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Model for Life Cycle Assessment (LCA) of buildings

EFIResources: *Resource Efficient Construction towards Sustainable Design*

Gervasio, H. & Dimova, S.

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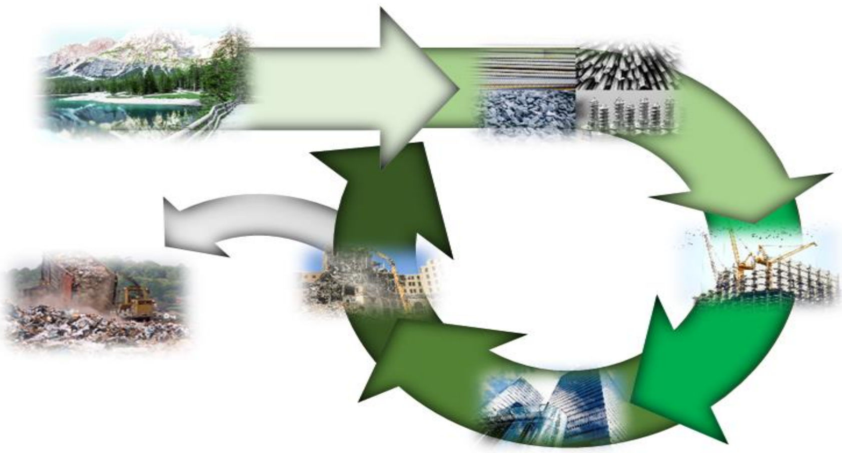

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Authors

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Abstract

The project *EFIResources*: *Resource Efficient Construction towards Sustainable Design*, focusses on the development of a performance based approach for sustainable design, enabling to assess resource efficiency of buildings, in the early stages of building design, and supporting European policies related to the efficient use of resources in construction.

The proposed approach aims for the harmonization between environmental criteria and structural criteria in the design of buildings and thus, it provides the chance for structural engineers to foster a more efficient use of resources throughout the life cycle of buildings and reduce the environmental impacts of construction works.

The work plan of the project is organized into the following main tasks:

- Task 1: Development of a life cycle model for the assessment of buildings, which will enable the benchmarking;
- Task 2: Identification of best practices and development of a set of benchmarks for residential and office buildings;
- Task 3: Development of an approach for sustainable design consistent with the reliability approach of the Eurocodes;
- Task 4: Recommendations for standardization and guidelines for sustainable design.

This report focuses on the development of the model for life cycle analysis (LCA) and on its implementation into a software tool. This model will be used for the benchmarking of the environmental life cycle performance of the structural system of buildings.

The model is applied to common construction materials, at the material level, and structural systems, at the building level, to provide additional guidance in its application and to identify main limitations.

Therefore, some limitations are identified but these affect mainly other building components rather than the structural system of the building, which is the main focus of the developed model.

1 Introduction

The built environment is responsible for a high global share of environmental, economic and social impacts. An enhanced construction in the EU would influence 42% of our final energy consumption, about 35% of our greenhouse gas emissions, more than 50% of all extracted materials and enable savings of water up to 30% [1]. Therefore, the standard practices of the construction of buildings are jeopardizing the chances for future generations to meet their own needs.

Huge efforts have been made over the last years towards the efficient use of energy in buildings during the use stage due to heating and cooling needs. The aim of the European Union is to make all new buildings nearly zero-energy by 2020 [2]. Hence, since the operational energy of buildings is being reduced, materials and embodied energy are becoming increasingly more important for resource efficient construction. In fact, one of the measures to reduce the energy bill due to comfort requirements is usually to increase the insulation of the building envelope, leading to a higher resource consumption and a higher embodied energy [3]. However, earth has a finite number of resources and their used in buildings should be optimized to make the best use of the resources invested into buildings, over the full lifespan. These crucial aspects should be taken into account in the design of buildings and other construction works.

Aiming to force the improvement in the use of resources, the EU launched a roadmap [1] to a resource efficient Europe, in which the building sector has been identified as one of the key sectors. Ambitious targets are foreseen in this plan: by 2020, all new buildings will be highly material efficient, 70% of non-hazardous construction and demolition waste will be recycled, and policies for renovating the building stock will be introduced so that the rate of cost efficient refurbishment rises to 2% per year.

Life Cycle Analysis (LCA) applied to buildings aims to assess the potential environmental of buildings over the complete life cycle, from materials production to the end-of-life and management of waste disposal. LCA were initially developed for the analysis of simple products, i.e., products with short periods of life and very specific functions. This is not the case of buildings, which have usually a very long span and are multi-functional. Therefore, CEN TC 350 was mandated for the development of standards for the sustainability assessment of construction works. The series of standards developed by this TC, which have been published in the recent years, work into two levels, the product level and the building level, and they comprehend the assessment of environmental, economic and social aspects of construction works. These standards do not provide benchmarks of reference values for the different criteria considered.

LCA is becoming very popular among the scientific community; however, in practice, the evaluation of the building performance in terms of sustainability usually relies on rating systems like BREEAM, LEED, HQE, SBTool, DGNB, etc. These type of tools are voluntary certification schemes, developed by national and international green council organizations, to motivate a demand for green buildings. They are based on the evaluation of selected criteria by comparing the performance of the building with pre-defined thresholds or reference values. Quantitative and qualitative indicators are then translated into grades that are further aggregated into a final score. The main drawbacks of these systems are: (i) the systems are not comparable due to several disparities in terms of system boundaries, indicators reference values and calculation methods [4]; (ii) they are time consuming and a lot of documentation is needed to show compliance with the criteria; and (iii) they are expensive and often experts, recognised by the organization issuing the certification label, are required to conduct the assessment and achieve the label. These last two reasons may explain why this kind of systems influences only a very small part of the building stock worldwide. Moreover, the use of such systems in buildings has not led to significant reductions in terms of CO_2 emissions [5].

The research project *EFIResources*: *Resource Efficient Construction towards Sustainable Design*, launched in September 2016, supports European policies related to the efficient use of resources in construction and its major goal is the development of a performance based approach for sustainable design, enabling to assess resource efficiency of buildings in the early stages of building design.

In the proposed approach for sustainability design, the performance of the building, focussing on resource use, is benchmarked against standard and/or best practices. This approach provides major innovations with respect to other available methodologies:

- The model for the assessment of buildings is based on a standardized procedure for LCA that was developed specifically for the assessment of construction works (provided by the series of CEN TC 350 standards); thus enabling comparability and benchmarking;
- The approach is meant to be used in early stages of design so that proper decisions, with regard to design options, can be made in the most influential stages of design;
- The methodology enables a widespread application within building designers, without the need of a great level of expertise;
- The proposed approach for sustainability design complies with the design rules and reliability provisions of the European standards for structural design (the Eurocodes), thus enabling an harmonization between structural safety and sustainability in the design process, thus complying with the basic requirements for construction works of the Construction Products Regulation [6];
- The development of benchmarks for the environmental performance of buildings will enable to set consistent targets for the reduction of the consumption of resources and other environmental problems.

The results of this project will facilitate the incorporation of sustainability criteria in construction practices in consistence with the safety requirements of the design standards, thus providing building designers with an approach for safe and clean construction.

In this project, the assessment is limited to the structural system of residential and office buildings; thus focussing on the work for which structural engineers are directly responsible. However, in the future, the developed approach may be applied to other building components and other building types.

The work plan of the project is organized into the following main tasks:

- Task 1: Development of a life cycle model for the assessment of buildings, which will enable the benchmarking;
- Task 2: Identification of best practices and development of a set of benchmarks for residential and office buildings;
- Task 3: Development of an approach for sustainable design consistent with the reliability approach of the Eurocodes;
- Task 4: Recommendations for standardization and guidelines for sustainable design.

This report corresponds to the first output of the project and aims to provide full details about the model for life cycle analysis (LCA) that will be used for benchmarking.

Following this introductory section, the report is organized into the following sections: Section 2 provides a brief description of how the proposed approach supports European policies related to resource efficiency; Section 3 provides the background for the development of the LCA model; Section 4 aims to describe the LCA model and to provide guidance on its use for the life cycle assessment of buildings and further benchmarking; the model is implemented into a software tool for LCA and this is described in Section 5; the LCA model is applied at the material level and at the building level in Sections 6 and 7, respectively, aiming to provide further guidance on its use; finally, conclusions are drawn in the end of the report (Section 8) about the adequacy of the model to fulfil the aims of the project.

2 European policies pursuing resource efficiency in the building sector

The construction sector has a huge responsibility on the consumption of natural resources, on the use of energy and on the production of waste due to construction and demolition activities. Therefore, it plays a primordial role in Sustainable Development.

The use of energy in buildings is usually related to the energy requirements for the heating and cooling of the building over its operation stage, usually known as operational energy. This issue had been intensively addressed over the last years and major EU directives were put into practice leading to considerable reductions in the operational energy of buildings.

This reduction highlighted the importance of another component of the energy requirements of buildings: the energy embodied in the materials and processes that are needed for the construction and use of the building, over its service life.

The *EFIResources* project aims for a more efficient use of the natural resources in the building sector and thus, the project focusses on the embodied energy and embodied impacts, which are directly related to the consumption of resources for the production of building materials and their use throughout their service life. The operational energy of buildings will not be further addressed in this report, although references will be made to it where appropriate.

The aim of this chapter is to provide a description of main European regulations and directives that have been issued over the last years in order to promote a better use of resources in buildings and to explain how the proposed approach aims to support these initiatives.

2.1 Construction Products Regulation

The Construction Products Regulation (CPR) [6], replacing the Construction Products Directive (CPD) [7], provides a set of harmonised technical rules to assess the performance of construction products so that different products from different manufacturers in different countries may be compared, thus ensuring the free circulation of construction products in the European market.

According to this regulation, construction works must satisfy basic requirements for an economically reasonable working life.

In this new regulation, an additional basic requirement on sustainability was introduced: the sustainable use of natural resources. In this case [6], "*The construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and in particular ensure the following:*

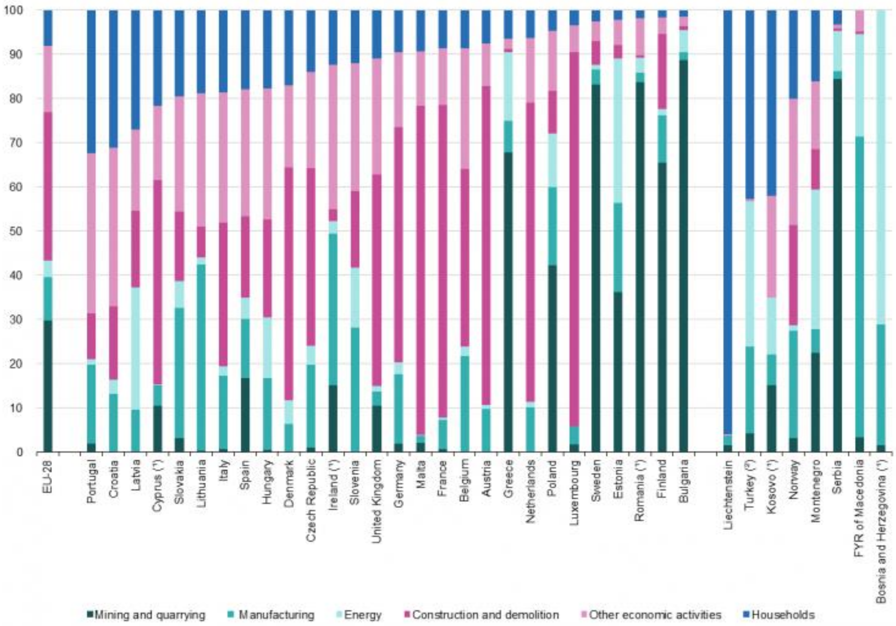
> *(a) reuse or recyclability of the construction works, their materials and parts after demolition;*
>
> *(b) durability of the construction works;*
>
> *(c) use of environmentally compatible raw and secondary materials in the construction works.*"

The series of European Standards for the structural design of buildings and other civil engineering works, the Eurocodes (EN 1990 - EN 1999), provide the recommended methods to enable a presumption of conformity with the basic requirements of the CPR, except for the new basic requirement of "sustainable use of natural resources". In relation to the latter, currently there is not a single generally accepted approach for its assessment but the regulation states that Environmental Product Declarations (EPDs) can be used to show compliance with this new requirement.

2.2 Construction and demolition waste

Construction and demolition waste (C&DW) is one of the most important waste streams generated in the EU, accounting for approximately 25% - 30% of all waste generated in the EU and consists of numerous materials with potential for recycling. As observed in Figure 1, there are considerable variations across EU-28 Member States, both for waste generated and for the activities that mostly contributed to waste generation. Nevertheless, C&DW is responsible for a major share is most countries.

Figure 1. Waste generation by economic activities and households, EU-28, 2014 (%) [8]



The Waste Framework Directive [9] established as major goal the move towards a European recycling society with a high level of resource efficiency. Towards this goal, the directive provided a waste hierarchy establishing a priority order for waste management (in decreasing order of importance): prevention, preparing for reuse, recycling, other recovery and finally, disposal.

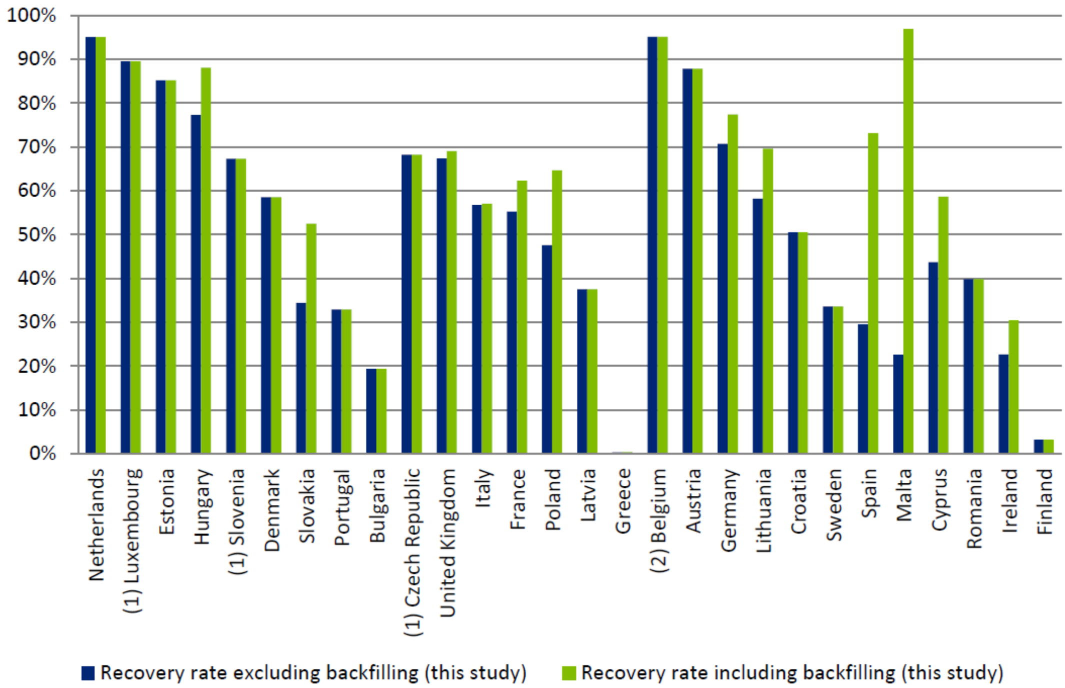
Additionally, the amount of non-hazardous C&DW reused, recycled or recovered should be increased to a minimum of 70% by weight by 2020. It is noted that currently, the level of recycling and material recovery of CDW varies greatly across European countries. As illustrated in Figure 2, some countries claimed that the target value of 70% has already been reach; while, in order countries this target is far from being achieved [10].

Finally, in relation to the life cycle perspective of materials and goods, this Directive introduced two important concepts: the "polluter pays principle" and the "extended producer responsibility". The former allocates to the waste producer and waste holder, "the responsibility to manage the waste in a way that guarantees a high level of protection of the environment and human health"; while, the latter aims to support the design and production of goods fully accounting for the efficient use of resources, throughout their whole life cycle.

2.3 Resource efficiency

Buildings are responsible for about 50% of all materials that are extracted from earth [11]. In fact, the use of resources for building construction in terms of mass represents one of the biggest challenges in resource consumption. In relation to popular construction materials, concrete used in buildings account for about 75% of total consumption, the use of aggregate materials accounts for about 65%, and the use of steel and wood in buildings account for approximately 21% and 37.5%, respectively [12]

Figure 2. Recovery rates of C&DW in EU-28 in 2012 (extracted from [10])



Aiming to enhance the use of resources and to decouple economic growth from resource use, the EU launched a Roadmap to a Resource Efficient Europe [11], in which the building sector was identified as one of the key sectors. In a milestone for improving buildings, ambitious goals and targets were foreseen: by 2020 all new buildings will reach high resource efficiency levels, life cycle approaches will be widely spread, 70% of non-hazardous construction and demolition waste will be recycled, and policies for renovating the building stock will be introduced so that the rate of cost efficient refurbishment rises to 2% per year.

Moreover, one of the measures outlined in this document to promote the use of resource efficient building practices is to extend the scope of the Eurocodes to include criteria related to sustainability.

Additionally, to promote a more efficient use of resources in buildings and to reduce their life cycle impacts, a set of measures was proposed by the Communication on Resource Efficiency opportunities in the Building Sector [13], focussing on: (i) an improved building design taking into consideration the complete life cycle of the building; and (ii) an increase use of construction materials with recycled content and materials with potential for recycling and/or reuse.

However, it was stressed that currently there is a lack of reliable and comparable data and methodologies for the analysis and benchmarking of materials and buildings. Hence, a set of reliable indicators for building performance and a consistent framework for life cycle assessment were recommended to enable decision makers, in general, to incorporate environmental considerations into their decisions.

2.4 Circular Economy

The EU action plan for the Circular Economy [14] aims to promote the transition to a more circular economy, where the values of products and materials is maintained in the economy for as long as possible, thus minimizing the production of waste and reducing/avoiding the extraction of new resources.

The main barriers in the construction sector towards the circular principles are the lack of appropriate design methodologies to enable a better use of C&DW and the lack of links and cooperation between the long chain of stakeholders in the construction process [15].

Currently, recycling and reusing of C&DW is encouraged by EU policies and ambitious targets were set but still many valuable materials and not collected or properly recovered and therefore, they end up in landfills. This is mainly due to [10]: (i) unfavorable market conditions, with low prices of natural raw materials, low landfill costs and a lack of trust in recycled materials from C&DW; and (ii) lack of a legislative framework enforcing the implementation of good practices in the management of C&DW and lack of political motivation leading to further improvements.

Therefore, the transition from linear economy towards circular economy will require both business and consumers to change, potentially creating new business opportunities and more efficient ways of designing buildings and safeguarding natural resources.

Design for deconstruction or design for disassembly plays an important role in circular economy as, in this case, buildings are designed in order to maximize the reuse and recycling of valuable materials and components during the disassemble stage.

However, circular economy is not only to maintain the value of the products at the end-of-life stage, it is also to maintain the value of products in the economy for the longest possible period of time. Therefore, design for adaptability, enabling buildings to fulfil their functions for a longer period of time, and design for durability, promoting the use of materials with a long service life and less maintenance requirements, are design strategies that enable to comply with the above requirement.

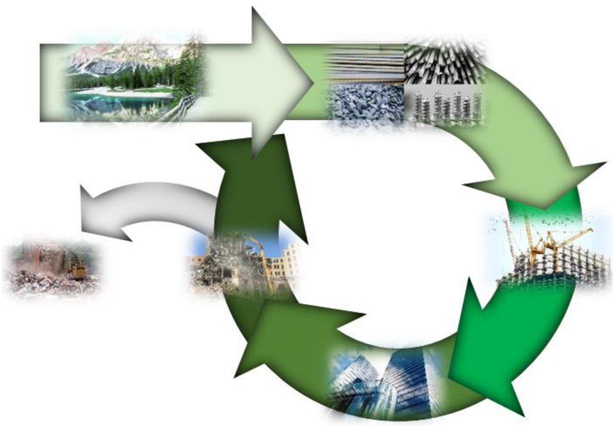
2.5 Supporting EU policies

The above policies are interlinked and they all have as major goal a more efficient use of resources in the construction sector. This is also the major goal pursued by the methodology proposed in the project *EFIResources*.

Hence, in order to support the above European initiatives, the development of the proposed approach is based on the following:

- The efficiency use of resources in buildings is understood as a minimization of the amount of natural resources used throughout the life cycle of the building; this entails the promotion of materials with recycled content (input side), materials with high durability and materials with reuse and/or recycling potential (output side);

Figure 3. Life cycle assessment of buildings



- The approach provides credits to design strategies such as design for adaptability and deconstruction, in order to extend the service life of buildings and to increase the potential for recycling or recover of materials after the disassembly of the building;
- The assessment of the environmental performance of the building takes into account the complete life cycle, from the stage of material production to the end-of-life stage of the building and further reuse and/or recycling of materials and components, as illustrated in Figure 3;
- The quality of the secondary materials resulting from the end-of-life stage is taken into account in the assessment of the building;
- The proposed approach for the environmental assessment of buildings is in line with the methodology for structural assessment adopted in the Eurocodes, thus enabling an

harmonization between both design approaches and potential integration of environmental criteria into the existing codes;

- The life cycle assessment is based on a standardized procedure for LCA and relies on data from professional LCA databases and/or peer review data such as EPDs; thus ensuring comparability between the assessment of different buildings and enabling benchmarks;
- The development of benchmarks for the environmental performance of buildings will enable to set realistic targets towards a more efficient use of resources and the minimization of related environmental impacts.

3 Background for Life Cycle Assessment of buildings

Buildings are designed for a long life span and they may perform different functions. Thus, the application of Life Cycle Assessment (LCA) to buildings is a complex problem, as LCA was initially developed for the assessment of simpler products.

This section aims to provide a brief insight into specific aspects of the life cycle analysis of buildings and to support the methodological choices that were taken in the development of the model for the LCA of buildings that is described in the following section of this report (Section 4).

The model for the life cycle assessment of buildings was developed taking into account that it will be used in the very beginning of the design process, as it is during this stage that the most important decisions regarding the building design are taken, which will influence the building performance over its whole life [16].

Therefore, the aim of the LCA model referred in the previous paragraph is two-fold: (i) to enable the life cycle assessment of buildings, at the early stages of the design process; and (ii) to enable the benchmarking of the life cycle performance of buildings.

Since the project *EFIResources* is focussed on residential and office buildings, the model presented in this report is applied to these two types of buildings; however, it may easily be adapted for other building typologies.

3.1 Structural system of buildings

As already referred, the proposed approach aims for the harmonization between environmental criteria and structural criteria in the design of buildings, leading to an enhanced design and coping with the required safety demands, but with lower pressure on the environment and on the use of natural resources.

The weight, by mass, of the structural system of a building is usually dominant in relation to the weight of the full building. Structural engineers have the ability to decide, during the design process, about which materials and structural systems to adopt in the process. Therefore, providing the chance for structural engineers to include environmental criteria in the decision making process of building design will foster a more efficient use of resources and, consequently, will enable to reduce the environmental impacts of construction works. In this perspective, structural engineers play a leading role in the pursuit of a sustainable built environment [17].

Hence, to cope with the above goals, the life cycle analysis is limited to the structural system or frame of the building, including the foundations. It is observed that the structural system of a building is composed by all building elements that the eventual case of its collapse leads to the potential, total or partial, collapse of the adjacent components of the building.

Nevertheless, it is observed that although the scope of the analysis is limited to the structural system, the LCA model described in this report enables the LCA of the full building.

3.2 Framework and scope of the analysis

The benchmarking of the life cycle performance of buildings should rely on a consistent methodology for life cycle assessment. Therefore, the methodology herein proposed is based on the framework for the life cycle assessment of construction works, provided by the recent set of standards from CEN TC350.

This set of standards embrace the three main aspects of sustainability: environmental, economic and social. In relation to the life cycle environmental assessment, the analysis may be performed at the product level, according to EN 15804 [18] and at the building level, EN 15978 [19]. In the proposed approach, the economic and social aspects of buildings are not covered and therefore they will not be referred hereafter. However, it is acknowledge that the sustainability assessment of buildings should embrace at least the three main aspects referred above. Moreover, in the future the proposed approach may be easily extended in order to cover any additional aspect of sustainability.

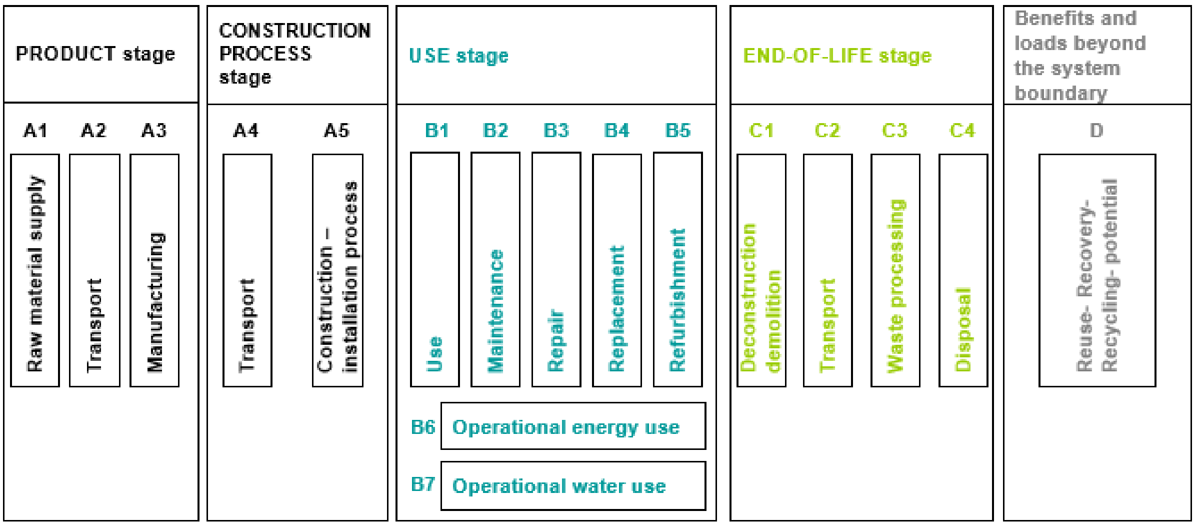
The scope of the analysis takes into account the complete life cycle of the building, from the product stage to the end-of-life stage. A modular concept was introduced by CEN TC350 standards, for the definition of the system boundaries of buildings, which is illustrated in Figure 4. According to this framework, the potential environmental impacts occurring over the life cycle of the building are allocated to the stage in which they occur, thus enabling full transparency of the results of the analysis. The modular concept indicated in Figure 4 is adopted in the present approach.

Hence, according to EN15978, the system boundary of the analysis entails the stage of material production (Modules A1 to A3), the construction stage (Modules A4 and A5), the use stage (Modules B1 to B7), the end-of-life stage (Modules C1 to C4) and Module D, which allocated the benefits and loads due to recycling, recover or reuse of materials. In the standard, only Modules A1 to A3 are mandatory, which correspond to a cradle-to-gate analysis.

Moreover, Module D, is considered beyond the system boundary of the analysis and its use is optional even when a complete life cycle analysis of the building is performed.

As already referred, the general framework for LCA, briefly described in the previous paragraphs, is adopted in the approach for the LCA of buildings presented in this report. Thus, all additional assumptions needed for the analysis that are not referred in this report, should be considered from EN 15804 and EN 15978.

Figure 4. Scope of the LCA of buildings according to CEN TC350 standards [18][19]



However, in order to comply with the goals and scope of the analysis, two main adaptations will be made in the scope of the analysis:

- The model for LCA described in this report enables to consider all the modules represented in Figure 4. However, in the development of benchmarks, since the analysis is limited to the structural system, Modules B6 and B7 will not be considered in the scope of the analysis;
- In the proposed approach Module D plays an important role as it enables to close the loop for the case of materials with potential for reuse, recycling and/or recover. Therefore, the LCA model proposed in this report considers Module D a mandatory part of the analysis. The allocation procedure for reusing and recycling of materials and/or components will be later addressed in this report.

3.3 Indicators for life cycle environmental performance

This subsection provides a description of the indicators provided by CEN TC350, followed by an overview of other available indicators for the sustainability assessment of construction works, focussing on the environmental component.

It is noted that according to ISO 14044 [20], the selection of impact categories must be consistent with the goal of the study and the intended applications of the results, and it must be comprehensive in the sense that it covers all the main environmental issues related to the system.

3.3.1 Requirements for selection of indicators

The project *EFIResources* focuses on the efficient use of resources throughout the life cycle of the structural system of buildings. This major goal is directly linked to the structural components of buildings, rather than building physics (e.g. thermal comfort, indoor air quality, etc.).

Hence, in order to fulfil the above goal, the design of the structural system should take into account the following aspects:

- **Design optimization**: The design of structures is made according to structural requirements prescribed by structural Eurocodes or other codes. The choice of materials shall be made taking into account the proper use of the mechanical properties of each material and taking advantage of those properties, thus minimizing the use of resources/materials. This may include the use of mew materials in order to improve the structural behaviour (e.g.: composite materials, FRP, glass, high strength steel, high strength concrete, etc) and/or the use of materials with recycling content. Furthermore, design optimization should take into account the optimization of the building performance over the complete life cycle of the building, minimizing the need of maintenance and maximizing the recovery of materials in the end of life;
- **Reduction of construction and demolition waste**: The waste produced during construction and demolition processes shall be reduced to a minimum and the residues that are unavoidable should be recycled or reused. Emphasis should be given to new construction methods and technologies such as lightweight construction, modular construction, prefabrication and industrial construction;
- **Design for flexibility and adaptability**: Buildings have a long life span and thus, the eventual change of use or requirements should be considered in the design process, in order to extend the period of life and to prevent the building to get obsolete with consequent demolition. Design for flexibility and adaptability should be considered in the initial design process, in order to avoid the need of a deep refurbishment over the life span of the building. Particular importance should be given to load bearing elements and flexibility of partition walls;
- **Durability of materials and components**: The durability of the materials should be taken into account to minimize maintenance needs and avoid the need for replacement;
- **Robustness**: The ability of a structure to withstand unforeseen events, without being damaged to an extent disproportionate to the original cause, is of particular importance in places prone to hazard events and to face potential higher loading demands due to climate change and/or terrorism actions;
- **Resilience**: Similarly, the capacity of the structure to adapt to and easily recover from hazards, shocks or stresses without compromising long-term prospects is of particular importance in places prone to hazard events or other unforeseen events;

- **Design for deconstruction and disassembly**: The way the structure is demolished has extreme influence on the amount and quality of materials and/or structural components that can be further use in another structure, thus avoiding the need to produce new materials from virgin materials. Design for deconstruction and disassembly should be considered in the initial design process in order to be effective, for example, the way structural elements are connected influences the way they are disassembled;
- **Reuse and/or re-assembly of materials or structural components**: The further use of materials and/or structures should take into quality of the materials and an estimation of their remaining service life.

The above aspects are in most cases correlated and the links between them are illustrated in Figure 5.

Figure 5. Links between aspects of structural design over the life cycle

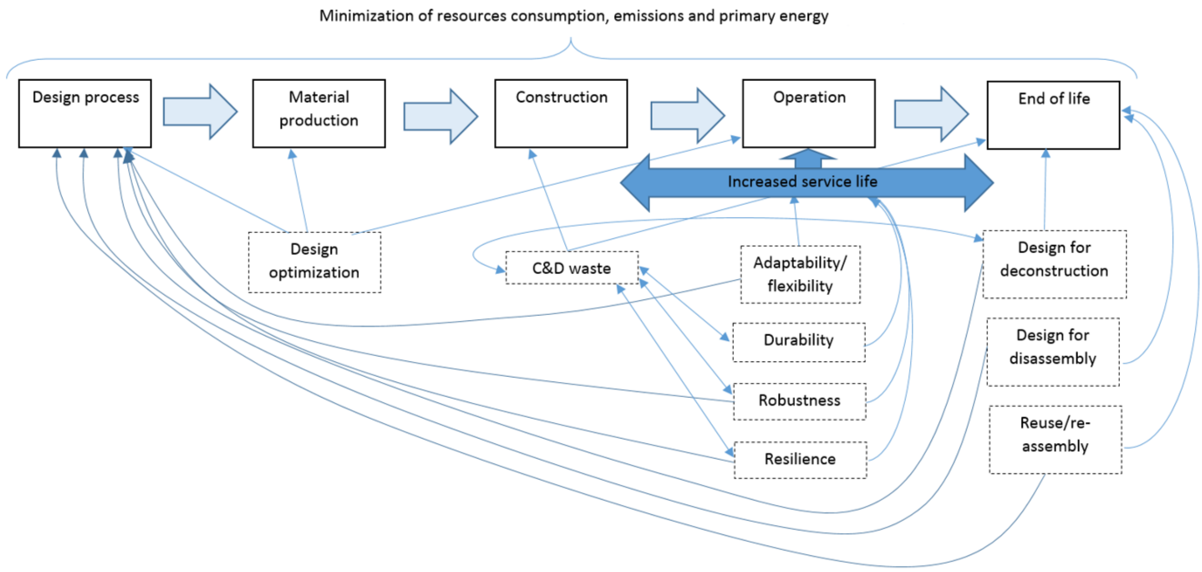


Figure 5 highlights the pressure that is put on the design process. As already referred, the earlier the above aspects are taken into account in the design process, the higher is the chance to positively influence the performance of the building over its working life.

Currently, there are no environmental indicators available to 'measure' aspects such as adaptability and/or flexibility, durability, robustness or resilience. However, these aspects affect the duration of the working life of the building and are therefore, extremely relevant for the minimization and optimization of the use of resources. Hence, the framework for the assessment of the environmental indicators should take this into consideration.

Taking into account the objectives of the approach and the above considerations, the requirements for the selection of indicators were the following:

- The indicators are based on sound scientific characterization models (mid-point indicators are preferred to end point indicators, as the level of uncertainty is reduced in the former);
- The indicators are quantifiable (quantifiable indicators are preferred to quantitative ones) enabling easier comparisons between alternative products or buildings;

- The indicators are representative of the use of resources in construction, so that its minimization would effectively represent a lower use of natural resources in buildings, throughout the period of reference;
- A higher number of indicators is preferred to the use of a single indicator to avoid the shift of burdens between environmental problems;
- The indicators are appropriate for the assessment of the building performance at the preliminary stages of design, when available data is usually scarce.

3.3.2 Indicators provided by CEN TC 350 series of standards

The indicators adopted in the proposed approach are the ones provided by the set of standards developed by CEN TC 350 for the sustainability assessment of construction works. These indicators fulfil the above requirements for the selection of indicators.

Indicators are provided for the assessment of each main environmental problem, taking into account a life cycle perspective of the building, from the construction to the end-of-life. For the assessment of the environmental performance of buildings, indicators describing environmental problems are provided at the product level in EN 15804 [18]. To assure consistency between the assessment at the product level and at the building level, the same indicators are used at the building level in EN 15978 [19].

Additionally, EN 15804 provides core product category rules for construction products and services, ensuring that Environmental Product Declarations (EPDs) of construction products are developed and verified in a harmonised way.

Two main types of environmental indicators are provided in EN 15804 for the environmental assessment: (i) indicators focussing on impact categories using characterisation factors, and (ii) indicators focussing on environmental flows. In relation to the former, seven indicators are provided, as indicated in Table 1.

Table 1. Indicators describing environmental impacts [18]

Indicator	Abbreviation	Unit
Global Warming Potential	GWP	kg CO_2 eq.
Depletion potential of the stratospheric ozone layer	ODP	kg CFC 11 eq.
Acidification potential of land and water	AP	kg SO_2- eq.
Eutrophication potential	EP	kg PO_4^{3-} eq.
Formation potential of tropospheric ozone photochemical oxidants	POCP	kg C_2H_4 eq.
Abiotic Resource Depletion Potential for elements	$ADP_{elements}$	kg Sb eq.
Abiotic Resource Depletion Potential of fossil fuels	$ADP_{fossil\ fuels}$	MJ, net calorific value

The Characterization Factors (CFs) used for the quantification of these indicators are provided from the *Centrum voor Milieuwetenschappen Leiden Impact Assessment* approach (CML-IA - version 4.1) [21] and they can be downloaded from the CML-IA website [22].

It is noted that in the proposed model for LCA, the impact category of GWP is further divided into GWP including biogenic carbon and GWP excluding biogenic carbon, for a higher transparency of the results.

In relation to indicators based on inventory flows, different types are provided in EN 15804. The indicators describing input flows are listed in Table 2.

Table 2. Indicators describing input flows [18]

Indicator	Unit
Use of renewable primary energy excluding energy resources used as raw material	MJ, net calorific value
Use of renewable primary energy resources used as raw material	MJ, net calorific value
Use of non-renewable primary energy excluding primary energy resources used as raw material	MJ, net calorific value
Use of non-renewable primary energy resources used as raw material	MJ, net calorific value
Use of secondary material	kg
Use of renewable secondary fuels	MJ
Use of non-renewable secondary fuels	MJ
Net use of fresh water	m^3

In relation to output flows, indicators are provided for waste categories and other flows leaving the system, as indicated in Table 3.

Table 3. Indicators describing output flows waste categories [18]

Categories	Indicator	Unit
Waste flows	Hazardous waste disposed	kg
	Non-hazardous waste disposed	kg
	Radioactive waste disposed	kg
Other flows leaving the system	Components for re-use	kg
	Materials for recycling	kg
	Materials for energy recovery (not being waste incineration)	kg
	Exported energy	MJ for each energy carrier

For the assessment of the social dimension of sustainability, the 1st generation of standards focuses on the evaluation of building impacts in relation to their occupants and other users. The quantification of social impacts is done by the indicators of Table 4 [23]. It is noted that the evaluation of these indicators is mainly qualitative, by the use of a checklist.

Table 4. Indicators for social assessment of buildings [23]

Indicator	Unit
Health and comfort	n.a.
Adaptability	n.a.
Loadings on the neighbourhood	n.a.
Maintenance requirements	n.a.
Safety and security	n.a.
Accessibility	n.a.
Sourcing of materials and services	n.a.
Stakeholder involvement	n.a.

Finally, in relation to the economic dimension, the calculation of the economic impact of a building is based on quantification of the costs occurring over the different life cycle stages of the building [24].

Social and economic indicators are not covered in the proposed approach and they will not be further addressed in this report.

The environmental indicators indicated in Table 1 to Table 3, cover the most relevant environmental problems and are also recommended by other life cycle approaches, as described in the following paragraphs.

3.3.3 Other indicators available in the literature

In the following paragraphs a review of other available indicators for the assessment of the sustainability of buildings is provided from different sources. Likewise, some approaches provide indicators for the assessment of different aspects of sustainability; however, focus is given to environmental indicators.

3.3.3.1 Indicators from the ILCD Handbook and PEF approach

The *International Reference Life Cycle Data System* (ILCD) Handbook [25] aimed to provide guidelines for good practice in life cycle impact assessment in the European context and provided the main basis for the development of the *Product Environmental Footprint* (PEF) [26].

The PEF approach, developed by the EC, aims to provide a harmonized methodology for the calculation of the environmental footprint of products. The list of environmental categories and respective assessment methods, recommended in this approach are indicated in Table 5.

Table 5. Recommended indicators by PEF [26]

Impact category	Indicator	Unit	LCIA method
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq.	Baseline model of 100 years of the IPCC(*)
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq.	EDIP model based on WMO assessment(1)
Particulate matter/ Respiratory inorganics	Intake fraction for fine particles	kg PM2.5 eq.	RiskPoll model(*)
Ionising radiation, human health	Human exposure efficiency relative to U235	kg U^{235} eq.	Human health effect model(*)
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq.	LOTOS-EUROS model(*)
Acidification	Accumulated Exceedance (AE)	mol H+ eq.	Accumulated Exceedance(*)
Eutrophication - terrestrial	Accumulated Exceedance (AE)	mol N eq.	Accumulated Exceedance(*)
Eutrophication - aquatic	Fraction of nutrients reaching freshwater end compartment (P) or marine end compartment (N)	kg P eq. kg N eq.	EUTREND model(*)
Ecotoxicity (freshwater)	Comparative Toxic Unit for ecosystems	CTUe	USEtox model(*)
Human toxicity - cancer effects	Comparative Toxic Unit for humans	CTUh	USEtox model(*)
Human toxicity, non-cancer effects	Comparative Toxic Unit for humans	CTUh	USEtox model(*)
Land use	Soil Organic Matter	kg C (deficit)	Model based on Soil Organic Matter (SOM)(*)
Resource depletion - water	Water use related to local scarcity of water	m^3	Model for water consumption as in Swiss Ecoscarcity(*)
Resource depletion – mineral, fossil	-	kg Sb eq.	CML 2002(*)

(*) the references of the different methods are given in [26]

It is observed that EC is currently promoting the harmonization between CEN TC350 and PEF approaches, and most probably, in the near future, the list of indicators provided in Table 1 will be extended to include the additional indicators provided in Table 5.

3.3.3.2 Indicators from the EU approach Level(s)

More recently, an EU framework for the assessment of the sustainability of buildings was developed, Level(s) [27], which provides a set of common indicators to report the life cycle environmental performance of buildings. Additional indicators are provided to assess health and comfort and life cycle costs.

The set of core indicators and tools, indicated in Table 6, was developed to provide compliance with a pre-set of macro-objectives, which were established based on EU and Member State policies. These indicators and tools are supposed to be used in different project stages and in different levels of assessment. Therefore, the calculation method considered for each indicator varies according to the stage and level considered in the assessment.

Table 6. Indicators proposed in Level(s) [27]

Macro-objective	Description	Indicator/tool
Greenhouse gas emissions along a buildings life cycle	Minimise the total GHG emissions along the building lifecycle	Use stage energy performance
		Life cycle global warming potential
Resource efficient and circular material life cycles	Optimise building design to support lean and circular flows, extend long-term material utility and reduce significant environmental impacts	Life cycle tools: bill of materials
		Life cycle tools: scenarios for life span, adaptability and deconst.
		Construction and demolition waste and materials
		Cradle-to-grave LCA
Efficient use of water resources	Make efficient use of water resources	Total water consumption
Healthy and comfortable spaces	Create buildings that are comfortable, attractive and productive to live and work in and which protect human health.	Indoor air quality
		Time outside of thermal comfort range
Adaptation and resilience to climate change	Futureproof building performance to projected changes in the climate	Life cycle tools: scenarios for projected future climatic conditions
Optimise life cycle cost and value	Optimise the life cycle cost and value of buildings	Life cycle costs
		Value creation and risk factors

The calculation methods recommended for the LCA indicators are provided by CEN standards EN 15804 and EN 15978.

3.3.3.3 Indicators from research projects dealing with LCA indicators

Over the last years, different EU research projects dealing with the sustainability of the built environment have been developed and recommendations have been provided in relation to the use of indicators in the life cycle assessment of buildings. Some of the most relevant projects are briefly described in the following paragraphs. Focus is given on the indicators recommended for the environmental category.

3.3.3.3.1 ENSLIC – Building Intelligent Energy Europe LCA pilot

The ENSLIC project (2007-2010) [28], founded by the EC through the Intelligent Energy Europe (IEE) program, aimed for the life cycle assessment of buildings, in the design stage, and to promote the use of LCA to stakeholders, by a simplified life cycle approach.

The selection of indicators in this project is related to the selection of the tool to perform life cycle analysis. Moreover, according to the findings of the project, the LCA tool to be used should be a simplified tool rather than an expert tool like SIMAPRO or GaBi.

Therefore, no list of indicators is recommended; however, since there is general interest by different stakeholders on CO_2 emissions and operational energy use, the indicators indicated in Table 7 were suggested [28]:

Table 7. Recommended indicators for building assessment [28]

Indicator	Unit
Global Warming Potential (GWP)	kg CO_2 equiv.
Use of primary energy expressed as the indicator Cumulative Energy Demand	MJ

3.3.3.3.2 SuPerBuildings - Sustainability and Performance Assessment and Benchmarking of Buildings

The SuPerBuildings project (2012) [29] was a FP7 funded project (2010-2012) that aimed for the development and improvement of sustainable building indicators, with a special emphasis on their validity and comparability, and for the development of methods for the assessment and benchmarking of buildings. Moreover, during the development of this project and since the aim was to achieve a convergence, at a European level, in relation to the selection and use of sustainability indicators, the project was harmonised with similar projects running at the same time (namely OPEN HOUSE project) by the exchange of information and results.

Different indicators addressing environment, society and economy were recommended, but in Table 8 only the environmental indicators are indicated. The ones considered as core indicators are indicated in the last column.

Table 8. Environmental indicators selected in the project SuPerBuildings [29]

Subject of concern	Issue	Indicator	Core
Resources	Depletion of non-renewable energy resources	Consumption of non-renewable primary energy	x
	Non-renewable and scarce material resources	-	
	Sustainable management of renewable resources	-	
	Rational use of water	Embodied water use Operational water use Wastewater production	x
	Land use / Change of land use	Soil sealing Change of land use	x (add.)
Biodiversity	Loss of biodiversity Preservation / improvement / restoration of local biodiversity	-	
Ecosystem	Protection of atmosphere and climate	Global warming potential	x
	Protection of atmosphere (other pollutants)	-	
	Protection of water and soil quality (pollution and waste)	Construction and demolition waste generation - Non-hazardous waste to disposal - Hazardous waste to disp. - Nuclear waste to disposal	x
		Water pollution due to material leaching	Add.
Climatic systems	Climatic systems (risk of extreme climatic events) Adaptation to climate change	-	
Transversal	Eco-mobility	Eco-mobility potential of a building in its context	Add.

3.3.3.3.3 OPENHOUSE project

The OPEN HOUSE project (2010-2013) [30], a FP7 funded project, aimed for the development and implementation of a common European building assessment methodology, complementing the existing ones, for planning and constructing sustainable buildings by means of an open approach and technical platform. The approach is supposed to be used in the early stage of building design or in early operation (10 years since completion).

The project proposed a list of 56 indicators, splitted into two sets of indicators ("open house full system" and "open house core system) and grouped into six categories: environmental quality, social/functional quality, economic quality, technical characteristics, process quality and the location. The list of environmental indicators is indicated in Table 9, and the indicators considered essential for the assessment, the core indicators, are identified in the last column.

Table 9. List of environmental indicators from Open house project [30]

Indicator	Core
Global Warming Potential (GWP)	x
Ozone Depletion Potential (ODP)	x
Acidification Potential (AP)	x
Eutrophication Potential (EP)	x
Photochemical Ozone Creation Potential (POCP)	x
Risks from materials	
Biodiversity and Depletion of Habitats	
Light Pollution	
Non-Renewable Primary Energy Demand (PE_{nr})	x
Total Primary Energy Demand and Percentage of Renewable Primary Energy (PE_{tot})	x
Water and Waste Water	x
Land use	x
Waste	x
Energy efficiency of building equipment (lifts, escalators and moving walkways	

3.3.4 Remarks about the impact category of resource depletion

In LCA the depletion of natural resources is usually addressed by the impact category of Abiotic Depletion, which describes the decrease of availability of total reserves of resources. However, this is an impact category that is subjected to several discussions as there is no scientifically accurate approach for its evaluation [31].

The method for Abiotic Depletion adopted in CEN standards (see Table 1) is based on the baseline method recommended by the Dutch LCA handbook [21]. In this case, the evaluation of Abiotic Depletion Potentials (ADPs), is based on the quantity of a resource that is ultimately available in the earth crust, the "ultimate reserve". It is noted that in these standards, currently two types of indicators are considered for abiotic depletion: $ADP_{elements}$ for the depletion of non-renewable abiotic material and $ADP_{fossil\ fuel}$ for all fossil resources. The former is measured in Antimony equivalent (Sb eq.) and the later in MegaJoules (MJ).

Two alternative methods for Abiotic Depletion are provided in the Dutch LCA handbook to enable a sensitivity analysis: one based on the "reserve base" and another based on the "economic reserve". The "reserve base" refers to "resources that have a reasonable potential for becoming economically and technically available"; while the "economic reserve" is the "part of the reserve base which can be economically extracted at the time of determination" [32]. It is noted that both the ILCD handbook and the PEF approach adopted ADPs based on the "reserve base" instead of "ultimate reserve".

The discussion of the most suitable method for ADP is outside the scope of this report. What is important to highlight is that, for many raw materials used in the production of common construction materials, Characterization Factors (CFs) are difficult to be quantified due to the lack of data in terms of reserves, reserve bases and ultimate reserves [32].

For instance, taking into account two of the most common construction materials, concrete and steel, the main raw materials for the production of a concrete mix and for the production of steel are indicated in Table 10 and Table 11, respectively. In addition, the CFs[1] available for each resource are indicated in the respective tables.

Table 10. Main non-fossil raw materials for concrete production [33]

		Characterization factors (CFs)		
Raw material		Elements	Reserve base	Economic reserves
Cement production	Limestone	-	-	-
	Cement rock	-	-	-
	Shale	-	-	-
	Clay	-	-	-
	Iron, iron ore	√	√	√
	Gypsum, anhydrite	√	√	√
Coarse aggregate		-	-	-
Fine aggregate		-	-	-

In the production of a concrete mix, aggregates consisting of crushed stone, sand and gravel, are the most important resources, with a contribution (by mass) of about 80% [33]. This is followed by cement with an importance of 7%-14%, depending on the required compressive strength of the concrete mix. In relation to the production of cement, one of the most important constituents is limestone (with a share above 70% of all raw materials in cement production). As observed in Table 10, no CFs are currently available, which means that more than 80% of the raw materials are not taken into account in this environmental category.

In relation to the production of steel, the situation is difference. Taking into account the production of steel in a Blast Furnace (BF) plant, the main non-fossil resources needed for the production of steel are listed in Table 11. In this case, iron ore accounts for more than 60% of all fossil and non-fossil resources [34].

Table 11. Main non-fossil raw materials for steel production [34]

	Characterization factors (CFs)		
Raw material	Elements	Reserve base	Economic reserves
Dolomite	√	-	-
Iron ore	√	√	√
Limestone	-	-	-
Zinc	√	√	√

Therefore, in this case, the impact category of ADP based on ultimate reserve (as given in EN15804 and EN15978) is better characterized than in the case of concrete production.

The lack of characterization factors for most common raw materials required for the production of construction materials and the consequent inconsistencies found for different materials lead to bias results. This is particularly relevant in comparative assertions.

Hence, at the present, in the assessment of buildings or any other construction work, the impact category of ADP based on ultimate, base or economic reserves, should not be used as a proxy indicator for resource depletion.

This enhances the importance of considering a set of indicators, instead of a single indicator, for the assessment of the efficient use of resources in the life cycle assessment of buildings.

[1] Taking into account the list of CFs provided in GaBi software [40].

3.4 Data categories for environmental assessment

One of the major barriers in the life cycle analysis of construction materials and buildings is the lack of credible and verifiable environmental data that is required for the assessment.

Generally, there are two main categories of data: generic data from available databases and specific data from manufactures and producers, which can be provided by Environmental Product Declaration (EPDs).

Generic data provided by available databases is based on average data related to a region, a country, a continent (e.g. Europe) or in a global scale. Average data is usually produced by LCA consultancy companies (e.g., GaBi or ecoinvent), by academics or by industrial sectors (e.g., the worldsteel database of steel products). A list of available databases is provided in the *European Platform for Life Cycle Assessment* [35].

On the other hand, specific data from manufactures is usually provided by Environmental Product Declarations (EDPs), which are Type III environmental declarations according to ISO 14025 [36]. EPDs are voluntary environmental declarations; however, over the last years there has been a growing demand for this type of data.

Most EPDs are currently complying with EN15804; however, in many countries adaptations are introduced by national annexes to take into account national specifications. EDPs are available in registration programs from different countries. Some European registration programs providing EPDs for construction-related products, compliant with EN 15804 and ISO 14025, are listed in Table 12.

Table 12. EPD registration programs

Operator name	Country	Website
Bau EPD GmbH (BAU-EPD)	Austria	www.bau-epd.at
EPD Danmark (epddanmark)	Denmark	www.epddanmark.dk/site/index_eng.html
Les données environnementales et sanitaires de référence pour le bâtiment (INIES)	France	www.inies.fr
Institut Bauen und Umwelt e.V. (IBU)	Germany	www.bau-umwelt.de
Næringslivets miljøstiftelse EPD Norge (NEF)	Norway	www.epd-norge.no
Sistema DAP Habitat (DAPHabitat)	Portugal	www.daphabitat.pt/?page_id=11
Sistema Declaraciones Ambientales de Productos por la construcción (DAPc)	Spain	www.csostenible.net/index.php/es/sistema_dapc
International EPD System (IES)	Sweden	www.environdec.com

The use of one category of data or the other should be done with careful as there are data deviations between the two categories. This is particularly important when comparative assertions are intended, in order to avoid the comparison of products based on different assumptions.

Lasvaux et al. [37] compared the use of generic and specific data for different construction materials and deviations in the LCA results were found depending on the selected indicator and on the type of material. The authors concluded that indicators linked to fossil fuel consumption are less variable than the others. Thus, for environmental categories of GWP, PED and ADP_{fossil}, deviations between the two categories of data were up to 25%; while for other indicators (e.g. $ADP_{elements}$ and POCP) the deviations reached values higher than 100%. The main reasons for the deviations were found to be linked to different assumptions such as data representativeness, background data, site specific conditions, etc.

It is further observed that even within the same category of data there may be deviations in the LCA results. For example, in a comparison made from two versions of an EDP, differences were found when using generic data against specific data for the foreground system [38]. Nevertheless, in a comparison between EPDs from different registration programs all over the world, performed by Modahl et al. [39], it was concluded that there are more similarities than differences between the different programs. Nevertheless, the authors emphasized that further harmonization between the programs is desired.

According to EN 15804, as a general rule, specific data should be used for the calculation of EPDs. In particular, specific data or average data derived from specific production processes should be used for foreground processes; while, for the upstream and downstream processes that the producer cannot influence, i.e. the background processes, generic data may be used. In this case, technological, geographical and time related representativeness shall be documented.

To be consistent with the above standard, specific data should be preferred for the LCA of buildings. However, it is observed that the aim of the proposed approach is to enable the assessment of buildings in the early stages of design. Therefore, the use of specific data may not be possible as the source of construction materials is usually not know at this stage of the design process. In this case, generic data may be used but preference should be given to generic data related to the location (e.g. country) where the building is supposed to be built.

In the LCA model proposed in this document, generic data is provided by GaBi databases [40]. Two databases are used: the Professional database, which is the standard database, and the database extension of Construction Materials. However, when data is missing in these databases for any material or process, data from EDPs is used to fill the gap. In all cases, data should comply with the quality requirements provided by EN 15804.

3.5 Design strategies for enhanced life cycle performance

Buildings are made of huge quantities of materials and therefore, extending the life of buildings enables to achieve the most effective use of the resources invested into the building. Likewise, increasing the potential of buildings materials to be recovered for reuse or recycling after the deconstruction avoids the need to produce new materials from virgin resources, thus safeguarding the natural environment.

Therefore, two main design options are herein highlighted for an enhanced life cycle performance of buildings: design for adaptability and design for deconstruction. It is stressed once again that, in order to produce effective improvements over the building life cycle, both design strategies should be considered in the early stages of building design.

3.5.1 Design for adaptability and flexibility

3.5.1.1 Basic requirements

Buildings are designed for long life spans. According to the Eurocode 1990 [41], the structural system of a building is designed for a period of 50 years, the design working life. Nevertheless, with proper maintenance and with the ability to accommodate changes in technical and functional requirements, buildings can last much longer than the design working life, sometimes even centuries.

Given the long period of time, it should be expected that the function requirements of the building may change during this period. Buildings should be able to accommodate these changes and adapt to new functional requirements, otherwise they reach was is known as the ‘limit state of obsolescence’. In this case, the end-of-life is reached because the building is either worn-out or outdated and not able to satisfy the users’ requirements.

In this section, given the scope of the proposed approach, focus is given to the structural system of a building; however, it is noted that other components of the building, such as the internal partitions, play a fundamental role towards this quest.

Hence, some brief recommendations towards an adaptable and flexible structural system are given below (it is observed that the list is not exhaustive, it simply aims to provide general guidelines particularly related with the structural system) [42]:

- Maximize the internal net space of the building in order to enable a flexible open space. This may be achieved by maximizing the length of the spans of beams and slabs and thus reducing the number of internal columns. The German system DNGB uses a ratio between the usable area and the gross floor area to evaluate the efficient use of floor area, and maximum points are achieved for a high value of the ratio [43];
- Consider slender internal columns to maximize the internal net space, but allow a slight overdesign of the columns and respective foundations, mainly in the perimeter of the building, to enable future extensions of the building structure;
- Ensure that the structural system is designed for loads that account for future changes in the function(s) of the building;
- Some redundancy and/or overdesign of the structural elements may be useful to enable future changes and extensions of the system;
- Avoid irreversible connections between structural elements to enable an easily and economic replacement of elements and/or connection of additional elements to the structure (for instance, in steel structures preference should be given to bolted connections instead of welded connections);
- Connections should be easily accessed to enable an easy removal or addition of new elements;
- Maximize the free height between floors. In DGNB a height between floors higher than 3 m enables to achieve the maximum score; while lower heights do not provide any points in the assessment [43].

Other recommendations may be provided for other building components, which may play equally important roles in the adaptability and flexibility of the building:

- Internal partitions should not support loads and should be easily added to the building or removed when not needed anymore;
- The building services, such as the heating and cooling systems or the ventilation system, should easily accommodate changes in the building requirements, requiring different distribution arrangements or change of size of the ducts.

3.5.1.2 Adaptability index

An adaptability index (I_{adap}) is herein proposed to account for the adaptability and flexibility of the building to cope with new technical and functional requirements, without the need for major construction work, and therefore extend the reference number of years considered for the standard life cycle analysis.

This index may be linked to the functional equivalent of the building (see sub-section 4.1.2), by increasing the reference period of time considered in the analysis. In this case, the result of each environmental category is given by expression (1):

$$Building\ performance = \frac{Environmental\ result}{GFA\ (in\ m^2) \times I_{adap} \times Ref.period\ of\ analysis\ (in\ years)} \quad (1)$$

However, in order to use the expression above, in the assessment of the environmental performance a building, there should be evidence that measures, such the ones described above, were taken into account in the conceptual design of the building.

3.5.2 Design for deconstruction

3.5.2.1 Basic requirements

Design for deconstruction is herein understood as a design strategy that takes into account the way the building will be disassembly, so that the amount of materials resulting from the demountable process, with potential for reuse/recycling or recover, is maximized.

In relation to the structural system, some construction systems may provide advantages towards deconstruction, such as [44]:

- Prefabrication of structures or structural components enables to reduce the time for deconstruction and increase the potential for reuse;
- Modular construction systems, apart from improving the adaptability of the building, enable an easier disassembly of the building, thus increasing the potential for reuse of building components;
- Structures with reversible connections enable an easier disassembly of structural elements.

The type of materials used in the structural system may also influence the ability of the structure to be disassembled and to be reuse or recycled:

- The durability of the materials increases the potential for building components to be reused after removal;
- The use of hazardous materials should be avoided, as they may contaminate other components and therefore, they are required to be removed before recycling;
- The use of a large number of different materials should be avoided, as it adds complexity to the structure and may reduce the potential for reuse or recycling.

3.5.2.2 Deconstruction index

A deconstruction index (I_{deco}) is proposed to account for the potential of building components and materials to be recycled or recovered in the deconstruction process.

This index affects the standard recycling rate (RR) considered for each material (see section 3.5) as given by expression (2). It is noted that for a same material, the effective recycling rate depends of the complexity of the structure and thus may change from case to case.

$$RR_{efect} = I_{deco} \times RR \tag{2}$$

In order to increase the standard recycling/reuse or recover rate, by the use of the expression above, the design of the structural system of the building should provide evidence that measures were taken to enable such improved rate.

3.6 Reuse and recycling of materials

To comply with European policies related to the efficient use of resources and waste production, the reuse and recycling of the materials resulting from any construction and demolition activities are crucial aspects in the life cycle analysis of buildings.

Accurate information about current recycling rates for construction materials does not exist. However, in this sub-section, indicative values of recycling rates are provided, followed by an overview of the main methodologies for the allocation of burdens and credits, due to the recycling process, between the primary and the secondary systems.

3.6.1 Rates of recycling and reuse of construction materials

The rates of recycling and recover of Construction and Demolition Waste (C&DW) varies across European countries, as observed from Figure 2. Moreover, the available data on recovering and recycling rates is highly variable and not very consistent among Member States due to different assumptions and differences in the levels of reporting C&DW [45].

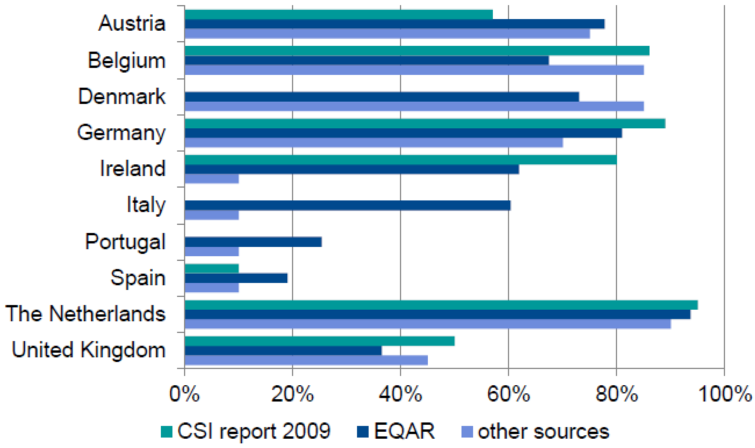
In the following paragraphs, indicative values of recycling rates from the literature are provided for two of the most popular construction materials.

3.6.1.1 Concrete

Concrete is one of the most consumed materials for construction and is also one of the most important contributors for the amount of waste produced annually.

The recycling rates of concrete vary from country to country and also to the source of data, as illustrated in Figure 6. As observed from the graph below, in some countries the target value of 70% have already been reached; while, in other countries the target value is far from being reached. A reason for this variation may be related to different assumptions in reporting but also to physical reasons, like the more or less availability on natural resources in each place [46].

Figure 6. Recycling rates in Europe for concrete (extracted from [46])



Concrete can be recycled into coarse or fine aggregates. Recycled aggregates resulting from crushing concrete have usually two main destinations: to be used in the sub-base and base for road construction or to be used in the production of new concrete.

Table 13. Use of recycled aggregates in different countries [46]

	Germany	Netherlands	UK
Use of recycled aggregates in concrete sand asphalt	19%	14%	7%
Use of recycled aggregates in road construction and earthworks	81%	86%	93%

The former destination is usually the most common, as indicated in Table 13, since the use of recycled aggregates in the production of new concrete is limited according to current regulations [46].

3.6.1.2 Steel products

Steel is one of the most recycled materials in the world but current rates of reuse and recycling vary according to the source of data.

A survey conducted by Tata Steel with data from the *National Federation of Demolition Contractors* in UK, led to the recycling and reuse rates indicated in Table 14.

Table 14. Reuse and recycling rates from Eurofer [47]

Product	% Reused	% Recycled	% Lost
Heavy structural sections/tubes	7	93	0
Rebar (in concrete superstructures)	0	98	2
Rebar (in concrete sub-structure or foundations)	2	95	2
Steel piles (sheet and bearing)	15	71	14
Light structural steel	5	93	2
Profile steel cladding (roof/facade)	10	89	1
Internal light steel (e.g. plaster profiles, door frames)	0	94	6
Other (e.g. stainless steel)	4	95	1

In this case, a surprisingly high rate is indicated for steel rebars or reinforcement steel, justified by the fact that concrete crushing was already a standard procedure by the time the survey was performed [47].

However, according to the Steel Recycling Institute [48], in 2014, the recycling rate for structural steel was about 98% and 71% for reinforcement steel. These rates are close to the rates indicated by ArcelorMittal [49], with rates of 95% and 50%, respectively for structural steel and reinforced steel.

3.6.2 Allocation strategies

In LCA, a system producing recycling materials is a multi-output system and, in this case, an allocation procedure is needed to allocate the burdens and credits due to recycling processes between the primary system and the secondary system. However, according to ISO 14044 [20], allocation should be avoided either by dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes or by expanding the product system to include the additional functions related to the co-products (system expansion). Nevertheless, when neither subdivision of processes nor system expansion are feasible, then allocation is unavoidable. In this case, one of two alternatives is recommended by ISO 14044: (i) the partition of inputs and outputs of the system is based on physical (e.g. mass, resistance, etc.) relationships; or when this is not possible (ii) allocation should be based on other relationships, such as the economic value of the products (e.g. market price of the recycled material).

In addition, when addressing recycling materials in LCA it is important to take into account the changes in the inherent properties of the recycling material leaving the system. In this case, three main situations may occur [50]:

- the material's inherent properties are not changed over the considered product system and the material is to be reused in the same application;
- the material's inherent properties are changed over the considered product system and the material is to be reused in the same application;
- the material's inherent properties are changed over the considered product system and the material is to be used in other applications.

The selection of an appropriate allocation procedure depends of the case considered. In the first case, there is a closed-loop situation in which the substitution of primary material is assumed to be complete and therefore, no environmental burdens from primary material production or final disposal are allocated to the product system. The second case corresponds to an open-loop approach assuming a closed-loop situation. In this case, the changed material properties are considered irrelevant and recycling is addressed as a closed-loop situation. According to ISO 14044 [20], in the case of a closed-loop situation allocation is avoided since the use of secondary material replaces the use of virgin materials.

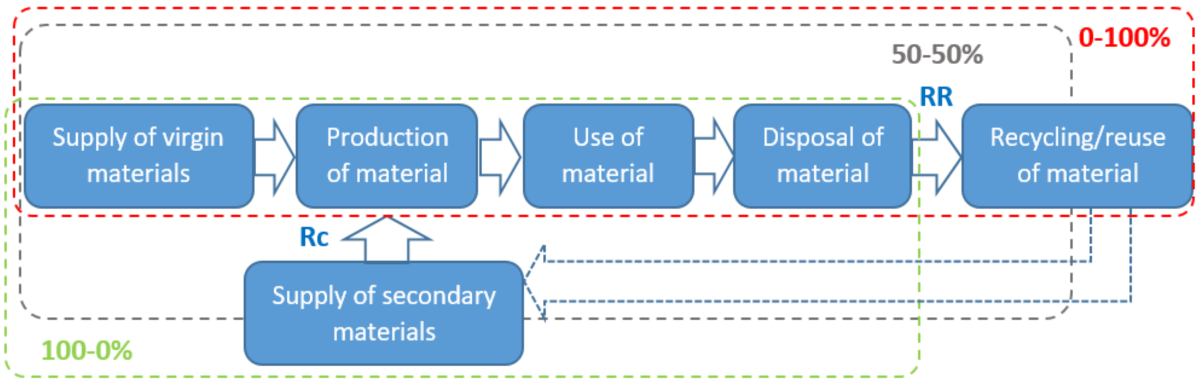
In the last case, there is an open-loop situation where the substitution of primary material is assumed to be partial. This case is also referred as "down-cycling". In this case, environmental burdens due to primary material production or final disposal have to be partially allocated to the system under study.

In an open-loop situation, three different types of allocation procedures are generally considered:

- The recycled content approach; also known as the 'cut-off' rule or the 100:0 method;
- The avoided impact approach; also known as the substitution method or the 0:100 approach;
- The 50:50 method, which may be considered as a compromise between the above approaches.

The scope of the three different approaches are illustrated in Figure 7 and will be further described in the following paragraphs.

Figure 7. Allocation procedures of recycling materials



Additionally the allocation approaches adopted in the Product Environmental Footprint [26] and in CEN TC350, which are based on these general approaches, will also be addressed in the following sub-sections.

3.6.2.1 General approaches

3.6.2.1.1 The recycled content approach or the 100:0 approach

The 100:0 method allocates 100% of the benefits of using recycled materials in the production stage (modules A1 – A3) to the system under consideration but neglects all eventual benefits of creating recycled materials at the end of life stage. Hence, the resulting environmental profile is given by,

$$[(1-R_c)E_V + R_c \times E_R] + (1-RR)E_D \quad (3)$$

Where, E_V are environmental burdens arising from the acquisition and pre-processing of virgin material; E_R are environmental burdens arising from the recycling process of the recycled material, including collection, sorting and transportation processes; E_D are environmental burdens arising from disposal of waste material at the EoL of the analysed product; R_c is the recycled content of material and *RR* recycling (or reuse) fraction of material.

In this case, the input of secondary material is modelled as being free from any primary material burden and a small benefit is provided in the EoL stage by reducing the amount of waste sent to landfill by the amount to be recycled. This approach enables an easy application and it's useful when data about the recycling of materials at the end-of-life stage in not available. Likewise, it enables to reduce the uncertainty associated with future recycling and/or reuse technologies.

However, the main drawback of this approach is that no incentives are given to the party that makes the effort to promote the use of materials with recycling potential, nor the quality of the recycling material is taken into account.

3.6.2.1.2 The avoided impact approach or the 0:100 approach

On the other side, the 0:100 method allocates 100% of the benefits of creating recycled materials at the end of life stage to the system under consideration but neglects all benefits of using recycled materials in the production stage (modules A1 – A3). Thus, in this case, the resulting environmental profile is given by,

$$E_V + [(1 - RR)E_D] + [RR(E_R^* - E_V^*)] \tag{4}$$

Where, E^*_R are environmental burdens arising from the recycling process at the end-of-life stage; E^*_V are environmental burdens arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials; and all other variables are described as for expression (3). It is noted that, in case of closed-loop, $E^*_R = E_R$ *and* $E^*_V = E_V$.

This approach takes advantage of the use of materials with potential for reuse, recycling and recovering.

In this case, the main drawback of this approach is that no incentives are given to the party that makes the effort to use materials with recycling content and no incentives are given to the development of new materials based on recycled materials instead of virgin materials.

3.6.2.1.3 The 50:50 approach

The 50:50 method allocates 50% of the benefits of using recycled materials in the production stage (modules A1 – A3) and 50% of the benefits of creating recycled materials at the end-of-life stage, to the system under consideration. In this case, the resulting environmental profile is given by the following expression:

$$[(1 - 50\% \times R_c)E_V + 50\% \times R_c \times E_R] + [(1 - 50\% \times RR)E_D] + [50\% \times RR(E_R^* - E_V^*)] \tag{5}$$

Where all variables are described as for expressions (3) and (4). This allocation procedure, also known as partition rule, is a compromised between the two previous approaches.

3.6.2.2 Other approaches

3.6.2.2.1 Allocation approach of the Product Environmental Footprint (PEF)

The allocation approach adopted in the Product Environmental Footprint (PEF) [26], which was developed by the European Commission to measure the environmental performance of a good or service throughout its life cycle, is based on the 50%-50% approach.

In this case, the resulting environmental profile is given by the following expression [26]:

$$\left[\left(1 - \frac{R_c}{2}\right)E_V + \frac{R_c}{2} \times E_R\right] + \left[\left(1 - \frac{RR}{2}\right)E_D - \frac{R_c}{2} \times E_D^*\right] + \left[\frac{RR}{2}(E_R^* - E_V^* \times K)\right] \tag{6}$$

Where, K is the ratio for any differences in quality between the secondary material and the primary material; and E^*_D are environmental burdens arising from disposal of waste material at the EoL of the material where the recycled content is taken from.

The above expression comprehends 3 main blocks: (i) the 1st block represents the environmental profile due to virgin material acquisition, recycled material input and pre-processing; (ii) the 2nd block in the expression represents the environmental profile due to the disposal of fraction of material that has not been recycled (or reuse/recover); and (iii) the 3rd block represents the environmental profile due to the recycling process, subtracted by the credit from avoided virgin material input, taking into account an eventual down-cycling. Factor *K* enables to take into account the down-cycling and is given by the ratio between the quality of the recycled or reused material (Q_s) and the quality of the primary material, i.e. the quality of the virgin material (Q_p).

Furthermore, when there a share of material in the product to be used for energy recovery (R_3), an additional term is added to the 3rd block:

$$R_3 \times \left[E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec}\right] \quad (7)$$

Where, E_{ER} are specific emissions and resources consumed arising from the energy recovery process; $E_{SE,heat}$ and $E_{SE,elec}$ are specific emissions and resources consumed that would have arisen from the specific substituted energy source, heat and electricity respectively; *LHV* is the Lower Heating Value of the material in the product that is used for energy recovery; and $X_{ER,heat}$ and $X_{ER,elec}$ are respectively the efficiency of the energy recovery process for both heat and electricity.

In this case, the impacts due to the disposal of the material to be used for energy recovery ($R_3 \times E_D$) should be subtracted in the 2nd block.

3.6.2.2.2 Module D approach of EN 15804

According to EN 15804, the net environmental benefits or loads due to recycling, reuse or energy recover are allocated to Module D. Net impact has a twofold meaning: (i) in relation to environmental impacts, net impact is the difference between the impacts due to the recycling process which substitutes primary production and the impacts due to the production of the avoided primary material; and (ii) in relation to mass, net impact is the difference between the output of secondary material from the system and the input of secondary material to the system. In this case, the resulting environmental profile is given by expression (8):

$$[(1 - R_c)E_V + R_c \times E_R] + [(1 - RR)E_D] + [(RR - R_c) \times (E_R^* - E_V^*)] \quad (8)$$

In case of Module D, the quality of the secondary material leaving the system is not taken into account. However, secondary material may only be considered as substituting primary production when it reaches the functional equivalence of the substituted primary material [18]. Hence, following the guidance from the PEF approach, a value-correction factor (C_f) is herein adopted to reflect the differences in the functional equivalence of the secondary material in relation to the substituted primary material. Therefore, expression (8) becomes:

$$[(1 - R_c)E_V + R_1 \times E_R] + [(1 - RR)E_D] + \left[(RR - R_c) \times \left(E_R^* - E_V^* \times C_f\right)\right] \quad (9)$$

The determination of the value-correction factor (C_f) is described in the following paragraphs.

3.6.2.3 Value-correction factor

When the material undergoes a change to its inherent properties, i.e. in a down-cycling process, the replacement of the primary material is only partial and this may be taken into account by the use of a value-correction factor (C_f). Hence, the value-correction factor reflects the quality of the secondary material in relation to the value of the primary material [51].

The value-correction value (C_f) may be considered as the ratio between the price of the secondary material and the price of primary material [51][52]:

$$C_f = (Price\ secondary\ material/Price\ primary\ material) \quad (10)$$

The main limitation on the use of this coefficient is that it requires the correct identification of the appropriate point of substitution. Moreover, the use of expression (10) requires the existence of a stable market for the secondary material.

An additional expression, which takes into account the existence of the market for the secondary material (M) and the quality of the secondary material in comparison to the quality of the primary material, at the point of substitution (Q), is given by expression [53]:

$$C_f = M \times Q \quad (11)$$

The coefficient M that takes into account the existence of a market for the secondary material (i.e. it's 0 when there is no market, or 1 when all the material is used in the market); while, Q represents to what extent the inherent properties of the material underwent a change in recycling activities. Likewise, the calculation of the coefficient Q requires identification of the appropriate point of substitution.

3.6.2.4 Discussion of the methods

The five approaches are summarized in Table 15, according to the modular concept of CEN TC350 standards.

Table 15. Relation of allocation approaches with EN 15804 modular concept

Approach	Modules A1 – A3	Modules C1 – C4	Module D
100% - 0%	$[(1-R_c)E_V + R_c \times E_R]$	$[(1-RR)E_D]$	-
50% - 50%	$\left[\left(1-\frac{R_c}{2}\right)E_V + \frac{R_c}{2} \times E_R\right]$	$\left[\left(1-\frac{RR}{2}\right)E_D\right]$	$\frac{RR}{2}(E_R^* - E_V^*)$
0% - 100%	E_V	$[(1-RR)E_D]$	$RR(E_R^* - E_V^*)$
PEF	$\left[\left(1-\frac{R_c}{2}\right)E_V + \frac{R_c}{2} \times E_R\right]$	$\left[\left(1-\frac{RR}{2}\right)E_D - \frac{R_c}{2} \times E_D^*\right]$	$\frac{RR}{2}(E_R^* - E_V^* \times F)$
EN15804 - Module D(*)	$[(1-R_c)E_V + R_c \times E_R]$	$[(1-RR)E_D]$	$(RR - R_c)(E_R^* - E_V^* \times C_f)$

(*) Module D with a value-correction factor

The adoption of an allocation approach should be consistent with the goals and scope of the life cycle study.

In the scope of the proposed approach, both the use of materials with recycled content and materials with potential for reuse, recycling or recover are encouraged. A sustainable design of a building should consider both types of materials. This means that both present and future impacts are important and neither should be neglected in a LCA, obviously taking due care not to double count impacts.

As observed from Table 15, only two approaches take advantage of the recycling content and the potential for recycling, simultaneously: the 50-50%/PEF approach and the Module D approach. Therefore, in the scope of the proposed approach, only these two approaches are considered to be appropriate for the allocation of credits and debits to the product system.

Both the PEF approach and the Module D approach have advantages and disadvantages. A common difficulty in both cases is the definition of the value-corrected value, as already described.

The estimated benefits occurring on the future, due to recycling or reuse of materials, are estimated based on present technology and current practices [19]. Taking into account the long life span of buildings, this may lead to an overestimation of future benefits due to technological improvements. This provides a level of uncertainty to the data. In the PEF approach, only 50% of future benefits are allocated to the system, which enables to reduce the uncertainty associated with the method.

On the other hand, it is important to document the results in a transparent manner, both in terms of assumptions and results. Hence, the aggregation of results is not recommended and the results should be provided in relation to the stage they are related, which is the case of CEN standards.

Following the guidance from CEN TC350 standards, the allocation procedure provided by expression (9) is adopted in the proposed approach for the allocation of recycling and recovering of materials. However, for comparative reasons and sensitivity analysis, the other approaches will also be considered in this report.

4 Model for Life Cycle Assessment (LCA) of buildings

The proposed model for the Life Cycle Assessment (LCA) of buildings is based on the standardized framework for LCA developed by CEN TC 350 for the sustainability assessment of construction works. Two main standards will be herein addressed: EN 15804 [18] for the assessment at the product level and EN 15978 [19] for the assessment at the building level. The adoption of a standardized procedure ensures the use of a consistent approach that was developed specifically for the assessment of construction works. Furthermore, it enables comparability between different building assessments and benchmarking, which is one of the major goals pursued in the proposed approach.

Hence, this section aims to describe the model adopted in the approach for sustainable design and to provide guidance in its use for the life cycle assessment of buildings and benchmarking. It includes the description of basic requirements and assumptions needed to conduct the calculations. In addition, this section describes the deviations of the model in relation to the referred standards, which were implemented in order to comply with the goals of the approach proposed in this report. This model is further implemented into a professional software for LCA, as described in the following section of this report.

Any additional aspect or specification that is omitted in this section should be considered from EN 15804 and/or EN 15978.

Finally, it is observed that the model described in the following paragraphs may be used for the life cycle assessment of the complete building. However, since the benchmarking will focus on the structural system of buildings, the following sub-sections are referring only to this building component.

4.1 Aims and boundaries of the analysis

4.1.1 Goals of the analysis

The goal of the analysis is to assess the environmental performance of the structural system of a building, in a life cycle perspective, i.e. taking into account all stages from material production to the end-of-life.

The ultimate goal in the development of this model is to provide a consistent tool for the life cycle analysis of buildings, enabling the benchmarking of the structural system of residential and office buildings.

4.1.2 Functional equivalent

The functional equivalent adopted in the approach includes the type of use of the building (residential or office building), the total Gross Floor Area[2] (GFA) and a reference period of time. The results of the life cycle analysis are provided for the functional equivalent, normalized per the GFA of the building and per year.

For office buildings, an optional functional equivalent may be used, which takes into account the number of working places instead of the GFA. In this case, the results of the life cycle analysis are provided for the functional equivalent of the building, per the number of working places and per year.

In the proposed approach, the reference period of time is given by the estimated working life of the building, according to the code or regulation used in the design of the structural system of the building. In case the estimated working life of the building is not provided in the project documentation, a period of time of 50 years may be considered, which is the design working life recommended by EN1990 [41] for residential and office

[2] The GFA is measured according to the external dimensions of a building; this includes all areas inside the building including supporting areas.

buildings. Adequate scenarios should be taken into account in the use stage of the building to comply with the period of time considered.

4.1.3 Boundaries of LCA

The model takes into account the complete life cycle of the building, from the product stage to the end-of-life stage. As already referred, the modular concept introduced by CEN TC350 standards for the definition of the system boundaries of the LCA, which is illustrated in Table 16, is adopted in the present methodology. All modules are taken into account except Modules B6 and B7, which address the consumption of operational energy and water, respectively, during the use stage of the building. It is assumed that these two modules do not depend on the structural system of the building and therefore they are excluded from the scope of the analysis.

It is further noticed that, in order to comply with the goals of the proposed approach and support EU policies related to resource efficiency, Module D is included in the life cycle analysis of the building. This is a deviation from CEN TC 350 standards, which consider Module D as optional in the LCA of buildings.

Table 16. Scope of the LCA

Product stage			Process stage		Use stage							End-of-life stage				
A1	A2	A3	A4	A4	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse-recycling-recover
x	x	x	x	x	x	x	x	x	x	n.a.	n.a.	x	x	x	x	x

Taking into account the functional equivalent and the scope of the analysis, the information contained in each module of Table 16 is the following:

- Modules A1 to A3 – Include the production of all buildings materials that are used in the foundations and structure of the building, until the gate of the factory. Data for these modules is usually provided from the Bill of Materials (BoM) of the building;
- Module A4 - Transportation of the materials needed for the foundations and structure of the building, from the production place to the construction site. This information is based on best guesses or scenarios taking into account the location of the building and the type of transportation;
- Module A5 – Use of equipment and machinery for the construction of the foundations and erection of the structure; in case this information is not available, scenarios may be considered. In the model, the preparation of the terrain for the construction of the building, the installation of auxiliary infrastructures and the construction of accesses to the construction site are not taken into account;
- Modules B1-B5 – These modules include all relevant data in relation to the maintenance, repair and refurbishment of the structural system of the building. This should include the use of materials and equipment, and the management of the waste created. In case secondary materials are created, credits should be

allocated in Module D. Data for these modules should be based on scenarios taking into account the estimated working life of the structural components of the building;

- Module C1 – C4 – These modules include all relevant data from the decommission of the structural system of the building to the stage in which the end-of-waste state is reached by all the structural materials. This includes the use of equipment and machinery for the deconstruction of the building structure, sorting of materials and transport of the resulting materials to their final destination. This data should be based on scenarios;
- Module D – This module allocates net benefits due to the reuse, recycling and recover of materials. Data for this module should be based on scenarios taking into account the average available technology, current practices and current rates of recycling, reuse and recover of materials.

4.2 Indicators for life cycle environmental performance

The indicators adopted from the life cycle analysis are the ones provided by EN 15804 and EN 15978, which are indicated in Table 1 to Table 3. However, it is observed that the model is opened and additional indicators can be added when relevant.

As discussed in sub-section 3.3.4, the results for construction materials provided by the impact category of Abiotic Depletion of non-renewable abiotic material ($ADP_{elements}$) are limited as characterization factors are missing for many common raw materials required for the production of the materials. Hence, its use may be only informative but it should not be used for benchmarking.

4.3 Quality of data

The requirements for the quality of data provided in EN15804 and EN15978 are based on the requirements provided by ISO14044:

- Time-related coverage - datasets should be recent or updated within the last 10 years for generic data and 5 years for specific data from producers;
- Geographical coverage – according to the aim of the study, the geographical area from which data is collected should be representative;
- Technological coverage – all relevant technologies should be covered and they should reflect the reality for each product;
- Completeness – datasets should be complete according to the goal and scope of the analysis.

As previously indicated in Sub-section 3.4, there are two main categories of data: generic data from available databases and specific data from manufactures and producers.

For the life cycle assessment of the buildings provided in this report and for the benchmarking (not addressed in this report), the two categories of data are used. In relation to the first category, data is provided by GaBi databases; while, in relation to the second category, data is provided from available EDPs registered in European programs. In general, all data comply with the quality requirements above.

Furthermore, these requirements are checked for some common construction materials in Section 6 of this report.

4.4 Scenarios for life cycle analysis

Scenarios are defined to assess the behaviour of the structural system of the building over the period of time considered for the analysis.

The processes and assumptions considered in these scenarios should be based on current technological developments and standard practices. This approach may be conservative, particularly for recycling and reuse of materials, for which major improvements are expected, as the market for secondary materials is in an early stage of development.

Additional details about the scenarios for some common construction materials are provided in Section 6.

4.4.1 Construction stage

The construction stage includes Modules A4 and A5 in Table 16.

4.4.1.1 Module A4

Module A4 includes the transport of materials from the gate of the manufacture place to the construction site. The distances should be estimated for each material, taking into account the place where they are produced and the location of the building. When these distances are not possible to be evaluated, its calculation may be done based on average distances.

In addition, the type of transport considered for each material should take into account whether the material is produced locally or produced in far distances (or imported).

4.4.1.2 Module A5

All on-site activities related to the construction of the building are considered in Module A5. This includes the preliminary works on the construction site to enable the construction of the building, the use of equipment, the transport of materials and equipment on-site, waste management of products lost during the construction activities, etc. In addition, inventory data should also include emissions due to combustion engines.

However, in practice, there are very few studies focussing on this life cycle stage and currently, it is hard to found appropriate values for its quantification.

According to Sjunnesson [54], the use of electricity for the construction of houses varies from 0.5 to 3.3 kWh per the gross floor area; while for apartments, the electricity demand varies from 1.1 to 18.2 kWh/GFA.

In another study [55], the electricity consumption of two office buildings were about 18.2 kWh/m^2 and 91.7 kWh/m^2. In this case, the author concluded that the electricity demand due to the construction of the building frames has only a minor contribution to the total electricity demand (lower than 0.1%).

Hence, when no better information is collected for this stage, a value in the range of about 1-5 kWh/GFA may be considered for residential houses and values in the ranges of 5-20 kWh/GFA and 20-80 kWh/GFA may be considered for multi-storey residential and office buildings, respectively. It is noted that these are only rough assumptions.

4.4.2 Operation stage

Modules B1-B5 include all relevant data in relation to the maintenance, repair and refurbishment of the structural system of the building, during the period of time considered in the analysis.

Scenarios should be considered for the relevant modules, taking into account the estimated service life of the structural components of the building.

When special features are considered in the design of the building, enabling the adaptability of the building to new functional requirements, then scenarios should be considered taking this into account, and eventually extending the period of time considered in the analysis (see sub-section 3.5).

4.4.3 End-of-life stage

The end-of-life stage includes Modules C1-C4 and D in Table 16. In addition, when special features are considered in the design of the building, enabling an easier disassembly of the building, then scenarios should be considered taking this into account and eventually increasing the recycling rate considered in the analysis (see sub-section 3.5).

4.4.3.1 Modules C1-C4

Module C1 includes all processes and activities used on-site for the deconstruction of the building frame. This shall ideally include the use of equipment, supply of fuel and the quantification of other emissions due to the activities performed on-site.

Currently, there is not much information about this life cycle stage to enable a comprehensive assessment of the corresponding potential environmental impacts.

When more accurate data is not available, the values provided in Table 17 may be used, which are based on a study, conducted by the Athena Institute [56], on the deconstruction of three different types of structures: wood, steel and concrete. These values include the demolition/deconstruction of the foundations for each type of frame.

Table 17. Energy used (in MJ/kg) for the demolition/deconstruction of different structural frames in buildings [56]

	Frame to be recycled (in MJ/kg)	Frame to be reuse (in MJ/kg)
Steel frame	0.239	0.432
Concrete frame	0.070	0.061
Wood frame	0.323	0.176

The higher use of energy for the deconstruction of the steel structure was justified by the need to handle heavy steel members and thus, the need for a longer time for the operation. On the other side, the lower values provided in general for concrete frames is because the process is usually quicker and requires less machine time [56].

Module C2 includes the transport of the materials resulting from the disassembling of the structure to disposal or until the end-of-waste state is reached. The transportation distances may be based on average transport distances for the materials.

Module C3 includes all the processes until the end-of-waste state is reached. Hence, appropriate scenarios should be considered for each material, taking into account additional processes (if applicable) that are needed to further process the materials, until they reach the end-of-waste state.

Finally, for Module C4, scenarios should be considered that include all the necessary processes or activities that are needed before disposal and the final disposal of materials.

4.4.3.2 Module D

Module D allocates net benefits due to the substitution of primary materials. Hence, scenarios should be considered for each material to enable the quantification of the net benefits. These scenarios should be based on average available technology, current practices and current rates of recycling, reuse and recovering of materials.

Currently, no accurate rates are available and the existing values vary across different European countries (see Sub-section 3.6.1). For concrete, and unless more accurate information is provided, a recycling rate of 70% may be considered. It is noted that this value is maybe overestimated for some countries, as illustrated in Figure 6. In relation to steel products, a recycling rate of 90% may be considered for structural steel and a rate of 70% for reinforcement steel.

4.5 Uncertainty and variability in LCA

The uncertainty and variability of the parameters and methodological choices considered in the life cycle analysis should be taken into account [20]. This is particularly important in the LCA of buildings and other construction works, which entails long reference periods of time.

This topic will not be detailed address in this report, but a sensitivity analysis followed by a probabilistic analysis are herein proposed to take into account some of the uncertainties in LCA of buildings.

The aim of the sensitivity analysis is to determine how different methodological choices and changes in the parameters affect the results of the analysis, and thus enabling to identify the most important inputs in the analysis.

Hence, scenario analysis is performed to evaluate the influence on the outcome of the assessment of the different scenarios considered in the different modules of the analysis, as described in the previous paragraphs.

In addition, a perturbation analysis is considered, in which a small variation is introduced to each parameter to determine the effect on the result of the analysis. The identification of the most important parameters in the analysis is performed by the use of the Sensitivity Ratio (SR) [57], which represents the ratio between the relative change of the result of the analysis and the relative change of the parameter, as given by expression (12):

$$SR = \frac{\frac{\Delta result}{initial\_result}}{\frac{\Delta parameter}{initial\_parameter}} \tag{12}$$

Once, the most important parameters are identified, their uncertainty is evaluated and a probabilistic analysis may be performed to take into account the simultaneous uncertainty in all parameters and evaluate the uncertainty in the outcome of the analysis.

Uncertainty propagation is performed by the use of a sampling method: the Monte Carlo Simulation.

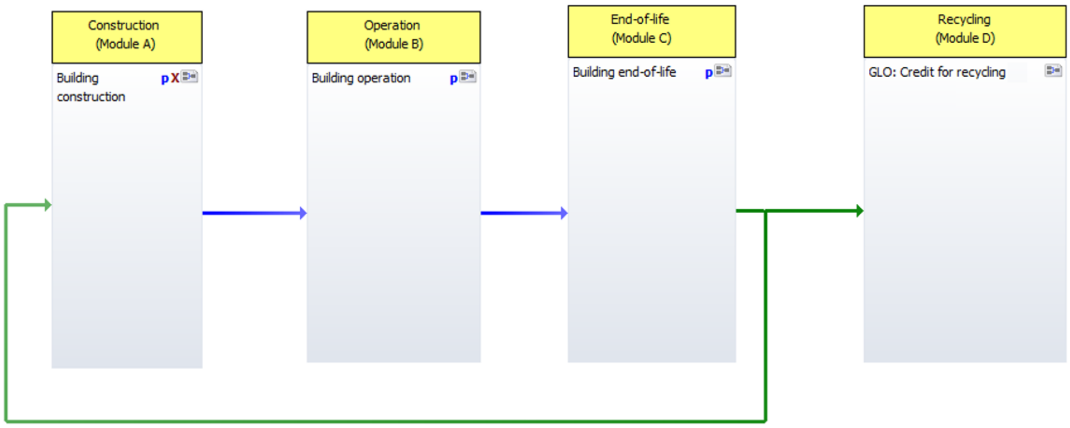
5 Software tool for LCA of buildings

The model for the LCA of buildings described in the previous section of this report was implemented into the expert software for LCA GaBi (version 8.1.0.29) [40]. The databases used in the model are the 'Professional database' and the 'Extension database XIV: Construction materials'. The version of the databases is 8.6 (service pack 34).

Although the scope of the proposed approach is limited to the structural system, the model was developed in order to enable the analysis of the full building, including all the remaining components, as described in the following paragraphs.

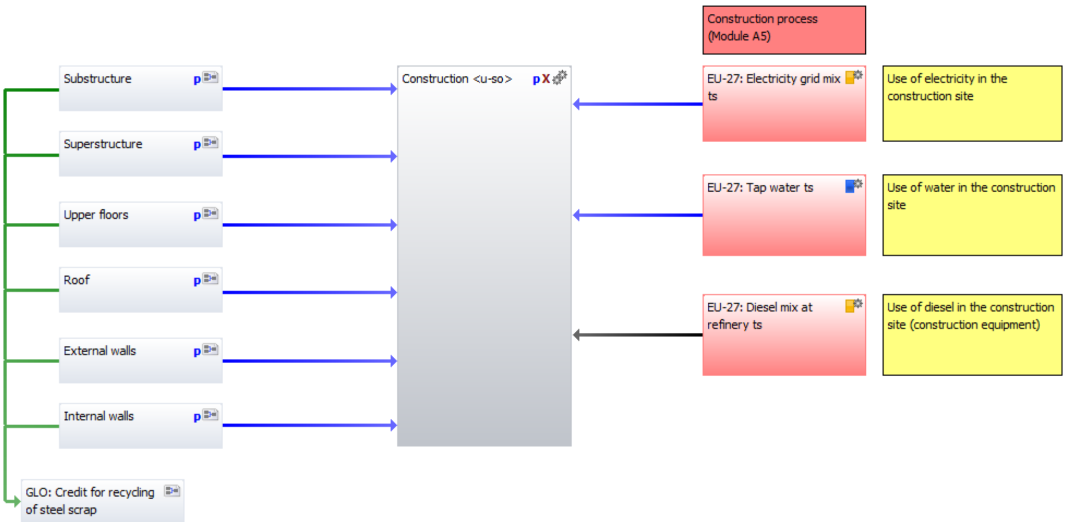
The GaBi software enables the model to be assembled in different plans (layers) that are inter-linked. The main plan of the model represents the main stages of the life cycle of the building, as illustrated in Figure 8.

Figure 8. Life cycles stages of the building



Each main stage is further divided to include all relevant processes in each stage. Therefore, the construction stage, which is represented in Figure 9, includes the assemblage of the main parts (components) of the building, namely: the substructure, the superstructure, the upper floors, the roof, and the internal and external walls.

Figure 9. Plans and processes included in the construction stage of the building

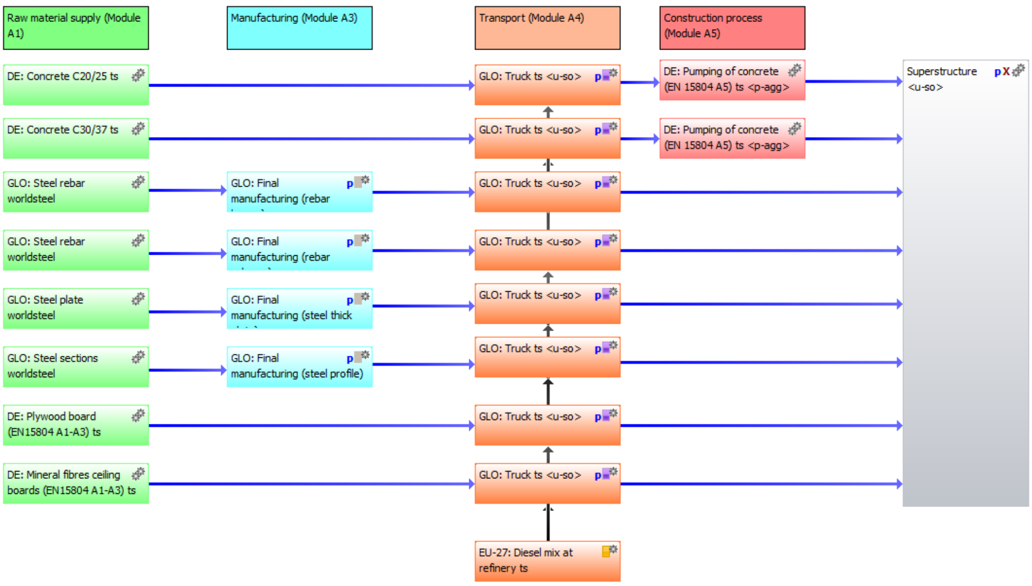


The substructure includes the preparatory works that are needed in the terrain for the construction of the building, the foundations and all auxiliary materials such as waterproofing membranes. All vertical load-bearing elements, such as columns and walls, as assigned to the superstructure. The upper floors include all structural elements and all other finishing materials that are needed for the internal slabs. The roof is similar to the upper floors but relates to all elements that are used on the top slab of the building. The component of external walls includes the building façade, insulation layers and finishing materials. Internal walls include all internal partitions of the building and all related finishing materials.

The construction of the building includes additional processes that are usually related to the construction of the building on site, for example: the use of electricity, the use of water and the use of diesel to operate machinery and other equipment. These processes are included in module A5 according to EN 15875 [19].

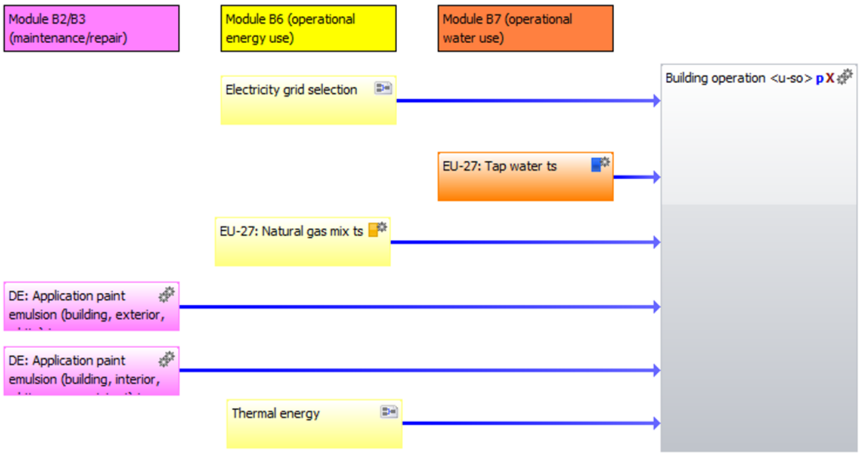
Similarly, each main part of the building constitutes and additional plan, as exemplified by the plan correspondent to the superstructure in Figure 10. Each part of the building includes all main processes related to that building component. Hence, for the superstructure of the building, the corresponding plan includes the production of main materials (modules A1 – A3), the use of formwork and the transportation of the materials to the construction site (module A4). For some materials, processes related to the construction site (module A5), such is the case of the pumping of concrete, are included in the plan.

Figure 10. Processes included in the plan of the superstructure



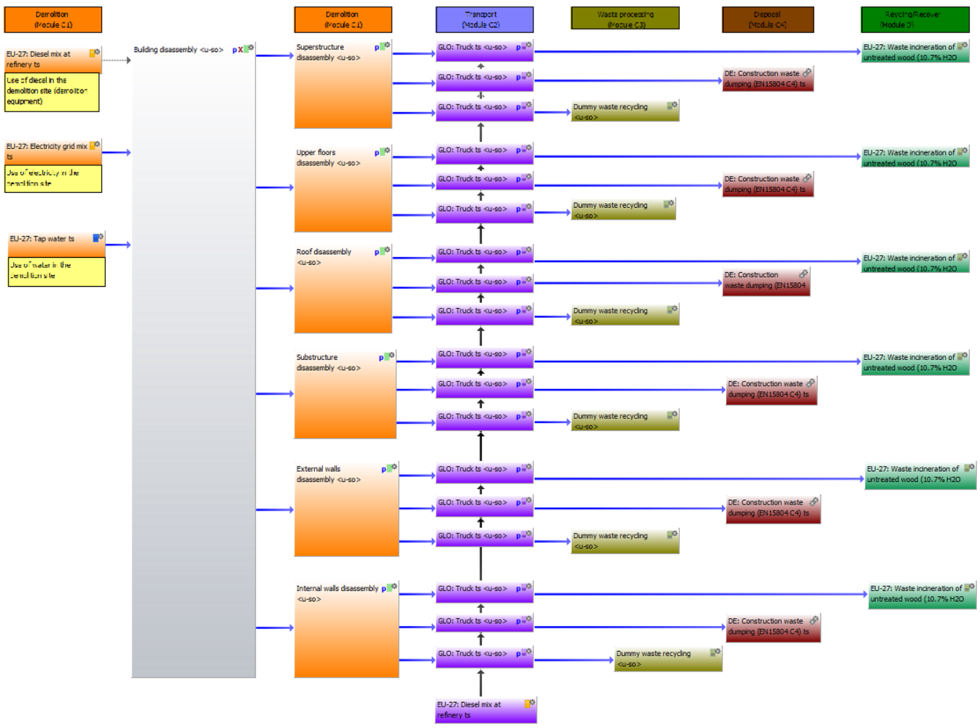
The operation stage of the building is considered in the plan illustrated in Figure 11. This plan includes the maintenance and refurbish of the building over its service life (modules B2-B3), the use of energy for cooling and heating (module 6) and the consumption of water (module 7).

Figure 11. Plans and processes included in the operation stage of the building



Finally, the end-of-life stage of the building is represented in Figure 12. In this case, the main processes included in the plan are: the disassembling of the main parts of the building and the final treatment of each resulting material (Modules C1 to C4) and the processes related to recycling or recovering of materials (Module D).

Figure 12. Plans and processes included in the end-of-life stage of the building



The LCA model described in the previous paragraphs is fully parametric, which enables to easily check the robustness of the results by means of scenario and/or sensitivity analyses.

Moreover, the uncertainty in input data and in other relevant parameters of the life cycle analysis may be taken into account by a probabilistic analysis. In this case, a range of values may be attributed to each parameter and the propagation of uncertainty in the model is performed by Monte Carlo Simulation (MCS). Two types of distributions are allowed for each parameter: an uniform distribution or a Gaussian distribution.

The model described in this section is applied to two popular construction materials (in Section 6) and to two buildings with distinct structural systems (in Section 7).

6 Life cycle analysis at the material level

This section aims to provide a detailed life cycle analysis of two of the most popular construction materials, using the LCA model described in the previous sections of this report. In this section, the analysis is performed at the material level, according to EN 15804 [18]. It is noticed that the results of the life cycle analysis provided at this level, for the different materials, are not comparable.

Moreover, in this section, several aspects of the life cycle analysis of construction materials are discussed, namely:

- The use of generic data versus specific data from producers;
- The influence of the use of different allocation procedures in the life cycle performance of the material;
- The sensibility of the results to the variation of parameters that are usually more uncertain when the assessment should be performed, i.e. in the early stages of the building design; in particular, those related to the last stages of the life cycle of the building;
- The uncertainty in the most relevant parameters of the life cycle analysis and how this uncertainty is propagated throughout the analysis.

6.1 Concrete products

Concrete is one of the most popular construction materials worldwide. Its application in structures is usually coupled with reinforcement steel or any other reinforced material to enhance its performance to tension forces. However, for simplification, in this sub-section, concrete is analysed as a single material. The reinforcement steel is addressed in the following sub-section.

Hence, the declared unit considered for the analysis is '1 tonne of concrete to be used as construction material in the structural system of a building for a period of 50 years, after which the structure is demolished'.

6.1.1 Life cycle stages considered in the analysis

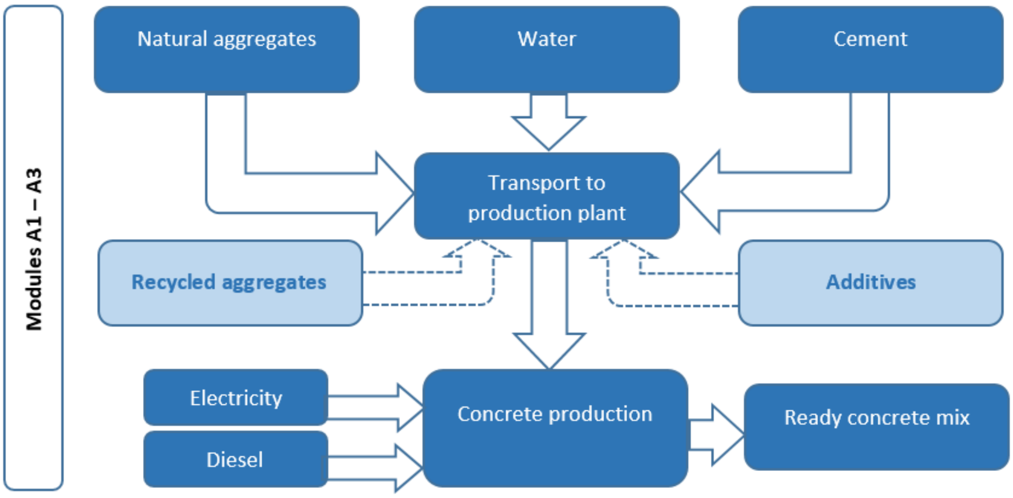
6.1.1.1 Material production stage

Concrete is usually made from coarse aggregate (stone and gravel), fine aggregate (sand), cement and water. The use of by-products from other industries, such as fly ash, slag and silica fume, is also common to reduce the cement content. Additionally, concrete additives and admixtures can be used to enhance concrete properties in fresh and/or hardened state.

Currently, the production of concrete to be used in structural elements is usually made from natural aggregates and therefore, the life cycle herein described will not considered the use of recycled aggregates in the production of a concrete mix. Nevertheless, the production of recycled aggregates, at the end-of-life stage, will be addressed in the correspondent sub-section.

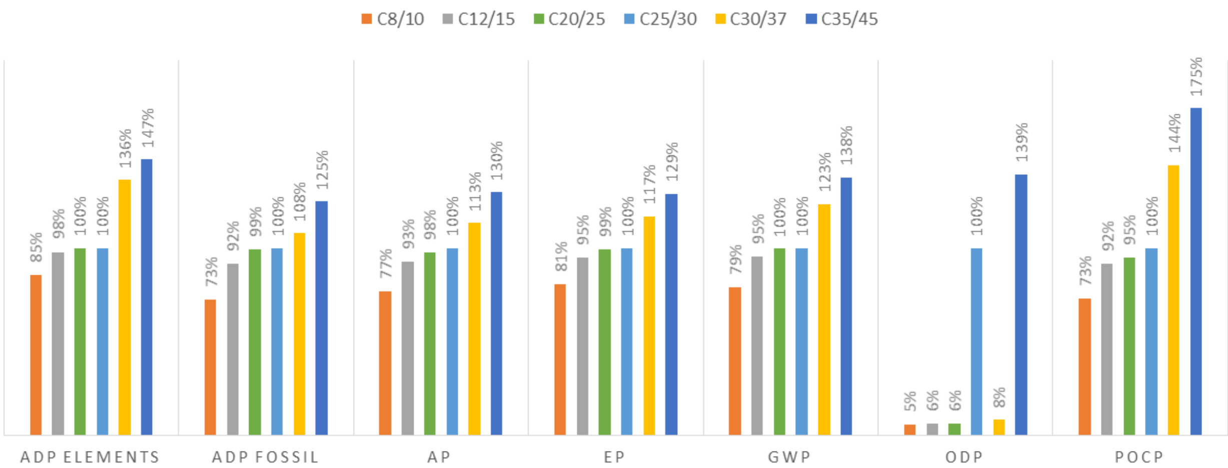
The professional database of GaBi provides environmental data for concrete for six different classes: C8/10, C12/15, C20/25, C25/30, C30/37 and C35/45. Data included in these datasets is limited to modules A1 to A3, as illustrated in Figure 13.

Figure 13. Production of concrete (Modules A1 – A3)



Taking into account the datasets representing the annual average production in Europe, the comparison between the six concrete grades is illustrated in Figure 14 and Figure 15, for the indicators describing environmental categories and for primary energy demand (P.E.D.), respectively, taking C25/30 as a reference value. The base year of reference for these datasets is 2016 and they are valid until 2019.

Figure 14. Environmental impact indicators for different concrete grades

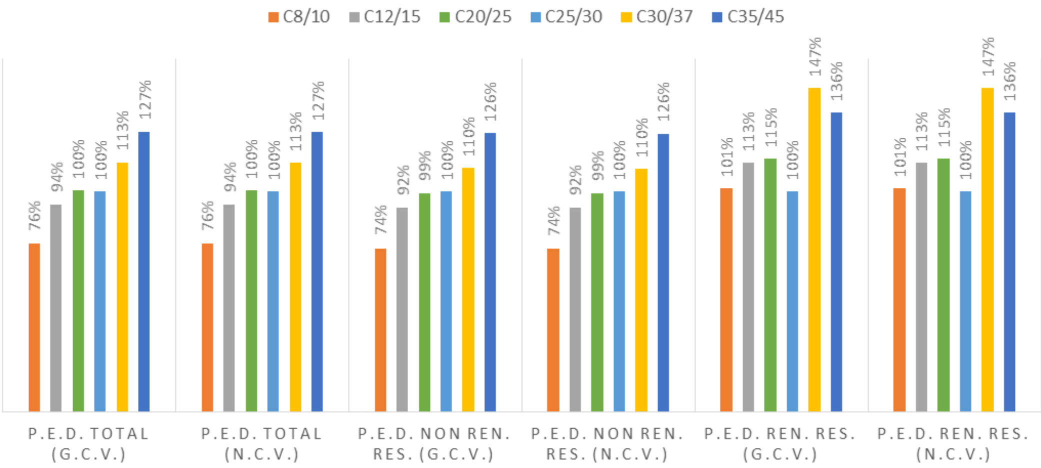


As observed, for all impact categories, except ODP, the higher the class of the concrete, the higher is the potential environmental impact. For ODP very small values are found (see Table 21).

The results for primary energy are further divided into renewable and non-renewable resources. In both cases, gross calorific value (g.c.v.) net calorific value (n.c.v.) are provided. Thus, from Figure 15, the same is observed for the category of primary energy, except for the renewable component, which is slightly lower for concrete grade C25/30.

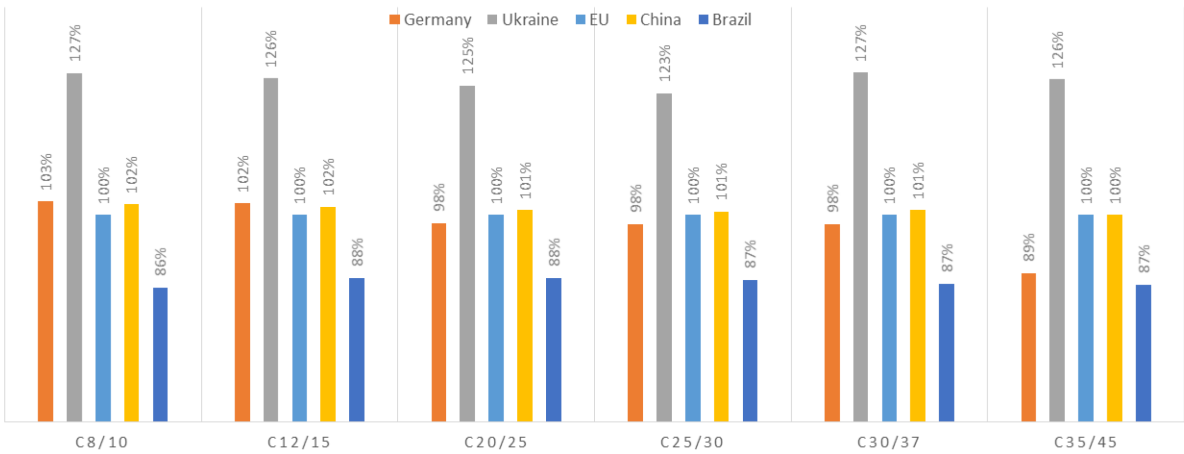
The variability of data for each concrete class in the professional database of GaBi, in terms of the geographical location, is illustrated in Figure 16 for the environmental category of GWP, taking EU values as reference. All data was provided from GaBi, taking into account the same boundaries and about the same period of reference (with a few exceptions taking into account a base year of 2015).

Figure 15. Primary energy indicators for different concrete grades



The average value of concrete production in the EU provides similar values to the values in Germany and China. The values for Brazil are usually lower than European values (less than 20%) and of the other side, the values found for Ukraine are usually higher for all concrete grades (higher than 20% compared with average EU values). Similar variabilities were found for the other indicators, except ODP and POCP, for which the variability is extremely high.

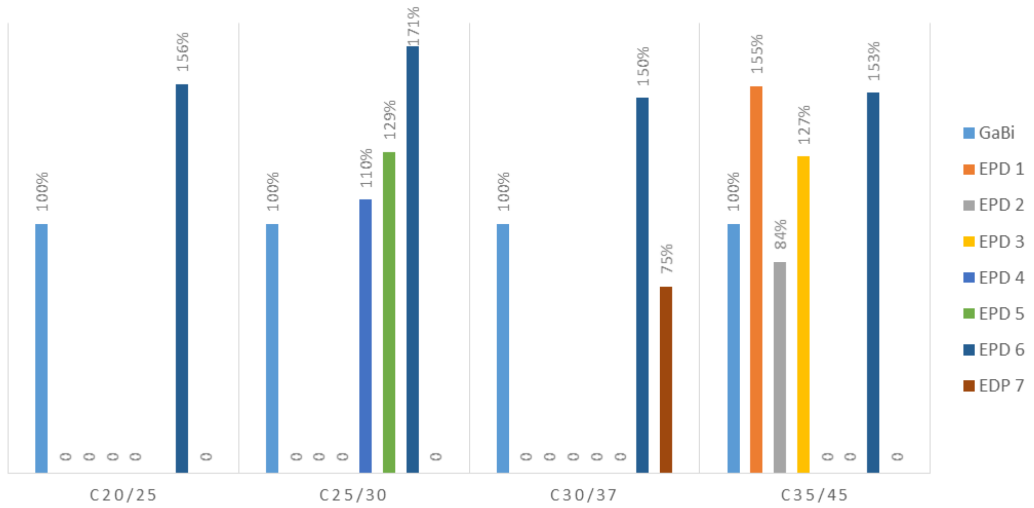
Figure 16. Variability of data from GaBi, taking into account geographical representativeness, for the environmental category of GWP



In addition, to compare the use of generic data with the use of specific data from different producers, data from GaBi database (considering the European average) is compared with data from available EPDs retrieved from two European registration programs: The *Institut Bauen und Umwelt e. V.* (IBU) [58], in Germany, and *The International EPD System* [59], in Sweden. The EPDs considered in this analysis are listed in Table 18.

The results are illustrated in Figure 17 for the environmental category of GWP, based on the values from the GaBi database. The comparison shows a huge variation, it goes up to 70% for concrete grade C25/30. However, it is observed that, in some cases, the comparison is not really accurate since some EPDs represent average values for different concrete classes. For instance, EPD 4 and EDP 5 are referring to an average of different concrete mixes in different plants in Italy and Romania, respectively. In this case, the values provided by these EPDs were compared with C25/30. On the other hand, EPD 1, EDP 2 and EDP 3 are referring to concrete mixes with grades higher than the maximum grade available in GaBi for Europe (C35/45). In this case, the values provided by these EPDs were compared with C35/45, which may be a rough approximation, particularly for EPD 1 that refers to a concrete with a compressive strength of 85 N/mm².

Figure 17. Variability of data taking into different types of data, for the environmental category GWP



Likewise, similar variabilities were found for the other indicators, except ODP and POCP, with extremely high variations.

Table 18. Information about the EDPs used in the comparison

	Ref. of EDP	Ref. year/ validity	Geog. repres.	Description	Funct. unit	Scope	Owner	Program. holder
1	EPD-BAS-20160040-CAA1-EN	2016-2021	UK	ready-mixed concrete (compressive strength 85 N/mm²)	1 m³	A1-A3	Aggregate Industries UK Ltd	IBU
2	EPD-BAS-20160227-CAA1-EN	2016-2021	UK	ready-mixed concrete (compressive strength 50 N/mm²)	1 m³	A1-A3	Aggregate Industries UK Ltd	IBU
3	EPD-BAS-20170093-CAA1-EN	2017-2022	UK	ready-mixed concrete (compressive strength 40 N/mm²)	1 m³	A1-A3	Aggregate Industries UK Ltd	IBU
4	S-P-00108	2006-2010	IT	ready-mixed concrete (average value in 2006 for different classes)	1 m³	A1-A3	Buzzi Unicem Italy	The International EPD System
5	S-P-00526	2014-2019	RO	ready-mixed concrete (average value in 2012 for different classes)	1 m³	A1-A3	HOLCIM Romenia	The International EPD System
6	S-P-00555	2014-2019	NZ	ready-mixed concrete (comp. str. 17.5-50 N/mm²)	1 m³	A1-A3	Allied Concrete	The International EPD System
7	S-P-00896	2016-2021	BZ	ready-mixed concrete (comp. str. 30 N/mm²)	1 m³	A1-A3	Votorantim Cimentos	The International EPD System

6.1.1.2 Operation stage

The operation stage takes into account Modules B1-B5 (see Table 16). At the material level, it makes no real sense to consider these stages and thus, these modules may be neglected. However, in some available studies in the literature, carbonation of concrete is considered in the operation stage of the analysis.

Carbonation is the chemical reaction by which CO_2 diffusing into concrete reacts with calcium dihydroxide ($Ca(OH)_2$) leading to $CaCO_3$ [54]. This process is a function of ambient concentrations of CO_2 and depends on the exposed surface of the element to the air. Thus, some authors consider that CO_2 is absorbed by concrete through the carbonation process during the service life of cement-based materials and after demolition, when the exposed area in contact with air increases [46]. The absorption of CO_2 is beneficial to the impact category of GWP, resulting on a reduced environmental profile for the material.

However, in concrete structures, carbonation induces corrosion and this is an undesired effect for the working life of structures, which may require repair or replacement of the concrete cover of the affected structural elements. Therefore, when carbonation is considered, so should be the required maintenance and/or repair actions. In addition the amount of CO_2 absorbed is highly dependent on the exposed surface, which at the material level makes no sense to quantify.

6.1.1.3 End-of-life stage and recycling

This sub-section describes the processes considered after the demolition of the structure and until the 'end-of-waste' state has been reached (Modules C1 to C4) and the processes considered after the 'end-of-waste' state, which are allocated in Module D, according to EN 15804.

The modelling of the scenario for the recycling stage of concrete is based on process data from a typical stationary recycling plant in Germany, provided by [46] and illustrated in Figure 12. Data includes the energy demand of all processes but does not include emissions.

According to EN 15804, all processes from the demolition until the end-of-waste state is reached are assigned to Modules C1-C4. Thus, in this case, the following processes are considered:

- C1 – deconstruction of the concrete structure;
- C2 – transportation of the recycling share of concrete debris to a recycling plant and transportation of remaining waste to final disposal;
- C3 – conventional recycling, which includes size reduction;
- C4 – waste disposal and management of disposal site.

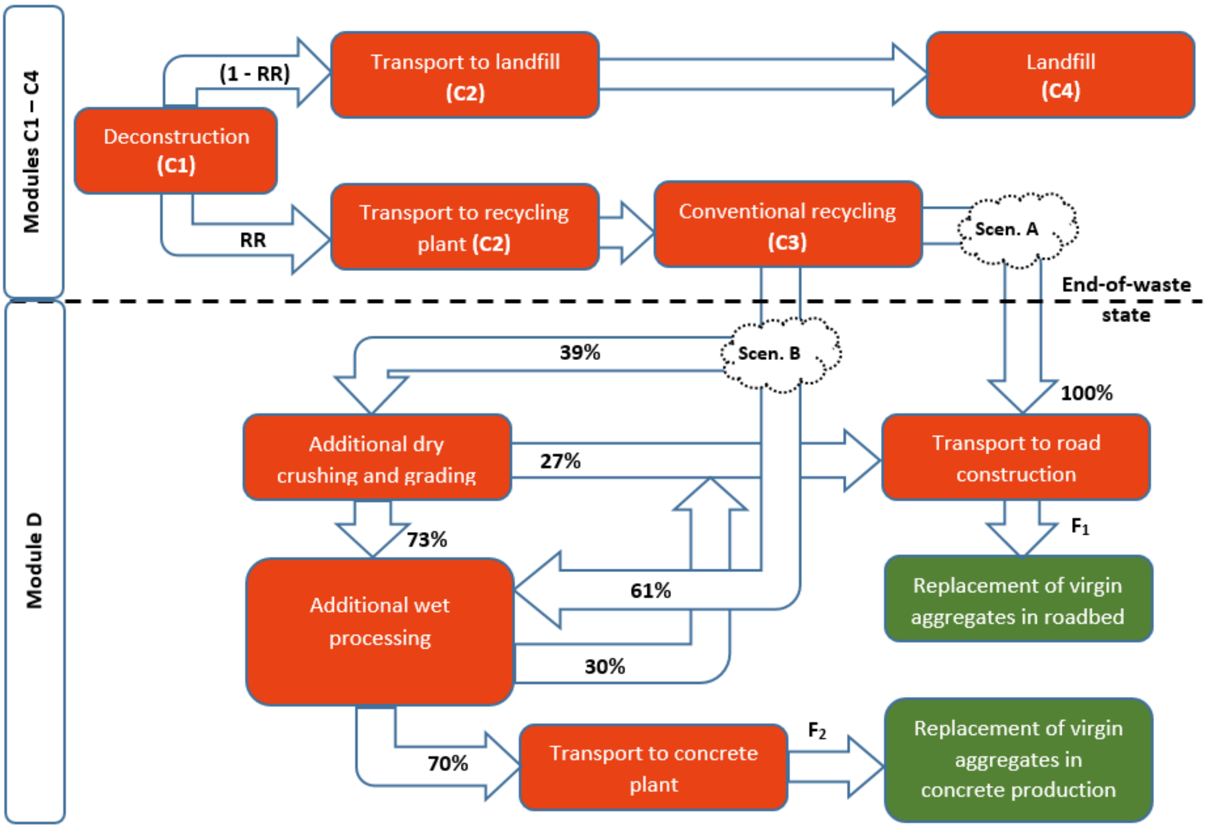
As indicated in Table 17, it is considered that the energy needed for the deconstruction of the concrete structure (module C1) in order to be recycled is 0.070 MJ/kg.

For this scenario, it is considered that a proportion of the waste flow (RR) is going to be recycled, while the remaining concrete debris (1 – RR) is sent to a landfill of inert materials. Thus, module C2 includes the transport of concrete debris to a recycling plant and transportation of the remaining waste to landfill.

In the case of landfill (module C4), carbonation of cement-based products may be considered when concrete is broken and the surface area of the material is exposed to air [60]. However, the quantification of the area of exposed elements in a landfill of inert materials is extremely hard to estimate. Therefore, no carbonation is considered in this module.

The end-of-waste state is reached when the material may be used for specific purposes [18]. Hence, in order for concrete debris to be used in another purpose, it should be further crushed. Therefore, Module C3 includes the size reduction of concrete debris by using an excavator with hydraulic crushers.

Figure 18. End-of-life stages concrete [46]



When the end-of-waste state is reached, two different scenarios are considered in Module D. In Scenario A, it is assumed that the crushed concrete is going to be used in road base or sub-base, avoiding the use of virgin material for road construction. Thus, in this case, Module D includes the impacts of the transport to the road construction site and the benefits (negative sign) due to the replacement of virgin material in the construction of roads.

On the other side, Scenario B assumes that the crushed concrete needs further processing so that it can be used as a replacement of virgin aggregates in concrete production. According to ECRA [46], 39% of the crushed concrete after the conventional recycling has a size greater than 22 mm. Thus, this share of aggregates goes through an additional dry crushing and grading process. In this additional process, the total electricity used is about 3.9 MJ/ton. After this grading process, 73% of the total aggregates have a size lower than 22 mm and undergo a subsequent wet crushing process, before being able to replace virgin aggregates in concrete production. The remaining 27% are used in base road, thus replacing the use of virgin material in road construction.

From the output of the wet processing, 70% of the total aggregates has the desired size fractions to be used as recycled aggregate, while the remaining 30% is used in base road. For the wet processing, the total electricity used is about 14.1 MJ/ton and the diesel consumption is about 0.2 l/ton [46].

6.1.2 Down cycling of concrete

In both scenarios of Figure 18, the virgin material that is replaced by the secondary material does not have the same quality of the virgin material that is used in the functional unit. Therefore, a down-cycling is considered and a value-correction factor (C_f) is considered in both cases, although with different values. It is noted that the C_f shall be calculated and applied at the point of substitution.

In the case of scenario A, the aggregates resulting from the conventional recycling are intended to replace the use of virgin aggregates in a roadbed. In this case, there is clearly a down cycling since the recycled aggregates will be used in a different function and the C_{f1} shall reflect the difference between the two functional equivalents, as indicated by expression (12).

$$C_{f1} = \frac{quality\ of\ recycled\ aggregates\ for\ road\ construction}{quality\ of\ virgin\ aggregates\ for\ structural\ concrete} \quad (13)$$

In scenario B, the aggregates resulting from additional crushing and upgrading processes are intended to replace the use of virgin aggregates in concrete mixes for structural applications.

However, the mechanic characteristics of a concrete mix made with recycled aggregates are not the same as a concrete mix made from virgin aggregates, mainly due to the existence of adherent old mortar in recycled aggregates, which requires additional water and cement for the production of a concrete mix with similar compressive strength [62]. Additionally, even when the concrete mixes have equivalent strength, the durability of a structure made with concrete from recycled aggregates is lower than that with a concrete made from virgin aggregates [61]. The discussion about the differences between the two mixes is beyond the scope of this report; however, additional information about this topic may be found in [62] [63] [64] [65][66][67].

Therefore, for structural applications, the quality of recycled aggregates for concrete production is not equivalent to the quality of natural aggregates. In this case, the C_{f2} is given by expression (13).

$$C_{f2} = \frac{quality\ of\ recycled\ aggregates\ for\ structural\ concrete}{quality\ of\ virgin\ aggregates\ for\ structural\ concrete} \quad (14)$$

The quality of the aggregates in both cases may be expressed by their monetary value. Currently, the market for secondary materials is not well defined and the value of secondary materials depend on the availability of natural resources in the area. However, the following values will be considered for this case [68]: (i) for recycled aggregates to be used in structural concrete applications – 5.75 to 6.5 ECU/ton; (ii) for recycled aggregates to be used in road sub-base and base – 5.25 ECU/ton; and (iii) for virgin aggregates to be used in structural concrete applications – 8.63 ECU/ton.

Hence, a value C_{f1} = 0.50 will be considered for down cycling in Scenario A and a value C_{f2} = 0.70 will be considered for down cycling in Scenario B.

6.1.3 Quality of data for concrete life cycle

All the processes included in the life cycle of concrete are listed in Table 19.

The quality of data is considered to be good: (i) in terms of time representativeness, almost all datasets are very recent (much less than 10 years); (ii) for geographical representativeness, most datasets are based on EU averages, thus representative for Europe; and (iii) in terms of technological representativeness, most of the technologies are updated and representative of the technologies available in Europe.

The processes requiring further improvements are the ones provided by the available sources in the literature, which have a limited time and geographical representations and a limited consideration of inputs and outputs flows.

Table 19. Quality check of the processes considered in the life cycle of concrete

Process	Dataset	Ref.yr /exp.	Time rep.	Geographical rep.	Technology rep./ completeness	Source
Concrete production	EU-28: C8/10, EU-28: C12/15, EU-28: C20/25, EU-28: C25/30, EU-28: C30/37, EU-28: C35/45	2016-2019	Annual average	Europe	Data for materials represent typical values for the production of ready-mix concrete in Germany; electricity is modelled according to the individual country-specific situations	Professional database (GaBi)
Road transport	GLO:Truck, Euro 5, 28 - 32t gross weight / 22t payload capacity	2016-2019	Annual average	Germany, Austria and Switzerland (but representative for the EU	The technologies are representative Europe-wide and can be adapted for worldwide locations with some minor restrictions	Professional database (GaBi)
Demolition	Demolition of concrete structure	1997		Canada	Only energy demands are considered	Literature
Waste processing	EU-28: Construction waste treatment plant (C3)	2016-2019	Annual average	Europe	The current data set represents an average for construction waste processing	Professional database (GaBi)
Waste landfill	EU-28: Construction waste dumping (EN15804 C4)	2016-2019	Annual average	Europe	The proportionate share of impacts over a period of 100 years is considered	Professional database (GaBi)
Recycling	Recycling of concrete	2010	n.a.	Germany	Energy data from a typical stationary recycling plant, but emissions not considered	Literature

Therefore, in general, all datasets comply with the quality criteria described in sub-section 4.3.

6.1.4 LCA of concrete for the base scenario

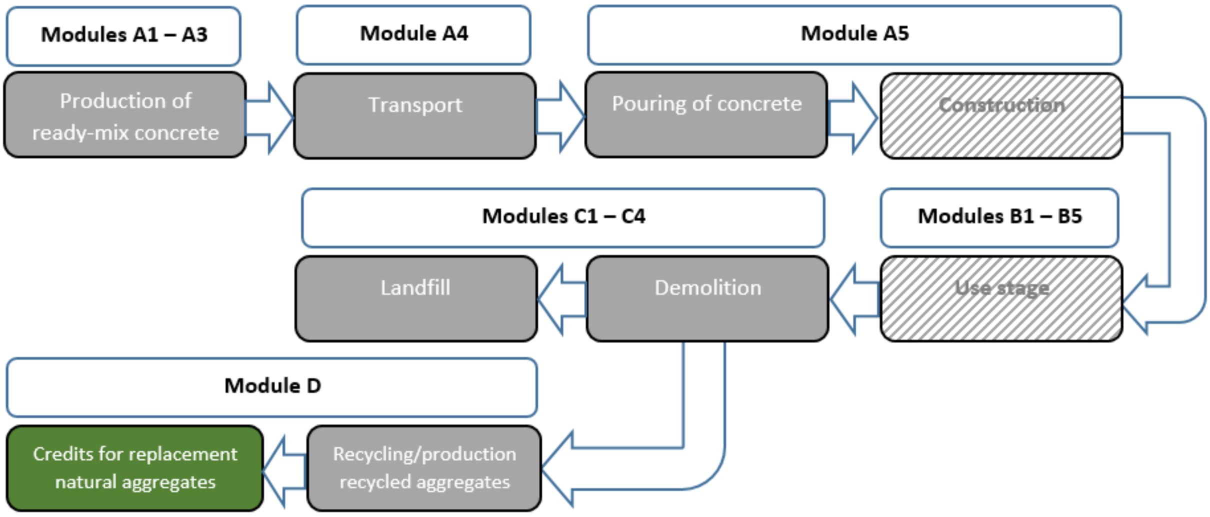
A base scenario is defined for the life cycle analysis of concrete (at the material level), which aims to assess the potential environmental impacts of 1 ton of concrete, throughout its life time. This scenario is based on standard procedures and current technologies, as described in the previous paragraphs. The life cycle includes all processes indicated in Figure 19, except the process of construction and all processes in the use stage.

The production of ready-mix concrete in a plant (modules A1 to A3) and all processes after demolition (Modules C1 to D) were detailed in (6.1.1.1) and (6.1.1.3), respectively. In this base scenario, it is assumed that concrete is recycled and the resulting recycled aggregates are used for road construction (scenario A in Figure 18). Thus, credits are considered for the production of recycled aggregates. The allocation procedure is Module D with a value-corrected value to represent the different between the two functional equivalents.

Additionally, the system boundary includes the transportation of the ready-mix concrete in a fresh state to the construction site by truck (Module A4) and the pouring of concrete into formwork in the construction site, which is allocated to Module A5.

Ready-mix concrete may be produced in stationary or mobile concrete batching plants. In places where the availability of raw materials is not a problem, small distances may be considered to the construction site. A distance of 20 km was considered in this case. Higher distances (50 km) were considered for the transport to landfill and to the recycling place. The parameters considered for this base scenario are indicated in Table 20. The relative importance of each parameter will be later assess in a sensitivity analysis.

Figure 19. System boundary for LCA of concrete



The recycling rate of concrete varies from country to country, as illustrated in Figure 6. In this case, a recycling rate of 70% is assumed, which may be overestimated for some locations.

Table 20. Reference values of the basic parameters

Parameter	Basic value
Distance in A4	20 km
Distances in C2	50 km
Distances in D	50 km
Recycling rate (RR)	70%
Value-corrected factor (C_{f1})	0.50
Value-corrected factor (C_{f2})	0.70

The results for the LCA of 1 ton of concrete are indicated in Table 21 , for each module considered in the scope of the analysis.

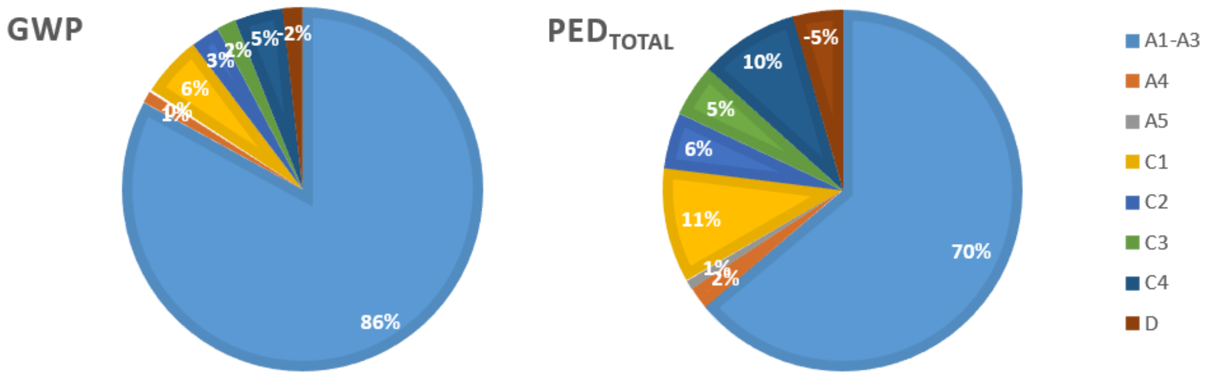
Table 21. Results of the LCA for 1 tonne of concrete (base scenario)

	A1-A3	A4	A5	C1	C2	C3	C4	D
ADP $_{elements}$	1,37E-04	9,14E-08	1,15E-07	1,85E-07	2,28E-07	3,23E-06	1,70E-06	-8,58E-07
ADP $_{fossil}$	4,33E+02	1,56E+01	3,06E+00	8,31E+01	3,89E+01	3,50E+01	6,26E+01	-2,15E+01
AP	1,79E-01	2,52E-03	8,20E-04	8,92E-03	6,30E-03	1,48E-02	2,86E-02	-4,08E-03
EP	2,77E-02	5,98E-04	7,42E-05	1,23E-03	1,49E-03	3,03E-03	3,90E-03	-5,77E-04
GWP	9,15E+01	1,14E+00	2,88E-01	6,01E+00	2,84E+00	1,89E+00	4,81E+00	-1,92E+00
ODP	5,06E-09	3,78E-13	1,27E-11	1,66E-12	9,45E-13	8,98E-12	4,92E-12	-1,44E-11
POCP	5,78E-03	-7,94E-04	5,23E-05	9,25E-04	-1,99E-03	1,45E-03	2,25E-03	-2,03E-03
PED_{total}	5,22E+02	1,64E+01	6,74E+00	8,36E+01	4,10E+01	3,85E+01	7,24E+01	-3,63E+01
$PED_{non.ren}$	4,81E+02	1,56E+01	5,03E+00	8,34E+01	3,90E+01	3,63E+01	6,48E+01	-2,72E+01
PED_{ren}	4,11E+01	7,83E-01	1,71E+00	2,37E-01	1,96E+00	2,16E+00	7,56E+00	-9,12E+00

The importance of each module for the total life cycle result is illustrated in Figure 20, for the impact categories of GWP and PED_{total}. As observed from the table above and from the figure below, Modules A1 – A3 are dominant for both environmental impact categories.

In Table 21, it is noted that negative values are found for Modules A4 and C2 for the impact category of POCP, which are both relating to the transport of materials. According to information provided from [40], for the calculation of the environmental category of POCP of trucks, the CML methodology [21] splits NO_x emissions into NO_2 and NO emissions. The reason for a negative value is due to NO emissions, which provide a credit for POCP by reducing the close ground ozone formation.

Figure 20. Importance of each module in LCA of concrete



On the other side, Module D has only a minor importance for both impact categories. As observed from Figure 20, the contribution of Module C2 is higher than that of Module D, which means that when higher distances are considered, the credits due to the recycling process may become negligible. Without a comparative scenario, these results may lead to the conclusion that, in a location where the availability of aggregates is high, the recyclability of concrete may not be considered as the best option.

The recycling of concrete does not contribute to a significant reduction of CO_2 emissions. The main reason for this is that the major contributor to CO_2 emissions in the production of concrete is cement production. The recycling of concrete enables to replace natural aggregates with recycled aggregates, therefore it does enable *per si* a reduction of emissions. However, it is noted that the use of by-products, such as fly ash, slag and silica fume, as cementious materials enables to reduce the cement content and thus, relative CO_2 emissions.

6.1.5 Sensitivity analysis

A sensitivity analysis is performed to assess the variability of the results when different scenarios and different values are used.

6.1.5.1 Scenario analysis

In the base scenario, it was assumed that concrete was recycled and recycled aggregates were replacing virgin aggregates in road construction or backfilling. To assess the importance of different end-of-life treatments and allocation procedures, different scenarios are considered as indicated in Table 22. All other parameters are kept constant in the following analysis.

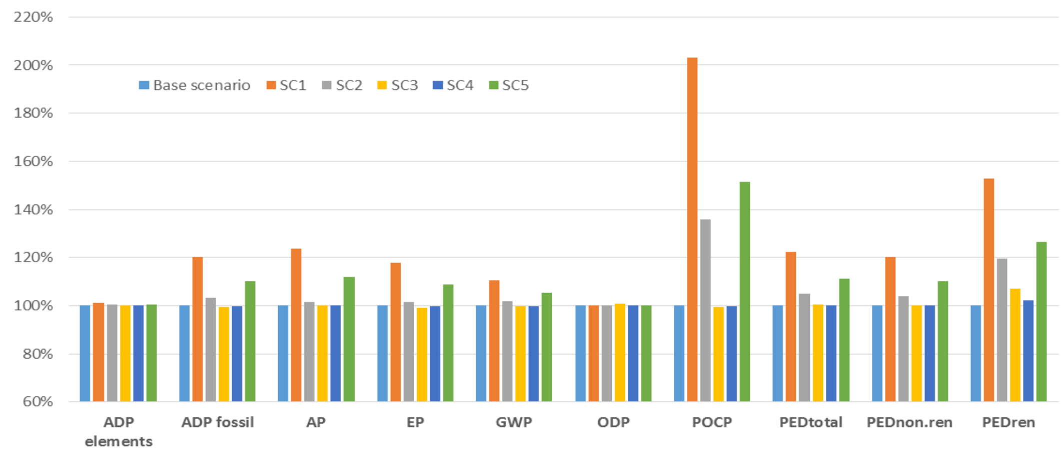
The results for the different scenarios are illustrated in Figure 21, for all impact categories. The comparison is made assuming the base scenario as reference. As expected, the scenarios that do not take into account any credits due to recycling (scenarios 1 and 2) have, in general, a worst performance. When comparing the results of scenario 1 with all the other scenarios, it becomes clear that recycling instead of landfill is beneficial.

Table 22. Scenarios for end-of-life stage of concrete

Ref.	Scenario description	Credits	Allocation procedure	RR (%)	F_1	F_2
Base	Recycling of concrete	Recycled aggregates for road construction or backfilling	Module D (with correction factor)	70	0.50	-
SC1	Landfill of concrete	No credits due to recycling	-	0%	-	-
SC2	Recycling of concrete	No credits due to recycling	100%-0%	70%	-	-
SC3	Recycling of concrete	Recycled aggregates for concrete production	Module D (with correction factor)	70%	0.50	0.70
SC4	Recycling of concrete	Recycled aggregates for road construction or backfilling (70%) and concrete production (30%)	Module D (with correction factors)	70%	0.50	0.70
SC5	Recycling of concrete	Recycled aggregates for road construction or backfilling	50%-50%	70%	0.50	-

Comparing the base scenario with scenarios 3 and 4, the differences are negligible for all impact categories. Although in scenario 4 higher credits may be achieved due to the production of recycled aggregates for concrete, the downstream processes that are needed to upgrade the aggregates compensate the additional credits. Scenario 5 is usually considered as a compromise between the 100%-0% approach and the 0%-100% approach. However, in this case the results of scenario 5 are higher than the 100%-0% approach (scenario 2) because, as already referred, the recycling process is not free of burdens and simultaneously, the amount of waste sent to the landfill increases.

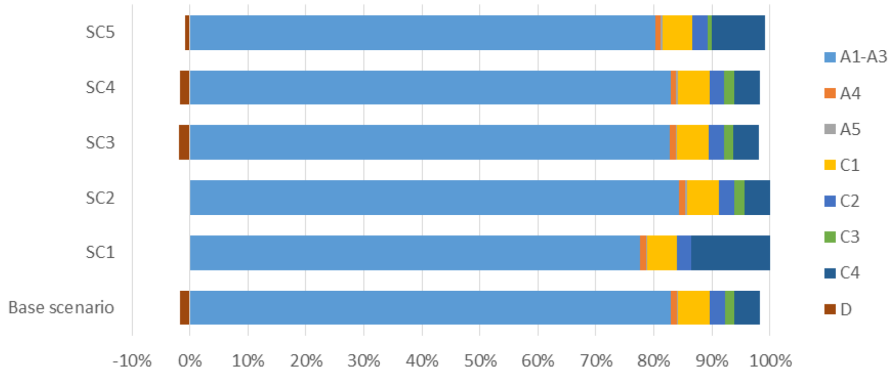
Figure 21. Results of the scenario analysis



The most important stages in each scenario are indicated in Figure 22 and Figure 23, for impact categories of GWP and PE, respectively. In relation to GWP, the initial stages of the life cycle (A1 – A3) have a dominant importance (above 80%) in all cases except scenario 1, with a result slightly lower than 80% as the impact due to landfill increases its importance. The dominant importance of Modules A1-A3 is the main reason for no significant differences between the total results of each scenario.

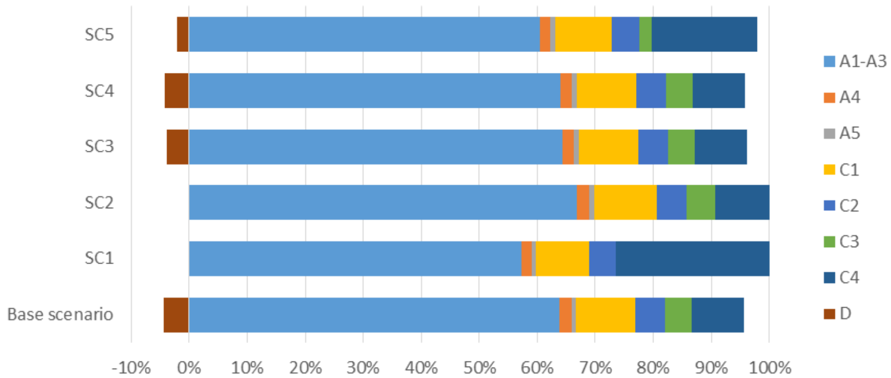
As already noticed for the base scenario, the relative contribution of Module D is almost negligible. However, it is observed that this does not mean that the recycling option is not beneficial for the life cycle performance of concrete, as clearly illustrated in Figure 21.

Figure 22. Results of the contributional analysis for GWP



In relation to the impact category of PE, the initial stages of the life cycle (A1 – A3) have still a major importance (above 60%). However, in this case, the importance of other modules increases. In particular, for Modules C1 and C4 due to the use of energy in the respective processes. Module D has also a slight increase but, even in this case, the importance of the module is lower than 5%.

Figure 23. Results of the contributional analysis for PE



6.1.5.2 Perturbation analysis

In the base scenario, parameters were defined assuming a standard location in Europe. However, in order to assess the variability of the results in relation to the variability of the parameters, a range of plausible values was allocated to each basic parameter in Table 20. These ranges are assumed to represent the variability of each parameter in each scenario. The minimum and maximum values for each parameter are indicated in Table 23.

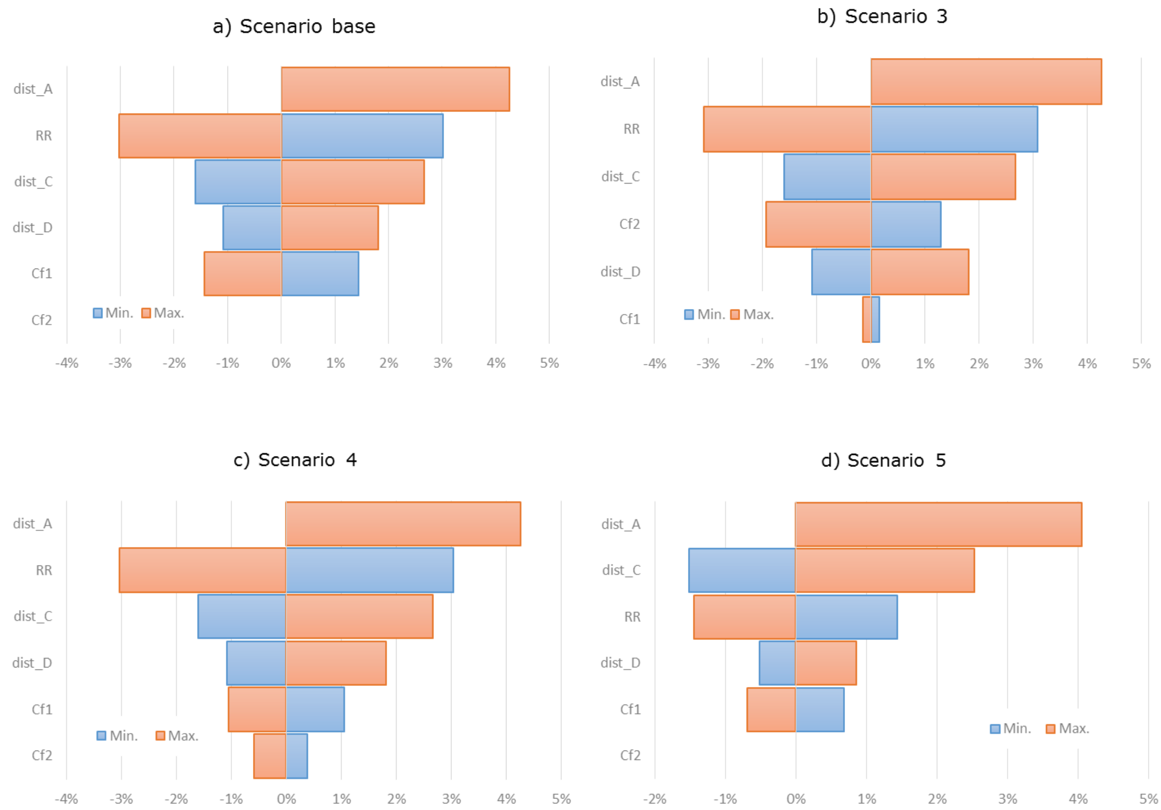
Table 23. Range of values for the parameters

Parameter	Name	Min. value	Base value	Max. value
Distance in A4	dist_A4	20 km	20 km	100 km
Distances in C	dist_C	20 km	50 km	100 km
Distances in D	dist_D	20 km	50 km	100 km
Recycling rate	RR	50%	70%	90%
Value-corrected factor (expression 13)	C_{f1}	0.30	0.50	0.70
Value-corrected factor (expression 14)	C_{f2}	0.50	0.70	1.00

The analysis is performed for all scenarios, except for the scenarios that do not take into account the recycling of the material at the end-of-life stage (scenarios 1 and 2). The results of the analysis are illustrated in Figure 24 for the impact category of GWP.

In the graphs below, the maximum and minimum variations of the aggregated result of the LCA, indicated in the horizontal axis, are showed for the maximum and minimum values of each parameter indicated in the vertical axis.

Figure 24. Tornado graphs for the impact category GWP



As illustrated in Figure 24, the variations considered for each parameter do not have a significant impact in the result of the analysis. In all cases, the maximum variation of the result of the LCA was below 5%.

In addition, the sensitivity ratios (SR) for each parameter, given by expression (12), are indicated in Table 24.

Table 24. Sensitivity ratios (SR) for each parameter

Parameter	Base Scenario	Scenario 3	Scenario 4	Scenario 5
dist_A4	0.01	0.01	0.01	0.01
dist_C	0.03	0.03	0.03	0.03
dist_D	0.02	0.02	0.02	0.01
RR	-0.11	-0.11	-0.11	-0.05
C_{f1}	-0.04	0.0	-0.03	-0.02
C_{f2}	0.0	-0.05	-0.01	0.0

Hence, it is noticed that the most important parameter in all scenarios is the recycling rate (RR). However, even in this case, the maximum value of the sensitivity ratio is -0.11, which implies that when increasing the value of the RR by 50%, the final result is reduced only by 5.5%.

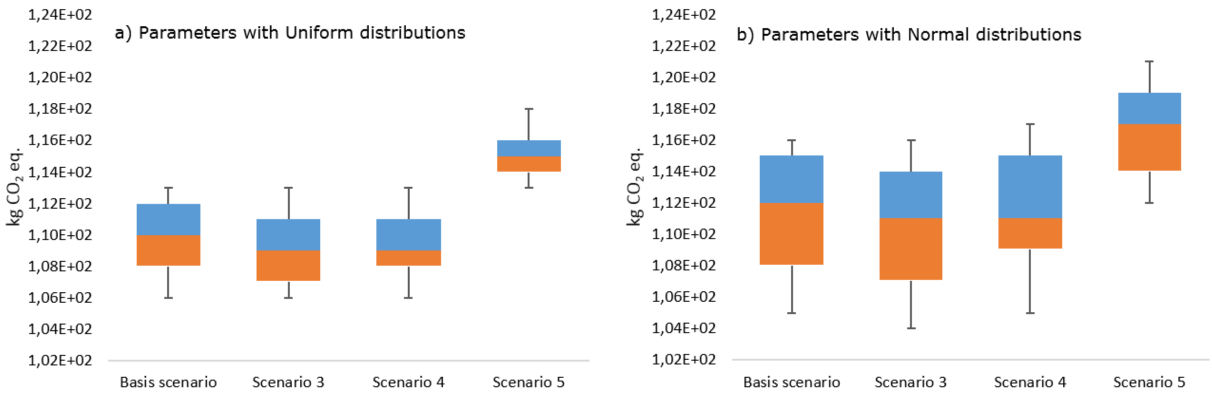
6.1.6 Uncertainty analysis

To take into account the uncertainty and/or variability of the parameters in Table 23 simultaneously, a probabilistic analysis was performed. Uncertainty propagation was performed by Monte Carlo Simulation. Two different types of distributions were considered for each parameter: a uniform distribution and a Gaussian distribution. It was considered that each parameter was independent; therefore, no correlation was taken into account.

For the uniform distribution, the minimum and maximum values indicated in Table 23, were considered as the boundary points of the distribution. In the case of the Gaussian distribution, the minimum and maximum values correspond to the negative and positive deviations, respectively.

Monte Carlo Simulations were performed considering 1000 iterations. The results of both analysis for the impact category of GWP are illustrated in Figure 25 by the box plots, which represent the median, lower quartile (Q1) and upper quartile (Q3) for the different scenarios.

Figure 25. Box plots for impact category GWP, considering uniform and normal distributions



It is noted that the results represented in Figure 25 correspond to the total result of the life cycle analysis (aggregation of all modules considered in the analysis). As observed from these graphs, given the scatter of values, the differences in the results of the base scenario and scenarios 3 and 4 are not significant.

In addition, it is noticed that the scatter of values for scenario 5 is lower than the other scenarios. This was expected as, according to this scenario, only 50% of the benefits are allocated in the end-of-life stage. As the variability of the parameters considered in this analysis mainly affected this stage, the range of values obtained is lower. This may be an advantage of this allocation procedure, since the latter stages in a life cycle analysis are the ones subjected to a higher degree of uncertainty due to the long life span considered.

6.2 Steel products

The variety of steel products used in the construction of steel-framed buildings is huge. Moreover, steel reinforcement is used in the construction of reinforced concrete structures. However, in this sub-section, the focus is on two main steel products: steel reinforcement and steel sections.

In this case, the declared unit for the LCA of a steel product is '1 tonne of steel to be used as construction material in the structural system of a building for a period of 50 years, after which the structure is demolished'.

6.2.1 Life cycle stages included in the analysis

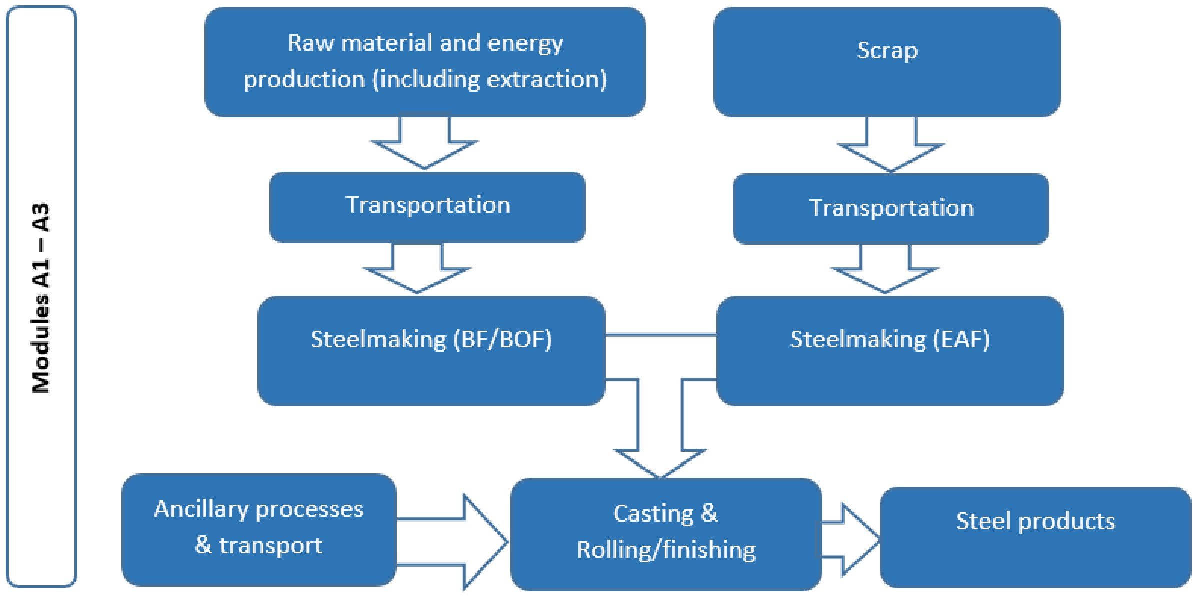
6.2.1.1 Material production stage

Independently of the final product, steel is usually produced by two main routes [34]: the blast furnace (BF)/basic oxygen furnace route and the electric furnace (EAF) route. The main difference between these two routes is the percentage of scrap introduced into the steelmaking process. In the BOF route the input of scrap may be up to 35%, while in the EAF route the input is close to 100%. After the steel making process, the downstream processes of casting and rolling are the same, independently of the upstream route, as illustrated in Figure 26.

According to [34], all products can be produced through both routes, depending on the plan in which they are produced.

Currently, one of the most reliable sources of generic data for steel products is provided by the Worldsteel Organization. Peer-reviewed data is provided for 15 products, which includes plate, hot-rolled coil, pickled hot-rolled coil, cold-rolled coil, finished cold-rolled coil, hot dip galvanized steel, electrogalvanized steel, organic coated steel, tinplated steel, electrolytic chrome coated steel (tin-free steel), UO pipe, welded pipe, sections, rebar and wire rod.

Figure 26. Steel production (based in [34])



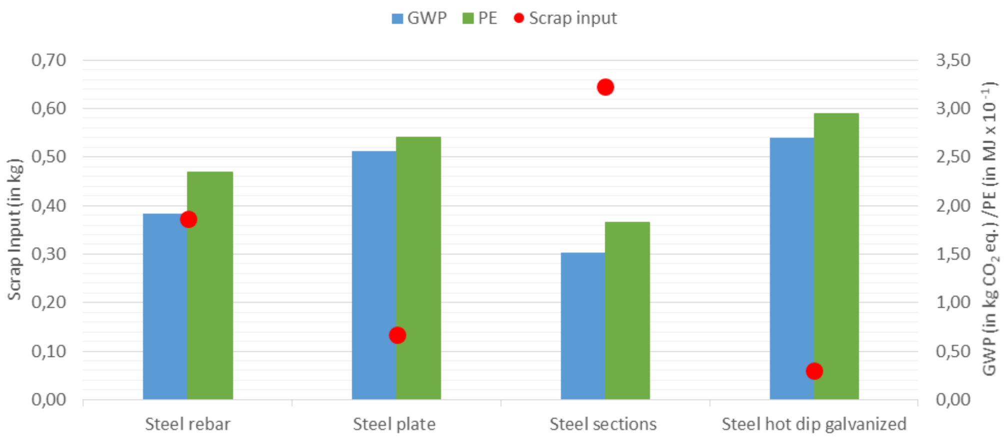
The average data for steel products, collected from 49 sites and operated by 15 companies, is provided at two levels: Global (GLO) and Europe (EU). The companies contributing to this data account for about 25% of global crude steel production and 30% of European steel production. This database is included in GaBi software and will be used in the LCA of the steel products presented in the following paragraphs.

It is noted that the database of Worldsteel provides data for all processes for the production of intermediate or semi-finished steel products, at the gate of the plant. In some cases, steel products can be used directly (e.g. steel rebars), but in order cases, further processes are needed to convert intermediate or semi-finished steel products into finished steel products (e.g. steel plate). For example, the production of steel girders or tapered beams, usually involves additional processes such as cutting and welding of steel plates, and these processes may account up to 15% and 10% of the energy consumption and CO_2 emissions, respectively, in comparison to the whole life cycle impacts of the steel products [69]. Hence, in case no more accurate data for steel fabrication is provided, the production of steel products may be increased by an additional amount to account for the conversion of intermediate or semi-finished products into finished products. However, at the product level, since no specific function was allocated to the material, no additional impacts were considered.

As already referred, every steel product can be produced by BF/BOF or EAF. Naturally, the percentage of scrap introduced into the steel manufacturing process will affect the respective environmental profile of the product. The environmental performance of four steel products is represented in Figure 27 from the GaBi/worldsteel database (hereafter referred as simply *worldsteel*), considering the global average (GLO).

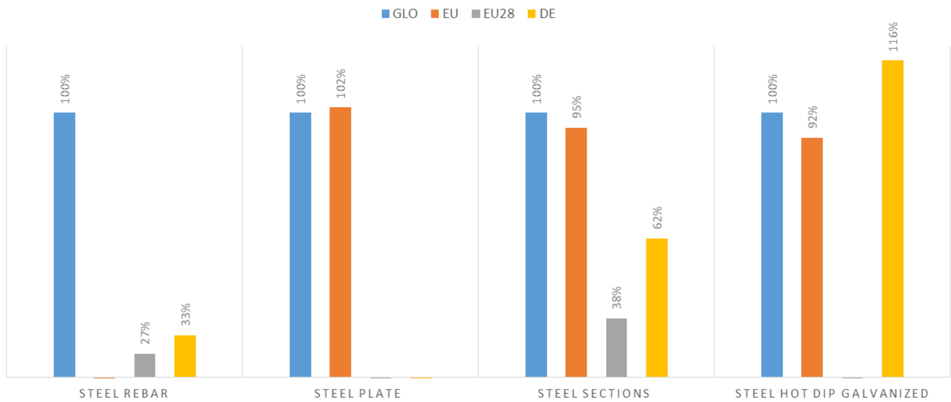
The results presented in Figure 27 refer to impact categories of GWP and PE and are referring to modules A1-A3. Additionally, the amount of scrap input into the manufacturing process is provided for each product. It is clearly observed that the higher the input of scrap, the lower are the respective potential environmental impacts. Therefore, in this case, for steel sections, with a scrap input close to 65%, the environmental profiles for both indicators are lower than the other products.

Figure 27. GWP and PE for 1 kg of a steel product with different inputs of scrap, from GaBi/Worldsteel (GLO)



The variability of steel data considering the global (GLO) and European (EU) averages from worldsteel database is shown in Figure 28 for the environmental category GWP and for different steel products. Data for the same products, but from the Professional database of GaBi, is also displayed in Figure 28, for Germany (DE) and for an additional European average (EU28). The observed variability is due to the amount of scrap considered in the steel making process.

Figure 28. Variability of data taking into account geographical representation, for GWP



Likewise, the use of generic data is compared with the use of specific data from different producers. Hence, data from worldsteel database is compared with data from available EPDs retrieved from *The Institut Bauen und Umwelt e. V.* (IBU) [58] and *The International EPD System* [59].

For steel rebars (considering the Global average), the EPDs considered in the analysis are listed in Table 25. The comparison is shown in Figure 29, the amount of scrap considered in the steel making process is also indicated for each case.

Figure 29. GWP for 1000 kg of steel rebar from GaBi and EPDs from Table 25.

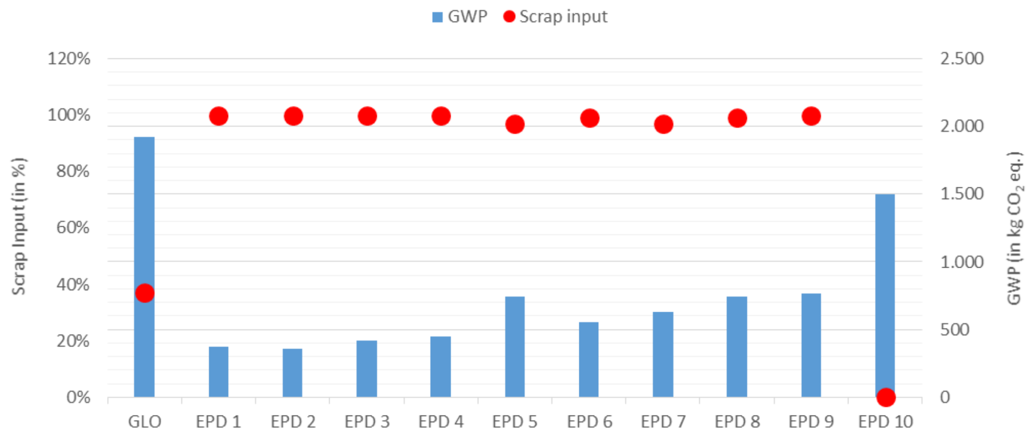


Figure 29 shows that in most cases, steel rebar is produced through the EAF route.

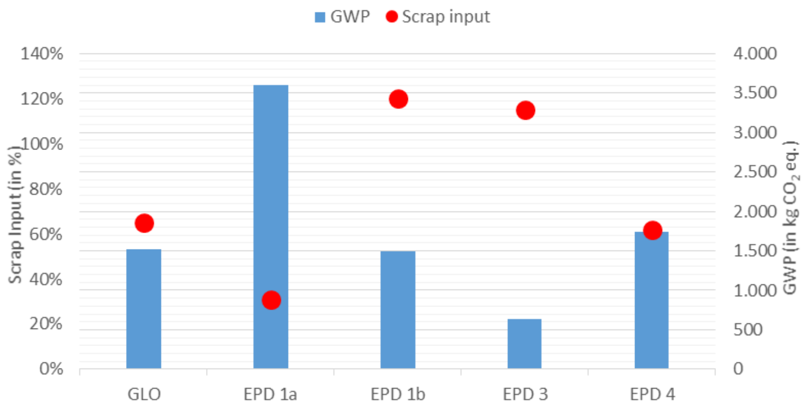
Table 25. Data for steel reinforcement production from available EPDs

	Ref	Ref. year/ validity	Geog. repres.	Description	Funct. unit	Scope	Owner	Program. holder
1	S-P-00305	2012-2020	SE	Steel reinforcement products for concrete	1 t	A1-A3	Celsa Steel	The International EPD System
2	S-P-00306	2012-2020	NO	Steel reinforcement products for concrete	1 t	A1-A3	Celsa Steel	The International EPD System
3	S-P-00307	2012-2020	FI	Steel reinforcement products for concrete	1 t	A1-A3	Celsa Steel	The International EPD System
4	S-P-00308	2012-2020	DK	Steel reinforcement products for concrete	1 t	A1-A3	Celsa Steel	The International EPD System
5	S-P-00254	2017-2020	IT	Hot-rolled reinforcing steel for concrete in bars and coils	1 t	A1-A3 (*)	Alfa Acciai SpA	The International EPD System
6	S-P-00255	2015-2020	IT	Hot-rolled reinforcing steel for concrete in bars and coils	1 t	A1-A3 (*)	Acciaierie di Sicilia	The International EPD System
7	S-P-00256	2015-2020	IT	Hot-drawn reinforcing steel for concrete in bars and coils	1 t	A1-A3 (*)	Feralpi Siderurgica SpA	The International EPD System
8	S-P-00257	2017-2020	IT/EU	Hot- drawn reinforcing steel for concrete in bars and coils	1 t	A1-A3 (*)	Industrie Riunite Odolesi	The International EPD System
9	S-P-00696	2017-2022	Chile	Reinforcing steel bar	1 t	A1-A3	Gerdau	The International EPD System
10	S-P-00855	2016-2021	Aus-tralia	Reinforcing rod, bar & wire	1 t	A1-A3 (**)	OneSteel	The International EPD System

(*) The EDP includes Module A4 but comparison was made only for Modules A1-A3
(**) The EDP includes Modules C3-C4 and D but comparison was made only for Modules A1-A3

In the case of steel sections (considering the Global average), the EPDs considered in the analysis are listed in Table 26, and the comparison is shown in Figure 30.

Figure 30. GWP for 1000 kg of steel section from GaBi and EPDs from Table 26.



It is observed that EPD4 represents an average between sections and steel plate.

Table 26. Data for steel section production from available EDPs

	Ref	Ref. year/ validity	Geog. repres.	Description	Funct. unit	Scope	Owner	Program. holder
1a	S-P-00856	2016-2021	AU	Hot rolled structural	1 t	A1-A3 (*)	OneSteel	The International EPD System
1b	S-P-00856	2016-2021	AU	Merchant bar products	1 t	A1-A3 (*)	OneSteel	The International EPD System
3	EPD-CEL-20130219-IBD1-EN	2014-2019	SP/PL	Sections	1 t	A1-A3	Celsa	The IBU System
4	EPD-BFS-20130094-IBG1-EN	2013-2018	DE	Sections and plates	1 t	A1-A3 (**)	bauforumstahl e.V.	The IBU System

(*) The EDP includes Module A4 but comparison was made only for Modules A1-A3
(**) The EDP includes Module D but comparison was made only for Modules A1-A3

6.2.1.2 Operation stage

At the material level, Modules B1-B5 may be neglected. However, it is noticed that, at the building level, the steel structure, when required, is usually coated to provide protection against corrosion and/or fire and in this case, maintenance may be required.

6.2.1.3 End-of-life stage and recycling

This sub-section describes the subsequent processes after the demolition and until the 'end-of-waste' state has been reached (Modules C1 to C4) and the processes considered after the 'end-of-waste' state, which are allocated in Module D, according to EN 15804.

At the end-of-life stage, steel is usually recycled and steel scrap is collected to produce new steel. Steel is completely recyclable and there are no changes to its inherent properties. Furthermore, it can be recycled over and over again, without losing its properties [34].

Hence, the processes included in Modules C1-C4, which take into account all processes from the demolition until the end-of-waste state is reached (according to EN 15804), are the following:

- C1 – deconstruction of the steel structure;

- C2 – transportation of steel scrap to a recycling plant and transportation of remaining waste to final disposal;
- C3 – it may be considered that the end-of-waste stage is reached after the deconstruction and, therefore, no further processing is needed before the use of the scrap in the production of new steel. Therefore, at the material level, Module C3 may be neglected. However, additional processes related to the sort of materials are considered in Module C3, as this will be the situation at the building level;
- C4 – waste disposal and management of disposal site.

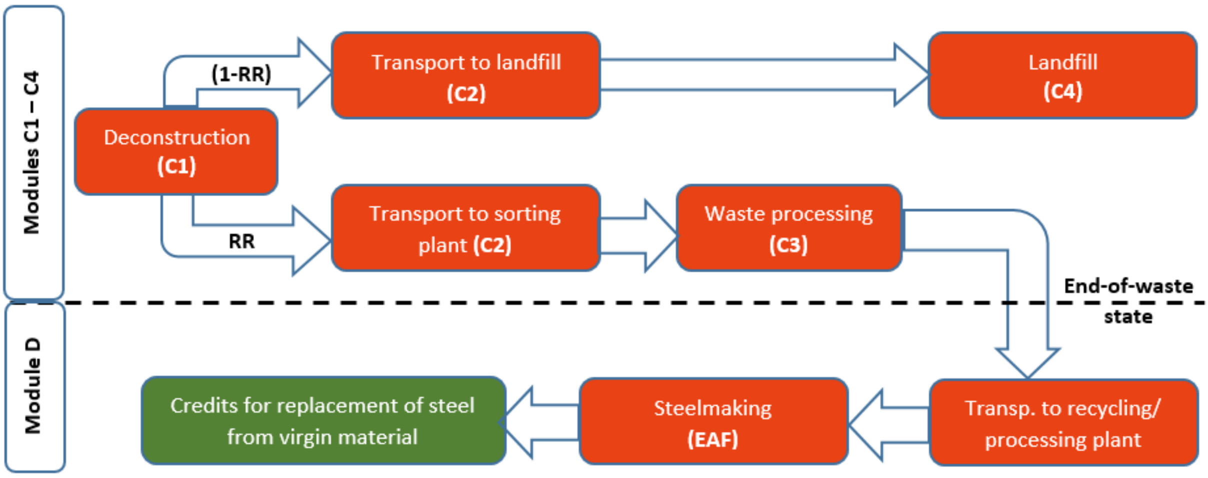
As indicated in Table 17, it is considered that the energy required for the deconstruction of the steel structure (module C1), in order to be recycled, is about 0.239 MJ/kg.

For this scenario, it is considered that a proportion of the waste flow (RR) is going to be recycled, while the remaining steel (1 – RR) is sent to a landfill of inert materials. Thus, module C2 includes the transport of steel scrap to a recycling plant and transportation of the remaining scrap to landfill.

The credits due to scrap arising from the deconstruction of the structure are allocated to Module D. As referred above, there are no changes to the inherent properties of the steel when it is recycled. Therefore, in this case the value-correction factor is considered as one (C_f = 1).

The modules C1-C4 and D are illustrated in Figure 31.

Figure 31. End-of-life stages of steel products



6.2.2 Quality data for steel life cycle

All the processes included in the life cycle of steel are listed in Table 27.

Likewise, all datasets comply with the quality criteria described sub-section 4.3, except the ones provided by the literature, which have a limited time and geographical representations and a limited consideration of inputs and outputs flows.

Table 27. Quality check of the processes considered in the life cycle of steel

Process	Dataset	Ref.yr /exp.	Time rep.	Geographical rep.	Technology rep./ completeness	Source
Steel r production	EU: steel rebar GLO: steel sections	2014-2020	Annual average	Weighted average site-specific data of European steel producers	The dataset includes raw material extraction and processing, e.g. scrap, coke making, sinter, blast furnace, basic oxygen furnace, electric arc furnace, rolling mil	Professional database (GaBi)/ Worldsteel
Road transport	GLO:Truck, Euro 5, 28 - 32t gross weight / 22t payload capacity	2016-2019	Annual average	Germany, Austria and Switzerland (but representative for the EU	The technologies are representative Europe-wide and can be adapted for worldwide locations with some minor restrictions	Professional database (GaBi)
Demolition	Demolition of steel structure	1997		Canada	Only energy demands are considered	Literature
Waste processing	EU-28: Construction waste treatment plant (C3)	2016-2019	Annual average	Europe	The current data set represents an average for construction waste processing	Professional database (GaBi)
Waste landfill	EU-28: Construction waste dumping (EN15804 C4)	2016-2019	Annual average	Europe	The proportionate share of impacts over a period of 100 years is considered	Professional database (GaBi)
Recycling	GLO: Value of scrap	2014-2020	Annual average	Data set is based on weighted average site-specific data of Global steel producers.	The dataset includes raw material extraction and processing, e.g. scrap, coke making, sinter, blast furnace, basic oxygen furnace, electric arc furnace, rolling mil	Professional database (GaBi)/ Worldsteel

6.2.3 LCA for steel products – base scenario

A base scenario is defined for the life cycle analysis of a steel product, which aims to assess its potential environmental impacts of 1000 kg, throughout its life time. This general scenario, illustrated in Figure 32, is based on standard procedures and current technologies and applies to all types of steel products.

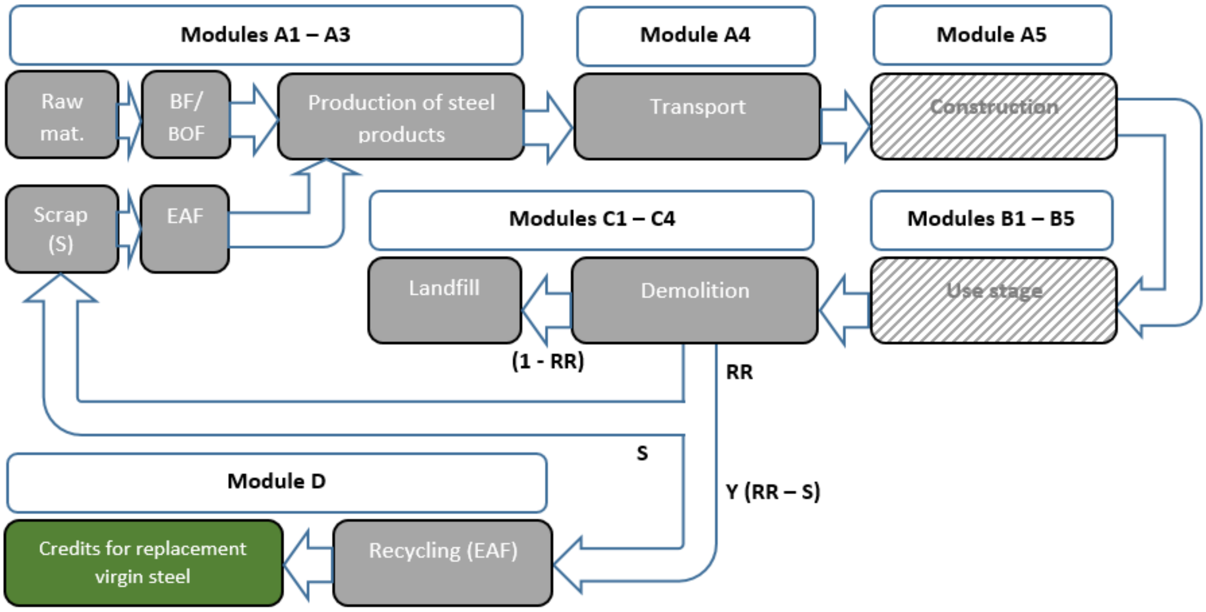
The life cycle includes all processes indicated in Figure 32, except construction and use stage. The production of steel (modules A1 to A3) and all processes after demolition (Modules C1 to D) were detailed in (6.2.1.1) and (6.2.1.3), respectively.

In this base scenario, it is assumed that after the demolition process, steel scrap (RR) is recycled and the resulting steel is used in the construction of steel structures. Thus, credits are considered for the production of new steel. The allocation procedure is Module D with a value-corrected value to represent the different between the two functional equivalents (in this case, $C_f = 1$).

According to EN15804, Module D allocates only net credits. Therefore, as in the production of a steel product there is usually an input of scrap (S), the credits are given only to the net scrap arising from the system that is (RR – S). In case the amount of scrap introduced to the system (S) is lower than the amount of steel that is recycled (RR), than credits for net scrap (RR – S) are allocated to the system. However, in case S > RR, than a burden is allocated instead.

It is noted that a yield factor (Y) is introduced in Module D, representing the efficiency of the recycling process. This factor is given by the ratio of steel output to scrap input, which is usually lower than 1, meaning that more than 1 kg of scrap is required to produce 1 kg of steel [34]. Therefore, the allocation for scrap is adjusted for this.

Figure 32. Model for LCA of steel products



Two based scenarios are herein considered: one scenario for the LCA of steel reinforcement and one scenario for the LCA of steel sections. The parameters considered in each case are indicated in Table 28.

Steel products have usually a high rate of recycling, as indicated in Table 14. The recycling rate depends of the steel application. For instance, structural steel is usually more easily recovered than reinforced steel from concrete debris. Thus, for this scenario, recycling rates (RR) of 70% and 90% were considered for steel reinforcement (rebars) and sections, respectively.

Table 28. Reference values for the basic parameters

Parameter	Basic value
Distance in A4	500 km
Distance in C2 for landfill	50 km
Distance in C2 for waste processing	50 km
Distance in D for recycling	500 km
Recycling rate for rebars (RR)	70%
Recycling rate for sections (RR)	90%
Value-correction factor (C_f)	1

The results for the LCA of 1 ton of steel sections are indicated in Table 29, for the modules considered in the scope of the analysis. Likewise, the results for the LCA of 1 ton of reinforcement steel are indicated in Table 30.

Table 29. Results of the LCA of 1 tonne of steel sections

	A1-A3	A4	A5	C1	C2	C3	C4	D
$ADP_{elements}$	-4,21E-04	2,28E-06	-	6,31E-07	2,28E-07	4,15E-06	5,66E-07	-1,22E-03
ADP_{fossil}	1,82E+04	3,89E+02	-	2,84E+02	3,89E+01	4,49E+01	2,09E+01	-3,70E+03
AP	4,67E+00	6,30E-02	-	3,05E-02	6,30E-03	1,91E-02	9,55E-03	-7,78E-01
EP	3,54E-01	1,49E-02	-	4,21E-03	1,49E-03	3,90E-03	1,30E-03	-4,81E-02
GWP	1,69E+03	2,84E+01	-	2,05E+01	2,84E+00	2,42E+00	1,60E+00	-4,02E+02
ODP	-5,38E-06	9,45E-12	-	5,65E-12	9,45E-13	1,16E-11	1,64E-12	2,39E-06
POCP	7,12E-01	-1,99E-02	-	3,16E-03	-1,99E-03	1,87E-03	7,51E-04	-2,17E-01
PED_{total}	2,03E+04	4,10E+02	-	2,85E+02	4,10E+01	4,94E+01	2,41E+01	-3,26E+03
$PED_{non.ren}$	1,89E+04	3,90E+02	-	2,85E+02	3,90E+01	4,67E+01	2,16E+01	-3,55E+03
PED_{ren}	1,44E+03	1,96E+01	-	8,08E-01	1,96E+00	2,78E+00	2,52E+00	2,94E+02

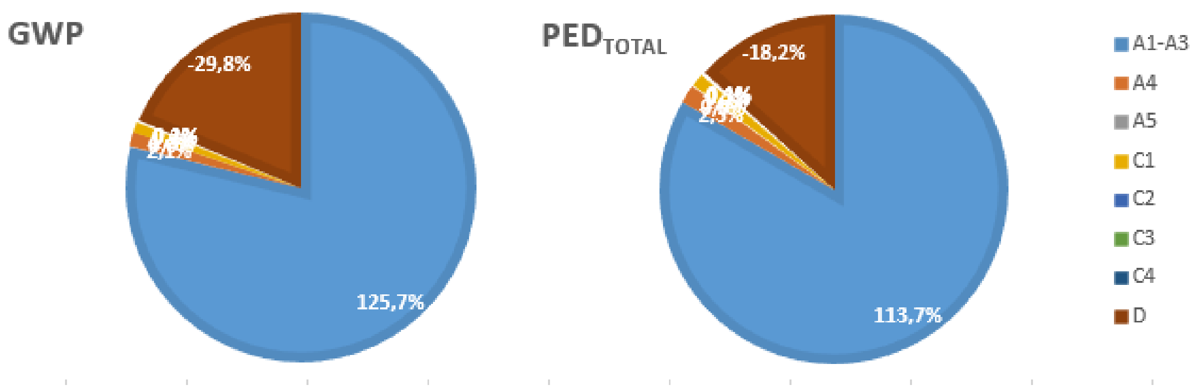
In Table 29 and Table 30 negative values are found for the impact categories of $ADP_{elements}$ and ODP in Modules A1-A3. These negative values are due to credits from the allocation of co-products [34]: in relation to $ADP_{elements}$ credits are provided for EAF dust as replacement of zinc production; while, in relation to ODP, credits are provided for BF slag as replacement of cement production. It is noted that according to EN15804, these credits are not allocated in Module D.

Table 30. Results of the LCA of 1 tonne of steel reinforcement (rebars)

	A1-A3	A4	A5	C1	C2	C3	C4	D
$ADP_{elements}$	-3,36E-04	2,28E-06	-	6,31E-07	2,28E-07	3,23E-06	1,70E-06	-1,73E-03
ADP_{fossil}	2,50E+04	3,89E+02	-	2,84E+02	3,89E+01	3,50E+01	6,26E+01	-5,48E+03
AP	9,26E+00	6,30E-02	-	3,05E-02	6,30E-03	1,48E-02	2,86E-02	-1,14E+00
EP	5,77E-01	1,49E-02	-	4,21E-03	1,49E-03	3,03E-03	3,90E-03	-7,71E-02
GWP	2,13E+03	2,84E+01	-	2,05E+01	2,84E+00	1,89E+00	4,81E+00	-5,86E+02
ODP	-7,52E-06	9,45E-12	-	5,65E-12	9,45E-13	8,98E-12	4,92E-12	3,38E-06
POCP	8,73E-01	-1,99E-02	-	3,16E-03	-1,99E-03	1,45E-03	2,25E-03	-2,96E-01
PED_{total}	2,65E+04	4,10E+02	-	2,85E+02	4,10E+01	3,85E+01	7,24E+01	-4,86E+03
$PED_{non.ren}$	2,51E+04	3,90E+02	-	2,85E+02	3,90E+01	3,63E+01	6,48E+01	-5,26E+03
PED_{ren}	1,37E+03	1,96E+01	-	8,08E-01	1,96E+00	2,16E+00	7,56E+00	4,05E+02

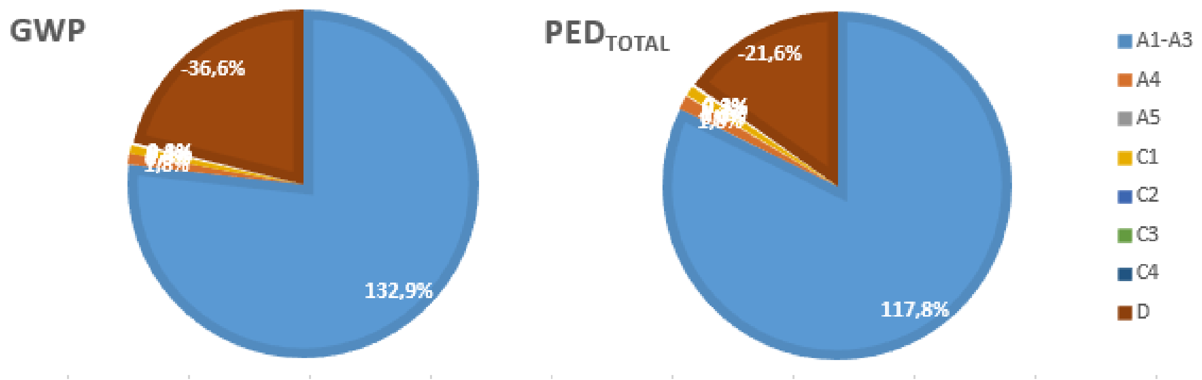
The importance of each module for the total life cycle result is illustrated in Figure 33, for the impact categories of GWP and PED_{total}, for steel sections.

Figure 33. Importance of each module in LCA of steel sections (base scenario)



In relation to reinforcement steel, the importance of each module for the total life cycle result is illustrated in Figure 34, for the two categories indicated above.

Figure 34. Importance of each module in LCA of steel reinforcement (base scenario)



It is observed from Figure 33 and Figure 34 that the importance of Modules A1-A3 to the aggregate result is very similar for both products, although the amount of steel for the production of 1 kg of rebars is about 0.372 kg; while for the production of 1 kg of sections is about 0.646 kg. This is because for steel rebar a higher contribution from Modules A1-A3, in relation to steel sections, is compensated by a higher contribution from Module D.

6.2.4 Sensitivity analysis for steel

Likewise, to check the variability of the results when changing the base parameters a sensitivity is performed as described in the following paragraphs.

6.2.4.1 Scenario analysis

The base scenarios described in the previous paragraphs aimed to describe a standard situation for steel products. In Table 31, different end-of-life scenarios and respective allocation procedures are considered.

Table 31. Scenarios for end-of-life of steel products

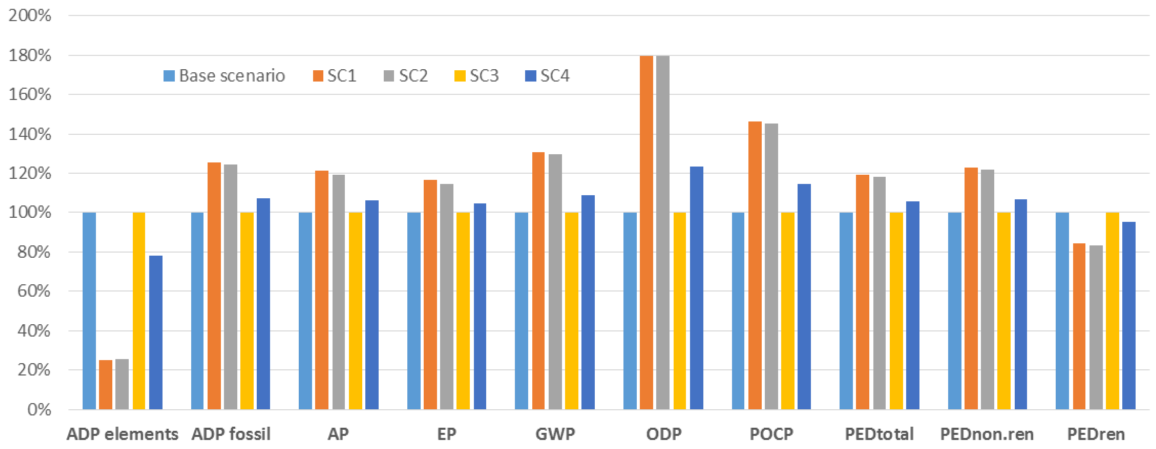
Ref.	Scenario description	Credits	Allocation procedure	RR sections	RR rebar	F
Base	Recycling of steel	Recycled steel for construction	Module D (with correction factor)	90%	70	1.00
SC1	Landfill of steel	No credits due to recycling	-	0%	0%	-
SC2	Recycling of steel	No credits due to recycling	100%-0%	90%	70%	-
SC3	Recycling of steel	Recycled steel for construction	0%-100%	90%	70%	1.00
SC4	Recycling of steel	Recycled steel for construction	50%-50%	90%	70%	1.00

The aggregated results for the different scenarios, assuming the base scenario as reference, are illustrated in Figure 35 for all impact categories and for steel sections.

As expected, the scenarios that do not take into account any credits due to recycling (scenarios 1 and 2) have, in general, a worst performance.

Comparing the base scenario with scenario 3, it is observed that both scenarios lead to the final aggregated result. This is because, in the base scenario (with Module D), only net credits are allocated to the system, thus leading to the same aggregated result of scenario 3. However, the influence of modules A1-A3 and D is different for both scenarios, as observed in Figure 37 and Figure 38.

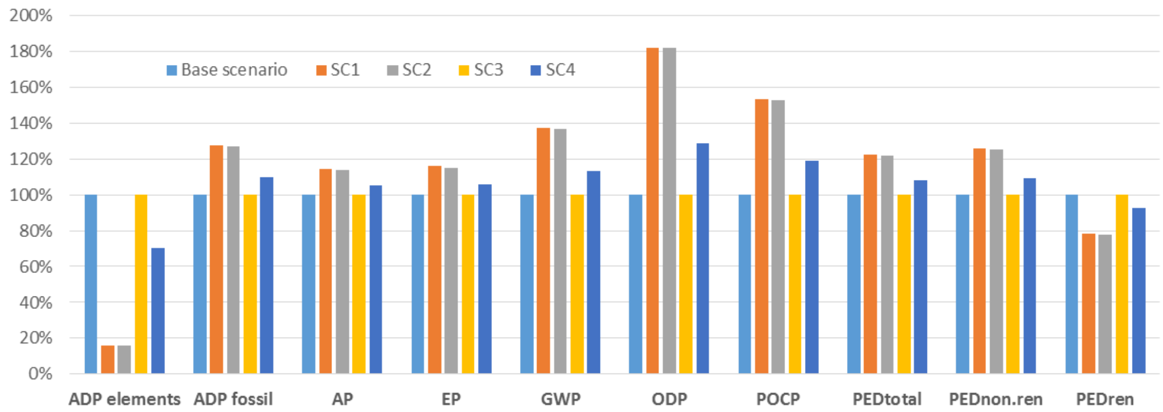
Figure 35. Results of the scenario analysis for steel sections



In addition, since in scenario 4 there are credits in the production stage and in the end-of-life stage, this scenario leads to a compromise between the 100%-0% approach (scenario 2) and the 0%-100% approach (scenario 3).

Very similar conclusions may be taken in relation to steel reinforcement as illustrated in Figure 36.

Figure 36. Results of the scenario analysis for steel reinforcement

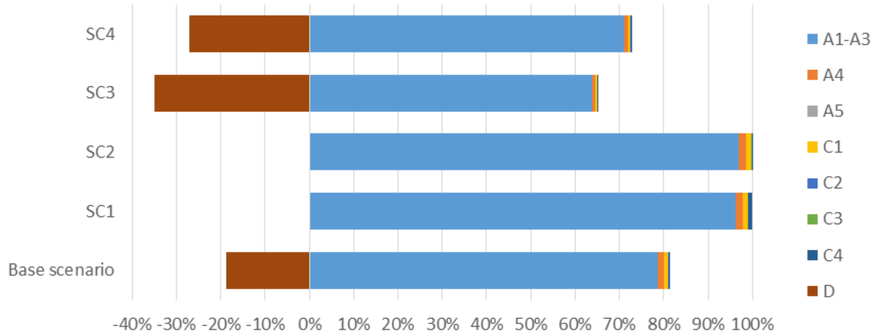


The contribution of each module in the life cycle analysis of steel sections is illustrated in Figure 37 and Figure 38, respectively for impact categories of GWP and PE.

In terms of GWP, for the scenarios not considering the credits due to recycling (scenarios 1 and 2), the importance of Modules A1-A3 is close to 100%. For the other scenarios, the importance of these modules is about 60% for scenario 3 and close to 80% for the base scenario.

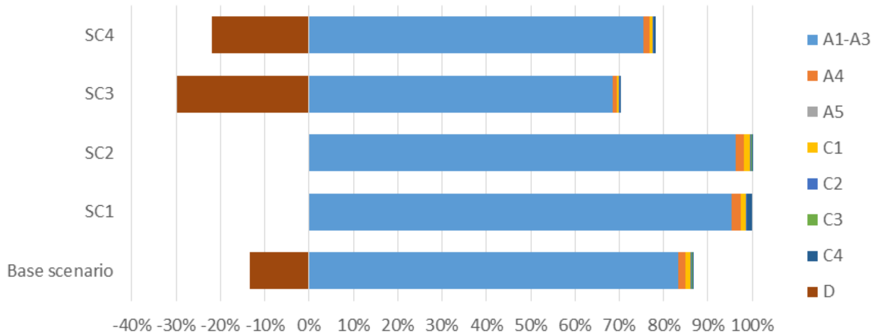
In contrast to the life cycle of concrete, in the case of steel products, Module D has an important contribution to the aggregated final value. In the specific case of steel sections, the importance varies from close to 20%, for the base scenario, to about 35% for scenario 3. It is noticed that for steel products originated from a steel making process in which the BF/BOF is the primordial route, the importance of Module D would be even higher.

Figure 37. Results of the scenario analysis for GWP and for steel sections



For PE, similar conclusions may be taken for the contribution of each module in the life cycle analysis of steel sections, as observed in Figure 38.

Figure 38. Results of the scenario analysis for PE and for steel sections



The results obtained for rebars are very similar with the ones presented for steel sections and the same conclusions are reached for the different scenarios. Therefore, they are not provided in this report.

6.2.4.2 Perturbation analysis

In order to assess the variability of the results in relation to the variability of the parameters, a range of values representing the variability of each parameter in each scenario, was allocated to each basic parameter. The minimum and maximum values for each parameter are indicated in Table 32.

In this case, a minimum value of 0.8 is considered for the value-correction factor, assuming slight changes in the properties of recycled steel.

Table 32. Range of values for the parameters

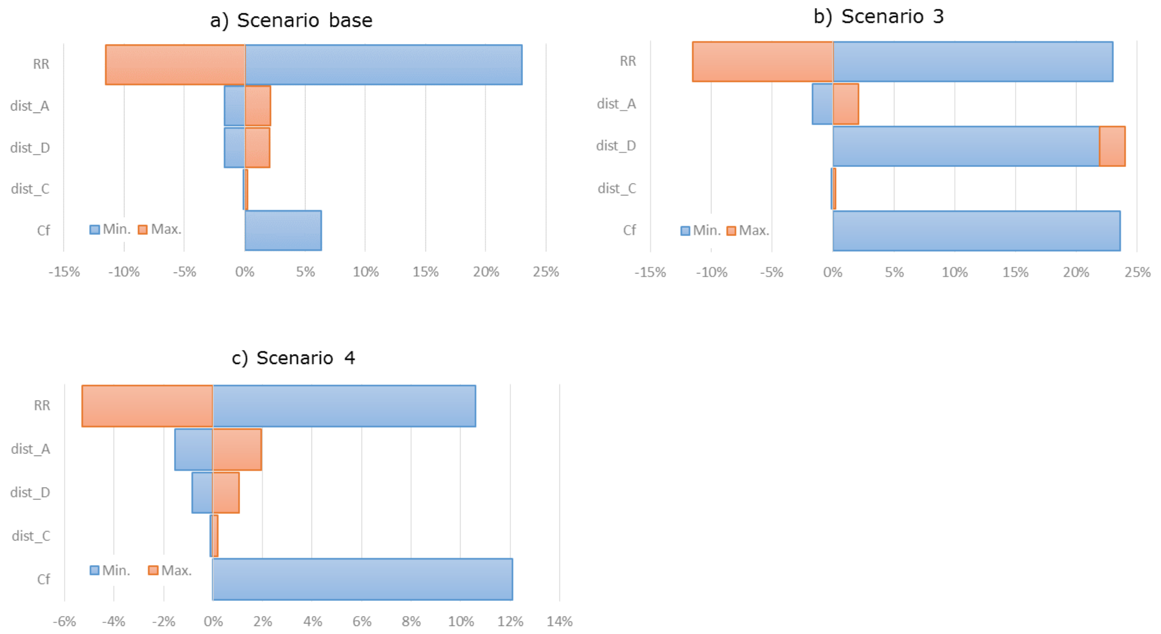
Parameter	Name	Min. value	Base value	Max. value
Distance in A4	dist_A4	100 km	500 km	1000 km
Distance in C2 for landfill	dist_C2	20 km	50 km	100 km
Distance in C2 for waste processing	dist_C2	20 km	50 km	100 km
Distance in D for recycling	dist_D	100 km	500 km	1000 km
Recycling rate for rebars	RR	40%	70%	90%
Recycling rate for sections	RR	70%	90%	100%
Value-correction factor	C_f	0.8	1	1

The analysis is performed for the base scenario and scenarios 3 and 4. Scenarios 1 and 2, which do not take into account the recycling of the material at the end-of-life stage, are not considered in the analysis. The results of the analysis for steel sections are illustrated in Figure 39 for the impact category of GWP. In addition, the sensitivity ratios (SR) for each parameter, given by expression (12), are indicated in Table 33.

It is observed that, in the following, only the results for steel sections are presented, as the results for steel rebars are very similar with the ones presented below.

The variation considered for some of the parameters shows a considerable impact in the result of the analysis. This is the case of the recycling rate (RR) and the correction factor (C_f) for the base scenario and scenario 3. The former, when reduced from 90% to 70%, leads to an increase of about 23% of the result of the analysis. In fact, taking into account the Sensitivity Ratios (SR), the parameter RR has a SR of -1.04.

Figure 39. Tornado graphs for impact category GWP and for steel sections



On the other hand, the importance of the travelling distances is not significant (the maximum value of the sensitivity ratio is 0.02).

For scenario 4, the maximum variation was about 12% for the correction factor and the corresponding SR is about -0.60. As expected, in this scenario, the RR has about half the importance of the other scenarios.

Table 33. Sensitivity ratios (SR) for each parameter

Parameter	Base Scenario	Scenario 3	Scenario 4
dist_A4	0.02	0.02	0.02
dist_C	0.002	0.002	0.002
dist_D	0.02	0.02	0.01
RR	-1.04	-1.04	-0.48
C_f	-0.32	-1.18	-0.60

6.2.5 Uncertainty analysis

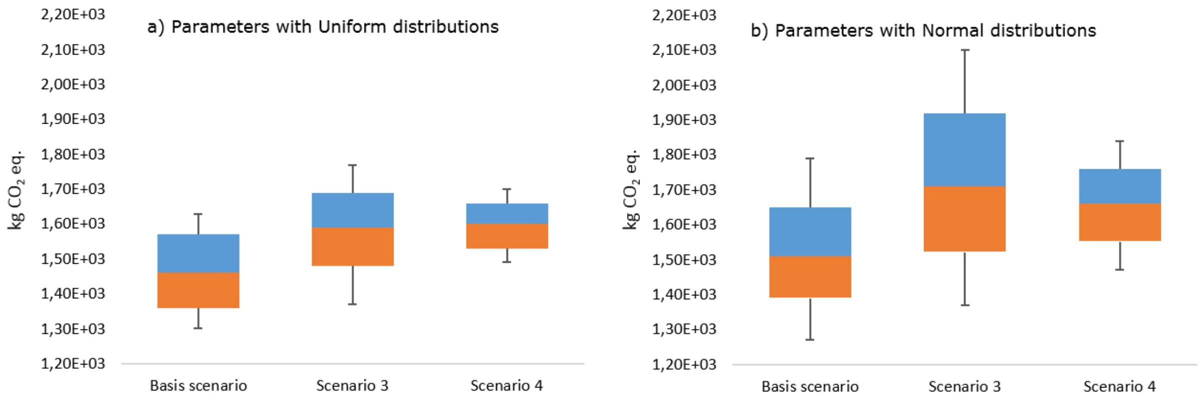
To take into account the uncertainty and/or variability of the parameters in Table 32 simultaneously, a probabilistic analysis was performed. Uncertainty propagation was performed by Monte Carlo Simulation, considering 1000 iterations.

In addition, two different types of distribution were considered for each parameter: a uniform distribution and a Gaussian distribution. For the uniform distribution, the minimum and maximum values indicated in Table 32, were considered as the boundary points of the distribution. In the case of the Gaussian distribution, the minimum and maximum values correspond to the negative and positive deviations, respectively.

In the following, only the results for steel sections are presented, as steel rebars lead to similar results.

The results of both analysis for steel sections and for the impact category of GWP are illustrated in Figure 40 by the box plots, which represent the median, lower quartile (Q1) and upper quartile (Q3) for the different scenarios.

Figure 40. Box plots for impact category GWP, considering uniform and normal distributions



It is noticed that when performing the deterministic analysis, the base scenario and scenario 3 lead to the same final aggregated value, although the importance of the stages varied from one scenario to the other, as indicated in Figure 37 and Figure 38. However, when uncertainty is considered, and since in the scenarios considered the uncertainty affects mainly the final stages, the difference in the final outcome of the analysis is significant, not only in terms of the median value but also in terms of the scatter of results. For the same reason, the scatter of values for scenario 4 is lower than the other scenarios.

7 Life cycle analysis at the building level

In this section, the LCA model is applied to buildings and therefore, the analysis is performed at the building level, according to EN 15978 [19].

Two office buildings were selected as case studies. The structural system of the first building is a concrete structure; while, the second building has a composite steel-concrete structure.

It is noticed that it's not the aim of this section to make a comparative analysis of the two buildings. In fact, the level of input data and the scope of the life cycle analysis are not the same for the two building, thus preventing any comparisons.

These analyses aim to discuss the influence of two of the most popular structural systems in the full life cycle analysis of the each building. For this reason, the scope of the life cycle analysis presented in this section entails the complete building and not only the structural system.

Finally, it is observed that due to confidentiality reasons, data for the buildings provided in this report is restricted and only the information that is needed for the understanding of the analysis is herein provided.

7.1 Building with a concrete frame

7.1.1 General description

This first case study refers to an office building that is currently being built in Italy. Upon completion, the building will accommodate about 265 working stations; however, its maximum capacity is about 301 working stations.

The building has three floors above ground in the West side and four floors in the other sides. The total gross floor area of the building is about 10 500 m².

The new building will implement innovative technologies, such as concrete core activation for heating and cooling, free cooling, natural air pre-conditioning and external heat pumps in order to reach the high-energy standards indicated in Directive 2010/31/EU on "nearly zero energy buildings".

Moreover, the project was subjected to BREEAM evaluation and has reached a total rating of 'Excellent'. The highest scores were received in the fields: Management (100% of possible credits), Water (100%), Energy (78%) Health and Wellbeing (77%) and in Land and Ecology (70%).

The data of the building is summarized in the following table:

Table 34. Building data

Type of building	Office building
Location of the building	Italy
Total GFA of the building (m^2)	10 500
Number of floors	3-4
Number of working places	265 (301 maximum)
Design service life (years)	60
Building ref. year	2017
Seismic area	n.a.
Climatic area	n.a.
Operational energy consumption	845 888 kwh/yr, from which 148 680 kwh/yr will be provided from solar energy (photovoltaics panels)

7.1.2 Goal and scope of the analysis

The goal of the analysis is a twofold: (i) to discuss the life cycle performance of a real building and to highlight the most important stages and processes throughout the time period considered for the analysis; and (ii) to check the consistency of the life cycle model that was developed for LCA and to identify the strongest features but also the limitations of the model.

Moreover, the LCA is made for the complete building and not only the structural system. This will enable to compare the importance of embodied impacts in relation to global impacts of the building.

The functional equivalent of the analysis is "an office building with a GFA of 10 500m^2 and a reference study period of 60 years". It is noted that the reference study period is the designed working life of the building that, in this case, is 60 years.

In the design of the building no special design strategies were taken into account, in order to extend the working life of the building nor to enable an easier disassembling in the end-of-life stage of the building. Thus, from sub-sections 3.5.1.2 and 3.5.2.2, I_{adap} = 1.0 and I_{deco} = 1.0, respectively.

The analysis is performed from cradle-to-grave. The system boundaries of the analysis take into account the modules indicated in Table 35.

Table 35. Life cycle stages included in the analysis

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

All the materials and quantities considered for the construction of the building were taken from the bill of materials (BoM) provided by the building designer. However, for certain items, the BoM was not clear and the description provided was not enough to enable the identification and quantification of the materials included in these items.

It is noted that although the building is currently being built, the analysis was performed taking into account data available at the design stage and not as-built data.

Except for modules A1-A3, all the remaining modules are based on scenarios and assumptions, as described in the following paragraphs.

7.1.3 Scenarios and assumptions for life cycle analysis

7.1.3.1 Material production (A1-A3) and construction (A4-A5) stages

As previously referred, all materials quantities considered for the building are taken from the BoM used in the bidding process for the construction of the building. It is noted that during the actual construction stage of the building, these quantities may change and same materials may even be replaced by alternative ones.

It is observed that data considered for the building was limited to civil works; data relative to mechanical equipment and other infrastructures were not taken into account.

The transportation distances of all materials were estimated based on the location of the building and of the availability of construction materials in the area.

Since, currently, no data is available for the construction of the building, the electricity required is based on information collected from the literature (see 4.4.1.2). In this case, it was considered a value of about 50 kWh per the GFA of the building.

7.1.3.2 Operation stage (B1 – B7)

The operation stage takes into account Modules B1-B7 (see Table 35). Modules B1-B5 cover the need for maintenance and repair of the structural system and all other building components; while Modules B6-B7 address the energy and water requirements of the building over the time considered in the analysis.

In relation to the former, it is assumed that the structural system does not need any type of maintenance over the period of time considered but other building components, in particular the internal finishes and the external cladding system, should require some maintenance needs. The frequency and type of each main maintenance or repair activity depend on the type of material and this information may be retrieved from the respective product manufacturer (in some cases, this information is given in the EDPs). However, in this case study, no information was gathered for Modules B1-B5.

As previously stated, carbonation of concrete is considered in some studies available in the literature. At the building level, the concrete structure is usually protected, either painted or coated by other materials, in order to reduce the need for maintenance and repair over its working life. Carbonation takes place on the surface of cement-based products that are not covered and this is not usually the case in buildings. Therefore, in this case study, carbonation will not be considered in the operational stage of the building.

The information about the energy requirements of the building was provided by building designers, as indicated in Table 34. In relation to the operational water use, since no data was provided, a value of 15.8 l/per employee and per day (assuming 253 days per business year) was considered for the building [70].

7.1.3.3 End-of-life (C1-C4) and recycling (D) stages

This sub-section describes the processes considered after the demolition of the structure and until the 'end-of-waste' state has been reached (Modules C1 to C4) and the processes considered after the 'end-of-waste' state, which are allocated in Module D, according to EN 15978.

The modelling of end-of-life scenarios for the recycling of concrete and steel reinforcement was described in sub-sections 6.1.1.3 and 6.2.1.3, respectively. For the remaining materials, the final destination was either recycling, recovering or landfill, depending on the current practices considered for each case.

7.1.4 Data collection and quality of data

The environmental data for most of the building materials and processes was taken from the database of GaBi software (either from the Professional Database and the Extension for Construction Materials).

In some cases, data was not available in the referred databases and thus, data was retrieved from available EPDs registered in European registration programs (see Table 12).

However, it is noted that for some other materials data was not available in neither sources. The lack of data affected mainly materials used in external and internal walls, materials for cladding or other finishes, and materials for fittings and fixtures.

The quality of data for the most popular construction materials have already been discussed at the material level and, in general, it complies with the quality criteria described in sub-section 4.3.

All additional data, which was retrieved from third-party audited EDPs, is also compliant the quality criteria referred above.

7.1.5 Life cycle environmental performance of the building

The life cycle environmental analysis was performed taking into account the environmental indicators considered in EN 15978 [19] and the results are presented for the complete building and per the functional unit of the building.

7.1.5.1 Indicators describing environmental problems

Table 36. LCA results of the building for potential environmental problems

	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Abiotic depletion potential for fossil resources (ADPF)	[MJ]	5,86E+07	1,05E+06	2,89E+06	2,85E+08	1,61E+05	2,06E+06	1,07E+06	9,62E+05	-9,40E+06	5,86E+07
Abiotic depletion potential for non fossil resources (ADPE)	[kg Sb eq.]	6,56E-01	5,51E-03	9,28E-02	1,53E+01	1,20E-03	7,34E-02	5,60E-03	8,80E-02	-2,69E+00	6,56E-01
Acidification potential (AP)	[kg SO_2 eq.]	2,02E+04	2,41E+02	7,22E+02	3,76E+04	2,96E+01	5,10E+02	1,72E+02	4,05E+02	-2,07E+03	2,02E+04
Eutrophication potential (EP)	[kg PO_4^{3-} eq.]	1,92E+03	5,82E+01	8,03E+01	5,32E+03	1,32E+01	4,83E+01	4,03E+01	8,26E+01	-1,52E+02	1,92E+03
Global warming potential (GWP)	[kg CO_2 eq.]	6,15E+06	7,59E+04	2,64E+05	2,27E+07	2,76E+04	1,93E+05	7,72E+04	4,98E+04	-9,13E+05	6,15E+06
Ozone Depletion Potential (ODP)	[kg CFC11 eq.]	-6,31E-03	2,55E-08	1,07E-05	8,59E-04	3,24E-08	8,57E-06	2,59E-08	4,99E-07	1,76E-03	-6,31E-03
Photochemical Ozone Creation Pot. (POCP)	[kg C_2H_4 eq.]	1,66E+03	-8,38E+01	5,24E+01	3,71E+03	2,58E+00	3,52E+01	-5,45E+01	3,99E+01	-4,70E+02	1,66E+03

Table 37. LCA results for potential environmental problems per functional unit

	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Abiotic depletion potential for fossil resources (ADPF)	$MJ/m^2.yr$	9,31E+01	0,00E+00	1,67E+00	4,58E+00	4,53E+02	2,56E-01	3,27E+00	1,69E+00	1,53E+00	3,04E+00
Abiotic depletion potential for non fossil resources (ADPE)	kg Sb eq./ m^2.yr	1,04E-06	0,00E+00	8,75E-09	1,47E-07	2,43E-05	1,90E-09	1,16E-07	8,89E-09	1,40E-07	2,50E-08
Acidification potential (AP)	kg SO_2 eq./ m^2.yr	3,20E-02	0,00E+00	3,82E-04	1,15E-03	5,96E-02	4,69E-05	8,10E-04	2,74E-04	6,43E-04	1,38E-03
Eutrophication potential (EP)	kg PO_4^{3-} eq./ m^2.yr	3,04E-03	0,00E+00	9,25E-05	1,27E-04	8,44E-03	2,10E-05	7,67E-05	6,39E-05	1,31E-04	1,87E-04
Global warming potential (GWP)	kg CO_2 eq./ m^2.yr	9,77E+00	0,00E+00	1,21E-01	4,19E-01	3,61E+01	4,38E-02	3,06E-01	1,22E-01	7,90E-02	2,35E-01
Ozone Depletion Potential (ODP)	kg CFC11 eq./ m^2.yr	-1,00E-08	0,00E+00	4,05E-14	1,69E-11	1,36E-09	5,14E-14	1,36E-11	4,11E-14	7,92E-13	2,72E-13
Photochemical Ozone Creation Pot. (POCP)	kg C_2H_4 eq./ m.yr ^{2}	2,63E-03	0,00E+00	-1,33E-04	8,32E-05	5,89E-03	4,10E-06	5,59E-05	-8,65E-05	6,33E-05	1,09E-04

7.1.5.2 Indicators describing resource use

Table 38. LCA results of the building for resource use

	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Non-renewable primary energy resources used as raw materials (PENRM)	MJ	-1,01E+06	-	-	-	-	-	-	-	-	-
Primary energy resources used as raw materials (PERM)	MJ	-3,19E+06	-	-	-	-	-	-	-	-	-
Total use of non-renewable primary energy resources (PENRT)	MJ	6,15E+07	1,05E+06	4,54E+06	3,20E+08	1,69E+05	3,38E+06	1,07E+06	1,00E+06	-9,38E+06	6,15E+07
Total use of renewable primary energy resources (PERT)	MJ	8,32E+06	5,28E+04	1,46E+06	2,32E+08	1,14E+04	1,15E+06	5,37E+04	6,04E+04	2,23E+05	8,32E+06
Use of net fresh water (FW)	m^3	1,34E+04	9,79E+01	2,07E+03	2,34E+05	6,61E+04	1,64E+03	9,95E+01	2,91E+02	-5,23E+03	1,34E+04

Table 39. LCA results for resource use per functional unit

	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Non-renewable primary energy resources used as raw materials (PENRM)	MJ/ m^2.yr	-1,60E+00	-	-	-	-	-	-	-	-	-
Primary energy resources used as raw materials (PERM)	MJ/ m^2.yr	-5,07E+00	-	-	-	-	-	-	-	-	-
Total use of non-renewable primary energy resources (PENRT)	MJ/ m^2.yr	9,76E+01	0,00E+00	1,67E+00	7,20E+00	5,08E+02	2,68E-01	5,37E+00	1,70E+00	1,59E+00	3,15E+00
Total use of renewable primary energy resources (PERT)	MJ/ m^2.yr	1,32E+01	0,00E+00	8,39E-02	2,31E+00	3,68E+02	1,81E-02	1,83E+00	8,53E-02	9,59E-02	3,67E-01
Use of net fresh water (FW)	m^3/ m^2.yr	2,12E-02	0,00E+00	1,55E-04	3,29E-03	3,71E-01	1,05E-01	2,61E-03	1,58E-04	4,61E-04	6,00E-04

7.1.5.3 Indicators describing waste categories

Table 40. LCA results of the building for waste categories

	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Hazardous waste disposed (HWD)	kg	4,72E+01	5,53E-02	7,94E-01	1,88E-01	2,79E-04	1,37E-03	5,62E-02	1,83E+00	-1,21E+01	4,72E+01
Non-hazardous waste disposed (NHWD)	kg	1,12E+06	8,05E+01	2,80E+03	3,81E+05	8,13E+03	2,23E+03	8,18E+01	4,38E+02	-5,39E+04	1,12E+06
Radioactive waste disposed (RWD)	kg	9,14E+02	1,44E+00	6,55E+02	1,36E+04	3,05E+00	5,26E+02	1,46E+00	1,52E+01	-1,08E+02	9,14E+02

Table 41. LCA results for waste categories per functional unit

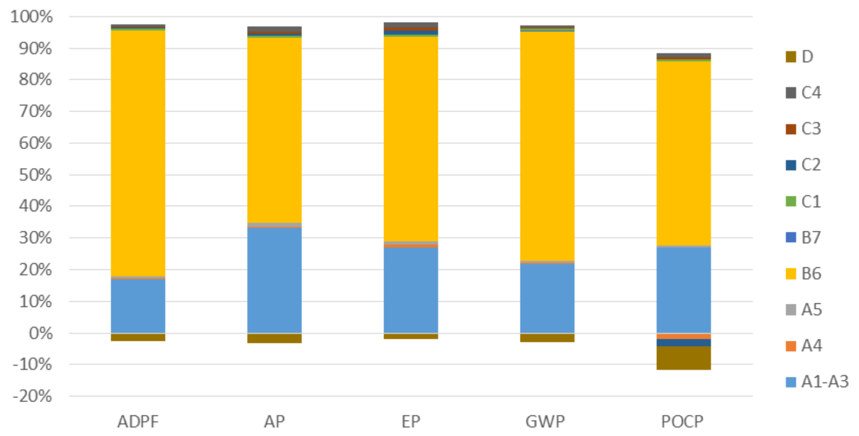
	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Hazardous waste disposed (HWD)	kg/ m^2.yr	7,49E-05	0,00E+00	8,78E-08	1,26E-06	2,99E-07	4,44E-10	2,18E-09	8,92E-08	2,90E-06	1,12E-05
Non-hazardous waste disposed (NHWD)	kg/ m^2.yr	1,77E+00	0,00E+00	1,28E-04	4,44E-03	6,05E-01	1,29E-02	3,53E-03	1,30E-04	6,95E-04	1,46E+01
Radioactive waste disposed (RWD)	kg/ m^2.yr	1,45E-03	0,00E+00	2,28E-06	1,04E-03	2,15E-02	4,84E-06	8,35E-04	2,32E-06	2,42E-05	4,30E-05

7.1.5.4 Summary of results

The results for the indicators describing environmental problems are summarized in Figure 41, showing the contribution of each module to the life cycle performance of the building. It is observed that the contribution of Module B6 is dominant in all impact categories, overshadowing the importance of other modules, in particular, the modules of small importance like A4-A5 and C1-C4.

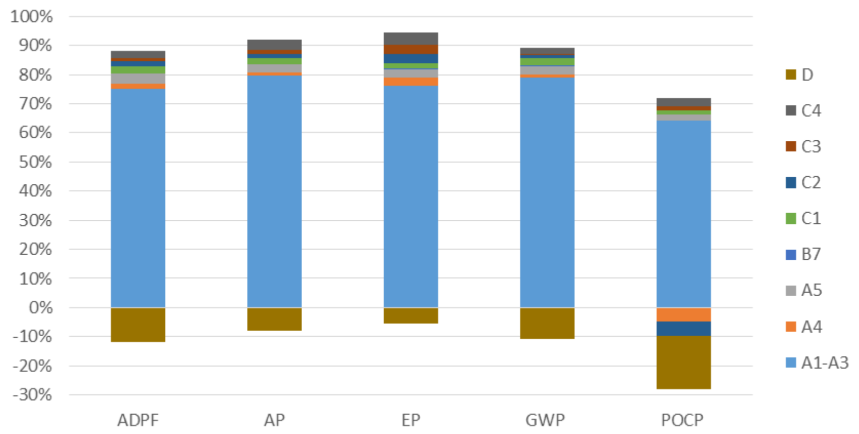
Modules A1-A3 have an importance of about 20% to 30%, while Module B6 has an importance varying from 60% to 80%.

Figure 41. Contribution of the modules for environmental indicators



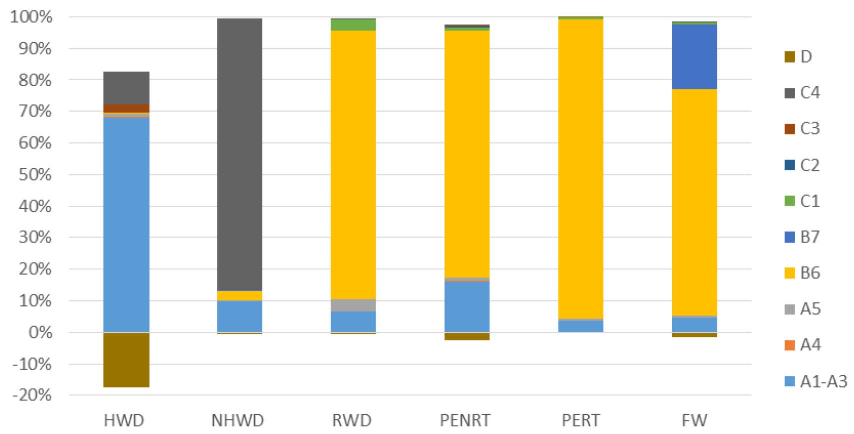
Thus, when removing Module B6 from the analysis, the results for the remaining modules are summarized in Figure 42. In this case, the importance of Modules A1-A3 becomes evident, varying from 60% to 80%. Module D has also a significant importance, about 10% to 20%. The remaining modules have a much lower importance.

Figure 42. Contribution of the modules (except B6) for environmental indicators



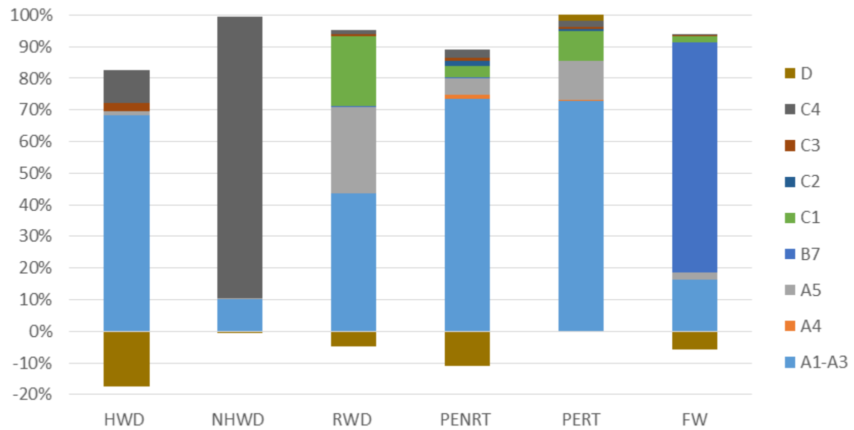
For the indicators describing resource use and waste, the results are summarized in Figure 43.

Figure 43. Contribution of the modules for resource use and waste indicators



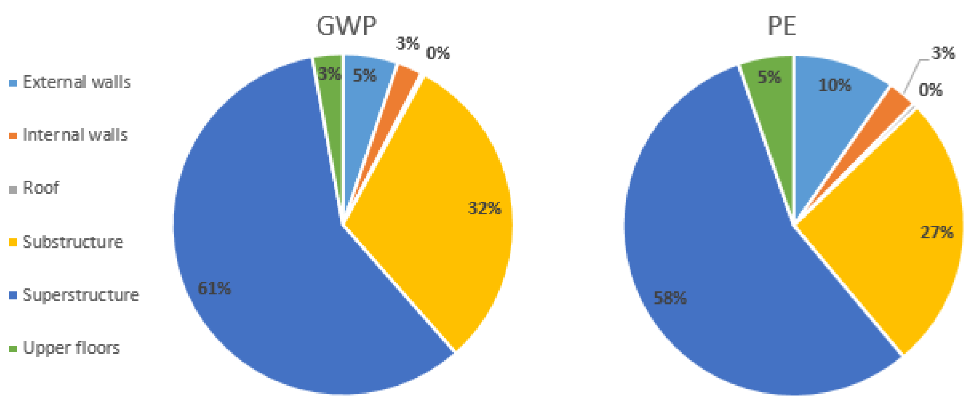
Likewise, when removing Module B6 from the analysis, the importance of Modules A1-A3 becomes evident for most waste and resource use categories. It is also noticed the importance of Module B7 for the category of 'Use of net fresh water' (FW).

Figure 44. Contribution of the modules (except B6) for resource use and waste indicators



The results of Modules A1-A3 are indicated in Figure 45 by taking into account building components. The contribution of substructure and superstructure is about 85% and 80% for GWP and PE, respectively.

Figure 45. Contribution of building components in Modules A1-A3



7.1.6 Sensitivity analysis

7.1.6.1 Scenario analysis

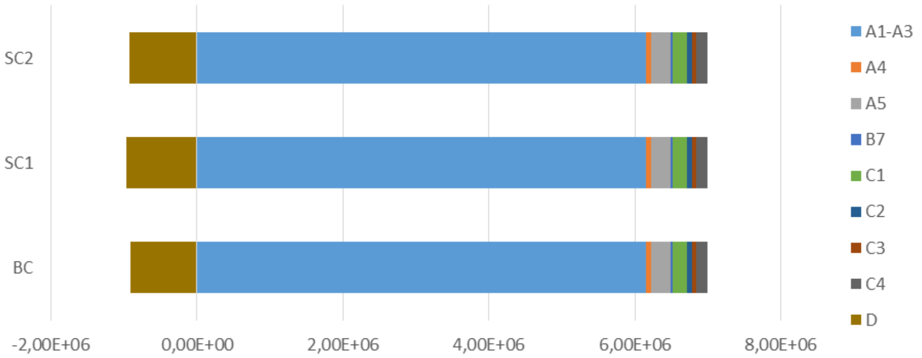
The main construction materials in this case study are concrete and steel reinforcement. Therefore, the different end-of-life scenarios considered in the analysis are focussed on these materials. Hence, three end-of-life scenarios are considered, as indicated in Table 42. The end-of-life scenarios for all other materials are not changed.

Table 42. Scenarios for end-of-life stage of reinforced concrete

Ref.	Scenario description	Credits	Allocation procedure	RR	F_1	F_2
Base	Recycling of reinforced concrete	Recycled aggregates for road construction or backfilling	Module D (with correction factor)	70%	0.50	-
		Recycled steel reinforcement		70%	1.0	-
SC1	Recycling of reinforced concrete	Recycled aggregates for concrete production t	Module D (with correction factor)	70%	0.50	0.70
		Recycled steel reinforcement		70%	1.0	-
SC2	Recycling of reinforced concrete	Recycled aggregates for road construction or backfilling (70%) and concrete production (30%)	Module D (with correction factors)	70%	0.50	0.70
		Recycled steel reinforcement		70%	1.0	-

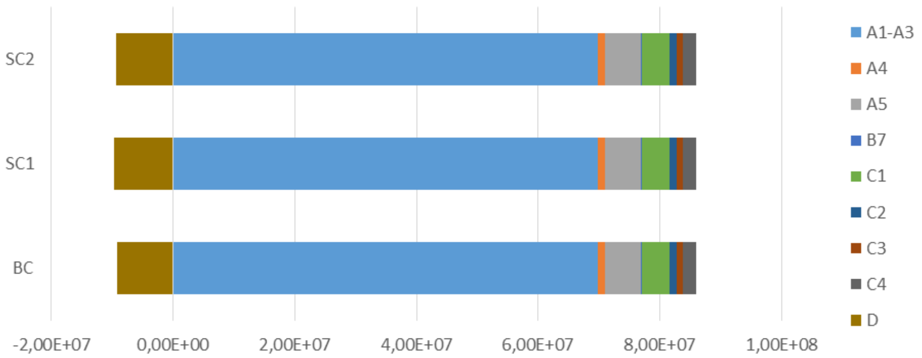
The results of the scenario analysis are illustrated in Figure 46 for the impact category of GWP. It is noted that Module B6 is not shown in these results, as it does not change the final result of each scenario.

Figure 46. Results of the scenario analysis for GWP



In addition, for the impact category of PE, the results of the scenario analysis are illustrated in Figure 47.

Figure 47. Results of the scenario analysis for PE



The variation of the aggregated result for each scenario is almost negligible as observed from the above graphs. This was already expected from the results of the life cycle analysis of concrete (see sub-section 6.1).

7.1.6.2 Perturbation analysis

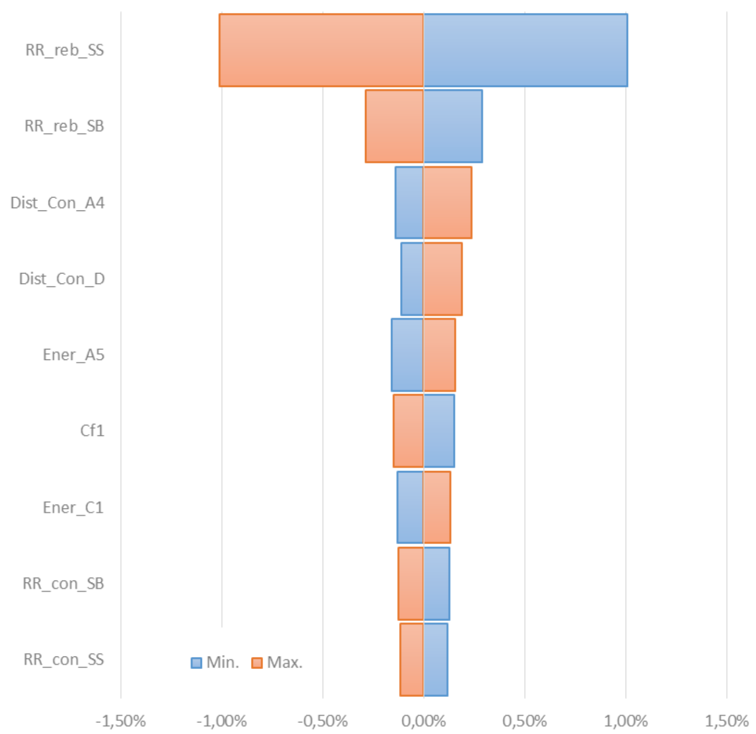
To assess the variability of the outcome of the analysis in relation to the variability of the parameters, a range of plausible values was allocated to each basic parameter, representing the variability of each parameter. The minimum and maximum values for each parameter are indicated in Table 43. Since the variation between the scenarios is negligible, the sensitivity analysis if performed only for the base scenario.

Table 43. Range of values for the parameters

Parameter	Name	Min. value	Max. value
Distance in A4	dist_A4	-60%	+100%
Distances in C	dist_C	-60%	+100%
Distances in D	dist_D	-60%	+100%
Recycling rate of concrete	RR_con	-25%	+25%
Recycling rate of steel reinforcement	RR_reb	-25%	+25%
Value-corrected factor for concrete	C_{f1}	-40%	+40%
Use of energy in A5	Ener_A5	-20%	+20%
Energy consumption in B6	Ener_B6	-20%	+20%
Use of energy in C1	Ener_C1	-20%	+20%

The results of the analysis are illustrated in Figure 48 for the impact category of GWP. In this graph only the parameters with variations higher than ±0.1% are represented. The Sensitivity Ratios (SR) for each parameter, given by expression (12), are shown in Table 44.

Figure 48. Tornado graph for impact category GWP



In Table 44, the parameters indicate to each material (concrete - con or rebars - reb) and to each building component (SubStructure - SB or SuperStructure - SS) they are referring to.

Table 44. Sensitivity ratios (SR) for each parameter

Parameter	Sensitivity ratios (SR)
dist_con_A4	0.002
dist_con_D	0.002
RR_con_SB	-0.005
RR_con_SS	-0.005
RR_reb_SB	-0.012
RR_reb_SS	-0.040
C_{f1}	-0.004
Ener_A5	0.008
Ener_B6	0.80
Ener_C1	0.007

As expected, the dominant parameter was found to be the consumption of electricity in Module B6, with a SR of 0.80; however, this parameter is not indicated in the graph above otherwise the variation of the other parameters would not be distinguished. The variation of all other parameters lead to small variations of the outcome of the analysis. Among these, the recycling rate of steel reinforcement may be highlighted with a SR of -0.04 and -0.01, respectively for steel reinforcement in the superstructure (SS) and substructure (SB).

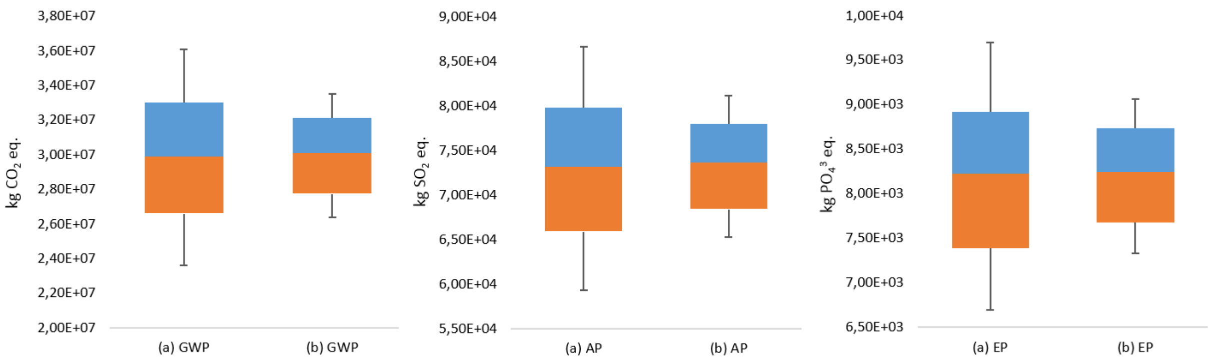
7.1.7 Uncertainty analysis

To take into account the uncertainty and/or variability of the parameters in the life cycle analysis of the building, a probabilistic analysis was performed. Two different types of distribution were considered for each parameter: a uniform distribution and a Gaussian distribution. For the uniform distribution, the minimum and maximum values indicated in Table 43, were considered as the boundary points of the distribution. In the case of the Gaussian distribution, the minimum and maximum values correspond to the negative and positive deviations, respectively.

Uncertainty propagation was performed by Monte Carlo Simulation, considering 1000 iterations. The results of both analysis are illustrated in Figure 49, by the median values and main quartiles, for the impact categories of GWP, AP and EP.

Figure 49. Probabilistic analysis for three environmental categories

(a) Parameters with Gaussian distributions; (b) Parameters with uniform distributions



In this case, the two probabilistic analyses lead to very similar results in terms of the median values. As expected, the scatter of values is higher for the Gaussian distribution than the uniform distribution.

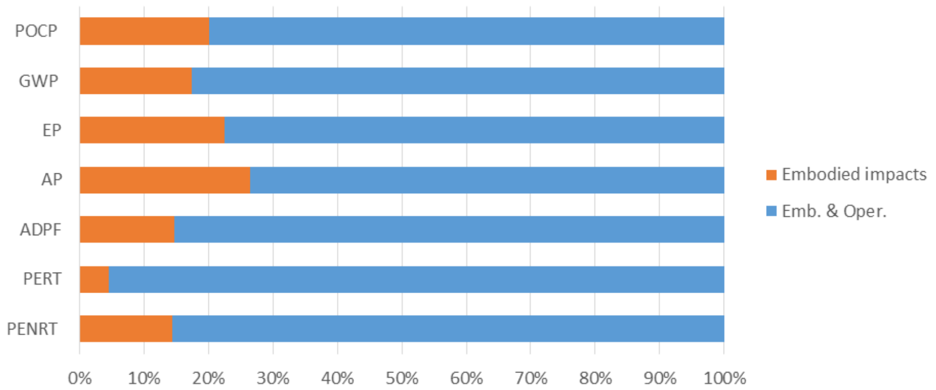
Finally, it is observed that the probabilistic analysis herein performed was limited to the parameters indicated in Table 32. These parameters do not affect Modules A1 to A3, which have the higher importance, when Module B6 is not taken into account. If the uncertainty in Modules A1-A3 have been taken into account, the scatter of results would have been higher.

7.1.8 Weight of embodied impacts

This case study took into account the operational energy of the building (Module B6) and thus, the contribution of the remaining modules was overshadowed by the dominant contribution of Module B6. Only when the contribution of Module B6 was removed from the aggregated result of the LCA, it was possible to conclude about the contribution of the remaining ones.

The contribution of embodied impacts in relation to the aggregated value of each indicator is illustrated in Figure 50. It is noted that, in this case, embodied impacts take into account all modules except modules B6 and B7.

Figure 50. Weight of embodied impacts in the LCA of the building



Thus, it is observed from Figure 50 that embodied impacts have a contribution lower than 20% for most impact categories, except Eutrophication Potential and Acidification Potential.

7.1.9 Final remarks about the case study

This case study comprehended the life cycle analysis of a complete building with a concrete structure. Some difficulties and limitations were identified during the analysis. These limitations were mainly related to the correct identification and quantification of all materials included in the BoM of the building, and to the availability of environmental data to perform the assessment.

Due to the above limitations, about 30% (in terms of costs) of the items included in the BoM of the building were not taken into account in the LCA of the building. This is not complying with the cut-off rules of EN 15978. However, it is noticed that, in relation to the structural system of the building, the materials considered in the analysis were close to 100%.

7.2 Building with a composite frame

7.2.1 General description

The second case study refers to an office building in Australia. The building has four floors above ground and one underground floor. The total gross floor area of the building is 10 050 m².

The structural system of the building is composed by a steel frame with composite slabs. The building was designed to be fire engineered so that no passive protection is needed on the beams; while, the columns have a 2 hours protection provided by fire spray or encasement.

Moreover, the building was designed to meet a 5 star AGBR rating under the Australian Building Greenhouse rating scheme and also a 5 star under the GBCA rating scheme.

The data of the building is summarized in Table 45.

Table 45. Building data

Type of building	Office building
Location of the building	Sidney - Australia
Total GFA of the building (m²)	10 054
Number of floors	4
Number of working places	n.a.
Design service life (years)	50
Building ref. year	n.a.
Seismic area	n.a.
Climatic area	n.a.
Operational energy consumption	n.a.

7.2.2 Goal and scope of the analysis

In this case, the main goal of the analysis is assess the weight of the structural system of the building in relation to the complete building. Hence, the LCA is made for the complete building and not only the structural system.

The functional equivalent of the analysis is "an office building with a GFA of 10054 m^2 and a reference study period of 50 years". The analysis is performed from cradle to grave. The system boundaries of the analysis takes into account the modules indicated in Table 46.

Table 46. Life cycle stages included in the analysis

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

The analysis is performed taking into account data availability at the design stage of the building.

For Modules A1-A3, all the materials and quantities considered for the building were taken from the bill of materials (BoM), provided by the building designer. However, for some items, the BoM was not clear and the description provided was not enough to enable the identification and proper quantification of the materials included in these items.

For all the remaining modules, data considered in the analysis is based on scenarios and assumptions, as described in the following paragraphs.

7.2.3 Scenarios and assumptions for life cycle analysis

7.2.3.1 Material production (A1-A3) and construction (A4-A5) stages

All material quantities considered for the building were taken from the BoM of the building, as described in the previous paragraphs.

As already referred in sub-section 6.2, the database of worldsteel provides data for all processes for the production of intermediate or semi-finished steel products, at the gate of the plant. Therefore, in order to account for the conversion of intermediate or semi-finished products into finished products, an additional 10% of the steel production is considered in Modules A1-A3, for the steel products used in the structural system of the building.

The transportation distances of all materials were estimated based on the location of the building and of the availability of construction materials in the area.

Since, currently, no data is available for the construction of the building, the electricity required is based on information collected from the literature (see 4.4.1.2). In this case, a value of about 50 kWh per the GFA of the building was considered.

7.2.3.2 Operation stage (B1 – B7)

The operation stages takes into account Modules B1-B7 (see Table 46). Modules B1-B5 cover the need for maintenance and repair of the structural system and all other building components; while Modules B6-B7 address the energy and water requirements of the building over the time considered in the analysis.

As previously stated, the frequency and type of each main maintenance or repair activity depend on the type of material and this information may be retrieved from the respective product manufacturer. However, in this case study, no information was gathered for Modules B1-B7. Likewise, no information was collected for Modules B6 and B7.

7.2.3.3 End-of-life (C1-C4) and recycling (D) stages

This sub-section describes the processes considered after the demolition of the structure and until the 'end-of-waste' state has been reached (Modules C1 to C4) and the processes considered after the 'end-of-waste' state, which are allocated in Module D, according to EN 15978.

The modelling of end-of-life scenarios for the recycling of concrete and steel products was fully described in sub-sections 6.1.1.3 and 6.2.1.3, respectively. For the remaining materials, the final destination was either recycling, recovering or landfill, depending on the current practices considered for each case.

7.2.4 Data collection and quality of data

The environmental data for building products and processes was taken from the database of GaBi software (either from the Professional Database, version, and the Extension for Construction Materials, version). In cases when data was not available in the referred databases, data was retrieved from available EPDs registered in European registration programs (see Table 12). Unfortunately, in few cases, data was not found in any of the sources.

The quality of data for the most popular construction materials have already been discussed at the material level and, in general, it complies with the quality criteria described in sub-section 4.3.

Additional data from third party audited EDPs, is also compliant the quality criteria referred above.

7.2.5 Life cycle environmental performance of the building

The life cycle environmental analysis was performed taking into account the environmental indicators considered in EN 15978 [19] and the results are presented for the complete building and per the functional unit of the building.

7.2.5.1 Indicators describing environmental problems

Table 47. Life cycle results of the building for potential environmental problems

	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Abiotic depletion potential for fossil resources (ADPF)	[MJ]	2,83E+07	3,15E+05	2,73E+06	-	-	1,51E+06	2,03E+05	1,83E+05	3,24E+05	-4,60E+06
Abiotic depletion potential for non fossil resources (ADPE)	[kg Sb eq.]	2,93E+00	2,21E-02	1,06E-01	-	-	5,38E-02	1,07E-03	1,68E-02	2,66E-03	-1,43E+00
Acidification potential (AP)	[kg SO_2 eq.]	9,73E+03	8,21E+01	7,51E+02	-	-	3,74E+02	3,28E+01	7,74E+01	1,47E+02	-9,54E+02
Eutrophication potential (EP)	[kg PO_4^{3-} eq.]	1,74E+03	1,97E+01	9,18E+01	-	-	3,54E+01	7,67E+00	1,58E+01	1,99E+01	-7,14E+01
Global warming potential (GWP)	[kg CO_2 eq.]	2,72E+06	2,17E+04	2,50E+05	-	-	1,41E+05	1,47E+04	9,44E+03	2,51E+04	-4,76E+05
Ozone Depletion Potential (ODP)	[kg CFC11 eq.]	5,66E-02	1,31E-03	3,22E-03	-	-	6,28E-06	4,94E-09	4,71E-08	2,55E-08	2,44E-03
Photochemical Ozone Creation Pot. (POCP)	[kg C_2H_4 eq.]	9,74E+02	-2,01E+01	4,74E+01	-	-	2,58E+01	-1,04E+01	7,63E+00	1,17E+01	-2,26E+02

Table 48. Life cycle results for potential environmental problems per functional unit

	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Abiotic depletion potential for fossil resources (ADPF)	$MJ/m^2.yr$	5,64E+01	6,26E-01	5,44E+00	-	-	3,00E+00	4,04E-01	3,65E-01	6,45E-01	-9,15E+00
Abiotic depletion potential for non fossil resources (ADPE)	kg Sb eq./ $m^2.yr$	5,83E-06	4,40E-08	2,10E-07	-	-	1,07E-07	2,12E-09	3,35E-08	5,30E-09	-2,85E-06
Acidification potential (AP)	kg SO_2 eq./ $m^2.yr$	1,94E-02	1,63E-04	1,49E-03	-	-	7,44E-04	6,53E-05	1,54E-04	2,93E-04	-1,90E-03
Eutrophication potential (EP)	kg PO_4^{3-} eq./ $m^2.yr$	3,46E-03	3,91E-05	1,83E-04	-	-	7,05E-05	1,53E-05	3,14E-05	3,96E-05	-1,42E-04
Global warming potential (GWP)	kg CO_2 eq./ $m^2.yr$	5,41E+00	4,31E-02	4,98E-01	-	-	2,81E-01	2,92E-02	1,88E-02	4,98E-02	-9,46E-01
Ozone Depletion Potential (ODP)	kg CFC11 eq./ $m^2.yr$	1,13E-07	2,61E-09	6,40E-09	-	-	1,25E-11	9,82E-15	9,37E-14	5,07E-14	4,85E-09
Photochemical Ozone Creation Pot. (POCP)	kg C_2H_4 eq./ $m.yr^2$	1,94E-03	-3,99E-05	9,42E-05	-	-	5,13E-05	-2,06E-05	1,52E-05	2,32E-05	-4,49E-04

7.2.5.2 Indicators describing resource use

Table 49. Life cycle results of the building for resource use

	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Non-renewable primary energy resources used as raw materials (PENRM)	MJ	6,97E+06	0,00E+00	8,48E+04	-	-	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Primary energy resources used as raw materials (PERM)	MJ	-2,50E+05	0,00E+00	0,00E+00	-	-	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Total use of non-renewable primary energy resources (PENRT)	MJ	3,86E+07	3,17E+05	4,38E+06	-	-	2,48E+06	2,04E+05	1,90E+05	3,36E+05	-4,46E+06
Total use of renewable primary energy resources (PERT)	MJ	4,85E+06	1,15E+04	1,36E+06	-	-	8,45E+05	1,02E+04	1,13E+04	3,91E+04	2,65E+05
Use of net fresh water (FW)	m^3	1,97E+04	4,22E+01	2,01E+03	-	-	1,21E+03	1,89E+01	5,53E+01	6,39E+01	-2,63E+03

Table 50. Life cycle results for resource use per functional unit

	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Non-renewable primary energy resources used as raw materials (PENRM)	MJ/ m^2.yr	1,39E+01	0,00E+00	1,69E-01	-	-	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Primary energy resources used as raw materials (PERM)	MJ/ m^2.yr	-4,98E-01	0,00E+00	0,00E+00	-	-	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Total use of non-renewable primary energy resources (PENRT)	MJ/ m^2.yr	7,68E+01	6,31E-01	8,71E+00	-	-	4,93E+00	4,06E-01	3,78E-01	6,68E-01	-8,88E+00
Total use of renewable primary energy resources (PERT)	MJ/ m^2.yr	9,64E+00	2,29E-02	2,71E+00	-	-	1,68E+00	2,03E-02	2,25E-02	7,78E-02	5,27E-01
Use of net fresh water (FW)	m^3/ m^2.yr	3,93E-02	8,39E-05	4,00E-03	-	-	2,40E-03	3,77E-05	1,10E-04	1,27E-04	-5,23E-03

7.2.5.3 Indicators describing waste categories

Table 51. Life cycle results of the building for waste categories per functional unit

	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Hazardous waste disposed (HWD)	kg	7,68E+01	7,72E-02	1,90E-01	-	-	1,01E-03	1,07E-02	5,59E-03	5,31E-03	-3,05E-01
Non-hazardous waste disposed (NHWD)	kg	4,19E+05	5,10E+03	3,20E+03	-	-	1,63E+03	1,56E+01	8,25E+01	1,56E+06	2,89E+04
Radioactive waste disposed (RWD)	kg	2,24E+02	1,02E+00	6,14E+02	-	-	3,86E+02	2,78E-01	2,78E+00	4,59E+00	-1,08E+01

Table 52. Life cycle results for waste categories per functional unit

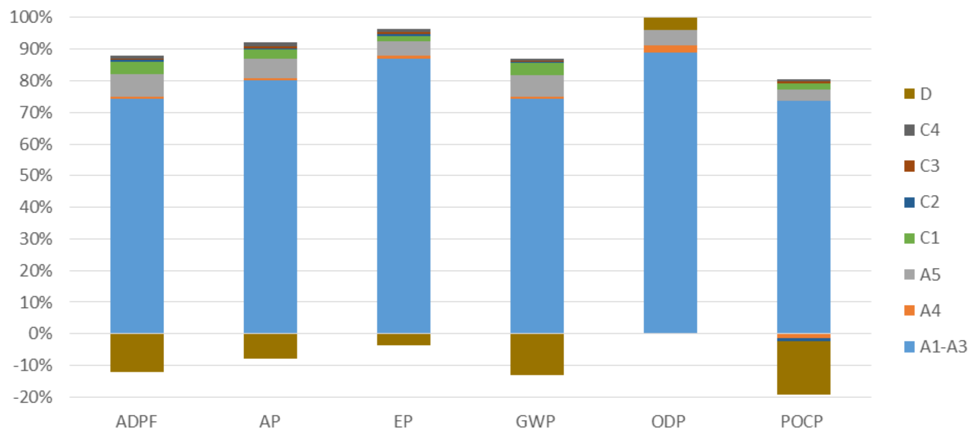
	Unit	A1-A3	A4	A5	B6	B7	C1	C2	C3	C4	D
Hazardous waste disposed (HWD)	kg/ m^2.yr	1,53E-04	1,53E-07	3,78E-07	-	-	2,00E-09	2,13E-08	1,11E-08	1,06E-08	-6,06E-07
Non-hazardous waste disposed (NHWD)	kg/ m^2.yr	8,34E-01	1,01E-02	6,36E-03	-	-	3,25E-03	3,10E-05	1,64E-04	3,10E+00	5,74E-02
Radioactive waste disposed (RWD)	kg/ m^2.yr	4,46E-04	2,03E-06	1,22E-03	-	-	7,67E-04	5,53E-07	5,52E-06	9,12E-06	-2,14E-05

7.2.5.4 Summary of results

The results for the indicators describing environmental problems are summarized in Figure 51, showing the contribution of each module to the life cycle performance of the building. In this case, it is observed that Modules A1-A3 are dominant in all impact categories, although Module D has also a significant contribution. The importance of the remaining modules is reduced.

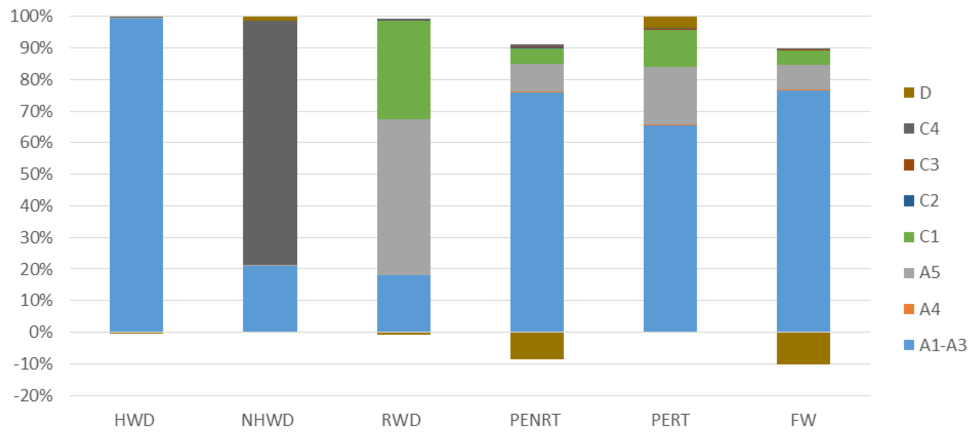
Modules A1-A3 have an importance of about 60% to 80%, while Module D has an importance varying from 10% to 20%.

Figure 51. Contribution of the modules for environmental indicators



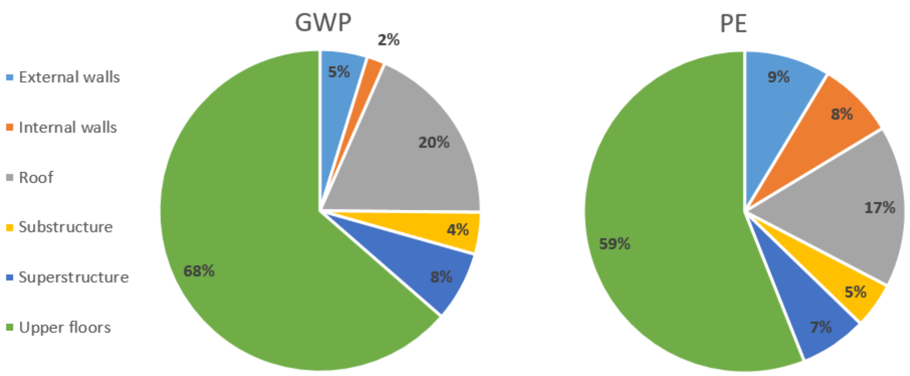
For the indicators describing resource use and waste, the results are summarized in Figure 52. The same conclusions may be drawn for the importance of Modules A1-A3 in relation to the indicators describing resource use, hazard and non-hazard wastes.

Figure 52. Contribution of the modules for resource use and waste indicators



The results of Modules A1-A3 are indicated in Figure 45 by taking into account building components.

Figure 53. Contribution of building components in Modules A1-A3



In this case, the upper floors and the roof have a major contribution, about 88% and 76% for GWP and PE, respectively

7.2.6 Sensitivity analysis

7.2.6.1 Scenario analysis

The main construction materials in this case study are steel products, although concrete has also an important share of the BoM. Therefore, the different end-of-life scenarios considered in the analysis are focussed on these materials. Hence, three end-of-life scenarios are considered, as indicated in Table 53. The end-of-life scenarios for all other materials are not changed.

Table 53. Scenarios for end-of-life stage of steel and concrete

Ref.	Scenario description	Credits	Allocation procedure	Concrete			Steel	
				RR (%)	F_1	F_2	RR (%)	F_1
Base	Recycling of steel & concrete	Recycled steel and recycled aggregates for road construction or backfilling	Module D (with correction factor)	70	0.5	-	90	1.0
SC1	Recycling of steel & concrete	Recycled steel and recycled aggregates for concrete production		70	0.5	0.7	90	1.0
SC2	Recycling of steel & concrete	Recycled steel and recycled aggregates for road construction or backfilling (70%) and concrete production (30%)		70	0.5	0.7	90	1.0

The results of the scenario analysis are illustrated in Figure 54 and Figure 55 for the impact categories of GWP and PE, respectively.

Figure 54. Results of the scenario analysis for GWP

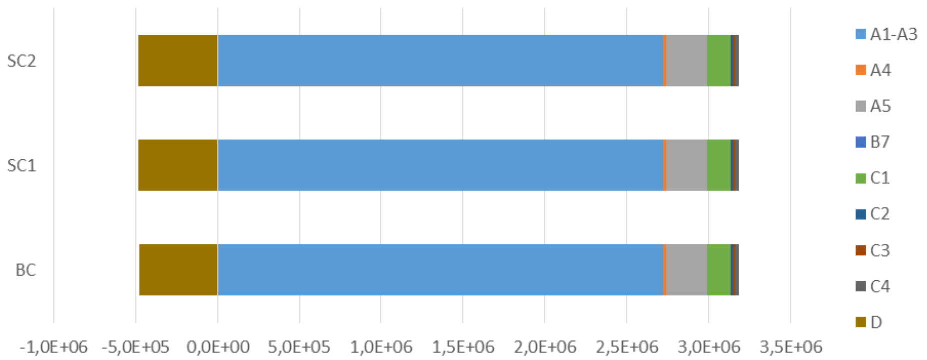
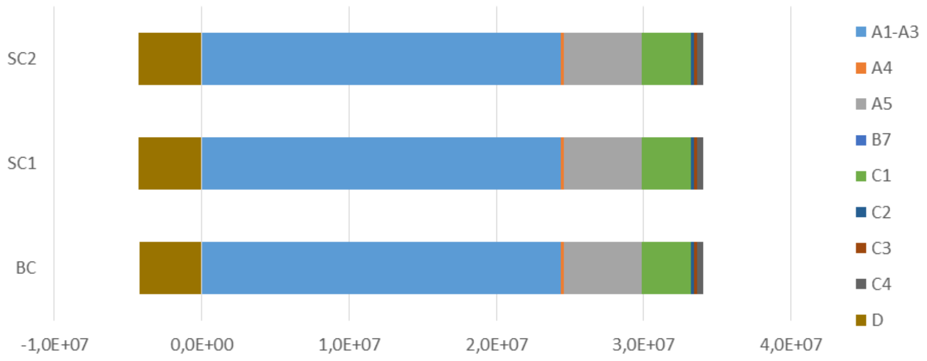


Figure 55. Results of the scenario analysis for PE



Likewise, given the importance of Modules A1-A3, the variation of the final aggregated results, for each scenario, is almost negligible, as observed from the above graphs.

7.2.6.2 Perturbation analysis

To assess the variability of the outcome of the analysis in relation to the variability of the parameters, a range of plausible values was allocated to each basic parameter, representing the variability of each parameter. The minimum and maximum values for each parameter are indicated in Table 54, for the base scenario.

Table 54. Range of values for the parameters

Parameter	Name	Min. value	Max. value
Distance in A4	dist_A4	-60%	+100%
Distances in C	dist_C	-60%	+100%
Distances in D	dist_D	-60%	+100%
Recycling rate concrete	RR_con	-25%	+25%
Recycling rate steel reinforcement	RR_reb	-25%	+25%
Recycling rate steel sections	RR_sec	-10%	+10%
Value-corrected factor for concrete	C_{f1}	-40%	+40%
Energy use in construction stage	Ener_A5	-20%	+20%
Energy use in demolition stage	Ener_C1	-20%	+20%

The results of the analysis are illustrated in Figure 56 for the impact category of GWP. In this graph, only the parameters with variations higher than ±0.1% are represented.

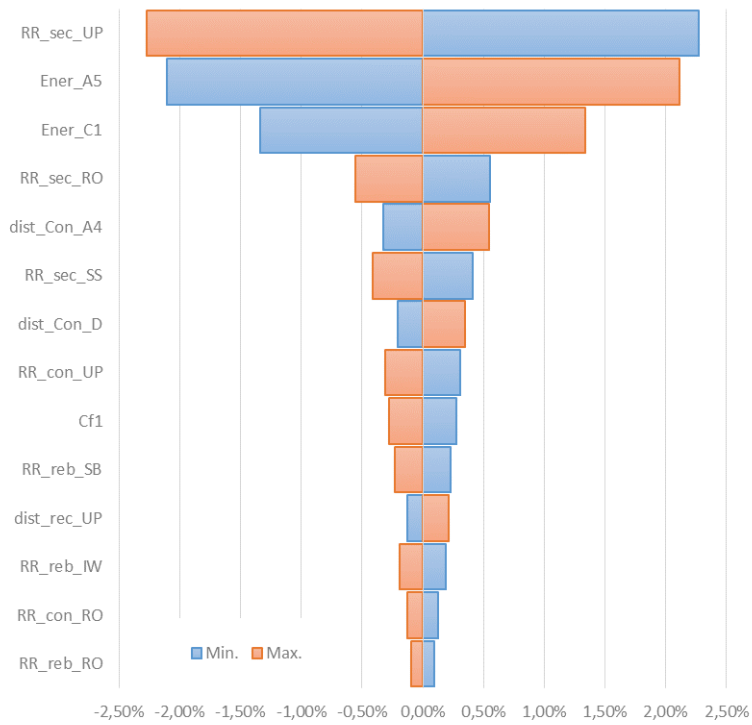
The Sensitivity Ratios (SR) for each parameter, given by expression (12), are indicated in Table 55.

Table 55. Sensitivity ratios (SR) for each parameter

Parameter	Sensitivity ratios (SR)
RR_sec_UP	-0,227
Ener_A5	0,106
Ener_C1	0,067
RR_sec_RO	-0,055
dist_Con_A4	0,005
RR_sec_SS	-0,041
RR_reb_UP	-0,073
dist_Con_D	0,003
RR_con_UP	-0,012
C_{f1}	-0,007
RR_reb_SB	-0,009
dist_rec_UP	0,002
RR_reb_IW	-0,008
RR_con_RO	-0,005

The parameters shown in Table 55 indicate to each material (sections - sec, rebars - reb or concrete - con) and to each building component (Upper floors – UP, Roof – RO, SubStructure - SB or SuperStructure - SS) they are referring.

Figure 56. Tornado graph for the impact category of GWP



The variation of the parameters considered in Table 54 do not lead to significant variations in the aggregated result of the LCA. As observed from Figure 56, the maximum and minimum variations are close to +2.5% and -2.5%, respectively. In this case, the most important parameter is the recycling rate for steel sections in the upper floors (RR_sec_UP), with a sensitivity ratio of -0.227. This was expected since the importance of upper floors was already identified in Figure 53.

Apart from the use of energy in the construction stage (Ener_A5), all the remaining parameters lead to small variations of the outcome of the analysis.

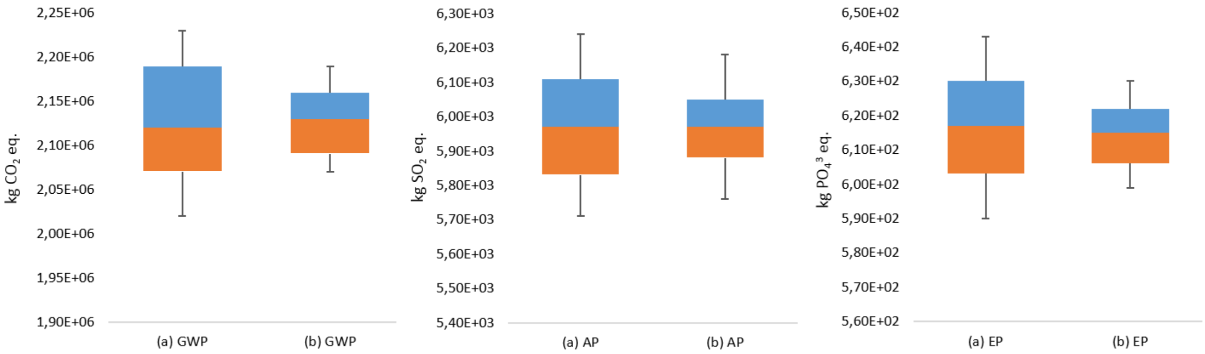
7.2.7 Uncertainty analysis

To take into account the uncertainty and/or variability of the parameters a probabilistic analysis was performed. Two different types of distribution were considered for each parameter: a uniform distribution and a Gaussian distribution. For the uniform distribution, the minimum and maximum values indicated in Table 54, were considered as the boundary points of the distribution. In the case of the Gaussian distribution, the minimum and maximum values correspond to the negative and positive deviations, respectively.

Uncertainty propagation was performed by Monte Carlo Simulation, considering 1000 iterations. The results of both analysis are illustrated in Figure 57, by the median values and main quartiles, for the impact categories of GWP, AP and EP.

Figure 57. Probabilistic analysis for three environmental categories

(a) Parameters with Gaussian distributions; (b) Parameters with uniform distributions

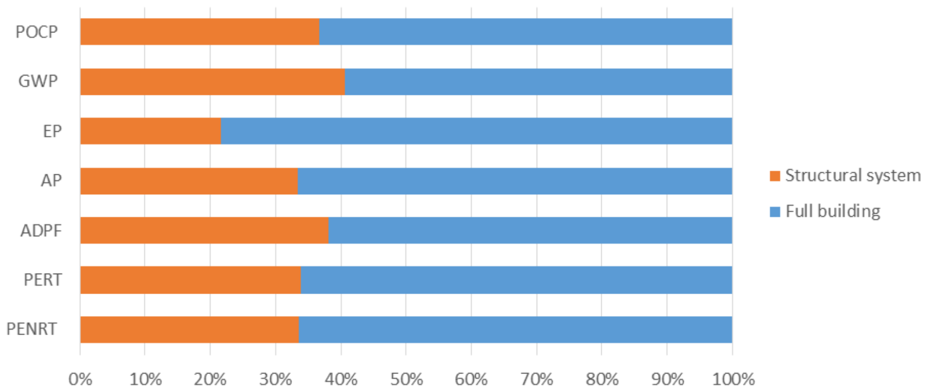


In this case, the two probabilistic analysis lead to very similar results in terms of the median values. The scatter of values is higher for the Gaussian distribution than the uniform distribution. However, it is observed that the scatter of results in Figure 57 would increase if uncertainty was considered also in Modules A1 - A3.

7.2.8 Weight of the structural system

This case study took into account the structural system of the building and all other non-structural building components. However, in this sub-section, the structural system of the building is compared with the full building (structural and non- structural components), in order to evaluate the weight of the former. This comparison is illustrated in Figure 58 for some impact categories.

Figure 58. Weight of the structural system in relation to the whole building



It is noted that these results are referring to the complete life cycle of the building (Modules A1-A3 to D).

Hence, it is observed from Figure 58 that the structural system has an importance above 30% for most impact categories, and in the case of GWP, the importance is up to 40%.

7.2.9 Final remarks about the case study

In this case study the life cycle analysis of a building with a composite structure was performed. The analysis included all processes over the building life cycle, except the energy and water requirements during the operation of the building.

Like in the previous case study, some difficulties and limitations were identified, which were mainly related to the BoM of the building and to the availability of environmental data to perform the assessment.

In this case, the above limitations led to a cut slightly lower than 30% (in terms of costs) of the items included in the BoM of the building, which is not in agreement with the cut-off rules of EN 15978.

Nevertheless, in relation to the structural system of the building, the materials considered in the analysis account for about 100%.

8 Conclusions

The major goal of the project *EFIResources*: *Resource Efficient Construction towards Sustainable Design*, is the development of a performance based approach for sustainable design, enabling to assess resource efficiency of buildings in the early stages of building design and supporting European policies related to the efficient use of resources in construction.

The proposed approach aims for the harmonization between environmental criteria and structural criteria in the design of buildings, leading to an enhanced design, coping with the required safety demands but with lower pressure on the environment and on the use of natural resources. Therefore, it provides the chance for structural engineers to include environmental criteria in the decision making process of building design, thus fostering a more efficient use of resources throughout the life cycle of buildings and reducing the environmental impacts of construction works.

This report focussed on the development of the model for life cycle analysis (LCA) and on its implementation into a software tool. The model is based on a standardized procedure for LCA, thus enabling comparability and a clear communication of results. Furthermore, this model will be used for the benchmarking of the life cycle performance of the structural system of buildings.

The model was applied to two common structural systems of buildings, in order to identify major difficulties and limitations. In these case studies, the LCA was made taking into account the full building and not only the structural system.

Two main problems were identified: (i) the lack of details and a full description of some items indicated in the BoM, which lead to rough assumptions in the definition of the materials and relative quantities; and (ii) the lack of environmental data for some materials included in the BoM of the buildings. These limitations were affecting mainly external walls and cladding systems, internal partitions, finishing materials and other auxiliary materials and components. This problem will become even worse if the assessment is made in early stages of design, when some of the items above are not yet defined.

However, the above limitations are not affecting, at the same extent, the structural system of the building, for which materials and respective quantities have usually a much better definition and environmental data is, in most cases, available in databases and EPDs.

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List of abbreviations and definitions

$ADP_{elements}$	Abiotic Resource Depletion Potential for elements
$ADP_{fossil\ fuels}$	Abiotic Resource Depletion Potential of fossil fuels
AP	Acidification potential
BoM	Bill of Materials
C&DW	Construction and Demolition Waste
C_f	Value-correction value
EDP	Environmental Product Declaration
EoL	End-of-Life
EP	Eutrophication potential
FW	Use of net fresh water
GFA	Gross Floor Area
GWP	Global Warming Potential
HWD	Hazardous waste disposed
I_{ada}	Adaptability index
I_{deco}	Deconstruction index
LCA	Life Cycle Analysis/Assessment
MCS	Monte Carlo Simulation
NHWD	Non-hazardous waste disposed
ODP	Depletion potential of the stratospheric ozone layer
PE	Primary Energy
PEF	Product Environmental Footprint
PENRM	Non-renewable primary energy resources used as raw materials
PENRT	Total use of non-renewable primary energy resources
PERM	Primary energy resources used as raw materials
PERT	Total use of renewable primary energy resources
POCP	Formation potential of tropospheric ozone photochemical oxidants
RR	Recycling (or reuse) Rate of material
RWD	Radioactive waste disposed
SR	Sensitivity ratio

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