Integration of life-cycle perspective in PED design

Date of document

10/09/2024

University of the Basque Country (UPV/EHU)

Published and produced by	
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Date	10-09-2024
Project Name	**oPEN Lab**
Project Coordinator	VITO
Project Duration	Oct. 2021 – Mar. 2026
Website	https://openlab-project.eu/

Document History

Version	Date	Organisation	Comments
1	03/05/2024	UPV/EHU	The first draft of the deliverable for peer review
2	21/05/2024	UPV/EHU	Final version after review by TALTECH
3	29/05/2024	UPV/EHU	Final version after second review by TALTECH and proofreading
4	15/08/2024	UPV/EHU	Final version after review by VITO and proofreading
5	10/09/2024	UPV/EHU	Final version after final review by VITO

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Acronyms

Acronym	Description
AECO	Architecture, Engineering, Construction & Operations
BAU	Business as Usual
BIM	Building Information Modelling
BIPV	Building Integrated Photovoltaics
BMS	Battery Management System
BREEAM	Building Research Establishment Environmental Assessment Methodology
CAD	Computer-aided Design
CAES	Certificados de Ahorro Energético (Energy Efficiency Certificates)
CEEP	Clean Energy for all Europeans Package
CEN/TC	European Committee for Standardization/Technical Committee
CHP	Combined Heat and Power
DGNB	Deutche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)
DHW	Domestic Hot Water
DQR	Data Quality Rating
DU	Declared Unit
EF	Environmental Footprint
EFTA	European Free Trade Association
EN	European Standard
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene Insulation
ESL	Estimated Service Life
EVs	Electric Vehicles
FU	Functional Unit
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
HVAC	Heating Ventilation Air Conditioning
ICE	Internal Combustion Engine
ICT	Information and Communications Technology
IFC	Industry Foundation Classes
INA	Indicator Not Assessed
IOA	Input-Output Analysis
ISO	International Organization for Standardization
JPI	Joint Programming Initiatives
JRC	Joint Research Centre
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LEED	Leadership in Energy and Environmental Design
LLs	Living Labs
LOD	Level of Development
LREC	Local Renewable Energy Communities
MFA	Material Flow Analysis
MNA	Module Not Assessed
mPt	Millipoints
NBS	Nature Based Solutions
NEST	Neighbourhood Evaluation for Sustainable Territories
nZEB	Net Zero Energy Building
OVAM	Openbare Vlaamse Afvalstoffenmaatschappij (Public Waste Agency of Flanders)
PCR	Product Category Rules
PED	Positive Energy District
PEF	Product Environmental Footprint
PEN	Positive Energy Neighbourhoods
Pt	Point
PV	Photovoltaic
ReqSL	Required Service Life
RES	Renewable Energy Sources
RSL	Reference Service Life
RSP	Reference Service Period
SUMP	Sustainable Urban Mobility Plan
TOTEM	Tool to Optimise the Total Environmental impact of Materials
V2B	Vehicle to Building
V2G	Vehicle to Grid
XPS	Extruded Polystyrene Insulation

Executive Summary

Within the framework of developing positive energy districts (PEDs) under the oPEN Lab project, an analysis of the environmental impact of such transitions is required to determine the improvement achieved and their sustainability.

This report is divided into five main sections.

The first section is an overall introduction and provides the background.

The second presents a short introduction to life cycle assessment (LCA), describing in general terms how it is carried out, what steps need to be followed and what should be taken into account during the assessment. This section is only intended to contextualise and serve as an introduction to the following sections which focus on the LCA for the design of PEDs and the oPEN Lab project.

The third section describes how LCA can be integrated into the design of PEDs. First, a state of the art study is conducted to identify how LCA is currently approached at all the levels that apply to PEDs (product, material, element, building and district), paying special attention to the district level. Furthermore, an explanation is given of the potential issues that may arise in PEDs impacting the LCA outcomes. It is therefore necessary to explore the impact that these issues may have, either through a sensitivity analysis or through their possible integration into LCA. Next, to try to discern how LCA can be more effectively integrated into the design of PEDs, data flows are analysed, with a special focus on the potential use of BIM. This is followed by an analysis of the stakeholders involved in the design and how they can be supported to integrate LCA into their decision-making in a simpler and more efficient way (display system using labels, lists of possible strategies to integrate, etc.).

The fourth section presents the common LCA framework and protocol that will be implemented and tested in the oPEN Lab project. This will be used to compare the results from the three living labs and to validate the proposed protocol to establish an LCA approach for PED design which can be extrapolated to other contexts and, in the future, be integrated into the standards.

The last section presents conclusions and recommendations, highlighting the challenges of integrating LCA into the workflow and decision-making processes of the different actors involved in the design and development of PEDs. It is not only necessary to establish a common protocol for assessing LCA at the PED level, but also a simple and easy way of presenting the results and data exchange systems, thereby enabling all stakeholders, whatever their level of expertise in LCA, to understand the environmental impact of a solution or strategy and make appropriate decisions. This will increase their awareness and involvement in the environmental transition required in cities. In addition, the need to adapt the LCA methodology is also stressed, especially with a view to the fast transition that cities are undergoing (the implementation of the new strategies and actions) in order for European neutral climate goals to be achieved.

1. Introduction

The European Union's aim to be climate-neutral by 2050 requires a total decarbonisation of the existing building stock [1, 2]. Furthermore, the Renovation Wave initiative aims to at least double the annual energy renovation rate by 2030 [3], making it a priority to redesign and retrofit existing buildings and neighbourhoods to make them future-proof with no adverse impact on climate change and with a minimised environmental footprint, while having a positive impact on society. Both the construction and energy sectors should be subject to adjustments, such as implementing the digitisation of design and construction processes, decentralising energy technologies, and supporting the uptake of energy communities and energy flexibility services. To this end, positive energy neighbourhoods (PENs) are being advocated. PENs are highly energy-efficient and flexible urban neighbourhoods in which the buildings, energy systems and mobility infrastructure work in harmony to achieve a surplus production of renewable energy. A full decarbonisation of the building sector will require a broad penetration of PENs and related innovations. In this regard, positive energy districts (PEDs) have also been defined by Joint Programming Initiative (JPI) Urban Europe as:

'*energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility, and ICT systems, while securing the energy supply and a good life for all in line with social, economic, and environmental sustainabilit*y.' [4].

As part of the transition of neighbourhoods and districts towards PEN/PED to achieve climate-neutral cities, it is essential to take into account the environmental impact of the required interventions. During their implementation and their subsequent improvement at the operational level. The use of more environmentally efficient technologies and strategies would be expected to result in a decrease in primary energy demand, embodied energy and environmental emissions over the full life cycle of the building and the entire neighbourhood. The environmental impact of such solutions will be determined through an environmental impact assessment and the results should also be taken into account in the design of the PEN/PED.

Accomplishing this reduction in the environmental impact begins by choosing the strategies, materials and products during the design process that will help to achieve the PEN/PED and, consequently, climate neutrality. This entails environmental awareness, education, and the implementation of life cycle assessment (LCA). Moreover, it is necessary to consider the environmental impact of each action or solution, and bring about changes in the way of working, decision-making and behaviour of the citizens and all actors involved in the process (builders, architects, owners, decision-makers, etc.).

Within the framework of the oPEN Lab project, a Europe-wide project that aims to work towards the creation of PEDs, this report will analyse how LCA should be introduced into the design of PEN/PED to support the above-mentioned transition. It will also establish a protocol and a framework that will enable LCA to be carried out at PEN/PED level, determining the reduction in the environmental impact achieved. This protocol will be tested in the three Living labs of the project for evaluation, validation and adaptation for future scalability to other projects and contexts. It will serve as an example for establishing and adapting standards at district level, specifically for PEDs. Level of study that can be considered part of the innovation of the project as there are currently no concrete standards or guidelines for it.

2. General introduction to the LCA methodology

An LCA is a methodological tool used to measure the environmental impact of a material, product, element, building, process or system throughout its life cycle, from the acquisition and transport of the raw materials until its end of life. It is based on the collection and analysis of the input (raw materials, energy, water) and output (emissions to air, water soil, waste, products) data of the system to obtain results that show their potential environmental impacts. Calculating the environmental impacts makes it possible to understand the environmental performance of the product, process, system, building or district. The most dangerous areas are identified from an environmental perspective and, ultimately, useful information is obtained that can help technical decisions to make better use of materials and reduce energy consumption, among other benefits.

The methodology used in this project is based on the ISO international standards, in combination with the following European standards:

- **ISO 14040:2006/A1:2020** [5] - Environmental management – Life cycle assessment – Principles and framework;
- **ISO 14044:2006/Amd 2:2020** [6] - Environmental management – Life cycle assessment – Requirements and guidelines;
- **EN 15804:2012+A2:2019** [7] - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products;
- **prEN 15978-1:2021** [8] - Sustainability of construction works - Methodology for the assessment of performance of buildings - Part 1: Environmental Performance.

According to ISO 14040:

'*LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e., cradle-to-grave*)' [5].

In addition to the above ISO and EN standards, an LCA comprises four steps:

- **Goal and scope definition;**
- **Life cycle inventory analysis (LCI);**
- **Life cycle impact assessment (LCIA);**
- **Interpretation.**

The relationship between the different phases is illustrated in Figure 1. It shows that these four phases, described in the sub-sections below, are not independent of each other.

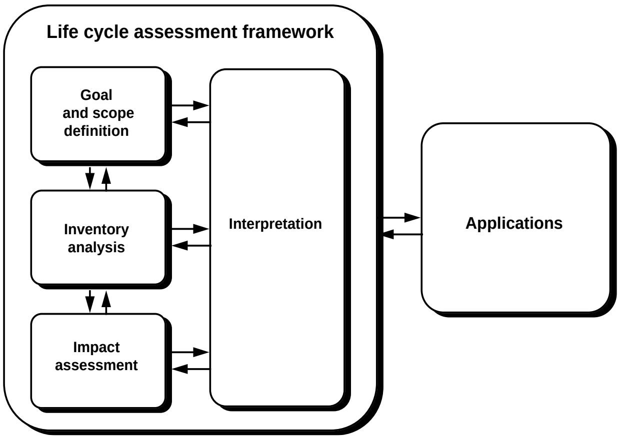


Figure 1. Methodological framework of an LCA [5, 6].

2.1 Goal and scope definition

In the first phase of an LCA, its intended use (the goal) and the width and depth of the study (the scope) have to be clearly defined. The scope definition must be consistent with the goal of the study. In the following paragraphs, some aspects are briefly discussed that should be clear, unambiguous and agreed upon at the start of the study [5, 6].

2.1.1 Goal of the LCA

Defining the goal of an LCA includes an unambiguous description of:

- The reasons for carrying out the LCA;
- The intended use of its results;
- The audience to which the results are intended to be communicated.

In general, different reasons exist for conducting an LCA:

- Specific LCA:
  - Determining the environmental profile of a product system;
  - Discovering opportunities to improve the environmental performance of the product system studied.
- Comparative LCA:
  - Determining the environmental profile of different existing product systems;
  - Comparing the different environmental profiles.

An LCA study can have different purposes:

- **Internal use:** the results will be used internally;
- **External use:** the results can be used to communicate the environmental performance of the production system to external parties using an objective method, as well as for commercial use (note: ISO 14040 says, '*in the case of comparative assertions disclosed to the public, the evaluation shall be conducted in accordance with the critical review process and presented category indicator by category indicator.'* [5, 6]). This critical review process should be carried out by a person with expertise in LCA, either internal or external to the organisation, but who has not been involved in any part of the LCA process.

2.1.2 Scope of the LCA

The scope should be sufficiently well-defined to ensure that the width, depth and detail of the study are compatible and sufficient to address the goal. In its definition, the following items should be considered and clearly described:

- The product system to be studied;
- The functions of this product system;
- The functional unit;
- The product system boundaries;
- Allocation procedures;
- Types of impact and methodology of impact assessment, and subsequent interpretation to be used;
- Data requirements;
- Data quality requirements;
- Assumptions;
- Limitations;
- Type of critical review, if any;
- Type and format of the report required for the study.

Product system(s) to be studied

According to ISO 14044 [6], a product system is a collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product. Therefore, a product system involves the identification and consideration of all processes interrelated with the object of study, without omission of any aspect that is attributable to it throughout its life cycle.

Function of the product system and functional unit

The function covers the performance characteristics of the product. The Commission recommendation on the use of environmental footprint methods to measure and communicate the life cycle environmental performance of products and organisations [9] establishes four aspects related to the function that should be considered when defining a functional unit:

- The function(s)/service(s) provided: 'what?';
- The extent of the function or service: 'how much?';
- The expected level of quality: 'how well?';
- The duration/lifetime of the product: 'how long?'.

A functional unit is a quantified description of the performance of the product systems, for use as a reference unit [6]. This means that the product or object to be analysed must be specified and clearly defined, covering the product system indicated above and responding to the specifications of the function previously stated. The functional unit measures the performance of the product system and provides a reference to which the input and output data will be normalised. In other words, the functional unit represents the quantified performance of a product system for use as a reference unit in an LCA study.

In comparative LCAs, comparisons can only be made based on equivalent functions, i.e. LCA data can only be compared if they are normalised to the same functional unit.

Reference study period (RSP) and reference service life (RSL)

In EN standards for the life cycle assessment of buildings, such as EN 15978 [8], time-related parameters such as the reference study period (RSP) of buildings and the reference service life (RSL) of building products are only generically defined. Therefore, it is important to choose them correctly.

RSP and RSL are defined in EN 15978 [8] and EN 15804 [7] respectively as:

- **RSP:** the period over which the time-dependent characteristics of the object of the assessment are analysed [8];
- **RSL:** known or expected period of time of the service life of a construction product under a particular set of in-use conditions, which can serve as a basis for the service life under other in-use conditions [7].

System boundaries

The system boundaries are defined as a set of criteria specifying which unit processes are part of a product system [6].

The system boundaries of the LCA should be clearly defined. This includes a statement of:

- Which processes will be included in the study;
- To which level of detail these processes will be studied;
- Which releases to the environment will be evaluated;
- To which level of detail this evaluation will be made.

EN 15804:2012+A2:2019 [7] and prEN 15978-1:2021 [8] define four groups of modules:

- **Module A** (from A1 to A5): relating to the product stage and construction stage, and the predesign stage for buildings (A0);
- **Module B** (from B1 to B7): relating to the use stage of the product/building;
- **Module C** (from C1 to C4): covering de-construction/demolition, transport to waste processing, waste processing (reuse, recycling and incineration with energy recovery) and disposal (incineration without energy recovery and landfilling);
- **Module D**: covering benefits and loads beyond the system boundary related to reuse, recycling and (energy) recovery of waste or products.

Table 1. LCA phases.

Product stage	Construction process		Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	User activities not covered in B1- B7	End-of-life stage	Benefits/loads beyond system boundary
A1-A3	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**C1-C4**	**D**

Ideally, all life cycle stages, from the extraction of raw materials to the final waste treatment, should be taken into consideration. In practice, however, there is often not enough time, data or resources to conduct such a comprehensive study, resulting in decisions having to be made regarding which life cycle stages, processes or releases to the environment should be included in the study. Any omissions should be clearly stated and justified in the light of the defined goal of the study.

Allocation procedures

Allocation procedures are the partitioning of the input or output flows of a process or a product system between the product system under study and one or more other product systems [6].

Allocation procedures are needed when dealing with systems involving multiple products. The materials, energy flows and associated environmental releases must be allocated according to clearly stated, documented and justified procedures. When a system produces two or more products, these are referred to as co-products. In such cases, it is necessary to allocate the resources used by the system and any associated environmental impacts among these generated products or co-products.

For processes where allocation is necessary (multiple input or output processes), the allocation procedure described in Chapter 4.3.4 of the ISO14044:2006/Amd 2:2020 [6] will be followed. The allocation procedure defined in this standard is summarised as follows:

- **Step 1:** wherever possible, allocation should be avoided or minimised by detailing multiple processes into two or more sub-processes, some of which can be located outside the system boundaries, or by expanding the system boundaries so that inputs/outputs remain inside the system. This is called 'avoiding allocation by system expansion';
- **Step 2:** where allocation cannot be avoided, it should preferentially be based on physical relationships between the system inputs and outputs;
- **Step 3:** where physical relationships cannot be established, allocation to various products may be based on their economic value.

Traditionally there are two approaches to LCA which may influence the allocation procedures: the attributional life-cycle approach and the consequential life-cycle approach [10]:

- **The attributional life-cycle approach** (classical definitions such as 'accounting', 'book-keeping', 'retrospective' or 'descriptive') represents the system in a real, specifically planned or value chain related way (considering its use and end of life). This is the traditional LCA approach, which consists of a description of the actual flows of the system and its subsystems. The flows represent the physical relationships between the inputs and outputs of the processes;
- **The consequential life-cycle approach** (classical definitions such as 'change-oriented', 'effect-oriented', 'decision-based', 'market-based') represents, in a general way, the value chain as it is theoretically expected to occur as a consequence of analysed decisions. The product system interacts with markets, and these changes are represented dynamically. It consists of a description of how the flows of the system vary according to the decisions taken, and therefore requires a thorough knowledge of the economic market. It is used for decision making by policy makers.

The recycled content allocation procedure is included in the attributional approach. The 'allocation, recycled content' or 'cut-off' allocation procedure for the system boundaries is based on the approach that the primary production of materials is always allocated to the primary user of a material. If a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. The consequence is that recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes. Moreover, producers of waste do not receive any credit for the recycling or re-use of products resulting from any waste treatment. This approach is in line with 'the polluter pays' principle, widely used by the European Commission [11].

Types of impact and methodology of impact assessment, and subsequent interpretation to be used

The impact assessment phase of the LCA is aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory (LCI) analysis. In general, this process involves associating inventory data with specific environmental impacts and attempting to understand those impacts. The level of detail, choice of impacts evaluated, and methodologies depend on the goal and scope of the study. The methodology considered for the life cycle impact assessment (LCIA) must be clearly defined.

Data and data quality requirements

The data needed to meet the goal of the study must be identified, as must the level of detail required for the different data categories. The different data sources used should be stated. This may include measured, calculated or estimated data, or those obtained from published sources. The data requirements are dependent on the questions that are raised in the study. The quantification of minor or negligible inputs and outputs that will not significantly change the overall results of the study is not necessary.

A complete description of the required data quality includes the following parameters:

- Geographical coverage;
- Time period covered;
- Technology coverage;
- Precision, completeness, and representativeness;
- Consistency and reproducibility;
- Sources of the data and their representativeness;
- Variability and uncertainty of the information and methods.

Assumptions and limitations

The models used during the course of the LCA and the assumptions underlying those choices should be described and identified. For example, it is very common to use end of life scenarios when the way the product will be used or managed at its end of life is unknown.

The cut-off criteria used in a study should be clearly understood and described. If a cut-off rule is established, the criteria applied must be explained.

Type and format of the report

The results of the LCA will be fairly, completely, and accurately reported to the intended audience, compliant with ISO 14040 and ISO 14044 [5, 6] combined with additional requirements from EN 15804:2012+A2:2019 [7] (for the product level) and prEN15978-1:2021 [8] (for the building or district perspective).

Critical review

A critical review is a process to verify whether an LCA has met the requirements of the selected methodology and standards. Whether and how a critical review will be conducted should be specified in the scope of the study.

Three types of critical review are defined by ISO 14040 and ISO 14044 [5, 6]:

- **Internal review:** performed by an internal expert independent of the LCA study;
- **Expert review:** performed by an external expert independent of the LCA study;
- **Review by interested parties:** performed by a review panel chaired by an external independent expert. The panel includes interested parties that will be affected by conclusions drawn from the LCA study, such as government agencies, non-governmental groups, or competitors.

If an LCA study will be used to make a comparative assertion that is disclosed to the public, the ISO-standards require a critical review by interested parties to be conducted. In all other cases, critical reviews in LCA are optional and may utilise any of the three review options mentioned above.

2.2 Life Cycle Inventory (LCI)

The inventory analysis involves data collection and calculation procedures to quantify the inputs and outputs that are associated with the product system under study. This includes the use of resources and releases to air, water, and soil. The data collection and calculation procedures should be consistent with the goal and the scope of the study. The results of the inventory analysis may constitute an input for a life cycle assessment as well as an input for an interpretation phase.

Input and output data have to be collected for each process included in the system boundaries. After collection, the data for the different processes have to be related to the functional unit (FU) or declared unit (DU) and aggregated.

Inventory analysis is an iterative process. As data are collected and the system is better known, new data requirements or limitations may become apparent. This may require better or additional data to be collected or system boundaries to be refined.

2.3 Life Cycle Impact Assessment (LCIA)

In the impact assessment, the results of the inventory analysis are linked to specific environmental damage categories (e.g. CO_2 emissions are related to damages to human health caused by climate change, SO_2 emissions are related to damages to the ecosystem caused by acidification, etc.). It is important to note that the inventory results generally do not include spatial, temporal, dose-response, or threshold information. Therefore, impact assessment cannot and is not intended to identify or predict **actual** environmental impacts. Instead, the impact assessment predicts **potential** environmental damage (impacts) related to the system under study.

In LCA, environmental impacts are expressed with environmental indicators by using characterisation factors. The EN 15804:2012+A2:2019 standard [7] prescribes thirteen core environmental impact indicators and six additional environmental impact indicators (see Table 2). For all indicators, the characterisation factors from the Joint Research Centre (JRC) of the European Commission need to be applied [12].

Table 2. Core and additional environmental impact indicators, units, and models EN15804+A2:2019 [7].

Impact category	Indicator	Unit	Model
Core environmental impact indicators			
Climate change – total (= fossil + biogenic + luluc)	Global-warming potential total (GWP-total)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013 [13].
Climate change - fossil	Global-warming potential fossil fuels (GWP-fossil)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013 [13].
Climate change - biogenic	Global-warming potential biogenic (GWP-biogenic)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013 [13].
Climate change - land use and land use change	Global-warming potential land use and land use change (GWP-luluc)	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013 [13].
Ozone Depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC 11 eq.	Steady-state ODPs, WMO 2014 [14].
Acidification	Acidification potential, accumulated exceedance (AP)	mol H+ eq.	Accumulated exceedance [15, 16].
Eutrophication aquatic freshwater	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-freshwater)	kg PO_4 eq.	EUTREND model, [17], as implemented in ReCiPe.
Eutrophication aquatic marine	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-marine)	kg N eq.	EUTREND model, [17] as implemented in ReCiPe.
Eutrophication terrestrial	Eutrophication potential, Accumulated Exceedance (EP-terrestrial)	mol N eq.	Accumulated Exceedance [15, 16].
Photochemical ozone formation	Formation potential of tropospheric ozone (POCP)	kg NMVOC eq.	LOTOS-EUROS, [18], as applied in ReCiPe.
Depletion of abiotic resources – minerals and metals	Abiotic depletion potential for non-fossil resources (ADP-minerals&metals)	kg Sb eq.	CML 2002, [19, 20].
Depletion of abiotic resources - fossil fuels	Abiotic depletion potential for fossil resources (ADP-fossil)	MJ, net calorific value	CML 2002, [19, 20].

Impact category	Indicator	Unit	Model
Water use	Water (user) deprivation potential, deprivation-weighted water consumption (WDP)	m^3 world eq. deprived	Available WAter REmaining (AWARE) [21].
Additional environmental impact indicators			
Particulate matter emissions	Potential incidence of disease due to PM emissions (PM)	Disease incidence	SETAC-UNEP [22].
Ionising radiation, human health	Potential human exposure efficiency relative to U235 (IRP)	kBq U235 eq.	Human health effect model as developed by Dreicer et al. [23] update by Frischknecht et al. [24].
Ecotoxicity (freshwater)	Potential comparative toxic unit for ecosystems (ETP-fw)	CTUe	Usetox version 2 until the modified USEtox model is available from EC-JRC [25].
Human toxicity, cancer effects	Potential comparative toxic unit for humans (HTP-c)	CTUh	Usetox version 2 until the modified USEtox model is available from EC-JRC [25].
Human toxicity, non-cancer effects	Potential comparative toxic unit for humans (HTP-nc)	CTUh	Usetox version 2 until the modified USEtox model is available from EC-JRC [25].
Land use related impacts / soil quality	Potential soil quality index (SQP)	dimensionless	Soil quality index based on LANCA [26].

Various methods are in use to assess the environmental effects of products and systems. Most of these operate on the assumption that a product's entire life cycle should be analysed. The framework proposed by ISO 14040 and ISO 14044 [5, 6] consists of the following elements:

- Selection of impact categories, category indicators and characterisation models;
- Classification: assignment of inventory data to impact categories;
- Characterisation: calculation of category indicator results;
- Normalisation: calculating the magnitude of the category indicator results relative to a chosen reference information data set;
- Grouping: sorting and possibly ranking of the impact categories;
- Weighting (valuation): converting and possibly aggregating indicator results across impact categories using numerical values based on value-choices.

The first three elements are mandatory, while the others are optional. Some of the most comprehensive impact assessment methods (e.g. ReCiPe 2016, Environmental Footprint 3.1) consider all the six phases, whereas others include mainly the mandatory ones (e.g. CML-IA 2016 includes the mandatory ones and also the normalisation phase). ISO 14040 [5] states that '*in the case of comparative assertions disclosed to the public, the evaluation shall be conducted in accordance with the critical review process and presented category indicator by category indicator*'.

The JRC, within the product environmental footprint (PEF) guide [12, 27], proposes the use of the single score value, which is quantified in points (Pt) or millipoints (mPt) per DU. It allows all environmental results to be expressed in a dimensionless unit that facilitates comparison between environmental indicators and categories. The single score values are calculated using the normalisation and weighting values as shown in Table 3.

Table 3. Normalisation, weighting, and single score factor values [12].

	Normalisation	Weighting	Single score factor
Climate change – total (= fossil + biogenic + luluc)	0.000132396265000545000	21.06%	0.0000278826534091148000
Climate change - fossil	-	-	-
Climate change - biogenic	-	-	-
Climate change - land use and land use change	-	-	-
Ozone Depletion	19.1027866641876000000	6.31%	1.2053858385102400000000
Acidification	0.0179954697817319000	6.20%	0.0011157191264673800000
Eutrophication aquatic freshwater	0.6223348013145160000	2.80%	0.0174253744368064000000
Eutrophication aquatic marine	0.0511635053040380000	2.96%	0.0015144397569995200000
Eutrophication terrestrial	0.0056575485909539900	3.71%	0.0002098950527243930000
Photochemical ozone formation	0.0244742935603176000	4.78%	0.0011698712321831800000
Depletion of abiotic resources – minerals and metals	157176814608394000000	7.55%	1.1866849502933700000000
Depletion of abiotic resources - fossil fuels	0.00001538360724618110	8.32%	0.0000012799161228822700
Water use	0.00008719377493347470	8.51%	0.0000074201902468387000
Particulate matter emissions	1679.6367626089800000000	8.96%	150.4954539297650000000000
Ionising radiation, human health	0.00023695765010758800	5.01%	0.0000118715782703902000
Ecotoxicity (freshwater)	0.00001763152658830920	1.92%	0.0000003385253104955370
Human toxicity, cancer effects	57961.27816104330000000000	2.13%	1234.5752248302200000000000
Human toxicity, non-cancer effects	7767.8509384927000000000	1.84%	142.9284572682660000000000
Land use related impacts / soil quality	0.00000122025895949292	7.94%	0.0000000968885613837378

2.4 Interpretation

According to ISO 14040 and ISO 14044 [5, 6], in the interpretation phase of an LCA, the results of the inventory analysis and the impact assessment are critically analysed and interpreted in line with the defined goal and scope of the study. The findings of this interpretation may be presented as conclusions and recommendations to decision-makers. Furthermore, they may be presented as an improvement assessment (e.g. the identification of opportunities to improve the environmental performance of products or processes).

LCAs do not represent a complete picture of the environmental impact of a system. They represent a picture of those aspects that can be quantified. Any judgements that are based on the interpretation of LCI data must bear in mind this limitation and, if necessary, obtain additional environmental information from other sources (hygiene aspects, risk assessment, etc.). The LCIA results are relative expressions and do not predict impacts on category endpoints, exceeding thresholds, safety margins or risks.

3. Integration of LCA into the work process for PED design

3.1 PED definition

Contributing to the ambitious targets of the European Strategic Energy Technology Plan (SET Plan Action 3.2) [28], the programme 'Positive Energy Districts and Neighbourhoods for Sustainable Urban Development' supports the planning, deployment, and replication of 100 positive energy neighbourhoods by 2025. It is backed by 20 EU member states and conducted by JPI Urban Europe. The programme involves stakeholders from Research and Innovation (R&I) funding networks, cities, industry, research organisations and citizen organisations.

As a basis for such implementation measures, as mentioned in the introduction section, a common reference framework for PEDs and PENs has been elaborated with the aim of anticipating the various dimensions and aspects related to their implementation. Within the national consultations, the PED reference framework proposed by the PED Programme Management has been widely discussed and agreed. As a result, the reference framework definition for PED/PENs is as follows:

'*Positive energy districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while ensuring the energy supply and a good life for all in line with social, economic and environmental sustainability*' [28].

3.2 State of the art LCA approach for PEDs

3.2.1 Hierarchical approach

LCA is integrated into PEDs on several levels (see Figure 2). A hierarchical structure is applied with five levels of analysis: district, building, element, component or product and material. Each higher level is based on the previous level. A district is made out of buildings, and consequently a building comprises a number of elements (such as floors, external walls, internal walls, roofs, technical installations, etc.), which in turn consist of several products or components (e.g. a masonry wall, an insulation layer). The components or products are again built up of different building materials (e.g. hollow bricks and mortar). The definitions considered are listed hereunder [8]:

- **Materials, elements, and products** implemented in PEDs in an urban environment or at building level.
    - Material: the usual name given to the substances from which products are made. They can be natural, such as wood or metal, or synthetic, such as plastic or composite materials. Raw materials can be virgin or secondary (recovered from previous use or waste).;

- Product: manufactured or processed item used in construction work;
- Element: component or a set of assembled components incorporated into a building or into construction work. This definition also refers to the terms building component and building element.

- **Building:** construction work that has the provision of shelter for its occupants or contents as one of its main purposes and is usually enclosed and designed to stand permanently in one place. It includes operational phase.
  - In the case of a new building, all the construction phase and materials (production, installation, maintenance and eventually end-of-life) used are considered;
  - In the case of an existing building, only the renovation processes and materials (production, installation, maintenance and eventually end of life) used will be assessed.
- **District:** the set of buildings and urban elements (green spaces, installations, networks, etc.)

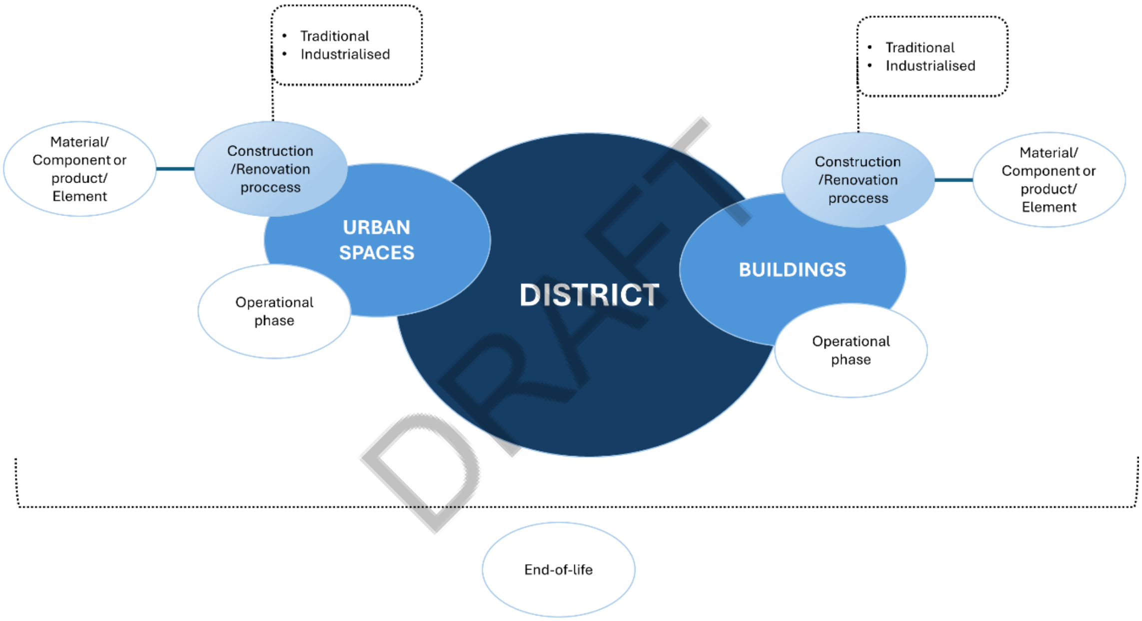


Figure 2. Relationship between different levels of LCA that could be addressed in PEDs.

The following sections describe the state of the art of the LCA methodology implementation at the different levels. Subchapter 3.2.2 combines the material, product, element and building levels, mainly covered by the existing standards developed under the umbrella of CEN TC 350 'Sustainability of Construction Work' [29]. Subchapter 3.2.3 presents the state of the art for the district level, mainly based on a literature review. Subchapter 3.2.4 discusses and summarises the main points of the previous sections and formulates key takeaways for their integration at the PED level in the framework of the oPEN Lab project (presented in Chapter 4. oPEN Lab project LCA approach for materials, products and buildings integrated in the respective PEDs).

3.2.2 LCA state of the art for materials, products, elements and buildings

Analysis current methodological framework

The calculation and clear communication of the environmental performance of materials used in buildings require a transparent methodological framework. Under the umbrella of CEN TC 350 'Sustainability of Construction Work' [29], harmonised European standards have been developed.

The CEN TC 350 committee is responsible for the development of standardised horizontal methods for the assessment of sustainability aspects of new and existing buildings and civil engineering works in the context of the UN Sustainable Development Goals and the circular economy. The methodological basis will be developed in the context of current needs and European strategies such as mitigation, adaptation and resilience to climate change, and life cycle thinking. The standards describe coherent methodologies for the assessment of the sustainability of construction works, covering the environmental, social and economic performance (aspect and impacts) of buildings and civil engineering works, and the provision of environmental information (environmental product declaration) for construction products. This covers:

- **Environmental performance assessment:** circularity principles (the circular economy in the construction sector), energy efficiency and decarbonisation, sustainable use of resources (resource efficiency, waste minimisation), and the protection of the environment and biodiversity;
- **Social performance assessment:** health and comfort, safety and security, adaptability and accessibility in response to user needs, resilience against external events such as the impact of climate change, and sourcing of materials;
- **Economic performance assessment:** life cycle cost, whole life costs and impact on economic value, and 'green finance' initiatives (taxonomy);
- **The implementation of the standards** in response to trends in digitalisation (e.g. BIM, CAD).

Note: The committee is also entrusted with an advisory function to CEN committees to ensure the effective implementation of horizontal core rules regarding the development of specific product category rules based on EN 15804 [30].

The standards developed by CEN/TC 350 relevant to LCA in PEDs are:

- **EN 15804+A2** Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products (CEN 2019) [7];
- **EN 15978** Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method [8];
- **EN 15643** Sustainability of construction works – Framework for assessment of buildings and civil engineering works [31];
- **TR 15941** Sustainability of construction works – Environmental product declarations – Methodology for selection and use of generic data (CEN 2010) [32].

Environmental product declarations (EPD) are regulated by ISO 14025:2006 [33] and EN 15804 (specifically for construction) [30]. They provide key data on a product's environmental impact in a convenient, standardised format. EPDs currently provide a numerical representation of a product's environmental impact, which is why they are mainly used in business to business relationships. They are based on LCA, currently the best tool for gauging a product's environmental impact, comparing materials and preventing misconceptions about certain materials and products. LCAs provide unique insights into the complex life of a construction product, from resource extraction to its end of life and beyond. Ultimately, burden shifting (shifting the negative impact to a different part of the cycle by improving an aspect elsewhere in the cycle) needs to be eliminated where possible and calculations should be facilitated at the product and building level. The objective of an EPD is not to present a consumer-friendly label with an A to D score or red to green scale but to offer a transparent view of the impacts. EPDs must comply with specific product category rules (PCRs), which specify how the LCA should be conducted and how the information will be displayed. They are indispensable for future-proofing businesses that manufacture building materials and products. Product-level LCAs are a key element of the EU Green Deal [2], the EU Circular Economy Action Plan [34] and are also prominently addressed in the new construction products regulation [35].

Generating an EPD for building materials and products means more administration, but the extra effort is worth it. An outline of the **added value** that an EPD **for building materials or building products** represents is provided below:

- It **quantifies information about the environmental impact of building materials and products**. It is scientifically based, adheres to standardised European methods, and assesses the environmental impacts (e.g. climate, acid rain, particulate matter, etc.) across every phase of the life cycle (from raw materials extraction and production to transport and waste disposal). EPDs are also unique in that they contain information about the building material or product's reversibility. That signals how easily the product can be dismantled at the end of its service. Consequently, public procurement proposals that include EPDs have a competitive edge in the tendering process;
- It is a prime **asset for contractors and architects** working with **building sustainability certification or rating schemes** such as BREEAM, LEED, DGNB, etc. These schemes award additional sustainability credits to buildings that employ EPD-certified materials. Ultimately, that incentivises designers, procurers and other stakeholders to make decisions based on credible, robust environmental data. Moreover, EPDs can be a great asset or even a requirement for public procurement access. Accessibility in building assessment schemes and tools (e.g. BREEAM, LEED, TOTEM) enhances the visibility of building materials and products vis-a-vis designers and customers. Architects are also more likely to choose brand-specific data generated by EPDs because it offers them transparency and efficiency that generic data cannot provide;
- It provides insight into the overall environmental performance, burdens and benefits alike, of building materials and products. This cradle-to-grave perspective helps to **identify hotspots**. The building material or product's biggest environmental impact might not be in the production process. Experience has shown that bottlenecks can happen at any stage. For instance, the hotspot might be due to a supplier or on how the building material or product is used. EPDs make it possible to pinpoint it and optimise accordingly;
- A detailed picture of a building material or product's cradle-to-grave environmental impact reveals new opportunities for upgrading and streamlining processes. That, in turn, leads to **economic cost reductions** (e.g., less energy or raw materials needed) and a smaller environmental footprint (EF);
- EPDs are an excellent key performance indicator (KPI) for a company's annual reports (e.g. sustainability reports). The clear, comprehensive data contained in them stands to benefit the building material or product producer's internal sustainability strategy and facilitates harmonisation with rapidly evolving EU and international standards.

Tools and sources

Several tools have been developed for the assessment of environmental impacts. These tools allow LCA to serve multiple purposes, such as structural and design optimisation, certification, research and educational endeavours, benchmarking exercises, facilitation of the design process, and fulfilment of regulatory requirements within the building approval process. The principal beneficiaries of these specialised LCA tools encompass not only architects but also construction engineers, developers, homeowners, and other stakeholders actively engaged in the building design workflow. These tools manifest across diverse platforms, spanning web-based interfaces, spreadsheet applications, standalone assessment software, building information modelling-LCA (BIM-LCA) integrations, and LCA seamlessly incorporated into 3D design programs.

The tools vary in purpose and operation, ranging from the more user-friendly to more complex, the latter aimed at experts. A brief overview of some of these tools and the scale they are applicable to is shown in Table 4 and Table 5.

Table 4. Environmental impact assessment sources by scale.

Scale	Source	Difficulty of use	Characteristics	Strengths	Weaknesses
Material Product Element	EPD [36]	High	Expresses environmental impacts in different tables.	Allows comparability, by use of PCR. Several impact categories: it allows a complete vision of the environmental impact.	Continuous updates to the PCR. It requires experience and command of technical words domain. It usually has a limited number of environmental indicators.
Building	National building carbon footprint methodo-logies [37]	Medium	PAS 2050 [38], ISO/TS 14067 [39], GHG protocol. The carbon footprint analysis is the total amount of GHG emissions occurring during the life cycle stages of the building.	Measuring and reporting GHG emissions from buildings is critical for producing significant and cost-effective strategies. Although carbon emission methodologies vary among countries, the foundation framework is usually the well-established LCA process.	Only one impact category. Carbon emission calculations often vary in terms of boundaries, scope, units of GHG, and methodologies. There is not an internationally accepted method for measuring, reporting, and verifying GHG emissions from existing buildings in a consistent and comparable way.

Table 5. Environmental Impact Assessment tools by scale.

Scale	Tool	Difficulty of use	Characteristics	Strengths	Weaknesses
Material Product Element	SimaPro (NL) [40]	High	**Description:** a program that allows the use of different libraries of materials and different methods to obtain the environmental impacts. All modules considered. **Platform**: web-based and app. **Payment required**: yes. **Software type**: closed-source commercial.	It depends on the database that is used. Good accuracy. The indicators can be tracked and adapted.	Experience and LCA knowledge required. Not operative without an indicator database (e.g. Ecoinvent).
	Open LCA (DEU) [41]	High	**Description:** a program that allows the use of different libraries of materials and different methods to obtain the environmental impacts. All modules considered. **Platform**: desktop application. **Payment required**: no. **Software type**: open-source software.	It offers the largest collection of data sets and databases worldwide for LCA software, some for purchase, some for free. Learning and support (free resources, training, case studies). It can model and assess the complete life cycle, from resource extraction to production, use and disposal. Different impact assessment methodologies can be used.	Not user-friendly. High level of knowledge required. The results are not presented in a visual or easily understandable way.
	TOTEM (BE) [42]	Low	**Description:** it enables the environmental impact of construction elements or buildings to be assessed according to a scientific method adapted to the particularities of the Belgian construction market. Modules A1-A3, A4-A5, B2, B4, B6, C4-C4. **Platform:** web-based. **Payment required:** no. **Software type:** closed-source government.	19 environmental impact indicators. Ease of use (intuitive). Visual.	Impacts related to Belgium. Limited database: it does not have all the elements, materials, and products.
	Greenly (FR) [43]	Low	**Description:** all-in-one carbon and ESG platform. It measures carbon assessment, sustainable procurement, and LCA. **Payment required:** yes (it depends on company size and activity). **Software type:** software-as-a-service platform.	Baseline product impact information across different phases following key industry standards like ISO 14040 and 14044. It can conduct multiple assessments of products. It helps to identify the most eco-friendly alternative. It shares results in a customisable and visually aesthetic format.	For companies. It does not specify what results you get (it is needed to request a demo).
	Material Pyramid	Low	**Description:** it draws on collections of EPD and LCA results to classify common building materials according	It clearly shows the materials with the most and least impact.	It only considers modules A1-A3. As a result, it creates a serious bias

Scale	Tool	Difficulty of use	Characteristics	Strengths	Weaknesses
	(DK) [44]		to different environmental indicators. Modules A1-A3. **Platform:** web-based. **Payment required:** no.		towards biobased materials regarding the global warming potential (GWP) impact. Not all these materials can provide the same functionality (e.g. different structural resistance or transmittance), hence preventing their comparison.
Building	SimaPro (NL) [40]	High	**Description:** allows the use of different libraries of materials and different methods to obtain the environmental impacts. All modules considered. **Platform:** web-based and app. **Payment required:** yes. **Software type:** closed-source commercial.	It depends on the database that is used. Good accuracy. The indicators can be tracked and adapted.	Requires experience and LCA knowledge. Not operative without an indicator database (e.g. Ecoinvent).
	Open LCA (DEU) [41]	High	**Description:** allows the use of different libraries of materials and different methods to obtain the environmental impacts. All modules considered. **Platform:** desktop application. **Payment required**: no. **Software type**: open-source software.	It offers the largest collection of data sets and databases worldwide for LCA software, some for purchase, some for free. Learning and support (free resources, training, case studies). It can model and assess the complete life cycle, from resource extraction to production, use and disposal. Different impact assessment methodologies can be used.	Not user friendly. A lot of knowledge required. The results are not presented in a visual or easily understandable way.
	One-Click LCA (FIN) [45]	Medium	**Description:** it calculates impacts using EPDs as materials. **Platform:** Revit® plugin. **Payment required:** yes. **Software type:** closed-source commercial.	Easier to use than other more complex programs.	Not accurate. If an EPD lacks a specific impact category, it considers it zero. The indicators cannot be adapted. Small range of products covered by EPDs.
	GaBi Build-It (USA) [40]	Medium	**Description:** the product life cycle and sustainability assessment (GaBi) software is based on the most robust LCA databases in the world. **Payment required:** yes.	A well-established LCA tool. Easy-to-understand reporting interface. Customisable reporting templates and automated reporting.	Most suited to LCA experts. Prior knowledge is required to see its full potential.

Scale	Tool	Difficulty of use	Characteristics	Strengths	Weaknesses
			Software type: closed-source commercial.	Built on trusted emissions factor data.	
	TOTEM (BE) [42]	Low	**Description:** it enables the environmental impact of construction elements or buildings to be assessed according to a scientific method adapted to the particularities of the Belgian construction market. Modules A1-A3, A4-A5, B2, B4, B6, C4-C4. **Platform:** web-based. **Payment required:** no. **Software type:** closed-source government.	19 environmental impact indicators. Ease of use (intuitive). Visual.	Impacts related to Belgium. Limited database: it does not have all the elements, materials and products of the building.
	LCAbyg (DK) [46]	Low	**Description:** it calculates life cycle assessment for buildings. It is for education, public, and private bodies. All modules considered. **Platform:** desktop application. **Payment required:** no (nationally freely available tool). **Software type:** closed-source.	It can calculate a building's environmental profile and resource consumption. The program automatically computes the results in a table and generates figures and a summary report. Environmental impacts are calculated over the entire life cycle of the building. It offers the possibility to create different scenarios.	Intended for the Danish construction industry and focuses on a Danish context.
	Eco-bat (CH) [12]	Low	**Description:** the building's composition can be defined by adding elements (walls, windows, roofs, etc.) made of different materials that can be selected from its database. **Platform:** computer program. **Payment required:** yes. **Software type:** closed-source.	User friendly. It provides detailed numerical and graphical results (global, by element, by material, by phase). The life cycle impacts assessment methodology used is compliant with ISO 14040 standards. It includes energy demand and construction materials of the building. The energy consumption can be detailed by selecting energy vectors for the different kinds of consumption. It takes into account the main phases of the building lifespan, from the manufacture of the materials used to the elimination of the waste resulting to the dismantling of the building.	It uses its own database of materials and energy production installations, using impact values extracted from the Ecoinvent database. The range of materials and indicators is limited compared to the full Ecoinvent database.
	Eco2soft (AU) [47]	Low	**Description:** life cycle assessments for buildings can be created quickly and easily and the costs of construction, renovation and disposal are clearly	It is a specialised calculator. It can be used independently of other calculation programs. It is specialised in the preparation of life cycle	For Austrian context.

Scale	Tool	Difficulty of use	Characteristics	Strengths	Weaknesses
			displayed. **Platform:** online tool. **Payment required:** yes. **Software type:** closed-source.	assessments in all balance limits required for the Oekoindex. The waste disposal indicator and all common LCA indicators can be calculated and the overall balance, including operation, can be presented. Time-saving through simplified calculation methods.	
	Athena Impact Estimator for Buildings (CA) [48]	Medium	**Description:** it allows construction industry professionals to compare alternative design scenarios and incorporate environmental considerations beginning at the conceptual stage of a project, when most critical decisions are made. Modules A1-A3, A4-A5, B2, B4, C1-C4. **Platform:** standalone. **Payment required:** no. **Software type:** closed-source freeware.	It complies with LCA methodology standards developed by the International Organisation for Standardisation (ISO) 14040 and 14044 series. Robust life cycle inventory databases provide accurate scientific cradle-to-grave information for building materials and products, transportation, and construction and demolition processes.	Regionally customised. Focused on North America context. It does not report 19 indicators (only global warming potential, acidification potential, human health respiratory effects potential, ozone depletion potential, smog potential, and eutrophication potential). The impact estimator additionally reports fossil fuel consumption.
	Elodie (FR) [49]	Medium	**Description:** it assesses the impacts of construction products and equipment in a building, drawing on the EPDs available in the French national EPD database INIES. Modules A1-A3, A4-A5, B1-B7, C1-C4. **Platform:** online tool. **Payment required:** voluntary licence-based. **Software type:** closed-source.	Developed to help building designers and project owners to identify the environmental impacts generated by their building from the early design stage. The goal is to identify the components of the project with the biggest impact and enable alternative, less impacting scenarios. It can be used to evaluate both new construction and renovation work.	Results for France (based on the national EPD database). Depending on the EPD, some indicators may be missing.
	Tally (USA) [48]	High	**Description:** it conducts whole-building LCA during design to run comparisons of design options and analyse their environmental impacts. Modules A1-A3, A4-A5, B2, B4, C1-C4. **Platform:** Revit® plugin. **Payment required:** yes. **Software type:** closed-source commercial.	It assesses the embodied environmental impact of the whole building. It can compare two or more distinct sets of building components side by side. It compares LCA impacts and components of materials and assemblies, including information from manufacturer EPDs. Integration with BIM.	Prior knowledge is needed. It requires Revit. Intended for architects and engineers.

Scale	Tool	Difficulty of use	Characteristics	Strengths	Weaknesses
	Epic Grasshopper (BE) [48]	Medium	**Description:** it makes calculations using hybrid embodied environmental flow coefficients from the EPiC Database (developed by the University of Melbourne). **Platform:** grasshopper plugin. **Payment required**: no. **Software type:** open-source freeware.	It enables users to define their own custom materials, to export results to csv and to suggest a feature or report a bug directly from Grasshopper. It provides advanced data visualisation and slicing capabilities, enabling users to quickly evaluate the total life cycle embodied environmental flows of assemblies and/or built assets, compare them, and break them down by material contribution.	It does not report 19 indicators (for embodied energy, greenhouse gas emissions and water consumption). It requires Rhino 3D. Familiarity with EPiC Database required.

Focusing on the building level, these life cycle assessment (LCA) tools are available to quantify embodied environmental impacts. Despite their availability, these tools are not commonly integrated into the decision-making processes of building designers, particularly in the early stages, where the greatest potential exists to influence a building's environmental performance [50]. In addition, as commented by Prideaux et al. [48], two primary obstacles have been detected hindering the integration of LCA tools into the building design process. First, LCA tools are not generally intended for use during the design phase. Moreover, they do not have the capacity to cover every design phase, mainly because they are usually conceived for post-evaluation after the design has been completed. Substantial challenges remain related to data provision for LCA, notably concerning data consistency, transparency, and geographical coverage. Despite improvements evidenced by the proliferation of life cycle inventory (LCI) databases and EPDs for construction materials, many regions suffer from data scarcity, and discrepancies persist in methodologies, comprehensiveness and transparency across databases.

3.2.3 LCA state of the art for districts

A district can be understood as a set of buildings and urban elements. At present, there is no standardisation available regarding the application of LCA methodology at district level. For this reason, a study of the state of the art has been carried out by means of two complementary analyses:

- Analysis of **scientific publications** to evaluate different district LCA approaches;
- Analysis of **existing tools and certifications** used at district level analysis.

Analysis of scientific publications

This section presents a comparison of representative LCA studies of large-scale building stocks. The analysis was performed according to the four steps of the LCA at material/product/element and building level: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation. Table 6 below provides an overview of representative review studies on the topic. This overview is not all-encompassing but provides a representative sample of works published between 2010 and 2023. Most papers start with a definition of PENs. The concept of positive energy building (PEB) derives from of the net zero energy building (nZEB) concept. By extending the scale of the project to exploit the energy mutualisation between buildings, the concepts of PEN and PED are obtained.

Typically addressed key questions include:

- What are the new goals for urban environmental sustainability? And given the interconnected and multifaceted nature of sustainability, have integrated sustainability approaches been obtained? What is the scope of the study?;
- Which KPIs are used and what impact categories are integrated into the evaluation framework?;
- What are the main challenges that should be addressed in the LCA of PEDs by assessing the level of detail?

Table 6. Analysis of scientific publications.

Title	Pub. Year	Topic	Level	Type	Environmental Indicators	Level of Detail
Life cycle embodied, operational, and mobility-related energy and greenhouse gas emissions analysis of a green development in Melbourne, Australia [51]	2022	Neighbourhood development LCA	Neighbourhood	LCA	GWP/CO2-eq, life cycle energy.	Buildings (structure, façade, roof, flooring, internal walls, operational energy), mechanical ventilation, PV production.
Developing a new data driven LCA tool at the urban scale: The case of the energy performance of the building sector [52]	2022	City LCA	City	LCA	Climate change, ozone depletion, ionising radiation, photochemical ozone formation, particulate matter formation, human toxicity non-carcinogenic, human toxicity carcinogenic, acidification, eutrophication freshwater, eutrophication marine, eutrophication terrestrial, ecotoxicity freshwater, land use, water use, energy resources, non-renewable, material resources, metals, and minerals.	Buildings (location), and energy use (heating, cooling, domestic hot water).
Urban retrofit of the Leipzig-Grünau District. A screening LCA to measure mitigation strategies [53]	2021	Neighbourhood renovation LCA	Neighbourhood	LCA	GWP/CO2-eq.	2,700 m² of open area, 28,203 houses with 1,013,603 m² of living space and 43,904 inhabitants.
Sustainability in energy and buildings [54]	2021	Building sustainability	Building	/	/	/
Environmental benchmarks for buildings: a critical literature review [55]	2020	LCA benchmark comparison	Building	LCA, scoring	GWP/CO2-eq, non-renewable primary energy demand, total primary energy demand, acidification potential, ozone depletion potential, eutrophication potential, photochemical ozone creation potential, renewable primary energy demand, and other.	Floors on grade, retaining walls, foundations, external walls, internal walls, storey floors, stairs, ramps, frames, windows, external doors, internal doors, waste, disposal, and drainage.
Balancing data requirement and modelling quality in neighbourhood life cycle assessments [56]	2020	LCA data requirements	Neighbourhood	LCA	Non-renewable primary energy, renewable primary energy, abiotic depletion, abiotic depletion (fossil fuels) ADP fossil, global warming potential, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation,	Encompassing structure, exterior and interior walls, stairs, finishes, windows and doors, installations and building services, as well as the infrastructure enclosure, energy

Title	Pub. Year	Topic	Level	Type	Environmental Indicators	Level of Detail
					acidification potential, and eutrophication potential.	network (light poles and PV panels), and street network.
LCA modelling for Zero Emission Neighbourhoods in early-stage planning [57]	2019	Neighbourhood LCA	Neighbourhood	LCA	GWP/CO2-eq.	Buildings, mobility, open spaces, networks, and on-site energy.
A life-cycle assessment model for zero emission neighbourhoods [58]	2019	Neighbourhood LCA	Neighbourhood	LCA	GWP/CO2-eq.	Buildings (materials and operation), PV production, and mobility (materials and operation).
Inventory of the existing residential building stock for the purpose of environmental benchmarking [59]	2019	Building stock assessment	Neighbourhood	/	/	Buildings.
Diagnosis of uncertainty treatment in neighbourhood life cycle assessments [60]	2019	Uncertainty and sensitivity analysis in neighbourhood LCA	Neighbourhood	LCA	/	/
Current trends and limitations of life cycle assessment applied to the urban scale: critical analysis and review of selected literature [61]	2018	City LCA literature comparison	City	LCA	/	/
Towards life cycle sustainability assessment of cities. A review of background knowledge [62]	2017	City LCA issue review	City	LCA, scoring	/	/
Elaboration of a sustainability assessment method for neighbourhoods [63]	2017	Neighbourhood LCA	Neighbourhood	LCA	Global warming, depletion of the stratospheric ozone layer, acidification of land and water sources, eutrophication freshwater and marine, photochemical oxidant formation, abiotic depletion of non-fossil resources, abiotic depletion of fossil resources, human toxicity, cancer and non-cancer effects, particulate matter formation, ionising radiation human	Buildings (ground substructure, structure, secondary elements, finishes, services, loose furniture), roads (external works), utilities (services piped and electrical), and open

Title	Pub. Year	Topic	Level	Type	Environmental Indicators	Level of Detail
					health, ecotoxicity (freshwater), land use land occupation (agricultural/forest and urban), and land use land transformation (tropical rain forest).	spaces.
Critical review of life cycle assessment (LCA) for the built environment at the neighbourhood scale [64]	2015	Neighbourhood LCA comparison	Neighbourhood	LCA	Most LCAs focus on environmental indicators: primary energy consumption and GWP.	Buildings, open spaces, networks, and mobility.
Model for the environmental impact assessment of neighbourhoods [65]	2014	Neighbourhood configuration LCA	Neighbourhood	LCA	Global warming, depletion of the stratospheric ozone layer, acidification of land and water sources, eutrophication freshwater and marine, photochemical oxidant formation, abiotic depletion of non-fossil resources, human toxicity, cancer and non-cancer effects, particulate matter formation, ionising radiation human health, ecotoxicity (terrestrial, freshwater and marine), land use land occupation (agricultural/forest and urban), and land use land transformation (tropical rain forest).	Buildings (ground substructure, structure, secondary elements, finishes, services, loose furniture), roads (external works), utilities (services piped and electrical), and open spaces.
A multi-criteria approach to compare urban renewal scenarios for an existing neighbourhood. Case study in Lausanne (Switzerland) [66]	2013	Sustainable urban development	Neighbourhood	Scoring	Water and soil resources, energy, domestic water, and wastewater.	Site and architecture, comfort and health, land and landscape, infrastructures, building concept, community, viability, safety, and operating costs.
A critical review of seven selected neighbourhood sustainability assessment tools [67]	2013	Neighbourhood sustainability assessment	Neighbourhood	Scoring	/	/
LCA of the Zero Emission Neighbourhood Ydalir [68]	2009	Neighbourhood LCA	Neighbourhood	LCA	GWP/CO_2-eq.	Buildings, mobility, infrastructure, networks, and on-site energy.

The studies reviewed share the main objective of evaluating building stock sustainability from a life cycle perspective to support and assess urban planning and/or policymaking. The goal is generally related to the specific spatial scale and planning time horizons of the study. The spatial scale of these studies ranges typically from urban to transnational and they have a medium-to long-term time horizon.

A variety of different FUs are used, including absolute, spatial, and per capita ones. FUs are not always explicitly specified in the studies, but spatial scale seems to play a minor role. The most common area analysed is the use of a heated floor area or the gross floor area. This approach ensures comparability between different LCA analyses. However, Brown et al. [69] used a different approach consisting of establishing a **FU for each identified measure** for the evaluation of the embodied emission associated with refurbishment measures. This enabled the total to be calculated as the product of the quantity required and the embodied emissions of the relevant measures. Another approach commented is to use **per capita FUs** (inhabitant, person). These FUs have advantages when including different sectors such as buildings (residential and non-residential) and transportation. They also allow for a fairer comparison as impacts are shared among people and not square meters [70].

Regarding LCI, in addition to LCA approach, it is found in the literature review that there are other assessment methods such as **material flow analysis** (MFA) **and input-output analysis** (IOA) which can be used to perform an environmental and economic assessment of products and systems such as complex buildings and districts [71]. Input-output analysis is a top-down approach informed by macro-economic analysis based on the economic sector associated with the system. Hence, national economic input-output accounts are coupled with environmental data for major industrial sectors to account for construction materials in the LCA. One of the main advantages of this technique is that it takes into account economy-wide impacts, and it is not constrained by arbitrary system boundaries. Using MFA as a basis for the analysis can increase the consistency, robustness, and transparency of the input data [72]. Hence, MFA data is used as input for the bottom-up IOA for value chains on a regional scale and provides top-down information. The bottom-up technique requires extrapolation to the entire building stock. This can be achieved by using the **archetypes technique** to broadly classify the building stock according to construction year, size, house type, etc. Each archetype represents a specific class of buildings from which it is possible to extrapolate the impacts of the entire building stock. This process requires the definition of upscaling parameters representing the number of buildings per type or the floor area per type. A different approach to the archetypes technique is the **building-by-building approach**. Instead of modelling a limited number of archetypal buildings and subsequently extrapolating results to the building stock, all buildings belonging to the stock are modelled individually. The total performance of the building stock can subsequently be calculated by summing-up the performance of the individual buildings [73].

The hierarchical structure inherent in the elemental method enables the utilisation of results from lower-scale levels to inform analyses at higher-scale levels. This characteristic makes the method particularly well-suited for upscaling the life cycle approach from the building scale to the neighbourhood scale. Additionally, this method can be effectively employed at various stages of the design process. During the sketch design phase, for instance, designers can make preliminary impact estimations using a selection of predefined building elements [63].

Concerning the LCIA, most research papers focus on energy-related impact categories (primary energy consumption and climate change). Fact that is also confirmed by Trigaux et al., [55] in their study (see Figure 3).

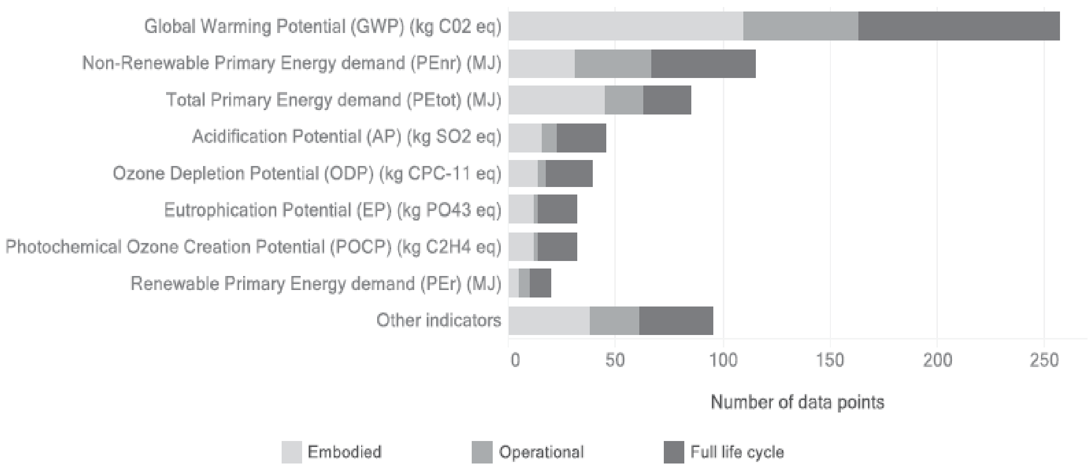


Figure 3. Summary of indicators analysed by collected papers [36].

Analysis of tools and certifications

To complement the study above, a second analysis was focused on the tools and certifications available and the elements considered within a practical LCA at neighbourhood and district level. The study compared the district elements taken into account by different tools (NEST, PLANHEAT Mapping Module and Ecocity Standards) and certifications (LEEDS, BREEAM, VERDE), as shown in Table 7.

To analyse the level of interest in their use and their replicability, an analysis was performed of their objectives and scope, strengths and weaknesses.

Table 8 presents the analysis of the data collected and considered in each LCA. This is structured in the following blocks and categories:

- **General information**: geographical data, climate data, key data (e.g. number of intended users, building stock, area, population density, and number of houses);
- **Building level**: building description, general (e.g. year of construction, geometry, construction system, and use), economic (euros/m²), areas to be built, types of roof, construction (materials, floors, façades), occupancy, consumption energy, consumption water, and solar thermal/photovoltaic energy production;
- **District level uses**: sector (e.g. residential, non-residential, tertiary) and types of floors (e.g. green or permeable spaces, built or impermeable spaces);
- **District level green spaces**: conditioning component and ecological assessment;
- **District level installations**: public lighting, water, district heating, thermal/photovoltaic solar, networks, mobility; potential heat, and cooling supply;
- **Community**: accessible design, participation, user guide (accessible information for end-users), and management and operation (facilities, open spaces, meeting places, etc.);
- **Economic data**: investments and energy price increase;
- **Environmental assessment:** GWP, noise pollution, and air quality.

The compilation of the elements assessed by each tool and certification has helped to identify those that may be most relevant to include in the LCA at district level, either because they are considered fundamental to the study or because they have been omitted from other studies and, therefore, may represent an innovation for the project and PEDs.

Table 7. Analysis of LCA tools and certifications used at district level.

Name	Type	Software	Difficulty of use	Goal and scope	Strengths	Weaknesses
NEST (Neighbourhood Evaluation for Sustainable Territories) [74, 75]	Tool	Sketchup plugin	Low	Based on LCA. Enables simultaneous environmental, economic and social analyses to be performed at a district scale, and refurbishment scenarios to be evaluated. Four major neighbourhood components: buildings, land use (roads, parking, green spaces, etc.), infrastructure (public lighting), and mobility of neighbourhood users. It enables the calculation of two indicators over the entire life cycle of planning operation: Total primary energy consumption (MJ or kWh/user/yr) and climate change (kgCO2eq/user /yr).	Based on LCA. Designed to compare simultaneously several urban planning scenarios (compare the environmental efficiency of each scenario). Helps in defining environmental project guidelines based on a multicriteria assessment. Optimises the performance of urban planning projects. Enhances the communication of projects using objective indicators. Web application linked to the city's EEGLE digital platform which can be used online via any browser. Stages included: A1-A4, B2, B4, B6, B7, C1-C4.	It only enables the calculation of two indicators over the entire life cycle of a planning operation (total primary energy consumption, and climate change). Not open access. Payment required.
PLANHEAT Mapping Module [76]	Tool	PLANHEAT plugin embedded in QGIS software	High	The main objective is to develop and demonstrate an integrated and easy-to-use tool which will support local authorities (cities and regions) in selecting, simulating, and comparing alternative low carbon and economically sustainable scenarios for heating and cooling that will include the integration of alternative supply solutions (from a panel of advanced key technologies for the new heating and cooling supply) that could balance the forecast demand.	Developed and validated through real use cases. It focuses on defining, simulating, and evaluating appropriate sustainable heating and cooling strategies. It evaluates the benefits of the proposed scenarios via energetic, economic, and environmental KPIs. Open-source code. It calculates KPIs in different domains to	Not for general use. Intended only for public authorities (cities and regions). Mainly for energy consumption calculations. It is not innovative in terms of the indicators it reports: CO_2 emissions, pollutants emissions, and noise pollution. Some PLANHEAT approaches are quite data-demanding and time-demanding in terms of scenario preparation.

Name	Type	Software	Difficulty of use	Goal and scope	Strengths	Weaknesses
					compare baseline and future scenarios. Provides information about the transport sector. It produces a final report summarising all the information associated with the simulated scenario.	
ECOCITY STANDARS [77]	Tool	Web-based application Geonode (open source Geoespatial Content Management System)	Low	It seeks to provide support and criteria by which cities can successfully move toward becoming ecocities. It comprises 18 standards in four categories: urban design, bio-geophysical conditions, socio-cultural features and ecological imperatives. It is a diagnostic tool for cities and citizens to measure progress towards ecocity conditions. Designed for a wide range of users, from novices to experts.	Prioritisation of appropriate indicators is based on existing indicators that can be successfully applied statistically, practically, and economically at the necessary scale (city, metropolitan statistical area (MSA) or bioregion). It considers different aspects: based on four pillars (urban design, bio-geo-physical conditions, socio-cultural conditions, and ecological imperatives). Designed for a wide range of users, from novices to experts. Each of the 15 assessment standards on which it is based are well defined by one main indicator and one associated benchmark for assessing whether a city is in balance with nature. The ecoCity Footprint Tool enables a community to evaluate its ecological footprint, 'territorial' greenhouse gas (GHG) emissions, and consumption-based GHG emissions. Critical data to inform about sustainable consumption and climate mitigation efforts. It considers the impacts associated with the	Not based on LCA. The methodology is not easily understandable and can only be applied within its own framework: it is based on a point system to determine whether it is considered an ecocity and at which level. Some indicators it considers may be subjective and not quantifiable scientifically (e.g. happiness index).

Name	Type	Software	Difficulty of use	Goal and scope	Strengths	Weaknesses
					many goods a community consumes.	
BREEAM (Building Research Establishment Environmental Assessment Methodology) [78]	Certification	Excel	Medium	It promotes a more sustainable construction that has an impact on saving, health and environmental benefits for all those involved in the life of a building (tenants, users, developers, owners, managers, etc.). Thus, it supports solutions to reduce carbon emissions to net zero, improve whole life performance, manage health and social impacts, boost circularity, resilience and biodiversity, and support disclosures and reporting. The certificate improves the functionality, flexibility and durability of buildings. The suite of schemes enables consistent and comparable assessment and verification: new construction, refurbishment and fit out, in-use, communities, infrastructure, and home quality mark.	It enables dialogue between developers and planning agents. Internationally recognised. It brings market recognition to sustainable urban projects. It raises awareness among planners, developers, residents, consultants and policymakers. It sets higher criteria and standards than those required by regulations in both design and implementation of the project. Science-based. It takes into consideration six categories to assess and certify the sustainability of each development project: governance, social and economic well-being, resources and energy, land use and ecology, transport and mobility, and innovation.	Not open access. Payment required. It increases in project costs. Deadlines for achieving certification must be met. Environmental assessment: energy demand, CO_2 emissions, and air quality. It does not consider other impacts.

Name	Type	Software	Difficulty of use	Goal and scope	Strengths	Weaknesses
LEED (Leadership in Energy and Environmental Design) [79]	Certification	Excel	Medium	It provides a framework for healthy, highly efficient, and cost-saving green buildings. The goal is to create better buildings that: reduce contributions to global climate change, enhance individual human health, protect and restore water resources, protect and enhance biodiversity and ecosystem services, promote sustainable and regenerative material cycles, and enhance community quality of life. It considers all building types and building phases including new construction, interior fit outs, operations and maintenance, and core and shell.	It evaluates the construction project as a whole (design, construction, operation and maintenance). Goals: climate action, quality of life, and ecological conservation and restoration. Internationally recognised. LEED categories can also contribute toward meeting the U.N.'s sustainable development goals.	Not open access. Payment required. Increase in project costs. Deadlines for achieving certification must be met. Environmental assessment: only energy demand and CO_2 emissions. It does not consider other impacts.
VERDE [80]	Certification	Excel	Medium	The VERDE tools aim to provide a methodology for assessing the sustainability of buildings. It considers: location of the building, indoor environmental quality (air, light, noise, comfort), resource management (energy, water, materials), social integration (accessibility, training, communication), and the technical quality of the building (monitoring, documentation, maintenance).	The methodology used is based on life cycle assessment. Evaluation of the reduction of the impacts generated at social, environmental, and economic levels. Flexible, adaptable and accessible to different levels of knowledge. It allows the implementation of quality processes throughout the project, construction and use processes. Stages included: A1-A3, B4, B6, C3-C4, D.	The tool is fully developed and conceived from the point of view of the market and Spanish regulations. Not open access. Payment required. Increase in project costs. Deadlines for achieving certification must be met. Environmental assessment: energy consumption and climate change, resource use fossils, resources use minerals and metals, eutrophication freshwater, acidification soil and water, ozone depletion, photochemical ozone formation. Not all indicators.

Table 8. Comparison of elements taken into account within LCA at district level.

				NEST [53,54]	PLANHEAT [55]	ECOCITY [56]	BREEAM [57]	LEED [58]	VERDE [59]
General info	**Geographical data**		Country		X				
			Village	X	X		X		X
			City	X	X	X		X	X
	Climate data		Climate zone	X		X			X
			Precipitation (mm/year)	X					
			Radiation (kWh/m2year)	X					
			Winter/summer period		X				
			Solar shading			X			
			Outside air temperature (hourly)		X				
			Heat island effect				X	X	X
			Flood risk				X	X	X
	Key data		Number of intended users						
			Building stock						
			Number of houses				X		
			Area				X		X
			Population density		X				X
Building Level	**Building**	Description	Building ID		X		X		X
			Building status (new or existing)	X		X	X		X
	General		Year of construction	X	X				
			Protected or not	X	X				
			Degree of protection		X				
			Construction system	X					
			Geometry of the building (shape and height)		X				
			Height		X				
			Number of floors		X				
			Building use (if more than one, the predominant one per		X				X
			U-value or envelope info		X				
	Economic	Cost	Real cost (euros/m2)	X					
	Areas to be built		Gross floor area (m2)	X	X		X		
			Usable floor area (m2)		X		X		X
			Roof area		X				
			Footprint area		X				
			Commercial floor area (m2)	X					
			Dwellings floor area (m2)	X					
			Office floor area (m2)	X					
			Other activities floor area (m2)	X					
			Green spaces floor area (m2)	X					X
			Parking floor area (m2)	X					
	Types of roof		Geothermal boreholes connected to geothermal heat	X					
			Photovoltaic solar panels	X					
			Solar thermal panels	X					
			Green roof	X		X			X
	Construction	Area	Usable area (m²)	X					
		Materials	Construction materials			X	X		X
			Insulation						
		Floors	Ground floor area, intermediate and roof area, total	X					X
		Facades	Wall area, glass area,	X					
			Type of windows						
			Window to wall ratio		X				

				NEST [53,54]	PLANHEAT [55]	ECOCITY [56]	BREEAM [57]	LEED [58]	VERDE [59]
Building Level	**Occupancy**	Occupancy patterns	Building occupancy		X				
			Schedule		X				
			Ventilation		X	X			
			Base temperature		X				
			Internal gains (occupancy, appliances, lighting)		X				
	Consumption Energy	Energy	Control system						
			Energy performance			X	X	X	X
			Primary energy use (renewable and non-renewable)						X
			Heating (demand or consumption, production system)	X	X				X
			Cooling (demand or consumption, production system)	X	X				X
			DHW (demand or consumption, production system)	X	X				X
			Energy systems (boiler, heat pumps...)		X				
			Energy sources (natural gas, biomass, fossil fuels...)		X	X			
			Appliances (consumption or demand)	X	X				X
			Lighting (consumption or demand)	X	X				X
			Heating degree hour		X				
			Cooling degree hour		X				
	Production	Solar thermal and/or photovoltaic energy production	Area	X					
			Orientation (location)	X				X	
			Inclination	X					
			Collector type	X					
			Gains		X				
			Losses	X					
			Production (Kwh/year)	X					
	Consumption Water	Water	Water consumption						X
			Reduction system		X			X	
			Reuse system						
District level - Uses	**Sector**		Residential		X		X		
			Non-residential				X		
			Tertiary sector		X				
			Community areas (public and civic spaces, recreational				X	X	X
			Brownfield				X	X	
	Types of floor		Urbanised land				X		
			Green or permeable space	X		X	X		
			Public car parks	X		X	X	X	
			Private land	X					X
			Roads	X			X		
			Pedestrian walkway	X		X	X	X	
			Pavement						X
			Built or impermeable space						
District level - green spaces	**Conditioning component**		Deciduous tree						
			Evergreen tree						
			Thorny tree						
			Grassed areas						
			Native plants			X	X		X
	Ecological assessment		Biodiversity protection, management and conservation of			X	X	X	X
			Agricultural land			X		X	
District level - installations	**Public lighting**		Type of bulbs (LED, fluorescent, induction, etc.)	X					
			Energy consumption						
			System (none, dimmer, renewable power supply, etc.)	X					
			Light pollution reduction				X	X	X

			NEST [53,54]	PLANHEAT [55]	ECOCITY [56]	BREEAM [57]	LEED [58]	VERDE [59]
District level - installations	Water	Treatment plant (city size, number of inhabitants)	X				X	
		Water consumption			X	X		X
		Water consumption of landscaped areas			X			X
		Rain water recovery			X	X	X	X
		Groundwater				X		
	District heating	Connected thermal demand						
		Total district heating demand		X				
		Distribution by boiler type						
	Thermal solar	Area	X					
		Orientation	X					
		Inclination	X					
		Collector type	X					
		Losses	X					
		Production (Kwh/year)	X					
	Photovoltaic solar	Area	X	X				
		Orientation	X	X			X	
		Inclination	X	X				
		Collector type	X	X				
		Losses	X	X				
		Production (Kwh/year)	X	X				
	Networks	Energy				X	X	
		Renewable energy			X	X	X	
		Water			X			
		Heating		X			X	
		Cooling		X			X	
		Heat and power excess						
		Waste management				X	X	
	Mobility	Public transport network			X	X		X
		Electric car charging points				X		X
		Bicycle facilities			X	X	X	X
		Type of population						
		Type of transport by type of population					X	
		Average distances			X			
		Mobility of non-resident workers						X
	Potential heat and cooling supply	Biomass from forestry		X				
		Agriculture		X				
		Deep geothermal		X				
		Excess heat sources from industry		X				
		Unconventional sources (subway networks, indoor car		X				
Community	Accesible design	Accesible buildings and open spaces				X		
	Participation	Actively involve the community			X	X		
	User guide	Accessible information for end-users (transport, services,				X		
	Management and	Community management of facilities, open spaces,			X	X		
Economic data	Investment	Total investment cost	X					
	Energy price increase	Natural gas increase (%)	X					
		Electricity increase (%)	X					
		Biomass increase (%)	X					
		Diesel fuel increase (%)	X					

				NEST [53,54]	PLANHEAT [55]	ECOCITY [56]	BREEAM [57]	LEED [58]	VERDE [59]
Environmental assessment			Energy consumption		X		X	X	X
			Renewable energy production						
		GWP	CO2 eq emissions		X	X	X		X
		Other	Ozone depletion, acidification, eutrophication,		X				X
			Air quality			X			
			Noise pollution		X				
			19 indicators						

The goal of the tools and certifications analysed is to promote and evaluate a more sustainable type of construction that allows districts to move towards a more environmentally friendly model. In addition, regarding the environmental assessment, most of them focus on CO_2 emissions and energy consumption. Only two (PLANHEAT and Verde) consider other environmental impacts. None of them reports all 19 indicators.

3.2.4 Conclusions

Some interesting conclusions from the state of the art can be drawn to be taken into account when carrying out an LCA at PED level:

- At product, element, and material level, it is worth highlighting the **potential of EPDs**, which are scientifically based, adhere to standardised European methods, and assess the environmental impacts. Currently, they have a business to business used interest but their add value is also, as they quantify the environmental impact of building materials and products, their interest in decision making and as a KPI to demonstrate environmental impact (e.g. company reports, certifications, etc.). Certifications such as BREEAM, LEED, DGNB, etc. also support their use as they give additional sustainability credits to buildings utilising EPD-certified materials. However, it is noteworthy that they usually include a limited number of environmental indicators [36], so the LCA methodology is not exploited at its greatest potential;
- **LCA tools** must be better harmonised with the building design process and associated workflows. This presents a multifaceted challenge, as the design process lacks standardisation. While some designers employ intricate digital workflows, others adhere to analogue methods [73];
- The **functional unit** must be well defined. A decision must be made as to which will be chosen for the analysis as there are a large number of possibilities and none is established as the most appropriate. The objectives of the study and a clear presentation of the results seem to be a greater driver [73];
- The **boundaries** to take into account in the analysis are both in terms of different life **cycle stages** and the various **physical elements** in a neighbourhood (e.g. buildings, mobility, open spaces and infrastructure). Concerning physical elements, buildings are one of the elements common to all the assessments. However, some studies highlight the suitability of incorporating other elements [75] that may define PEDs. Regarding cycle stages, there is not a common framework developed, so there are tools that include a wide range of stages defined by EN 15978 such NEST or VERDE [74, 80], but others focus only on some stages, such as, for example, on the product stage or the operational energy [81]. When focusing on PEDs, the number of relevant life cycle modules from A1 to C4 is closely related to the definition and ambition of the PEN level and the zero-emission ambition for each of the physical elements. To enable their smooth incorporation, a modular approach during the project and beyond, it is

considered of interest to apply the same approach in PED design as that followed at the product and building level. It is also of interest for PED level to include production (building), maintenance and end of life. In addition, as scholars have indicated, the contribution of impacts related to transportation are important (up to 45%) and, thus, they should be included in the use stage (module B8);

- **Material flow analysis** (MFA), **input-output analysis** (IOA) and **life cycle assessment** (LCA) are appropriate **methods** to perform an environmental and economic assessment of products and systems such as complex buildings and districts [71]. Each offers its own advantages;
- There is **no standardised approach** to LCA at **district level**. The elements considered when carrying out such an analysis are diverse, and no minimum common requirements are set.

Based on said conclusions, it has been considered necessary to develop an LCA proposal system at district level that can be extrapolated to any PED. This proposal will be tested in the oPEN Lab project in order to validate it and advance in the definition of a common LCA framework for all PEDs. This issue is further discussed in Chapter 4. oPEN Lab project LCA approach for materials, products and buildings integrated in the respective PEDs LL.

3.3 Variables with potential to affect LCA for PEDs

The LCA baseline study period at district level is usually long-term. Due to the current climate emergency and the prompt urban energy transition proposed as a consequence, it is considered that LCA should take into account possible changes in environmental sustainability issues over the years, as they are expected to affect LCA results.

Such changes may be driven by market trends, changes in citizenship and by legislative impositions. In this regard, in Europe, government institutions and bodies, both at EU and national level, are legislating to make the building sector more sustainable, which may directly affect the design of PEDs [2].

3.3.1 European framework of energy and decarbonisation transition

The European Union's long-term framework concerning energy development and sustainability that could affect life cycle calculation is constituted by the 'Clean energy for all Europeans package' (CEEP) adopted in 2019 [82]. This consists of eight new laws to enforce the energy union strategy and to help to bring about the EU's long-term objective of becoming carbon neutral by 2050. It is in line with the European Climate Law [83]. The CEEP includes among others the following initiatives:

- Energy performance in buildings directive [84];
- Renewable Energy Directive [85];
- Directive on Energy Efficiency [86];
- Regulation on the Governance of the Energy Union and Climate Action and National Energy and Climate Plans [87];
- Electricity market design [88];
- Measures to define and monitor energy poverty [89].

Many of the previously mentioned initiatives have been or are being revised at the time of writing of this report, prominently the Renewable Energy Directive and the Energy Performance of Buildings Directive.

Energy accounts for 75% of the EU's greenhouse gas emissions and, therefore, decarbonising the energy system became a priority requiring structural transformation, replacing fossil fuels with renewable and low-carbon energy sources [83]. Phasing out fossil fuels from electricity generation will significantly change the energy mix, although these changes will differ depending on the generation infrastructure of member states. Therefore, as life cycle assessment is a long-term analysis, usually with a scope of 50-60 years, **changes in the energy mix over time will have to be internalised in line with EU policies and other foreseeable macroeconomic events**. In this sense, the **'**Fit for 55 Package' [90], the EU's strategic legislative framework to achieve a 55% reduction in greenhouse gas emissions by 2030, is one of the initiatives that will drive both change and national strategies. For instance, Estonia is aiming to accelerate its clean energy transition with a target of 100% renewable electricity generation by 2030 as part of a larger package to achieve climate neutrality by 2050 [91].

In addition, the advent of **new enabling technologies**, or the decrease in the cost of acquiring existing ones, is another factor that could favour the drive towards a fully renewable energy supply and, as such, it should be taken into consideration for life cycle assessment. Among the most relevant enabling technologies, **electricity storage**, in its many forms, is being developed at a fast pace and will become market-competitive in the coming decades [92]. It should also be highlighted that in the next few years, major battery projects will be rolled out based on existing technologies, as well as vehicles capable of **vehicle-to-building** (V2B) or **vehicle-to-grid** (V2G), which could provide necessary grid balancing capabilities to further allow renewable energy to be deployed [93].

Another factor to consider for life cycle analysis is the **changing behaviour** of users as they are becoming more aware of energy use and of how their consumption decisions affect the environment. Consequently, they make a more rational use of energy and goods [94]. Consumption is also dependent on price levels or paradoxical phenomena such as the Jevons effect [95], in which enhanced efficiency of use leads to an increase in demand and the overall increase in the resource or good. The latter is known in the scientific literature as the rebound effect from improved energy efficiency [96]. Finally, another behavioural phenomenon is known as the prebound effect, in which consumer demand is lower than expected as a result of awareness of the inefficiency of the use of the commodity, for instance, energy [97].

The promotion of green mobility is one of the action points of the European Green Deal. In February 2023, the report from the commission to the European Parliament and the Council promotion of e-mobility through buildings policy [98] highlighted the importance of buildings that provide the necessary infrastructure for recharging electric cars, motorcycles, bicycles, and other personal mobility devices. The Energy Performance Building Directive's evolution fully acknowledges and includes provisions to support this shift towards green mobility [99, 100]. In addition, the adoption of the RepowerEU plan [101] following the Russian invasion of Ukraine increased the need to accelerate the installation of recharging infrastructure in residential and non-residential buildings and offices. Furthermore, more stringent regulations concerning internal combustion engine (ICE) vehicles and more efficient public transportation will increase the use of the latter. provided no paradoxical effects resulting from the limited perceived environmental impact of electric vehicles (EVs) occur.

The progressive replacement of ICE vehicles with EVs will drive an increase in electricity consumption as a replacement for fossil-fuels [102]. In December 2021, the European Commission presented a proposal for a revised trans-European transport network [103], highlighting the role of cities and designating more than 400 of them as urban nodes that should adopt a sustainable urban mobility plan (SUMP). This should be strategically designed to satisfy the mobility needs of cities while stimulating the push toward a more sustainable future in terms of transportation. As a general rule, SUMPs set targets to promote more efficient public transportation, to create pedestrian walkways, and to allocate lanes to bicycles and personal mobility devices, gradually discouraging the use of cars.

A very relevant piece of regulation that has undergone modifications over the years is the Energy Performance of Buildings Directive (EPBD) [84]. In December 2023, co-legislators reached a provisional agreement and, finally, on March 12th, 2024, the Council of the European Union approved the recast of this directive, which will drive the transition to zero energy standards for new buildings and boost the energy efficiency of existing ones, particularly those that are currently least efficient. The directive sets out significant requirements for new and existing buildings, putting emphasis on energy renovation and the implementation of clean energy and technologies. New buildings are expected to be climate-neutral from 2030, with earlier targets for buildings occupied by public administrations. Specific targets have been set for energy efficiency in the residential and non-residential sectors, as well as the creation of a national building retrofitting plan by member states. In addition, the EPBD imposes a reduction in primary energy consumption for residential buildings of at least 16% by 2030 and by at least 20%-22% by 2035, primarily through upgrading the least efficient buildings. In the case of non-residential buildings, a mandatory renovation of no less than 16% of the least efficient buildings should be achieved by 2030 and at least 26% by 2033. Contrary to expectations, the revised EPBD does not mandate an EU-level phase-out date or ban on new fossil fuel boilers. Instead, it introduces a clear legal basis for national bans, allowing member states to set requirements for heat generators based on greenhouse gas emissions, the type of fuel used, or the amount of renewable energy used for heating. Therefore, district level LCAs should internalise the very significant EU trend that in the following decades will change the face of districts.

As renovation strategies in the coming decades will focus their efforts on the least efficient buildings, operational energy will be significantly reduced and, therefore, embodied energy will gain prominence. In line with the EU's 2050 climate neutrality goal under the Green Deal, in March 2022 the European Commission proposed the first package of measures to speed up the transition towards a circular economy, as announced in the Circular Economy Action Plan [34]. The proposals include boosting sustainable products, and the reuse and repurposing of existing materials and products. Therefore, LCA should take these factors into account in their assessment.

Finally, demographic changes and the geographical distribution of the population, with increasing numbers of renovated buildings in existing urban areas, could drive up the consumption of energy and resources and the demand for energy-intensive services such as transportation. All these initiatives at EU, national and even regional level, provide an insight into forthcoming structural changes, which will have a significant impact on life cycle assessment. Below, three examples of different contexts (southern, central, and northern Europe) are presented in which the legal framework and expected energy developments are discussed. The examples highlight issues that are considered to affect LCAs and should, therefore, be taken into account in their implementation in PEDs.

3.3.2 Examples of different contexts in southern, central and northern Europe

Estonia

Estonia is developing an ambitious sustainability plan aimed at the transition to a sustainable energy model and a reduction in its GHG emissions [91]. The country's approach not only emphasises the need to adapt to modern energy solutions but also highlights the potential for Estonia to lead the green transition, setting an exemplary path for sustainable development. Some of the highlights of its plan are:

- **Produce 100% renewable energy to grid by 2030** [91].
  Estonia is ambitiously setting a course towards a future with sustainable energy, aiming to meet 100% of its electricity demand with renewable sources by 2030, significantly elevating its previous target of 40% to a complete transition. This bold move is part of a broader strategy to achieve climate neutrality by 2050, reflecting a decisive shift away from the country's historical reliance on oil shale, which has seen a 50% reduction in usage since 2018. Supported by €354M from the EU, particularly benefiting Ida-Viru, the county most affected by this transition, Estonia's plan includes extensive investment in renewable energy infrastructure, including wind farms and solar generation, alongside initiatives to boost grid readiness and efficiency;
- **Mandatory carbon footprint regulation for buildings** (latest 1st January 2028) [104].
  The LCA method, set to refine Estonia's carbon footprint calculation, is nearing completion, with a comprehensive preliminary analysis planned for 2024-2025 to establish new regulatory limits. This LCA includes specific modules for building components and excludes others, aiming for a 50-year reference period. Importantly, it differentiates between new builds and renovated, emphasising the role of managing material waste. Enhancements to the current method will include clearer indicators, such as adding GWP bio and EN 15804+A2 indicators and a more extensive range of materials. Thereby, ensuring a more equitable treatment across construction materials. These improvements, particularly in accurately assessing the immediate and long-term environmental impact of buildings and including dynamic carbon footprint calculations, aim to reduce urban district carbon emissions by promoting more sustainable construction practices and materials. Thus, contributing to the broader goal of circular construction and lower emissions in urban settings;
- Updated **building energy performance regulation** on 1st March 2025 [105].
  From1st March 2025, Estonia will implement updated building energy performance regulations to enhance the climate resilience of buildings and provide a more precise assessment of their energy consumption. Key updates include refined energy use calculations, a new online solar electricity calculator for more accurate solar potential estimations, and revised energy label scales to better reflect modern standards. The regulations also incorporate updated climate data from 1970-2000 to account for recent temperature rises and heatwave frequency, aiding in the design of effective cooling strategies. Additionally, adjustments in heating and cooling set points aim to align energy calculations more closely with actual building temperatures, enhancing comfort and efficiency. These changes, accessible on the Ministry of Climate's website, signify an important step towards sustainable building practices in Estonia, aligning with broader EU initiatives for energy efficiency.

Other factors expected to affect the LCA calculation at PED level are the issues presented below:

- Urban space upgrade (e.g. more trees);
- The increase in the maintenance, quality and lifetime of construction materials;
- More solar panels on apartment building roofs and façades.

Spain

In line with European guidelines, Spain is regulating the energy and construction sector in the interest of decarbonisation and the transition to a more sustainable energy model.

- Implementation of the **Spanish Urban Agenda: Urban Regeneration and Rehabilitation Plan September 2023** [106].

The main objective is to produce a substantial acceleration in the renovation of the building stock with models that allow energy efficiency and renewable energy integration targets to be achieved, aiming to have all buildings become 'zero emissions' by 2050;

- The **Circular Economy Strategy Spain 2030** [107].
This strategy is aligned with the objectives of the two circular economy action plans of the European Union. With regard to 2010, the main goals of the Circular Economy Strategy are as follows:
  - To reduce the national consumption of materials in relation to GDP by 30% and to reduce waste generation by 15%;
  - To reduce food waste generation over the entire food chain;
  - 50% per capita reduction at household and retail consumption level and 20% in the production and supply chains from 2020;
  - To increase the reuse and preparation for reuse of municipal waste generated to 10%;
  - To improve water efficiency by 10%;
  - To reduce greenhouse gas emissions to below 10 million tonnes of CO_2 equivalent.
- **Management of waste and contaminated soils for a circular economy. Law 7/2022 of 9th April** [108].
This law, which aims to achieve the 70% waste recovery rate set by the European Commission in 2008, will mean a change in the way waste is recovered in buildings in the coming years;
- **Climate Change and Energy Transition Law. Law 7/2021 of 22nd May** [109].
It is aligned with the sustainable development objectives of the 2030 Agenda and with the general objective of becoming CO_2 neutral by 2050. Its main goals for the year 2030 are:
  - To reduce the greenhouse gas emissions of the Spanish economy as a whole by at least 23% compared to 1990;
  - To achieve a renewable energy share in the final energy consumption of at least 42% and a system in which at least 74% of the electricity generated comes from renewable sources;
  - To improve energy efficiency by reducing primary energy consumption by at least 39.5% compared to the baseline in accordance with EU regulations.

These objectives are to be achieved through a series of cross-cutting and governance measures, as well as specific measures in terms of mobility, transport and, above all, will be focused on renewable energies, energy efficiency and building refurbishment, retrofitting and renovation. The materials used in construction and the analysis of their carbon footprint are also taken into account. At the regional level in Navarre, these regulations have been extended with the Foral Law 4/2022 of 22 March, on Climate Change and Energy Transition [110], which develops specific measures aligned with the objectives above for the specific case of the Community of Navarre;

- **Draft Royal Decree developing the figures of renewable energy communities and citizen energy communities** [111].
Through this new regulation, Directive (EU) 2018/2001 and Directive (EU) 2019/944 will come into force in Spain. The development of energy communities implies a decentralisation of energy generation models, including changes in mobility and energy efficiency services, which helps to reduce CO_2 emissions from electricity generation, thermal generation, and mobility. The implementation in Spain of the energy saving certificate system (CAES), promoted by the Ministry for Ecological Transition and the

Demographic Challenge, is intended to triple the use of renewable energies and achieve a two-fold improvement in energy efficiency by 2030 [112]. It is a novel instrument that makes it possible to monetise energy savings, recovering part of the cost of investments in energy efficiency (change of lighting, improvements in thermal insulation, renovation of industrial or domestic equipment, etc.). The end user will be compensated for selling the energy savings obtained, for their subsequent certification through the CAES system. In the coming years, there will be a change in how building renovations are subsidised. So, when renovating a building and certifying the energy savings achieved through these regulations, it will be possible to sell these certificates to CO_2-producing companies. If these companies buy these certificates, they will be able to offset their CO_2 production and avoid paying for it. It is a different way of financing improvements in the energy efficiency of buildings compared to the current system where autonomous communities give direct aid for the renovation of buildings.

It is also worth mentioning industrialised construction, a method that is gaining momentum within the sector and becoming a driving force thanks to the advances that it brings [113]. This construction method has the following benefits:

- 60% waste reduction. In traditional construction in Spain, more than 50% of the waste is ceramic (from bricks and tiles). In industrialised construction, waste could be reduced and much of what is produced is reused;
- Reduced costs, lead times, occupational accidents, and environmental impact;
- Circular economy: surplus material can be reincorporated into the production chain thanks to collaboration between partners, giving rise to the circular economy and further reducing the carbon footprint.

The take-off of industrialisation will come from more pedagogy and the change urgently required in the **National Technical Building Code**. As commented at the REBUILD summit in 29th March 2023 [114], the largest technology and innovation summit for the building sector: '*the need has been tabled for the sector to move from artisanal to industrial methods. Automated and industrialised construction are the production model that will allow this transformation to take place. However, in Spain it only represents 2% of the total amount of construction carried out in the country, while in areas such as Germany and the United Kingdom it represents 9% and 7%, respectively'.*

One of the main demands of the sector is to create specific regulations aimed at stimulating industrialised construction in all areas. An urgent change in the Spain's technical building code would pave the way for industrialised construction, enabling 30% of the works in the country to follow this model, thereby boosting reindustrialisation. All the agents involved in it have highlighted the need to inform end clients better about industrialisation, which would accelerate its expansion. These issues will directly affect the LCA process, in which, for example during replacement calculations (B4), there will be a significant reduction in the impact thanks to the development of a more automated and industrialised system.

Belgium

It is important to note that, in terms of regulation and governance, Belgium is structured on several different levels: Federal level, Flemish level, Brussels Region level, and Wallon level.

In Belgium, the federal government is responsible for product policy (including building materials) and the regional authorities are responsible for buildings and waste. Therefore, it is important for the Belgian construction sector that federal policies are harmonised with those of the regional authorities. Fortunately, the federal government and the three regions (Flanders, Wallonia, and Brussels) are working closely together on the transition to a more sustainable built environment in which circular strategies are becoming increasingly important.

Federal level

The federal level in Belgium has several key levers to support the transition towards a circular built environment. They typically focus on product policy, certification, and fiscal aspects.

- **The Federal Council for Sustainable Development** [115].
  This is an important consultation platform between the different levels of government. In the national plan for recovery and resilience, the built environment has a prominent place. The renovation of existing buildings and the circular use of materials are two of the key aspects. These are further elaborated and developed on the Flemish level in a specific relaunch plan [116];
- **Belgian EPD Programme of the Belgian Federal Public Service - Health and Environment** [117].
  Belgium is a frontrunner in the development of EPDs for construction products in terms of legal framework and programme design. A B-EPD is an EPD that conforms to the general principles of the Belgian EPD Programme of the Belgian Federal Public Service - Health and Environment [118] as part of their B-EPD programme. B-EPDs can be drafted for construction products, as well as for civil engineering technical installations and materials. A B-EPD applies to any construction product sold in Belgium or intended for use in Belgian buildings. That means that if a company completes an LCA proving the sustainability of its product, it will be eligible for a B-EPD. The core rules are largely based on international standards (ISO 14040, ISO 14044, ISO 14025) and the EU standards committee CEN TC 350 - Sustainability of Construction Works (EN 15804:2012+A2:2019). This programme can be considered significant for promoting the implementation of LCA in the construction sector and increasing awareness of the environmental impact of materials;
- **TOTEM** [119].
  B-EPDs in Belgium are integrated into TOTEM (Tool to Optimise the Total Environmental Impact of Materials), Belgium's unique building assessment tool. OVAM, Brussels Environment, and the Public Service of Wallonia, representing the three Belgian regions as policymakers, developed TOTEM to assess the environmental performance of buildings and building elements. TOTEM is intended to quantify and reduce the impact that buildings have on the environment. All three Belgian regions recommend that architects use TOTEM, not only because it unifies Belgian efforts to make the construction sector more sustainable, but because it provides them with the means to assess products in the proper context. Building elements and products are listed in TOTEM according to environmental performance. Until recently, however, that performance has been based on default generic data. The advent of B-EPD specific data in TOTEM spells a huge advantage for the Belgian construction sector because it transforms TOTEM into an even more authentic reflection of the reality of the sector. The specific data result in a more accurate evaluation of the environmental impact of building element types or buildings. It also enables companies to gauge their performance vis-à-vis the competition at the building level. Given TOTEM's growing acceptance within the Belgian construction community, its compatibility with B-EPDs has considerable potential to boost its relevance and popularity in the Belgian market.

Flemish level

- **Circular economy and sustainable economic growth policy programs**.

One of the key aspects in the current Flemish coalition agreement (2019 – 2024) [120] is the circular economy and sustainable economic growth. Hence, the building sector, as one of Flanders' most important economic sectors, needs to play an important role in achieving different goals. Policy programs have launched initiatives to stimulate the construction sector to develop circular value chains and design modular buildings, such as Visie 2050 [121], Vlaams klimaat actie plan [122], and Vlaanderen Circulair [123];

- **Towards circular construction** [124].
  A new policy program of OVAM (Public Waste Agency in the region of Flanders) 'Towards circular construction' will run until 2030 and is in line with the broader objectives of Flanders for the transition to a circular economy by 2050. The new policy programme provides a guiding framework for the transition in the construction sector, with emphasis on the development of circular construction and construction materials. In the coming years, OVAM will prioritise the following facets to stimulate circular initiatives in the built environment:
  - The origin and quality of building materials need to be measured and logged to boost market acceptance;
  - Numerous initiatives together with important market players will be supported to establish the cost-benefit of circular solutions;
  - The dissemination of best practices and lessons learned will play a key role in convincing the sector.

Brussels Region level

- **Regional Programme for Circular Economy by Brussels environment** [125].
  This programme pays special attention to the building sector. The programme was originally planned for the 2016-2019 period but was extended in 2020. In the coming years, the Brussels Environment administration will prioritise the following actions to stimulate circular initiatives in the built environment:
  - A strategy and action plan for the implementation of the circular economy will be elaborated in collaboration with all stakeholders from the construction sector;
  - Actions introduced for designers through the implementation of information, awareness-raising and training actions, development of supporting tools and stimulation of pilot projects in the circular economy;
  - The 'Platform of the Actors for the Reuse of Building Elements' [126] will develop channels for the reuse of building materials to conserve Brussels resources and reintroduce them into local economic circuits.

Moreover, to provide guidelines for applying the principles of the circular economy to new construction and renovation projects, the region has just published a vade mecum on the integration of circularity into public procurement [127].

Walloon level

The Wallonia region focuses on three key aspects: a social ambition, an ecological ambition, and an economic ambition. The development of a circular economy plays a key role in achieving these drives in a sustainable manner.

- **Circular Wallonia.**
  This is the result of a political evolution that has largely taken place since the Marshall Plan 4.0 (2015-2019) [128]. A variety of initiatives and support schemes have been established over recent years aimed at the development of the circular economy.

Particularly in terms of support, financing of projects, and the reuse and management of waste resources;

- **The Wallonia Waste Resources Plan (PWD-R)** [129].
  Related to waste management policy by integrating the principles of the circular economy.

Given the cross-sectional nature of the challenges, other plans and strategies of the region address certain facets of the circular economy, in particular the Smart Specialisation Strategy, a long-term strategy for the energy renovation of buildings and other initiatives [130].

3.3.3 Conclusions of variables applying to LCA in PEDs

As a consequence of the above-mentioned context, the realities of the construction and energy sectors are expected to evolve in the coming years, so the possibility of certain changes that will affect the accuracy of LCA results must be taken into account. The current static nature of LCAs (linked to RSP defined in LCA) and the option of making calculations more dynamic should be considered.

Some aspects have been identified as most likely to change over time and, therefore, they are interesting to explore through sensitivity analysis because their evolution will affect PED LCA results over time. Some of these are listed below:

- Changing energy mix over time and new technologies installed to achieve PED (PV, BMS, batteries, etc.);
- Changes in human behaviour in terms of energy consumption (thanks to awareness-raising and engagement strategies or new regulations);
- Changes in mobility behaviour (shift from private vehicles to public and especially low-impact vehicles such as bikes, scooters, etc.);
- Changes in regulations that will affect the replacement phase in the LCA (e.g. heat pumps will replace boilers);
- How to deal with the lifetime of buildings;
- Collective versus individual approach;
- Assess the shifts between embedded and operational-related impacts;
- Changes in population density due to lack of built space or necessary due to low income (reduction m^2 per person);
- Multi-cycle material use;
- Changes/developments in waste processing over time (e.g. recycling of steel);
- Quantifying the percentage of reuse.

3.4 Stakeholders involved in PED design

For the design and development of the PED, a series of actors have been identified who could be involved in the value chain (see Table 9).

Table 9. Stakeholders that could be involved in value chain of PED development.

Building stakeholders	Description
Designer, civil engineer or architect	They design the building or neighbourhood to meet the property developer's requirements. They ensure compliance with relevant technical and urban regulations.

Building stakeholders	Description
Builder or contractor	The builder or contractor is the stakeholder contractually bound to the property developer that assumes the commitment to execute all or part of the works with their own or third-party human and material resources subject to the project and the contract.
Building quality control entities and laboratories	Building quality control entities are qualified to provide technical assistance and ensure compliance with specifications and regulations in force for the project, the materials, and the execution of the work and its facilities following the project and the applicable regulations.
Construction manager	The stakeholder who, as part of the facultative management, directs the development of technical, aesthetic, urban planning, and environmental aspects of the works defined in the project, and is responsible for the building license, as well as the relevant authorisations and the terms of the contract, to ensure their suitability for the proposed purpose.
Director of the execution of the work	The director of the execution of the works is the stakeholder who, as part of the facultative management, assumes the technical function of directing the material execution of the works and of qualitatively and quantitatively controlling the construction and quality of the building.
Property owner / user	The property owner is responsible for keeping the building in good condition through proper use and maintenance in accordance with the instructions for use and maintenance contained in the documentation of the works carried out. They are also duty bound to receive, preserve, and transmit the documentation of the works carried out.
Product suppliers	Product suppliers are considered manufacturers, stockists, importers or sellers of construction products.
Property developer	Any person, physical or legal, public, or private, who individually or collectively decides, promotes, programs, and finances, with their own or third-party resources, the building works for themselves or their subsequent sale, delivery, or assignment to third parties under any title.
Public administration	The entity in charge of legislating, guaranteeing the suitability of the project, granting the relevant licenses, and providing incentives or stimuli. They can also be property developers or owners.
Surveyor	A person who examines the condition of the land and buildings.
LiDAR / Laser scanner operator	A person who operates a laser to make high-resolution 3D representations of areas and/or buildings.

Building stakeholders	Description
BIM manager	A person who understands the BIM methodology and is capable of coordinating and managing a BIM project.
Manufacturer	A specific type of product supplier. They create prefabricated and modular building elements.

Stakeholders are a heterogeneous group of people from different backgrounds and sectors, and with varied knowledge. Bearing that in mind, their knowledge and experience with LCA can be assumed to be very different, which is a factor to consider when deciding on the best way to integrate LCA into the work and decision-making of each of these actors as presented in the following chapter 3.5 Analysis of the integration of LCA into stakeholder's workflow and decision-making.

3.5 Analysis of the integration of LCA into stakeholder's workflow and decision-making

3.5.1 Analysis of the current situation of stakeholders: LCA knowledge and its integration into their decision-making

As mentioned in the previous section, to ensure that LCA is taken into consideration by the different stakeholders and that it becomes a part of their work dynamics, it is important to understand their needs and try to tailor the information in an attractive and relevant way. Both the profile of the different users in relation to LCA and the way in which the information is presented to them need to be considered.

For that reason, activities such as workshops and surveys are necessary in order to:

- Determine their base knowledge and general interest in LCA;
- Know their limitations and ambitions;
- Detect the problems and needs they face when implementing LCA;
- Be able to take measures to improve their understanding on the subject.

For this purpose, a couple of actions (listed below) have been carried out to better understand the context in which LCA should be integrated, to enable LCA to be made accessible to all, allowing it to be included into their work processes and decision-making. It is therefore necessary to undertake such activities with a sample of actors representing all those involved in PED design and development. The sample of participants was taken from the partners of the oPEN Lab project, which comprises this whole range of actors.

Action 1: **workshop.** This engaged different stakeholders involved in the renovation process to detect their level of knowledge of LCA and their needs to integrate LCA into their work. The participants included four architects, two building quality control entities and laboratories, a product supplier, a BIM manager, a director of the execution of the works, as well as one business development consultant. These participants were from the construction and architecture, environmental impact/LCA, energy and business sectors. In total, ten people attended the workshop, three women and seven men.

The following conclusions can be drawn from the workshop:

- There is difficulty integrating LCA into their work processes and decision-making due to lack of LCA training/culture or information;
- It is necessary to be aware that several assumptions have to be made for a study with a life cycle perspective, which can lead to considerable amounts of uncertainty in the results;
- The overall LCA level knowledge of the participants is low. Many have little understanding of what it is, how it works, what it is for, its value and how it can be implemented.

Action 2: survey. A total of 32 people from different countries around Europe (Spain, Belgium, Greece, Estonia, Germany, Netherlands and Switzerland) completed the survey. They were from different organisations and sectors that are involved in the value chain of the design and development of the PED such as: architecture, monitoring, social innovation, environmental impact/LCA, HVAC, energy, housing, business development, engineering and technology, marketing and communication. They also had different roles such as owners, designers, architects and engineers, etc. The number of participants per role is presented in Figure 4.

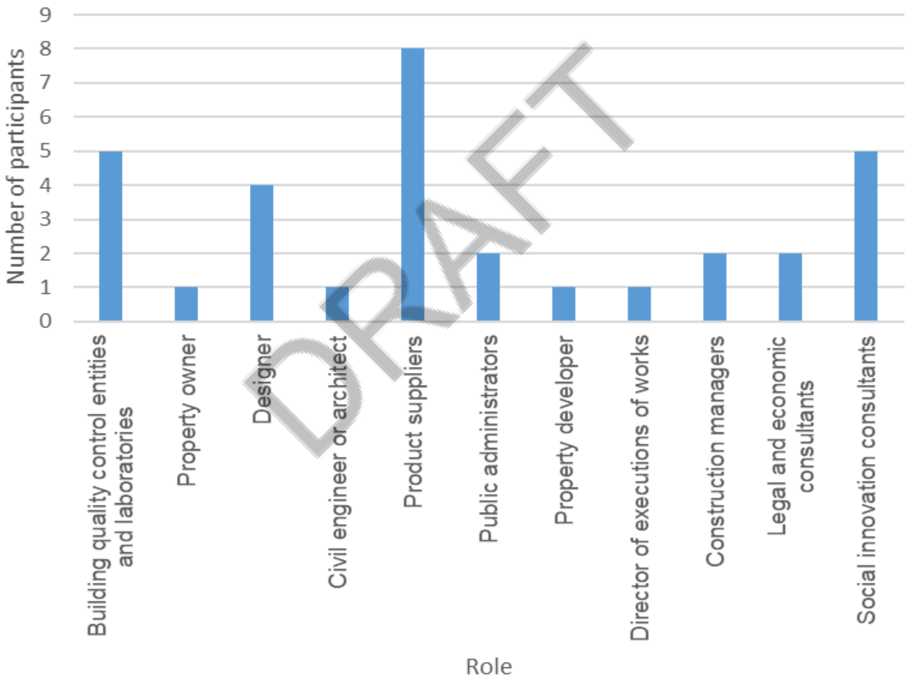


Figure 4. Number of stakeholders participating in LCA survey per role.

This wide variety of actors with different knowledge and backgrounds, as well as the context of application in which they work, allows the study to have an indicative sample that represents the reality of different European contexts.

The questions of the survey were aimed at finding out:

- Level of awareness of LCA or other environmental impact assessment methodologies;
- Problems and difficulties encountered when interpreting an LCA;
- Level of interest in learning more about LCA;
- The importance given to the environmental impact of a product/service/activity;
- Their economic valuation of LCA or similar methodologies.

The survey produced the following results:

- **The level of LCA knowledge is low**. Half of the respondents have little or no knowledge of LCA (40.6% low level, 9.4% none). The other half consider that they have a medium level. No one reported having a high level of knowledge. While 46.9% had had previous contact with LCA, only 28.1% had had experience with other environmental analysis methodologies (mainly carbon footprint), as shown in Figure 5. By field of expertise, the most knowledgeable participants with regard to LCA were those working in HVAC and Social Innovation, claiming to have a medium level of LCA knowledge.

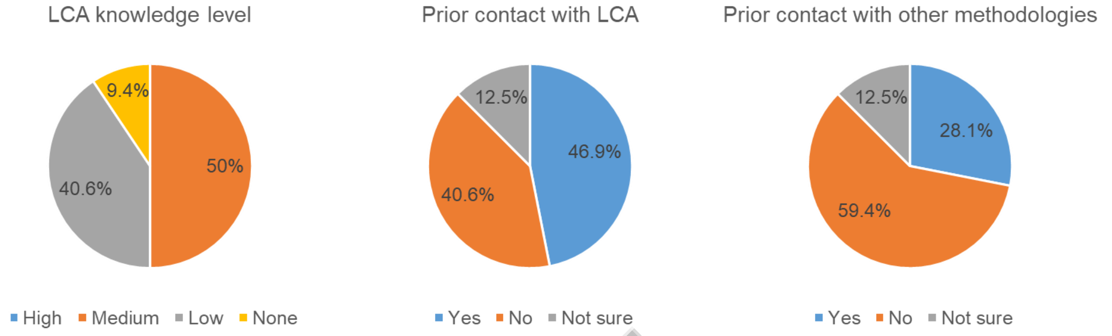


Figure 5. Survey results. From left to right, indicating level of LCA knowledge, prior contact with LCA, and other methodologies.

- Among those who have experience with LCA (46.9% out of the total), less than half (48.1%) considered that the information was presented in a clear manner. The main difficulties encountered when interpreting an LCA study were a **lack of both information and a prior explanation**, which accounted for 55.1% of the responses. For 37.9%, there is too much technical information. A smaller percentage, 7%, reported other problems related to a lack of data or data accuracy (see Figure 6).

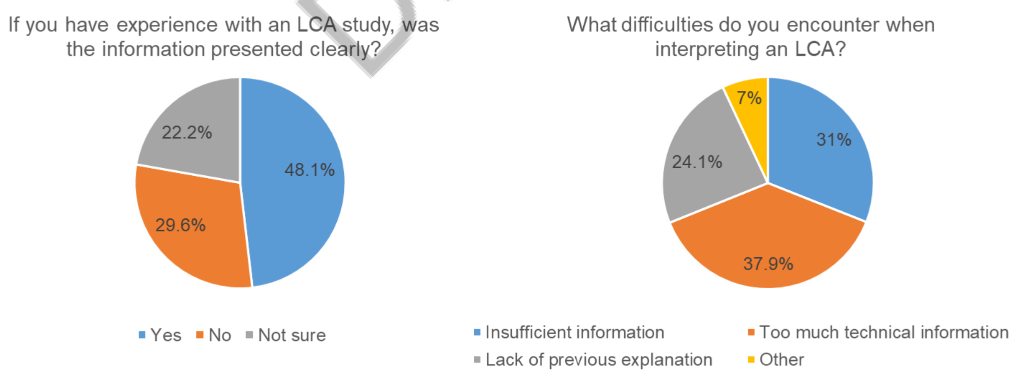


Figure 6. Survey results. From left to right, indicating experience and clarity of information and difficulties encountered.

- **Most respondents showed interest in LCA and in learning more about it**. The majority (84.4%) consider it useful to apply methodologies such as LCA. In terms of interest in learning more about LCA, 56.3% said they were interested and 34.4% very interested (see Figure 7).

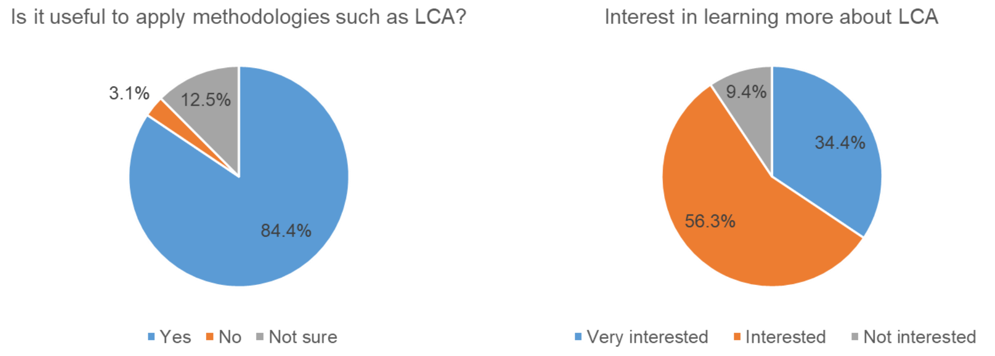


Figure 7. Survey results. From left to right, perception of usefulness of LCA methodology and interest in learning more about it.

- A higher percentage of respondents (96.9%) think that more **efforts should be made to assess and communicate the environmental impacts** of a product, service or activity. In addition, among the participants, 90.6% considered that environmental aspects should be valued in addition to economic ones.
- In total, 81.3% of the respondents **would sometimes choose the most sustainable version** of a product, service or activity even if it involves a higher financial investment, while 15.6% would always choose it.
- The vast majority of participants were environmentally aware, reporting that they would choose the most sustainable option even if this might mean a greater financial investment. However, most of the people,78.1%, considered it to be an added value, whereas a small percentage, 3.1%, did not (see Figure 8).

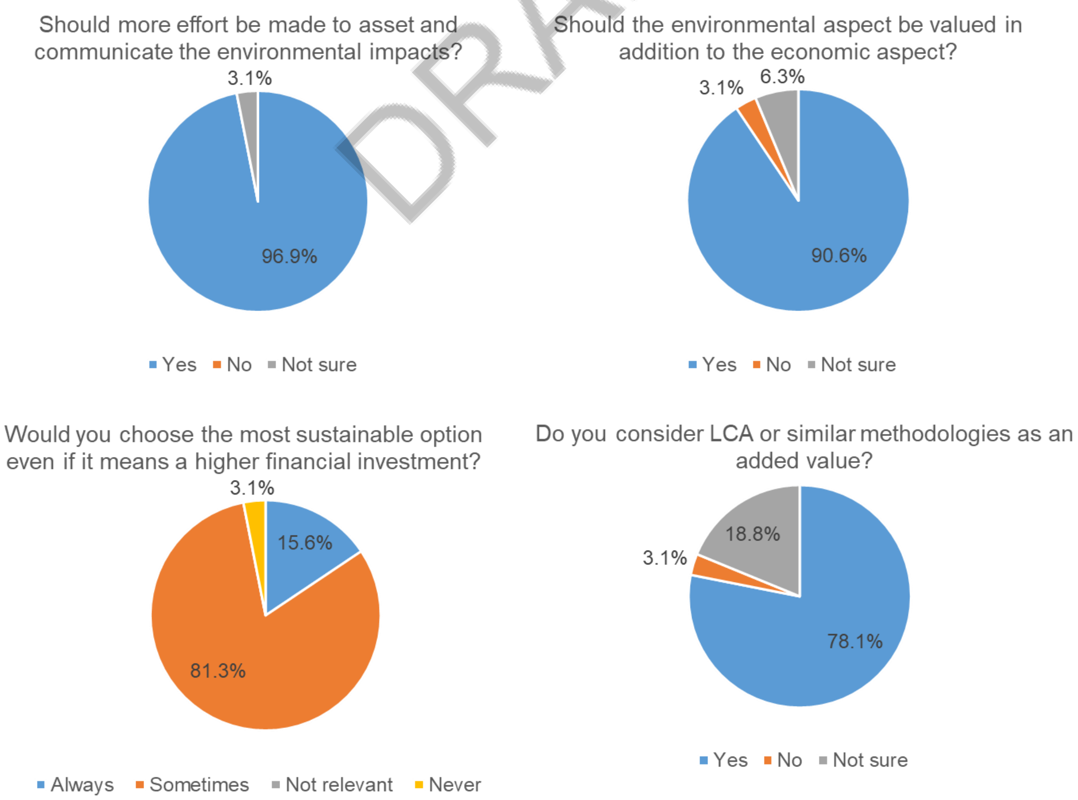


Figure 8. Survey results. From left to right and top to bottom, indicating if more effort should be made to communicate and analyse environmental impacts, if the environmental impact

aspect should be valued in addition to the economic aspect in the decision making, if a sustainable product is chosen even if it is more expensive, and if they consider LCA to have added value.

The most important conclusions that can be drawn from the survey results are:

- Low level of knowledge of LCA;
- LCA is not always taken into consideration in the work and decision-making process;
- LCA results are difficult to understand;
- The information can be too technical;
- There is an interest in learning more about;
- Applying methodologies such as LCA is considered useful.

After evaluating the results of both actions conducted, it was considered necessary to **develop a strategy to support stakeholders to integrate LCA into their internal work processes and decision-making**, **increasing LCA understanding and environmental awareness**. The strategy will address the following levels:

- **LCA integration in the work process:** analysis of different ways to integrate LCA results in the design process in an interactive way to support decision-making. Different solutions were studied, from static to dynamic solutions, including the option of linking LCA with BIM (building information modelling).
- **Understanding LCA results through visual representation**: to make the understanding of LCA results accessible by proposing an easy and visual way to present them, such as with a label.
- **Basic LCA knowledge through training**: provide guidance on how LCA results should be interpreted, explaining what each value means and how the label should be read.
- **Sustainable solutions/strategies to achieve PED – support decision-making**: development of a comparative list of strategies that could be implemented in the transformation of urban areas to create PEDs, indicating possible solutions for each strategy and comparing their respective environmental impacts.

3.5.2 Data workflow approach: integration of BIM in LCA

Integration of LCA in the work process: data representation systems

Systems with different LCA information were analysed to integrate LCA into work processes. The factors considered were whether they are digital or how the information is visualised.

Three options were considered:

- **PDF:** this is the least innovative option, but perhaps the most accessible for everyone. All the necessary information is available in a document that can be accessed by interested parties but cannot be modified or personalised. It has no added value.
- **Excel:** a more interesting option as it can be automated to provide tailored results. However, it could lack visual appeal and requires prior knowledge. It also takes time and resources to automate it. It has no added value.
- **BIM (building information modelling):** by means of a 3D viewer showing the LCA information obtained in BIM, simply by clicking on the desired element. It is the most innovative system and particularly interesting as it permits customisation of the results and provides a visually appealing and easily interpretable format for all types of audiences. No specific software installation is necessary as the viewer can be

accessed online. However, this option demands more resources and time as it requires a specific team for its development. In addition, it may present a challenge for individuals who are not acquainted with these technologies, particularly among the elderly population. It has innovation potential that should be further studied.

A summary comparison of the three solutions can be found in Table 10 below.

Table 10. Summary comparison between the systems considered.

	Innovative	Customisable	Automated	Prior knowledge needed	Visually appealing
PDF	No	No	No	No	No
Excel	No	Yes	Yes	Yes	No
BIM	Yes	Yes	Yes	Yes	Yes

Among these three options, BIM stands out as the most interesting one to be explored as it adds a higher degree of innovation, allows for the automation of environmental data results, and offers more options to customise how the results are displayed. In addition, it gives the option of sharing the work done among different stakeholders without the need to duplicate work (one shared environment). It is therefore worth exploring the linkage between BIM and LCA.

Integration of BIM in LCA for the design and analysis of PEDs

BIM is a process that involves creating and managing digital representations of the physical and functional characteristics of places. BIM is a 3D modelling technology that allows architects, engineers, and construction professionals to design and collaborate on building projects digitally before any construction work takes place.

Overall, BIM offers numerous advantages that improve efficiency, collaboration, sustainability, and cost-effectiveness in the construction industry.

- **Improved collaboration:** BIM facilitates collaboration among architects, engineers, contractors and other stakeholders by providing a centralised platform for sharing and accessing project information. This leads to better communication, coordination, and decision-making throughout the project lifecycle;
- **Enhanced display:** BIM allows stakeholders to visualise the entire building project in a virtual environment before construction begins. This allows for a better understanding of design intent, the early detection of potential issues, and improved stakeholder engagement;
- **Increased efficiency:** BIM streamlines the design and construction process by enabling the automated generation of drawings, schedules, and quantities. This reduces human errors, speeds up workflows, and ultimately leads to faster project delivery;
- **Cost savings:** by identifying errors and conflicts early in the design phase, BIM helps minimise costly rework during construction. Additionally, accurate quantity take-offs and better resource planning contribute to cost savings throughout the project lifecycle;
- **Sustainability:** BIM can support sustainable design and construction practices by analysing energy performance, material usage, and environmental impact. This allows

stakeholders to make informed decisions that reduce the environmental footprint of buildings;

- **Asset management:** BIM models can be used beyond construction for the management and maintenance of facilities. By incorporating information about building components, systems, and equipment, BIM allows for better asset management throughout the lifecycle of the building;
- **Regulatory compliance:** BIM facilitates compliance with building codes, regulations and standards by ensuring that designs are accurately documented and easily accessible for review by regulatory authorities;
- **Risk mitigation:** BIM helps identify and mitigate risks associated with the design, construction and operation of buildings. By simulating different scenarios and analysing potential impacts, stakeholders can make informed decisions to minimise project risks.

Linking BIM with LCA can be particularly interesting for several reasons:

- **Comprehensive sustainability analysis**: BIM provides detailed information about building materials, components and systems, while LCA evaluates the environmental impacts associated with the entire lifecycle of a building, from raw material extraction to disposal. By integrating BIM with LCA, stakeholders can conduct a comprehensive sustainability analysis, considering environmental factors at every stage of the building's lifecycle;
- **Early design stage optimisation**: BIM allows for the exploration of various design alternatives and material choices during the early stages of a project. By incorporating LCA into the design process, stakeholders can assess the environmental impacts of different design options and make informed decisions to optimise the building's sustainability performance from the outset;
- **Quantitative environmental assessment**: LCA provides quantitative data on the environmental impacts of building materials, energy consumption, and waste generation. By linking BIM with LCA software tools, stakeholders can generate accurate and reliable assessments of a building's environmental footprint, helping to identify areas for improvement and prioritising sustainable design strategies;
- **Regulatory compliance and certification**: many building codes and green building certification programs require the assessment of environmental impacts using LCA methodologies. By integrating BIM with LCA, stakeholders can streamline the process of obtaining regulatory approvals and certifications by automatically generating the necessary documentation and reports based on the BIM model data;
- **Whole-building performance evaluation**: BIM captures detailed information about building geometry, energy usage, and operational characteristics, which can be used to simulate and analyse the building's performance over its entire lifecycle. By coupling BIM with LCA, stakeholders can evaluate not only the environmental impacts of individual building components but also the overall sustainability performance of the entire building system;
- **Improved decision-making**: linking BIM with LCA enables stakeholders to make data-driven decisions that balance environmental considerations with other project requirements such as cost, schedule and performance. By quantifying the environmental impacts of design choices, material selections and construction methods, stakeholders can identify opportunities to reduce resource consumption, minimise waste, and enhance the overall sustainability of the building project.

This connection between BIM and LCA offers a holistic approach to sustainable design and construction, empowering stakeholders to optimise environmental performance throughout the entire lifecycle of a building. By leveraging the synergies between these two methodologies, stakeholders can create more sustainable and resilient built environments that meet the needs of today without compromising the ability of future generations to meet their own needs.

Currently, there are different software packages that connect LCA with BIM models and from which the environmental impacts of the materials in the model can be obtained. Those worth mentioning are detailed below in Table 11:

Table 11. List of main commercial software that links LCA and BIM.

Software	All impact indicators	Available in IFC format	LOD required	Data transparency	Based on EPD
Open BIM CYPe [131]	No, just some of them	Yes	Low, it has libraries	None	Yes
One click LCA Revit Plugin [45]	No, just some of them	Yes	Very high	Little	Yes
Cocon [132]	No, just some of them	Yes	Low, it has libraries	Yes	Yes
Tally CAT [133]	No, just some of them	No	Very high	Little	Yes

Several research projects have worked on the link between LCA and BIM in recent years. The following ones can be highlighted (see Table 12):

Table 12. List of main research projects in the field of integration of LCA within BIM.

Links between LCA and BIM	Year	File	Format	Programming innovation required	Indicators considered
XML, Revit and dynamo graphic programme [134]	2022	Native	XML	Yes	Various
Through xml and IFC [135]	2020	IFC	XML	Yes	Various
Through xml and IFC, and developing a Plugin [136]	2020	IFC	XML	Yes, plugin	Various
Revit Plugin+IFC Plugin Cype, Energy, and water cost [131]	2020	IFC	IFC	Yes, plugin	Various
Including data within the Revit models [137]	2019	Native	XML	Basic within Revit	Various

Nevertheless, at present, no software exists that fully links LCA and BIM. The current solutions consist of ‘linking’ the databases of LCA programs with BIM databases. They contain a great deal of information, but as they are databases that are still under development, some information or the quantification of certain indicators is missing, resulting in gaps in the analysis. In addition, operational phases are not generally taken into account.

3.5.3 LCA visual representation - label

The information obtained by an LCA is usually presented in charts. According to EN 15804 [30], EPDs for construction products must display the impacts of different categories in charts and include the different life cycles considered. However, these tables are difficult to understand. They should be accompanied by a description and an explanation so that the most important phases and impacts can be identified, and conclusions reached.

After analysing the results obtained in the survey and evaluating the pros and cons of each representation system presented above, a label was considered the most suitable option. Since one of the primary goals of this work is to achieve better integration of LCA into the workflow and decision-making process in PED design, a label was considered to represent LCA results in a simple and useful way, with information adapted to the knowledge and needs of the different actors involved in the process. This system was also considered simpler and more eye-catching than tables.

The label format has several favourable features:

- Synthesis and display of information in a way that is visually appealing and easy to understand;
- A familiar format. For example, energy efficiency certificates of household appliances at user level or PEF label at expert level;
- Tailored to the needs of each stakeholder (experts and non-experts);
- It can be integrated into any chosen representation system (pdf, Excel or BIM).

The existence of proposals for environmental labelling that can be used for LCA was analysed. The European Union is currently studying different proposals for product labelling [138–140]. PEF is one of the methods proposed by the European Commission as a common way of measuring environmental performance. It is still under analysis and development and have not yet been implemented in the market. One example is presented in Figure 9.

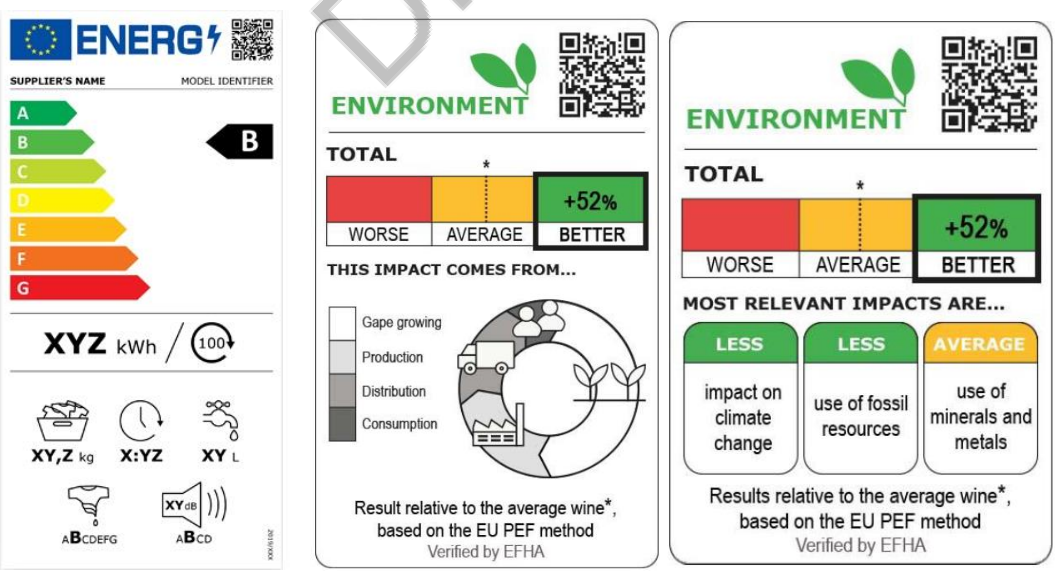


Figure 9. Examples of how environmental impact scoring might appear on products by European Union PEF method and new energy performance label [27, 138, 139].

Analysing the proposal for PEF labels, the following constraints have been observed:

- **Performance classes** (colour and letter scale): although they are very valuable and easy to interpret, these performance classes do not exist yet in the sector of study. It would therefore be necessary to create them specifically for this purpose, defining the possible range of environmental impact for each type of product, element, material, process, building, or district. Calculating them would be too expensive, time-consuming and resource-intensive and would go beyond the scope of this project;
- **Establishing an average:** along the same lines as the previous point, in order to create these performance classes (worse, average, better), it is necessary to establish a reference average. It is also difficult to define the upper and lower limits of the environmental impact. The problem lies in defining the benchmark. A large database is required of environmental impacts of all common products, as is a strong methodology that would allow results to be compared and ranking of impacts according to a traffic light system as proposed in the PEF label.

For this reason, the decision was made to take the PEF label proposal as a starting point and tailor it to make it more adaptable and useful. Examples of other labels, such as the energy performance of buildings and appliances, were taken into account in order to customise the environmental labelling in the most appropriate way for all audiences.

Initial work was carried out to develop the label, proposing the information that it should contain and assessing different display options. A thorough analysis was performed of what information is useful to share to help decision-making in PED design (how it is interpreted and what it is for), how it should be represented (visually or in text), how it is calculated, and at which levels of LCA in PEDs it can be used (material, product, element, digital renovation flow, building, and/or district).

In order to define this label, a number of questions were raised:

1. **What is the purpose of the label?** To assist the different actors involved in the value chain of PED design with decision-making, helping them to include environmental variables, not only economic and technical ones.
   A proper understanding of the life cycle of the different elements allows for a broader perspective when making decisions. For example, knowing the environmental impact of potential retrofitting strategies enables them to be compared with others, detecting which is the most environmentally advantageous taking into account the whole life cycle. A solution with a higher cost or a high initial environmental impact but causing low environmental impact over its lifetime could be more beneficial from a long-term point of view;
2. **Who are the target groups?** The fact that the information is addressed to different stakeholders, each with their own interests, must be taken into account. While it is important to know what level of knowledge and interest in LCA each one has, some preliminary assumptions can be made:
   - Landlords/tenants: their technical knowledge in LCA may be non-existent. The information provided to them should be as simple and easy to understand as possible;
   - Constructors: although they may know more about LCA, they may be more interested in the economic side than environmental aspects. The information provided to them could reflect what benefits they will get from taking LCA into account (e.g. identifying how much energy and resources are actually consumed and which steps are the most expensive);

- Architects/designers: it could be assumed that they are the most knowledgeable in the field and may be most interested in having more detailed information to help them make the most appropriate environmentally-friendly decisions (e.g. choosing the most suitable materials, design from a more sustainable perspective);
- Administrations: in general, they cannot be assumed to have much knowledge on the subject, although they usually have technicians on their staff (they may know that sustainability measures should be applied in the area of urban planning, but not necessarily what LCA entails). Knowing the environmental impact of the different solutions would allow them to better manage resources, provide quality information to citizens, and develop standards considering the environmental perspective. The information that they receive should be detailed but accessible and easy to understand.

The information should be presented to all of them in a simple and accessible way. It must be easy to understand at a glance and not require a great deal of time and effort. Otherwise, they might lose interest. Alongside this, more detailed information should be provided for those who want to learn more about the results of the LCA.

The first conclusions drawn from this initial work are as follows:

- Information should be presented at different levels depending on the target audience, and their level of knowledge or interest.
  - **Level 1.** Simple information that does not require any explanation, very visual and easy to interpret, for interested parties with no knowledge of the subject or for quick reference. This level will be comprised of two faces:
    - FACE A
      1. **Header**: title (environmental footprint) + type (material, element, building, pre-fabrication process, district);
      2. **Description**: name (identification) + DU + RSL + system boundaries;
      3. **Results:** most relevant phases + single score + climate change.
    - FACE B
      1. **Header:** title (environmental footprint) + type (material, element, building, pre-fabrication process, district);
      2. **Description:** name (identification) + DU + RSL;
      3. **Years to return:** environmental footprint investment of the renovation (only when two scenarios are compared);
      4. **Results:** contribution of each impact to the single score;
      5. **Three largest impacts.**
  - **Level 2.** More detailed and technical supplementary information. It will show the full results obtained from the analyses (19 environmental impact indicators, energy consumed, and energy saved). Aimed at users with more LCA expertise, while accessible for review by anyone interested in obtaining all the information relating to the LCA performed.
- The label is intended to be applied to different types of use:
  - **Materials/products/elements;**
  - **Buildings;**
  - **Districts.**
- The most relevant information that should be shared on Level 1 of the label is:

- **Description:** data needed to identify what has been analysed (name, functional unit, reference service life, system boundaries);
- **Most relevant phases**: the percentage each phase contributes to the total;
- **Global Warming Potential:** (GWP) in kg CO_2 eq per DU;
- **EF single score:** in points (Pt) or millipoints (mPt) per DU. Allows all the results to be expressed in a dimensionless unit. Facilitates comparison by summing up all environmental indicators to one value;
- **Contribution of each impact to the single score**: easy visualisation of results;
- **Largest impacts**: highlight the three most important environmental impact indicators. It responds to the need for more effort to communicate environmental impacts as they usually focus on the climate change indicator;
- **Years to return on investment in environmental footprint of the renovation:** only when two scenarios are compared (before and after renovation). Based on mPt. It provides insights into the environmental return on investment. This is calculated by comparing the change in embodied impact with the reduction in operational environmental impacts.

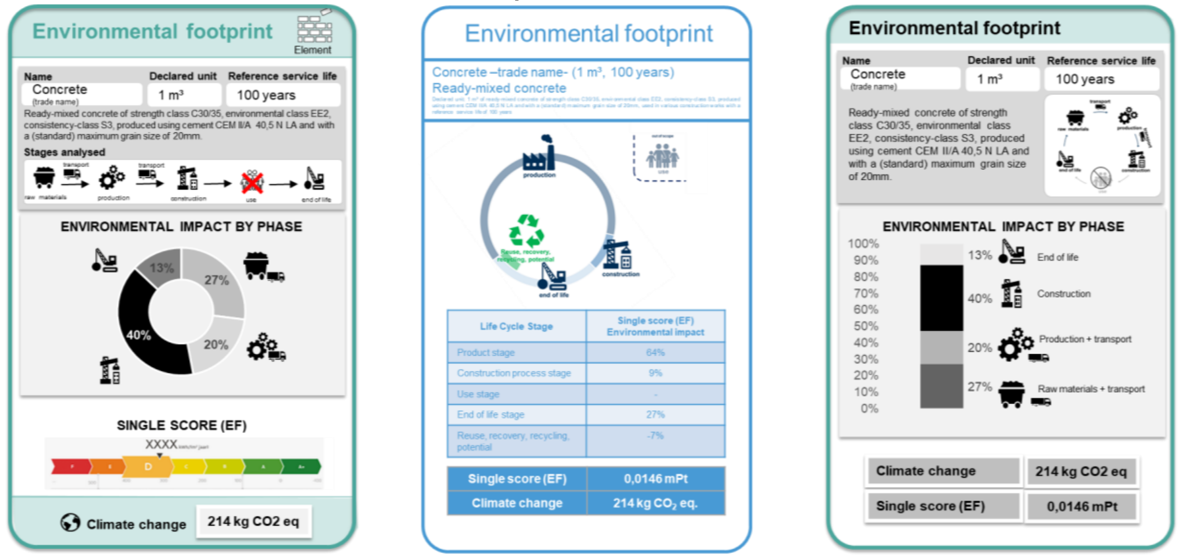
In addition, some information, such as **performance classes**, **reference average and display of the single score on a scale reference**, has been found to be of high interest because of its ease of interpretation. This information will make it possible to rate the impact from low to high. Nevertheless, it is not possible to develop it at this stage, as it involves a lot of work and resources to define a reference average, which is outside the limits and scope of the project. It should be raised at higher levels (e.g. European Commission) and further developed in future projects.

After deciding which information to display, work was done on the visual proposal. Taking into account the objective of synthesising the information and presenting it in a simple and easy-to-understand way, several alternatives were evaluated. In the end, the ones considered to be the best were chosen to be presented and evaluated during a workshop with a representation of the actors involved in PED design.

Several display options were proposed for the two types of labels (see Figure 10 and Figure 11):

1. **Option 1:** basic option, showing the results of a single analysis at any level (material, element, building, etc.);
2. **Option 2:** showing the results of the comparison of two scenarios (before and after renovation). This option only applies to building and district level.

Option 1 FACE A



Option 1 FACE B

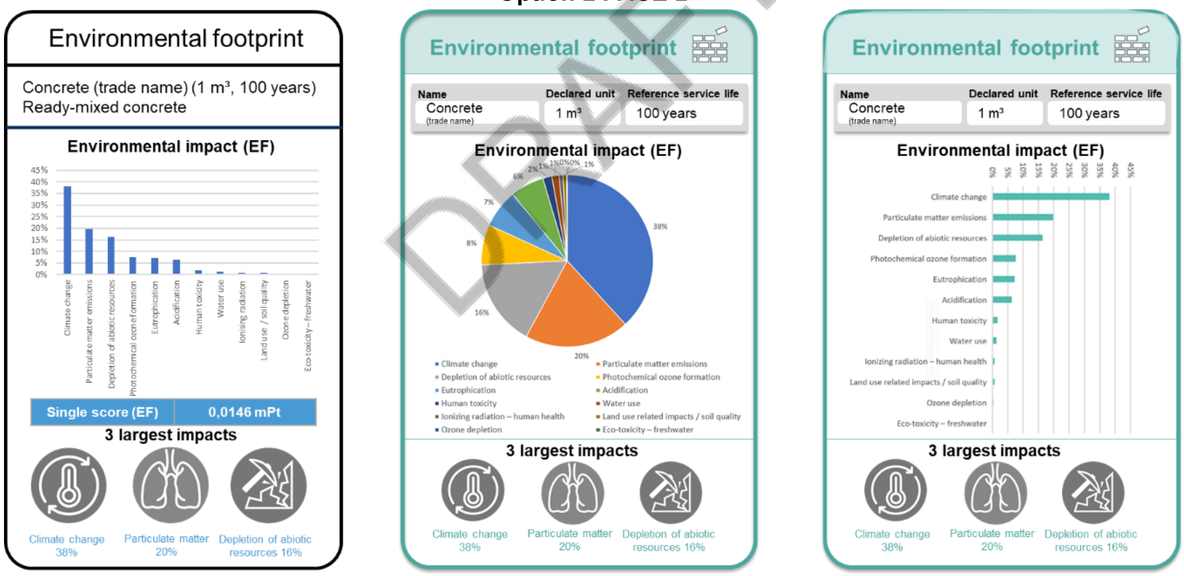
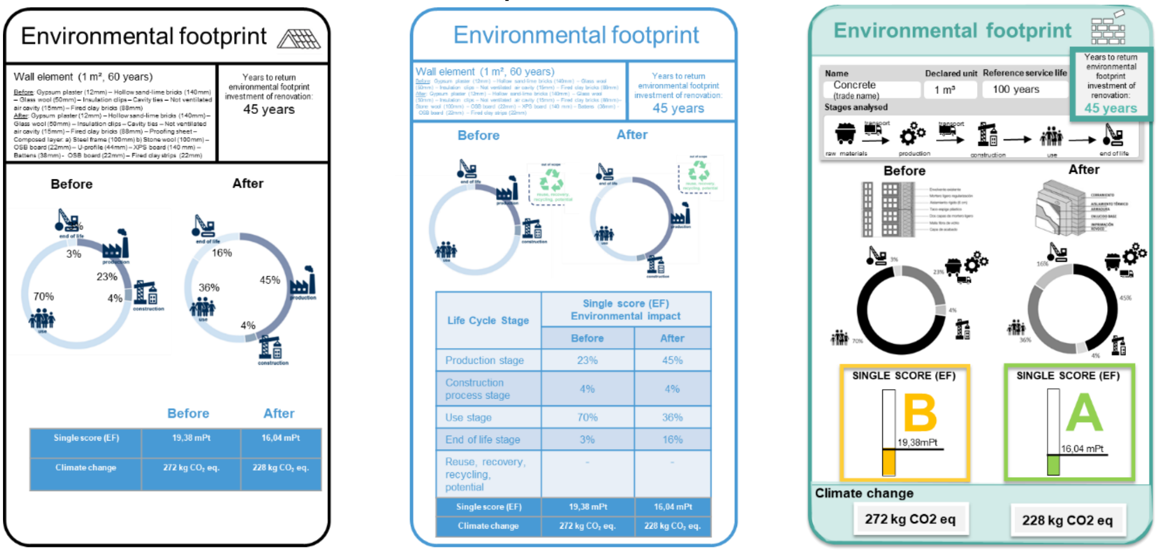


Figure 10. Proposals for label: option 1, face A and B when only one product, element, material, building, or district is studied.

Option 2 FACE A



Option 2 FACE B

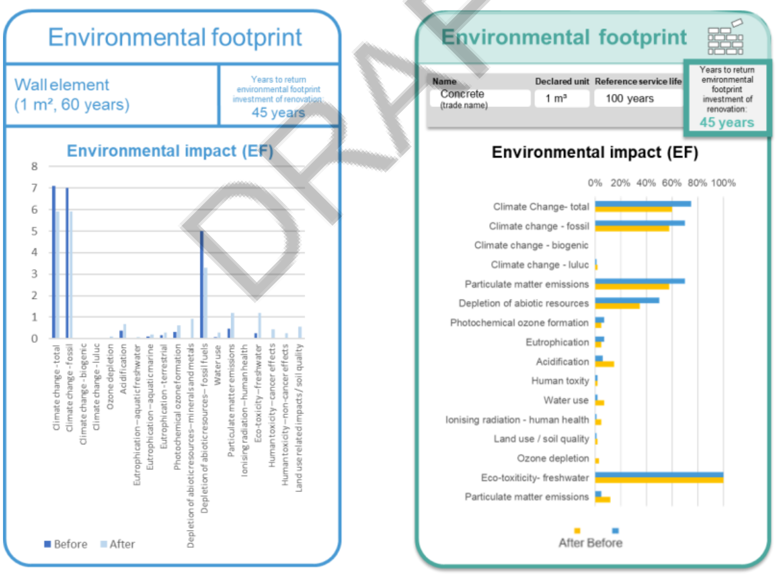


Figure 11. Proposal for label: option 2, face A and B when two scenarios are studied (before and after renovation).

3.5.4 Strategies to be implemented in PED design taking into account environmental impacts

In order to assist with the design of PEDs while taking environmental impacts into account, it is important to know that different solutions could be applied for the same purpose. Each solution will have a different environmental impact that should be considered during the decision-making process in addition to the technical and economic variables.

As an example, first, a list of different strategies was defined that could be implemented in the district to promote the transition towards a PED. This list compares different solutions (with greater or lesser environmental impact) for a similar implemented strategy. This list is not intended to be a database of solutions and strategies with their linked LCA, but a supporting document for stakeholders in the decision-making phase during the design of PEDs. The document aims to help them to understand the level of environmental impact that different solutions or strategies may have in responding to the same issue.

The set of strategies can be broadly divided into three groups:

- **Passive:** design of interior wall cladding to insulate houses, change of windows, refurbishing of façades, etc;
- **Active:** not necessarily renewable, installation of heat recovery systems, heat production by means of gas boilers or cogeneration;
- **Active renewable:** installation of solar panels on roofs, installation of heat pumps, use of biomass boilers, etc.

These, in turn, can be applied at three scales:

- **Individual** (ind.)**:** they serve a single zone within the building (e.g. a single dwelling, business premises, etc)**;**
- **Centralised** (centr.)**:** for the whole building;
- **District:** they affect the district as a whole (e.g. community solar panels).

The selected strategies cover different renovation solutions that could be implemented either at building or district level (see Table 13): building envelope; renewable energy production: heating, ventilation and air-conditioning (HVAC) and domestic hot water (DHW); nature based solutions (NNBS); recovery resources; shading system; batteries; and 5R approach.

Table 13. List of selected strategies.

Renovation solutions	Main strategy	Description	Classification	Scale
Envelope	Window refurbishment	Double glazing aluminium frame with thermal bridge break	Passive	Ind./Centr.
		Double glazing PVC frame 3 chambers		
		Double glazing wood frame		
		Triple glazing aluminium frame with thermal bridge break		
		Triple glazing PVC frame 5 chambers		
		Triple glazing wooden frame		
	Interior wall cladding	Air gap/insulation (cellulose)/ VCL/gypsum plasterboard	Passive	Ind./Centr.
		Air gap/insulation (mineral wool)/VCL/gypsum plasterboard		
		Air gap/insulation (PUR)/VCL/gypsum plasterboard		

Renovation solutions	Main strategy	Description	Classification	Scale
		air gap/insulation (VIP panel)/ VCL/gypsum plasterboard		
	Exterior wall cladding (ventilated façade)	Insulation (mineral wool)/air chamber/cladding (structure + concrete bonded polymer particle board)	Passive	Ind./Centr.
		Insulation (cellulose)/air chamber/cladding (structure + concrete bonded polymer particle board)		
		Insulation (PUR)/air layer/cladding (structure + concrete bonded polymer particle board)		
	Roof insulation	Green roof	Passive	Ind./Centr.
		Thatched roof		
		Attic insulation	Passive	Ind/Centr.
	Basement insulation	XPS	Passive	Ind/Centr.
	Ground floor insulation	XPS + EPS	Passive	Ind/Centr.
Renewable energy generation	Photovoltaic panels	Monocrystalline silicon cells	Renewable	District
		Polycrystalline silicon cells		
		Thin-film cells		
	Thermal collectors	Flat plate	Renewable	Centralised
		Evacuated tube		
	Vertical wind turbine	Vertical axis wind generator on roof	Renewable	District
HVAC+DHW	Biomass boiler	Biomass boiler for a single-family house	Renewable	Individual
		Biomass boiler for a building with 1-20 dwellings		Centralised
		Biomass boiler for high-density building (+20 dwellings)		
	Geothermal Heat Pump	Water-to-water	Renewable	Centralised
	Aerothermal Heat Pump	Air – Water	Renewable	Ind./Centr.
HVAC+DHW	Gas boiler	Gas boiler for a single-family house	Active	Individual
		Gas boiler for a building with 1-20 dwellings		Centralised

Renovation solutions	Main strategy	Description	Classification	Scale
		Gas boiler for high-density building (+20 dwellings)		
	Condensing gas boiler	Condensing gas boiler for a single-family house	Active	Individual
		Condensing gas boiler for a building with 1-20 dwellings		Centralised
		Condensing gas boiler for high-density building (+20 dwellings)		
	CHP - cogeneration	Biomass CHP for a single-family house	Active	Individual
		Biomass CHP for 1-20 dwellings		Centralised
		Biomass CHP for high-density building (+20 dwellings)		
		Natural gas CHP for single family house	Active	Individual
		Natural gas CHP for building with 1-20 dwellings		Centralised
		Natural gas CHP for high-density building (+20 dwellings)		
	Ventilation	Mechanical (without heat recovery)	Active	Individual
		Mechanical (without heat recovery)		Centralised
		Mechanical (with heat recovery)		
Resources recovery	Sewage heat exchanger	With or without heat pump	Active	
	Heat recovery solutions	Trombe wall	Passive	Ind./Centr.
		Water cistern		
		Greenhouse balcony		
	Water recovery	Rainwater harvesting (irrigation, swimming pool, domestic water, etc.)	Passive	Centralised
		Water reuse from buildings (for domestic use or irrigation, etc.)		
NBS	Integration of forest mass	Open spaces	Passive	District
	Natural water treatment systems	Phytoremediation	Passive	District
Shading system		Internal/External roller blind	Passive	Ind./Centr.
		Window foil		

Renovation solutions	Main strategy	Description	Classification	Scale
	Shading	Horizontal/Vertical overhand		
		Horizontal/Vertical louvers		
	Maximising/minimising natural solar energy input winter/summer	Control of shading systems taking into account season, time of day, climate, etc. in order to increase or reduce solar energy inputs.	Passive	Ind./Centr.
Batteries	New versus second life lithium batteries for energy storage	Batteries	Active	All
5R approach	Recover	Recovery of roof tiles	Passive	N/A
	Reduce	Architectural design fostering reduction of demolition waste	Passive	N/A
	Reuse	Reuse of demolition materials as aggregates for concrete or land conformation	Passive	N/A
		Reuse of piping	Passive	N/A
		Reuse of windows	Passive	N/A
	Repurpose	Repurpose of technical systems recovered from old building	Active	N/A
	Recycle	Transformation of materials into new products	Active	N/A

As an exercise, the LCA was conducted of some of the strategies in this list, especially those to be implemented in the oPEN Lab project. See Annex 1.

4. oPEN Lab project LCA approach for materials, products and buildings integrated in the respective PEDs

This chapter presents the LCA approach followed by the oPEN Lab project for each of the four stages of the LCA indicated in Chapter 2.1 Goal and scope definition. The oPEN Lab project is a Europe-wide project that aims to convert existing buildings and district facilities into PEDs. In terms of LCA, the project aims to establish a common framework and protocol for the three living labs (LLs), which can be tested for future scalability to other projects and contexts. This project will serve as an example for establishing and adapting standards at district level, specifically for PEDs. An explanation of what is included in the study of each of the Livings Labs at each level (common LCA framework and protocol) is presented below.

4.1 Description of living labs

4.1.1 Living lab of Pamplona

The living lab of Pamplona (Navarre, Spain) is established in the Rochapea district. Rochapea, with a population of 25,000 residents, is located in the north of Pamplona and has a poverty risk rate of 11.3%, making it one of the most vulnerable neighbourhoods of Navarre. The renovation is centred around the IWER complex, a former industrial building of private ownership, and two housing blocks from the San Pedro group owned by Pamplona City Council.

oPEN living lab Pamplona will deeply embed LCA thinking from very early design stages to ensure that embodied energy and emissions targets are met, as well as a reduction in pollutants. Moreover, during renovation, the following on-site actions will be carried out to meet these goals:

- 5R approach (renovation, recover, reduce, reuse, repurpose and recycle), that will reduce the amount of new materials and components used;
- On-site test bed of recovery and reuse of demolition materials to help establish a regulation or framework. Mainly focused on concrete, ceramic bricks, tiles and asphalt products;
- Experiment with the implementation of an optimised digitalised renovation process to reduce time, material waste, and trips during the design, renovation, and monitoring process with integrated LCA.

Key features are:

- Transforming two social housing apartment blocks and 20,000 m^2 of the IWER complex building into energy-positive buildings by means of a collective renovation concept;
- Testing, monitoring, and comparing combinations of renovation measures, energy technologies, and systems (e.g. development of local renewable energy communities (LREC); novel HVAC, BIPV and second life battery systems with reduced carbon and resource footprint; and an optimised building and local energy system through the dynamic balancing of RES, and flexibility aggregation and trading);
- Developing a community-based living lab to support PED establishment.

4.1.2 Living lab of Tartu

The Estonian oPEN living lab is located on the left bank of the Emajõe River in Annelinn, the largest district (by area – 540 ha) of Tartu. The district consists mostly of apartment buildings of five or more stories built after 1970.

The total area of the living lab is 13.29 ha and includes 22 apartment buildings, most of which are nine stories residential buildings. All the buildings were built between 1970 and 1980 using standardised large panels to optimise space and accommodate a large number of residents. These structural solutions, often comprising multiple stories, are a showcase of rational design, efficient floor plans, and uniform façades. Slabs are made from pre-cast concrete elements and the original two-panel windows have a wooden frame. The existing façade is mortar covered with plaster in several colours.

None of the buildings in the living lab area have been deeply renovated. The future renovation will reduce the thermal transmittance of several parts of the buildings such as the external walls, roof, the slab between the first floor and basement, and the windows. All the renovation strategies aim to improve climate control. To achieve a better indoor climate in line with current standards of comfort, the buildings will be installed with modern HVAC systems during the renovation as this is currently lacking. In addition, the building exteriors and the quality of the urban space will be upgraded.

The oPEN living lab Tartu will also deeply embed LCA thinking from very early design stages to ensure reductions in the environmental impact of the renovation process and operational phase of buildings. Moreover, during the renovation, the following on-site actions will be carried out to meet these goals:

- Deep analysis of the most effective strategies to reduce energy consumption and enhance efficiency;
- Analysis of renewable energy generation, particularly from solar panels, and of the forest area required to achieve PED status, considering the role of forests in compensating for emissions and the interconnection between urban planning and natural ecosystems in achieving sustainability goals;
- High prefabrication processes during the renovations to reduce time and material waste;
- Promotion of sustainable means of transport accessible for all.

Key features are:

- To transform 22 apartment buildings into nearly zero energy buildings by means of a collective renovation concept;
- To test, monitor, and compare combinations of renovation measures, energy technologies, and systems (e.g. smart home and smart house solutions, a demand-based ventilation system, prefabricated insulation elements, and combination of flexibility service with PV production and storage);
- To analyse what it means to achieve a zero-emission district, and the need of forests to offset emissions.

4.1.3 Living lab of Genk

The oPEN living lab Genk is in the suburban residential neighbourhood called 'Waterschei'. This neighbourhood consists of two distinct areas: a former miners district constructed in the 1920s and a more recent social housing district called 'Nieuw Texas', built in the 1990s.

Together with the suburban context, a very high level of social housing ownership (85%) in Nieuw Texas and the nearby presence of former mines, represent a unique opportunity for large-scale real-life demonstrations of promising technology, renovation processes, and social innovation toward the creation of a PEN.

The design of the PEN will include a highly energy-efficient building retrofit, combined with optimal control of innovative building services at individual and/or collective levels. These concepts will be brought together in a collective renovation concept, applicable to both rental and owner-occupied dwellings.

As with the other two Living Labs, oPEN living lab Genk will also follow an LCA approach within the full life cycle renovation process, embedding LCA in the renovation and energy production processes to minimise embodied energy, emissions, and pollutants. Moreover, the following on-site actions will be carried out during the renovation work to meet these goals:

- Analysis of how to recycle, reduce, and/or reuse the construction materials (or industrial by-products) and components;
- Evaluation of the environmental impact of possible façade solutions to implement in the renovation process;
- Exploration of the ways to optimise the sustainability of the buildings throughout their full life.

Key features are:

- To transform 33 houses into energy-positive buildings by means of a collective renovation concept, applicable to both rental and private dwellings;
- To test, monitor, and compare combinations of renovation measures, energy technologies, and systems (e.g. integration of BIM models to facilitate rapid prototyping of PEN concepts and technologies such as coupling them to the detailed BIPV simulation modules, integration of all HVAC services into one prefabricated unit, and smart bidirectional control systems);
- To create an 'Open' living lab, test infrastructure for future developments.

4.2 Goal and scope definition within oPEN Lab

4.2.1 Definition of the goal of LCA within oPEN Lab

Several retrofitting, refurbishment or renovation strategies have been proposed to facilitate the transition towards PEDs. However, the correct selection of strategies can be a complex task, and this is where LCA comes in. The life cycle assessment within the oPEN Lab project aims to identify the critical points of the different strategies to be implemented from an environmental point of view. The LCA methodology will be followed to analyse the proposed strategies and their strengths and weaknesses will be identified and compared with other scenarios.

In conclusion, the aim of LCA in the oPEN Lab project is to **incorporate it into the decision-making to reduce the environmental impact of the district and move towards the development of PEDs.**

As stated above, each living lab has a different casuistry, and the level of intervention is different. It can range from rehabilitation to renovation or retrofitting. Therefore, although the definitions of these terms are not the same, as discussed by Shadi et al [141], they will be used interchangeably in this study. Since all three have energy efficiency in their scope, which is the main focus of the targeted actions to be undertaken in the project. Therefore, any type of activity that contributes to improving the energy efficiency of the building and the district can be included, without being limited to these three types of interventions.

4.2.2 Definition of the scope of the LCA in oPEN Lab

The different items defined during the scope definition are detailed below.

Levels of analysis

For each section, a distinction is made between the material/product/element level (including energy technologies and systems) that will play a part in the renovation strategies, the building level, and the district level. Definitions considered in the oPEN Lab project are the ones provided in Chapter 3.2.1 Hierarchical approach. Thus, the three following levels of analysis will be considered:

- **Materials/products/elements;**
- **Buildings;**
- **Districts.**

Scenarios

The oPEN Lab project aims to evaluate the environmental achievement of the PEDs. To this end, different scenarios will be compared and evaluated during the project:

- **Baseline scenario**: considered as the current state of the buildings to be retrofitted in the three living lab case studies: Genk, Tartu, and Pamplona;
- **Business as usual (BAU) scenario**: considered as the scenario of how the building would be renovated following traditional methods (not following the oPEN Lab strategy). In order to carry out this analysis, it is necessary to define:
    - <u>Characterisation of the current built stock situation</u> in the studied area. This may include an analysis at regional or national level for comparative purposes. This analysis will be based on characterisation studies carried out by partners or other recognised organisations;
    - <u>Characterisation of the most common current systems and strategies used for the refurbishment</u> of buildings in compliance with the current regulations. The study is based on local references and the experience of the project partners.
- **Final scenario:** considered as the scenario after the retrofitting process within the oPEN Lab project.

Functional/declared unit

The distinction between functional unit and declared unit is specific to the European construction sector, as they are defined in the CEN standards. The functional unit is used primarily as the reference unit for the product of the LCA study. The term ‘declared unit’ is specific to product LCAs, as defined in EN 15804:2012+A2:2019 [7]. It is used instead of the ‘functional unit’ if the precise function of the product or scenarios at the building level is not stated or is unknown. Furthermore, EN 15804:2012+A2:2019 states that the declared unit shall be used if an LCA study does not cover the entire life cycle (‘cradle to grave’), but only certain modules (e.g. only ‘cradle to gate’). Thus, in this project, the term **‘Declared Unit’ (DU)** is considered to be the most suitable because all the life cycle phases are not always taken into account and scenarios in which some information is unknown must sometimes be considered.

The declared unit will consider the four aspects explained in Chapter 2.1 Goal and scope definition.

- The function(s)/service(s) provided: ‘what?’;
- The extent of the function or service: ‘how much?’;
- The expected level of quality: ‘how well?’;
- The duration/lifetime of the product: ‘how long?’.

The declared unit will depend on the scale at which the LCA is performed. Thus, the DU by scales is shown below.

Material/product/element level

At the material, product, or element level, the declared unit shall be the one that is indicated in any of the references shown in Table 14 (from the best to the worst option):

Table 14. Order of priority for establishing DU at the material/product/element level.

Declared Unit (DU)	
1	EPD of the material/product/element
2	Product-specific PCR or c-PCR
3	PCR for construction products
4	Following the instructions given in chapter 6.3.3 of EN15804+A2

It may be the case that different functional/declared units are found for the same or similar material/product/element. In these cases, a conversion will be applied so that all materials/products/elements are comparable. If product category rules (PCR) exist for the product group under study, these shall be applied. If they do not exist, a functional unit shall be defined that can be implemented easily at the building level and is in accordance with EN 15804:2012+A2:2019.

Building level

According to prEN 15978-1:2021 [8], the functional unit of the building shall take the following characteristics into account:

- Building type (e.g. office, factory);
- Relevant technical and functional requirements (e.g. the regulatory and clients' specific requirements);
- Patterns of use (occupancy);
- Retired service life;
- Other characteristics.

Within oPEN Lab, depending on whether the building is new or refurbished, the declared unit for its assessment is proposed in Table 15.

Table 15. Declared unit at building level for new and refurbished buildings.

Declared Unit (DU) for the new building	
What?	**The new building**
How much?	Climatised/Heated m^2/year
How well?	
How long?	

Declared Unit (DU) for the refurbished building	
What?	**The refurbished building**
How much?	Climatised/Heated m^2/year
How well?	
How long?	

District level

The main objective of the oPEN Lab project is to upgrade the existing building stock of each living lab to develop PEDs. Each of the living labs can be considered as a district to which the life cycle analysis can be applied. As commented, this level of study can be regarded as innovative, as there are currently no concrete standards or guidelines for it.

Defining a declared unit at district level is a difficult task as there are not many references. To help with this, we can refer to the work done in CAVIAR [142], which identified various possible indicators that can serve as a declared unit. A summary of these can be seen in Table 16.

Table 16. Possible solutions for FU or DU at district level.

Functional Unit (FU) or Declared Unit (DU)	
Unit	**Comments**
Total	It shows the total impact of the district, irrespective of the number of inhabitants or lifespan. It provides a general idea of the city; however, it makes comparison difficult, and, in the case of oPEN Lab, it would not allow solutions to be compared.
People	This indicator shows the impact of each person in the district. It allows the social factor to be included in the project. The main drawback is that population density would be a factor that may predominate over other social or economic factors.
People/year	It adds the useful life of the district elements to the functional unit.
Urbanised m²	It shows the impact of the developed m² (road, pavement, green area and building floors). It helps to isolate the land manipulated for renovation but does not include the inhabitants.
Urbanised m² / year	It improves the previous unit by considering the useful life of each element.
Buildable m²	Like the previous cases, it shows the impact of the district's buildable m². It leaves out the 'inhabitant' factor.
Buildable m²/year	It improves the previous unit by considering the useful life of each element.

In addition, regarding available literature, it is observed that multiple articles on the topic discuss the existence of a variety of functional units. It highlights the need to adopt a per capita FU (m² of living space/inhabitant) when applying LCA at neighbourhood scale [53]. Several studies have recommended combining different types of functional units (absolute, spatial and per person) [64, 143]. The use of a primary and a secondary functional unit, as well as different sub-units when conducting LCA at neighbourhood scale, has also been raised by other authors [58].

For oPEN Lab, the first option chosen for DU at district level is: **(m² / inhabitants) * year**. This decision is based on the fact that the analysis will cover a whole life cycle after the refurbishment, and both occupation and inhabitants are topics that carry weight in different phases of the life cycle. The surface area would be the most appropriate indicator for the renovation phase, while the number of people who will occupy the district will be key for calculating the impacts in the use phase. That way it is possible to combine both and obtain a comparable indicator between the different demonstrators. As a second option, the **number of district inhabitants * year** is also considered to be a DU**.** This option could be an additional declared unit to the main one established, since it will make it possible to put into perspective the energy consumption linked to the actual inhabitants of the district without relating it to the surface.

For the definition of 'What?', the DU must include the refurbishment activities carried out in buildings and the public areas covered by the district.

Table 17. Declared Unit at district level.

Declared Unit (DU) for District	
What	Refurbished buildings and public areas of the district
How much	Option 1: m^2/inhabitants * year Option 2: number of inhabitants * year
How well	
How long	

Reference study period (RSP) and reference service life (RSL)

The right choice of RSP and RSL is essential, as it will affect the resulting environmental impact. In addition, the reference service life (RSL) should be based on declared functional and technical performance, as well as any maintenance or repair work necessary to maintain the declared performance during the declared RSL.

Material/product/element level

The RSL of a material/product/element may be based on empirical, probabilistic, or statistical methods or data based on scientific research. The RSL is described in EN 15804+A2:2019 [7] as part of the functional unit and considered in the calculation of replacements at both the construction product level and construction works (B4) and refurbishment levels (B5).

When establishing an RSL, different values for the same or similar material/product/element are found. For these cases, the alternatives proposed are those shown in Figure 12. It is worth noting that, when different RSLs are proposed for the same material/product/element, the choice of one or the other will have a direct impact on the substitution and refurbishment stage (number of replacements).

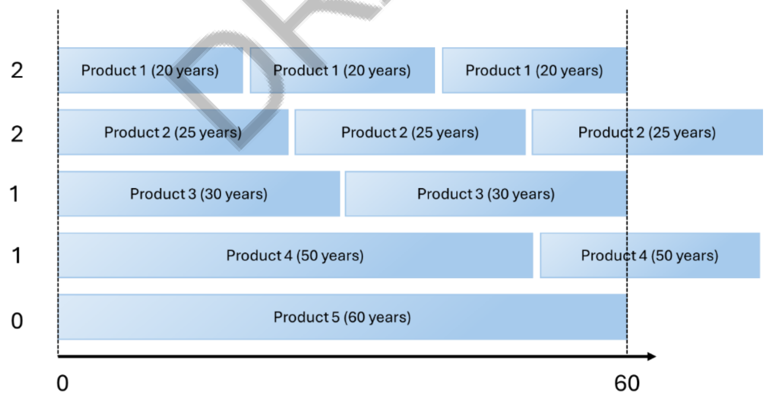


Figure 12. Number of replacements (B4 stage impact) to be made (y axis) in an RSP of 60 years (x axis) for the same product installed in a building with different RSLs.

Furthermore, at material/product/element level, the RSP shall be established following the order of priority shown in Table 18.

Table 18. Reference service life for material, product and element levels.

Reference Service Life	
Material	1) EPD 2) product-specific PCR 3) EN15804+A2
Product	1) EPD 2) product-specific PCR 3) EN15804+A2
Element	1) EPD 2) product-specific PCR 3) EN15804+A2

Building level

For the building level, assessments are based on a chosen RSP. Its default value should be the required service life (ReqSL). If there is no required service life specified, the estimated service life (ESL) of the building based on empirical, probabilistic, or statistical data can be used, although this is not the specific case of oPEN Lab. For the specific case of the buildings to be refurbished in the oPEN Lab project, an RSP of **60 years** is established, as shown in Table 19. However, if national PCRs recommend another RSP, this may be applied. For example, in the case of Tartu in Estonia, an RSP of 50 years will be considered in accordance with national regulations.

Table 19. Reference study period for new and refurbished buildings.

Reference Study Period (RSP)	
Building (new + refurbished) Spain, Belgium	60 years
Building (new + refurbished) Estonia	50 years

District level

It is complicated to establish an RSL at the district level. A district is not only comprised of buildings, whose reference study period can be between 50-100 years, but also urban elements such as streets, roads, green areas, etc. Therefore, the reference study period is higher. Nevertheless, due to the detected variables that can affect LCA explained in Chapter 3.3 Variables with potential to affect LCA for PEDs, it has been considered that the RSP should be no more than the one used at the building and material level. Thus, the oPEN Lab project proposes a reference study period for the district of **60 years or 50 years,** as shown in Table 20.

Table 20. Reference study period at district level.

Reference Study Period (RSP)	
District (Spain, Belgium)	60 years
District (Estonia)	50 years

System boundaries

The system boundaries have been differentiated by scale (product, element, material, and building). The phases included in the LCA for each one are defined by the standards. EN 15804:2012+A2:2019 [7] specifies the system boundaries for the product level (material/product/element). EN 15978:2011 (under revision, to make the alignment with the product level - prEN 15978-1:2021 [8]) specifies the system boundaries for the buildings level. No EN standard is yet available for LCAs at district level. Thus, within this project, a proposal has been made based on the analysis of the state of the art conducted in Chapter 3.2 State of the art LCA approach for PEDs.

Table 21. LCA system boundaries for material/product/element, building, and district level. Green boxes are mandatory stages to be included in the system boundaries and blue boxes are optional but recommended and could be excluded from the LCA assessment.

		Product stage	Construction process		Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	User activities not covered in B1- B7	End-of-life stage	Benefits/loads beyond system boundary
	Standard	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	C1-C4	D
Material	15804:2012+A 2:2019 [7]													
Product														
Element														
Building (new)	prEN 15978-1:2021 [8]													
Building (refurbished)														
District	None													

Material/product/element level

At the material/product/element level (building materials, components and elements used for construction, energy technologies installed in the buildings), the European standard EN 15804:2012+A2:2019 [7] is applied, where the basic product category rules for environmental declarations of construction products are defined.

Building level

At the building and district level, the European standard prEN 15978-1:2021 [8] will be used. This standard describes the methodology for assessing the environmental performance of buildings. At the building level, a distinction will be made between new and refurbished buildings.

It is worth mentioning that in the literature it is possible to find articles where the life cycle assessment of a refurbished building is studied, where the stages to be studied are limited. The omission of these stages is mainly due to the lack of information, the difficulty of predicting scenarios, and to the low impact of some of the stages compared to the total impact of the whole life cycle. For example, Sartori and Hestnes [144] showed that the construction process accounts for less than 1% of the life cycle impact. Other studies [145, 146] show that the end-of-life phase also represents 1% of the total impact. In this study, an attempt will be made to study all of them.

In the case of oPEN Lab LLs buildings, it should be noted that:

- LCA focuses on the renovation process, so the whole renovation will not be included in module B5 as the LCA aims to evaluate the effect of the renovation performed on the building (and not the building itself). This interpretation (the DU will be the renovation of the building, rather than the building) will help in the interpretation phase, modelling a life cycle of a structure similar to the new building;

- The impacts of the production of the pre-existing materials in the building (A1-A3) and the construction of the previous building (A4-A5) stages are outside the system boundaries. Nevertheless, the retrofit and refurbishment materials and works are considered in phase A, and also on the end of life of the demolition waste generated;
- Regarding the use stages (B1-B8), the aspects related to the materials that remain in the building (B1-B5) will not be considered, but the ones related to the new materials will be included for these phases. For instance, if new insulation is included and its service life is inferior to the RSP, the disposal and replacement with new materials will be included in module B. Phases B6, B7 and B8 will be considered in full because they depend on the whole building operation, and not on specific material, products, or elements;
- The end-of-life stage (C1-C4) will cover the demolition of the building.

District level

Since the district is mainly composed of buildings, the main focus of study, it has been decided that the mandatory modules should be the same as for buildings.

Allocation procedures

oPEN Lab has chosen to follow **the attributional approach (cut off approach)**. As in other retrofit projects, throughout the LCA of the retrofit strategies of the project, there will be specific situations where allocation will need to be applied. These could include the following:

- **Allocations at the material/product/element level:** in cases where information for a specific product from a supplier is lacking, allocations could be made on a physical or economic basis. For example, if the specific energy used to make a prefabricated item is not known, an allocation can be made using one of the followings equations:
    - Physical allocation: energy for the product = total energy used in the facility · kg of the product / kg of products produced in the factory;
    - Economic allocation: energy for the product = total energy used in the facility · € of sales of one product / € of sales of all the products produced in the factory.

  These allocations are not desirable and are only to be used if the supplier cannot give specific information for the product;

- **Renewable energy generation in the building**: when energy is generated locally, the benefits obtained should be reflected in the LCA. When heat or electricity is generated on-site, there are two situations:
    - The generated heat or electricity is consumed within the system as a closed loop and therefore no allocation is necessary. If this is the case, this energy generation will be reflected in the LCA by omitting/reducing energy consumption in the B6 use stage;
    - On the other hand, if (part of) the generated heat or electricity is exported, this flow leaves the system boundaries and will enter the system boundaries of another product system. As mentioned above, in these cases, allocation is needed, and this will be reflected in module D. In oPEN Lab LCA calculations, the module D will be calculated according to the description in EN15804:2012+A2:2019 [7]. For this purpose, the formula described below can be used.

$$e_{moduleD} = e_{moduleD1} + e_{moduleD2} + e_{moduleD3} + e_{moduleD4}$$ **Equation 1**

$$\boldsymbol{e_{moduleD1} = beingtheloads \wedge benefitsrelatedtheexportofsecondarymaterials}:$$

$$\boldsymbol{e_{moduleD1}} = \sum_{i}$$ **Equation 2**

$$e_{moduleD2} = beingtheloads \wedge benefitsrelatedtheexportofsecondarymaterials:$$

$$e_{moduleD2} = \sum_{i}$$ **Equation 3**

$$e_{moduleD3} = beingtheloads \wedge benefitsrelatedtheexportofenergyasaresultofwasteincineration(forR_1 < 60\% \wedge R_1 > 60\%)$$

$$e_{moduleD3} = -M_{INCout} \cdot (LHV \cdot X_{INCheat} \cdot E_{SEheat} + LHV \cdot X_{INCelec} \cdot E_{SEelec})$$ **Equation 4**

$$e_{moduleD4} beingtheloads \wedge benefitsrelatedtheexportofenergyasaresultoflandfilling:$$

$$e_{moduleD4} = -M_{LF} \cdot (LHV \cdot X_{LFheat} \cdot E_{SEheat} + LHV \cdot X_{LFelec} \cdot E_{SEelec})$$ **Equation 5**

Where:

$M_{MRout/in}$: amount of scrap content exiting/entering the system.

$M_{MRafter\ EoW\ out}$: the amount of emissions, resources, and waste from material made from recycled scrap material.

$E_{VMSub\ out}$: the amount of emissions, resources and waste from material made from primary materials.

$Q_{R\ out}/Q_{R\ sub}$: coefficient of quality difference, where $Q_{R\ out}$ corresponds to material made of recycled material and Q_{Sub} to material made of primary material.

$M_{ER\ in}$: amount of material entering the product system that has reached the end-of-waste state before incineration in a previous system and enters the product system as secondary fuel. This amount equals the output flow of “materials for energy recovery [kg]” of a previous system.

$M_{ER\ out}$: amount of material leaving the product system where it has reached the end-of-waste state before incineration and leaves the product system as secondary fuel. This amount equals to the value reported for the indicator output flow of “materials for energy recovery [kg].

$E_{ER\ after\ EoW\ out}$: specific emissions and resources consumed per unit of analysis arising from processing and combustion of secondary fuels in a subsequent system after the end-of-waste state (where waste is no longer considered as waste but as secondary fuel).

$E_{ER\ average}$: specific emissions and resources per unit of analysis that would have arisen from specific current average substituted energy source: heat and electricity.

$M_{INC\ out}$: amount of waste that will be incinerated with efficiency of energy recovery lower than 60 % or that is used for energy recovery with energy efficiency greater than 60 % but which has not reached the end-of-waste state.

LHV: lower heating value of the waste.

$X_{INC\ heat/elec}$: efficiency for the energy recovery process for heat/electricity.

M_{LF}: amount of material in the product that will be landfilled.

$E_{SE\ heat/elec}$: specific emissions and resources per MJ substituted current average heat/electricity production.

$X_{LF\ heat/elec}$: efficiency of the landfilling process for heat/electricity.

No system expansion will be allowed. Consequential LCAs are not to be made.

- **Retrofit strategies will be implemented in existing buildings**, so one of the points to be discussed in this respect will be the allocation of impacts from the 'old' building to the renovated one. Following the guidelines of prEN15978-1:2021 [8], module D states the potential loads and benefits of secondary material, secondary fuels or recovered material leaving the system;
- Another case is the allocation of the impacts and benefits of **waste incineration and secondary fuels**. The allocation of these loads depends on the waste end point. The specifications given in EN15804+A2:2019 [7] should be followed to decide whether the flow is to be included in module C or in module D.

Data requirements and data quality requirements

Data needed to meet the goal and the scope of the LCAs, and the required level of detail for different data categories are identified.

LCA data requirements

For all life cycle stages an input-output balance is made:

- **Input data** concerning the consumption of energy, water and raw materials;
- **Output data** are emissions (to air, water, soil, other), waste and useful (by) products.

For the correct analysis of the impacts of the target retrofitted building, it will be necessary to calculate the impacts of each of the materials/products/elements included in the retrofitting strategies. Therefore, using reliable data is the basis for ensuring the quality of the LCA results. The main objective of the project is to reduce the impact of buildings through retrofitting measures and, to this end, it will be necessary to select the most interesting materials. To identify the best alternatives, it will be important to have access to comprehensive and robust databases. In LCA studies, different levels of data requirements and data collection exist. A distinction is made between the following data sources:

1) **Primary data** (EPD, sector EPD or primary data from consortium members or other relevant stakeholders): when an EPD or a sector EPD is used, to be considered as primary data, the material/element/product should be included in the products covered by the EPD. An EPD from a product not being used (from other company, for instance) will be considered generic data. Primary data represents the highest possible quality and uses information pertaining to the product to be used itself;
2) **Adjusted generic data** (e.g. Ecoinvent datasets, adjusted using primary data from consortium members or other relevant stakeholders) with information from generic databases (e.g. Ecoinvent data): when no specific data can be found for the materials/products/elements under study, Ecoinvent datasets, adjusted using primary data from consortium members or other relevant stakeholders, can be used providing

they meet the minimum quality requirements and do not compromise the reliability of the results. Within this context, it is also possible to obtain data from the literature if its quality is not compromised;

3) **Generic data**: a generic database is an LCA database, examples of which are Ecoinvent or GaBi. These databases provide the environmental impacts related to a material, product, flow, etc. when specific information about the object under study is not available. This information can be based on that from another manufacturer in that sector. At this level, it is also possible to turn to the literature for data on the material/product/elements under study. Databases can be multi-sectoral as well as sector specific. In the case of oPEN Lab, both sources can be used. In European research projects, the use of European databases such as Ecoinvent, GaBi, ELCD or ESUCO may be appropriate.

Therefore, to complete the life cycle inventory, one of these sources will be used. The order of priority is always: **1. Primary data, 2. Adjusted generic data, and 3. Generic databases.**

The data quality requirements described in the EN 15804 [7] and EN 15978-1 [8] standards will be considered. In this project, primary data will be used for modules A4 and A5. In the remaining modules, the data used should be of the highest available quality.

In general, **consistent data from a single source** should be used during the LCA study. Mixing background data from different databases for comparative statements should be avoided. This is especially true if data from different databases are not used in a similar way in the compared models, or if methodological standards and quality guidelines do not match between the blended data. However, in practice, background data can be mixed, for example if a background dataset (e.g. commodity production or energy supply) is more representative for the context of the study than that of the main database being used. In this case, the reference data provider must ensure that the use of its data does not lead to a bias in the comparative claims. The adaptation of data in terms of methodology and cut-off rules can be a problem for the LCA study. Some databases that provide unit process data can easily be adapted to the objective and scope of the LCA study, and to the other background data that cannot be changed, but some databases cannot be adapted in this way. If the lack of specific datasets in a background database leads practitioners to combine data from different literature sources, they have to decide whether it is more important to use a consistent but roughly estimated dataset (and possibly data that are not relevant to the context of the study), or to use a dataset that may be more representative but is methodologically inconsistent with the alternative data. In this context, one possible solution is to use data quality indicators to assess both the representativeness of the data and the consistency of the methodology. In any case, the database used should be clearly reported for each dataset.

LCA data quality requirements

As stipulated in ISO 14040 and ISO 14044 [5, 6], data quality requirements are mandatory in LCA. For its assessment for the processes studied during the LCA, EN 15804:2012+A2:2019 [7] proposes three parameters: the geographical, technological, and time period of the data. The data quality can be very good, good, average, poor, or very poor. A table that sets out the minimum requirements for each category makes it possible to calculate the level of quality of the data for the study. However, the proposal of standard EN 15804:2012+A2:2019 [7] does not give a quantitative value for this quality of the data. To obtain a numerical data quality value, it is possible to use the approach proposed by PEF [27]. Four quality criteria are considered: technological, geographical, time-related representativeness, and precision.

These criteria shall be subject to a scoring procedure. For this method, the PEF [27] methodology provides the following formula (Equation 6 of the guide):

$$DQR = \frac{TeR + GeR + TiR + P}{4} \qquad (6)$$

Where:

DQR: data quality rating of the LCI data set.
TeR: technological representativeness.
GeR: geographical representativeness.
TiR: time-related representativeness.
P: precision uncertainty.

Moreover, the following quantitative value for the quality of the data is given by PEF [147], which can be linked to the EN 15804 [7] quality levels:

Table 22. Quantification of the quality level.

EN 15804 quality levels	Overall data quality level, specified by PEF
Very good	1
Good	2
Fair	3
Poor	4
Very poor	5

Furthermore, five quality levels (from excellent to poor) can be achieved according to the data quality rating (DQR). The DQR formula is applicable to:

- Company-specific datasets;
- Secondary datasets;
- PEF study (in this case the oPEN Lab life cycle assessment study).

To score the quality indicators proposed by the PEF methodology [147], the guide provides a set of scales. These are set out in two tables (reference within the guide: Table 22 and 23) as well as the guidance for the calculation. Table 22 will be the corresponding table for assessing company-specific datasets, while Table 23 will be for secondary datasets. Finally, to calculate the DQR of the complete study, calculating the TeR, TiR, GeR and P separately is proposed. They shall be calculated as the weighted average of the DQR scores of all the most relevant processes, based on their relative environmental contribution to the single overall score, using Equation 7 of the guide.The categorisation proposed by the PEF methodology and used in oPEN Lab would be summarised according to the score achieved, shown in **Table 23** below.

Table 23. Overall data quality level.

Overall data quality rating (DQR)	Overall data quality level
DQR ≤ 1.5	Excellent
1.5 < DQR ≤ 2.0	Very good
2.0 <DQR ≤ 3.0	Good
3.0 <DQR ≤ 4.0	Fair
DQR > 4	Poor

Assumptions and limitations

The assumptions and limitations of an LCA should be clearly identified, described and listed to show the transparency of the study. In the oPEN Lab project, different assumptions and limitations can be found and should be recorded:

Material/product/system level.

The limitations and assumptions will be those assumed by the source consulted (1. Primary data, 2 Adjusted generic data, 3. Generic databases).

Building and district level.

Some of the assumptions and limitations have already been established during the generation of the theoretical framework, such as those previously set out in the standards (described below), the system boundaries, the RSL/RSP or the allocation method. Others that may need to be defined include the distances products are transported to the site, the impact of the workers (transport), the percentage of landfill, the performances of the chosen energy systems, etc.

While completing the LCI, it is necessary to describe all limitations and assumptions by providing a list of data gaps, if any, and the way in which these gaps were filled. It is also necessary to provide a list of the proxy datasets used. Finally, limitations and the possible need to take assumptions as the project progresses that will have to be reported.

Exclusion of inputs/outputs

Following the guidelines of EN 15804+A2:2019 [7], the criteria for the exclusion of inputs and outputs (cut-off rules) in the LCA and information modules and any additional information are intended to support an efficient calculation procedure. They shall not be applied to hide data. Any application of the criteria for the exclusion of inputs and outputs shall be documented.

The following procedure shall be followed for the exclusion of inputs and outputs:

- **All inputs and outputs** to a (unit) process for which data are available shall be included in the calculation. Data gaps may be filled by conservative assumptions with average or generic data. Any assumptions for such choices shall be documented;
- **Mass and energy**: in the event of insufficient input data or data gaps for a unit process, the cut-off criteria shall be 1 % of renewable and non-renewable primary energy usage and 1 % of the total mass input of that unit process. The total neglected input flows per stage (product and construction stage, use stage, end-of-life stage, and benefits beyond the product system boundary) shall be a maximum of 5 % of energy use and mass. Conservative assumptions in combination with plausibility considerations and expert judgment should be used to demonstrate compliance with these criteria (if cut-offs are necessary);
- **Environmental relevance**: omissions of any material flows that may have a relevant contribution to the selected impact categories of the system underlying the LCA shall be justified, if applicable, by a sensitivity analysis;
- **Emission to air, water, and soil**: special care should be taken to include material and energy flows known to have the potential to cause significant emissions to air, water, or land, in relation to the environmental indicators of this standard. Conservative assumptions may be used in conjunction with plausibility considerations and expert opinion to demonstrate compliance with the criteria;
- Electricity use from the grid (including renewable energy purchases).

The criteria for modelling the electricity consumed from the grid are taken from the PEF guide [27]. The following lines set out the corresponding criteria as well as the allocation.

Electricity from the grid shall be modelled as precisely as possible giving preference to supplier-specific data. If (part of) the electricity is renewable, it is important that no double counting occurs. Therefore, the supplier shall guarantee that the electricity supplied to the organisation to produce the product is indeed generated using renewable sources and is not available anymore for other consumers.

Two types of electricity mixes are considered:

1. **The consumption grid mix:** the total electricity mix transferred over a defined grid including claimed green or tracked electricity;
2. **The residual grid mix:** a consumption mix (also named residual consumption mix) which characterises the unclaimed, untracked or publicly-shared electricity only.

In PEF studies, the following electricity mix shall be used in hierarchical order:

- Supplier-specific electricity product shall be used if, for a country, there is a 100% tracking system in place, or if:
  - Available;
  - The set of minimum criteria is met to ensure the contractual instruments are reliable.
- The supplier-specific total electricity mix shall be used if:
  - Available;
  - The set of minimum criteria is met to ensure the contractual instruments are reliable.
- The 'country-specific residual grid mix, consumption mix'. Country-specific means the country in which the life cycle stage or activity occurs. This may be an EU or non-EU country. The residual grid mix prevents double counting with the use of supplier-specific electricity mixes in (a) and (b);
- As a last option, the average EU residual grid mix, consumption mix, EU-28 + European free trade association (EFTA), or region representative residual grid mix, consumption mix shall be used.

How to model 'country-specific residual grid mix, consumption mix'

Datasets for residual grid mix, consumption mix, per energy type, per country, and per voltage are made available by data providers. If no suitable dataset is available, the following approach should be used: determine the country consumption mix (e.g. X% of MWh produced with hydro energy, Y% of MWh produced with coal power plant) and combine it with LCI datasets per energy type and country/region (e.g. LCI dataset for the production of 1MWh hydro energy in Switzerland):

- Available LCI datasets per fuel technologies. The LCI datasets available are generally specific to a country or a region in terms of:
  - Fuel supply (share of resources used, by import and/ or domestic supply);
  - Energy carrier properties (e.g. element and energy contents);
  - Technology standards of power plants regarding efficiency, firing technology, flue-gas desulphurisation, NOx removal, and de-dusting.

Electricity use at the use stage.

For the use stage, the last available consumption grid mix of the country or region in which the building is located shall be used. No time-projection scenario is to be used, except for the sensitivity analysis described in Chapter 4.5 Interpretation of LCA results.

How to deal with on-site electricity generation?

If on-site electricity production is equal to the site's own consumption, two situations apply:

- **No contractual instruments have been sold to a third party:** the user of the PEF method shall model its own electricity mix (combined with LCI datasets). For this specific project, if the on-site generation infrastructure has been included in the LCA, only the emissions derived from its operation should be taken into account. In cases where the on-site generation facility generates renewable electricity, it will be possible not to consider any impact (since the losses will be minimum);
- **Contractual instruments have been sold to a third party:** PEF indicates that the user of the PEF method shall use 'country-specific residual grid mix, consumption mix' (combined with LCI datasets).

If more electricity is produced than the amount consumed on-site within the defined system boundary, and is sold to, for example, the electricity grid, this system may be seen as a multifunctional situation. The system will then provide two functions (product + electricity) and the following rules shall be followed:

- If possible, apply subdivision. Subdivision applies both to separate electricity productions or to a common electricity production where it may be allocated based on electricity amounts upstream and direct emissions to the own consumption and to the share the company sells (e.g. if a company has a windmill on its production site and exports 30% of the produced electricity, emissions related to 70% of produced electricity should be accounted for in the PEF study);
- If subdivision is not possible, direct substitution shall be used, using the country-specific residual consumption electricity mix;
- Subdivision is considered not possible when upstream impacts or direct emissions are closely related to the product itself;
- Note that for this specific project, if the on-site generation infrastructure has been included in the LCA, only the emissions derived from its operation should be taken into account. If the on-site generation facility generates renewable electricity, it will be possible not to consider any impact (except from that from the operation) since the losses will be minimal.

Type and format of the report required for the LCA project

After carrying out an LCA of a material/product/element, building, or district, the results and conclusions of the project must be published in a report.

In oPEN Lab, the format to be used will be as stipulated in the standards EN 15804:2012+A2:2019 [7] at material/product/element level, and EN 15978-1:2021 [8] for buildings. For district level, it will be followed the same structure than at building level as there is no specific standard for this level.

Material/product/element level

The EN 15804:2012+A2:2019 [7] standard does provide a script that specifies the points that an LCA report should have at material/product/element level, which would be the following:

- **General aspects**: person responsible for the study (internal or external), date of the report and the statement that the study complies with the requirements of the relevant standards;
- **Purpose of the study:** the reasons for carrying out the project, the application, as well as the intended audience;
- **Scope of the study**: functional/declared unit, the system boundary (mentioning omitted steps, quantification of energy and material inputs and outputs, assumptions on electricity production and other relevant data, and assumptions on system boundaries where relevant, including how net impacts are calculated in module D), and the cut-off criteria (description of the application of the criteria and assumptions as well as a list of excluded processes);
- **Life cycle inventory analysis:** qualitative or quantitative description of the unit process needed to model the life cycle stages of the declared unit, summary of biogenic carbon transfer, emission, and removals between the system, nature, and other product systems in the different modules, the source of generic data or literature used, data validation, allocation principles and procedure;
- **Life cycle impact assessment:** the procedures applied to the assessment, calculations and results; the relationship of the assessment results to the inventory; a reference to all characterisation models, factors and methods used and a statement that the assessment results are relative expressions and do not predict impacts, exceedance of thresholds, safety margins or risks;
- **Interpretation:** the results, assumptions and limitations associated with the interpretation of the results, whether generic data are stated from several sources or for a range of similar products, assessments of the quality of the data, and full transparency on the choice of values, justifications, and expert opinion.

Building and district level

For building and the district level, the guidelines provided in EN 15978-1:2021 [8] are followed. The information for reporting the LCA of a building can be found in the following summary:

- **Purpose and scope** of the project, information regarding the building, target audience, reference unit, assessment method, validity period of the study, date of the study, statement on the verification of the assessment, name and qualification of the verifier if verification is applied, general information on the object of the assessment, statement of limits and scenarios, and source of the data;
- **The information on the object to be studied:** the building type, functionality, use and RSL. The RSP should also be included. Relevant information such as number of occupants, their schedules, the uses of the heating, cooling and DHW systems, lighting, etc. could also be included;
- **Information on LCA and its stages:** the system boundaries and assumptions, a statement on the description of the building model with details of what was included in the building model used for the assessment. It should also enlist details of the data used, source, type, and quality of the data. Finally, in the assessment stage of the life cycle assessment, the indicators used for the assessment should be declared and listed. For each life cycle module, the values of all indicators shall be reported. If any module contains only partial information, this shall be clearly indicated, and the omission of such information shall be justified.

If an indicator is not covered or a module is omitted, it shall be reported as **INA (indicator not assessed) or MNA (module not assessed)** and the reasons for omitting this information shall be given.

Energy use shall be broken down according to the energy vector/s to be reported. The results of impacts and aspects arising from reuse, recycling, and energy recovery and other recovery operations beyond the life cycle of the building (i.e., system boundary) shall be included separately as additional information in module D. The results of impacts and aspects derived from exported utilities (electrical energy, thermal energy, and drinking water) shall be included separately as additional information.

Critical review

As mentioned above, the guidelines for conducting an LCA review are contained in ISO 14040 [5] and 14044 [5]. In the specific case of oPEN Lab and considering the objective of the LCA study, the ISO guidelines should be followed for cases where comparative statements are to be made. This statement is based on the fact that the oPEN Lab project aims to calculate and compare the impacts of different retrofitting strategies to determine which is the most suitable. These results will be communicated to the other partners and the information may be shared with the public in events such as workshops.

For these cases, ISO 14044 states textually: '*to decrease the likelihood of misunderstandings or negative effects on external interested parties, a panel of interested parties shall conduct critical reviews on LCA studies where the results are intended to be used to support a comparative assertion intended to be disclosed to the public'*.

An independent review panel is defined as '*a panel of independent external reviewers with at least two members in addition to the panel chair. Each of them must guarantee an independent review of the study*' [148]. The commissioner has to choose a reviewer who then, selects further members of a panel on their behalf. However, this still allows a third party to choose a reviewer on behalf of the commissioner, thus improving the credibility. The review panel may include people representing interested parties, such as suppliers, employees, competitors, customers, government agencies or non-governmental groups, which is why this type of review has been entitled review by interested parties in the ISO standards.

When comparative statements do not refer to specific commercial products, the critical review can be carried out by an external person who is an expert in LCA at district and building level, but who has not had any contact or any type of relationship with the project.

The critical review process shall ensure that:

- The methods used to carry out the LCA are consistent with this international standard;
- The methods used to carry out the LCA are scientifically and technically valid;
- The data used are appropriate and reasonable in relation to the goal of the study;
- The interpretations reflect the limitations identified and the goal of the study;
- The study report is transparent and consistent.

4.3 LCI: Life Cycle Inventory for oPEN Lab

The inventory phase gathers all the data needed to analyse the environmental impacts associated with the three levels defined in the oPEN Lab Project. In summary, this means that all the input (material, energy, and water) and output flows (emissions, wastes, and useful by-products) are described and quantified. The inventory phase of the overall project is performed according to ISO 14040, ISO 14044, EN 15804:2012+A2:2019 and prEN 15978-1:2021 [5–8].

4.3.1 Data to collect

To be able to collect the accurate data needed for the correct assessment of LCA, both in the factory and on the construction site, it has been considered necessary to define common templates tailored for each type of agent involved in the renovation process. The following templates can be found in Annex 2.

Material/product/element and building level:

- **Manufacturer's LCA data collection template**: to collect information directly from manufacturers (raw materials, transport, and manufacturing). For materials, phases A1-A3;
- **Constructors LCA data collection template**: to collect the data related to the construction phase (A4-A5), such as transport to site, construction and installation consumptions, construction waste, water and energy used, etc.;
- **Inventory of materials**: to record the building materials, elements and products that are reused, recycled, repaired, recovered or discarded during the renovation works (related to phase D);
- **Indicators of prefabricated elements workflow template**: as a complement to data collection during the renovations (constructors LCA data collection template), a specific one has been defined to monitor the workflow of the installation of prefabricated solutions. The aim is to be able to analyse the improvement achieved with integrated construction processes based on the optimisation of the workflow through digitalisation compared with the traditional process. This study is related to environmental and cost impacts.

District level data:

Based on the analysis of the state of the art conducted and presented in Chapter 3.2.3 LCA state of the art for districts, a proposal of the elements to be taken into account in the assessment has been defined. Some are considered mandatory for the three Living Labs, others are recommended because they are considered of interest, but may not always be possible to obtain, while others are optional because they are of less interest but could be useful to make the analysis as complete as possible. All this information is presented in Table 24.

Table 24. District level data to be analysed in LCA in oPEN Lab.

Funtional Unit	m2/inhab*year
	Number of inhabitants*year
Reference Study Period (RSP)	60 years
System Boundaries	A1-A3
	A4-A5
	B1-B5
	B6
	B7
	C1-C4
	D

				MANDATORY	RECOMMENDED	OPTIONAL	OBJECTIVE
GENERAL INFO	Geographical data		Country	x			Geographically locate the district/neighbourhood to be studied.
			Village	x			
			City	x			
	Climate data		Climate zone	x			Know the climatic conditions that can influence key parameters such as: heating/cooling demand, etc. A city located in Northern Europe or Spain, in the Mediterranean or Cantabrian area, etc. is not the same.
			Precipitation (mm/year)			x	For the use of rainwater harvesting in particular
			Radiation (kWh/m2year)		x		Important for photovoltaic energy production and cooling demand.
			Outside air temperature (hourly)			x	Influences the indoor temperature: energy demand (heating/cooling).
	Key data		District area (m2)	x			Calculate results per m2
			Population density	x			To be known in case there is a need to know results per inhabitant.
BUILDING LEVEL	Building	Description	Building ID	x			Used to identify the building under study
	General		Year of construction	x			To be able to know the constructive characteristics of the building in case of not having data.
			Year of renovation	x			
			Geometry of the building (shape and height)	x			If no specific building plans are available, general surface area data can be derived from these data. In case of no energy demand/consumption data, it can be used for simulations.
			Number of floors	x			In case there are no specific building plans, general surface area data can be derived from this data. In case no energy demand/consumption data is available, it can be used for simulations.
			Building use (if more than one, the predominant one per plant)	x			If no data is available, it can be used to simulate energy demand.
			U-value or envelope info	x			Necessary to be able to define the renovation to be carried out in order to reach the technical requirements of the region (CTE in case of Spain). If not known, it will be done with the year of construction.
	Construction		Usable area (m²)	x			To extract quantities of materials in case of not having specific data. Also for simulations for the calculation of energy demand (consumption).
			Construction materials (considered in the renovation)	x			Necessary for LCA calculation Also for simulations for energy demand (consumption) calculation.
		Facades	Wall area, glass area,	x			
			Type of windows	x			
	Occupancy	Occupancy pattern	Building occupancy			x	Determine the energy demand if not known
			Schedule			x	
			Ventilation			x	
			Base temperature			x	
			Internal gains (occupancy, appliances, lighting)			x	
	Consumption	Energy	Control system		x		Calculate energy demand of the building
			Energy performance		x		To know the energy performance of the building (if it is more or less efficient) for LCA calculation.
			Primary energy use (renewable and non-renewable)		x		Know the total renewable and non-renewable energy consumption of the building for LCA calculation.
			Heating (demand or consumption, production system)		x		To know the energy consumption associated with heating for the LCA calculation
			Cooling (demand or consumption, production system)		x		To know the energy consumption associated with cooling for the LCA calculation
			DHW (demand or consumption, production system)		x		To know the energy consumption associated with hot water for the LCA calculation
			Energy systems (boiler, heat pumps...)		x		To know the energy consumption by type of boiler for the LCA calculation
			Energy sources (natural gas, biomass, fossil fuels...)		x		To know the energy consumption and emissions by fuel type for LCA calculation
			Appliances (consumption or demand)		x		To know the energy consumption associated with household appliances
			Lighting (consumption or demand)		x		To know the energy consumption associated with lighting for the LCA calculation
			Heating degree hour			x	Determine energy demand in case it is not known
			Cooling degree hour			x	Determine energy demand in case it is not known

				MANDATORY	RECOMMENDED	OPTIONAL	OBJECTIVE
BUILDING LEVEL	Production	Solar thermal and/or photovoltaic energy production	Area	x			Data to calculate energy production in case the data is not known.
			Orientation (location)	x			
			Inclination		x		
			Collector type		x		
			Gains		x		
			Losses		x		
			Production (Kwh/year)		x		
	Consumption	Water	Water consumption			x	Calculation of water expenditure if known
			Reduction system			x	
			Reuse system			x	
DISTRICT LEVEL- USES	Types of floor		Green or permeable space	x			Calculate how much CO2 they capture in case there is a change of use oculd be interesting to include in the calculations
			Built or impermeable space	x			To know the impact of the district infrastructure . Unless in the project there are changes on these uses that need to be inlcuded in the PEN LCA, these calculations will be only be considered in the sensitivity analysis
			Public car parks	x			
			Private land	x			
			Roads	x			
			Pedestrian walkway	x			
			Pavement	x			
			Reference Service Life of each type	x			To know the impacts and energy consumption related to replacement
			Maintenance of each type	x			To know the impacts and energy consumption related to maintenance
DISTRICT LEVEL – GREEN SPACES	Conditioning component		Deciduous tree			x	Calculate how much CO2 they capture.According to previous studies, this impact is very low, so it can be considered negligible in case of no change of use.
			Evergreen tree			x	
			Grassed areas			x	
DISTRICT LEVEL – INSTALATIONS	Public lighting		Type of bulbs (LED, fluorescent, induction, etc.)		x		To know the energy consumption related to public lighting
			Energy consumption		x		
			System (none, dimmer, renewable power supply, etc.)		x		
			Reference Service Life		x		To know the impacts and energy consumption related to replacement
			Maintenance		x		To know the impacts and energy consumption related to maintenance
	Water		Water consumption of landscaped areas			x	Calculation of water expenditure if known
			Rain water recovery			x	
	District heating		Connected thermal demand	x			To know energy consumption and CO2 emissions related to district heating (if any)
			Total district heating demand	x			
			Reference Service Life	x			To know the impacts and energy consumption related to replacement
			Maintenance	x			To know the impacts and energy consumption related to maintenance
	Thermal solar		Area	x			Calculate hot water production
			Orientation	x			
			Inclination		x		
			Collector type		x		
			Losses		x		
			Production (Kwh/year)		x		
			Reference Service Life	x			To know the impacts and energy consumption related to replacement
			Maintenance	x			To know the impacts and energy consumption related to maintenance
	Photovoltaic solar		Area	x			Data to calculate the energy production in case of not knowing it
			Orientation	x			
			Inclination		x		
			Collector type		x		
			Losses		x		
			Production (Kwh/year)		x		
			Reference Service Life	x			To know the impacts and energy consumption related to replacement
			Maintenance	x			To know the impacts and energy consumption related to maintenance
	Mobility		Type of transport by type of population	x			To know the production produced by the use of the different transports (averages)
			Average distances	x			
			Mobility of non-resident workers	x			
RESULTS OBTAINED							
ENVIRONMENTAL ASSESSMENT			Energy consumption	x			
			Renewable energy production	x			
			19 indicators	x			
			Air quality			x	
			Noise pollution			x	

4.3.2 Data collection sources

Within oPEN Lab framework, when conducting the life cycle inventory, it is necessary to have guidelines that allow the inventory to be completed under minimum requirements. First, the material/product/element used in the retrofitting of the target building must be known. With this first level identified, data on these components will be taken from the available sources for each stage of the life cycle included in the system boundaries according to priority. As mentioned in the section on data requirements, primary data (EPD, sector EPD or primary data from consortium members or other relevant stakeholders) shall be used first. If these data are not available, adjusted generic data (e.g. Ecoinvent datasets, adjusted using primary data from consortium) or a combination of EPD data can be used. Information from the literature can also be utilised. As a last option, data can be obtained from generic databases. Table 23 shows different databases that could be used in the LCI.

Table 25. List of databases that could be used in LCI in oPEN Lab.

Type of data base	Name	Link
Multisectoral generic environmental databases	Global LCA data Access	https://www.globallcadataaccess.org/
	Ecoinvent database	https://ecoinvent.org/
	GaBi database	https://gabi.sphera.com/databases/gabi-databases/
	U.S. Life-Cycle Inventory database	https://www.nrel.gov/lci/
	Input – Output database	https://lca-net.com/services-and-solutions/input-output-databases-life-cycle-assessment/
	GEMIS	https://iinas.org/en/work/gemis/
	CPM LCA Database	http://cpmdatabase.cpm.chalmers.se/
	Environmental Footprint Database	https://eplca.jrc.ec.europa.eu/
Generic database for the construction sector	The Athena institute Database (Canada)	http://www.athenasmi.org/about-asmi/overview/
	DIOGEN (France)	http://www.diogen.fr/
	Ökobau.dat (Germany)	https://www.oekobaudat.de/en.html
	IBO LCA database (Austria)	https://www.baubook.at/?SW=6
	ITec (Spain)	https://metabase.itec.cat/vide/ca/bedec

All data, both primary and generic, must comply with the minimum quality requirements established, and special care must be taken in particular with regard to geographical, temporal, and technological representativeness.

To understand the flows within the analysed system, a tree diagram showing the influence of each component and the recycling loops is key. An example of this can be seen in Figure 13, showing the process tree of a shed.

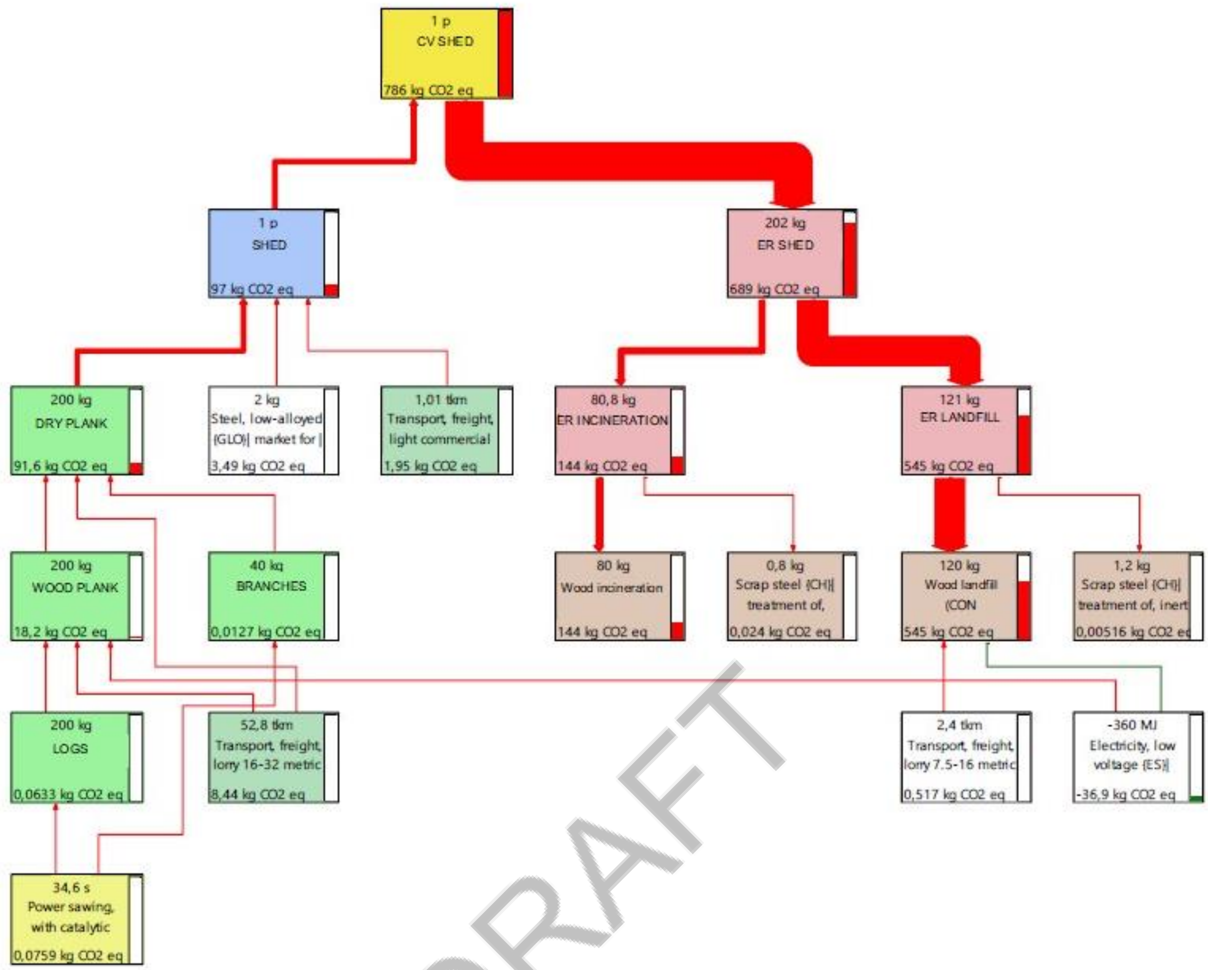


Figure 13. Example of a process tree of a shed [40].

4.4 LCIA: Life Cycle Impact Assessment for oPEN Lab

4.4.1 Environmental Indicators

In the oPEN Lab project, all 19 environmental indicators, explained in Chapter 2.3 Life Cycle Impact Assessment (LCIA) and shown in Table 2 will be included [31].

The standard EN 15804+A2:2019 [7] also requires so-called indicators describing resource use and environmental information based on LCI to be declared. For instance, the number of kilograms of secondary material used, hazardous waste disposed of, materials for energy recovery, and biogenic carbon content. As the project focuses on the environmental impact categories, these additional indicators will be excluded from this oPEN Lab project. Additionally, a single score will be calculated to simplify the interpretation of the results as explained in Chapter 2.3 Life Cycle Impact Assessment (LCIA) and shown in Table 3.

For the interpretation of the results, the project will focus on the **climate change** indicator, and the **single score values**, allowing all the environmental indicators to be taken into account.

4.4.2 Software for LCA

Each partner will use an LCA software package to perform the LCIA and generate the environmental profiles. The latest available version of Ecoinvent will be used in this framework (Ecoinvent 3.9.1 or later).

The software to carry out the LCA will be: openLCA for the LL of Pamplona; Tartu LL will be using One-Click LCA for single buildings. However, as district buildings require more data, Excel and R are used, all based on standard EN 15978 calculations and Estonian carbon footprint methodology. In the case of the LL of Genk, the LCA will be conducted using TOTEM and Simapro.

4.5 Interpretation of LCA results

While all the environmental indicators are reported, the interpretation of the results will focus on the **GWP-total impact and the PEF single score**. As commented, the single score simplifies interpretation of the results and facilitates comparison by summing up all environmental indicators to one value, expressed in points (Pt) or millipoints (mPt) per declared unit. This is done using factors such as normalisation and weighting. The single score takes all environmental indicators into account and is, therefore, very relevant in LCA.

The interpretation of the results comprises the last step of the LCA. It is important to understand that an LCA is not a complete study if it only presents isolated results without an interpretation of the results and a sensitivity analysis or possible improvement scenarios.

For the oPEN Lab project, a **hotspot analysis** is proposed following the identification methodology of the PEF guide [27] and a **sensitivity analysis**.

- **Procedure to identify the most relevant impact categories:** the identification of the most relevant impact categories shall be based on the normalised and weighted results. These impact categories shall cumulatively contribute to at least 80% to the total environmental impact and shall start with the ones with the largest contributions. At least three relevant impact categories shall be identified as the most relevant;
- **Procedure to identify the most relevant life cycle stages**: the most relevant life cycle stages are those that together contribute to at least 80% of any of the most relevant impact categories identified. This shall start from the largest to the smallest contributions;
- **Procedure to identify the most relevant processes:** each of the most relevant impact categories shall be further investigated by identifying the most relevant processes used to model the product in scope. The most relevant processes are those that collectively contribute to at least 80% of any of the most relevant impact categories identified. Identical processes taking place in different life cycle stages (e.g. transportation, electricity use) shall be accounted for separately. Identical processes taking place within the same life cycle stage shall be accounted for together;
- **Procedure to identify the most relevant elementary flows**: the most relevant elementary flows are defined as those contributing cumulatively to at least 80% of the total impact for each most relevant process, starting with those with the largest contribution. This analysis shall be reported separately for each most relevant impact category;
- **Sensitivity analysis**: taking into account the analysis conducted in Chapter 3.3 Variables with potential to affect LCA for PEDs, the following variables will be considered in the oPEN Lab sensitivity analysis:

- Evolutive LCA taking into account changing energy mix over time, new technologies installed to achieve PED (PV, BMS, batteries, etc.), and regulations that will affect replacements in the LCA (e.g. heat pumps will replace the boilers);
- Collective versus individual approach;
- Assessment of the shifts between embedded and operation-related impacts;

The three above-mentioned variables will be analysed by the three living labs. Nevertheless, each living lab may decide to carry out complementary sensitivity analyses.

4.6 Renovation strategies: BAU model versus proposed innovative oPEN Lab solution

It is important to mention that the LCA of the strategies to be studied constitute one more pillar within the oPEN Lab project, which will act in parallel with decision-making processes. This section explains briefly what is involved in the BAU (Business-as-Usual) model versus the proposed innovative oPEN Lab solution at each level. Both situations will be mapped in oPEN Lab by means of the LCA methodology presented in this document. The focus will be on the comparison of the current BAU situation with the new expected oPEN Lab situation integrating several renovation and retrofitting strategies.

Material/product/element level

Knowledge of the materials/products/elements used in the construction sector is crucial for the subsequent comparison and evaluation of the options included in the strategies to be followed. Applying concepts such as the **circular economy**, strongly linked to LCA, gives rise to the design of new materials/products/elements, and strengthens a new current of thought within production systems.

An example can be seen in the Figure 14, in which the BAU scenario for wood in building applications is depicted in blue, while the more innovative and circular approach is depicted in green. In this scenario, the wood is used in multiple cycles, at the end of which it is (down) cycled into new applications.

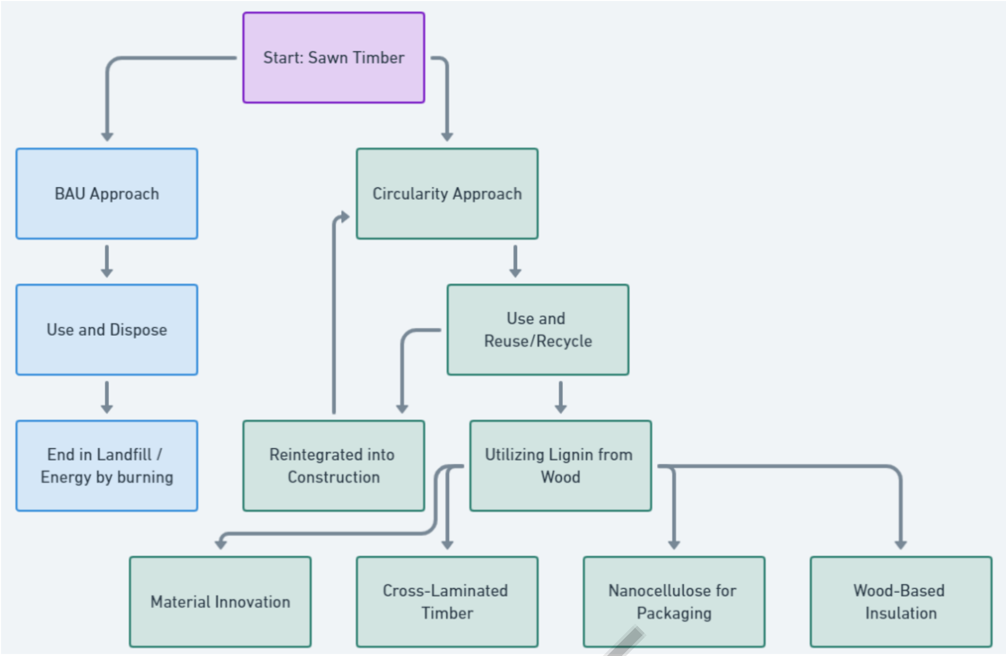


Figure 14. Practical example of the BAU situation of use of sawn timber versus the circularity approach.

Building level

After choosing the materials/products/elements that will comprise the systems to be implemented in the building, the LCA of the building itself will be carried out. Numerous studies report clear examples of the impacts of certain retrofitting strategies in buildings, such as window replacement, renewable energy generation sources, and façade renovations [142, 149, 150]. However, these studies focus only on the performance of the building after the retrofitting, without taking into account the impacts generated by the strategy throughout its life cycle (see Figure 15).

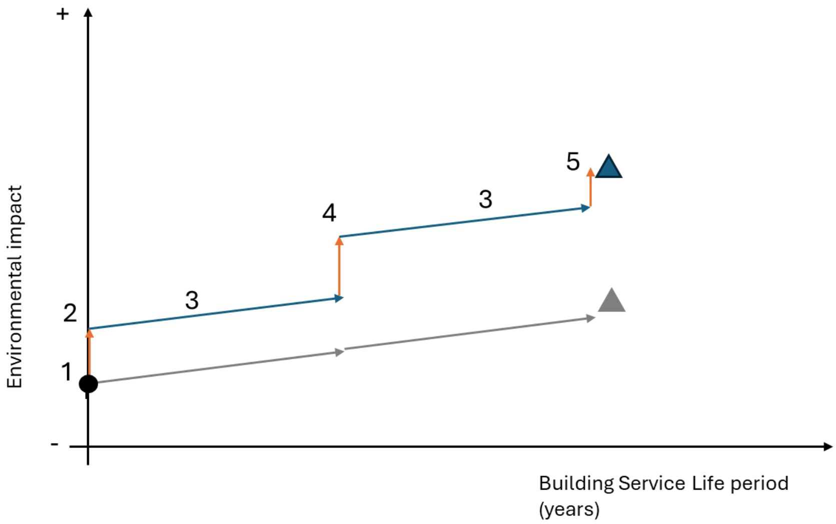


Figure 15. Example of when only the performance of the building is considered after retrofitting (grey) and when the environmental impact of the materials installed is also taken into account (blue + orange) [142].

In Figure 15, **Point 1** represents the building before retrofitting. In this scenario (grey line), only the performance of the building is considered, not the impact of the materials installed. **Points 2, 4, and 5** represent the replacement of materials along the estimated service life of the building. **Point 3** shows the impact of the operational phase.

In oPEN Lab, the assessments will compare the current situation before renovation (baseline), the BAU renovation scenario and the oPEN Lab renovation scenario. All the stages affecting the renovation process will be considered, from the extraction of the raw materials to the end of life, including the possibility of recycling and reuse. Similar to the material/product/element level, the LCA assessment will mainly focus on the differences before and after integration of strategies at building level.

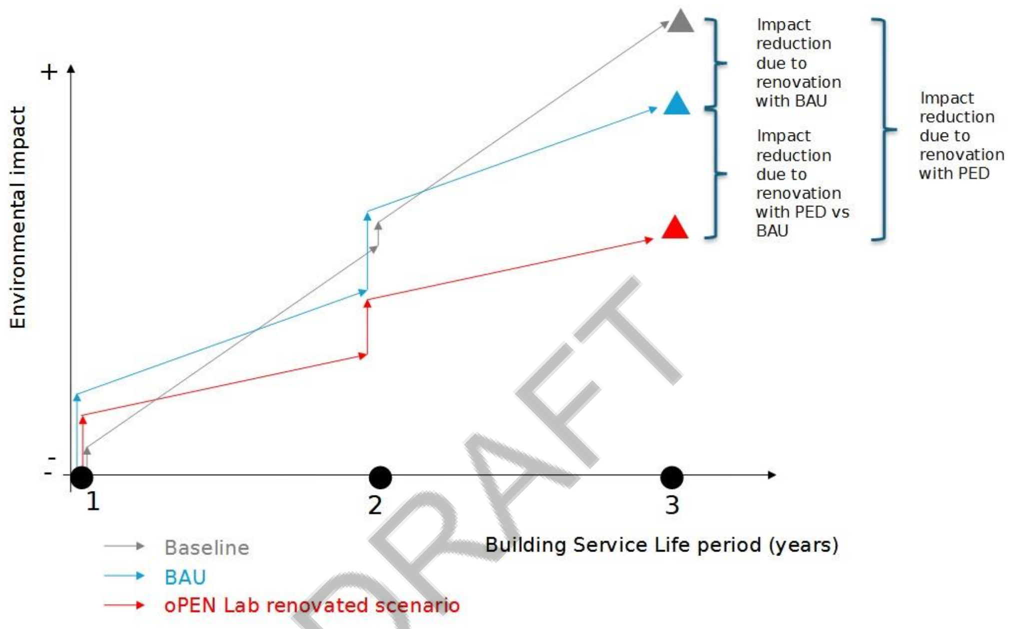


Figure 16. Example of environmental impact expected between baseline, BAU and oPEN Lab renovation scenarios.

Figure 16 shows the differences between the LCA of a building considering the three scenarios proposed in oPEN Lab (baseline, BAU and oPEN Lab final scenarios). The baseline (grey line) represents the scenario in which no renovation has occurred. In the BAU scenario (blue line), a retrofit according to current standards took place, while in the oPEN lab renovation scenario (in red), more sustainable and efficient solutions with better performance are considered. **Point 1** represents the installation of materials. At **Point 2**, a replacement is taken into account. In the baseline scenario, only maintenance is considered, while in the BAU and oPEN Lab renovation scenarios maintenance and replacement are included in the assessment. **Point 3** represents the impact reduction due to the renovation. The increase between points 1 & 2 and 2 & 3 is also lower in the BAU and oPEN lab approaches because of the additional investment in embodied impacts, resulting in lower operational impacts.

District level

Although information on this subject is more scarce in comparison with the material/product/element or building levels, it is assumed that a district can be studied in a similar way to a building (explained in the previous paragraphs). Consequently, the BAU scenario and the oPEN Lab scenario at the district level shall be compared in a similar way to the building level.

4.7 Data workflow approach: integration of BIM in oPEN Lab

As part of the optimised digitalisation workflow in the oPEN Lab project renovation process (from the design to the operational phase), it has been considered of interest to study BIM as an innovative system to be implemented both in the data collection for LCA within the design, renovation, and operation phases and in the visual presentation of the results. Thus, research was performed into the potential and feasibility for developing a BIM workflow to this end and a 3D viewer for gathering necessary LCA data and presenting the outcomes of the LCA. The aim is to have a user-friendly display feature that would allow the user to obtain information about the environmental impacts of the desired element, building, or district by simply selecting it within the 3D model. This tool would help all stakeholders with their decision-making during the design, renovation, and operational phases of the PEDs.

4.7.1 Procedures to calculate LCA through BIM models

After studying the state of the art (see Chapter 3.5.2 Data workflow approach: integration of BIM in LCA), three procedures of how to link BIM and LCA are worth highlighting as having potential within the oPEN Lab project (see Figure 17):

- **Linked with a BIM model only**: LCA requires a recapitulation or inventory of all the types and quantities of materials involved in the buildings or infrastructures evaluated. BIM models contain all the parametric and geometric information of the elements that make up the specific project. In this way, from these BIM models, it is possible to extract the inventory of quantities of materials in such a way that it can later be linked to a database of impacts generated by each material or process and, thus, obtain the total impact generated by the product and building. On the other hand, this type of analysis and data extraction from BIM models implies a very high level of development or detail at the geometric level (greater than a Level of Development (LOD) 300). So that the analysis is representative and includes as many materials and elements as possible. The main difficulty is to represent processes in BIM models in such a way that they can also be evaluated in the analysis;
- **Linked with a BIM model and an economic database:** as an alternative, and a better system for extracting the inventory given its wider coverage, it is possible to extract all the materials and processes involved if the BIM models are combined with price databases. In this case, the database used is obtained by means of the open format BC3, which is widely recognised and there is a multitude of databases from different institutions that reflect the current panorama very well and include any construction technique or material used. In the case of BIM models, we will use the open representation format .IFC, which allows the whole of the inventory to be extracted directly and indirectly by linking both databases;
- **Linked with EPD of similar buildings:** the final calculation alternative implies that a calculation for a building has already been made with some environmental product declarations (EPD) in exactly the same way as in the case study. However, given the particularity and idiosyncrasy of this type of product, it is impossible that there is one that can be used as a substitute, at least in its entirety. This type of calculation will be used more and more as industrialisation is implemented in the architecture,

engineering, construction and operations (AECO) sector resulting in a bigger database of building elements that will facilitate the final calculation.

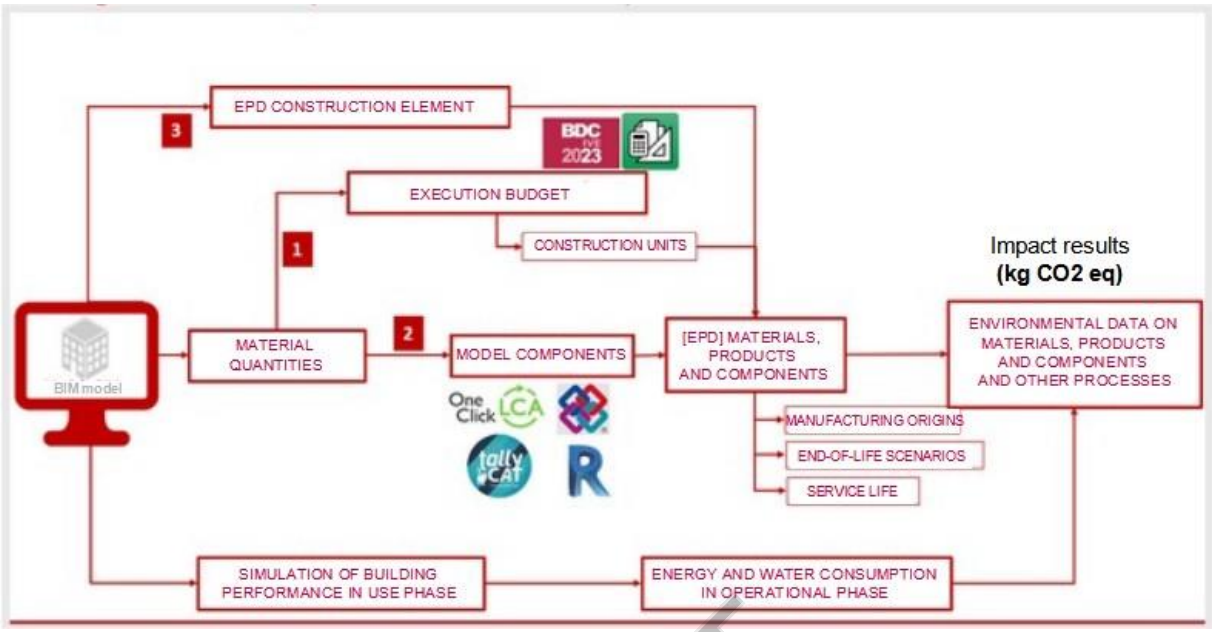


Figure 17. Workflow of the three options to calculate LCA through BIM models.

4.7.2 Theoretical proposal to link LCA and BIM

Based on the above literature, a proposal is made of how LCA could be integrated into BIM models. This integration has considered how to integrate BIM in the data collection flows for conducting the LCA. Thereby, reducing the modelling and measurement calculation workload. In addition, aligned with the oPEN Lab project, this link should be able to support the calculation of the 19 environmental impact indicators that will be analysed in the project, as well as including the operational phase. This proposal helps to automate the data collection for LCA and it can be considered as a first step towards the complete integration of LCA in a common environment such as BIM, for all the actors of the value chain within PED design.

First, the main data workflow with the elements involved in the process has been defined and is shown in Figure 18, and Figure 19.

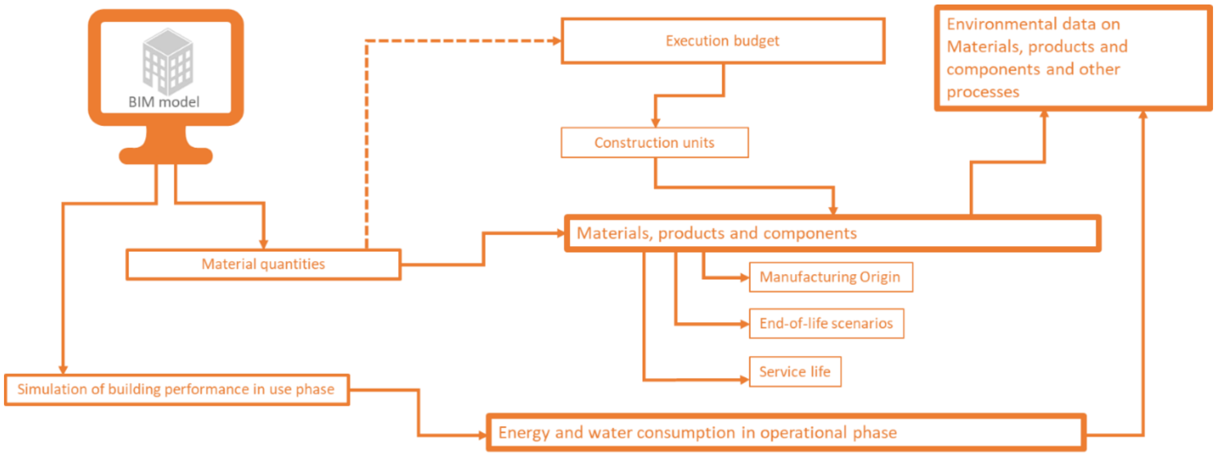


Figure 18. Workflow of the main processes involved in the calculation of LCA through BIM models.

On one side, the BIM 3D model can be exported to software such as:

- **Simulation software** (e.g. DesignBuilder) to calculate the operational phase of the baseline and renovation scenarios at building and district level. If real data is available, energy consumption and renewable energy production will be collected through monitoring systems instead of by simulations. However, if no real data are available, the energy consumed and produced in each scenario and, therefore, the energy saved in the improvement scenario can then be calculated.
- **Measurement software** (e.g. budgeting generator of CYPE or PRESTO) to obtain the quantities of each product, material, or element of the building and district. Their impacts can be obtained by means of environmental impact databases or calculations with LCA programs.

On the other side, **databases of the environmental impact** of materials, products, and elements will be used to conduct the LCA at the different levels. The link between the quantities of material and environmental impacts can be visualised in a user-friendly 3D viewer (see Figure 19).

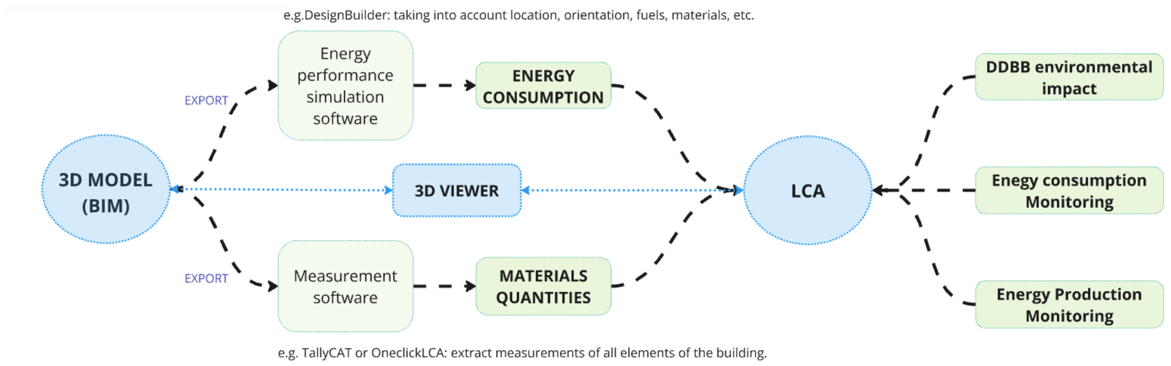


Figure 19. Proposal of data flow linking BIM and LCA.

To validate this proposal, it is necessary to study how the different data obtained can communicate with BIM software (return years, millipoints, etc.) to evaluate the full range of possibilities of linking LCA with BIM. It is also necessary to include intelligence in the BIM software to account for the building energy performance related to factors such as orientation, insulation, shadows, etc.

For this purpose, a case study was conducted, creating a simplified model tailored to the needs of the project and analysing three materials of the building. Although a simplified model was used. The case study is intended to serve as an example of what such integration could offer, the information that can be obtained, and how it would be displayed in a 3D viewer to make it easier to understand.

In this case study, a simple apartment project has been used. In order to obtain as complete an inventory as possible, the data in the file extensions BC3 and IFC have been linked. The first step was the definition of the system boundaries. As it is a simplified practical example, the operational phase was excluded. Then, the complete data flow between BIM and the LCA software was developed, from the extraction of data from the BIM models that comprise the sample building to the final environmental assessment. The full case can be found in Annex 3.

4.7.3 Conclusions regarding the integration of BIM in LCA for oPEN Lab

A series of conclusions can be drawn from the case study regarding its application, usefulness, and feasibility within the oPEN Lab project. These are summarised below.

- It is possible to link OpenBIM format BIM models with economic (BC3) and environmental (EPD) data, resulting in outcomes that can be organised in different ways. Thereby, allowing the end user to make decisions based on them (a concept known as 'data-driven decisions'). The capacity of BIM models to enhance this process in obtaining the necessary inventory for conducting LCA has been demonstrated.
- The main contributions of the study are:
  - A theoretical flowchart of how to integrate BIM with LCA based on the state of the art (shown in Figure 19);
  - Reducing the measurement calculation workload of LCA through the automatic data collection of BIM models.
- Limitations found during the study:
  - The full integration of BIM and LCA would need considerable time and resources that are out of the scope of the current project;
  - Similarly, more programming of specific software would be required to integrate LCA into BIM. The time and resource limitations in the project meant it was impossible to automate some of the software processes that were carried out manually in the case study.

4.8 Display of LCA label in oPEN Lab

After establishing what LCA data should be shared in the framework of oPEN Lab project, it was decided to test the label visualisation proposals, presented in section 3.5.3 LCA visual representation - label, with all the partners involved in the PED design. In order to get their feedback, a workshop was held to analyse the proposed label and its possible variables.

The aim was to review label proposals and co-design a final version with all the project partners. Being part of the process helped them to integrate LCA into their workflow and decision-making process and helped in adapting the LCA visualisation system to their needs. In addition, this workshop aimed to identify the strengths and weaknesses of the label, difficulties that could be encountered when interpreting it, display options that would work best, and possible problems and alternative proposals that could arise.

4.8.1 LCA label workshop

The workshop was divided into two activities. First, the participants worked individually and in the second activity they were in teams. Work was carried out on a Miro board shared by all the participants. The sectors that participated in the workshop were: architecture, legal/politics, monitoring, social innovation, environmental/LCA, business development, HVAC, energy, and housing. In total, eight women and twelve men took part.

- **Activity 1 (voting and comments):** participants were shown the display options proposed for labels 1 and 2. They were asked to indicate which option they liked the most, a little less, and the one they did not like. They could also add any comments they thought appropriate;
- **Activity 2 (design):** the participants were divided into groups. Each group had to create their own label on a blank template. They could choose from several proposed designs for the different parts or propose a new one. They could also add comments, drawings, or images that they thought would work best.

The conclusions drawn from the workshop were:

- The participants were generally in agreement about the options;
- All agreed to include the single score on a colour scale. Although this option is not possible at the moment, as commented in section 3.5.3 LCA visual representation - label, it is worth noting that it is of interest, and efforts should be made in the future to implement it. Some of the comments were:
  '*I like the simple score for climate change, the single score doesn't mean a lot to me in figures, but the colour scale makes sense*'; '*I suggest adapting this option to the single score and climate change as we have both the colour scale and the numeric value*';
- A prior explanation of some parts is needed to make them easier to understand, such as what the single score is or what is compared when there are two scenarios. To this end, a brief explanatory guide to the data represented on the label was developed (see Annex 4);
- A circular phase display system is preferred;
- Options where information is easy to visualise, and elements can be clearly identified (graphs and colours rather than tables with data) are preferred;
- It is better to provide all the necessary information and not to take anything for granted, such as adding text to complement images. Some comments were:
  '*Proposal to add text also near to the sectors'; 'Show % of each bar corresponding to each phase, maybe with colours'; 'Maybe use colours and legend for the system boundaries (blue=included; grey=excluded)'; 'Graphic design option is ok, but adding the numeric values is suggested'.*

4.8.2 Final label proposal

Based on the results obtained in the workshop and the previous work, the final proposal for the label is shown in Figure 20 and Figure 21. As commented, annex 4 includes a guideline explaining how to correctly interpret each section.

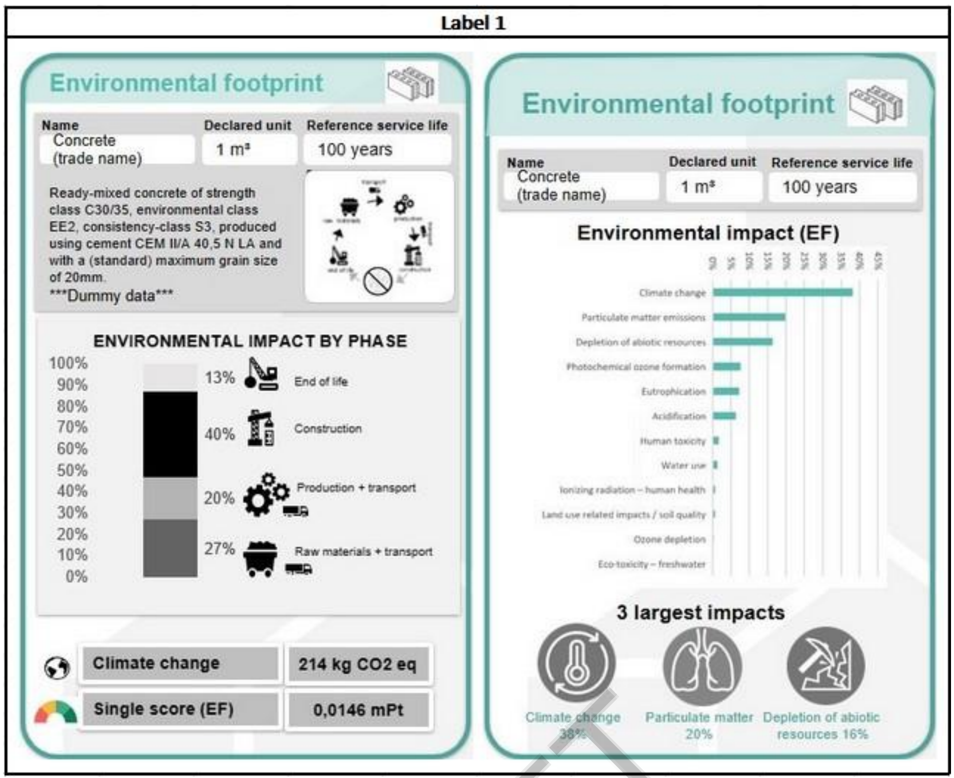


Figure 20. LCA label option 1 proposal for oPEN Lab project.

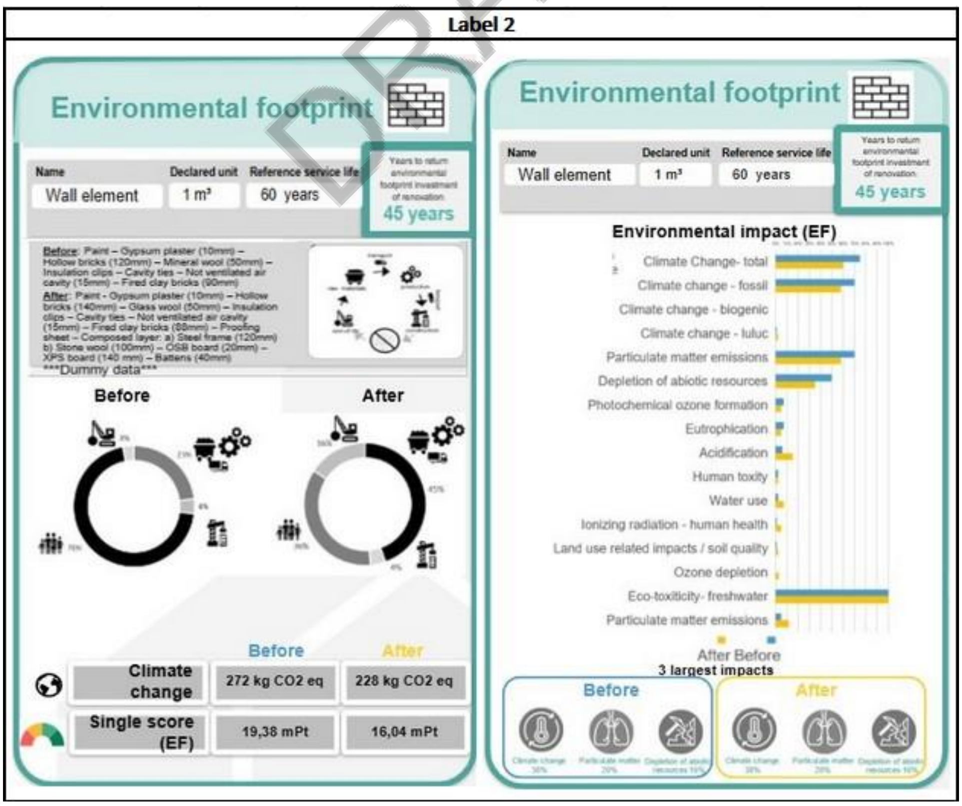


Figure 21. LCA label option 2 proposal for oPEN Lab project.

5. Conclusions & recommendations

The design of a PED comprises several levels of life cycle analysis. First, there are the material, product, element, and building levels, which are well-known and have standards that frame their corresponding LCA. However, at the district level, which can be defined as an entity composed of a set of buildings and urban elements such as mobility, spaces, lighting, operational phase, etc., there are no standards defining how such an analysis should proceed. Therefore, a common protocol and framework to carry out LCA at district level should be defined. In this regard, the oPEN Lab project proposes an LCA protocol and framework adapted to districts, in particular to PEDs, to be tested and validated in the three Living Labs of the project with the aim of being replicated and scaled up to other LCA analysis contexts in districts in the future.

Nevertheless, to achieve PEDs, decisions need to be made during the design phase that not only take into account the performance and economic sides of the strategies and solutions to be implemented, but also their environmental impact. This will contribute positively to achieving a PED in the most efficient way. For this purpose, it is essential that all stakeholders involved in the value chain integrate the environmental factor into their decision-making. Difficulties may arise for several reasons, most notably due to the stakeholders' lack of knowledge and capacity to understand the results of LCA, despite their willingness and interest to take it into account in their decision-making. To remedy this, first, it is necessary to get the different actors to understand the interest in taking environmental impact into account in their decision-making. This could be achieved through awareness-raising and training activities to increase knowledge on the subject, thereby allowing stakeholders to be able to take decisions based on a full understanding of the data obtained from the LCA.

In addition, special emphasis should be placed on the development of a display system that allows the results obtained from the LCA to be displayed in an easy and eye-catching way, adapted to the different needs and levels of knowledge of the actors involved in the design of PEDs. This could be achieved by presenting the results with a two-level environmental label, a simple one appealing to all audiences, and a more complete one in which all the impact indicators are presented for those actors with more knowledge on the subject. In spite of being outside the scope of the project, the interest in carrying out further work on a reference scale that allows the impacts to be classified is highlighted. This scale would facilitate the comparison of solutions or strategies and improve the understanding of their global level of impact. Similarly, it is considered of interest to have access to such data in a simple and automated way that allows different possible scenarios to be visualised quickly and accurately, taking into account both the impact of the materials or strategies to be implemented and the operational phase (normally not calculated). This could be achieved by further work to integrate LCA in the BIM ecosystem, linking model data with the software required to obtain the necessary data to develop LCA and LCI databases.

Finally, it is observed that the current realities of the energy transition that cities are undergoing to move towards PEDs and consequently reach climate neutrality make the current LCA methodology very static and in need of a dynamism that is currently not integrated in the analyses. Sensitivity analysis studies are required to investigate whether these new factors have a significant impact that needs to be taken into account in LCA. If this is the case, systems to introduce these factors will have to be studied and the current LCA methodology will have to be adapted as it could be outdated under the current situation (e.g. length of the study period, energy mix, replacement phase considering a change to more efficient systems, etc.).

During the oPEN Lab project, some of these variables will be studied, but in future research, it is of interest to analyse all the factors detected and discussed in this report that will not be covered by oPEN Lab project.

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Annexes

Annex 1. LCA of selected strategies

1. Introduction

Living Labs play a crucial role as real-life testing grounds for innovative solutions in sustainable urban development. This annex presents a comprehensive overview of the strategies followed and analyses performed to support the decision-making processes from the design to the construction phases of the renovation process in each Living Lab. The goal of each Living Lab is to become a positive energy district (PED) while focusing on aspects such as energy efficiency and carbon footprint reduction.

2. Comparison of environmental impact of different renovation strategies

The LCA obtained for each of the strategies are presented below, comparing similar solutions for the same strategy. The data has been made available to the different Living Labs to support decision-making during the design phase. The strategies analysed and presented below are the envelope (windows, internal wall cladding and external wall), photovoltaic panels (PV) and HVAC+DHW.

The tables are available in editable format at the following link:

https://openlab-project.eu/toolbox/

Table 1. Strategies overview, main characteristics.

Main strategy	Description	Classification	Scale	FU	Lifetime (years)	Thickness (cm)	Power
Interior wall cladding	Air gap (1cm)/Insulation (cellulose+woodframe 10cm)/VCL (0.022cm)/Gypsum plasterboard (2.5cm)	Passive	Ind./Centr.	1m2	30	14	/
	Air gap (1cm)/Insulation (PUR 8cm)/VCL (0.022cm)/Gypsum plasterboard (2.5cm)			1m2	30	12	/
	Air gap (1cm)/Insulation (stone wool 14cm)/VCL(0.022cm)/Gypsum plasterboard (2.5cm)			1m2	30	18	/
	Air gap (1cm)/Insulation (VIP 2.5cm)/VCL (0.022cm)/Gypsum plasterboard (2.5cm)			1m2	30	6	/
Interior wall cladding components	Cellulose (Board | Cellulose (10cm) | For between timber frame | Friction fitted)	Passive	Ind./Centr.	1m2	60	10	/
	Gypsum plasterboard (Board | Gypsum plaster (2x1.25cm) | Screwed | Including joint filler)			1m2	30	2.5	/
	PUR (RECTICEL | Board | PUR - Multilayer facer (8cm) | Excluding fixations)			1m2	60	8	/
	Stone wool (Board | Stone wool (14cm)			1m2	60	14	/
	VCL (Vapour barrier) Proofing sheet | PP - PE (0.022cm) | Taped			1m2	60	0.022	/
	VIP (Vacuum Insulated Panel fumed silica 2.5cm)			1m2	60	2.5	/
	Wood frame (Frame | Softwood (10cm) | Screwed | Untreated | Belgian mix)			1m2	60	10	/
	Cellulose 80% + wood frame 20% (10cm)			1m2	60	10	/
Exterior wall	Bricks_Fired clay/Blanket_Stone wool (13cm)/Hollow bricks_Sand-lime (29.8x15x14.8cm)/Thick coating_Gypsum plaster	Passive	Ind./Centr.	1m2	60	/	/
Window refurbishment	Double Glazing Aluminium frame with thermal bridge break	Passive	Ind./Centr.	1m2	30	/	/
	Double Glazing PVC frame 3 chambers			1m2	30	/	/
	Double Glazing Wood frame			1m2	30	/	/
	Triple Glazing Aluminium frame with thermal bridge break			1m2	30	/	/
	Triple Glazing PVC frame 5 chambers			1m2	30	/	/
	Triple Glazing Wooden frame			1m2	30	/	/
	Reynaers epd			1m2	30	/	/
Photovoltaic panels	Monocrystal solar panel	Renewable	District	1m2	25	/	400W
	Polycrystal solar panel			1.65m2	25	/	280W
HVAC + DHW	Heat pump_Metals - Plastics (3-10 kW)/Storage vessel_Metals - Plastics (150 l)	Active	Ind./Centr.	1 system	60	/	3-10kW
	Heat pump air/water production			1 system	60	/	/
	Gas condencing heating production			1 system	60	/	/
	Mechanical ventilation production			1 system	60	/	/

Table 2. LCA results for interior wall cladding.

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	8.90E+01	-1.20E+01	4.90E-01	2.10E+00	6.10E-01	0	4.40E+01	0	7.00E-02	3.30E-01	9.80E+00	4.40E+01	
	Climate change - fossil	kg CO2 eq.	8.70E+01	4.00E+01	4.90E-01	2.10E+00	5.90E-01	0	4.30E+01	0	7.00E-02	3.20E-01	9.60E-03	5.60E-01	
	Climate change - biogenic	kg CO2 eq.	1.80E+00	-5.20E+01	2.10E-04	4.20E-02	1.50E-02	0	8.80E-01	0	1.30E-05	1.30E-04	9.80E+00	4.30E+01	
	Climate change - land use and land use change	kg CO2 eq.	1.80E-01	8.30E-02	1.70E-04	4.20E-03	2.00E-04	0	8.80E-02	0	5.50E-06	1.10E-04	9.90E-06	5.30E-05	
	Ozone depletion	kg CFC 11 eq.	6.20E-06	2.70E-06	1.10E-07	1.50E-07	4.20E-08	0	3.10E-06	0	1.50E-08	7.40E-08	2.00E-09	4.30E-08	
	Acidification	mol H+ eq	5.50E-01	2.50E-01	2.00E-03	1.30E-02	2.10E-03	0	2.70E-01	0	7.30E-04	1.30E-03	6.70E-05	1.60E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	3.60E-03	1.70E-03	4.00E-06	8.50E-05	9.80E-06	0	1.80E-03	0	2.50E-07	2.60E-06	1.40E-07	1.70E-06	
	Eutrophication aquatic marine	kg N eq.	1.10E-01	5.00E-02	6.00E-04	2.60E-03	5.40E-04	0	5.50E-02	0	3.20E-04	3.90E-04	2.70E-05	6.40E-04	
	Eutrophication terrestrial	mol N eq.	1.20E+00	5.60E-01	6.60E-03	2.90E-02	6.10E-03	0	6.10E-01	0	3.50E-03	4.40E-03	3.00E-04	7.20E-03	
Cellulose/VCL/Gypsum plasterboard	Photochemical ozone formation	kg NMVOC eq.	4.00E-01	1.80E-01	2.10E-03	9.40E-03	1.70E-03	0	2.00E-01	0	9.70E-04	1.30E-03	8.20E-05	2.00E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	2.70E-04	1.30E-04	9.30E-07	6.50E-06	3.00E-07	0	1.40E-04	0	1.80E-08	6.30E-07	1.30E-08	1.30E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	1.64E+03	7.62E+02	7.50E+00	3.90E+01	4.20E+00	0	8.18E+02	0	9.60E-01	4.90E+00	2.30E-01	3.20E+00	
	Water use	m3 world eq. deprived	3.50E+01	1.60E+01	2.30E-02	8.20E-01	6.50E-02	0	1.70E+01	0	1.30E-03	1.40E-02	1.70E-03	9.00E-02	
	Particulate Matter emissions	Disease incidence	6.60E-06	3.00E-06	3.60E-08	1.50E-07	3.10E-08	0	3.30E-06	0	1.00E-07	2.30E-09	1.50E-09	2.40E-08	
	Ionizing radiation, human health	kBq U235 eq.	3.30E+00	1.50E+00	3.30E-02	7.90E-02	2.00E-02	0	1.70E+00	0	4.10E-03	2.10E-02	2.10E-03	1.50E-02	
	Eco-toxicity (freshwater)	CTUe	3.07E+03	1.44E+03	6.10E+00	7.30E+01	8.90E+00	0	1.53E+03	0	5.80E-01	3.90E+00	1.30E-01	2.40E+00	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	5.60E-08	2.50E-08	1.70E-10	1.30E-09	1.50E-10	0	2.80E-08	0	2.00E-11	1.10E-10	5.50E-12	7.00E-10	
	Human toxicity, non-cancer effects	CTUh	1.30E-06	5.80E-07	6.60E-09	3.00E-08	5.10E-09	0	6.30E-07	0	5.00E-10	4.30E-09	1.00E-10	3.60E-09	
	Land use related impacts/Soil quality	dimensionless	6.23E+03	2.95E+03	6.10E+00	1.48E+02	6.60E+00	0	3.11E+03	0	1.20E-01	3.40E+00	1.40E-01	5.60E+00	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	4.70E+01	1.50E+01	5.50E-01	1.10E+00	6.10E-01	0	2.30E+01	0	7.00E-02	3.10E-01	3.30E-03	6.80E+00	
	Climate change - fossil	kg CO2 eq.	4.70E+01	1.50E+01	5.50E-01	1.10E+00	5.90E-01	0	2.30E+01	0	7.00E-02	3.10E-01	3.30E-03	6.50E+00	
	Climate change - biogenic	kg CO2 eq.	1.50E-01	-2.80E-01	1.90E-04	3.10E-03	1.50E-02	0	6.50E-02	0	1.30E-05	1.30E-04	8.10E-06	3.40E-01	
	Climate change - land use and land use change	kg CO2 eq.	8.60E-02	4.00E-02	1.50E-04	2.00E-03	2.00E-04	0	4.30E-02	0	5.50E-06	1.10E-04	4.80E-06	1.80E-04	
	Ozone depletion	kg CFC 11 eq.	2.30E-06	7.50E-07	1.30E-07	5.30E-08	4.20E-08	0	1.10E-06	0	1.50E-08	7.00E-08	6.70E-10	1.10E-07	
	Acidification	mol H+ eq	1.80E-01	7.30E-02	2.20E-03	4.20E-03	2.10E-03	0	8.80E-02	0	7.30E-04	1.30E-03	1.80E-05	6.50E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	1.10E-03	5.00E-04	3.50E-06	2.60E-05	9.80E-06	0	5.40E-04	0	2.50E-07	2.40E-06	6.20E-08	6.50E-06	
	Eutrophication aquatic marine	kg N eq.	4.00E-02	1.40E-02	6.50E-04	9.20E-04	5.40E-04	0	2.00E-02	0	3.20E-04	3.80E-04	6.70E-06	3.40E-03	
	Eutrophication terrestrial	mol N eq.	4.30E-01	1.50E-01	7.20E-03	9.90E-03	6.10E-03	0	2.10E-01	0	3.50E-03	4.20E-03	7.50E-05	3.20E-02	
PUR/VCL/Gypsum plasterboard	Photochemical ozone formation	kg NMVOC eq.	1.30E-01	5.00E-02	2.20E-03	3.10E-03	1.70E-03	0	6.50E-02	0	9.70E-04	1.30E-03	2.10E-05	7.70E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	6.40E-05	2.80E-05	7.70E-07	1.50E-06	3.00E-07	0	3.20E-05	0	1.80E-08	6.00E-07	6.00E-09	5.00E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	6.39E+02	2.83E+02	8.20E+00	1.50E+01	4.20E+00	0	3.18E+02	0	9.60E-01	4.70E+00	9.50E-02	5.60E+00	
	Water use	m3 world eq. deprived	1.20E+01	5.40E+00	1.90E-02	2.80E-01	6.50E-02	0	5.90E+00	0	1.30E-03	1.30E-02	7.80E-04	2.10E-01	
	Particulate Matter emissions	Disease incidence	2.00E-06	7.10E-07	3.20E-08	4.10E-08	3.10E-08	0	9.60E-07	0	1.00E-07	2.20E-08	3.70E-10	5.30E-08	
	Ionizing radiation, human health	kBq U235 eq.	5.40E+00	2.50E+00	3.60E-02	1.30E-01	2.00E-02	0	2.70E+00	0	4.10E-03	2.00E-02	9.50E-04	2.40E-02	
	Eco-toxicity (freshwater)	CTUe	7.46E+02	3.15E+02	6.10E+00	1.80E+01	8.90E+00	0	3.69E+02	0	5.80E-01	3.70E+00	4.80E-02	2.60E+01	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	2.20E-08	8.70E-09	1.50E-10	5.20E-10	1.50E-10	0	1.10E-08	0	2.00E-11	1.10E-10	1.90E-12	1.30E-09	
	Human toxicity, non-cancer effects	CTUh	4.10E-07	1.70E-07	6.00E-09	9.70E-09	5.10E-09	0	2.00E-07	0	5.00E-10	4.10E-09	3.60E-11	1.50E-08	
	Land use related impacts/Soil quality	dimensionless	4.06E+02	1.75E+02	5.20E+00	9.50E+00	6.60E+00	0	2.00E+02	0	1.20E-01	3.20E+00	5.50E-02	6.20E+00	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	6.90E+01	3.00E+01	6.80E-01	1.60E+00	6.10E-01	0	3.40E+01	0	7.00E-02	5.90E-01	3.30E-03	8.30E-01	
	Climate change - fossil	kg CO2 eq.	6.80E+01	3.00E+01	6.80E-01	1.60E+00	5.90E-01	0	3.40E+01	0	7.00E-02	5.90E-01	3.30E-03	8.30E-01	
	Climate change - biogenic	kg CO2 eq.	3.10E-01	1.40E-01	2.80E-04	7.00E-03	1.50E-02	0	1.50E-01	0	1.30E-05	2.40E-04	8.10E-06	2.30E-04	
	Climate change - land use and land use change	kg CO2 eq.	9.40E-02	4.40E-02	2.40E-04	2.20E-03	2.00E-04	0	4.70E-02	0	5.50E-06	2.10E-04	4.80E-06	1.10E-04	
	Ozone depletion	kg CFC 11 eq.	5.10E-06	2.00E-06	1.50E-07	1.20E-07	4.20E-08	0	2.50E-06	0	1.50E-08	1.40E-07	6.70E-10	1.10E-07	
	Acidification	mol H+ eq	5.90E-01	2.70E-01	2.80E-03	1.40E-02	2.10E-03	0	2.90E-01	0	7.30E-04	2.40E-03	1.80E-05	3.90E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	2.90E-03	1.40E-03	5.40E-06	6.90E-05	9.80E-06	0	1.40E-03	0	2.50E-07	4.70E-06	6.20E-08	3.50E-06	
	Eutrophication aquatic marine	kg N eq.	6.80E-02	2.90E-02	8.20E-04	1.60E-03	5.40E-04	0	3.40E-02	0	3.20E-04	7.20E-04	6.70E-06	1.60E-03	
	Eutrophication terrestrial	mol N eq.	1.10E+00	4.70E-01	9.10E-03	2.50E-02	6.10E-03	0	5.30E-01	0	3.50E-03	8.00E-03	7.50E-05	1.70E-02	
Stone wool/VCL/Gypsum plasterboard	Photochemical ozone formation	kg NMVOC eq.	3.10E-01	1.30E-01	2.80E-03	7.20E-03	1.70E-03	0	1.50E-01	0	9.70E-04	2.40E-03	2.10E-05	4.80E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	1.20E-04	5.30E-05	1.20E-06	2.80E-06	3.00E-07	0	5.90E-05	0	1.80E-08	1.20E-06	6.00E-09	2.50E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	8.57E+02	3.78E+02	1.00E+01	2.00E+01	4.20E+00	0	4.26E+02	0	9.60E-01	9.00E+00	9.50E-02	8.00E+00	
	Water use	m3 world eq. deprived	2.00E+01	9.00E+00	3.10E-02	4.60E-01	6.50E-02	0	9.70E+00	0	1.30E-03	2.50E-02	7.80E-04	1.90E-01	
	Particulate Matter emissions	Disease incidence	3.90E-06	1.60E-06	5.00E-08	8.80E-08	3.10E-08	0	1.90E-06	0	1.00E-07	4.10E-08	3.70E-10	9.00E-08	
	Ionizing radiation, human health	kBq U235 eq.	2.40E+00	9.90E-01	4.50E-02	5.60E-02	2.00E-02	0	1.20E+00	0	4.10E-03	3.90E-02	9.50E-04	3.80E-02	
	Eco-toxicity (freshwater)	CTUe	1.57E+03	7.23E+02	8.30E+00	3.70E+01	8.90E+00	0	7.82E+02	0	5.80E-01	7.20E+00	4.80E-02	5.20E+00	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	2.10E-07	1.00E-07	2.30E-10	5.10E-09	1.50E-10	0	1.10E-07	0	2.00E-11	2.00E-10	1.90E-12	2.40E-10	
	Human toxicity, non-cancer effects	CTUh	8.20E-07	3.70E-07	9.10E-09	1.90E-08	5.10E-09	0	4.10E-07	0	5.00E-10	7.80E-09	3.60E-11	4.60E-09	
	Land use related impacts/Soil quality	dimensionless	5.72E+02	2.45E+02	8.40E+00	1.30E+01	6.60E+00	0	2.83E+02	0	1.20E-01	6.20E+00	5.50E-02	9.30E+00	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	2.93E+01	1.42E+01	1.25E+00		6.10E-01	0		0				3.45E+00	
	Climate change - fossil	kg CO2 eq.	2.56E+01	1.38E+01	1.25E+00		5.90E-01	0		0				1.17E+00	
	Climate change - biogenic	kg CO2 eq.	2.82E+00	4.73E-01	8.36E-04		1.50E-02	0		0				2.28E+00	
	Climate change - land use and land use change	kg CO2 eq.	8.12E-02	4.42E-02	5.49E-04		2.00E-04	0		0				1.33E-04	
	Ozone depletion	kg CFC 11 eq.	4.44E-06	3.40E-06	1.02E-07		4.20E-08	0		0				4.24E-08	
	Acidification	mol H+ eq	1.42E-01	7.03E-01	4.48E-03		2.10E-03	0		0				2.06E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	7.94E-03	7.32E-03	6.62E-05		9.80E-06	0		0				1.17E-04	
	Eutrophication aquatic marine	kg N eq.	3.41E-02	1.45E-02	1.48E-03		5.40E-04	0		0				6.24E-03	
	Eutrophication terrestrial	mol N eq.	3.00E-01	1.47E-01	1.58E-02		6.10E-03	0		0				7.55E-03	
VIP/VCL/Gypsum plasterboard	Photochemical ozone formation	kg NMVOC eq.	8.67E-02	4.16E-02	6.15E-03		1.70E-03	0		0				2.97E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	6.55E-05	4.90E-05	3.17E-06		3.00E-07	0		0				4.46E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	3.65E+02	2.10E+02	1.86E+01		4.20E+00	0		0				4.87E+00	
	Water use	m3 world eq. deprived	7.54E+00	4.49E+00	8.44E-02		6.50E-02	0		0				1.68E-01	
	Particulate Matter emissions	Disease incidence	1.56E-06	6.10E-07	1.16E-07		3.10E-08	0		0				5.73E-08	
	Ionizing radiation, human health	kBq U235 eq.	2.08E+00	1.56E+00	4.06E-02		2.00E-02	0		0				1.90E-02	
	Eco-toxicity (freshwater)	CTUe	4.97E+02	2.27E+02	1.08E+01		8.90E+00	0		0				1.51E+01	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	1.50E-08	7.54E-09	5.17E-10		1.50E-10	0		0				8.47E-10	
	Human toxicity, non-cancer effects	CTUh	2.91E-07	1.53E-07	1.43E-08		5.10E-09	0		0				1.23E-08	
	Land use related impacts/Soil quality	dimensionless	3.09E+02	1.35E+02	1.76E+01		6.60E+00	0		0				8.19E+00	

Table 3. LCA results for interior wall cladding components.

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Cellulose	Climate change - total	kg CO2 eq.	8.20E+01	-1.00E+01	0	2.00E+00	0	0	4.10E+01	0	0	0	0	5.00E+01	
	Climate change - fossil	kg CO2 eq.	8.00E+01	3.80E+01	0	1.90E+00	0	0	4.00E+01	0	0	0	0	0.00E+00	
	Climate change - biogenic	kg CO2 eq.	2.10E+00	-4.90E+01	0	4.90E-02	0	0	1.00E+00	0	0	0	0	5.00E+01	
	Climate change - land use and land use change	kg CO2 eq.	1.00E-01	4.80E-02	0	2.40E-03	0	0	5.00E-02	0	0	0	0	0.00E+00	
	Ozone depletion	kg CFC 11 eq.	4.90E-06	2.40E-06	0	1.20E-07	0	0	2.50E-06	0	0	0	0	0.00E+00	
	Acidification	mol H+ eq	5.00E-01	2.40E-01	0	1.20E-02	0	0	2.50E-01	0	0	0	0	0.00E+00	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	3.20E-03	1.50E-03	0	7.50E-05	0	0	1.60E-03	0	0	0	0	0.00E+00	
	Eutrophication aquatic marine	kg N eq.	9.70E-02	4.60E-02	0	2.30E-03	0	0	4.90E-02	0	0	0	0	0.00E+00	
	Eutrophication terrestrial	mol N eq.	1.10E+00	5.20E-01	0	2.60E-02	0	0	5.40E-01	0	0	0	0	0.00E+00	
	Photochemical ozone formation	kg NMVOC eq.	3.70E-01	1.80E-01	0	8.90E-03	0	0	1.90E-01	0	0	0	0	0.00E+00	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	2.80E-04	1.30E-04	0	6.70E-06	0	0	1.40E-04	0	0	0	0	0.00E+00	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	1.67E+03	7.94E+02	0	4.00E+01	0	0	8.34E+02	0	0	0	0	0.00E+00	
	Water use	m3 world eq. deprived	3.60E+01	1.70E+01	0	8.60E-01	0	0	1.80E+01	0	0	0	0	0.00E+00	
	Particulate Matter emissions	Disease incidence	5.00E-06	2.40E-06	0	1.20E-07	0	0	2.50E-06	0	0	0	0	0.00E+00	
	Ionizing radiation, human health	kBq U235 eq.	2.80E+00	1.30E+00	0	6.60E-02	0	0	1.40E+00	0	0	0	0	0.00E+00	
	Eco-toxicity (freshwater)	CTUe	3.11E+03	1.48E+03	0	7.40E+01	0	0	1.56E+03	0	0	0	0	0.00E+00	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	4.70E-08	2.30E-08	0	1.10E-09	0	0	2.40E-08	0	0	0	0	0.00E+00	
	Human toxicity, non-cancer effects	CTUh	1.20E-06	5.60E-07	0	2.80E-08	0	0	5.90E-07	0	0	0	0	0.00E+00	
	Land use related impacts/Soil quality	dimensionless	1.16E+03	5.52E+02	0	2.80E+01	0	0	5.80E+02	0	0	0	0	0.00E+00	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Cellulose+wood frame	Climate change - total	kg CO2 eq.	7.10E+01	-1.90E+01	1.30E-01	1.70E+00	0	0	3.60E+01	0	0	7.40E-02	9.80E+00	4.30E+01	
	Climate change - fossil	kg CO2 eq.	6.90E+01	3.30E+01	1.30E-01	1.70E+00	0	0	3.50E+01	0	0	7.30E-02	6.30E-03	2.20E-02	
	Climate change - biogenic	kg CO2 eq.	1.70E+00	-5.20E+01	5.20E-05	4.00E-02	0	0	8.40E-01	0	0	3.00E-05	9.80E+00	4.30E+01	
	Climate change - land use and land use change	kg CO2 eq.	1.10E-01	5.00E-02	4.20E-05	2.50E-03	0	0	5.30E-02	0	0	2.60E-05	5.10E-06	7.40E-06	
	Ozone depletion	kg CFC 11 eq.	4.70E-06	2.20E-06	2.90E-08	1.10E-07	0	0	2.30E-06	0	0	1.70E-08	1.30E-09	3.10E-09	
	Acidification	mol H+ eq	4.40E-01	2.10E-01	5.20E-04	1.00E-02	0	0	2.20E-01	0	0	3.00E-04	4.90E-05	6.50E-04	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	2.80E-03	1.30E-03	9.90E-07	6.70E-05	0	0	1.40E-03	0	0	5.80E-07	8.00E-08	4.10E-07	
	Eutrophication aquatic marine	kg N eq.	8.90E-02	4.20E-02	1.60E-04	2.10E-03	0	0	4.40E-02	0	0	8.90E-05	2.00E-05	3.00E-04	
	Eutrophication terrestrial	mol N eq.	9.90E-01	4.70E-01	1.70E-03	2.40E-02	0	0	5.00E-01	0	0	9.80E-04	2.20E-04	3.40E-03	
	Photochemical ozone formation	kg NMVOC eq.	3.30E-01	1.60E-01	5.40E-04	8.00E-03	0	0	1.70E-01	0	0	3.00E-04	6.10E-05	9.00E-04	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	2.50E-04	1.20E-04	2.20E-07	6.00E-06	0	0	1.30E-04	0	0	1.40E-07	7.40E-09	3.50E-08	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	1.41E+03	6.66E+02	1.90E+00	3.30E+01	0	0	7.02E+02	0	0	1.10E+00	1.40E-01	2.70E-01	
	Water use	m3 world eq. deprived	2.90E+01	1.40E+01	5.70E-03	7.00E-01	0	0	1.50E+01	0	0	3.10E-03	8.70E-04	-2.40E-02	
	Particulate Matter emissions	Disease incidence	5.40E-06	2.50E-06	9.70E-09	1.30E-07	0	0	2.70E-06	0	0	5.10E-09	1.20E-09	5.50E-09	
	Ionizing radiation, human health	kBq U235 eq.	2.50E+00	1.20E+00	8.40E-03	6.00E-02	0	0	1.30E+00	0	0	4.80E-03	1.10E-03	8.60E-04	
	Eco-toxicity (freshwater)	CTUe	2.62E+03	1.24E+03	1.50E+00	6.20E+01	0	0	1.31E+03	0	0	8.90E-01	7.70E-02	5.00E-01	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	4.40E-08	2.00E-08	4.20E-11	1.00E-09	0	0	2.20E-08	0	0	2.50E-11	3.60E-12	5.90E-10	
	Human toxicity, non-cancer effects	CTUh	1.10E-06	5.00E-07	1.70E-09	2.50E-08	0	0	5.30E-07	0	0	9.70E-10	6.50E-11	1.90E-09	
	Land use related impacts/Soil quality	dimensionless	5.96E+03	2.83E+03	1.60E+00	1.42E+02	0	0	2.98E+03	0	0	7.60E-01	8.20E-02	1.00E-01	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Gypsum plasterboard	Climate change - total	kg CO2 eq.	1.60E+01	6.30E+00	3.60E-01	3.50E-01	6.10E-01	0	7.50E+00	0	7.00E-02	2.50E-01	3.30E-03	1.00E-01	
	Climate change - fossil	kg CO2 eq.	1.50E+01	6.30E+00	3.60E-01	3.50E-01	5.90E-01	0	7.40E+00	0	7.00E-02	2.50E-01	3.20E-03	1.00E-01	
	Climate change - biogenic	kg CO2 eq.	9.90E-02	3.90E-02	1.60E-04	2.00E-03	1.50E-02	0	4.20E-02	0	1.30E-05	1.00E-04	8.00E-06	9.20E-05	
	Climate change - land use and land use change	kg CO2 eq.	6.90E-02	3.30E-02	1.30E-04	1.60E-03	2.00E-04	0	3.50E-02	0	5.50E-06	8.70E-05	4.80E-06	4.40E-05	
	Ozone depletion	kg CFC 11 eq.	1.50E-06	5.00E-07	8.20E-08	3.40E-08	4.20E-08	0	7.30E-07	0	1.50E-08	5.60E-08	6.70E-10	3.90E-08	
	Acidification	mol H+ eq	1.10E-01	4.50E-02	1.50E-03	2.40E-03	2.10E-03	0	5.20E-02	0	7.30E-04	1.00E-03	1.80E-05	9.20E-04	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	7.50E-04	3.50E-04	3.00E-06	1.80E-05	9.80E-06	0	3.70E-04	0	2.50E-07	1.90E-06	6.10E-08	1.20E-06	
	Eutrophication aquatic marine	kg N eq.	2.00E-02	8.00E-03	4.40E-04	4.50E-04	5.40E-04	0	9.90E-03	0	3.20E-04	3.00E-04	6.70E-06	3.20E-04	
	Eutrophication terrestrial	mol N eq.	2.20E-01	8.80E-02	4.80E-03	5.00E-03	6.10E-03	0	1.10E-01	0	3.50E-03	3.30E-03	7.40E-05	3.50E-03	
	Photochemical ozone formation	kg NMVOC eq.	5.80E-02	2.20E-02	1.50E-03	1.30E-03	1.70E-03	0	2.80E-02	0	9.70E-04	1.00E-03	2.00E-05	1.00E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	2.10E-05	8.40E-06	7.10E-07	4.80E-07	3.00E-07	0	1.00E-05	0	1.80E-08	4.80E-07	6.00E-09	8.90E-08	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	2.01E+02	8.00E+01	5.50E+00	4.60E+00	4.20E+00	0	9.80E+01	0	9.60E-01	3.70E+00	9.50E-02	2.90E+00	
	Water use	m3 world eq. deprived	4.40E+00	1.90E+00	1.70E-02	1.00E-01	6.50E-02	0	2.20E+00	0	1.30E-03	1.00E-02	7.80E-04	1.20E-01	
	Particulate Matter emissions	Disease incidence	1.20E-06	4.00E-07	2.60E-08	2.30E-08	3.10E-08	0	5.90E-07	0	1.00E-07	1.70E-08	3.70E-10	1.80E-08	
	Ionizing radiation, human health	kBq U235 eq.	7.90E-01	3.10E-01	2.40E-02	1.80E-02	2.00E-02	0	3.90E-01	0	4.10E-03	1.60E-02	9.50E-04	1.40E-02	
	Eco-toxicity (freshwater)	CTUe	4.36E+02	1.94E+02	4.50E+00	1.00E+01	8.90E+00	0	2.14E+02	0	5.80E-01	3.00E+00	4.80E-02	1.80E+00	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	1.10E-08	5.00E-09	1.30E-10	2.70E-10	1.50E-10	0	5.60E-09	0	2.00E-11	8.40E-11	1.90E-12	4.50E-11	
	Human toxicity, non-cancer effects	CTUh	1.90E-07	7.90E-08	4.90E-09	4.40E-09	5.10E-09	0	9.40E-08	0	5.00E-10	3.30E-09	3.60E-11	1.30E-09	
	Land use related impacts/Soil quality	dimensionless	2.66E+02	1.11E+02	4.40E+00	6.20E+00	6.60E+00	0	1.30E+02	0	1.20E-01	2.60E+00	5.40E-02	5.50E+00	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
PUR	Climate change - total	kg CO2 eq.	3.00E+01	7.60E+00	1.90E-01	7.10E-01	0	0	1.50E+01	0	0	5.80E-02	0	6.30E+00	
	Climate change - fossil	kg CO2 eq.	3.00E+01	7.90E+00	1.90E-01	7.10E-01	0	0	1.50E+01	0	0	5.80E-02	0	5.90E+00	
	Climate change - biogenic	kg CO2 eq.	4.40E-02	-3.20E-01	3.10E-05	1.10E-03	0	0	2.20E-02	0	0	2.40E-05	0	3.40E-01	
	Climate change - land use and land use change	kg CO2 eq.	1.50E-02	7.10E-03	1.60E-05	3.60E-04	0	0	7.60E-03	0	0	2.00E-05	0	1.30E-04	
	Ozone depletion	kg CFC 11 eq.	7.50E-07	2.30E-07	4.30E-08	1.80E-08	0	0	3.70E-07	0	0	1.30E-08	0	6.60E-08	
	Acidification	mol H+ eq	6.80E-02	2.60E-02	6.70E-04	1.60E-03	0	0	3.40E-02	0	0	2.40E-04	0	5.50E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	2.90E-04	1.30E-04	4.60E-07	7.00E-06	0	0	1.50E-04	0	0	4.60E-07	0	5.20E-06	
	Eutrophication aquatic marine	kg N eq.	1.90E-02	5.60E-03	2.10E-04	4.40E-04	0	0	9.30E-03	0	0	7.10E-05	0	3.00E-03	
	Eutrophication terrestrial	mol N eq.	1.90E-01	6.10E-02	2.30E-03	4.60E-03	0	0	9.70E-02	0	0	7.80E-04	0	2.80E-02	
	Photochemical ozone formation	kg NMVOC eq.	7.00E-02	2.60E-02	6.50E-03	1.70E-03	0	0	3.50E-02	0	0	2.40E-04	0	6.60E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	4.10E-05	1.90E-05	5.70E-08	9.70E-07	0	0	2.00E-05	0	0	1.10E-07	0	4.00E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	4.04E+02	1.86E+02	2.70E+00	9.60E+00	0	0	2.02E+02	0	0	8.80E-01	0	2.60E+00	
	Water use	m3 world eq. deprived	6.60E+00	3.00E+00	1.90E-03	1.60E-01	0	0	3.30E+00	0	0	2.50E-03	0	1.00E-01	
	Particulate Matter emissions	Disease incidence	6.90E-07	2.80E-07	5.70E-09	1.60E-08	0	0	3.50E-07	0	0	4.10E-09	0	3.50E-08	
	Ionizing radiation, human health	kBq U235 eq.	4.50E+00	2.10E+00	1.20E-02	1.10E-01	0	0	2.30E+00	0	0	3.80E-03	0	9.70E-03	
	Eco-toxicity (freshwater)	CTUe	2.94E+02	1.14E+02	1.50E+00	7.00E+00	0	0	1.47E+02	0	0	7.10E-01	0	2.40E+01	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	1.00E-08	3.50E-09	2.50E-11	2.40E-10	0	0	5.00E-09	0	0	2.00E-11	0	1.20E-09	
	Human toxicity, non-cancer effects	CTUh	2.10E-07	8.50E-08	1.00E-09	5.00E-09	0	0	1.10E-07	0	0	7.70E-10	0	1.30E-08	
	Land use related impacts/Soil quality	dimensionless	1.34E+02	6.20E+01	7.80E-01	3.20E+00	0	0	6.70E+01	0	0	6.10E-01	0	7.00E-01	

Material	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	5.10E+01	2.30E+01	3.10E-01	1.20E+00	0	0	2.60E+01	0	0	3.40E-01	0	3.00E-01	
	Climate change - fossil	kg CO2 eq.	5.10E+01	2.30E+01	3.10E-01	1.20E+00	0	0	2.50E+01	0	0	3.40E-01	0	2.90E-01	
	Climate change - biogenic	kg CO2 eq.	2.10E-01	9.80E-02	1.30E-04	4.90E-03	0	0	1.00E-01	0	0	1.40E-04	0	1.30E-04	
	Climate change - land use and land use change	kg CO2 eq.	2.30E-02	1.10E-02	1.00E-04	5.60E-04	0	0	1.20E-02	0	0	1.20E-04	0	6.50E-05	
	Ozone depletion	kg CFC 11 eq.	3.60E-06	1.50E-06	7.10E-08	8.50E-08	0	0	1.80E-06	0	0	7.80E-08	0	7.20E-07	
	Acidification	mol H+ eq	4.80E-01	2.20E-01	1.30E-03	1.10E-02	0	0	2.40E-01	0	0	1.40E-03	0	2.90E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	2.10E-03	1.00E-03	2.40E-06	5.00E-05	0	0	1.10E-03	0	0	2.70E-06	0	2.20E-06	
	Eutrophication aquatic marine	kg N eq.	4.60E-02	2.00E-02	3.80E-04	1.10E-03	0	0	2.30E-02	0	0	4.20E-04	0	1.20E-03	
	Eutrophication terrestrial	mol N eq.	8.30E-01	3.80E-01	4.20E-03	2.00E-02	0	0	4.20E-01	0	0	4.60E-03	0	1.30E-02	
Stone wool	Photochemical ozone formation	kg NMVOC eq.	2.40E-01	1.10E-01	1.30E-03	5.80E-03	0	0	1.20E-01	0	0	1.40E-03	0	3.70E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	9.50E-05	4.40E-05	5.30E-07	2.30E-06	0	0	4.80E-05	0	0	6.70E-07	0	1.60E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	6.21E+02	2.81E+02	4.70E+00	1.50E+01	0	0	3.11E+02	0	0	5.20E+00	0	5.00E+00	
	Water use	m3 world eq. deprived	1.40E+01	6.70E+00	1.40E-02	3.40E-01	0	0	7.20E+00	0	0	1.40E-02	0	7.50E-02	
	Particulate Matter emissions	Disease incidence	2.70E-06	1.10E-06	2.40E-08	6.30E-08	0	0	1.30E-06	0	0	2.40E-08	0	7.20E-08	
	Ionizing radiation, human health	kBq U235 eq.	1.50E+00	6.70E-01	2.10E-02	3.70E-02	0	0	7.70E-01	0	0	2.30E-02	0	2.40E-02	
	Eco-toxicity (freshwater)	CTUe	1.12E+03	5.22E+02	3.80E+00	2.70E+01	0	0	5.60E+02	0	0	4.10E+00	0	3.30E+00	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	2.00E-07	9.60E-08	1.00E-10	4.80E-09	0	0	1.00E-07	0	0	1.20E-10	0	1.40E-10	
	Human toxicity, non-cancer effects	CTUh	6.20E-07	2.80E-07	4.20E-09	1.50E-08	0	0	3.10E-07	0	0	4.50E-09	0	2.90E-09	
	Land use related impacts/Soil quality	dimensionless	3.00E+02	1.32E+02	4.00E+00	7.20E+00	0	0	1.50E+02	0	0	3.60E+00	0	3.80E+00	

Material	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	2.20E+00	6.00E-01	3.10E-03	5.20E-02	0	0	1.10E+00	0	0	4.00E-03	1.60E-05	4.30E-01	
	Climate change - fossil	kg CO2 eq.	2.20E+00	6.00E-01	3.10E-03	5.20E-02	0	0	1.10E+00	0	0	4.00E-03	1.60E-05	4.30E-01	
	Climate change - biogenic	kg CO2 eq.	2.90E-03	1.40E-03	1.30E-06	6.90E-05	0	0	1.40E-03	0	0	1.60E-06	3.80E-08	4.50E-06	
	Climate change - land use and land use change	kg CO2 eq.	8.70E-04	4.10E-04	1.00E-06	2.10E-05	0	0	4.30E-04	0	0	1.40E-06	2.20E-08	1.60E-06	
	Ozone depletion	kg CFC 11 eq.	4.00E-08	1.70E-08	7.20E-10	9.40E-10	0	0	2.00E-08	0	0	9.00E-10	3.20E-12	5.90E-10	
	Acidification	mol H+ eq	5.60E-03	2.60E-03	1.30E-05	1.30E-04	0	0	2.80E-03	0	0	1.60E-05	8.90E-08	6.20E-05	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	3.70E-05	1.80E-05	2.40E-08	8.90E-07	0	0	1.90E-05	0	0	3.10E-08	2.90E-10	6.60E-08	
	Eutrophication aquatic marine	kg N eq.	1.10E-03	4.70E-04	3.80E-06	2.50E-05	0	0	5.30E-04	0	0	4.80E-06	3.30E-08	2.80E-05	
	Eutrophication terrestrial	mol N eq.	1.20E-02	5.20E-03	4.20E-05	2.80E-04	0	0	5.90E-03	0	0	5.30E-05	3.70E-07	3.10E-04	
VCL (Vapour barrier)	Photochemical ozone formation	kg NMVOC eq.	4.80E-03	2.20E-03	1.30E-05	1.10E-04	0	0	2.40E-03	0	0	1.60E-05	1.00E-07	8.40E-05	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	2.00E-06	9.40E-07	5.40E-09	4.80E-08	0	0	1.00E-06	0	0	7.70E-09	2.80E-11	5.90E-09	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	3.50E+01	1.60E+01	4.80E-02	8.30E-01	0	0	1.70E+01	0	0	6.00E-02	4.50E-04	4.40E-02	
	Water use	m3 world eq. deprived	8.40E-01	4.00E-01	1.40E-04	2.00E-02	0	0	4.20E-01	0	0	1.70E-04	3.60E-06	-1.30E-03	
	Particulate Matter emissions	Disease incidence	4.80E-08	2.20E-08	2.40E-10	1.10E-09	0	0	2.40E-08	0	0	2.80E-10	1.80E-12	5.40E-10	
	Ionizing radiation, human health	kBq U235 eq.	3.20E-02	1.40E-02	2.10E-04	7.50E-04	0	0	1.60E-02	0	0	2.60E-04	4.40E-06	1.90E-04	
	Eco-toxicity (freshwater)	CTUe	1.60E+01	7.50E+00	3.80E-02	3.90E-01	0	0	8.10E+00	0	0	4.80E-02	2.30E-04	1.40E-01	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	4.90E-10	1.70E-10	1.00E-12	1.20E-11	0	0	2.50E-10	0	0	1.30E-12	9.00E-15	6.00E-11	
	Human toxicity, non-cancer effects	CTUh	1.10E-08	4.70E-09	4.20E-11	2.60E-10	0	0	5.50E-09	0	0	5.20E-11	1.70E-13	4.40E-10	
	Land use related impacts/Soil quality	dimensionless	5.50E+00	2.50E+00	4.00E-02	1.30E-01	0	0	2.70E+00	0	0	4.10E-02	2.50E-04	3.40E-02	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	1.11E+01	7.34	8.89E-01					0				2.92E+00	
	Climate change - fossil	kg CO2 eq.	8.42E+00	6.89E+00	8.88E-01					0				6.39E-01	
	Climate change - biogenic	kg CO2 eq.	2.71E+00	4.33E-01	6.75E-04					0				2.28E+00	
	Climate change - land use and land use change	kg CO2 eq.	1.13E-02	1.08E-02	4.18E-04					0				8.76E-05	
	Ozone depletion	kg CFC 11 eq.	2.90E-06	2.88E-06	1.94E-08					0				2.86E-09	
	Acidification	mol H+ eq	2.68E-02	2.27E-02	2.97E-03					0				1.08E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	7.16E-03	6.95E-03	6.32E-05					0				1.15E-04	
	Eutrophication aquatic marine	kg N eq.	1.30E-02	6.03E-03	1.04E-03					0				5.90E-03	
	Eutrophication terrestrial	mol N eq.	6.80E-02	5.33E-02	1.09E-02					0				3.74E-03	
VIP	Photochemical ozone formation	kg NMVOC eq.	2.39E-02	1.74E-02	4.64E-03					0				1.89E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	4.25E-05	3.97E-05	2.45E-06					0				3.52E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	1.29E+02	1.14E+02	1.31E+01					0				1.93E+00	
	Water use	m3 world eq. deprived	2.30E+00	2.19E+00	6.72E-02					0				4.97E-02	
	Particulate Matter emissions	Disease incidence	3.16E-07	1.88E-07	8.97E-08					0				3.88E-08	
	Ionizing radiation, human health	kBq U235 eq.	1.26E+00	1.24E+00	1.64E-02					0				4.77E-03	
	Eco-toxicity (freshwater)	CTUe	4.48E+01	2.55E+01	6.25E+00					0				1.31E+01	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	3.50E-09	2.37E-09	3.86E-10					0				7.42E-10	
	Human toxicity, non-cancer effects	CTUh	8.97E-08	6.97E-08	9.40E-09					0				1.06E-08	
	Land use related impacts/Soil quality	dimensionless	3.72E+01	2.13E+01	1.32E+01					0				2.66E+00	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	2.60E+01	-5.40E+01	6.30E-01	6.20E-01	0	0	1.30E+01	0	0	3.70E-01	4.90E+01	1.60E+01	
	Climate change - fossil	kg CO2 eq.	2.60E+01	1.10E+01	6.30E-01	6.20E-01	0	0	1.30E+01	0	0	3.70E-01	3.20E-02	1.10E-01	
	Climate change - biogenic	kg CO2 eq.	1.90E-01	-6.50E+01	2.60E-04	4.60E-03	0	0	9.60E-02	0	0	1.50E-04	4.90E+01	1.60E+01	
	Climate change - land use and land use change	kg CO2 eq.	1.30E-01	6.10E-02	2.10E-04	3.10E-03	0	0	6.40E-02	0	0	1.30E-04	2.60E-05	3.70E-05	
	Ozone depletion	kg CFC 11 eq.	3.50E-06	1.40E-06	1.50E-07	8.40E-08	0	0	1.80E-06	0	0	8.30E-08	6.50E-09	1.60E-08	
	Acidification	mol H+ eq	1.80E-01	7.80E-02	2.60E-03	4.30E-03	0	0	9.00E-02	0	0	1.50E-03	2.50E-04	3.20E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	1.40E-03	6.50E-04	5.00E-06	3.30E-05	0	0	6.90E-04	0	0	2.90E-06	4.00E-07	2.00E-06	
	Eutrophication aquatic marine	kg N eq.	5.30E-02	2.30E-02	7.80E-04	1.30E-03	0	0	2.70E-02	0	0	4.50E-04	1.00E-04	1.50E-03	
	Eutrophication terrestrial	mol N eq.	6.10E-01	2.60E-01	8.60E-03	1.40E-02	0	0	3.00E-01	0	0	4.90E-03	1.10E-03	1.70E-02	
Wood frame	Photochemical ozone formation	kg NMVOC eq.	1.80E-01	7.70E-02	2.70E-03	4.30E-03	0	0	9.00E-02	0	0	1.50E-03	3.10E-04	4.50E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	1.20E-04	5.50E-05	1.10E-06	2.90E-06	0	0	6.00E-05	0	0	7.20E-07	3.70E-08	1.80E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	3.51E+02	1.50E+02	9.60E+00	8.40E+00	0	0	1.76E+02	0	0	5.50E+00	6.90E-01	1.40E+00	
	Water use	m3 world eq. deprived	3.20E+00	1.60E+00	2.90E-02	7.50E-02	0	0	1.60E+00	0	0	1.50E-02	4.40E-03	-1.20E-01	
	Particulate Matter emissions	Disease incidence	6.80E-06	3.10E-06	4.80E-08	1.60E-07	0	0	3.40E-06	0	0	2.60E-08	5.90E-09	2.70E-08	
	Ionizing radiation, human health	kBq U235 eq.	1.50E+00	6.30E-01	4.20E-02	3.50E-02	0	0	7.40E-01	0	0	2.40E-02	5.60E-03	4.30E-03	
	Eco-toxicity (freshwater)	CTUe	6.18E+02	2.79E+02	7.70E+00	1.50E+01	0	0	3.09E+02	0	0	4.40E+00	3.90E-01	2.50E+00	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	2.90E-08	1.10E-08	2.10E-10	7.00E-10	0	0	1.50E-08	0	0	1.20E-10	1.80E-11	3.00E-09	
	Human toxicity, non-cancer effects	CTUh	5.40E-07	2.40E-07	8.50E-09	1.30E-08	0	0	2.70E-07	0	0	4.80E-09	3.20E-10	9.50E-09	
	Land use related impacts/Soil quality	dimensionless	2.52E+04	1.20E+04	8.20E+00	5.99E+02	0	0	1.26E+04	0	0	3.80E+00	4.10E-01	5.00E-01	

Table 4. LCA results for exterior wall.

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Brick wall - stone wool	Climate change - total	kg CO2 eq.	1.05E+02	7.90E+01	6.00E+00	4.80E+00	3.10E+00	8.10E+00	0.00E+00		1.20E+00	2.10E+00	1.20E-01	2.70E-01	
	Climate change - fossil	kg CO2 eq.	1.02E+02	7.80E+01	6.00E+00	4.70E+00	2.80E+00	6.40E+00	0.00E+00		1.20E+00	2.10E+00	1.20E-01	2.70E-01	
	Climate change - biogenic	kg CO2 eq.	8.73E-01	7.50E-01	2.50E-03	3.90E-02	5.60E-02	2.40E-02	0.00E+00		2.20E-04	8.60E-04	3.40E-04	1.40E-04	
	Climate change - land use and land use change	kg CO2 eq.	2.27E+00	3.50E-01	2.00E-03	1.80E-02	2.00E-01	1.70E+00	0.00E+00		9.40E-05	7.30E-04	2.00E-04	6.40E-05	
	Ozone depletion	kg CFC 11 eq.	9.56E-06	5.90E-06	1.40E-06	4.70E-07	2.30E-07	7.20E-07	0.00E+00		2.60E-07	4.80E-07	2.50E-08	7.70E-08	
	Acidification	mol H+ eq	4.78E-01	3.00E-01	2.50E-02	1.80E-02	1.80E-02	9.20E-02	0.00E+00		1.30E-02	8.60E-03	6.00E-04	2.50E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	2.23E-03	1.50E-03	4.70E-05	8.60E-05	9.30E-05	4.80E-04	0.00E+00		4.40E-06	1.60E-05	2.60E-06	2.30E-06	
	Eutrophication aquatic marine	kg N eq.	9.22E-02	5.80E-02	7.30E-03	3.60E-03	3.10E-03	1.10E-02	0.00E+00		5.50E-03	2.50E-03	2.10E-04	9.80E-04	
	Eutrophication terrestrial	mol N eq.	1.03E+00	7.00E-01	8.10E-02	4.30E-02	2.90E-02	7.20E-02	0.00E+00		6.10E-02	2.80E-02	2.40E-03	1.10E-02	
	Photochemical ozone formation	kg NMVOC eq.	3.13E-01	2.10E-01	2.50E-02	1.30E-02	8.80E-03	2.70E-02	0.00E+00		1.70E-02	8.60E-03	6.50E-04	3.00E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	1.74E-04	1.30E-04	1.00E-05	7.50E-06	3.20E-06	1.80E-05	0.00E+00		3.10E-07	4.10E-06	2.50E-07	1.60E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	9.77E+02	6.53E+02	9.10E+01	5.50E+01	2.60E+01	9.50E+01	0.00E+00		1.60E+01	3.20E+01	3.90E+00	5.30E+00	
	Water use	m3 world eq. deprived	2.54E+01	1.70E+01	2.70E-01	1.00E+00	1.30E+00	5.50E+00	0.00E+00		2.20E-02	8.80E-02	3.30E-02	1.80E-01	
	Particulate Matter emissions	Disease incidence	5.91E-06	2.60E-06	4.50E-07	1.70E-07	1.60E-07	4.10E-07	0.00E+00		1.90E-06	1.50E-07	1.10E-08	5.80E-08	
	Ionizing radiation, human health	kBq U235 eq.	3.56E+00	2.20E+00	4.00E-01	3.20E-01	1.00E-01	2.60E-01	0.00E+00		7.10E-02	1.40E-01	4.00E-02	2.40E-02	
	Eco-toxicity (freshwater)	CTUe	1.42E+03	1.01E+03	7.30E+01	6.10E+01	5.30E+01	1.82E+02	0.00E+00		9.90E+00	2.50E+01	1.90E+00	4.30E+00	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	1.04E-07	8.00E-08	2.00E-09	4.30E-09	2.20E-09	1.40E-08	0.00E+00		3.50E-10	7.10E-10	7.40E-11	1.20E-10	
	Human toxicity, non-cancer effects	CTUh	1.17E-06	7.90E-07	8.00E-08	4.80E-08	3.90E-08	1.70E-07	0.00E+00		8.50E-09	2.80E-08	1.40E-09	3.00E-09	
	Land use related impacts/Soil quality	dimensionless	1.01E+03	6.81E+02	7.60E+01	4.30E+01	3.90E+01	1.37E+02	0.00E+00		2.10E+00	2.20E+01	2.40E+00	7.00E+00	

Table 5. LCA results for windows.

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Double Glazing Aluminium frame with thermal bridge break	Climate change - total	kg CO2 eq.	4.70E+02	2.22E+02	5.90E-01	1.10E+01	2.50E+00	0.00E+00	2.34E+02			1.60E-01	6.90E-03	8.10E-03	
	Climate change - fossil	kg CO2 eq.	4.66E+02	2.20E+02	5.90E-01	1.10E+01	2.40E+00	0.00E+00	2.32E+02			1.60E-01	6.90E-03	8.10E-03	
	Climate change - biogenic	kg CO2 eq.	1.47E+00	7.00E-01	2.70E-04	3.50E-02	8.70E-03	0.00E+00	7.30E-01			6.50E-05	2.30E-05	6.40E-06	
	Climate change - land use and land use change	kg CO2 eq.	1.42E+00	6.40E-01	2.40E-04	3.20E-02	7.40E-02	0.00E+00	6.70E-01			5.50E-05	1.40E-05	2.90E-06	
	Ozone depletion	kg CFC 11 eq.	2.79E-05	1.30E-05	1.30E-07	6.50E-07	9.30E-08	0.00E+00	1.40E-05			3.60E-08	1.40E-09	3.20E-09	
	Acidification	mol H+ eq	2.99E+00	1.40E+00	2.40E-03	7.20E-02	1.20E-02	0.00E+00	1.50E+00			6.50E-04	2.60E-05	7.40E-05	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	1.59E-02	7.50E-03	5.20E-06	3.80E-04	7.50E-05	0.00E+00	7.90E-03			1.20E-06	1.60E-07	9.50E-08	
	Eutrophication aquatic marine	kg N eq.	4.84E-01	2.30E-01	6.90E-04	1.10E-02	2.50E-03	0.00E+00	2.40E-01			1.90E-04	8.00E-06	2.60E-05	
	Eutrophication terrestrial	mol N eq.	5.25E+00	2.50E+00	7.60E-03	1.20E-01	2.30E-02	0.00E+00	2.60E+00			2.10E-03	9.10E-05	2.80E-04	
	Photochemical ozone formation	kg NMVOC eq.	1.53E+00	7.20E-01	2.30E-03	3.60E-02	1.30E-02	0.00E+00	7.60E-01			6.50E-04	2.50E-05	8.20E-05	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	8.93E-04	4.20E-04	1.40E-06	2.10E-05	1.00E-05	0.00E+00	4.40E-04			3.10E-07	1.60E-08	6.50E-09	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	5.21E+03	2.44E+03	8.80E+00	1.22E+02	7.10E+01	0.00E+00	2.57E+03			2.40E+00	2.40E-01	2.30E-01	
	Water use	m3 world eq. deprived	1.20E+02	5.40E+01	2.70E-02	2.70E+00	6.60E+00	0.00E+00	5.70E+01			6.60E-03	2.20E-03	9.80E-03	
	Particulate Matter emissions	Disease incidence	3.39E-05	1.60E-05	3.80E-08	7.90E-07	9.40E-08	0.00E+00	1.70E-05			1.10E-08	3.80E-10	1.40E-09	
	Ionizing radiation, human health	kBq U235 eq.	1.13E+01	5.30E+00	3.90E-02	2.70E-01	8.10E-02	0.00E+00	5.60E+00			1.00E-02	2.60E-03	1.00E-03	
	Eco-toxicity (freshwater)	CTUe	1.40E+04	6.64E+03	7.40E+00	3.32E+02	3.50E+01	0.00E+00	6.98E+03			1.90E+00	1.20E-01	1.50E-01	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	5.95E-07	2.80E-07	2.20E-10	1.40E-08	1.20E-09	0.00E+00	3.00E-07			5.40E-11	4.30E-12	3.40E-12	
	Human toxicity, non-cancer effects	CTUh	1.05E-05	5.00E-06	7.90E-09	2.50E-07	3.00E-08	0.00E+00	5.20E-06			2.10E-09	8.20E-11	1.00E-10	
	Land use related impacts/Soil quality	dimensionless	1.41E+03	6.57E+02	5.70E+00	3.30E+01	1.40E+01	0.00E+00	6.98E+02			1.60E+00	1.50E-01	4.60E-01	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Double Glazing PVC frame 3 chambers	Climate change - total	kg CO2 eq.	2.85E+02	1.06E+02	8.60E-01	6.70E+00	2.50E+00	0.00E+00	1.41E+02			4.50E-01	2.20E-02	2.70E+01	
	Climate change - fossil	kg CO2 eq.	2.83E+02	1.06E+02	8.60E-01	6.70E+00	2.40E+00	0.00E+00	1.40E+02			4.50E-01	2.20E-02	2.70E+01	
	Climate change - biogenic	kg CO2 eq.	9.89E-01	4.60E-01	3.80E-04	2.30E-02	8.70E-03	0.00E+00	4.90E-01			1.90E-04	6.30E-05	7.10E-03	
	Climate change - land use and land use change	kg CO2 eq.	4.15E-01	1.60E-01	3.50E-04	7.90E-03	7.40E-02	0.00E+00	1.70E-01			1.60E-04	3.70E-05	2.30E-03	
	Ozone depletion	kg CFC 11 eq.	5.77E-05	2.60E-05	1.90E-07	1.40E-06	9.30E-08	0.00E+00	2.90E-05			1.00E-07	4.50E-09	8.90E-07	
	Acidification	mol H+ eq	1.84E+00	8.50E-01	3.50E-03	4.40E-02	1.20E-02	0.00E+00	9.10E-01			1.90E-03	1.00E-04	1.90E-02	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	1.05E-02	4.90E-03	7.60E-06	2.50E-04	7.50E-05	0.00E+00	5.20E-03			3.60E-06	4.60E-07	9.20E-05	
	Eutrophication aquatic marine	kg N eq.	2.65E-01	1.20E-01	1.00E-03	6.20E-03	2.50E-03	0.00E+00	1.30E-01			5.50E-04	3.60E-05	4.70E-03	
	Eutrophication terrestrial	mol N eq.	4.80E+00	2.20E+00	1.10E-02	1.10E-01	2.30E-02	0.00E+00	2.40E+00			6.10E-03	4.00E-04	5.10E-02	
	Photochemical ozone formation	kg NMVOC eq.	8.72E-01	3.90E-01	3.40E-03	2.00E-02	1.30E-02	0.00E+00	4.30E-01			1.90E-03	1.10E-04	1.40E-02	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	3.81E-03	1.80E-03	2.10E-06	8.80E-05	1.00E-05	0.00E+00	1.90E-03			8.80E-07	4.60E-08	7.10E-06	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	3.84E+03	1.73E+03	1.30E+01	9.00E+01	7.10E+01	0.00E+00	1.88E+03			6.80E+00	7.00E-01	4.10E+01	
	Water use	m3 world eq. deprived	2.38E+02	5.90E+01	3.90E-02	5.50E+00	6.60E+00	0.00E+00	1.16E+02			1.90E-02	6.00E-03	5.10E+01	
	Particulate Matter emissions	Disease incidence	1.68E-05	7.70E-06	5.50E-08	4.00E-07	9.40E-08	0.00E+00	8.40E-06			3.20E-08	1.90E-09	1.30E-07	
	Ionizing radiation, human health	kBq U235 eq.	9.69E+00	4.30E+00	5.60E-02	2.30E-01	8.10E-02	0.00E+00	4.80E+00			3.00E-02	7.20E-03	1.90E-01	
	Eco-toxicity (freshwater)	CTUe	1.23E+04	4.34E+03	1.10E+01	2.92E+02	3.50E+01	0.00E+00	6.14E+03			5.50E+00	3.40E-01	1.49E+03	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	4.78E-07	2.20E-07	3.20E-10	1.10E-08	1.20E-09	0.00E+00	2.40E-07			1.50E-10	1.30E-11	4.90E-09	
	Human toxicity, non-cancer effects	CTUh	8.46E-06	3.60E-06	1.10E-08	2.00E-07	3.00E-08	0.00E+00	4.20E-06			6.00E-09	2.50E-10	4.10E-07	
	Land use related impacts/Soil quality	dimensionless	1.39E+03	6.19E+02	8.30E+00	3.30E+01	1.40E+01	0.00E+00	6.89E+02			4.70E+00	4.20E-01	2.40E+01	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Double Glazing Wood frame	Climate change - total	kg CO2 eq.	1.58E+02	4.60E+01	7.80E-01	3.70E+00	2.50E+00	0.00E+00	7.80E+01			3.00E-01	2.00E+01	6.80E+00	
	Climate change - fossil	kg CO2 eq.	1.48E+02	6.80E+01	7.80E-01	3.50E+00	2.40E+00	0.00E+00	7.30E+01			3.00E-01	2.40E-02	7.20E-02	
	Climate change - biogenic	kg CO2 eq.	5.64E+00	-2.40E+01	3.50E-04	1.30E-01	8.70E-03	0.00E+00	2.70E+00			1.20E-04	2.00E+01	6.80E+00	
	Climate change - land use and land use change	kg CO2 eq.	4.47E+00	2.10E+00	3.20E-04	1.00E-01	7.40E-02	0.00E+00	2.20E+00			1.00E-04	2.40E-05	2.40E-05	
	Ozone depletion	kg CFC 11 eq.	1.54E-05	7.00E-06	1.70E-07	3.70E-07	9.30E-08	0.00E+00	7.70E-06			6.80E-08	5.00E-09	1.10E-08	
	Acidification	mol H+ eq	1.20E+00	5.60E-01	3.10E-03	2.80E-02	1.20E-02	0.00E+00	5.90E-01			1.20E-03	1.70E-04	2.00E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	6.85E-03	3.20E-03	6.90E-06	1.60E-04	7.50E-05	0.00E+00	3.40E-03			2.40E-06	3.50E-07	1.30E-06	
	Eutrophication aquatic marine	kg N eq.	2.00E-01	9.20E-02	9.10E-04	4.70E-03	2.50E-03	0.00E+00	9.90E-02			3.60E-04	6.80E-05	9.30E-04	
	Eutrophication terrestrial	mol N eq.	2.20E+00	1.00E+00	1.00E-02	5.20E-02	2.30E-02	0.00E+00	1.10E+00			4.00E-03	7.50E-04	1.10E-02	
	Photochemical ozone formation	kg NMVOC eq.	6.35E-01	2.90E-01	3.10E-03	1.50E-02	1.30E-02	0.00E+00	3.10E-01			1.20E-03	2.10E-04	2.80E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	1.53E-03	7.20E-04	1.90E-06	3.60E-05	1.00E-05	0.00E+00	7.60E-04			5.80E-07	3.30E-08	1.10E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	1.99E+03	8.95E+02	1.20E+01	4.60E+01	7.10E+01	0.00E+00	9.59E+02			4.50E+00	5.80E-01	9.50E-01	
	Water use	m3 world eq. deprived	5.99E+01	2.50E+01	3.50E-02	1.30E+00	6.60E+00	0.00E+00	2.70E+01			1.30E-02	4.10E-03	-6.80E-02	
	Particulate Matter emissions	Disease incidence	1.25E-05	5.80E-06	5.00E-08	2.90E-07	9.40E-08	0.00E+00	6.20E-06			2.10E-08	3.90E-09	1.70E-08	
	Ionizing radiation, human health	kBq U235 eq.	7.74E+00	3.60E+00	5.10E-02	1.80E-01	8.10E-02	0.00E+00	3.80E+00			2.00E-02	5.20E-03	3.10E-03	
	Eco-toxicity (freshwater)	CTUe	6.68E+03	3.15E+03	9.70E+00	1.58E+02	3.50E+01	0.00E+00	3.32E+03			3.60E+00	3.10E-01	1.60E+00	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	2.04E-07	9.60E-08	2.90E-10	4.90E-09	1.20E-09	0.00E+00	1.00E-07			1.00E-10	1.40E-11	1.80E-09	
	Human toxicity, non-cancer effects	CTUh	3.64E-06	1.70E-06	1.00E-08	8.80E-08	3.00E-08	0.00E+00	1.80E-06			4.00E-09	2.50E-10	5.90E-09	
	Land use related impacts/Soil quality	dimensionless	2.49E+04	1.18E+04	7.50E+00	5.92E+02	1.40E+01	0.00E+00	1.24E+04			3.10E+00	3.50E-01	5.30E-01	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Triple Glazing Aluminium frame with thermal bridge break	Climate change - total	kg CO2 eq.	5.00E+02	2.36E+02	7.30E-01	1.20E+01	2.50E+00	0.00E+00	2.49E+02			2.00E-01	9.30E-03	1.00E-02	
	Climate change - fossil	kg CO2 eq.	4.98E+02	2.35E+02	7.30E-01	1.20E+01	2.40E+00	0.00E+00	2.48E+02			2.00E-01	9.20E-03	1.00E-02	
	Climate change - biogenic	kg CO2 eq.	1.67E+00	7.90E-01	3.30E-04	4.00E-02	8.70E-03	0.00E+00	8.30E-01			8.00E-05	3.00E-05	8.00E-06	
	Climate change - land use and land use change	kg CO2 eq.	1.46E+00	6.60E-01	3.00E-04	3.30E-02	7.40E-02	0.00E+00	6.90E-01			6.90E-05	1.80E-05	3.60E-06	
	Ozone depletion	kg CFC 11 eq.	2.80E-05	1.30E-05	1.60E-07	6.60E-07	9.30E-08	0.00E+00	1.40E-05			4.50E-08	1.90E-09	4.00E-09	
	Acidification	mol H+ eq	3.29E+00	1.60E+00	3.00E-03	7.80E-02	1.20E-02	0.00E+00	1.60E+00			8.00E-04	3.60E-05	9.20E-05	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	1.72E-02	8.10E-03	6.50E-06	4.10E-04	7.50E-05	0.00E+00	8.60E-03			1.50E-06	2.20E-07	1.20E-07	
	Eutrophication aquatic marine	kg N eq.	5.16E-01	2.40E-01	8.50E-04	1.20E-02	2.50E-03	0.00E+00	2.60E-01			2.40E-04	1.10E-05	3.20E-05	
	Eutrophication terrestrial	mol N eq.	5.67E+00	2.70E+00	9.50E-03	1.30E-01	2.30E-02	0.00E+00	2.80E+00			2.60E-03	1.30E-04	3.50E-04	
	Photochemical ozone formation	kg NMVOC eq.	1.64E+00	7.70E-01	2.90E-03	3.90E-02	1.30E-02	0.00E+00	8.10E-01			8.10E-04	3.50E-05	1.00E-04	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	7.70E-04	3.60E-04	1.80E-06	1.80E-05	1.00E-05	0.00E+00	3.80E-04			3.80E-07	2.20E-08	8.10E-09	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	5.60E+03	2.62E+03	1.10E+01	1.32E+02	7.10E+01	0.00E+00	2.77E+03			3.00E+00	3.20E-01	2.80E-01	
	Water use	m3 world eq. deprived	1.24E+02	5.60E+01	3.30E-02	2.80E+00	6.60E+00	0.00E+00	5.90E+01			8.20E-03	2.90E-03	1.20E-02	
	Particulate Matter emissions	Disease incidence	3.60E-05	1.70E-05	4.70E-08	8.40E-07	9.40E-08	0.00E+00	1.80E-05			1.40E-08	5.30E-10	1.80E-09	
	Ionizing radiation, human health	kBq U235 eq.	1.30E+01	6.10E+00	4.80E-02	3.10E-01	8.10E-02	0.00E+00	6.40E+00			1.30E-02	3.40E-03	1.30E-03	
	Eco-toxicity (freshwater)	CTUe	1.22E+04	5.79E+03	9.10E+00	2.90E+02	3.50E+01	0.00E+00	6.09E+03			2.40E+00	1.50E-01	1.80E-01	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	5.96E-07	2.80E-07	2.80E-10	1.40E-08	1.20E-09	0.00E+00	3.00E-07			6.70E-11	5.70E-12	4.30E-12	
	Human toxicity, non-cancer effects	CTUh	1.06E-05	5.00E-06	9.80E-09	2.50E-07	3.00E-08	0.00E+00	5.30E-06			2.60E-09	1.10E-10	1.30E-10	
	Land use related impacts/Soil quality	dimensionless	1.52E+03	7.06E+02	7.10E+00	3.60E+01	1.40E+01	0.00E+00	7.51E+02			2.00E+00	2.00E-01	5.70E-01	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	3.17E+02	1.21E+02	1.00E+00	7.50E+00	2.50E+00	0.00E+00	1.57E+02			4.90E-01	2.40E-02	2.70E+01	
	Climate change - fossil	kg CO2 eq.	3.14E+02	1.20E+02	1.00E+00	7.40E+00	2.40E+00	0.00E+00	1.56E+02			4.90E-01	2.40E-02	2.70E+01	
	Climate change - biogenic	kg CO2 eq.	1.18E+00	5.50E-01	4.50E-04	2.80E-02	8.70E-03	0.00E+00	5.90E-01			2.00E-04	7.00E-05	7.10E-03	
	Climate change - land use and land use change	kg CO2 eq.	4.56E-01	1.80E-01	4.10E-04	9.10E-03	7.40E-02	0.00E+00	1.90E-01			1.70E-04	4.20E-05	2.30E-03	
	Ozone depletion	kg CFC 11 eq.	5.87E-05	2.70E-05	2.20E-07	1.40E-06	9.30E-08	0.00E+00	2.90E-05			1.10E-07	5.00E-09	9.00E-07	
	Acidification	mol H+ eq	2.05E+00	9.60E-01	4.00E-03	4.90E-02	1.20E-02	0.00E+00	1.00E+00			2.00E-03	1.10E-04	1.90E-02	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	1.19E-02	5.50E-03	8.80E-06	2.80E-04	7.50E-05	0.00E+00	5.90E-03			3.90E-06	5.20E-07	9.20E-05	
	Eutrophication aquatic marine	kg N eq.	2.96E-01	1.30E-01	1.20E-03	7.00E-03	2.50E-03	0.00E+00	1.50E-01			6.00E-04	3.90E-05	4.70E-03	
	Eutrophication terrestrial	mol N eq.	5.21E+00	2.40E+00	1.30E-02	1.20E-01	2.30E-02	0.00E+00	2.60E+00			6.60E-03	4.40E-04	5.10E-02	
Triple Glazing PVC frame 5 chambers	Photochemical ozone formation	kg NMVOC eq.	9.76E-01	4.40E-01	4.00E-03	2.30E-02	1.30E-02	0.00E+00	4.80E-01			2.00E-03	1.20E-04	1.40E-02	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	3.61E-03	1.70E-03	2.40E-06	8.50E-05	1.00E-05	0.00E+00	1.80E-03			9.60E-07	5.10E-08	7.10E-06	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	4.23E+03	1.91E+03	1.50E+01	9.90E+01	7.10E+01	0.00E+00	2.08E+03			7.40E+00	7.80E-01	4.10E+01	
	Water use	m3 world eq. deprived	2.41E+02	6.10E+01	4.50E-02	5.60E+00	6.60E+00	0.00E+00	1.17E+02			2.10E-02	6.80E-03	5.10E+01	
	Particulate Matter emissions	Disease incidence	1.89E-05	8.70E-06	6.40E-08	4.50E-07	9.40E-08	0.00E+00	9.40E-06			3.40E-08	2.00E-09	1.30E-07	
	Ionizing radiation, human health	kBq U235 eq.	1.14E+01	5.10E+00	6.50E-02	2.70E-01	8.10E-02	0.00E+00	5.70E+00			3.20E-02	8.10E-03	1.90E-01	
	Eco-toxicity (freshwater)	CTUe	1.05E+04	3.49E+03	1.20E+01	2.50E+02	3.50E+01	0.00E+00	5.25E+03			5.90E+00	3.80E-01	1.49E+03	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	4.89E-07	2.30E-07	3.80E-10	1.20E-08	1.20E-09	0.00E+00	2.40E-07			1.70E-10	1.40E-11	4.90E-09	
	Human toxicity, non-cancer effects	CTUh	8.67E-06	3.70E-06	1.30E-08	2.10E-07	3.00E-08	0.00E+00	4.30E-06			6.50E-09	2.80E-10	4.10E-07	
	Land use related impacts/Soil quality	dimensionless	1.50E+03	6.67E+02	9.60E+00	3.50E+01	1.40E+01	0.00E+00	7.42E+02			5.10E+00	4.70E-01	2.40E+01	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	1.88E+02	6.00E+01	9.20E-01	4.40E+00	2.50E+00	0.00E+00	9.30E+01			3.40E-01	2.00E+01	6.80E+00	
	Climate change - fossil	kg CO2 eq.	1.79E+02	8.30E+01	9.20E-01	4.20E+00	2.40E+00	0.00E+00	8.80E+01			3.40E-01	2.60E-02	7.40E-02	
	Climate change - biogenic	kg CO2 eq.	5.74E+00	-2.40E+01	4.10E-04	1.30E-01	8.70E-03	0.00E+00	2.80E+00			1.40E-04	2.00E+01	6.80E+00	
	Climate change - land use and land use change	kg CO2 eq.	4.48E+00	2.10E+00	3.80E-04	1.10E-01	7.40E-02	0.00E+00	2.20E+00			1.20E-04	2.90E-05	2.50E-05	
	Ozone depletion	kg CFC 11 eq.	1.63E-05	7.40E-06	2.10E-07	3.80E-07	9.30E-08	0.00E+00	8.10E-06			7.70E-08	5.40E-09	1.20E-08	
	Acidification	mol H+ eq	1.43E+00	6.70E-01	3.70E-03	3.40E-02	1.20E-02	0.00E+00	7.10E-01			1.40E-03	1.80E-04	2.00E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	8.08E-03	3.80E-03	8.10E-06	1.90E-04	7.50E-05	0.00E+00	4.00E-03			2.70E-06	4.10E-07	1.30E-06	
	Eutrophication aquatic marine	kg N eq.	2.41E-01	1.10E-01	1.10E-03	5.60E-03	2.50E-03	0.00E+00	1.20E-01			4.10E-04	7.10E-05	9.30E-04	
	Eutrophication terrestrial	mol N eq.	2.61E+00	1.20E+00	1.20E-02	6.30E-02	2.30E-02	0.00E+00	1.30E+00			4.50E-03	7.90E-04	1.10E-02	
Triple Glazing Wooden frame	Photochemical ozone formation	kg NMVOC eq.	7.49E-01	3.40E-01	3.70E-03	1.80E-02	1.30E-02	0.00E+00	3.70E-01			1.40E-03	2.20E-04	2.80E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	1.40E-03	6.60E-04	2.20E-06	3.30E-05	1.00E-05	0.00E+00	6.90E-04			6.60E-07	3.90E-08	1.10E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	2.38E+03	1.08E+03	1.40E+01	5.50E+01	7.10E+01	0.00E+00	1.15E+03			5.10E+00	6.60E-01	1.00E+00	
	Water use	m3 world eq. deprived	6.29E+01	2.70E+01	4.20E-02	1.30E+00	6.60E+00	0.00E+00	2.80E+01			1.40E-02	4.80E-03	-6.50E-02	
	Particulate Matter emissions	Disease incidence	1.45E-05	6.80E-06	5.90E-08	3.40E-07	9.40E-08	0.00E+00	7.20E-06			2.40E-08	4.10E-09	1.80E-08	
	Ionizing radiation, human health	kBq U235 eq.	9.29E+00	4.30E+00	6.00E-02	2.20E-01	8.10E-02	0.00E+00	4.60E+00			2.20E-02	6.00E-03	3.40E-03	
	Eco-toxicity (freshwater)	CTUe	4.91E+03	2.30E+03	1.10E+01	1.16E+02	3.50E+01	0.00E+00	2.44E+03			4.10E+00	3.50E-01	1.60E+00	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	2.17E-07	9.90E-08	3.50E-10	5.00E-09	1.20E-09	0.00E+00	1.10E-07			1.10E-10	1.50E-11	1.80E-09	
	Human toxicity, non-cancer effects	CTUh	3.84E-06	1.80E-06	1.20E-08	9.20E-08	3.00E-08	0.00E+00	1.90E-06			4.50E-09	2.80E-10	5.90E-09	
	Land use related impacts/Soil quality	dimensionless	2.50E+04	1.19E+04	8.90E+00	5.94E+02	1.40E+01	0.00E+00	1.25E+04			3.50E+00	4.00E-01	6.40E-01	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Reynaers epd Triple Glazing Aluminium frame	Climate change - total	kg CO2 eq.	3.58E+02	3.29E+02	3.60E-01	1.70E+01	4.70E+00	0.00E+00	0.00E+00			3.30E-01	1.60E-02	6.80E+00	
	Climate change - fossil	kg CO2 eq.	3.55E+02	3.28E+02	3.60E-01	1.70E+01	2.20E+00	0.00E+00	0.00E+00			3.30E-01	1.60E-02	6.70E+00	
	Climate change - biogenic	kg CO2 eq.	1.02E+00	3.50E-01	1.90E-04	1.80E-02	6.40E-01	0.00E+00	0.00E+00			1.80E-04	2.00E-04	9.60E-03	
	Climate change - land use and land use change	kg CO2 eq.	2.73E+00	7.90E-01	1.40E-04	3.90E-02	1.90E+00	0.00E+00	0.00E+00			1.20E-04	3.30E-05	6.20E-04	
	Ozone depletion	kg CFC 11 eq.	9.15E-05	2.10E-05	8.10E-08	1.10E-06	6.90E-05	0.00E+00	0.00E+00			7.50E-08	3.30E-09	2.60E-07	
	Acidification	mol H+ eq	2.02E+00	1.90E+00	1.50E-03	9.60E-02	2.00E-02	0.00E+00	0.00E+00			1.40E-03	5.80E-05	5.40E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	2.43E-02	1.40E-02	3.10E-06	7.10E-04	9.60E-03	0.00E+00	0.00E+00			2.60E-06	3.90E-07	2.40E-05	
	Eutrophication aquatic marine	kg N eq.	3.97E-01	3.60E-01	4.30E-04	1.80E-02	1.70E-02	0.00E+00	0.00E+00			4.00E-04	1.70E-05	1.40E-03	
	Eutrophication terrestrial	mol N eq.	3.66E+00	3.40E+00	4.70E-03	1.70E-01	6.20E-02	0.00E+00	0.00E+00			4.40E-03	2.00E-04	1.50E-02	
	Photochemical ozone formation	kg NMVOC eq.	1.60E+00	1.50E+00	1.40E-03	7.60E-02	1.20E-02	0.00E+00	0.00E+00			1.40E-03	5.30E-05	4.30E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	2.85E-03	2.70E-03	8.20E-07	1.40E-04	9.40E-06	0.00E+00	0.00E+00			6.40E-07	4.00E-08	1.90E-06	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	4.30E+03	4.05E+03	5.40E+00	2.04E+02	2.40E+01	0.00E+00	0.00E+00			5.00E+00	5.80E-01	1.30E+01	
	Water use	m3 world eq. deprived	1.33E+02	1.07E+02	1.60E-02	6.00E+00	7.00E+00	0.00E+00	0.00E+00			1.40E-02	5.30E-03	1.30E+01	
	Particulate Matter emissions	Disease incidence	1.93E-05	1.80E-05	2.40E-08	9.10E-07	2.70E-07	0.00E+00	0.00E+00			2.30E-08	7.80E-10	4.60E-08	
	Ionizing radiation, human health	kBq U235 eq.	1.28E+01	1.20E+01	2.40E-02	6.00E-01	6.90E-02	0.00E+00	0.00E+00			2.20E-02	6.30E-03	6.00E-02	
	Eco-toxicity (freshwater)	CTUe	1.13E+04	1.00E+04	4.50E+00	5.20E+02	3.56E+02	0.00E+00	0.00E+00			4.00E+00	2.80E-01	3.70E+02	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	3.63E-07	3.40E-07	1.30E-10	1.70E-08	4.10E-09	0.00E+00	0.00E+00			1.10E-10	9.80E-12	1.20E-09	
	Human toxicity, non-cancer effects	CTUh	6.82E-06	6.30E-06	4.80E-09	3.20E-07	9.20E-08	0.00E+00	0.00E+00			4.40E-09	1.90E-10	1.00E-07	
	Land use related impacts/Soil quality	dimensionless	1.24E+03	1.05E+03	3.60E+00	5.40E+01	1.16E+02	0.00E+00	0.00E+00			3.40E+00	3.70E-01	1.00E+01	

Table 6. LCA results for photovoltaic panels.

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Monocrystal solar panel	GWP (Global Warming Potential)	kg CO2e	2.20E-01	3.42E-01	1.35E-02	8.56E-04						7.97E-04	5.73E-04	6.39E-06	-1.38E-01
	ODP (Ozone Depletion Potential)	kg CFC11e	3.40E-07	3.47E-07	2.28E-09	2.07E-11						1.46E-10	5.87E-11	4.56E-14	-9.02E-09
	POCP (Formation potential of tropospheric photochemi	kg C2H4e	2.53E-04	2.89E-04	1.13E-05	1.26E-07						4.15E-07	1.65E-07	2.58E-10	-4.84E-05
	AP (Acidification Potential of land and water)	kg SO2e	1.44E-03	1.86E-03	1.33E-04	7.42E-07						2.55E-06	2.18E-06	2.74E-09	-5.57E-04
	EP (Eutrophication Potential)	kg $PO_4{}^3e$	2.06E-04	2.60E-04	1.37E-05	1.55E-07						4.15E-07	3.05E-07	8.93E-10	-6.88E-05
	ADPM (Abiotic Depletion Potential for non fossil resourc	kg Sbe	3.83E-05	5.23E-05	2.39E-07	3.69E-09						2.18E-08	3.27E-09	3.58E-12	-1.43E-05
	ADPE (Abiotic Depletion Potential for fossil resources)	MJ	-1.14E+00	1.90E-01	2.06E-03	1.19E-02						5.37E-03	3.83E-06	-1.35E+00	3.83E-06

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Polycrystal solar panel	GWP (Global Warming Potential)	kg CO2e		3.81E+00	9.99E-02	0.00E+00						0.00E+00	/	6.98E+00	/
	ODP (Ozone Depletion Potential)	kg CFC11e		4.14E-05	6.55E-07	3.93E-09						0.00E+00	/	5.77E-07	/
	POCP (Formation potential of tropospheric photochemi	kg C2H4e		1.54E+01	3.70E-03	1.61E-05						0.00E+00	/	2.34E-03	/
	AP (Acidification Potential of land and water)	kg SO2e		4.75E+00	1.25E-04	0.00E+00						0.00E+00	/	2.30E-02	/
	EP (Eutrophication Potential)	kg $PO_4{}^3e$		1 69E-01	4.76E-03	2.68E-05						0.00E+00	/	4.81E-01	/
	ADPM (Abiotic Depletion Potential for non fossil resourc	kg Sbe		7 56E-03	6.31E-06	6.31E-03						0.00E+00	/	5.10E-05	/

Table 7. LCA results for HVAC+DHW.

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Heat pump_Metals - Plastics (3-10 kW) | Storage vessel_Metals - Plastics (150 l)	Climate change - total	kg CO2 eq.	2.05E+04	4.99E+03	1.30E+01	2.90E+02	8.61E+03	5.79E+03	0.00E+00		0.00E+00	8.70E+00	9.30E-02	7.92E+02	
	Climate change - fossil	kg CO2 eq.	2.05E+04	4.98E+03	1.30E+01	2.89E+02	8.61E+03	5.78E+03	0.00E+00		0.00E+00	8.70E+00	9.30E-02	7.92E+02	
	Climate change - biogenic	kg CO2 eq.	1.87E+01	1.10E+01	5.70E-03	5.40E-01	1.30E-01	7.00E+00	0.00E+00		0.00E+00	3.50E-03	3.10E-04	7.20E-03	
	Climate change - land use and land use change	kg CO2 eq.	9.76E+00	6.20E+00	4.80E-03	3.10E-01	3.50E-02	3.20E+00	0.00E+00		0.00E+00	3.00E-03	1.80E-04	2.20E-03	
	Ozone depletion	kg CFC 11 eq.	1.74E-02	4.00E-03	3.00E-06	2.00E-04	5.10E-03	8.10E-03	0.00E+00		0.00E+00	2.00E-06	1.90E-08	9.50E-07	
	Acidification	mol H+ eq	8.94E+01	3.70E+01	5.50E-02	1.80E+00	3.90E-01	5.00E+01	0.00E+00		0.00E+00	3.60E-02	3.50E-04	1.10E-01	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	7.17E-01	2.90E-01	1.10E-04	1.50E-02	1.70E-03	4.10E-01	0.00E+00		0.00E+00	6.80E-05	2.20E-06	8.80E-05	
	Eutrophication aquatic marine	kg N eq.	7.31E+00	3.60E+00	1.60E-02	1.80E-01	4.80E-02	3.40E+00	0.00E+00		0.00E+00	1.10E-02	1.10E-04	5.10E-02	
	Eutrophication terrestrial	mol N eq.	9.36E+01	4.40E+01	1.80E-01	2.20E+00	5.40E-01	4.60E+01	0.00E+00		0.00E+00	1.20E-01	1.20E-03	5.50E-01	
	Photochemical ozone formation	kg NMVOC eq.	2.92E+01	1.40E+01	5.50E-02	7.40E-01	2.50E-01	1.40E+01	0.00E+00		0.00E+00	3.60E-02	3.30E-04	1.30E-01	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	1.86E-01	7.20E-02	2.60E-05	3.60E-03	1.60E-04	1.10E-01	0.00E+00		0.00E+00	1.70E-05	2.20E-07	8.40E-06	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	8.73E+04	5.45E+04	2.02E+02	2.75E+03	7.02E+02	2.90E+04	0.00E+00		0.00E+00	1.31E+02	3.20E+00	8.50E+01	
	Water use	m3 world eq. deprived	2.31E+03	1.36E+03	6.10E-01	6.90E+01	3.80E+01	8.30E+02	0.00E+00		0.00E+00	3.70E-01	3.00E-02	8.80E+00	
	Particulate Matter emissions	Disease incidence	5.53E-04	3.30E-04	9.80E-07	1.70E-05	3.70E-06	2.00E-04	0.00E+00		0.00E+00	6.10E-07	5.10E-09	5.60E-07	
	Ionizing radiation, human health	kBq U235 eq.	2.30E+02	1.27E+02	8.80E-01	6.50E+00	1.70E+00	9.30E+01	0.00E+00		0.00E+00	5.70E-01	3.50E-02	3.20E-01	
	Eco-toxicity (freshwater)	CTUe	7.28E+05	2.68E+05	1.64E+02	1.38E+04	1.57E+03	4.37E+05	0.00E+00		0.00E+00	1.05E+02	1.60E+00	6.39E+03	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	2.46E-05	9.90E-06	4.60E-09	5.00E-07	1.80E-07	1.40E-05	0.00E+00		0.00E+00	3.00E-09	5.70E-11	2.80E-08	
	Human toxicity, non-cancer effects	CTUh	8.69E-04	3.10E-04	1.80E-07	1.60E-05	1.70E-06	5.40E-04	0.00E+00		0.00E+00	1.10E-07	1.10E-09	1.10E-06	
	Land use related impacts/Soil quality	dimensionless	2.93E+04	1.38E+04	1.63E+02	7.03E+02	1.18E+02	1.44E+04	0.00E+00		0.00E+00	9.00E+01	2.10E+00	5.60E+01	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
Heat pump air/water production	Climate change - total	kg CO2 eq.	2.55E+04	4.33E+03	8.40E+00	2.25E+02		1.13E+04	9.44E+03			3.30E+00	6.30E-02	1.50E+02	
	Climate change - fossil	kg CO2 eq.	2.54E+04	4.32E+03	8.40E+00	2.24E+02		1.13E+04	9.42E+03			3.30E+00	6.30E-02	1.50E+02	
	Climate change - biogenic	kg CO2 eq.	3.47E+01	8.00E+00	3.70E-03	4.00E-01		9.30E+00	1.70E+01			1.40E-03	2.20E-04	1.40E-03	
	Climate change - land use and land use change	kg CO2 eq.	1.14E+01	2.70E+00	3.20E-03	1.30E-01		2.90E+00	5.70E+00			1.20E-03	1.30E-04	4.40E-04	
	Ozone depletion	kg CFC 11 eq.	3.48E-02	5.50E-03	1.90E-06	2.70E-04		1.70E-02	1.20E-02			7.60E-07	1.30E-08	2.20E-07	
	Acidification	mol H+ eq	2.23E+02	4.00E+01	3.40E-02	2.00E+00		9.80E+01	8.30E+01			1.40E-02	2.10E-04	2.20E-02	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	1.83E+00	3.20E-01	7.20E-05	1.60E-02		8.10E-01	6.80E-01			2.60E-05	1.60E-06	1.80E-05	
	Eutrophication aquatic marine	kg N eq.	1.53E+01	2.90E+00	1.00E-02	1.40E-01		6.20E+00	6.00E+00			4.10E-03	5.70E-05	1.00E-02	
	Eutrophication terrestrial	mol N eq.	2.05E+02	3.80E+01	1.10E-01	1.90E+00		8.50E+01	8.00E+01			4.50E-02	6.60E-04	1.10E-01	
	Photochemical ozone formation	kg NMVOC eq.	6.47E+01	1.20E+01	3.50E-02	6.00E-01		2.70E+01	2.50E+01			1.40E-02	1.80E-04	2.60E-02	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	4.95E-01	9.00E-02	1.70E-05	4.50E-03		2.10E-01	1.90E-01			6.50E-06	1.60E-07	1.70E-06	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	1.37E+05	2.74E+04	1.27E+02	1.38E+03		4.99E+04	5.79E+04			5.00E+01	2.30E+00	1.90E+01	
	Water use	m3 world eq. deprived	3.93E+03	7.78E+02	4.00E-01	3.90E+01		1.47E+03	1.64E+03			1.40E-01	2.10E-02	1.80E+00	
	Particulate Matter emissions	Disease incidence	9.50E-04	1.90E-04	6.10E-07	9.50E-06		3.50E-04	4.00E-04			2.30E-07	2.50E-09	1.20E-07	
	Ionizing radiation, human health	kBq U235 eq.	4.12E+02	7.90E+01	5.50E-01	4.00E+00		1.61E+02	1.67E+02			2.20E-01	2.50E-02	7.20E-02	
	Eco-toxicity (freshwater)	CTUe	1.98E+06	3.46E+05	1.05E+02	1.74E+04		8.83E+05	7.30E+05			4.00E+01	1.10E+00	1.29E+03	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	5.25E-05	1.00E-05	3.00E-09	5.10E-07		2.10E-05	2.10E-05			1.10E-09	3.90E-11	5.30E-09	
	Human toxicity, non-cancer effects	CTUh	2.42E-03	4.20E-04	1.10E-07	2.10E-05		1.10E-03	8.80E-04			4.40E-08	7.60E-10	2.10E-07	
	Land use related impacts/Soil quality	dimensionless	5.32E+04	1.04E+04	1.06E+02	5.27E+02		2.00E+04	2.22E+04			3.50E+01	1.50E+00	1.60E+01	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	1.18E+04	3.53E+03	5.70E+00	1.79E+02		4.99E+02	7.54E+03			2.10E+00	4.70E-02	5.00E+01	
	Climate change - fossil	kg CO2 eq.	9.66E+03	2.86E+03	5.60E+00	1.46E+02		4.75E+02	6.13E+03			2.10E+00	4.70E-02	5.00E+01	
	Climate change - biogenic	kg CO2 eq.	8.91E+01	2.10E+01	2.40E-03	1.10E+00		2.30E+01	4.40E+01			8.60E-04	1.70E-04	3.80E-02	
	Climate change - land use and land use change	kg CO2 eq.	2.05E+03	6.51E+02	2.00E-03	3.30E+01		5.00E-01	1.37E+03			7.30E-04	1.00E-04	1.00E-03	
	Ozone depletion	kg CFC 11 eq.	8.02E-04	2.40E-04	1.30E-06	1.20E-05		2.80E-05	5.20E-04			4.80E-07	9.70E-09	4.10E-07	
	Acidification	mol H+ eq	1.35E+02	4.20E+01	2.30E-02	2.10E+00		2.40E+00	8.80E+01			8.60E-03	1.50E-04	2.70E-02	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	9.37E-01	2.90E-01	4.60E-05	1.40E-02		2.30E-02	6.10E-01			1.70E-05	1.20E-06	1.30E-04	
	Eutrophication aquatic marine	kg N eq.	1.68E+01	5.10E+00	6.80E-03	2.60E-01		4.50E-01	1.10E+01			2.50E-03	4.00E-05	5.20E-03	
	Eutrophication terrestrial	mol N eq.	1.26E+02	3.80E+01	7.60E-02	1.90E+00		4.80E+00	8.10E+01			2.80E-02	4.70E-04	6.20E-02	
Gas condencing heating production	Photochemical ozone formation	kg NMVOC eq.	4.51E+01	1.40E+01	2.40E-02	6.90E-01		1.40E+00	2.90E+01			8.60E-03	1.30E-04	2.30E-02	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	1.50E-01	4.50E-02	1.10E-05	2.30E-03		8.00E-03	9.50E-02			4.10E-06	1.20E-07	3.90E-06	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	1.29E+05	3.89E+04	8.60E+01	1.95E+03		6.24E+03	8.19E+04			3.20E+01	1.70E+00	3.70E+01	
	Water use	m3 world eq. deprived	6.32E+03	1.97E+03	2.60E-01	9.80E+01		1.28E+02	4.13E+03			8.80E-02	1.60E-02	1.00E+00	
	Particulate Matter emissions	Disease incidence	7.18E-04	2.20E-04	4.20E-07	1.10E-05		2.60E-05	4.60E-04			1.50E-07	1.70E-09	2.20E-07	
	Ionizing radiation, human health	kBq U235 eq.	3.68E+02	1.10E+02	3.80E-01	5.50E+00		1.90E+01	2.33E+02			1.40E-01	1.90E-02	8.90E-02	
	Eco-toxicity (freshwater)	CTUe	6.07E+05	1.84E+05	7.00E+01	9.22E+03		2.58E+04	3.87E+05			2.50E+01	8.20E-01	4.05E+02	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	4.35E-05	1.30E-05	1.90E-09	6.50E-07		2.80E-06	2.70E-05			7.10E-10	3.00E-11	3.90E-09	
	Human toxicity, non-cancer effects	CTUh	7.64E-04	2.40E-04	7.70E-08	1.20E-05		1.20E-05	5.00E-04			2.80E-08	5.70E-10	2.90E-07	
	Land use related impacts/Soil quality	dimensionless	1.72E+05	5.39E+04	7.20E+01	2.70E+03		1.60E+03	1.13E+05			2.20E+01	1.10E+00	1.80E+01	

	Impact indicator	Calculation unit	Total	A1-A3	A4	A5	B2	B4.1	B4.2	B6.2	C1	C2	C3	C4	D
	Climate change - total	kg CO2 eq.	1.22E+03	2.31E+02	7.90E-01	1.30E+01		4.21E+02	5.30E+02			3.60E-01	6.00E-03	2.00E+01	
	Climate change - fossil	kg CO2 eq.	1.21E+03	2.29E+02	7.90E-01	1.30E+01		4.18E+02	5.27E+02			3.60E-01	5.90E-03	2.00E+01	
	Climate change - biogenic	kg CO2 eq.	6.86E+00	1.30E+00	3.50E-04	6.30E-02		2.80E+00	2.70E+00			1.50E-04	2.10E-05	2.10E-04	
	Climate change - land use and land use change	kg CO2 eq.	1.96E+00	3.80E-01	2.90E-04	1.90E-02		7.60E-01	8.00E-01			1.30E-04	1.20E-05	6.20E-05	
	Ozone depletion	kg CFC 11 eq.	7.11E-05	1.60E-05	1.80E-07	8.20E-07		1.90E-05	3.50E-05			8.20E-08	1.20E-09	2.80E-08	
	Acidification	mol H+ eq	1.62E+01	4.50E+00	3.20E-03	2.30E-01		2.00E+00	9.50E+00			1.50E-03	2.00E-05	2.90E-03	
	Eutrophication														
	Eutrophication aquatic freshwater	kg P eq.	5.97E-02	1.30E-02	6.70E-06	6.60E-04		1.80E-02	2.80E-02			2.80E-06	1.50E-07	2.50E-06	
	Eutrophication aquatic marine	kg N eq.	1.38E+00	3.30E-01	9.50E-04	1.70E-02		3.30E-01	7.00E-01			4.40E-04	5.70E-06	1.40E-03	
	Eutrophication terrestrial	mol N eq.	5.66E+01	1.70E+01	1.10E-02	8.30E-01		3.70E+00	3.50E+01			4.80E-03	6.60E-05	1.50E-02	
Mechanical ventilation production	Photochemical ozone formation	kg NMVOC eq.	4.06E+00	9.10E-01	3.30E-03	4.60E-02		1.20E+00	1.90E+00			1.50E-03	1.80E-05	3.60E-03	
	Depletion of abiotic resources														
	Depletion of abiotic resources - minerals and metals	kg SB eq.	5.35E-02	1.40E-02	1.60E-06	7.20E-04		8.80E-03	3.00E-02			7.00E-07	1.50E-08	2.30E-07	
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value	1.58E+04	3.26E+03	1.20E+01	1.64E+02		5.49E+03	6.89E+03			5.40E+00	2.10E-01	2.50E+00	
	Water use	m3 world eq. deprived	5.11E+02	1.06E+02	3.70E-02	5.30E+00		1.76E+02	2.23E+02			1.50E-02	2.00E-03	2.40E-01	
	Particulate Matter emissions	Disease incidence	1.69E-04	4.20E-05	5.80E-08	2.10E-06		3.70E-05	8.80E-05			2.50E-08	2.50E-10	1.60E-08	
	Ionizing radiation, human health	kBq U235 eq.	4.76E+01	1.00E+01	5.30E-02	5.30E-01		1.50E+01	2.20E+01			2.40E-02	2.40E-03	9.80E-03	
	Eco-toxicity (freshwater)	CTUe	4.93E+04	1.16E+04	9.90E+00	5.93E+02		1.19E+04	2.49E+04			4.30E+00	1.00E-01	2.91E+02	
	Human toxicity														
	Human toxicity, cancer effects	CTUh	3.71E-06	8.90E-07	2.80E-10	4.40E-08		8.70E-07	1.90E-06			1.20E-10	3.70E-12	7.20E-10	
	Human toxicity, non-cancer effects	CTUh	4.68E-05	1.20E-05	1.10E-08	5.80E-07		9.20E-06	2.50E-05			4.70E-09	7.20E-11	2.90E-08	
	Land use related impacts/Soil quality	dimensionless	5.03E+03	1.15E+03	9.80E+00	5.80E+01		1.36E+03	2.45E+03			3.70E+00	1.40E-01	2.00E+00	

Annex 2. Further analysis of prefabricated wall compositions

As a supplementary study to the strategies presented above, the LCA of different prefabricated wall compositions was performed. The goal of this study was to support the coordination team of the Genk Living Lab with data about the environmental performance of the prefabricated walls. Hence, this study did not focus on the final composition of the prefabricated walls, but rather aimed to gain general insights into the choice of materials typically made when designing prefabricated walls. It also serves as support in the decision-making process for the other Living Labs.

This study was performed at element level. The functional unit of planar elements (e.g. external walls, floors, roofs) is defined as 1 m² of the element as built in practice. The advantage of an assessment at the level of individual elements is that it makes it possible to focus on one element without having to design a complete building. A disadvantage is that choices for one particular element may affect other elements (e.g. wider foundations are required for walls with thicker insulation layers), which can only be analysed at building level.

In absence of a specified service life, the assessment method uses a default reference service life of 60 years for dwellings.

As system boundaries, the European standards (CEN 2011, CEN 2019) are followed. The life cycle of a building is divided into several stages or modules (see Figure 1), each with clearly defined boundaries. The basic rule here is that an impact is assigned to the stage in which it occurs.

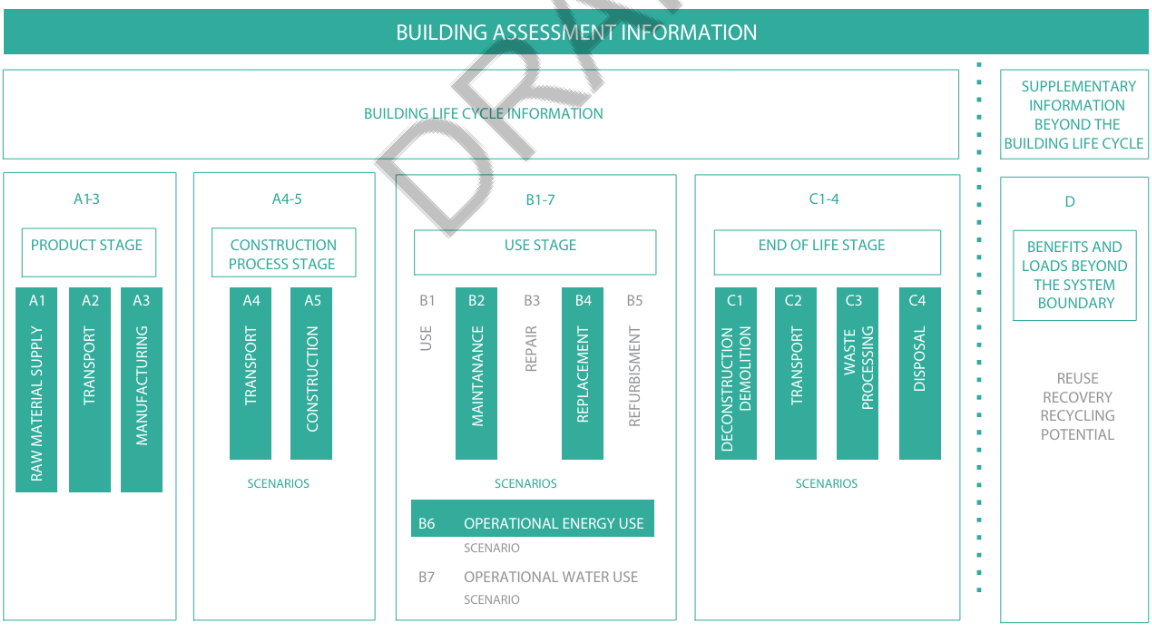
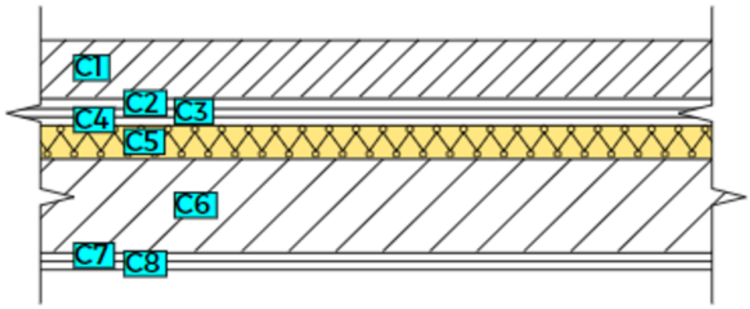


Figure 1. Stages taken into account in the study (in green).

The scenarios discussed are presented below:

1. **Scenario 1: no renovation**

In this scenario, no thorough renovation of the façade is carried out. The composition of the wall remains unchanged. This composition is schematically represented in Figure 2. The wall adheres to a typical Belgian design. From outside to inside, the wall comprises an outer brick layer, a cavity partially filled with insulation, and the load bearing wall, which is covered with gypsum plaster on the inside, which is painted.



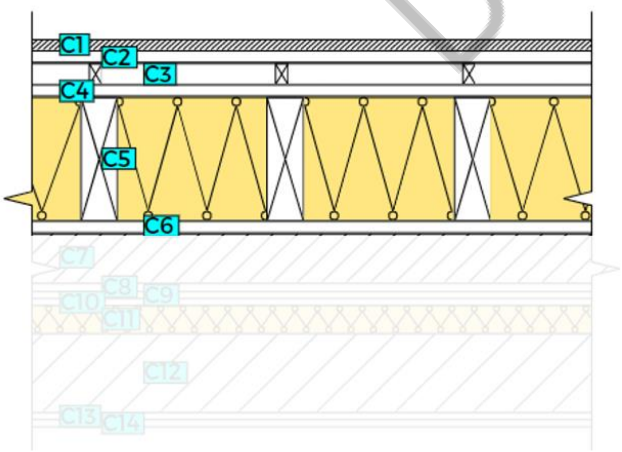
1. C1: brick outer leaf
2. C2: air layer
3. C2: insulation clips
4. C3: cavity ties
5. C5: insulation
6. C6: load bearing brick
7. C7: gypsum plaster
8. C8: paint

Figure 2. Wall composition, scenario 1.

2. Scenario 2: wood-based prefabricated wall

In the second scenario, the renovation involves adding a prefabricated wall in which the structural elements are made of a wooden frame. The composition is schematically represented in Figure 3. In this composition the insulation material, which has a thickness of 22 cm, is placed in between the wooden structural elements.

An additional scenario is also taken into consideration if the bricks of the outer façade of the original wall are demolished before being replace by the prefabricated wall.



1. C1: fired clay strips
2. C2: OSB board
3. C3: battens
4. C4: OSB board
5. C5: wood frame + insulation (22 cm)
6. C6: OSB board

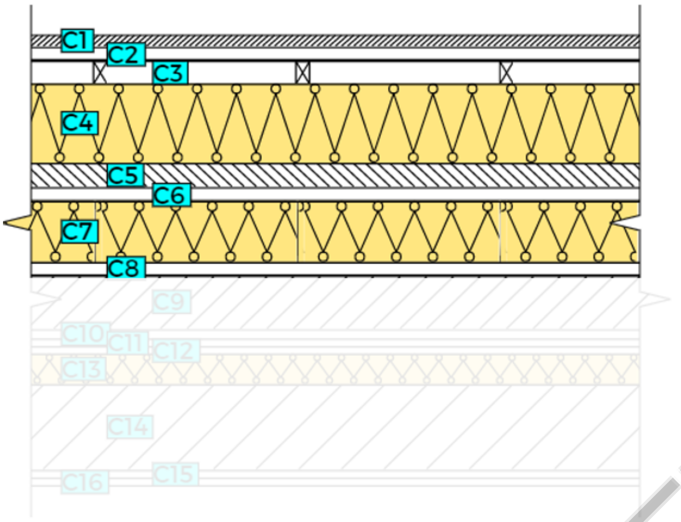
Figure 3. Wall composition, scenario 2.

3. Scenario 3: prefabricated steel-based wall

In the third scenario, the renovation involves adding a prefabricated wall in which the structural elements are made of steel beams. The composition is schematically represented in Figure 4.

In this composition, the insulation material is split into two layers, separated by a U-shaped steel profile.

Two additional scenarios are taken into consideration. Similar to the previous scenario, the option of removing the outer façade bricks of the original wall is taken into account. The second adaption is the replacement of the inner OSB layer with a membrane layer.



1. C1: fired clay strips
2. C2: OSB board
3. C3: battens
4. C4: insulation (13 cm)
5. C5: U-profile
6. C6: OSB board
7. C7: steel frame + insulation (10 cm)
8. C8: OSB

Figure 4. Wall composition. Scenario 3.

Results

The aim of assessing the environmental performance of buildings and building elements, namely to simplify the identification and selection of environmentally friendly materials and components, calls for an unambiguous decision model. A multiplicity of individual impact scores is rarely a good basis for decision-making. For this reason, the environmental profile of a building (element) via an aggregated score is used.

In this context the PEF weighting approach is used. This is in line with European developments in LCA. The PEF weighting approach consists of two steps:

- Normalisation: the characterised values are normalised by dividing them with normalisation factors that are expressed as impact per capita per year (based on a global value in reference year 2010). TOTEM applies the normalisation factors proposed by the European Platform on Life Cycle Assessment (EPLCA 2019[1]).
- Weighting: the normalised values are weighted by multiplying them with weighting factors to reflect the perceived relative importance of the environmental impact categories considered. TOTEM applies the weighting factors by Sala et al (2018)[2].

The results of the LCA of the different scenarios are shown. In the first scenario, where no renovation is taken into account, the impact of the materials is very low and only comprises

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[1] https://eplca.jrc.ec.europa.eu/LCDN/developerEF.html.

[2] Sala S., Cerutti A.K., Pant R. (2018), ***Development of a weighting approach for the Environmental Footprint***, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-68042-7, EUR 28562, doi:10.2760/945290.

the impacts associated with maintenance and the end-of-life scenarios. On the other hand, the impacts related to the operational energy use are very high.

In the subsequent four scenarios, a wall with a thermal transmittance of 0.5 W/m²K is compared. The prefabricated wall with wooden structural elements has the lowest environmental impact. This is mainly due to the environmental impacts of the material choices, which are analysed in Figure 5. Here the impacts of the use of OSB and XPS are highlighted.

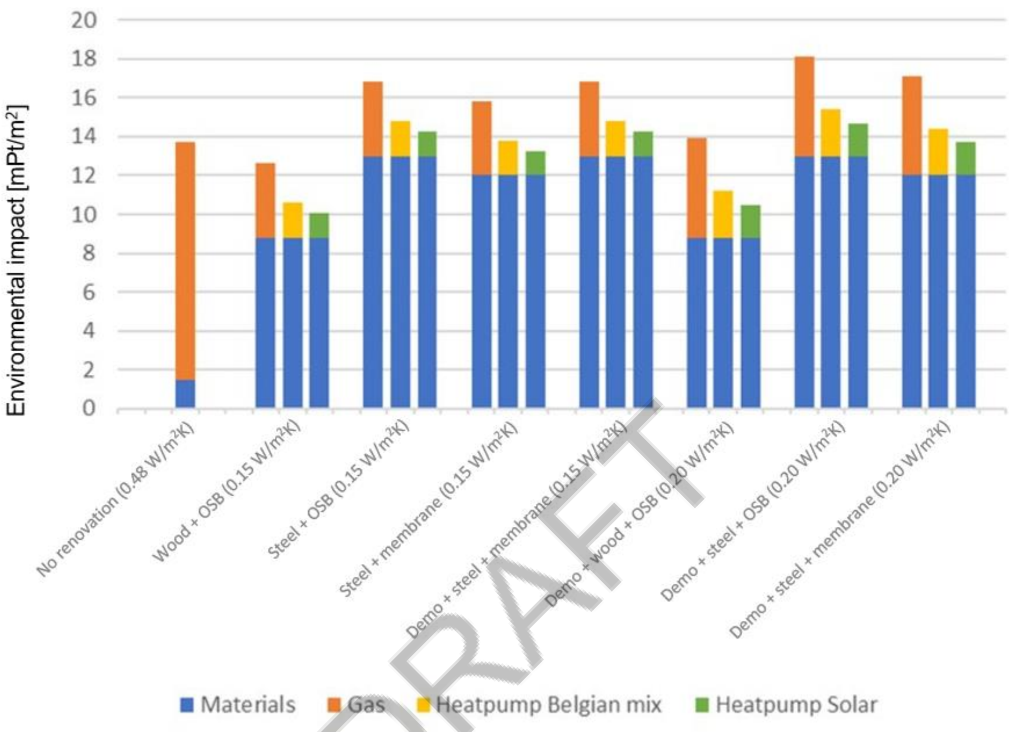


Figure 5. Environmental impact per element and scenario in mPt/m².

For the operational energy use, three scenarios are considered. The first is the use of a gas boiler; in the second scenario, an air-water heat pump is used with a Belgian electricity mix; finally, a heat pump with an electricity mix based on solar production is considered. The environmental impact related to the operational energy use becomes smaller for each scenario.

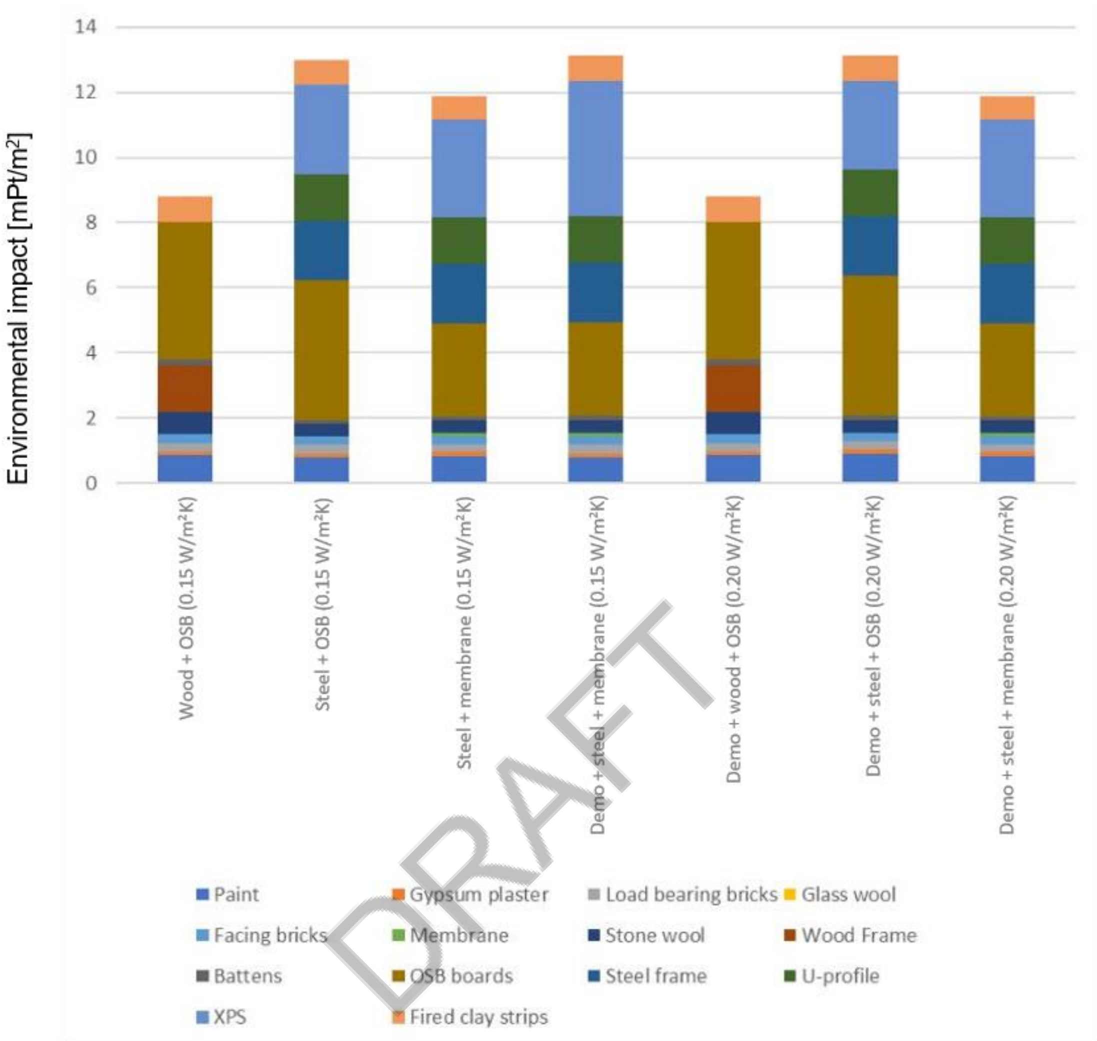


Figure 6. Environmental impact per material (what modules?) and scenario in mPt/m².

Conclusions

In this study, an integrated LCA approach was used to assess different prefabricated wall options. It had the following features:

- A comprehensive picture of the environmental profile of materials, components and elements, and the entire life cycle was taken into account (cf. “cradle-to-grave” LCA);
- Similarly, an extensive range of environmental indicators was implemented (19 at individual level, 16 at weighted value level and 1 at aggregated level) based on LCA principles and recent European standards and frameworks;
- Realistic scenarios were taken into account for the transport of materials and components to the building site and to the EOL processing site, for the type of EOL processing and for the service life of the building in a Belgian context.

Based on similar studies, it is known that as the duration of the study period diminishes and/or the degree of functional adaptation attenuates, the efficacy of customizable construction declines. This decline is pronounced to the extent that conventional construction methods demonstrably outperform adaptable counterparts within this paradigm. Moreover, adaptable iterations exhibit a wider dispersion across various scenarios. Notably, the relevance of end-of-life scenarios is accentuated within this discourse; marginal disparities vis-à-vis traditional construction methodologies are occasionally found, thereby amplifying the real-world impact when demountable structures are sub-optimally utilized, precipitating disposal when reuse remains plausible.

Broadly speaking, the study reiterates the notion that adaptability and circularity do not invariably denote superior sustainability. Rather, their efficacy hinges upon the anticipation of a requisite degree of replacements, necessitating judicious consideration by proficient designers well-versed in pertinent methodologies.

Annex 3. Templates for LCA data collection

This annex presents the templates to be used for data collection. They are tailored for the type of actor from which data are to be gathered.

The tables are available in editable format at the following link: https://openlab-project.eu/toolbox/

1. Manufacturers' LCA data collection template

COMPANY		**LOCATION**	
PRODUCT		**DATE**	
FUNCTIONAL UNIT (FU)		**WEIGHT OF A FUNCTIONAL UNIT (KG)**	

Examples of Functional Unit: 1 brick, 1m2 of panel, 1kg of steel

A1 RAW MATERIALS SUPPLY

Quantity of raw materials purchased for 1 FU:

Material	**Processing**	**% recycling (if known)**	**Quantity**	**Unit (kg, m2, etc)**	**Comments**
Steel	rolled and galvanised				
Plastic	injected				
xxxx					
xx					

A2 TRANSPORT

Indicate for each product:

Product	**Supplier**	**Distance (km)**	**Type of transport (choose from the drop-down list). If there are combined transports (e.g. plane + truck), fill in one line for each type of transport**	**Quantity (as above)**	**Unit**	**Comments**

A3 MANUFACTURE

2 options to answer: VIA 1: data per FU are known. VIA 2: only annual data for the whole plant are known.

When choosing via 2 (instead of via 1) to give some data, it is necessary to fill in the following table:

<table>
<tr><td colspan="3"></td><td>Concept</td><td>Quantity</td><td>Unit</td><td>Comments</td></tr>
<tr><td rowspan="4">VIA 2: ANNUAL DATA FOR WHOLE PLANT
ALLOCATION</td><td rowspan="4">Choose 1 of the 2 options</td><td rowspan="2">Option 1: mass allocation</td><td>Product weight</td><td></td><td></td><td></td></tr>
<tr><td>Weight of all products produced in the plant</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Option 2: economic allocation</td><td>% of total sales of the company represented by the product group indicated in the FU</td><td></td><td></td><td></td></tr>
<tr><td>No. of FU sold per year of this product group</td><td></td><td></td><td></td></tr>
</table>

GENERAL CONSUMPTIONS

	Process	Type of consumption	Quantity consumed per FU	Unit	Comments
Consumption VIA 1: consumption assigned to a Functional Unit		Electricity		kWh	
		Gas		kWh	
		Water		m3	
		Diesel		l	
		Gasoline		l	

	Process	Type of consumption	Total annual consumption of the plant	Unit	Comments
Consumption VIA 2: annual consumption of the plant		Electricity		kWh	
		Gas		kWh	
		Water		m3	
		Diesel		l	
		Gasoline		l	

WASTE GENERATED AT THE PRODUCTION SITE AND TRANSPORTED TO A WASTE MANAGER

	Process	Waste	Waste manager	Type of management (recycling, energy recovery, reuse...)	Quantity of waste generated for one FU	Unit	Distance to waste manager (km)	Type of transport (choose from the drop-down list)	Comments
VIA 1: waste assigned to a Functional Unit						m3			
						kg			

	Process	Waste	Waste manager	Type of management (recycling, energy recovery, reuse...)	Total quantity of waste generated in 1 year in the plant	Unit	Distance to waste manager (km)	Type of transport (choose from the drop-down list)	Comments
VIA 2: annual waste of the plant						m3			
						kg			

WASTE WATER MANAGEMENT

	Type	Discharge location	Quantity of waste water discharged for 1 FU	Unit	Comments
VIA 1: waste water assigned to a Functional Unit	Water discharged to	Watercourse		m3	
	Water discharged to	Sewage system		m3	
	Water discharged to	Others		m3	

	Type	Discharge location	Quantity of waste water discharged in 1 year in the plant	Unit	Comments
VIA 2: annual waste water of the plant	Water discharged to	Watercourse		m3	
	Water discharged to	Sewage system		m3	
	Water discharged to	Others		m3	

C1 DECONSTRUCTION-DEMOLITION

Product	Composition	% of final product by weight	Easily removable (YES/NO)	Esily separable from other elements (YES/NO)	Easily recyclable (YES/NO)	Comments
Plasterboard	Gypsum		YES	YES	NO	
	Cellulose					

2. Constructors' (on site) LCA data collection template

CONSTRUCTOR		**LOCATION**	
BUILDING		**DATE**	

A4 TRANSPORT TO CONSTRUCTION SITE							
Indicate for each product:				Choose 1 of the 2 options:			
				Option 1 (more precise)	**Option 2 (only valid for road transport)**		
Product	**Supplier**	**Distance (km)**	**Type of transport (choose from the drop-down list). If there are combined transports (e.g. plane + truck), fill in one line for each type of transport**	**Total quantity transported (kg)**	**Capacity of the transport used (tonnes)**	**Nº of one-way trips**	**Comments**

A5 CONSTRUCTION AND INSTALLATION							
Energies							
Consumption	**Process/input**	**Electricity supplier**	**Where it is used**		**Quantity**	**Unit**	**Comments**
ELECTRICITY			N/A			kWh	
GAS		N/A	N/A			kWh	
DIESEL		N/A				l	
GASOLINE		N/A				l	

Construction waste							
Process	**Waste**	**Type of management (recycling, energy recovery, reuse...)**			**Quantity**	**Unit**	**Comments**
Dismantling a wall	CDW (Construction and Demolition Waste)					m3	

Waste transport	Indicate for each product:			Choose one of the 2 options:			
				Option 1 (more precise)	**Option 2 (only valid for road transport)**		
	Waste	**Distance (km)**	**Type of transport (choose from the drop-down list). If there are combined transports (e.g. plane + truck), fill in one line for each type of transport**	**Total quantity transported (kg)**	**Capacity of the transport used (tonnes)**	**Nº of one-way trips**	**Comments**

3. Inventory of materials

Inventory of reused / recycled / repaired / recovered / discarded materials																							
MATERIAL/PRODUCT				SOURCE OF ORIGIN						QUANTITY		DESTINATION											
Name	Material identification	Description	Assumed lifetime (years)	Building	Block number	Part of the building (category)	Floor	Staircase	Room	Quantity	Unit	Main Destination	Estimated rate (%)	Use	Level of reusability	Type of waste	Building	Block number	Part of the building (category)	Floor	Staircase	Room	Comments

4. Indicators of prefabricated elements workflow template

	KPI	Unit of measurement	Comments
1. TIME	1.1 +Time spent reading and interpreting the plans delivered by the developer	Hours/ Minutes	
	1.2 +Time spent taking additional measurements on site	Hours/ Minutes	
	1.3 +Time generating drawings, sketches or templates to be able to manufacture both the initial prototypes and the final pieces of the framework and lining.	Hours/ Minutes	
	1.4 +Time used to calculate and order the material from the suppliers.	Hours/ Minutes	
	1.5 +Time spent going to take materials.	Hours/ Minutes	
	1.6 +Time used generating the initial prototypes, including its initial fitting on site to validate the prototype.	Hours/ Minutes	
	1.7 +Time used in the workshop during manufacture and assembly.	Hours/ Minutes	
	1.8 +Time used in the assembly and completion on site.	Hours/ Minutes	
	1.9 +Time spent transporting material and semi-assembled parts to site.	Hours/ Minutes	
	1.10 +Time spent responding to contingencies.	Hours/ Minutes	
2. COSTS	**Budget**	€/m2 projected	
	Work certifications	€/m2 executed	Find the increment /m2
	Cost and extra cost of staff work.	€/m2 executed	
	Cost and additional cost of transportation	€/m2 executed	Define the type of vehicle, number of trips and KM of route + COSTS
	Contingencies costs	€/m2 executed	Define the error / time involved (1.10) / cost overrun
	Others		
3. SUSTAINABILITY	**Dimensions of the industrialised elements**		
	Kg of materials **X** palets		The quantity of material recieved will be compared with the quantity ordered /m2 (SQUARE METER ACTUALLY EXECUTED on site)- will be compared to establish the excess material with respect to the BIM flow
	Transport:		Define the type of vehicle, number of trips and KM of travel used to transport the material. Calculate the total and then calculate per m2 (see proposed table)
	Energy: electricity consumption	kWh (total, not per m2 executed)	Define what electricity inputs there are (what is being used: power saws, screwdrivers, etc.) **No. of effective hours** performed for each of these energy consuming processes. Example: if a screwdriver is used, measure in one hour how many times it is used and how much it consumes.
	Energy: fuel consumption	l (diesel/gasoline) total, not per m2 executed	Detect and measure possible expenditure of fuel other than transport fuel (A4), such as cranes or generators (A5) Know the **type and quantity** of fuel (diesel/gasoline) Measure the number of effective hours carried out with each of these elements that consume fuel or the number of effective hours of use between each time the fuel tank of the equipment is filled and count the fuel filled in that load (if this is not possible, use generic data from a database).
	Waste	m3 (total, not per m2 executed)	Know which processes generate waste. What waste is generated by each process. Measure one hour of each process to extrapolate. Example: dismantling a wall generates x kg of CDW (Construction and Demolition Waste).

Annex 4. Case study of linking LCA and BIM

This annex summarises the practical study carried out in the oPEN Lab project to test the data flow and workflow of the link between LCA and BIM as commented in the report. In the case study, the option of linking data in file extensions BC3 and IFC has been used to obtain the most complete inventory possible. A simple apartment block has been used as the case study.

The steps involved in the process are described below.

1. Definition of system boundaries

This case study has been simplified by omitting the use phase; the rest of the phases are considered. Including the use phase implies evaluating energy efficiency in that phase, which is not considered for the current demonstration (see Figure 1).

<table>
<tr><td colspan="3" rowspan="2">Product / Manufacture Stage [A1-A3]</td><td colspan="2" rowspan="2">Constructio n Process Stage [A4-A5]</td><td colspan="7">Use [B1-B7]</td><td colspan="4" rowspan="2">End-of-Life Stage [C1-C4]</td><td rowspan="2">Benefit s & Loads Beyond [D]</td></tr>
<tr><td colspan="5">Building Fabric</td><td colspan="2">Operation of the Building</td></tr>
<tr><td>Raw Material Extract / Process / Supply</td><td>Transport</td><td>Manufacture</td><td>Transport to the Site</td><td>Assembly / Install in the building</td><td>Use / Application of Installed Products</td><td>Maintenance</td><td>Repair</td><td>Replacement</td><td>Refurbishment</td><td>Operational Energy Use</td><td>Operational Water Use</td><td>Deconstruction / Demolition</td><td>Transport to Waste Process</td><td>Reuse-Recovery-Recycle</td><td>Disposal</td><td>Reuse-Recovery-Recycle Potential</td></tr>
<tr><td>A1</td><td>A2</td><td>A3</td><td>A4</td><td>A5</td><td>B1</td><td>B2</td><td>B3</td><td>B4</td><td>B5</td><td>B6</td><td>B7</td><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td>D</td></tr>
<tr><td colspan="3">Cradle-to-Gate</td><td colspan="13">Gate-to-Grave</td><td rowspan="2"></td></tr>
<tr><td colspan="16">Cradle-to-Grave</td></tr>
<tr><td colspan="17">Cradle-to-Cradle</td></tr>
<tr><td colspan="17">System Boundaries</td></tr>
</table>

Figure 1. Case study system boundaries. Use phase (B1-B7) is excluded.

2. Data flow between BIM and LCA software

The steps for the data collection from BIM are outlined below.

1. **BIM data extraction from models**. For this purpose, the **Periscoope tool**[3] is used to extract CSV data. This data is imported into Excel and encompasses all BIM elements, along with the parameters required for linking with budgeting databases. Figure 2 provides an example of this type of BIM data:

[3] https://periscoope.io/

Periscoope_Basic/ModelFileName	Periscoope_Basic/GlobalId	Periscoope_Basic/Name	Periscoope_Basic/ExpressType	GVA_ConstructionSystemsMaterials/SCO_Classification
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	2jW9S3EkH4NgqYPrpLzDgk	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	3Okow_63PBiRCfZTAq6CNy	RHS-Steel - Rectangular - Pillar:EEHE_RHS_80_40_5_(RolledSt	IfcColumn	EEHE
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	3Okow_63PBiRCfZTAq6CNv	RHS-Steel - Rectangular - Pillar:EEHE_RHS_80_40_5_(RolledSt	IfcColumn	EEHE
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	3Okow_63PBiRCfZTAq6CNx	RHS-Steel - Rectangular - Pillar:EEHE_RHS_80_40_5_(RolledSt	IfcColumn	EEHE
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0QNy8FOPTCnOe69kzbtVXD	RHS-Steel - Rectangular - Pillar:EEHE_RHS_80_40_5_(RolledSt	IfcColumn	EEHE
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0QNy8FOPTCnOe69kzbtVcp	RHS-Steel - Rectangular - Pillar:EEHE_RHS_80_40_5_(RolledSt	IfcColumn	EEHE
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0QNy8FOPTCnOe69kzbtVcn	RHS-Steel - Rectangular - Pillar:EEHE_RHS_80_40_5_(RolledSt	IfcColumn	EEHE
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0QNy8FOPTCnOe69kzbtVct	RHS-Steel - Rectangular - Pillar:EEHE_RHS_80_40_5_(RolledSt	IfcColumn	EEHE
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0QNy8FOPTCnOe69kzbtVbz	RHS-Steel - Rectangular - Pillar:EEHE_RHS_100_100_5_(Rolled	IfcColumn	EEHE
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0QNy8FOPTCnOe69kzbtVbZ	RHS-Steel - Rectangular - Pillar:EEHE_RHS_240_100_5_(Rolled	IfcColumn	EEHE
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0QNy8FOPTCnOe69kzbtVbX	RHS-Steel - Rectangular - Pillar:EEHE_RHS_240_100_5_(Rolled	IfcColumn	EEHE
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0QNy8FOPTCnOe69kzbtVbd	RHS-Steel - Rectangular - Pillar:EEHE_RHS_150_40_5_(RolledS	IfcColumn	EEHE
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0QNy8FOPTCnOe69kzbtVbh	M_Concrete-Rectangular-Column:EEMH_20 cm_80 cm_(Rein	IfcColumn	EEMH
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0QNy8FOPTCnOe69kzbtVbf	M_Concrete-Rectangular-Column:EEMH_20 cm_104 cm_(Rein	IfcColumn	EEMH
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0p_65WpvD8kg4c_oubAQ37	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_AnQzjAv8QwTUzG9fJdwz	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0p_65WpvD8kg4c_oubAQH_	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_AnQzjAv8QwTUzG9fJdwC	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0p_65WpvD8kg4c_oubATfh	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_AnQzjAv8QwTUzG9fJdvk	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_AnQzjAv8QwTUzG9fJdxS	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_AnQzjAv8QwTUzG9fJdve	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_AnQzjAv8QwTUzG9fJdwi	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_AnQzjAv8QwTUzG9fJd$G	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_AnQzjAv8QwTUzG9fJd$T	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_AnQzjAv8QwTUzG9fJd$I	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	2wOoSyMh14GPJB8wR$pgi8	Basic wall:EEMM_10_cm_ (CLT_4-2-4):12643635	IfcOpeningElement	EEMM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_AnQzjAv8QwTUzG9fJd84	Basic wall:ECCM_25 cm_(ReinforcedConcreteXC2):12888031	IfcOpeningElement	ECCM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0AbssTkRfELuaajGsjG_PU	Basic wall:ECCM_25 cm_(ReinforcedConcreteXC2):12888029	IfcOpeningElement	ECCM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	189iMfSFfAROqxmL2ZHTN9	Basic wall:EEMH_20 cm_(ReinforcedConcreteXC2):12887920	IfcOpeningElement	EEMH
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_vl7uYgL7yPpFXY_m7W4E	Basic wall:EEMH_30 cm_(ReinforcedConcreteXS1):13111580	IfcWallStandardCase	EEMH
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1_vl7uYgL7yPpFXY_m7X_z	Basic wall:EEMH_30 cm_(ReinforcedConcreteXS1):13111215	IfcWallStandardCase	EEMH
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	2tgnJVDkX4iOf0qWJPudz6		IfcOpeningElement	EEFH
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	2GqbeA4$L4TBhs1_3GfEPg		IfcOpeningElement	EEFH
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1RckkL47bFE9IyMJYKKYeT	Basic wall:EEMH_20 cm_(ReinforcedConcreteXS1):12948047	IfcOpeningElement	EEMH
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1RckkL47bFE9IyMJYKKYdd	Basic wall:EEMH_20 cm_(ReinforcedConcreteXS1):12947284	IfcOpeningElement	EEMH
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1RckkL47bFE9IyMJYKKYdB	Basic wall:EEMH_20 cm_(ReinforcedConcreteXS1):12947284	IfcOpeningElement	EEMH
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	1RckkL47bFE9IyMJYKKYal	Basic wall:EEMH_20 cm_(ReinforcedConcreteXS1):12947284	IfcOpeningElement	EEMH
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	0wdefp8jP5Qf$nUzqmj$S$		IfcOpeningElement	EEFM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	3jCaudz_D6H9LQwIlF6$3e		IfcOpeningElement	EEFM
04Y02-18_IMB_CPL-CPL_ES_M3D_ESTRUCT.ifc	2wcR1iI4n5WeEESqEnf0sV		IfcOpeningElement	EEFM

Figure 2. CSV data extracted from an IFC BIM model using Periscoope.

This data has been extracted from the BIM models comprising the sample building. Figure 3 shows an image of the BIM model of the building extracted from the Periscoope viewer.

Figure 3. IFC BIM model in Periscoope.

2. **Extraction of BC3 data**. BC3 is the budgeting database created from the price database of IVE 2023[4] (Valencian Building Institute), through which the price tree and project budget have been generated. Figure 4 shows this budget and how it follows the structure proposed by the IVE:

[4] https://www.five.es/

Figure 4. Construction systems data in bc3 format.

Subsequently, this BC3 is converted to CSV format through Periscoope in order to have the data in a tabular format when inserted into Excel. Figure 5 shows part of the table involving this conversion of the budget to CSV:

Periscoope_BC3_Basic/GlobalId	Periscoope_BC3_Basic/Comment	Periscoope_BC3_Basico/Units	Periscoope_BC3_Basic/	Periscoope_BC3_Basic/W	Periscoope_BC3_Basic/H	Periscoope_BC3_Basic/Measurem	Periscoope_BC3_Basic/Amou
1_AnQzjAv8QwTUzG9fJdqw	E01-CIM-00	NULL	6.78	NULL	NULL	6.78	54.92
1_AnQzjAv8QwTUzG9fJdqu	E01-CIM-00	NULL	1.66	NULL	NULL	1.66	13.45
1_AnQzjAv8QwTUzG9fJdqy	E01-CIM-00	NULL	41.74	NULL	NULL	41.74	338.09
1waPDIqfrB7BtLgxDJeHTm	E01-CIM-00	NULL	2.82	NULL	NULL	2.82	22.84
0zOBTlRi5BvgnpBl2Zo79L	E01-CIM-00	NULL	1.52	NULL	NULL	1.52	12.31
3iVMwfa2H34hlgiku8YH7d	E03-FOR-P01	NULL	1.56	61.3	NULL	95.628	459.01
3iVMwfa2H34hlgiku8YH2K	E03-FOR-P02	NULL	4.54	61.3	NULL	278.302	1335.85
3iVMwfa2H34hlgiku8YHSx	E03-FOR-P03	NULL	4.54	61.3	NULL	278.302	1335.85
3iVMwfa2H34hlgiku8YHSd	E03-FOR-P03	NULL	1.56	61.3	NULL	95.628	459.01
3iVMwfa2H34hlgiku8YHRb	E03-FOR-P03	NULL	4.54	61.3	NULL	278.302	1335.85
3iVMwfa2H34hlgiku8YHQB	E03-FOR-P04	NULL	4.54	61.3	NULL	278.302	1335.85
3iVMwfa2H34hlgiku8YHQr	E03-FOR-P04	NULL	1.56	61.3	NULL	95.628	459.01
3iVMwfa2H34hlgiku8YHPX	E03-FOR-P05	NULL	4.54	61.3	NULL	278.302	1335.85
3iVMwfa2H34hlgiku8YHPh	E03-FOR-P05	NULL	1.56	61.3	NULL	95.628	459.01
3iVMwfa2H34hlgiku8YHN8	E03-FOR-P05	NULL	4.54	61.3	NULL	278.302	1335.85
3iVMwfa2H34hlgiku8YHM4	E03-FOR-P06	NULL	4.54	61.3	NULL	278.302	1335.85
3iVMwfa2H34hlgiku8YHME	E03-FOR-P06	NULL	1.72	61.3	NULL	105.436	506.09
3iVMwfa2H34hlgiku8YHLt	E03-FOR-P07	NULL	4.54	61.3	NULL	278.302	1335.85
3iVMwfa2H34hlgiku8YHLn	E03-FOR-P07	NULL	1.65	61.3	NULL	101.145	485.5
1fcBAQYuTA0worTZNjwUGr	E03-FOR-P08	NULL	4.59	61.3	NULL	281.367	1350.56
1DTL$Alab1lvL44$bND67T	E01-CIM-00	NULL	1.57	61.3	NULL	96.241	461.96
1DTL$Alab1lvL44$bND5$m	E01-CIM-00	NULL	0.28	61.3	NULL	17.164	82.39
1DTL$Alab1lvL44$bND5_4	E01-CIM-00	NULL	1.57	61.3	NULL	96.241	461.96
1DTL$Alab1lvL44$bND5_K	E01-CIM-00	NULL	0.91	61.3	NULL	55.783	267.76
1XcvggKuTAv9$iA8Veglv4	E03-FOR-P02	NULL	1.56	61.3	NULL	95.628	459.01
1fcBAQYuTA0worTZNjwUGt	E03-FOR-P08	NULL	14.36	8.13	NULL	116.747	560.39
1fcBAQYuTA0worTZNjwUGf	E03-FOR-P08	NULL	14.29	8.13	NULL	116.178	557.65
1fcBAQYuTA0worTZNjwUGh	E03-FOR-P08	NULL	3.07	8.13	NULL	24.959	119.8
1fcBAQYuTA0worTZNjwUGj	E03-FOR-P08	NULL	3.07	8.13	NULL	24.959	119.8
1fcBAQYuTA0worTZNjwUGl	E03-FOR-P08	NULL	3.07	8.13	NULL	24.959	119.8
1fcBAQYuTA0worTZNjwUGX	E03-FOR-P08	NULL	3.07	8.13	NULL	24.959	119.8
1fcBAQYuTA0worTZNjwUGP	E03-FOR-P08	NULL	14.53	8.13	NULL	118.129	567.02
1fcBAQYuTA0worTZNjwUGR	E03-FOR-P08	NULL	3.34	8.13	NULL	27.154	130.34
1$vtur90TCZudIA2$f0WeB	E03-FOR-P08	NULL	16.75	8.13	NULL	136.178	653.65

Figure 5. BC3 construction systems converted to csv format by Periscoope.

3. **Linking of both databases in Excel**: the next step is to link both databases using the unique identifier of the BIM model (IFCGlobalId), which makes it possible to match both databases and extract the total quantity of materials present in the project. The following table (Figure 6) shows the quantities of each material obtained and their unit of measurement.

Periscoope_BC3_Basic/Descc	Periscoope_BC3_Basic/Descompuesto_N	Periscoop	Periscoop	Periscoop	Periscoope_BC3_Basic/Material_Quant
PEAA,2cM	Steel B 500 S elaborado recic	kg	3	No	63643.25879
PFFC,2b	Brick perf n/visto 24x11.5x7	u	3	No	48687.6
PEAP60bbabbM	Steel S 275J0 lmnd cal acab galv RECI-REUT	kg	3	No	29402.422
PEAW,7a	Welding impact kg/est	u	3	No	29402.422
PFPP15a	Screw 25mm p/pnl gypsum	u	3	No	25258.32
PFPP15c	Screw 45mm p/pnl gypsum	u	3	No	15422.32
PFPP15b	Screw 35mm p/pnl gypsum	u	3	No	10451.7
PFPP19a	Self-drilling screw 13 mm p/PYL	u	3	No	8390.14
PBUA50aaa	Adh cementoso C1	kg	3	No	7362.004
MOOA,8a	First officer construction	h	1	No	4924.139776
PFPP20a	Tape p/gaskets PYL	m	3	No	4369.19
PFDB40fegalv	Plate a calibrado 40x8mm	kg	3	No	3503.262
PFPP,9b30	Frame 30 p/tab laminated plaster	m	3	No	3076.108
MOOC,8a	First officer carpentry	h	1	No	2849.36051
PBUT25bcej	Torn rsc total M-10x50 8.8	u	3	No	2770
PFPP,9b	Frame 48 p/tab laminated plaster	m	3	No	2698.528
PIEC,1daabb	Cbl Cu RZ1-K (AS) 0.6/1kV 1x2.5mm2	m	3	No	2520
PIEC,1eaaba_M	Cbl Cu SZ1-K (AS+) 0.6/1kV 1x1.5mm2	m	0	No	2362.5
PNIA,2ae	Geotextile non-woven polyester 300 gr/m2	m2	3	No	2262.34
MOOA12a	Ordinary labourer construction	h	1	No	2245.809095
PIAR35a	Coaxial cable c/atenuación 29	m	3	No	2046
PFPC,1ad	Laminated plasterboard A 15mm	m2	3	No	2038.061
MOOA11a	Specialised labourer construction	h	1	No	1724.29798

Figure 6. Databases linkage in CSV (ifc and bc3).

Figure 7, below, shows how the tables in Excel are connected through IFCGlobalId with the BIM model (two elements have been highlighted, one in yellow and another in red):

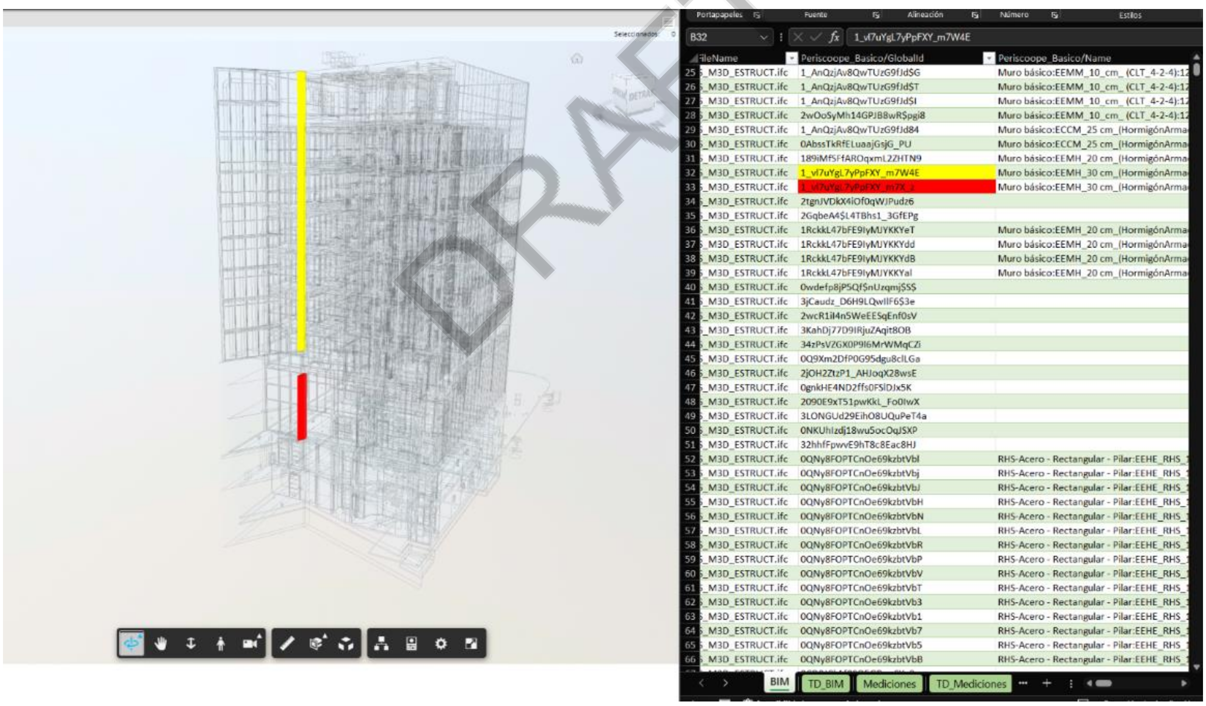


Figure 7. Periscoope model linked with the csv database where elements of the building can be highlighted through IFCGlobalId.

4. **Environmental impact link to materials:** after inventorying, it is necessary to link this data with the impact generated by each product/element/material unit so that the total impact can be quantified. To do so, in this case, data has been extracted from environmental product declarations (EPDs) of products similar to those used in the construction project (see example in Figure 8). The main sources for consultation were:
   - AENOR EPDs (EPDs, s.f.);

- OpenDAP (OpenDAP, s.f.);
- EC3 Tool (EC3, s.f.);
- EcoPlatform (EcoPlatform, s.f.).

Nevertheless, this data could be obtained from any of the data sources and in the ways discussed in the report.

ENVIRONMENTAL IMPACT CATEGORY	UNIT	MANUFACTURING STAGE			INSTALLATION STAGE		USE STAGE							END OF LIFE STAGE				LIFE CYCLE TOTAL	D
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4		
Global warming potential (GWP)	Kg CO2 eq.	-716.18	27.45	3.20	47.82	7.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.99	2.38	859.38	0.00	236.42	-56.52
Acidification potential (AP)	Kg SO2 eq.	9.20E-01	6.60E-02	2.10E-02	1.10E-01	5.00E-02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.80E-02	5.70E-03	0.00	0.00	1.22	-3.77E-01
Eutrophication potential (EP)	Kg PO4 3- eq.	2.10E-01	1.40E-02	4.70E-03	2.40E-02	1.30E-02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.70E-03	1.20E-03	0.00	0.00	2.78E-01	-9.55E-02
Formation potential of tropospheric ozone (POCP)	Kg C2H4 eq.	1.40E-01	4.20E-03	6.50E-04	7.40E-03	2.20E-03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00E-03	3.70E-04	0.00	0.00	1.58E-01	-3.60E-02
Abiotic depletion potential – Elements	Kg Sb eq.	4.00E-04	8.50E-05	1.20E-06	1.50E-04	3.40E-04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50E-06	7.30E-06	0.00	0.00	9.78E-04	-1.55E-04
Abiotic depletion potential – Fossil resources	MJ, net calorific value	1,900.62	440.19	60.12	766.78	116.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	76.8	38.11	0.00	0.00	3,399.58	-840.35
Ozone layer depletion	Kg CFC 11 eq.	1.90E-05	5.20E-06	4.30E-07	9.00E-06	1.20E-06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.10E-07	4.50E-07	0.00	0.00	3.57E-05	-6.22E-06
Water pollution	m3 eq.	195.60	29.07	2.55	50.63	9.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.24	2.52	0.00	0.00	294.12	-87.62
Air pollution	m3 eq.	35,448.32	2,705.98	341.8	4,713.78	1,320.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	609.7	234.25	0.00	0.00	45,374.02	-26,828.81

Figure 8. Environmental declaration for CLT product. 2023. EPD International, EGOIN Zurezko eraikuntzak. 2023.

Finally, the data on impact quantities per unit of product are converted to Excel so that they can subsequently be combined with the total quantities of the product involved in the building, as presented in Figure 9.

Periscoope_BC3_Basic/Descompuesto_Code	Periscoope_BC3_Basic/Descompuesto_Unit	Periscoop	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D	Total	Factor	NetTotal(KgC02eq)
PEAA,2cM	B 500 S Steel processed recycled	kg	4990	0	0	0	0	0	0	0	0	0	0	9.31	0	0.773	-0.000364	5000.082636	0.001	5.000082636
PEAA,3cd	Corrugated B 500 S steel ø12	kg	4990	0	0	0	0	0	0	0	0	0	0	9.31	0	0.773	-0.000364	5000.082636	0.001	5.000082636
PEAA,3ca	Corrugated B 500 S steel ø6	kg	4990	0	0	0	0	0	0	0	0	0	0	9.31	0	0.773	-0.000364	5000.082636	0.001	5.000082636
PEAA,3ac	Corrugated B 400 S steel ø10	kg	4990	0	0	0	0	0	0	0	0	0	0	9.31	0	0.773	-0.000364	5000.082636	0.001	5.000082636
PBPC,334dbbaaaN	HRA-25/B/20/XS1	m3	184	6.14	3.81	0	0	0	0	0	0	0	9.43	19.2	0	9.96	-14.3	218.24	1	218.24
PBPC,28abbaaaN	HRA-25/B/20/XC2	m3	184	6.14	3.81	0	0	0	0	0	0	0	9.43	19.2	0	9.96	-14.3	218.24	1	218.24
PEAP60bbabbM	S 275J0 laminated steel with galvanized finish RECI-REUT	kg	842	0	0	0	0	0		0	0	0	0	0	1.84	0	-97.8	746.04	0.001	0.74604
PFFC,2b	Brick perforated non-visible 24x11.5x7	u	236	4.69	0.567	0	0	0	0	0	0	0	0	3.85	1.21	8.67	0	254.987	0.00150696	0.38425521
PFFC,2c	Brick perforated non-visible 24x11.5x9	u	236	4.69	0.567	0	0	0	0	0	0	0	0	3.85	1.21	8.67	0	254.987	0.00193752	0.494042412
PFFC,1bf	Hollow brick double 24x11.5x9	u	236	4.69	0.567	0	0	0	0	0	0	0	0	3.85	1.21	8.67	0	254.987	0.00191268	0.487708535
PBUA50aaa	Cement adhesive C1	kg	231	12.4	0.361	0	0	0	0	0	0	0	0	11.7	0	9.26	0	264.721	0.000575374	0.152313579
PEML,3gbadaN	Solid CLT 160 mm visible on one side	m2	-685.35	47.82	7.39	0	0	0	0	0	0	0	4.99	2.38	859.38	0	-56.52	180.09	0.16	28.8144
PEML,3dbaaa	Solid CLT panel 100 mm, non-visible quality, >6 m2	m2	-685.35	47.82	7.39	0	0	0	0	0	0	0	4.99	2.38	859.38	0	-56.52	180.09	0.1	18.009
PEML,3bbaaa	Solid CLT panel 80 mm, non-visible quality, >6 m2	m2	-685.35	47.82	7.39	0	0	0	0	0	0	0	4.99	2.38	859.38	0	-56.52	180.09	0.08	14.4072
PFPC,1ad	Laminated gypsum board A 15mm	m2	3.7	0.227	2.19	0	0	0	0	0	0	0	0	0.429	0.05	0.05	0	6.646	1	6.646
PFPC,1cd	Laminated gypsum board FD 15mm	m2	3.7	0.227	2.19	0	0	0	0	0	0	0	0	0.429	0.05	0.05	0	6.646	1	6.646
PFPC,1bd	Laminated gypsum board H1 15mm	m2	3.7	0.227	2.19	0	0	0	0	0	0	0	0	0.429	0.05	0.05	0	6.646	1	6.646
PFPC,1bc	Laminated gypsum board H1 12.5mm	m2	3.7	0.227	2.19	0	0	0	0	0	0	0	0	0.429	0.05	0.05	0	6.646	1	6.646
PFPC,1ac	Laminated gypsum board A 12.5mm	m2	3.7	0.227	2.19	0	0	0	0	0	0	0	0	0.429	0.05	0.05	0	6.646	1	6.646
PFPC,1cd120N	Laminated gypsum board FOC 25mm	m2	3.7	0.227	2.19	0	0	0	0	0	0	0	0	0.429	0.05	0.05	0	6.646	1	6.646
PNIS,1daN	Laminated PVC 1.5mm	m2	4.76	0.134	0.113	0	0	0	0	0	0	0	0	0.0142	0.00228	0.0159	0	5.03938	1	5.03938
PNIS,9ba	Laminated PVC 1.5mm	m2	4.76	0.134	0.113	0	0	0	0	0	0	0	0	0.0142	0.00228	0.0159	0	5.03938	1	5.03938

Figure 9. Conversion of the product environmental data to csv.

5. **Environmental assessment of selected materials/elements/products, building or district: the** data of total quantities and the impact of each unit of product/element/material is combined to obtain the environmental impact results, which can be grouped as desired. The following images show some possible ways to present the results of environmental impact data grouped according to different parameters:
    - $KgCO_2$ equivalents sorted according to the budget structure:

CO2 budget

Periscoope_BC3_Ampliado/Capitulo_1_Codigo	Periscoope_BC3_Ampliado/Capitulo_1_Titulo	Sum from Periscoope_BC3_Basico/Descompuestos_TotalKgCO2Equiv
AM	Land conditioning	
AQ	Archaeology	
CC	Quality control, inspections, tests, and samplings	
DD	Demolitions and consolidations	
EC	Foundations and containment elements	236269.88
EE	Structures	332106.21
EF	Facades and partitions	47885.15
EI	Systems	106.53
EM	Equipment and furnishings	
EN	Insulation and waterproofing	1481.58
EQ	Roof	1692.27
ER	Coatings	13163.71
GR	Waste management	
SS	Safety and health	
UP	Urban roads and pavements	
Total general		632705.32

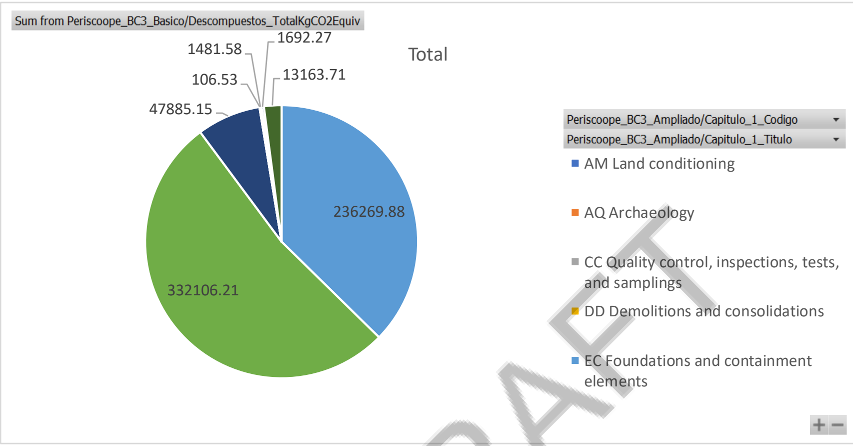


Figure 10. Results of the KgC02 equivalents of the specific building modelled in IFC.

- $KgCO_2$ classified by types of elements.

Periscoope_Basico/ExpressType	Sum from Periscoope_BC3_Basic/Materials_QuantityKgCO2Equiv
IfcBeam	3146.86
IfcBuildingElementProxy	106.53
IfcColumn	11741.85
IfcCovering	3368.99
IfcSlab	260363.62
IfcWall	29834.36
IfcWallStandardCase	288353.03
(blank)	35790.09
Total general	**632705.32**

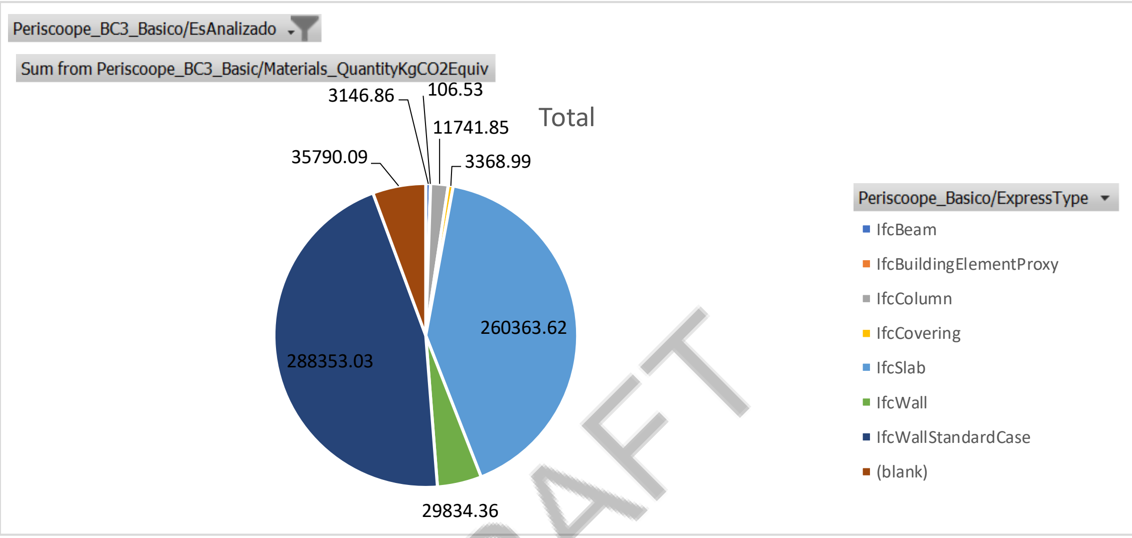


Figure 11. Results for CO2 grouped by type of elements.

- $KgCO_2$ ordered by a client parameter:

GVA_ConstructiveSystemsMaterials/SCO_Clasificacion	Sum Periscoope_BC3_Basic/Materials_QuantityKgCO2Equiv
ECCM	63655.30
ECCP	91927.95
ECDL	72411.30
ECSS	5769.94
EEFH	128046.15
EEFM	44200.61
EEHE	12093.56
EEMC	560.81
EEMH	107135.53
EEMM	11004.54
EESA	888.58
EFFC	18439.15
EFPY	27174.20
EISB	106.53
EQAW	1602.53
ERPA	196.49
ERSC	8333.09
ERTC	3368.99
(en blanco)	35790.09
Total general	**632705.32**

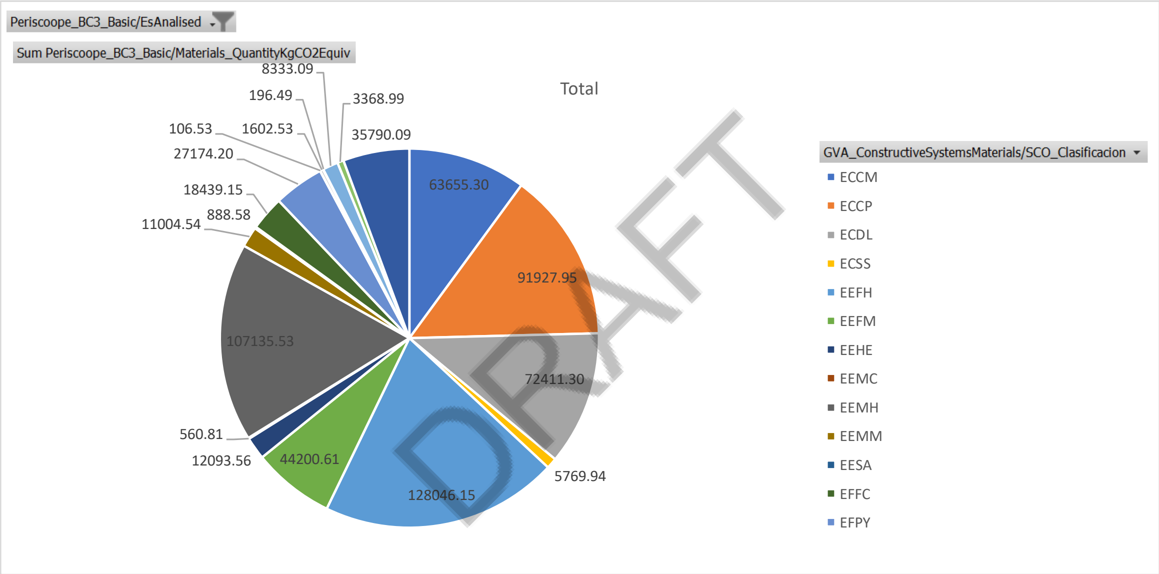


Figure 12. KgCO2 ordered by a client parameter (IVE classification).

Annex 5. Label interpretation guidelines

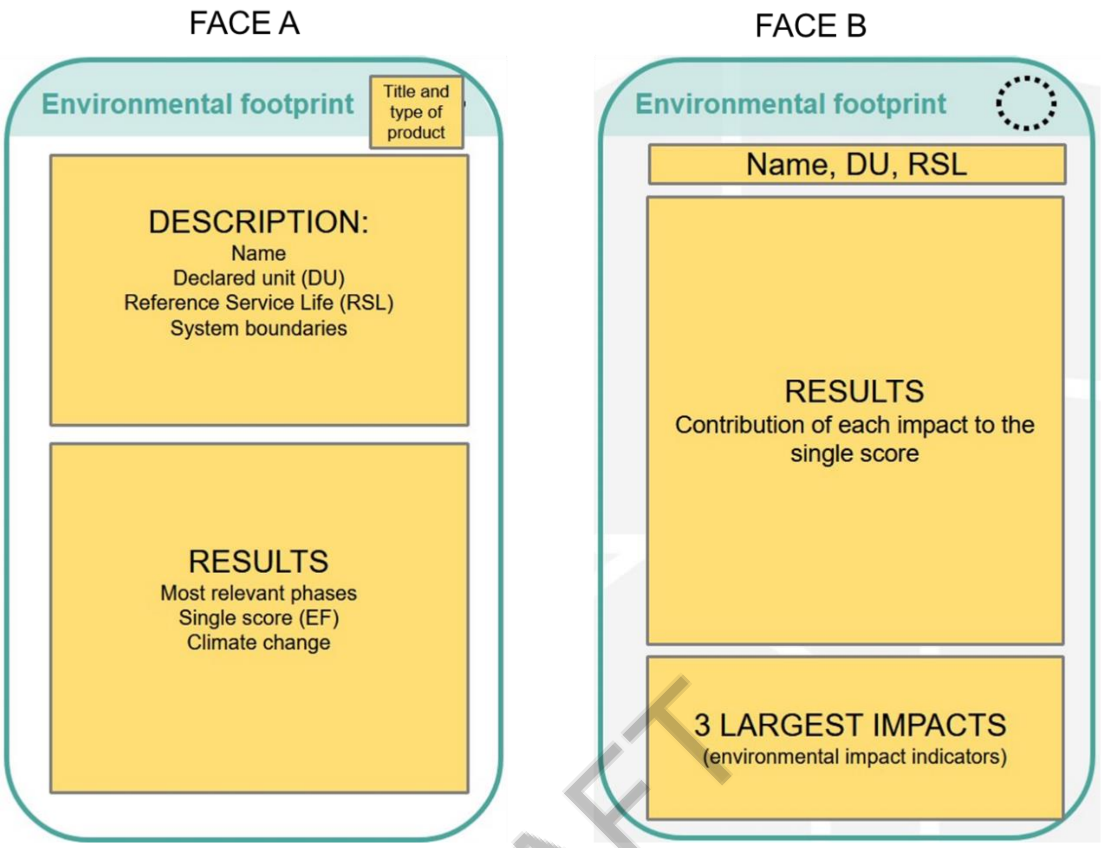
The results of an LCA analysis can often be complex to interpret, even for those with a high level of knowledge on the subject. For this reason, a label has been created with the intention of sharing these results in a user-friendly way. Furthermore, to help stakeholders with reading and understanding the terminology and information presented on the label, these guidelines have been developed.
The label information has been structured on two levels, each one adapted to stakeholders with different levels of expertise and different backgrounds that may read and use the label for decision-making during the design phase.

Level 1 (basic information)

This level presents the most relevant results in a simple way, and it is tailored to people with little knowledge of LCA. Thus, simple information that does not require complex explanations is provided.
Within this level, two types of labels can be distinguished:

- **LABEL 1.** It shows the results of a single analysis at any level (material, element, building, etc.)
- **LABEL 2.** It shows the results for when before and after scenarios are compared. This case only applies to building and district level and has to consider the operational phase of the life cycle. The example given is a solution implemented to renovate a building. The results are shown for the scenario before renovation (baseline scenario) and after renovation with the element installed (refurbishment scenario). The data are the same as in the previous case, but in the results the before and after data are shown for comparison.

In addition, this level is structured into two sides A and B, indicating the information listed below.



Face A

1. **Header:** title (environmental footprint) + type (material, element, building, pre-fabrication process, district).
2. **Description:** name (identification), declared unit (DU), reference service life (RSL), system boundaries.
3. **Results:** most relevant phases, single score, climate change.

Face B

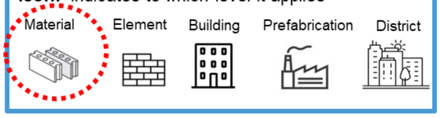
1. **Header:** title (environmental footprint) + type (material, element, building, pre-fabrication process, district)
2. **Description:** name (identification), DU, RSL + years to return (only when two scenarios are compared)
3. **Results:** contribution of each impact to the single score.
4. **Three largest impacts** among the 19 environmental impacts analysed.

LABEL 1- FACE A

Header

Title: environmental footprint. Common to every type of label.

Icon: indicates to which level it applies

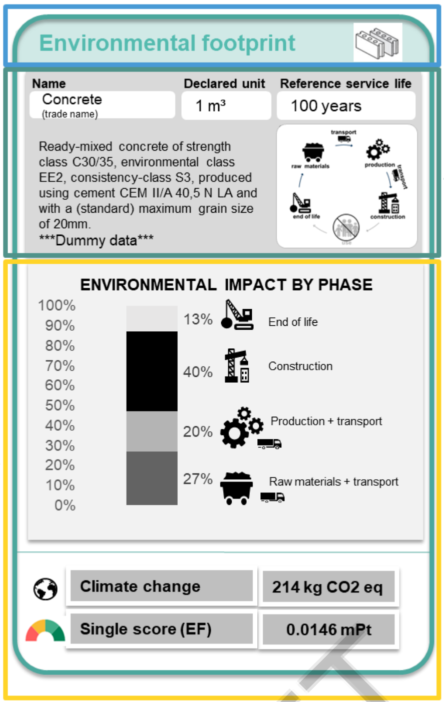


Results

Environmental impact by phase: most relevant phases. The impact of each phase on the total is indicated.

Climate change: CO2 emissions (kg CO2 eq) Global Warming Potential.

Single score: is a dimensionless value obtained by adding up all environmental indicators. The higher the value, the greater the impact. It is expressed in millipoints (mPt) per Declared Unit.



Description

Name: to identify what has been analysed (e.g. *Trade name* ready-mixed concrete)

Declared unit: according to “what”, “how much”, “how well” and “how long”.

Ready-mixed concrete of strength class C30/35, environmental class EE2, consistency-class S3, produced using cement CEM II/A 40,5 N LA and with a (standard) maximum grain size of 20mm.

Reference quantity for the declared unit | 1 m³

Reference Service Life: useful life to be expected (e.g. 100 years)

System boundaries: which phases are being analyzed (e.g. the analysis may not take into account use phase, which includes: use, maintenance, repair, replacement, rehabilitation, operational energy and operational water. Or it may only include the product manufacturing phases: extraction of raw materials, transport to factory and manufacturing). It should be clearly identified which ones are included and which are not.

LABEL 1- FACE B

Header

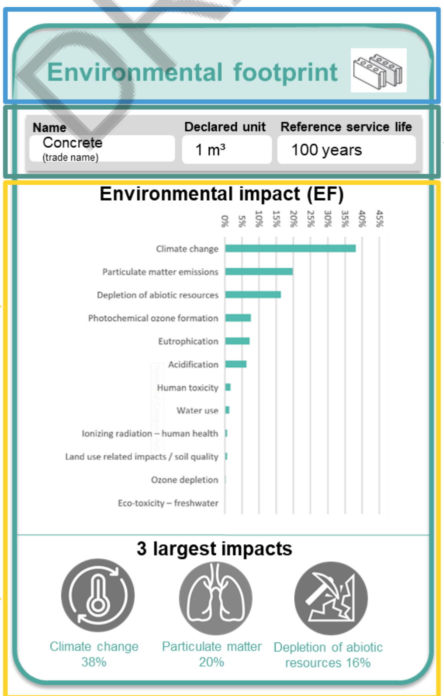
Title + icon: the same as in FACE A

Results

Environmental impact (EF): contribution of each impact indicator to the single score. Easy visualisation of how each indicator contributes to the single score. It is easy to identify which are the most and least impactful.

Results

3 largest impacts: the three most important environmental impact indicators (those that contribute more to the total single score) are highlighted.



Description

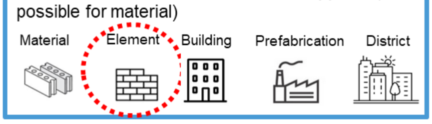
Name + Declared Unit + Reference Service Life: summarised version of Face A

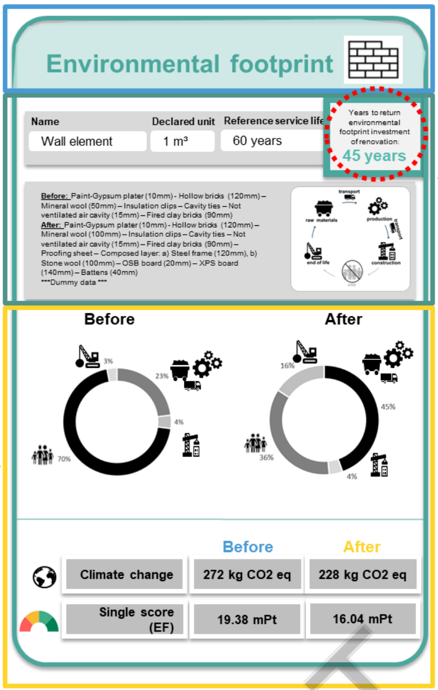
LABEL 2- FACE A

Header

Title: environmental footprint. Common to every type of label.

Icon: indicates to which level it applies (not possible for material)





Results

Environmental impact by phase: most relevant phases. The impact of each phase on the total is indicated. Comparison between two scenarios, before and after the renovation.

Climate change: CO2 emissions (kg CO2 eq) Global Warming Potential before and after.

Single score: comparison between the single score before and after renovation. It is expressed in millipoints (mPt) per Declared Unit.

Description

Name + Declared unit + Reference Service Life + Description before and after + System boundaries

Before: Paint-Gypsum plater (10mm) - Hollow bricks (120mm) – Mineral wool (50mm) – Insulation clips – Cavity ties – Not ventilated air cavity (15mm) – Fired clay bricks (90mm)
After: Paint-Gypsum plater (10mm) - Hollow bricks (120mm) – Mineral wool (100mm) – Insulation clips – Cavity ties – Not ventilated air cavity (15mm) – Fired clay bricks (90mm) – Proofing sheet – Composed layer: a) Steel frame (120mm), b) Stone wool (100mm) – OSB board (20mm) – XPS board (140mm) – Battens (40mm)
***Dummy data ***

Description before and after: to compare two scenarios they are described how they were before and after the renovation (e.g. building element: components, composed layers of the old and the new).

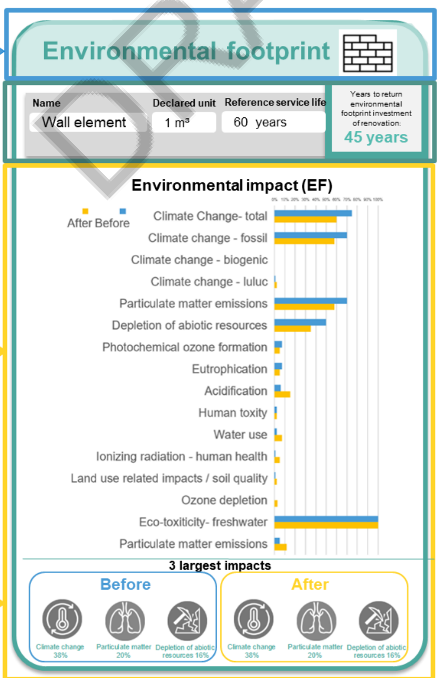
New data

Years to return environmental footprint investment of the renovation: based on mPt. Gives insights of the environmental return on investment. It indicates the years in which the environmental footprint of the solution used in the renovation would be amortised.

LABEL 2- FACE A

Header

Title + icon: the same as in FACE A



Results

Environmental impact (EF): contribution of each impact indicator to the single score. Before and after the renovation. Easy visualisation of how they change on both scenarios.

Results

3 largest impacts: the three most important environmental impact indicators (those that contribute more to the total single score) are highlighted before and after.

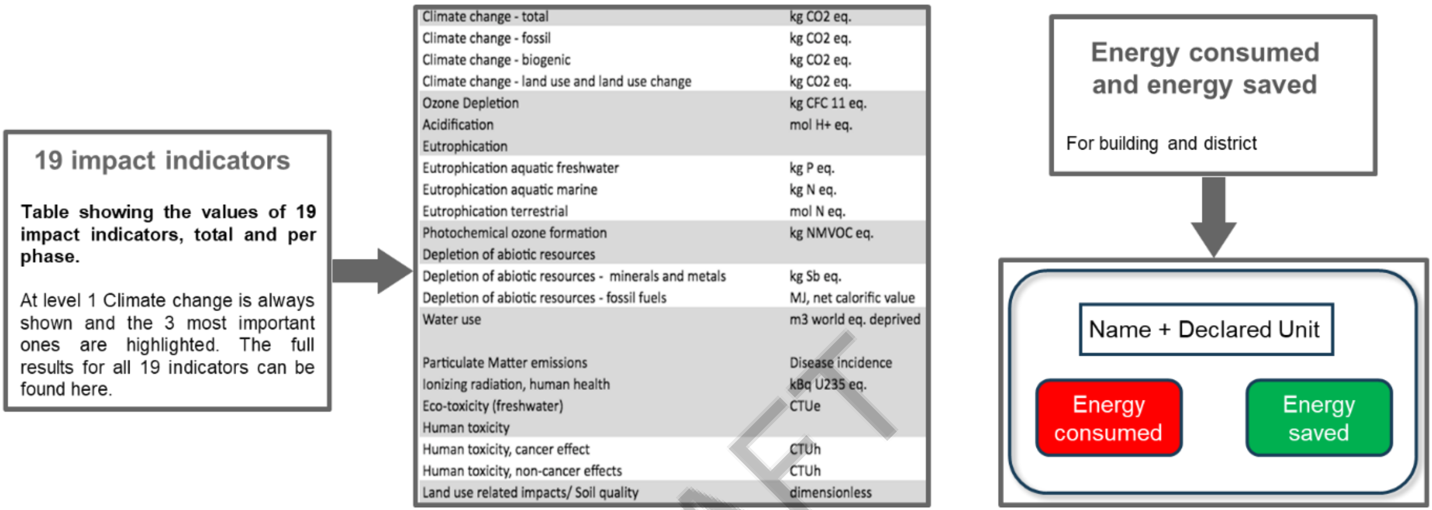
Description

Name + Declared Unit + Reference Service Life + Years to return environmental footprint of the renovation: summarised version of FACE A

Level 2 (detailed info)

This level presents more detailed and technical supplementary information. It is aimed at users with a higher level of LCA expertise, although it can be accessed for review by anyone interested in obtaining all the information relating to the LCA performed. It shows the full results obtained from the analysis.

- Nineteen environmental impact indicators;
- Energy consumed and energy saved.



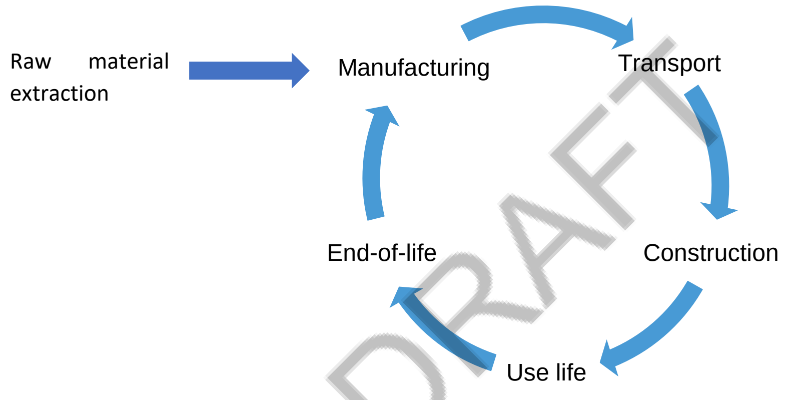
Definitions

Name: refers to the name of the material, element, product, building or district for which the LCA is performed and for which the corresponding label has been provided.

Declared unit (DU): this is the measurement unit for which the life cycle analysis is performed. For example: $1m^2$, $1m^3$, etc.

Reference service life (RSL): period of time for which the LCA is being conducted. In this period, depending on the considered lifetime (expected life) of the material, product, element, building or district, the number of replacement times in the defined time period should be considered. For example, when conducting an LCA with an RSL of 60 years for a product with a lifetime of 20 years, it will be necessary to replace the product twice. Thus, the total impact on the products in the selected RSL will be the result of multiplying by three the impact of the product (the initial impact plus the two necessary replacements).

System boundaries: phases of the life cycle (from raw materials extractions to end of life) that are considered.



- ***Phase A (A1-A3):*** the product creation phase, from the extraction of raw materials to their transport to the factory and its production process.
- ***Phase A (A4-A5):*** the phase of transporting the material/product/ element to the construction site and its subsequent installation on site (building, street, etc.).
- ***Phase B (B1 to B8):*** includes aspects during the use stage, from the operational phase (energy and water consumption) to the impact caused by the maintenance, repair, replacement and refurbishment processes required during the indicated RSL.
- ***Phase C (C1 to C4):*** includes all environmental impacts related to the activities related to the extraction (demolition), transport and disposal phases of the product/material/element/building or district.
- ***Phase D:*** related to recycling, recovery and reuse activities, giving it a second life.

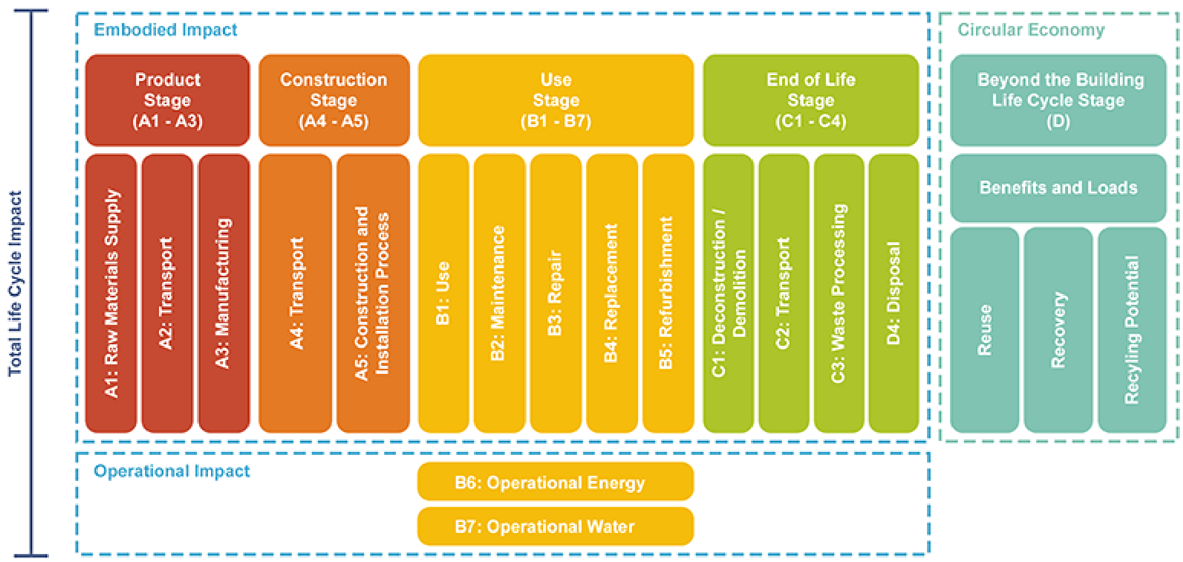


Figure 1. Phases of the life cycle. Source: https://browningday.com

Environmental indicators: This label comprises 19 environmental impact indicators. They are divided into 12 environmental impact categories:

- **Climate change:** increase in the average atmospheric concentration of various man-made substances (CO_2, CH_4, CFCs, etc.).
- **Ozone depletion:** emissions into the air (CFCs, HCFCs, halons, etc.) which contribute to the formation of the hole in the ozone layer.
- **Acidification:** increase in the quantity of acidic substances (NO_2, SO_2, etc.) in the lower atmosphere, causing acid rain and the loss of certain forest and freshwater ecosystems.
- **Eutrophication:** emissions into the air and water of substances causing excess nutrients in surface waters, overgrowth of algae and impoverishment of aquatic ecosystems.
- **Photochemical ozone formation:** emissions into the air of substances that lead to the production of tropospheric ozone (low ozone, summer smog).
- **Water use:** consumption of freshwater resources.
- **Depletion of abiotic resources:** calculated by dividing the quantities of raw materials used by their respective global reserves.
    - Minerals and metals: mineral raw materials such as Fe, Cu, Pb, Zn, etc.
    - Fossil fuels such as natural gas, oil, coal, etc.
- **Particulate matter**: air emissions of fine solid particles (dust) that cause heart and lung disease in humans.
- **Ionizing radiation:** emission of ionising (radioactive) radiation that can cause cell damage (effects on human health).
- **Eco-toxicity:** emission of substances (organic halogen compounds, heavy metals, PCBs, dichlorobenzene, polycyclic hydrocarbons) causing damage to aquatic ecosystems and freshwater organisms.
- **Human toxicity:** emissions into the air and water of substances (organic halogen compounds, heavy metals, PCBs, dichlorobenzene, polycyclic hydrocarbons, etc.) causing damage (natural or otherwise) to living organisms and, in particular, to humans.

- **Land use:** land use and changes in land use (arable land, forests and urban areas) and changes in the use of land (building land, forests and urban areas) over time.

Main environmental impact category	Environmental impact indicator	Unit
Climate change	Climate change - total[a]	kg CO_2 eq.
	Climate change - fossil	kg CO_2 eq.
	Climate change - biogenic	kg CO_2 eq.
	Climate change - land use and land use change	kg CO_2 eq.
Ozone depletion	Ozone depletion	kg CFC 11 eq.
Acidification	Acidification	mol H+ eq.
Eutrophication	Eutrophication - aquatic freshwater	kg P eq.
	Eutrophication - aquatic marine	kg N eq.
	Eutrophication - terrestrial	mol N eq.
Photochemical ozone formation	Photochemical ozone formation	kg NMVOC eq.
Depletion of abiotic resources	Depletion of abiotic resources - minerals and metals	kg Sb eq.
	Depletion of abiotic resources - fossil fuels	MJ, net calorific value
Water use	Water use	m^3 world eq. deprived
Particulate matter	Particulate matter emissions	Disease incidence
Ionizing radiation	Ionizing radiation - human health	kBq U235 eq.
Eco-toxicity	Eco-toxicity - freshwater	CTUe
Human toxicity	Human toxicity - cancer effect	CTUh
	Human toxicity - non-cancer effects	CTUh
Land use	Land use related impacts/soil quality	dimensionless

Figure 2. Environmental impact indicators per environmental impact categories. Source: https://www.totem-building.be

Climate change: one of the most commonly known environmental impact categories**.** It is related to the global warming potential of all greenhouse gas emissions. It is measured in kg CO_2eq, which is equivalent to the effect of one kg of CO_2 emission.

Single score: the sum of the 19 environmental indicators, expressed in a dimensionless unit. For each individual environmental indicator, the characterised values are first normalised by dividing them with their respective normalisation factors. These factors represent the yearly global impact per capita (e.g. the normalisation factor for climate change is 8.1·103 kg CO_2eq./person·year for reference year 2010) and allow all the results to be expressed in a dimensionless unit.

In a second step, the normalised results are weighted by multiplying them by their respective weighting factors to reflect the perceived relative importance of the environmental impact categories considered. After weighting, the results of the different environmental indicators can be added together to obtain a single overall score.

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