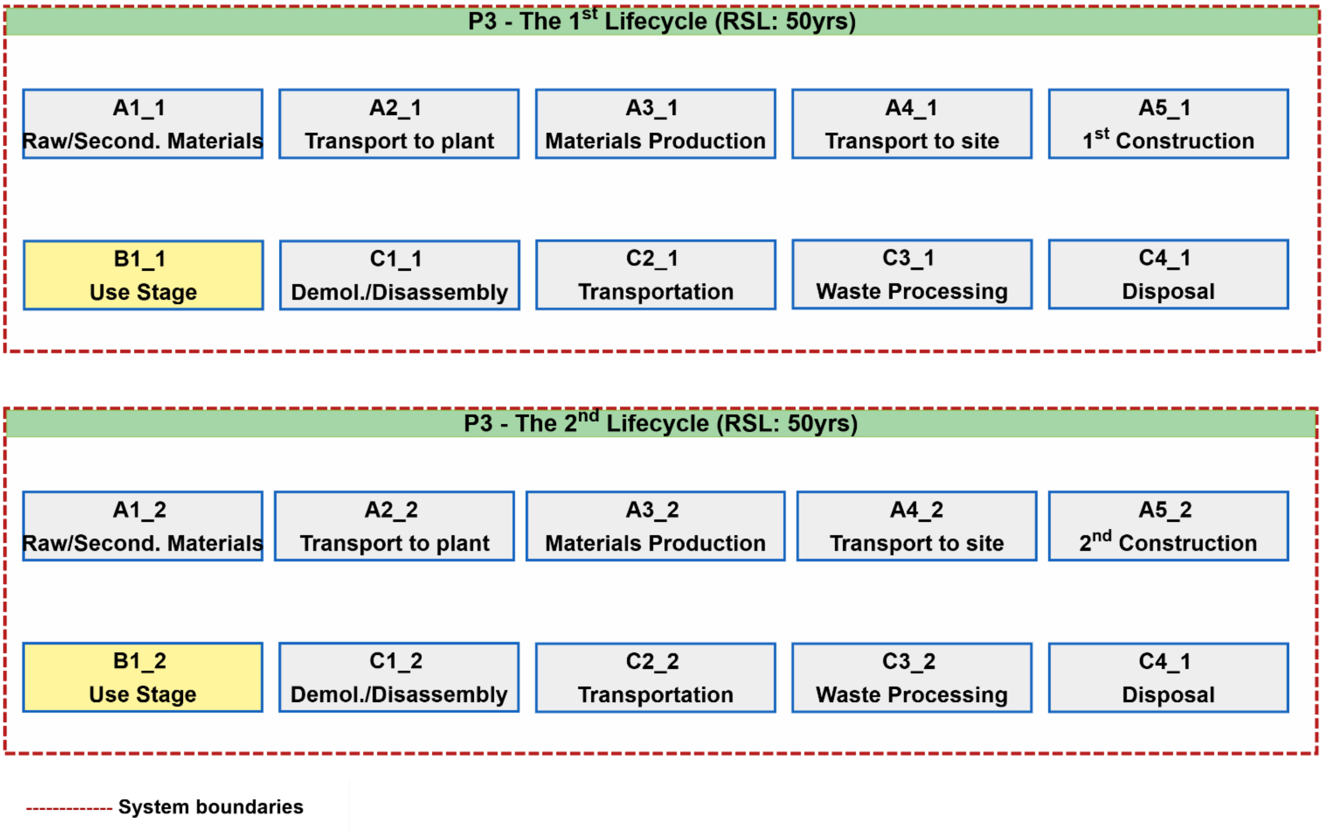


Figure 19. Social LCA system boundaries of Pilot 3, covering both the baseline and solution within the dual lifecycle approach.

Stakeholders' selection

Stakeholder groups were considered separately for each life cycle stage, as defined by (Benoît Norris et al., 2020). These categories were further refined into subcategories based on the stakeholder mapping conducted in Circ-Boost Task 2.2 and inputs from pilot partners. This approach ensures that the analysis is both methodologically robust and contextually relevant to the construction sector. A definition of the selected stakeholders, along with their type of relationship to the system, is presented in Table 13 for both the 3R Design for Disassembly/Reuse (DfD/R) and the conventional in-situ building of Pilot 3. Corresponding life cycle modules (in parentheses) indicate where each stakeholder group is involved.

Table 13. Definition of the stakeholder categories across S-LCA stages of Pilot 3's DfD/R and conventional in-situ building case, with corresponding life cycle modules indicated in parentheses.

Stakeholder group	Stakeholder Subcategory/Sub-Stakeholders	Definition	Type of relation
Workers	Primary material extraction workers: (NA, Cement, Steel, Brick, Rubber) | [baseline+pilot] (A1)	Employees involved in the extraction and initial processing of raw materials used in the construction sector.	Affected – they are affected by the system's practices and decisions.
	Secondary recycled material workers: (Recycled aggregate, Fly ash, Steel, Brick, Rubber) receiving/preprocessing workers [pilot] (A1)	Employees in secondary material collection facilities handling the intake and preparation of recycled materials for reuse in construction, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.

	Building material production workers: Building Panels/Concrete mix (A3)	Employees within the building material production sector, who work in precast concrete and concrete mix industry, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Construction workers/Equipment operators (A5)	Employees working within the construction sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Deconstruction/Demolition Workers (C1)	Employees working within the building deconstruction/demolition sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Recycling workers (C3)	Employees working within the CDW processing and recycling sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Landfill workers (C4)	Employees working within the landfill sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Transportation workers (A2, A4, C2)	Employees working in the transportation sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
Society	Academic Research Institutions	Bodies that execute applied research to find/test new applications in sustainable construction and circular economy.	Concerned – they are concerned by the environmental, social and economic performance of available products/technologies in the market. They develop novel products and conduct research studies for technology progress purposes.
			Involved – they are involved in the decision-making process.
	General Population (A1-A3, A5, B1, C1-C4)	Citizens and communities indirectly affected by the environmental, economic and social impacts of raw material savings, building materials production, construction, end-of-life processes.	Affected – they are affected by the system's practices and decisions and by economic performance of public buildings.
	Not-for-profit association committed to advancing the technical, economic, aesthetic and environmental performances of concrete structures worldwide (A1-A3)	Organizations engaged in the promotion of ecofriendly, sustainable and climate-smart technologies/materials and innovations.	Concerned – they are concerned by the environmental, social and economic performance of available products/technologies in the market and influence the

			promotion of sustainable practices.
	Policy Makers (C1-C3)	Government officials and institutions responsible for creating policies and regulations related to construction, waste, and sustainability.	Directly involved – they shape the legislative and strategic environment that enables or constrains the adoption of new solutions.
Local community	Neighborhood near virgin raw material extraction [baseline and pilot] (A1)	Residents living in proximity to sites where virgin raw materials (e.g. natural aggregates, limestone, clay) are extracted.	Affected – their well-being and environment may be influenced by extraction activities and associated infrastructure.
	Neighborhood near companies receiving/pre-processing secondary material [pilot] (A1)	Residents living near facilities that receive and pre-process secondary materials (e.g., recycled aggregates, fly ash, reclaimed steel).	Affected – they may experience impacts in the local environment e.g. noise, emissions.
	Neighborhood near concrete panel & concrete mix production facilities (A3)	Residents living close to facilities where building panels/components and concrete mix are manufactured.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
	Neighborhood near panel assembly facilities/construction site (A5)	Residents living near the location where DfD/R or in-situ buildings are assembled or constructed.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
	Neighborhood near deconstruction/demolition facilities (C1)	Residents close to sites where buildings are dismantled or demolished.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
	Neighborhood near waste processing/recycling plants (C3)	Residents living near facilities that process construction and demolition waste (CDW) for recycling.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
	Neighborhood near disposal landfill (C4)	Residents living near landfill sites used for construction waste disposal.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
Value chain actors	Primary & secondary material supply companies (A1)	Companies that extract/receive construction materials intended for manufacture building components.	Directly involved – they respond to project requirements and influence material availability, quality and circularity.
	Building materials production companies (suppliers) (A3)	Companies that produce construction elements/materials, including panels and concrete mix.	Directly involved – they respond to project requirements and influence material availability, quality and circularity.

	Material technology development companies (A1-A3)	Firms engaged in R&D and innovation related to construction materials, including durability, recyclability, and performance.	Directly involved – they enable circular design through material innovation and life-cycle optimization.
	Equipment/machinery companies (A5)	Providers of machinery used in the construction/assembly of buildings.	Directly involved – they supply the tools necessary for efficient construction.
	Construction technology development companies (Architectural bureau/Design bureau/Investor) (A5)	Stakeholders involved in designing, planning, and financing of buildings.	Directly involved – they shape project execution through design choices and strategic direction.
	Deconstruction/Demolition companies (C1)	Companies specialized in dismantling buildings and recovering materials.	Directly involved – they execute end-of-life activities and influence reuse and recycling potential.
	Recycling companies (C3)	Entities responsible for processing and managing construction and demolition waste.	Affected – they are affected by variations of waste volumes and may need to adapt to changing material flows.
	Landfill companies (C4)	Companies that manage the disposal of construction waste that cannot be reused or recycled.	Affected – their role may diminish or shift depending on material recovery and waste minimization efforts.
	Transportation companies (A2, A4, C2)	Entities responsible for transportation services of materials/waste.	Affected – they are affected by the system's practices and decisions regarding flow volumes of materials, products and waste and transportation distances.
Consumers	Private individuals as building buyers (private use)/Local and regional authorities or regulators as buyers (public use) (A5 & B1)	Individuals or entities purchasing buildings for private use.	Directly involved – they make purchasing decisions and influence market demand for the building sector. Affected - they are affected by economic performance of the building and the building construction processing time.

Impact categories and indicators

Stakeholder groups and subcategories were identified and mapped to each life cycle stage based on the modular structure of EN 15804. Each subcategory was then linked to relevant impact categories, which were subsequently connected to specific indicators. This correlation is presented in Table 14. It should be noted that Social Life Cycle Assessment (S-LCA) is inherently an iterative process, and the final selection of indicators will be determined based on data availability during the assessment phase. As the project progresses, certain indicators may be added or removed to reflect the realities of data accessibility, stakeholder input, and contextual relevance.

Table 14. Indicators selection for DfD/R and conventional in-situ building in Serbia (P3-FCE).

Life Cycle Stage	Stakeholder Group	Stakeholder Sub-Category	Impact Category	Indicator
A1 _ Raw material extraction / supply **A2** _ Transportation of materials to concrete plant **A3** _ Production of building materials / elements (concrete mix / precast elements in concrete plant)	**Workers**	Raw materials production (Primary material extraction workers (NA, Cement, Steel, Brick, Rubber) **vs** secondary recycled material (RA, FA, Steel, Brick, Rubber) receiving / preprocessing workers (A1)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Hours of Paid Employment (for all employees)
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Building materials/elements production workers (concrete mix **vs** concrete panels) (A3)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Hours of Paid Employment (for all employees)
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Transportation workers (A2)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
	Local Community	Neighborhood near the raw material production sites (virgin material extraction **vs** the secondary material production) (A1)	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
		Neighborhood near to building materials/elements production facilities (concrete mix vs concrete panels) (A3)	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
	Society	General population	Contribution to Circular Economy and Resource Efficiency	Raw materials savings (from the second life cycle as panels are reused from the first cycle and from

				the replacement of extracted materials with recycled materials used in the beginning of the first life cycle)
			Public health	Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
			Climate Change Adaptation and Societal Resilience (if LCA shows that it is affected due to emissions)	Reduced Societal Vulnerability to Climate Change Impacts
		Academic Research Institutions	Knowledge & Innovation	Contribution to R&D and Knowledge Dissemination on Sustainable Concrete
		Not-for-profit association committed to advancing the technical, economic, aesthetic and environmental performances of concrete structures worldwide	Knowledge & Innovation	Contribution to R&D and Knowledge Dissemination on Sustainable Concrete
	Value Chain Actors	Raw material companies (Primary material extraction companies vs Secondary recycled material receivers/pre-processers companies) (A1)	Economic growth/ Economic contribution	Factor Tax Payments
		Building materials production companies (suppliers) (A3)	Economic growth/ Economic contribution	Factor Tax Payments
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
			Affordability of raw materials for concrete producers	Affordability of raw materials for concrete producers
		Material Technology development companies	Economic growth/ Economic contribution	Factor Tax Payments
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
			Innovation & Contribution to Sustainable Construction	Development and Commercialization of Sustainable Material Technologies

			Contribution to Industry Advancement and Sustainable Construction	Development and Commercialization of Sustainable Material Technologies
		Transportation companies (A2)	Economic growth/ development	Factor Tax Payments
A4 _ Transportation of ready concrete mix / precast elements to construction site **A5** _ Construction / Assembly of building	**Workers**	Construction workers / Equipment operators (A5)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Transportation workers (A4)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
	Local Community	Neighborhood near to panel assembly facilities **vs** construction site	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
	Society	General population (public is affected by more sustainable practice e.g. GHG, resources - data derived from LCA)	Public health	Air quality
			Climate Change Adaptation and Societal Resilience	Reduced Societal Vulnerability to Climate Change Impacts
	Value Chain Actors	Equipment/machinery companies	Economic growth/ development	Factor Tax Payments
				Investment in new technologies/equipment
		Construction technology development companies (Architectural bureau/Design bureau/Investor)	Economic growth/ Economic contribution	Factor Tax Payments
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
			Innovation & Contribution to Sustainable Construction	Development and Commercialization of Sustainable Material Technologies

			Contribution to Industry Advancement and Sustainable Construction	Development and Commercialization of Sustainable Material Technologies
		Transportation companies (A4)	Economic growth/ development	Factor Tax Payments
	Consumer	Private individuals as building buyers (private use) / Local and regional authorities or regulators as buyers (public use)	Project execution speed	Project execution speed
B1 _ Use	**Consumer**	Private individuals as building buyers (private use) / Local and regional authorities or regulators as buyers (public use)	Affordability for users (Building buyers for private use, Local authority/regulator & user, Regional authority/regulator & user)	Affordability for the first life cycle
				Affordability for the second life cycle
			Adaptability	How well the building can be modified or adjusted to meet changing needs over time.
	Society	General public	More sustainable Economic performance for public buildings	Life Cycle Cost Savings for Public Buildings
C1 _ Demolition / Deconstruction of building **C2** _ Transport of Construction and Demolition waste (CDW) to Waste processing facility **C3** _ Waste processing (sorting, crushing) **C4** _ Disposal	**Workers**	Deconstruction/ demolition workers (C1)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Recycling workers (C3)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination

		Landfill workers (C4)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Transportation workers (C2)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
	Local Community	Neighborhood near to deconstruction/demolition facilities (C1)	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
		Neighborhood near to waste processing/recycling plants (C3)	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
		Neighborhood near to disposal landfill (C4)	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
	Society	General population	Waste Diversion and Reduced Landfill Burden	Volume of waste avoided from landfill
		Policy makers / Environmental NGOs	Alignment with CDW policy	Alignment with CDW policy
	Value Chain Actors	Deconstruction/Demolition companies (C1)	Economic growth/ Economic contribution	Revenues from deconstruction/demolition activities
		Recycling companies (C3)	Economic growth/ Economic contribution	Revenues from material treatment / Volume of treated material

		Landfill companies (C4)	Economic growth/ Economic contribution	Revenues from material treatment / Volume of treated material
		Transportation companies (C2)	Economic growth/ development	Factor Tax Payments

3.4 Pilot 4 (MNORD): Museum building elements from RAC (Vesterålen, Norway)

3.4.1 Technology Overview

Concrete is primarily made from coarse aggregates (such as crushed stone and gravel), fine aggregates (sand), cement and water. The use of by-products from other industries, such as fly ash, slag and silica fume, is also common to reduce the cement content, while concrete additives and admixtures can be used to enhance concrete properties in fresh and/or hardened state. Aggregates, however, remain the most dominant component, typically making about 60-75% of the concrete's volume (Chen et al., 2024). These aggregates used in concrete are either natural aggregates (NA), sourced from quarries and gravel pits, or recycled aggregates (RA), derived from processed construction and demolition waste. While natural aggregates are widely used due to their availability and performance, recycled aggregates could potentially offer a more sustainable alternative by reducing the demand for virgin material extraction and minimizing waste.

In Norway, structural concrete is predominantly produced using coarse aggregates extracted from quarries through blasting or excavation which are then transported to concrete mixing plants. Despite a national target to reuse 70% of construction and demolition waste (CDW) by 2020, only about 20% of concrete is currently reused in Norway. This is largely due to the prevalence of traditional demolition methods and the absence of specialized concrete recycling facilities. As a result, most concrete waste is processed merely to prepare it for waste management, typically involving steel removal and crushing into granulate (0–200 mm) for use as fill material—a process known as downcycling. The least sustainable path for CDW handling is the deposition of this granulate and other non-contaminated mineral waste (e.g. bricks) in the old quarries or other areas in nature that are not fully dedicated to material disposal. In addition to the unsustainable deposition of construction and demolition waste, the current techniques put extra stress on the availability of total reserves of resources due to increased necessity of extracting new virgin materials to meet the demand for aggregates in concrete production.

However, there is significant potential to enhance concrete reuse and recycling through advanced selective demolition and dedicated sorting and crushing techniques. These methods can increase the recovery rate of high-quality concrete from demolition waste, making it suitable for reuse in new structural applications. By improving the quality and consistency of recycled aggregates, these techniques help move beyond simple downcycling—where materials are reused in lower-value applications—and toward upcycling, where recycled aggregates can replace natural ones in the production of new structural concrete.

Within the Circ-Boost project, Pilot 4 proposes an upcycling approach: transforming concrete waste into high-quality recycled aggregates (RA) for use in new concrete, specifically for the construction of the GAIA Vesterålen Museum. The GAIA Vesterålen Museum, established by Museum Nord and Sortland Municipality, will be a pioneering landmark building in the Arctic region of Norway (See Figure 20).

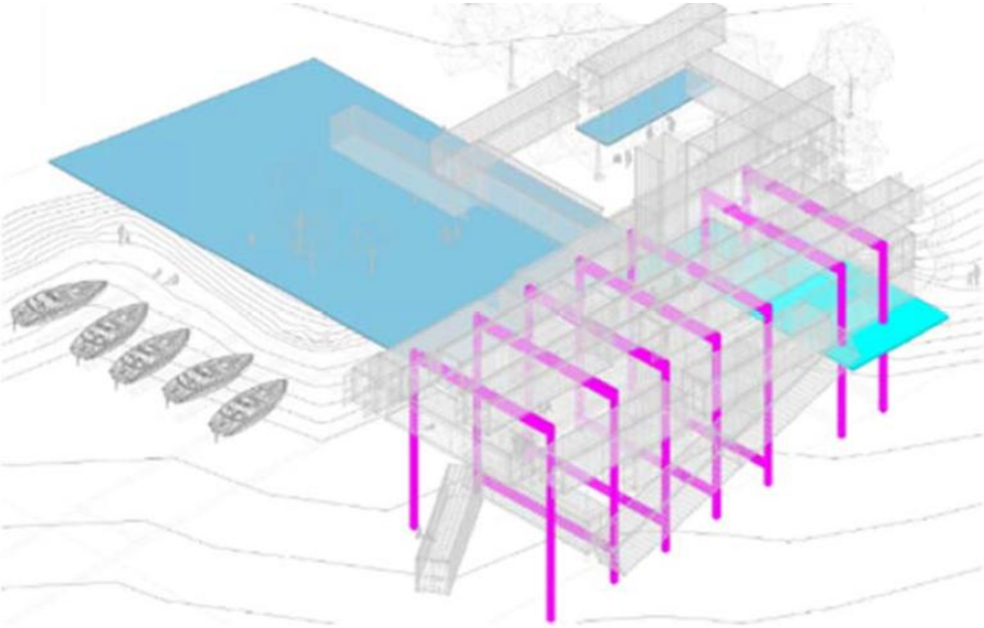


Figure 20. Preliminary architectural design of the Gaia Vesterålen Museum.

This innovative museum will be constructed, aiming to demonstrate an entire circular building process "from demolition to construction" by deploying leading construction technologies for the region and utilizing up to 95% of locally available waste stream materials such as construction and demolition waste (CDW) and used containers from the fishing industry. In this way, it will showcase how the waste stream can be converted into valuable secondary raw materials and trigger a green change in a sparsely populated area with harsh climate conditions.

For the GAIA Vesterålen museum, the pilot will span the entire construction value chain, from the demolition of two local buildings to the production of high-quality recycled concrete and the construction of the museum building, using cutting-edge solutions for the reuse and recycling of materials previously demolished. Nevertheless, as described in Deliverable D3.1 (Pilots Deployment Strategy), building the GAIA Vesterålen museum is a large undertaking, and it is not possible to cover all activities within the Circ-Boost project, therefore direct utilization of non-contaminated concrete from two buildings to produce 3 museum buildings blocks will be demonstrated. The pilot consists of the following three stages:

- Demolition stage that involves detail mapping of concrete part of structures prior to demolition, and selective demolition and sorting of recyclable and contaminated concrete
- Production of quality recycled concrete aggregates (RA) from non-contaminated concrete, employing modern crushing and sorting techniques with up to 75% of non-contaminated concrete planned to be used for RA production
- Production of RAC blocks stage where the RA will be transported to the production plant, the concrete mix will be adjusted, and the recycled concrete aggregates will be used as a replacement in the construction of new concrete elements. The concrete elements will be constructed by Recycled Aggregate Concrete (RAC) with RA content ranging from 5-100% depending on the amount of gained non-contaminated concrete

Other Circ-Boost partners will be also involved in the construction of the Museum. Activities will be composed of selective demolition and concrete recycling performed by Reno-vest, connected to architectural design by LUA with the support of the UIT researchers to ensure quality and integration of forefront research approaches. MNORD, as a building owner, will support the communication between individual partners and decision-making.

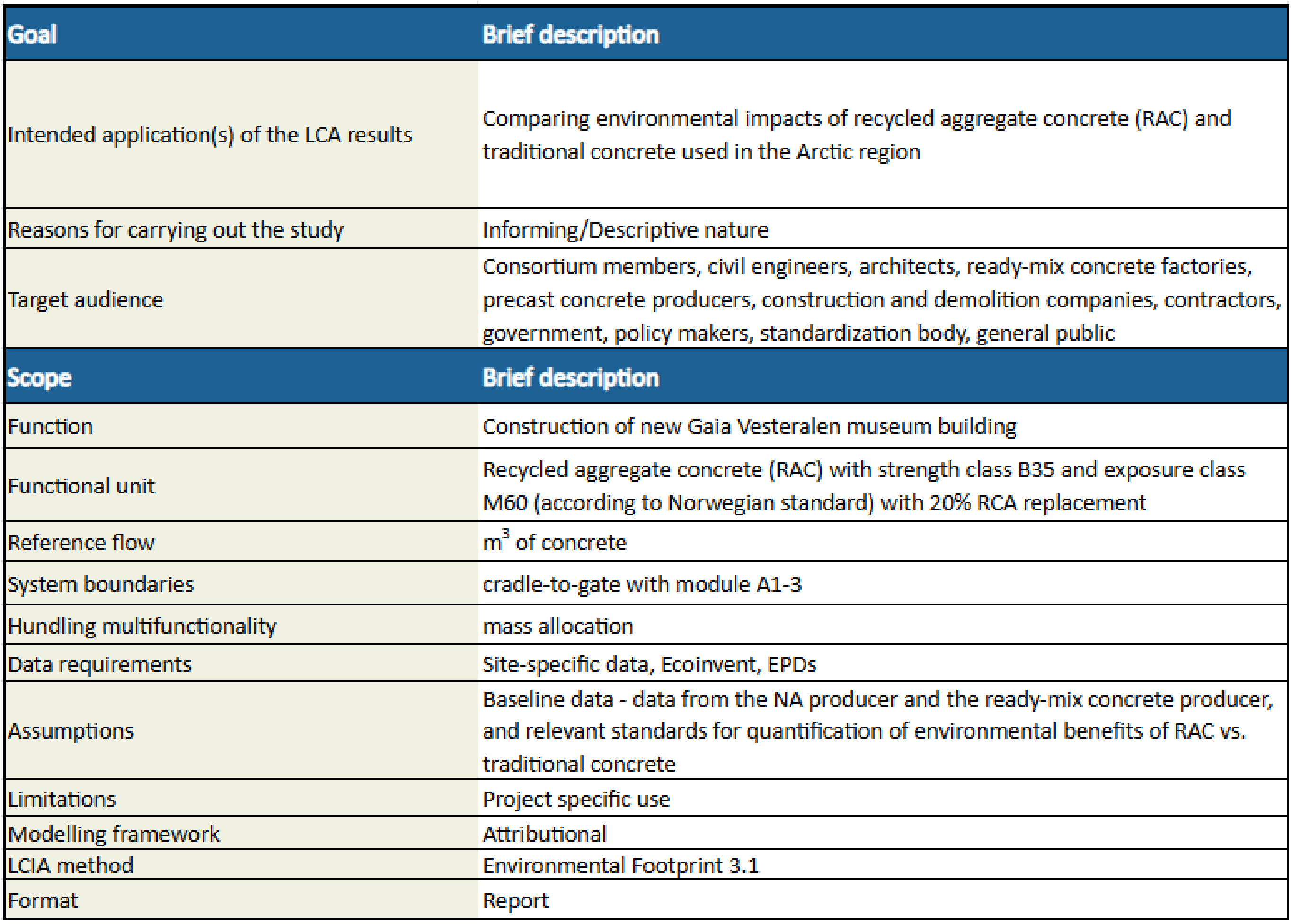
3.4.2 Life Cycle Assessment (LCA)

3.4.2.1 Goal and scope definition

The purpose of the study is to model and assess the environmental, economic and social impact of the pilot for the construction of three museum building blocks utilizing non-contaminated recycled concrete aggregates acquired from the demolition of two concrete buildings in the Sortland municipality. The pilot will be assessed as a standalone technology through hotspot analysis, evaluating the impacts of using recycled aggregate as replacement in the production of new concrete, as well as in comparison of the environmental impact between the newly introduced technology and the current baseline situation of concrete production in Norway. For this purpose, the goal and scope for both the current practice baseline and the solution introduced by Pilot 4 must be defined.

An initial meeting was set with the pilot to examine the progress and characteristics of the technology introduced and after a brief introduction to the LCA methodology and goal and scope definition, a template was sent to them for completion. Following this, a subsequent meeting was held to review the filled-in template and consolidate the goal and scope main characteristics. The template is shown in Table 15.

Table 15. Goal & Scope Template of Pilot 4 (MNORD).



Goal	Brief description
Intended application(s) of the LCA results	Comparing environmental impacts of recycled aggregate concrete (RAC) and traditional concrete used in the Arctic region
Reasons for carrying out the study	Informing/Descriptive nature
Target audience	Consortium members, civil engineers, architects, ready-mix concrete factories, precast concrete producers, construction and demolition companies, contractors, government, policy makers, standardization body, general public
Scope	**Brief description**
Function	Construction of new Gaia Vesteralen museum building
Functional unit	Recycled aggregate concrete (RAC) with strength class B35 and exposure class M60 (according to Norwegian standard) with 20% RCA replacement
Reference flow	m^3 of concrete
System boundaries	cradle-to-gate with module A1-3
Hundling multifunctionality	mass allocation
Data requirements	Site-specific data, Ecoinvent, EPDs
Assumptions	Baseline data - data from the NA producer and the ready-mix concrete producer, and relevant standards for quantification of environmental benefits of RAC vs. traditional concrete
Limitations	Project specific use
Modelling framework	Attributional
LCIA method	Environmental Footprint 3.1
Format	Report

Goal

Reasons for carrying out the study

The primary reason for conducting this study is to provide an informative and descriptive assessment of the environmental, economic, and social impacts of Pilot 4, which involves the use of non-contaminated recycled concrete aggregates (RCA) sourced from local demolition activities in Sortland municipality. By modeling the pilot as a standalone technology and comparing it to the current baseline of conventional concrete production in Norway, the study aims to highlight the potential benefits and trade-offs associated with integrating RCA into new construction.

Intended audiences

According to the declared applications of the study, the LCA study spanning across D5.1 and D5.2 is intended to be addressed to following audiences:

- The technology provider (Reno-vest, UiT, LUA)
- The local partner (MNORD)
- The European Union, as the main funding institution of the Circ-Boost project
- The European Commission, as the main reviewing mechanism of the Circ-Boost project
- Consortium members
- Civil engineers
- Architects
- Researchers
- Ready-mix concrete producers
- Precast concrete producers
- Construction and demolition companies
- Contractors
- The Norwegian government and Sortland municipality
- Policy makers,
- Standardization bodies
- Local community
- General public

Comparative assertions

The LCA study that is initiated in D5.1 and will be concluded in D5.2, is partially intended to support comparative claims meant for public disclosure via the conduction firstly of an independent LCA and afterwards a comparative LCA against the baseline scenario which is the manufacturing with traditional concrete in the geographical context of the Arctic region. This intention does not stem from commercial competitive purposes, but purely from a scientific research point of view. Therefore, no external review (besides the review procedure prescribed by the project's Grant/Consortium Agreements) will be necessary for the Deliverables 5.1 and 5.2, according to ISO 14040:2006 and ISO 14044:2006.

Scope

Functional Unit

All LCAs study one or more product systems composed of many processes throughout the life cycle of the product system. Knowledge of the function is key to define the functional unit and support a fair and relevant quantitative comparison (Hauschild et al., 2018). Moreover, adequately selecting a functional unit is of prime importance because different functional units could lead to different results for the same product system.

In the present study the function that our system provides is the construction of three museum building blocks, given that the Gaia Vesterålen museum's construction will extend beyond the project's duration; This production is performed through the replacement of natural aggregate with recycled aggregate in the concrete mixture. On the other hand, the baseline scenario considered in this LCA study focuses on the conventional production of concrete in Norway with the usage of natural aggregate, serving as a reference point for evaluating the potential environmental benefits of the proposed circular approach. It is important to note that this study does not aim to assess aggregate processing as an alternative waste management strategy for concrete and demolition waste.

To culminate to a functional unit, it is important to define the quantitative aspects of the function. For concrete, an appropriate functional unit can be defined based on different performance characteristics.

According to a review conducted by (Panesar et al., 2017), functional units for concrete can be classified as single variable (volume), two variables (volume, strength) and three or more variables (volume, strength and durability). Choosing one variable functional unit could be flawed since direct comparison of the impact between 1m^3 RAC and NAC does not correspond to a balanced/precise analysis because for RAC to achieve similar compressional strength as NAC, different volumes would be needed (Zhang et al., 2019). Thus, in this study, it was deemed sufficient to proceed with a two variable functional unit, that analyzes the environmental impact per strength, based on the same volume (usually 1m^3). In the current study, the functional unit was chosen as 1m^3 of ready-mix NAC and RAC in the same strength group B35. This means that the mix proportion of NAC and RAC was determined so that they have approximately the same compressive strength, through adding slightly additional cement (~5%).

To enable a more equal comparison, it is assumed also that both NAC and RAC are exposed to the same non-aggressive environment, such as indoor environment of residential and office buildings (Zhang et al., 2019). As described in Table 15, concrete of exposure class M60 (according to Norwegian standards) has been selected. Exposure class defines the environmental conditions concrete will face during its service life and is directly linked to its durability. In harsh environments—such as coastal or harbor areas where concrete is exposed to chlorides from seawater—specific exposure classes guide the mix design to ensure long-term resistance to corrosion and degradation.

System boundaries

Following again the modular concept introduced by CEN TC350 standards EN15804 & EN15978 (CEN), 2011, 2019) for the definition of the system boundaries of the LCA, all modules are considered except Modules B1-B7, which address the use phase of the material level. At the material level, it is not meaningful to include these stages in the analysis; therefore, these modules will be excluded. Additionally, concrete carbonation during the operation stage is not considered in this assessment. Carbonation is the chemical reaction by which CO_2 diffusing into concrete, reacts with calcium di-hydroxide (Ca (OH)2) leading to $CaCO_3$ (Gervasio & Dimova, 2018). This process is a function of ambient concentrations of CO_2 and depends on the exposed surface of the element to the air.

Table 16. Stages included in the LCA analysis of Pilot 4 reference and solution based on EN15978.

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction / inst. process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse/recovery/recycling
x	x	x	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Having in mind the goal of this study, system boundaries were chosen to represent a “cradle-to-gate” type of assessment. Thus, following the modular concept, as shown in Table 16, only stages A1-A3 are considered in this study. Stages A4 and A5 are excluded, since the 3 building blocks will not be installed in the new museum within the timeframe of this project.

Baseline scenario

For the baseline scenario, the processes taking place in each module from A1-A3, are depicted in the following Figure:

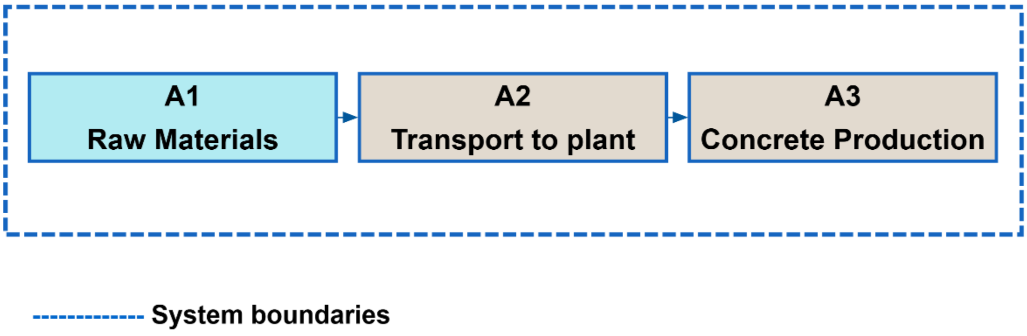


Figure 21. System boundaries of the Pilot 4 baseline concrete production using NAC.

The stages included in the specific LCA analysis for the baseline scenario are explained below and contain the following information:

- **Modules A1-A3**: Module A1 covers the conventional raw material acquisition process, including drilling and blasting in quarries, followed by crushing and sorting to produce natural aggregates (NA). All associated loading and unloading activities within the quarry area are also included. Module A2 describes the transportation of NA to the local concrete plant, while Module A3 focuses on the concrete mixing process, incorporating NA along with other ingredients. Energy and material input flows, as well as emissions and waste outputs related to concrete production, are accounted for in Modules A1 and A3.

Circ-boost solution

For the baseline scenario, the processes taking place in each module from A1-A3, are depicted in the following Figure:

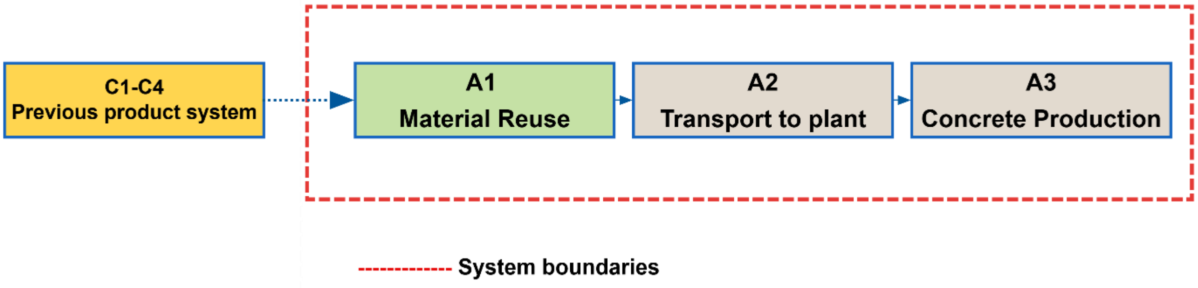


Figure 22. System boundaries of the Pilot 4 solution for concrete production using RAC.

In particular, the stages shown in Figure 22 for the P4 Circ-Boost solution are explained below and contain the following information:

- **Modules A1 – A3**: The utilization of recycled aggregates (RA) and their associated sub-processes replaces the conventional quarrying activities in Module A1. This includes all loading and unloading operations within the secondary material handling area. High-quality RA is produced from non-contaminated concrete using advanced crushing and sorting techniques, with up to 75% of the recovered concrete planned for RA production. Module A2 accounts for the transportation of RA to the concrete production plant. Subsequently, in Module A3, the production of Recycled Aggregate Concrete (RAC) blocks takes place. This involves adjusting the concrete mix design to incorporate RA, which will be used in the manufacture of new concrete elements. The RA content in RAC will range from 5% to 100%, depending on the availability of suitable non-contaminated concrete. Although an initial 20% replacement of natural aggregates with recycled aggregates (RA) is considered, testing will determine the optimal RA content in the concrete mix. Depending on testing results, one or two alternative RAC mixtures with varying RA percentages might also be explored to identify the most effective solution.
- Moreover, similar to the baseline scenario, energy and material input flows, as well as emissions and waste outputs related to concrete production, are included in Modules A1 and A3.
- Finally, the demolition stage—which includes detailed mapping of the concrete components of structures prior to demolition, as well as selective demolition and the sorting of recyclable and contaminated concrete—is not included within the system boundaries of the RAC solution proposed by P4, as demolition and initial waste processing should be attributed to the previous product system—i.e., the buildings being demolished, as further explained in the 3.4.2.2 multifunctionality section.

3.4.2.2 Multifunctionality

Multifunctionality doesn’t take place in the output side of the RAC system, since only one product comes out of it. On the other hand, on the input side, there are two fractions of RA derived from demolition, one that is non-contaminated and the other that is contaminated. The contaminated fraction is waste, since it is not possible to be decontaminated or used in any other way. Norwegian regulations forbid its utilization making disposal its only handling.

Since the scope of the project is not to examine a possible improvement in the process of waste management and separation, rather the production of concrete from useful recycled concrete, then the waste that comes out of the demolition stage, and that is not valorized in the Circ-Boost, is considered out of the system. Thus, the system boundaries are narrowed to include only the fraction of the aggregate that is valorized in the project, that being the non-contaminated concrete aggregate. In that case, an allocation on the input side and the recycled concrete feedstock is applied. This will attribute only a percentage of the demolition impact to our product system which is directly dependent on the percentage of non-contaminated useful recycled aggregate that enters our system. Given that there is no information in terms of demolition and separation costs, economic allocation couldn’t be applied, thus mass allocation is deemed the appropriate allocation procedure.

This is also corroborated by the EN 15804 standard core PCR (CEN, 2019), where the ‘polluter pays principle’ is stated. This is explained as follows: the processes of demolition and initial waste handling—such as the sorting of contaminated and non-contaminated concrete, as well as the removal of hazardous materials—are attributed to the product system that generates the waste, i.e., the buildings being demolished, until the waste is either reused or disposed. According to this allocation principle, all environmental impacts associated with these waste processing activities fall under the responsibility of the original product system. Only the subsequent processes directly related to additional crushing and sorting of the useful and non-contaminated concrete are included within the system boundaries of the studied product system.

3.4.2.3 Assumptions and limitations

- Fine recycled aggregates were not considered for the RAC production since their use in structural concrete is generally not recommended, mainly due to their high-water absorption and cohesion.
- Inputs of materials such as cement, sand, and other commonly used inputs is assumed to be covered by existing datasets, as these are common materials across both types of concrete. Therefore, primary data is collected and modelled separately only for aggregates, as these are more variable and locally sourced.
- Assumption that both NAC and RAC suffer the same exposure or the same conditions for both NAC and RAC.
- Only the coarse fraction (4-63 mm) is considered as replacement of NA.
- Concrete with 20% replacement of natural aggregates with recycled aggregates (RA) is considered as it aligns with the current regulation.
- Crushing and storage will take place right next to the concrete factory.
- Concrete producer will be the same both for NAC and RAC production.
- Fine recycled aggregates were not considered for the RAC production since their use in structural concrete is generally not recommended, mainly due to their high-water absorption and cohesion.
- As stated in the functional unit definition, additional cement might be required to compensate for performance loss of RAC. This parameter could potentially influence the environmental outcomes and may be considered in a sensitivity analysis to better understand its impact.
- The transportation distance of recycled aggregates from the demolition/recycling site to the concrete plant (A2) can be identified as a potentially influential factor. Variations in this distance could affect the results, and its inclusion in a sensitivity analysis could provide additional insight.

3.4.2.4 Cut-off criteria

A 1% cut-off criterion will be applied for excluding processes the impact of which contributes less than 1% of the total impact per selected impact category.

3.4.3 Life Cycle Costing (LCC)

During Task 5.1, the goal and scope of the Life Cycle Costing (LCC) assessment for Pilot 4 were clearly defined, ensuring full alignment with the framework conditions of the environmental Life Cycle Assessment (LCA). This alignment includes the use of consistent system boundaries and a shared functional unit, thereby guaranteeing coherence between environmental and economic evaluations.

The system boundaries for the LCC of Pilot 4 encompass modules A1-A3, following the boundaries selection of the environmental LCA.

Data collection for Pilot 4 is scheduled to begin in the coming months and will draw from both primary and secondary sources. The pilot will provide average cost estimates for materials, transportation, construction and deconstruction activities, as well as for any components that may need replacement. In cases where pilot-specific data is lacking, validated secondary sources, such as literature or industry pricing tools, will be utilized. All relevant cost data will be compiled using a project-specific LCC inventory template.

Finally, the Life Cycle Costing analysis phase will commence after Month 30, with the launch of Task 5.3, and will continue until Month 47. This phase will incorporate both fixed and variable costs provided by the involved partners, as well as external costs—indirect social costs typically associated with environmental degradation and emissions. These externalities will be quantified and included in the final deliverable, D5.2.

3.4.4 Social Life Cycle Assessment (S-LCA)

The Social Life Cycle Assessment of the current study relies on the general framework described in section 2.3.1 adjusted to the pilot case's particular objectives. The following section presents the methodology's application to define the goal and scope for Pilot 4.

3.4.4.1 Goal and Scope

The goal of the study

The Social Life Cycle Assessment (S-LCA) study for Pilot 4 investigates the potential social benefits and impacts associated with implementing Recycled Aggregate Concrete (RAC) for the production of three building elements for the MNORD museum within the Norwegian construction sector. The analysis compares a pilot scenario employing this recycled concrete against a baseline scenario based on concrete made from natural aggregate (NAC).

Focusing on the current product system and the geographic context of Vesterålen, Norway, the study aims to uncover both positive and negative social implications for key stakeholder groups, including production workers, material suppliers, local communities, and policymakers.

The results will be of interest to public authorities, construction and material production companies, recycling firms, sustainability consultants, circular economy practitioners, and academic researchers. Insights from this assessment will support future policy development, inform circular procurement strategies, and guide the design of socially responsible construction practices in Norway and beyond.

Functional unit

The functional unit for the specific S-LCA is consistent with the one used in the LCA and LCC studies. However, unlike LCA and LCC, the social impacts and effects in the S-LCA will not be quantitatively scaled to the functional unit. Nevertheless, this will be addressed in the later stages of the Social LCA study. In this study the functional unit was chosen as 1m^3 of ready-mix NAC and RAC in the same strength group B35. This means that the mix proportion of NAC and RAC was determined so that they have approximately the same compressive strength, through adding slightly additional cement (~5%). To enable a more equal comparison, it is assumed also that both NAC and RAC are exposed to the same non-aggressive environment, such as indoor environment of residential and office buildings (Zhang et al., 2019).

System boundaries

The system boundaries for this Social Life Cycle Assessment (S-LCA) are aligned with those defined in the LCA and follow the structure of EN 15804 and EN 15978 (CEN, 2011, 2019), encompassing all relevant activities within the examined construction system. Having in mind the goal of this study, system boundaries were chosen to represent a "cradle-to-gate" type of assessment. Thus, following the modular concept, only stages A1-A3 are considered in this study. Stages A4 and A5 are excluded, since the 3 building blocks will not be installed in the new museum within the timeframe of this project. Similarly to LCA, the demolition stage is considered outside of the system boundaries in the case of the recycled aggregate concrete production, thus it will not be examined in the social lifecycle assessment either. Moreover, as previously noted, Module D is excluded in the Social LCA of all pilot cases, as it involves long-term reuse and recycling scenarios that are difficult to predict and not directly linked to current stakeholder impacts.

Additionally, this S-LCA analysis focuses on the material level, using 1m^3 of concrete (NAC and RAC) as functional unit. Therefore, unlike the S-LCA of Pilots 1&3, the use stage (B) is excluded from the analysis, as the material itself does not directly involve stakeholder interactions during its end-use. Social impacts related to building occupancy or user experience are more relevant at the building level, not at the level of individual materials. Including Stage B would require assumptions beyond the scope of this study and could compromise consistency with the defined boundaries. Therefore, the assessment is limited to the stages where social aspects are directly linked to stages associated with raw material extraction and secondary material supply, transportation and concrete mixture production. For simplicity and visual clarity, the system boundaries are illustrated in a single graph (See Figure 23) representing both the baseline and the Circ-Boost solution.

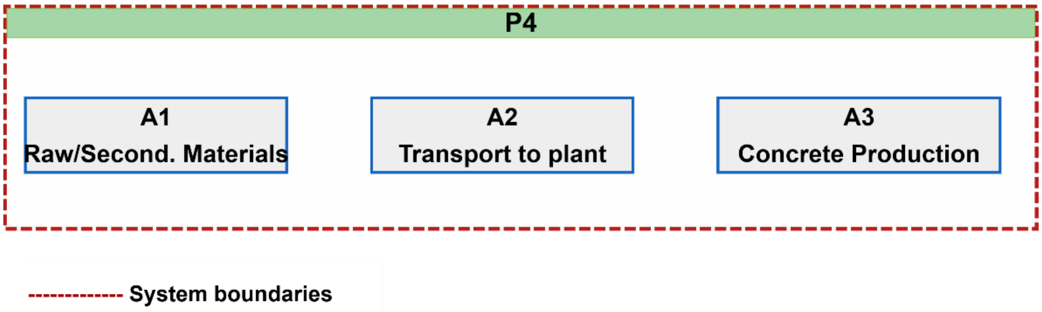


Figure 23. Social LCA system boundaries of Pilot 4 covering baseline and solution (NAC and RAC).

Stakeholders' selection

Stakeholder groups were considered separately for each life cycle stage, as defined by (Benoît Norris et al., 2020). These categories were further refined into subcategories based on the stakeholder mapping conducted in Circ-Boost Task 2.2 and inputs from pilot partners. This approach ensures that the analysis is both methodologically robust and contextually relevant to the construction sector. A definition of the selected stakeholders, along with their type of relationship to the system, is presented in Table 17, for all stages involved in NAC and RAC production. Corresponding life cycle modules (in parentheses) indicate where each stakeholder group is involved.

Table 17. Definition of the stakeholder categories across S-LCA stages of Pilot 4's NAC and RAC case, with corresponding life cycle modules indicated in parentheses.

Stakeholder group	Stakeholder Subcategory/Sub-Stakeholders	Definition	Type of relation
Workers	Primary material extraction workers: (Natural aggregate) [baseline] (A1)	Employees involved in the extraction and initial processing of raw materials used in the construction sector.	Affected – they are affected by the system's practices and decisions.
	Secondary recycled material workers: (Recycled aggregate) receiving/preprocessing (e.g. crushing and sorting) [pilot] (A1)	Employees in secondary material collection facilities handling the intake and preparation of recycled materials for reuse in construction, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Building materials/elements production workers: Conventional concrete mix in baseline vs concrete mix with recycled aggregate in pilot (A3)	Employees within the production sector, who work in concrete production industry, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Transportation workers (A2)	Employees working in the transportation sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.

Society	Academic Research Institutions	Bodies that execute applied research to find/test new applications in sustainable construction and circular economy.	Concerned – they are concerned by the environmental, social and economic performance of available products/technologies in the market. They develop novel products and conduct research studies for technology progress purposes.
			Involved – they are involved in the decision-making process.
	General Population (A1-A3, B1)	Citizens and communities indirectly affected by the environmental, economic and social impacts of building materials production and raw material savings.	Affected – they are affected by the system's practices and decisions and by economic performance of public buildings.
	Not-for-profit association committed to advancing the technical, economic, aesthetic and environmental performances of concrete structures worldwide (A1-A3)	Organizations engaged in the promotion of ecofriendly, sustainable and climate-smart technologies/materials and innovations.	Concerned – they are concerned by the environmental, social and economic performance of available products/technologies in the market and influence the promotion of sustainable practices.
Local community	Neighborhood near virgin raw material extraction [baseline and pilot] (A1)	Residents living in proximity to sites where virgin raw materials (e.g. natural aggregates) are extracted.	Affected – their well-being and environment may be influenced by extraction activities and associated infrastructure.
	Neighborhood near companies receiving/pre-processing secondary material [pilot] (A1)	Residents living near facilities that receive and pre-process secondary materials (e.g., recycled aggregates, reclaimed steel).	Affected – they may experience impacts in the local environment e.g. noise, emissions.
	Neighborhood near building material (concrete mix) production facilities (A3)	Residents living close to facilities where concrete mix and steel is manufactured.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
Value chain actors	Primary & secondary material supply companies (A1)	Companies that extract/receive construction materials intended for manufacture building components.	Directly involved – they respond to project requirements and influence material availability, quality and circularity.
	Building materials production companies (suppliers) (A3)	Companies that produce construction elements/materials, including panels and concrete mix.	Directly involved – they respond to project requirements and influence material availability, quality and circularity.

	Material technology development companies (A1-A3)	Firms engaged in R&D and innovation related to construction materials, including durability, recyclability, and performance.	Directly involved – they enable circular design through material innovation and life-cycle optimization.
	Transportation companies (A2)	Entities responsible for transportation services of materials.	Affected – they are affected by the system's practices and decisions regarding flow volumes of materials, products and transportation distances.

Impact categories and indicators

The stakeholder groups and subcategories were identified and mapped to each life cycle stage, following the modular structure of EN 15804. Each stakeholder subcategory was then linked to the most relevant social impact categories, which were subsequently connected to specific indicators. This structured and sequential approach ensures a consistent and traceable connection between stakeholders, potential social impacts, and the metrics used to assess them. This correlation is depicted in Table 18. It should be noted that Social Life Cycle Assessment (s-LCA) is inherently an iterative process, and the final selection of indicators will be determined based on data availability during the assessment phase. As the project progresses, certain indicators may be added or removed to reflect the realities of data accessibility, stakeholder input, and contextual relevance.

Table 18. Indicators selection for production of building elements from NAC and RAC in Norway (P4-MNORD).

Life Cycle Stage	Stakeholder Group	Stakeholder Sub-Category	Impact Category	Indicator
A1 _ Raw material extraction / supply **A2** _ Transportation of materials to concrete plant **A3** _ Production of building materials (concrete mix in concrete plant)	**Workers**	Raw materials production (Primary material extraction workers (aggregate) **vs** secondary recycled material (aggregate) receiving / preprocessing (e.g. crushing and sorting) workers (A1)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Hours of Paid Employment (for all employees)
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Building materials/elements production workers (conventional concrete mix **vs** concrete mix with recycled aggregate) (A3)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Hours of Paid Employment (for all employees)
			Labor Practices and Decent Work	Fair Salary

				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Transportation workers (A2)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
	Local Community	Neighborhood near the raw material production sites (virgin material extraction (baseline) **vs** the secondary material production (pilot) (A1)	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
		Neighborhood near to building materials/elements production facilities (A3)	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
	Society	General population (public is affected by more sustainable practice e.g. GHG, resources - data derived from LCA) {A1, A2, A3}	Contribution to Circular Economy and Resource Efficiency	Raw materials savings (from the replacement of extracted materials with recycled ones)
			Public health	Air quality
			Climate Change Adaptation and Societal Resilience (if LCA shows that it is affected due to emissions)	Reduced Societal Vulnerability to Climate Change Impacts
		Academic Research Institutions	Knowledge & Innovation	Contribution to R&D and Knowledge Dissemination on Sustainable Concrete

		Not-for-profit association committed to advancing the technical, economic, aesthetic and environmental performances of concrete structures worldwide.	Knowledge & Innovation	Contribution to R&D and Knowledge Dissemination on Sustainable Concrete
	Value Chain Actors	Raw material companies (Primary material extraction companies **vs** secondary recycled material receivers/pre-processers companies) (A1)	Economic growth/ Economic contribution	Factor Tax Payments
		Building materials production companies (suppliers) (A3)	Economic growth/ Economic contribution	Factor Tax Payments / Revenues
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
			Affordability of raw materials for concrete producers	Affordability of raw materials for concrete producers
		Material Technology development companies	Economic growth/ Economic contribution	Factor Tax Payments
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
			Innovation & Contribution to Sustainable Construction	Development and Commercialization of Sustainable Material Technologies
			Contribution to Industry Advancement and Sustainable Construction	Development and Commercialization of Sustainable Material Technologies
		Transportation companies (A2)	Economic growth/ development	Factor Tax Payments

3.5 Pilot 5 (SKA): Building elements from RAC (Prague, Czech Republic)

3.5.1 Technology overview

Concrete is the most widely used construction material globally, forming the backbone of modern infrastructure. Its dominance in the building sector, however, comes with a significant environmental cost. Concrete production—exceeding 25 billion tons annually—consumes vast quantities of natural resources and energy, emits significant CO_2 emissions (primarily from cement production), and generates large volumes of construction and demolition waste (CDW) (Marinković et al., 2023). Among its ingredients, aggregates are the most extracted solid resources by mass, with global consumption exceeding 40 billion tons annually (Zhuang et al., 2025).

This massive demand raises concerns about the availability of natural aggregates (NA) and the environmental impacts of their extraction. In the Czech Republic, demand for primary construction aggregates—especially crushed stone—has steadily increased over the past 50 years. Although production dropped after the economic shift in the late 1980s, it quickly recovered and remains high today. As Přikryl (2021) notes, crushed stone has overtaken natural sands and gravels, confirming that natural aggregate concrete remains the baseline.

Concrete continues to dominate due to its well-established supply chains and infrastructure. Its use has increased tenfold over the past 65 years, far outpacing the growth of steel and timber. Yet less than 1% of concrete currently incorporates recycled materials (UNEP & CEA Yale, 2023).

One promising strategy to address these challenges is the recycling of waste concrete into recycled concrete aggregates (RA) for use in new concrete production. While concrete cannot be returned to its original form, it can be crushed and reused as aggregate in new applications, forming Recycled Aggregate Concrete (RAC). This approach could potentially help to reduce the demand for virgin materials and diverts CDW from landfills.

Despite challenges related to the heterogeneity of construction and demolition waste (CDW) and the mechanical performance of recycled aggregate concrete (RAC) in structural applications, successful full-scale implementations have been carried out in both Europe and Asia, demonstrating its technical feasibility and environmental advantages. A notable example is the twin tower project in Shanghai, China, where recycled aggregates were used to replace up to 30% of natural coarse aggregates in the construction of one of the towers, showcasing RAC’s potential in structural concrete. (Wang et al., 2020).

A similar approach is being adopted in the Modřanský Cukrovar (MOCU) redevelopment project in Prague, Czech Republic, led by Skanska. This ambitious transformation of a former sugar refinery into a sustainable mixed-use community integrates residential, commercial, and recreational spaces while preserving the site's industrial heritage (See Figure 24). As part of the Circ-Boost project, Skanska aims to minimize the ecological footprint of the development by incorporating Recycled Concrete Aggregate (RAC) into structural elements, contributing to the project's goal of using at least 15% recycled materials.

Figure 24. The MOCU project (Photo from 24.10.2024).

Central to this effort is Rebetong®, a certified RAC product developed by Skanska and Skanska Transbeton. Produced at six concrete plants, Rebetong® allows for the use of up to 100% recycled aggregates and has demonstrated performance comparable to conventional concrete. The main objective of the Czech pilot SKANSKA is within the framework of the Circ-Boost project to harness cutting-edge technologies and innovative design principles to minimize the ecological footprint of this development and push the boundaries of sustainability and circularity in construction. Particularly, SKANSKA plans to demonstrate the use of Recycled Concrete Aggregate (RAC) for structural elements, thus contributing to the Circ-Boost goal of using at least 15% recycled materials in pilot projects.

In the MOCU project, Rebetong® will be used extensively—not only in structural elements but also in façade panels made from brick recycled aggregate concrete, showcasing its aesthetic and functional potential to the public.

Initially, RAC was used for base and sub-base concrete (C12/15, exposure class X0). Over time, its application expanded to reinforced internal walls (C25/30, XC1) and external walls not exposed to aggressive environments (C25/30, XC2). The quality of the recycled aggregate remains critical, requiring adjustments to the mix design whenever the RA source changes.

This pilot project serves as a testbed for the industrial upscaling of Rebetong®, with applications including sub-base slabs, reinforced concrete walls, façade panels with exposed surfaces, wall tiles, and public furniture—pushing the boundaries of circular construction in practice.

3.5.2 Life Cycle Assessment (LCA)

3.5.2.1 Goal and scope definition

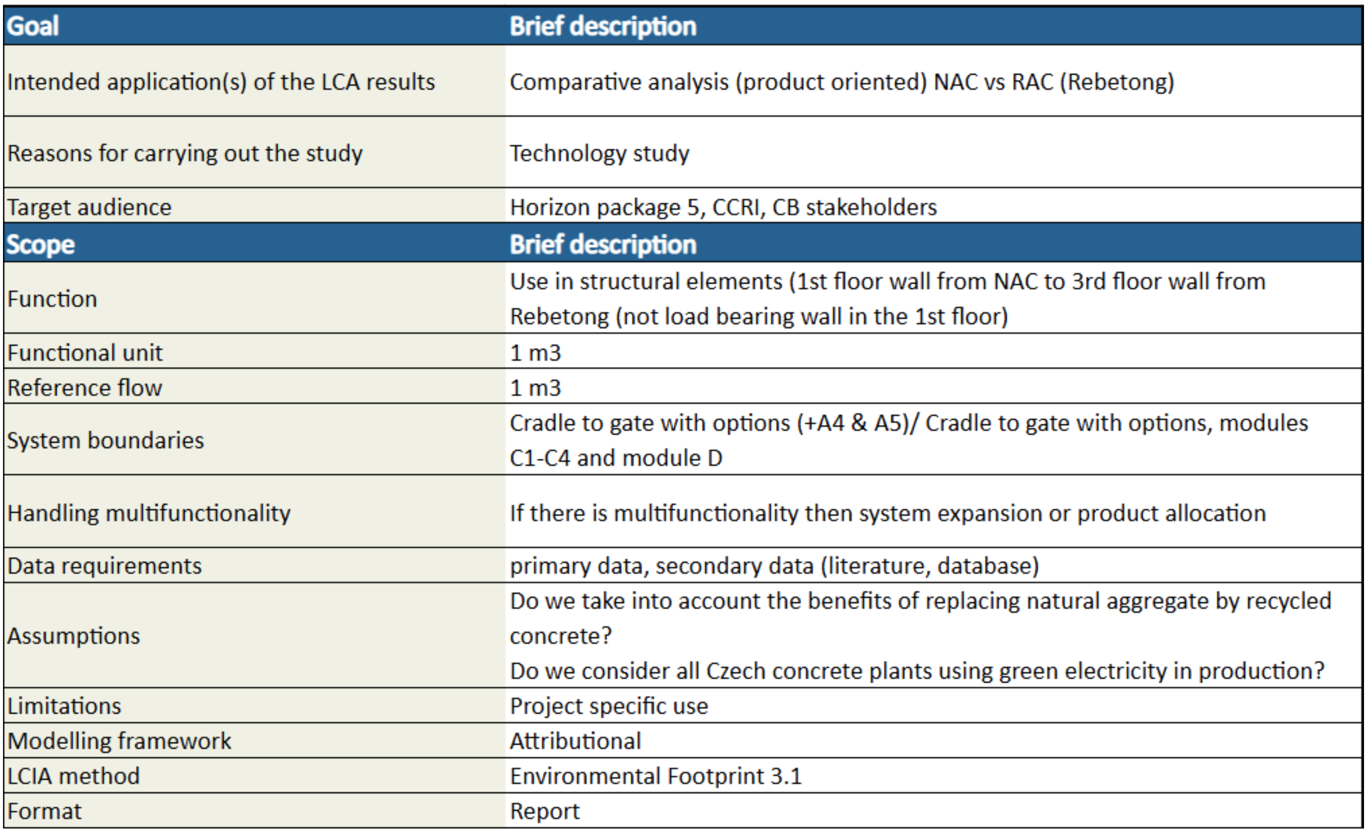
The overall aim of the pilot is the implementation and demonstration of sustainable and circular solutions in the residential project of MOCU. Although several solutions have been proposed and planned by SKANSKA within the Circ-Boost project, it was decided through communication with the representatives of the pilot, to proceed with the most prominent application of Rebetong®. it was agreed that Rebetong® structures, meaning the use of Rebetong® in concrete walls, sub-base layers etc. has been the most widely used application, therefore this will be the focus of the study.

The purpose of the study is to model and assess the environmental, economic and social impact of the pilot for the construction of structural building element made of recycled aggregate concrete to demonstrate the viability of using RAC as a sustainable and circular solution.

The pilot will be assessed as a standalone technology through hotspot analysis, evaluating the impacts of using recycled aggregate as replacement in the production of new concrete, as well as via a comparison of the environmental impact between the newly introduced technology and the current baseline situation of concrete production in Czech Republic using natural aggregates. For this purpose, the goal and scope for both the current practice baseline and the solution introduced by pilot 5 must be defined.

An initial meeting was set with the pilot to examine the progress and characteristics of the technology introduced and after a brief introduction to the LCA methodology and goal and scope definition, a template was sent to them for completion. Following this, a subsequent meeting was held to review the filled-in template and consolidate the goal and scope main characteristics. The template is shown in Table 19.

Table 19. Goal and Scope template of Pilot 5 (SKANSKA).



Goal	Brief description
Intended application(s) of the LCA results	Comparative analysis (product oriented) NAC vs RAC (Rebetong)
Reasons for carrying out the study	Technology study
Target audience	Horizon package 5, CCRI, CB stakeholders
Scope	**Brief description**
Function	Use in structural elements (1st floor wall from NAC to 3rd floor wall from Rebetong (not load bearing wall in the 1st floor)
Functional unit	1 m3
Reference flow	1 m3
System boundaries	Cradle to gate with options (+A4 & A5)/ Cradle to gate with options, modules C1-C4 and module D
Handling multifunctionality	If there is multifunctionality then system expansion or product allocation
Data requirements	primary data, secondary data (literature, database)
Assumptions	Do we take into account the benefits of replacing natural aggregate by recycled concrete? Do we consider all Czech concrete plants using green electricity in production?
Limitations	Project specific use
Modelling framework	Attributional
LCIA method	Environmental Footprint 3.1
Format	Report

Goal

Reasons for carrying out the study

The main purpose for conducting this analysis is to assess the performance of the building material, from a life cycle perspective, i.e. considering all stages from material production to the end-of-life via a comprehensive sustainability assessment at all three pillars of sustainability (environmental, economic, social). The LCA study, along with the LCC and S-LCA studies aim at the identification of the respective environmental, economic and social impact hotspots within the different life cycle stages of the implementation of the SKANSKA proposed solution through a hotspot analysis. The reasons for carrying out the study are the conduction of a technology study.

Intended audiences

According to the declared applications of the study, the LCA study spanning across D5.1 and D5.2 is intended to be addressed to following audiences:

- The technology provider (SKANSKA a.s.)
- The local partner (SKANSKA Residential)
- The European Union, as the main funding institution of the Circ-Boost project
- The European Commission, as the main reviewing mechanism of the Circ-Boost project
- Consortium members
- Civil engineers
- Architects
- CCRI
- Researchers (e.g. Czech Technical University)
- Ready-mix concrete producers (e.g. SKANSKA Transbeton)
- Construction and demolition companies
- Contractors
- The Czech government and Prague municipality
- Policy makers,
- Standardization bodies
- Local community
- General public

Comparative assertions

The LCA study that is initiated in D5.1 and will be concluded in D5.2, is partially intended to support comparative claims meant for public disclosure via the conduction firstly of an independent LCA and afterwards a comparative LCA against the baseline scenario which is the manufacturing with traditional concrete in the geographical context of Czech Republic. This intention does not stem from commercial competitive purposes, but purely from a scientific research point of view. Therefore, no external review (besides the review procedure prescribed by the project's Grant/Consortium Agreements) will be necessary for the Deliverables 5.1 and 5.2, according to ISO 14040:2006 and ISO 14044:2006.

Scope

Functional Unit

All LCAs examine one or more product systems, each comprising various processes throughout a product's life cycle. To ensure a fair comparison between systems, it is essential that they provide the same function to the user. This makes defining the function—and the corresponding functional unit—crucial for a relevant and quantitative assessment (Hauschild et al., 2018). In this study, the function is the construction of a structural element, specifically a concrete wall, using a concrete mix where natural aggregates are replaced with recycled aggregates. To define the functional unit, the quantitative aspects of this function must be clearly established.

The baseline scenario in this study is the use of ordinary concrete with natural aggregates and CEM II cement, which represents the standard practice in Czech construction. This will be compared to the main technology implemented in Circ-Boost Pilot 5: the application of Rebetong®, on selected floors. Due to slight differences in compaction, Rebetong® is applied selectively above the third floor of the building. The case study will focus on comparing conventional concrete (100% natural aggregates) with a 50–60% replacement using RAC, highlighting the environmental benefits and performance implications of this circular approach.

For concrete, an appropriate functional unit can be defined based on different performance characteristics. According to a review conducted by (Panesar et al., 2017), concrete functional units can be classified as single variable (volume), two variables (volume, strength) and three or more variables (volume, strength and durability). Choosing one variable functional unit can be flawed since direct comparison of the impact between 1m^3 RAC and NAC does not correspond to a balanced/precise analysis because for RAC to achieve similar compressional strength as NAC, different volumes would be needed (Zhang et al., 2019). Thus, in this study, it was deemed appropriate to proceed with a two variable functional unit, that analyzes the environmental impact per strength, based on the same volume (usually 1m^3). This type of functional unit requires that the NAC and RAC are exposed to the same non-aggressive environment, such as indoor environment of residential and office buildings to be considered as an equal comparison (Zhang et al., 2019).

In the current study, the functional unit was chosen as 1m^3 of concrete wall from NAC and RAC of C25/30 compressive strength class. This means that the mix proportion of NAC and RAC was determined so that they have approximately the same compressive strength, through adding slightly additional cement (~5%) and the same durability performance. In order to support an equal comparison, 1m^3 of a non-load bearing wall of the 1st floor of the building made from NAC would be compared with 1m^3 of a non-load bearing wall of the 3rd floor of the building made from RAC.

System boundaries

As already mentioned in section 2.1.5, the modular concept introduced by CEN TC350 standards EN15804 & EN15978 (CEN), 2011, 2019) for defining system boundaries. In line with the study's goal, the system boundaries follow a "cradle-to-gate with options" approach, as described in EN 15804. As shown in Table 20, the analysis includes modules A1–A3 (product stage) and A4–A5 (construction stage), covering the life cycle up to the practical completion of the structural element. Modules C1–C4 and module D are excluded from the system boundaries to avoid speculative modelling due to the lack of reliable data.

Modules B1–B7, which represent the use phase at the material level, are excluded from this study. Given the scope of the analysis and the material-level focus, including these stages—along with concrete carbonation during the use phase—is not considered meaningful and is therefore omitted.

Table 20. Stages included in the LCA analysis of Pilot 5 reference and solution based on EN15978.

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction / inst. process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Reuse/recovery/recycling
x	x	x	x	x	-	-	-	-	-	-	-	-	-	-	-	-

Baseline scenario

For the baseline scenario, the system boundaries are depicted in the following flow diagram:

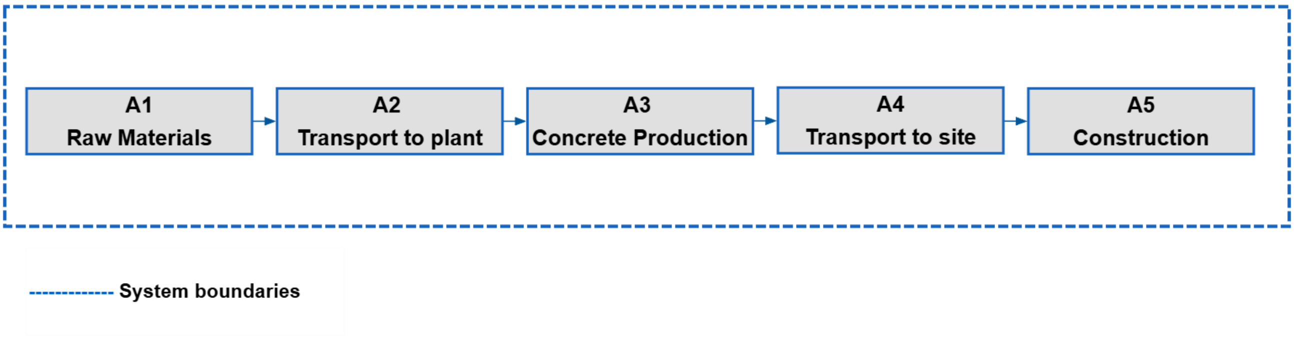


Figure 25. System boundaries of the Pilot 5 baseline for concrete production using NAC.

The stages included in the specific LCA analysis for the baseline scenario of NAC are explained below:

- **Modules A1 – A3**: They include the extraction of all ingredients (natural aggregates extraction from the quarry with the use of explosives, cement, sand, etc.) as well as crushing, sorting, loading and unloading in module A1. Additionally, they include transportation of all materials to the concrete plant (A2) and all processes and energy required for the production of the concrete mix at the concrete plant (A3) until the gate of the factory.
- **Modules A4 – A5**: These stages include transportation of the ready concrete mix from the concrete plant to the construction site (A4) and the use of equipment/machinery (cranes, extractors) and all processes required for the installation of the concrete mixture on the construction site (pumping concrete, mixing, compacting) in module A5. Internal transport on site with loader is also included.

Circ-boost solution

For the production of RAC, the stages involved are depicted in Figure 26.

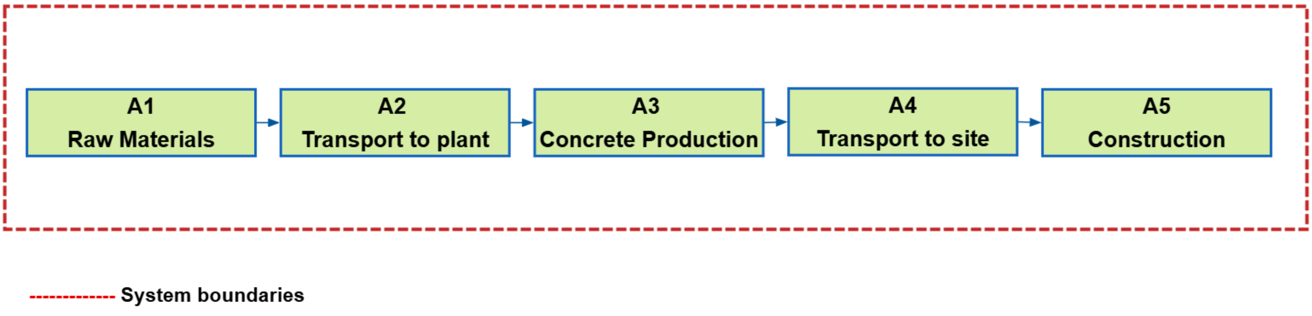


Figure 26. System boundaries of the Pilot 5 solution for concrete production using RAC.

The stages included in the specific LCA analysis for the P5 Circ-Boost solution for the production of RAC are briefly explained below:

- **Modules A1 – A3**: They include the supply of the Recycled aggregates (RA) and the rest of the materials in A1 without the need for additional crushing and sorting since the input material is already processed from the previous product system (A1), the transportation of materials to the concrete plant (A2) and the manufacturing of RAC concrete mix in the production plant (A3), until the gate of the factory. Utilization of recycled aggregate and its accompanied sub-processes have substituted the quarry process and the crushing and sorting processes in raw material acquisition in stage A1.
- **Modules A4 – A5**: These stages include transportation of the ready concrete mix from the concrete plant to the construction site (A4) and the use of equipment/machinery (cranes, extractors) and all processes required for the installation of the concrete mixture on the construction site (pumping concrete, mixing, compacting) in module A5. Internal transport on site with loader is also included.

3.5.2.2 Multifunctionality

Multifunctionality does not occur on the output side of the RAC system, as the process yields a single, well-defined product, eliminating the need for allocation among multiple outputs. On the input side, the system uses recycled materials, which are considered zero-burden. This means that these materials are considered to enter the system without carrying any environmental impacts from their previous life cycle. As such, no allocation is necessary for the burdens associated with their original production or prior use.

This approach is consistent with both EN 15804 (CEN, 2019), and the Environmental Footprint (EF 3.1) method, which allow for the zero-burden assumption under specific conditions, particularly when the upstream impacts are accounted for in the original product system. It also aligns with the polluter pays principle (PPP), as the environmental responsibility for the original product lies with the actor who caused the initial impacts, not the recycler or downstream user.

To account for these benefits, the assessment applies system expansion, extending the system boundary to include the avoided production of primary materials in a future product system. This allows the RAC system to be credited for the environmental savings resulting from the substitution of virgin resources, in line with EN 15804 and EF 3.1 guidance.

However, it is important to note that while the recycled input is considered burden-free at the point of entry, the current system remains responsible for all impacts associated with the collection, transport, and processing (further crushing or sorting of RA) of the recycled material. These are fully included within the system boundaries of the RAC process. This is also corroborated by the EN 15804 standard core PCR (CEN), 2019), where the ‘polluter pays principle’ is stated.

3.5.2.3 Assumptions and limitations

- Fine recycled aggregates were not considered for the RAC production since their use in structural concrete is generally not recommended, mainly due to their high-water absorption and cohesion.
- As stated in the functional unit definition, additional cement might be required to compensate for performance loss of RAC. This parameter could potentially influence the environmental outcomes and may be considered in a sensitivity analysis to better understand its impact.
- The transportation distance of recycled aggregates from the demolition/recycling site to the concrete plant (A2) can be identified as a potentially influential factor. Variations in this distance could affect the results, and its inclusion in a sensitivity analysis could provide additional insight.

3.5.2.4 Cut-off criteria

A 1% cut-off criterion was applied for excluding processes the impact of which contributes less than 1% of the total impact per selected impact category.

3.5.3 Life Cycle Costing (LCC)

During Task 5.1, the goal and scope of the Life Cycle Costing (LCC) assessment for Pilot 5 were clearly defined, ensuring full alignment with the framework conditions of the environmental Life Cycle Assessment

(LCA). This alignment includes the use of consistent system boundaries and a shared functional unit, thereby guaranteeing coherence between environmental and economic evaluations.

The system boundaries for the LCC of Pilot 5 include modules A1-A3 and A4-A5, in accordance with the environmental LCA boundaries.

Data collection for Pilot 5 is scheduled to begin in the coming months and will draw from both primary and secondary sources. The pilot will provide average cost estimates for key life cycle elements, including raw materials, transportation distances, construction and deconstruction activities, and replacement parts. Where pilot-specific data is not yet available, secondary sources—such as literature and price databases—will be used to fill gaps. All cost-related inputs will be gathered using a standardized LCC inventory template developed within the project.

The Life Cycle Costing analysis phase will commence after Month 30, with the launch of Task 5.3, and will continue until Month 47. This phase will incorporate both fixed and variable costs provided by the involved partners, as well as external costs—indirect social costs typically associated with environmental degradation and emissions. These externalities will be quantified and included in the final deliverable, D5.2.

3.5.4 Social Life Cycle Assessment (S-LCA)

The Social Life Cycle Assessment of the current study relies on the general framework described in section 2.3.1 adjusted to the pilot case's particular objectives. The following section presents the methodology's application to define the goal and scope for the S-LCA of Pilot 5.

3.5.4.1 Goal and Scope

The goal of the study

The Social Life Cycle Assessment (S-LCA) for Pilot 5 examines the potential social benefits and impacts of using Recycled Aggregate Concrete (RAC) as building material in the construction of an internal non-load-bearing wall within a building developed under the newly launched MoCu Project in Prague. The analysis compares a pilot scenario employing this recycled concrete (RAC) against a baseline scenario based on concrete made from natural aggregate (NAC).

Focusing on the current product system and the geographic context of Prague, Czech Republic, the study aims to uncover both positive and negative social implications for key stakeholder groups, including construction workers, material suppliers, local communities, and policymakers.

The results will be of particular interest to public authorities, construction and material production companies, recycling firms, sustainability consultants, circular economy practitioners, and academic researchers. Insights from this assessment will support future policy development, inform circular procurement strategies, and guide the design of socially responsible construction practices in Czech Republic and beyond.

Functional unit

The functional unit for the specific S-LCA is consistent with the one used in the LCA and LCC studies. However, unlike LCA and LCC, the social impacts and effects in the S-LCA will not be quantitatively scaled to the functional unit. Nevertheless, this will be addressed in the later stages of the Social LCA study. Thus, in the current study, the functional unit was chosen as 1m^3 of concrete wall of C25/30 compressive strength class. This means that the mix proportion of NAC and RAC was determined so that they have approximately the same compressive strength, through adding slightly additional cement (~5%), and the same durability performance. To support an equal comparison, 1m^3 of a non-load bearing wall of the 1st floor of the building made from NAC would be compared with 1m^3 of a non-load bearing wall of the 3rd floor of the building made from RAC.

System boundaries

In line with the LCA study, the system boundaries for the social life cycle assessment follow a “cradle-to-gate with options” approach, as described in EN 15804. This S-LCA analysis focuses on the material level, using 1m^3 of concrete as functional unit and system boundaries covering modules A1–A3 (product stage) and A4–A5 (construction stage). However, since the A4–A5 stages are identical for both the baseline and the Circ-Boost solutions (NAC and RAC)—as both materials are produced at the same concrete plant and subsequently transported to the construction site—it is assumed that the potential social impacts and benefits are equivalent. Therefore, Modules A4–A5 are excluded from the system boundaries of the S-LCA for Pilot 5.

In contrast to the pilots focusing on the building level, the use phase (B) is excluded from the analysis of Pilot 5, as the material itself does not directly involve stakeholder interactions during its use. Social impacts related to building occupancy or user experience are more relevant at the building level, not at the level of individual materials. For simplicity and visual clarity, the system boundaries are illustrated in a single graph (See Figure 27) representing both the baseline and the Circ-Boost solution.

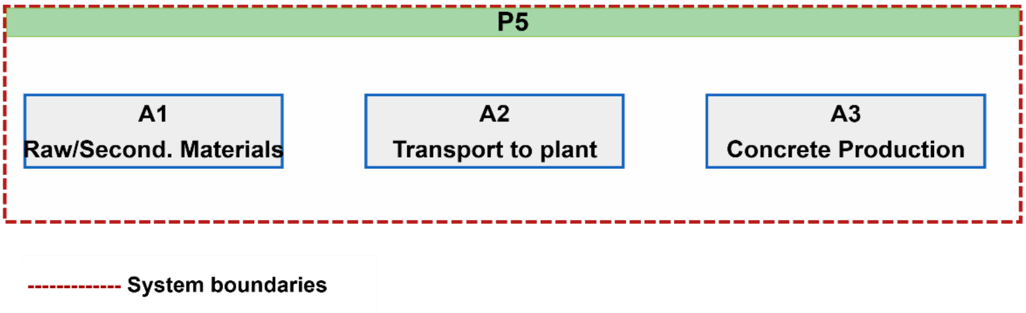


Figure 27. Social LCA system boundaries of Pilot 5 covering baseline and solution (wall from NAC and RAC).

Stakeholders’ selection

Stakeholder groups were considered separately for each life cycle stage, as defined by (Benoît Norris et al., 2020). These categories were further refined into subcategories based on the stakeholder mapping conducted in Circ-Boost Task 2.2 and inputs from pilot partners. This approach ensures that the analysis is both methodologically robust and contextually relevant to the construction sector. A definition of the selected stakeholders, along with their type of relationship to the system, is presented in Table 21 for both the Natural Aggregate Concrete (NAC) and Recycled Aggregate Concrete (RAC) internal wall of Pilot 5. Corresponding life cycle modules (in parentheses) indicate where each stakeholder group is involved.

Table 21. Definition of the stakeholder categories across S-LCA stages of Pilot 5’s NAC and RAC internal wall case, with corresponding life cycle modules indicated in parentheses.

Stakeholder group	Stakeholder Subcategory/Sub-Stakeholders	Definition	Type of relation
Workers	Primary material extraction workers: (Natural aggregate) [baseline] (A1)	Employees involved in the extraction and initial processing of raw materials used in the construction sector.	Affected – they are affected by the system's practices and decisions.

	Secondary recycled material workers: (Recycled aggregate) receiving/preprocessing (e.g. crushing and sorting) [pilot] (A1)	Employees in secondary material collection facilities handling the intake and preparation of recycled materials for reuse in construction, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Building materials/elements production workers: Conventional concrete mix vs concrete mix with recycled aggregate (A3)	Employees within the production sector, who work in concrete production industry, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Construction workers/Equipment operators (A5)	Employees working within the construction sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
	Transportation workers (A2, A4)	Employees working in the transportation sector, but do not own those businesses.	Affected – they are affected by the system's practices and decisions.
Society	Academic Research institutions	Bodies that execute applied research to find/test new applications in sustainable construction and circular economy.	Concerned – they are concerned by the environmental, social and economic performance of available products/technologies in the market. They develop novel products and conduct research studies for technology progress purposes.
			Involved – they are involved in the decision-making process.
	General Population (A1-A3, A5, B1)	Citizens and communities indirectly affected by the environmental, economic and social impacts of building materials production and raw material savings.	Affected – they are affected by the system's practices and decisions and by economic performance of public buildings.
	Not-for-profit association committed to advancing the technical, economic, aesthetic and environmental performances of concrete structures worldwide (A1-A3)	Organizations engaged in the promotion of ecofriendly, sustainable and climate-smart technologies/materials and innovations.	Concerned – they are concerned by the environmental, social and economic performance of available products/technologies in the market and influence the promotion of sustainable practices.
Local community	Neighborhood near virgin raw material extraction [baseline and pilot] (A1)	Residents living in proximity to sites where virgin raw materials (e.g. natural aggregates, limestone, clay) are extracted.	Affected – their well-being and environment may be influenced by extraction activities and associated infrastructure.

	Neighborhood near companies receiving/pre-processing secondary material [pilot] (A1)	Residents living near facilities that receive and pre-process secondary materials (e.g., recycled aggregates, reclaimed steel).	Affected – they may experience impacts in the local environment e.g. noise, emissions.
	Neighborhood near building material (concrete mix) production facilities (A3)	Residents living close to facilities where concrete mix and steel is manufactured.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
	Neighborhood near construction site (A5)	Residents living near the location where DfD/R or in-situ buildings are assembled or constructed.	Affected – they may experience impacts in the local environment e.g. noise, emissions.
Value chain actors	Primary & secondary material supply companies (A1)	Companies that extract/receive construction materials intended for manufacture building components.	Directly involved – they respond to project requirements and influence material availability, quality and circularity.
	Building materials production companies (suppliers) (A3)	Companies that produce construction elements/materials, including panels and concrete mix.	Directly involved – they respond to project requirements and influence material availability, quality and circularity.
	Material technology development companies (A1-A3)	Firms engaged in R&D and innovation related to construction materials, including durability, recyclability, and performance.	Directly involved – they enable circular design through material innovation and life-cycle optimization.
	Equipment/machinery companies (A5)	Providers of machinery used in the construction/assembly of buildings.	Directly involved – they supply the tools necessary for efficient construction.
	Transportation companies (A2, A4)	Entities responsible for transportation services of materials.	Affected – they are affected by the system's practices and decisions regarding flow volumes of materials, products and transportation distances.

Impact categories and indicators

The stakeholder groups and subcategories were identified and mapped to each life cycle stage, following the modular structure of EN 15804. Each stakeholder subcategory was then linked to the most relevant social impact categories, which were subsequently connected to specific indicators. This structured and sequential approach ensures a consistent and traceable connection between stakeholders, potential social impacts, and the metrics used to assess them. This correlation is depicted in Table 22. It should be noted that Social Life Cycle Assessment (s-LCA) is inherently an iterative process, and the final selection of indicators will be determined based on data availability during the assessment phase. As the project progresses, certain indicators may be added or removed to reflect the realities of data accessibility, stakeholder input, and contextual relevance.

Table 22. Indicators selection for production of building elements from NAC & RAC in Czech Republic (P5-SKA).

Life Cycle Stage	Stakeholder Group	Stakeholder Sub-Category	Impact Category	Indicator
A1 _ Raw material extraction / supply **A2** _ Transportation of materials to concrete plant **A3** _ Production of building materials (concrete mix in concrete plant)	**Workers**	Raw materials production (Primary material extraction workers (natural aggregate) **vs** secondary recycled material (recycled aggregate) (A1)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Hours of Paid Employment (for all employees)
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Building materials/elements production workers (this stakeholder subcategory could be skipped if no differences in impacts/benefits are observed between pilot and baseline scenario) (A3)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Hours of Paid Employment (for all employees)
			Labor Practices and Decent Work	Fair Salary
				Working Hours Compliance
				Social Security & Benefits Coverage
				Non-Discrimination
		Transportation workers (A2)	Health and Safety	Accidents
				Exposure to hazardous substances
			Employment	Jobs created or jobs lost
	Local Community	Neighborhood near the raw material production sites (virgin material extraction (baseline and pilot) **vs** the secondary	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)

		material production (pilot) (A1)		
		Neighborhood near to building materials/elements production facilities (this stakeholder subcategory could be skipped if no differences in impacts/benefits are observed between pilot and baseline scenario) (A3)	Local Resident Well-being and Environmental Disruption	Exceedance of Noise Limits
				Local Air Quality Compliance for Particulates (Levels of PM2.5/PM10 in ambient air)
	Society	General population	Contribution to Circular Economy and Resource Efficiency	Raw materials savings (from the replacement of extraction materials by recycled materials)
			Public health	Air quality
			Climate Change Adaptation and Societal Resilience	Reduced Societal Vulnerability to Climate Change Impacts
		Academic Research Institutions	Knowledge & Innovation	Contribution to R&D and Knowledge Dissemination on Sustainable Concrete
		Not-for-profit association committed to advancing the technical, economic, aesthetic and environmental performances of concrete structures worldwide.	Knowledge & Innovation	Contribution to R&D and Knowledge Dissemination on Sustainable Concrete

	Value Chain Actors	Raw material companies (Primary material extraction companies vs Secondary recycled material receivers/pre-processers companies)	Economic growth/ Economic contribution	Factor Tax Payments
		Building materials production companies (suppliers)	Economic growth/ Economic contribution	Factor Tax Payments
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
			Affordability of raw materials for concrete producers	Affordability of raw materials for concrete producers
		Material Technology development companies	Economic growth/ Economic contribution	Factor Tax Payments
			Human Capital Development	Skills Development and Job Enhancement in the Value Chain
			Innovation & Contribution to Sustainable Construction	Development and Commercialization of Sustainable Material Technologies
			Contribution to Industry Advancement and Sustainable Construction	Development and Commercialization of Sustainable Material Technologies
		Transportation companies	Economic growth/ development	Factor Tax Payments

4. Conclusions

Deliverable D5.1 has successfully defined the goal, scope, and system boundaries for the threefold sustainability assessment—Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA)—in support of evaluating the Integrated Circular Solutions (ICS) implemented by five pilot projects across Europe. This harmonized framework enabled consistent benchmarking of circular practices against conventional approaches, using standardized functional units and system boundaries aligned with EN 15978 and EN 15804.

- **Pilots 1 and 3** addressed modular, deconstructable single-story concrete buildings, assessed over a 100-year reference period through a dual-lifecycle approach. The functional unit was defined as one single-story building over 100 years, incorporating Design for Disassembly and Reuse (DfD/R) principles.
- **Pilot 2** introduced a mobile reuse and recycling platform in Île-de-France for inert waste, raised flooring systems, and skylights. The functional unit was defined as the treatment of one ton of each material type, assessed from a gate-to-gate with options perspective (C2–C3). Stakeholder mapping and social impact indicators were aligned with this scope.
- **Pilot 4** demonstrated the direct reuse of non-contaminated concrete from two buildings to produce three blocks for the GAIA Vesterålen Museum in Norway. The functional unit was one cubic meter of ready-mix concrete (NAC and RAC) of strength class B35, with system boundaries limited to modules A1–A3. LCC and S-LCA assessments followed the same boundaries and stakeholder structure.
- **Pilot 5** explored the use of Rebetong® in the MOCU Project in Prague, applied in structural and façade elements. The functional unit was one cubic meter of concrete wall (NAC vs. RAC) of strength class C25/30, comparing non-load bearing walls under equal environmental conditions. The system boundaries followed a cradle-to-gate with options approach (A1–A5), excluding modules C1–C4, D, and B1–B7 due to the material-level focus. LCC and S-LCA assessments were aligned with the goal and scope of the LCA with minor additions, maintaining consistency and enabling the thorough stakeholder mapping and indicator selection.

Across all pilots, the LCC and S-LCA frameworks were structured consistently, with stakeholder groups and indicators harmonized across life cycles. Minor adjustments to system boundaries were made to reflect pilot-specific contexts.

With the goal, scope, and system boundaries now clearly defined, the project will proceed to the next phases: data collection, Life Cycle Inventory (LCI) development, Life Cycle Impact Assessment (LCIA), and interpretation. These steps will further substantiate the findings and contribute to the broader deployment of circular solutions in the built environment.

References

Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Sala, S., & Ardente, F. (2023). *Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method*. https://doi.org/doi:10.2760/798894

Arzoumanidis, I., D'Eusanio, M., Raggi, A., & Petti, L. (2020). *Functional Unit Definition Criteria in Life Cycle Assessment and Social Life Cycle Assessment: A Discussion* (pp. 1–10). https://doi.org/10.1007/978-3-030-01508-4_1

Azimi, A. N., Dente, S. M. R., & Hashimoto, S. (2020). Social Life-Cycle Assessment of Household Waste Management System in Kabul City. *Sustainability*, *12*(8), 3217. https://doi.org/10.3390/su12083217

Benoît Norris. (2022). *Social Hotspots Database (Version 5)*. New Earth B. http://www.socialhotspot.org

Benoît Norris, C. , Traverzo, M., N. S. , Ekener, E., S. T. , & Russo Garrido, S. (2020). *UNEP, 2020. Guidelines for Social Life Cycle Assessment of Products and Organizations 2020*.

Bjørn, A., Owsianiak, M., Molin, C., & Laurent, A. (2018). Main Characteristics of LCA. In *Life Cycle Assessment* (pp. 9–16). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_2

CEN. (2011). *EN 15978:2011. Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method*. https://doi.org/10.3403/30204399

CEN. (2019). *EN 15804:2012+A2:2019. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products*. https://doi.org/10.3403/30259256

CEN. (2022). *EN 16757:2022. Sustainability of construction works. Environmental product declarations. Product Category Rules for concrete and concrete elements*.

Cerdas, F. (2022). *Integrated Computational Life Cycle Engineering for Traction Batteries*. Springer International Publishing. https://doi.org/10.1007/978-3-030-82934-6

Chen, X., Zhang, Y., & Ge, P. (2024). Research on the calculation method of concrete compressive strength based on volume content of recycled coarse aggregate and fine aggregate. *Journal of Asian Architecture and Building Engineering*, *23*(1), 204–219. https://doi.org/10.1080/13467581.2023.2238021

D Milinković. (2019). *The overview of the Serbian Construction Industry Sector covered by the European Regulation (EU)* (Tatjana Bojanić, Ed.). Institute for Standardization of Serbia (ISS) .

Dos Santos Gervasio, H., & Dimova, S. ,. (2018). *JRC - Model for Life Cycle Assessment (LCA) of buildings*. https://doi.org/https://dx.doi.org/10.2760/10016

Eberhardt, L. C. M., Birgisdóttir, H., & Birkved, M. (2019). Life cycle assessment of a Danish office building designed for disassembly. *Building Research & Information*, *47*(6), 666–680. https://doi.org/10.1080/09613218.2018.1517458

European Commission; JRC. (2011). *International reference life cycle data system (ILCD) handbook – General guide for life cycle assessment: provisions and action steps* (1st, EUR 24708 EN ed.). Publications Office. https://doi.org/doi/10.2788/33030

European Commission; JRC. (2016). *Guide for interpreting life cycle assessment result*.

European Commission; JRC. (2021). *Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organizations* (Vol. 471). Directorate-General for Environment.

Goedkoop, M., de Beer, I., Harmens, R., visser, diana, Saling, P., Florea, A., Hettinger, A., Indrane, D., Morão, A., Flores, E., Alvarado, C., Schenker, U., Viot, J., Wathelet, A., & laure, cormier. (2020). *Handbook for Product Social Impact Assessment 2020*.

GreenDelta. (2023). *openLCA 2.4*. https://www.openlca.org/

Haes, H., Finnveden, G., Goedkoop, M., Hauschild, M., Hertwich, E., Hofstetter, P., Jolliet, O., Klöpfer, W., Krewitt, W., Lindeijer, E., Müller-Wenk, R., Olsen, S., Pennington, D., Potting, J., & Steen, B. (2002). *Life-Cycle Impact Assessment: Striving Towards Best Practice*.

Hauschild, M., Rosenbaum, R., & Olsen, S. (2018). Life Cycle Assessment: Theory and Practice. In *Life Cycle Assessment: Theory and Practice*. https://doi.org/10.1007/978-3-319-56475-3

International Organization for Standardization (ISO). (2006a). *ISO 14040:2006; Environmental Management - Life Cycle Assessment - Principles and Framework.* https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en

International Organization for Standardization (ISO). (2006b). *ISO 14044:2006; Environmental Management - Life Cycle Assessment - Requirements and Guidelines.* https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en

International Organization for Standardization (ISO). (2024). *ISO14075:2024 - Environmental management — Principles and framework for social life cycle assessment*. https://www.iso.org/standard/61118.html

James A. Fava. (1991). *A Technical framework for life-cycle assessments: Workshop Report*. Society of Environmental Toxicology and Chemistry (SETAC): SETAC Foundation for Environmental Education, 1991. https://search.library.wisc.edu/catalog/9910250223802121

Mannan, M., & Al-Ghamdi, S. G. (2022). Complementing circular economy with life cycle assessment: Deeper understanding of economic, social, and environmental sustainability. In *Circular Economy and Sustainability* (pp. 145–160). Elsevier. https://doi.org/10.1016/B978-0-12-819817-9.00032-6

Marinković, S., Carević, V., & Dragaš, J. (2021). The role of service life in Life Cycle Assessment of concrete structures. *Journal of Cleaner Production*, *290*, 125610. https://doi.org/10.1016/j.jclepro.2020.125610

Marinković, S., Josa, I., Braymand, S., & Tošić, N. (2023). Sustainability assessment of recycled aggregate concrete structures: A critical view on the current state-of-knowledge and practice. *Structural Concrete*, *24*(2), 1956–1979. https://doi.org/10.1002/suco.202201245

Panesar, D. K., Seto, K. E., & Churchill, C. J. (2017). Impact of the selection of functional unit on the life cycle assessment of green concrete. *The International Journal of Life Cycle Assessment*, *22*(12), 1969–1986. https://doi.org/10.1007/s11367-017-1284-0

Pepe, M., Michels, J., Zani, G., Rampini, M. C., & Martinelli, E. (2023). Deconstructable Concrete Structures Made of Recycled Aggregates from Construction & Demolition Waste: The Experience of the DeConStRAtion Project. In A. Jędrzejewska, F. Kanavaris, M. Azenha, F. Benboudjema, & D. Schlicke (Eds.), *International RILEM Conference on Synergising Expertise towards Sustainability and Robustness of Cement-based Materials and Concrete Structures* (pp. 487–499). Springer Nature Switzerland.

PRé Sustainability. (2023). *SimaPro 9.5* (9.6.1). https://simapro.com/

Přikryl, R. (2021). Geomaterials as construction aggregates: a state-of-the-art. *Bulletin of Engineering Geology and the Environment*, *80*(12), 8831–8845. https://doi.org/10.1007/s10064-021-02488-9

Saidani, M., Cluzel, F., Leroy, Y., Pigosso, D., Kravchenko, M., & Kim, H. (2022). Nexus Between Life Cycle Assessment, Circularity and Sustainability Indicators—Part II: Experimentations. *Circular Economy and Sustainability*, *2*(4), 1399–1424. https://doi.org/10.1007/s43615-022-00160-2

SDES. (2022). *Chiffres Clés Du Logement 2022*. https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-du-logement/pdf/Chiffres-cles-logement-2022.pdf

UNEP & CEA Yale. (2023). *Building Material and the Climate: Constructing a New Future*. https://doi.org/10.59117/20.500.11822/43293

United Nations. (2019). *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*. http://creativecommons.org/licenses/by/3.0/igo/

Wang, C., Xiao, J., Zhang, C., & Xiao, X. (2020). Structural health monitoring and performance analysis of a 12-story recycled aggregate concrete structure. *Engineering Structures*, *205*, 110102. https://doi.org/10.1016/j.engstruct.2019.110102

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Zhang, Y., Luo, W., Wang, J., Wang, Y., Xu, Y., & Xiao, J. (2019). A review of life cycle assessment of recycled aggregate concrete. *Construction and Building Materials*, *209*, 115–125. https://doi.org/10.1016/j.conbuildmat.2019.03.078

Zhuang, S., Liu, Q., Sun, K., Lutter, S., Chen, R., & Liu, G. (2025). Tracking five decades of global sand and gravel stocks and flows in 184 countries. *Resources, Conservation and Recycling*, *222*, 108460. https://doi.org/10.1016/j.resconrec.2025.108460

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