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Management of Built Environment

Towards a sustainable construction:
LCA and LCC integration
in the early-design stage.

Comparison among residential building technologies:

single indicator proposal for decision-making purpose.

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Abstract (English version)

"In 2050, we live well, within the planet's ecological limits. Our prosperity and healthy environment stem from an innovative, circular economy where nothing is wasted and where natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance our society's resilience. Our low-carbon growth has long been decoupled from resource use, setting the pace for a safe and sustainable global society." (The 7th environment Action Programme (EAP), Decision N°1386/2013 EU).

The construction sector is responsible for the 36% of global energetic consume and for 40% of carbon dioxide emissions, with a steadily rising trend. In this context, the sector has set itself the target of reducing its incidence by 80% by 2050. Through a transition to sustainable construction, the challenge is to achieve a profound reduction in energy consumption and emission, thanks to a combination of best available technologies and intelligent public policies.

Our thesis has the goal to support the decision-making process in the early-design phase through the integration of BIM: this approach can lead to a comparison and choice of different technological solutions for what concerns economic and environmental impacts. The choice fell on the early-design phase because it is fundamental for providing design guidance and monitoring the effects of design decisions: to support an efficient and user-friendly application of this phase, a simplified building model is proposed.

LCA and LCC analyses have been carried out on different building technologies: timber prefabrication (X-Lam and frame), concrete structure and traditional masonry, the first one characterized by fast construction and ecological features (being the wood renewable and easy to dispose of), while the others are widely used in the residential building.

Finally, it has been proposed a method that allows to be more aware in the project choices about the economic and environmental impact in this preliminary phase. The carbon tax, which objective is to limit global warming by 1.5°C by 2050, was initially applied to the life cycle CO_2 emissions. Taxation has an impact of 5% on total life-cycle costs, which is interesting but does not have a relevant impact on decision-making. Therefore, the emissions' negative externalities have been economically evaluated through the eco-costs of emissions (VPPC, Virtual Pollution Prevention Costs), the IPCC estimates the damage of CO_2 emissions into the environment, quantifiable in 135 €/tCO_2 equivalent (IPCC 2007, GWP100). This methodology has led to considerable outputs: the average impact on the initial investment is 20%, which has a strong relevance in the decision-making.

Abstract (Versione italiana)

"Nel 2050 vivremo bene nel rispetto dei limiti ecologici del nostro pianeta. Prosperità e ambiente sano saranno basati su un'economia circolare senza sprechi, in cui le risorse naturali sono gestite in modo sostenibile e la biodiversità è protetta, valorizzata e ripristinata in modo tale da rafforzare la resilienza della nostra società. La nostra crescita sarà caratterizzata da emissioni ridotte di carbonio e sarà da tempo sganciata dall'uso delle risorse, scandendo così il ritmo di una società globale sicura e sostenibile." (Settimo Programma di Azione per l'Ambiente (PAA), Decisione N°1386/2013 EU).

Il settore delle costruzioni è responsabile del 36% del consumo energetico globale e del 40% delle emissioni di biossido di carbonio, con un trend in costante aumento. In questo contesto, il settore si è posto l'obiettivo di ridurre la sua incidenza dell'80% entro il 2050. Attraverso la transizione verso un'edilizia sostenibile, la sfida è quella di ottenere una profonda riduzione dei consumi energetici e delle emissioni, grazie ad una combinazione delle migliori tecnologie disponibili e di politiche intelligenti.

La nostra tesi ha l'obiettivo di supportare il processo decisionale nella prima fase di progettazione attraverso l'integrazione del BIM: questo approccio può portare ad un confronto e alla scelta di diverse soluzioni tecnologiche per quanto riguarda gli impatti economici e ambientali. La scelta è ricaduta sulla fase di progettazione preliminare, fondamentale per fornire una guida e monitorare gli effetti delle decisioni progettuali: per supportare un'applicazione efficiente e user-friendly di questa fase, viene proposto un modello 3D semplificato.

Le analisi LCA e LCC sono state effettuate su diverse tecnologie costruttive: prefabbricazione in legno (X-Lam e telaio), struttura in calcestruzzo e muratura tradizionale, la prima caratterizzata da rapidità costruttiva e buone prestazioni ecologiche (essendo il legno rinnovabile e facile da smaltire), mentre le altre sono ampiamente utilizzate nell'edilizia residenziale.

Infine, è stato proposto un metodo che permetta di essere più consapevoli nelle scelte progettuali rispetto all'impatto economico e ambientale in questa fase preliminare. Inizialmente è stata applicata la carbon-tax alla CO_2 emessa durante il ciclo di vita, il cui obiettivo è di limitare il riscaldamento globale di 1,5°C entro il 2050. La tassazione ha un impatto del 5% sui costi totali del ciclo di vita, il che è interessante ma non ha un impatto rilevante sul processo decisionale. Pertanto, le esternalità negative delle emissioni di CO_2 sono state valutate economicamente attraverso il concetto di eco-cost (VPPC, Virtual Pollution Prevention Costs) che l'IPCC definisce come il valore attribuibile ai danni ambientali provocati, quantificabili in 135 €/tCO_2Eq. (IPCC 2007, GWP100). Questa metodologia ha portato a risultati considerevoli: l'impatto medio sull'investimento iniziale è in questo caso del 20%, il che ha una forte rilevanza nel processo decisionale.

1 Assessment of environmental impact – LCA

Life Cycle Assessment (LCA) is a method for assessing the environmental impacts of a product throughout its life cycle, from the acquisition of raw material, production, use and disposal. This chapter describes the basic approach, starting with the presentation of the regulatory framework, then with the analysis of this methodology describing the various steps and the peculiarities in its application to the building sector.

1.1 Origins and regulatory framework of the LCA

The Life Cycle Assessment (LCA) was introduced in 1990 by SETAC (Society of Environmental Toxicology and Chemistry), Smuggler Notch (USA); this definition was given: "*a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to effect environmental improvements*" (J. Fava et al., Washington, DC, 1991).

Life Cycle Assessment (LCA) has been widely adopted to evaluate the environmental impact in both the manufacturing and construction sectors (Harris 1999; Petersen and Solberg 2002) throughout its life cycle, through the quantification of the flows of material and energy in input (consumption) and output (emissions), in the phases of raw materials extraction, transport, production, distribution, use and disposal. This method allows to objectively (quantitatively) evaluate the energy and environmental loads determined by a product, process, activity or service, throughout its life cycle, "from cradle to grave" or "from cradle to cradle" in the case of recycling.

The LCA method is a complete, holistic approach that considers all types of impact (thus defining an articulated framework of indicators) and all phases of the life cycle. All incoming resources and all outgoing emissions are tabulated for each life cycle phase. The life cycle in the construction field includes the provision of raw materials, the processes of processing and production, the building construction, the transfer to landfill or to a material recycling facility. The transport of materials that are necessary throughout the life cycle are also taken into consideration.

At the legislative level, the Ronchi Decree of 1997 indicates the life cycle analysis as one of the tools to identify actions to reduce waste production and to encourage and increase reuse, recycling and recovery operations. References to the usefulness of the LCA are also present in the European Regulation EMAS II and ISO 14001. In particular, the life cycle assessment is codified by the 1404X series of ISO standards; the first version of these rules was issued between 1997 and 2001 (Table 1).

ISO Standard	Description
UNI EN 14040	*Environmental management - Life cycle assessment - Principles and framework (1998)*
UNI EN 14041	*Environmental management - Life cycle assessment - Goal and scope definition and inventory analysis (1999)*
UNI EN 14042	Environmental management - *Life cycle assessment - Life cycle impact assessment (2001)*
UNI EN 14043	Environmental management - *Life cycle assessment - Life cycle interpretation (2001)*

Table 1: ISO Standards of the 1404X group

In 2006 there was an update of the standards of the ISO 1404X group which provided the new version of ISO 14040 and the suppression of the 14041, 14042, 14043 replaced by the new 14044 (Table 2).

ISO Standard	Description
EN 14040	*Environmental management - Life cycle assessment – Principles and framework (ISO 14040:2006)*
EN 14044	*Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006)*

Table 2: ISO Standards of the 1404X after the 2006 update

1.2 Theoretical framework of the LCA

The structure of an LCA can be simply described, as a first approximation, according to the four-step scheme that is proposed (Fig. 1):

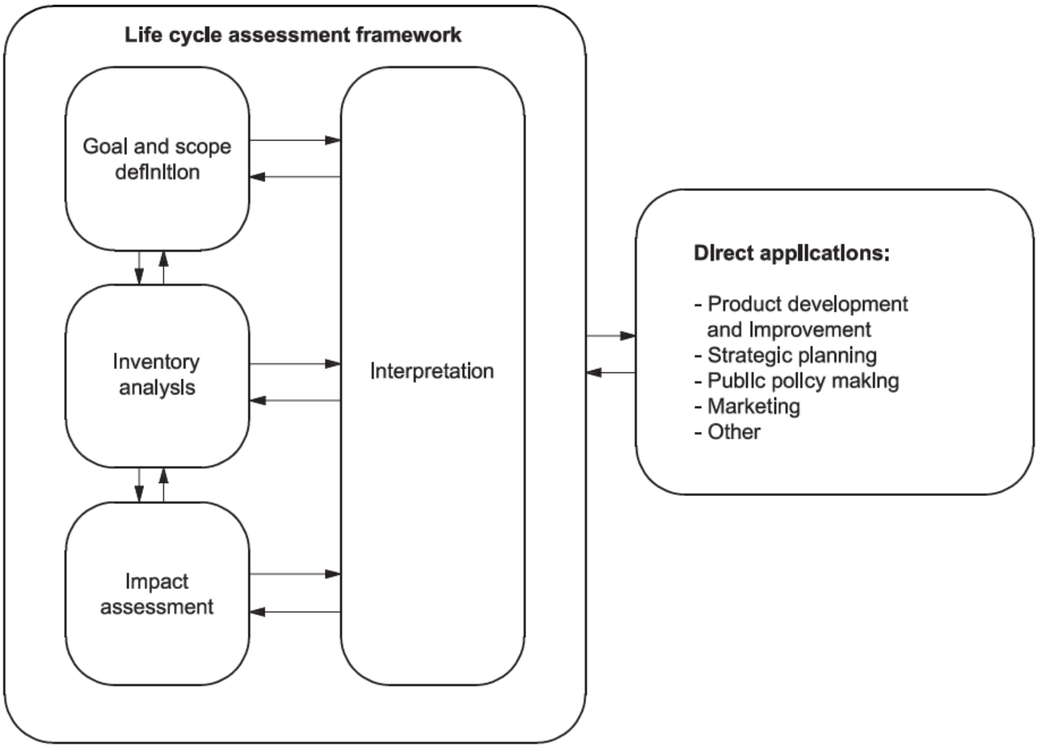

Figure 1: Stages of an LCA [Source: BS EN ISO 14040:2006]

1.3 Definition of objectives and boundaries of the study

The first step of an LCA evaluation is the definition of the aims of the study and the level of detail, and the explanation of who performs and to whom the study is directed. In relation to these initial assumptions, it is necessary to define the functional unit, the boundaries of the system, the duration of the life cycle and the phases of the life cycle that have to be analysed, which are the assumptions and the typology of data to be collected.

The study setting is important because different objectives correspond to a different approach to the problem and therefore a different method of performance of the LCA evaluation. This ability to adapt demonstrates the flexibility of the method, but also leads to adaptations in the use of the method that can distort the results. For this reason, all assumptions need to be clearly explained, not only in the setting, but also during the progress of the process.

In relation to the objectives, it is necessary to define the "boundaries of the system", that means which parts of the life cycle will be included in the analysis and which will be omitted and neglected because of minor importance and little incidence. The users of the LCA instrument in the building sector are on the one hand the designers who, by comparing the environmental impacts of different products, can have indications of support for design choices and have a tool for assessing the actual eco-compatibility of a product, on the other companies that, by identifying the phases of greatest impact, can adopt strategies to improve the product in terms of eco-efficiency and eco-compatibility.

In the light of the results of an LCA evaluation, strategies can be adopted to improve the environmental performance, the production system of the product or the product itself: in this case the objectives are "internal" to the company.

The results of the LCA evaluation can be used for the preparation of an Environmental Report and as a support for obtaining the Environmental Product

Declarations (EPD) and the eco-label: in this case the objectives become "external" to the company and the results of the LCA evaluation can be used by designers and manufacturers. The definition of goals affects the scene of the analysis and evaluation procedures, the level of analysis and the type of data to be collected.
Depending on the purpose of the study it is possible to realize different types of LCA:

- A "conceptual" LCA evaluation (Life Cycle Thinking), used to carry out an evaluation based on a reduced number of inventory and mostly qualitative data;
- A "simplified" (screening) or streamlined (LCA) assessment, where simplifications are implemented to reduce the time needed to carry out the study;
- A "detailed" LCA evaluation, which instead deepens all the data.

Any LCA evaluation is in some way a "simplified" model of the analysed system, since the real reconstruction of all processes and flows is almost impossible and therefore hypotheses and assumptions are always applied that tend to neglect parts of the real system. At the same time, excessive simplification is risky because parts considered negligible, but in fact important, can be omitted, altering the final result. A simplified LCA assessment should therefore only be carried out when a general idea is needed.

All these factors make the study setting the most important and determining moment for the final outcome. One of the most delicate steps in setting up the study is the definition of the functional unit, with respect to which the reference flow is determined, which will then be the object of the life cycle analysis. The functional unit consists of the quantity of product necessary to guarantee a certain performance which is identified as characterizing the type of product taken into consideration. The functional unit is the common unit of measurement that allows the comparison between products; to this all the inventory data must be reported: it is therefore transformed into the "reference flow" which is again expressed in weight/quantity of the material. The functional unit is therefore the measure of the performance that the system ensures. In the preliminary phase also, the categories of data associated with the processes must be defined and hypotheses and assumptions must be formulated regarding data that are taken into consideration.

1.4 Inventory

The "inventory" phase (Life Cycle Inventory) is the essence of the LCA study. The ISO 14041 standard defines the inventory as an activity to quantify the flows in and out of the system boundaries defined in the objectives.

During the setting, an accurate description of the entire life cycle of a product must be made, which is basically based on the description of a series of "processes", i.e. activities, procedures, processes that affect the product. It is translated into an analogue model of the real system that we intend to analyse. This scheme, called "flow chart", allows a qualitative and quantitative description of the process units. The ISO 14040 standard introduces the concept of "product system" to indicate "*collection of materially and energetically connected unit processes which performs one or more defined functions*".

To analyse the life cycle of a product, it is common to start from the production phase, then extending the analysis upstream and downstream of the production process, thus considering the extraction phase of the raw material, the transport from the extraction site to the production site, transport from the production site to the construction site, construction and use phase, disposal or recycling of materials. In the case of analysis of the life cycle of a building it is necessary to start from the analysis of the materials and components that make up the building, and then go back upstream to the production phases of the components.

The process flowchart is essential for the collection of inventory data, i.e. flows in and out of each process. The next step consists in the analysis of processes and in the identification and quantification of the flows expressed in terms of consumption of resources and of energy and emissions in the environment and in the creation of an inventory of input and output in relation to all the processes of the different phases of the life cycle. This means collecting quantitative data related to each process, measuring inputs and outputs. Incoming flows can be raw materials, energy, water. The outgoing flows are first and foremost the object of the analysis, the solid waste and the polluting emissions in air and water.

During data collection it is good to specify some information regarding the data collection procedure. The quality of data depends on their age, the reference source, the calculation method to obtain the mean values, variance and irregularities found in the measurements. Data used in accounting can be:

- Primary data (direct surveys);
- Secondary data (from literature, databases or other studies).

Due to the difficulty in obtaining primary data (data from a specific factory), databases are often used. Databases available at international level are based on processes developed in different locations (different energy mixes and different technologies): it is therefore important, for the reliability of the study, trying to have primary data available. If this is not possible, it should be indicated that data are secondary or tertiary and above all the geographical area to which data belongs. With respect to the data, it must be defined:

- Period;
- Geography;
- Technology;
- Representation;
- Multiple output allocation.

It is important to stress the need to pay attention to the provenance and therefore reliability of data used in the evaluation. There are databases, created through statistical sampling, which were made by specific countries; the available databases therefore contain data on the country of origin. The first operation to be performed when selecting a database is to take into account that its validity is linked to the context in which data were collected; above all, it affects an energy mix.

Once all data have been collected, it is possible to draw up the inventory: data are organized in a table in order of substances. The inventory is organized in:

- Energy and consumption of resources: renewable and non-renewable primary energy (MJ), renewable and non-renewable feedstock, electricity (counted separately based on the national energy mix);
- Raw materials consumption: non-renewable fuel resources (coal, natural gas, fuel oil), renewable fuel resources (biomass), renewable resources (raw materials), non-renewable resources (raw materials), recycled resources (secondary raw materials), consumption of water, consumption of soil;
- Air emissions: CO_2 (carbon dioxide), CO (carbon monoxide), CH4 (methane), SOX (sulphur oxide), NOX (nitric oxide), HCl (hydrochloric acid), HF (hydrogen fluoride), NH3 (ammonia), HCFC (hydrochlorofluorocarbons), halogenated hydrocarbons, PAH (polycyclic aromatic hydrocarbons), VOC (volatile organic compounds), NMVOC (non-methanogenic VOCs), particulate matter (PM10), Hg (mercury), phenol, CH2O (formaldehyde), As (arsenic), Pb (lead), N2O (nitric oxide), H2S (hydrogen sulphide), hydrocarbons;
- Emissions in water: suspended solid elements, BOD (biochemical oxygen demand), COD (chemical oxygen demand), N (nitrogen);
- Solid waste: dangerous, not dangerous.
- A critical aspect of the inventory phase is the correct distribution of consumption and impacts related to different products generated by a common production process. This distribution is called "allocation" of data: this step consists in sharing emissions and energy consumption with respect to the specific product that is being considered. Normally, in fact, one plant has more production lines, but for example the emissions are conveyed all in a single chimney and energy consumption is known as the overall company: defining consumption and emissions

of the single product requires careful study of the structure of the production process.

The allocation of data can be done according to three criteria:

- Allocation based on weight (data are assigned according to the weight of the co-products);
- Allocation based on the economic value (the allocation of data is based on the economic value of each product);
- Allocation based on the importance (the allocation of data is based on several factors, such as quality, cost and strategic relevance of the product).
- The most correct and reliable allocation system is based on weight, since the others are subject to excessive variability. During the data collection, a series of additional information on the analysed system becomes available, which could lead to modify some initial assumptions (for example to modify the system boundaries) in order to better realize the boundaries of the study.

The inventory phase is the most expensive and takes a long time to collect detailed and timely data: the greater the degree of analysis, the more detailed the LCA evaluation will be. The degree of detail with which inventory data is collected depends on the objectives of the study. Can be made "simplified" LCA assessments using data from the database and therefore "avoiding" data collection operations but focusing only on the definition of the flow diagram. In the case of a study dedicated to a specific product of a specific company, with the aim of environmental improvement of production processes or with the aim of accessing an environmental product certification (EPD), it must necessarily be "detailed" and related to the specific reality, operating a collection of primary data.

The collection of primary data is a complex operation, made even more difficult by the distrust of companies, which are not always willing to disseminate and publicize the information concerning them. For this reason, it is important that the development of detailed LCA takes place by request of the company itself. To encourage companies to carry out this type of operation, policies aimed at promoting eco-labelling, whether product (EPD) or factory (EMAS), are fundamental.

1.5 Life Cycle Impact Assessment

Data collected in the inventory are subsequently processed with the aim of making the results obtained in the previous phases legible, by visualizing the potential environmental impacts. Evaluation is a technical-quantitative process to calculate the effects of the substances identified in the inventory. The ISO 14042 standard describes how to set the assessment of the impacts associated with the flows identified in the inventory, based on the "category indicators", i.e. the parameters representative of the impacts related to resource consumption (input flows) and emissions (output flows).

The assessment of environmental impacts aims to highlight the extent of the changes generated by consumption and emissions calculated in the inventory. Environmental impact means the impact of a substance on the environment or on humans. With this passage we move from the objective data calculated in the inventory to the "judgment" of environmental hazard and potential damage.

The passage of the impact assessment, necessary to make the inventory data easily readable, represents the passage from purely quantitative (and therefore objective) data to "manipulated" data based on the type of reading that this data need to give. The first step is to choose the method of environmental assessment: in fact, there are different methods for assessing impacts, which allow to visualize different types of environmental repercussions. The choice of method can already highlight certain characteristics of environmental behaviour, and therefore "orient" the evaluation.

On the basis of the chosen method, the categories of environmental impact are selected, or classes of environmental effect (global warming, acidification, energy consumption, water consumption, etc.); then inventory data are sorted and aggregated, i.e. consumption and emissions, within each impact category chosen ("classification"). After it is possible to proceed to the "characterization", to quantify the impacts based on conversion factors established by an Authority.

The values obtained, absolute, can be insignificant, so it is possible to make a further, optional step, which is called "normalization" and consists in dividing the score of each environmental effect by the relative normal effect. Of course, the "environmental issues" displayed are the most difficult to compare, since it often happens that a product that is better than an impact indicator is worse than another indicator. This difficulty is often overcome by trying, by means of a weighing procedure (which determines the importance of individual environmental effects), to summarize the impacts in a single indicator (eco-point).

Impacts can be also grouped according to the scale of influence (Table 3).

Scale	*Effect*
Global	Greenhouse effect
	Thinning of the ozone layer
	Consumption of non-renewable resources
Regional	Acidification
	Eutrophication
	Photochemical smog formation
	Chronic toxicity
Local	Acute toxicity
	Degradation of the area
	Physical disorders

Table 3: Environmental impact classification according to the scale of influence

The weighing alters the results considerably, so it is necessary to be transparent on the weighing system used. This operation is the most delicate, because it risks becoming a tool for the manipulation of results.

1.6 Life Cycle Interpretation

Considering the above, the LCA scheme used up to now, can be replaced by the more exhaustive structure (Fig. 2):

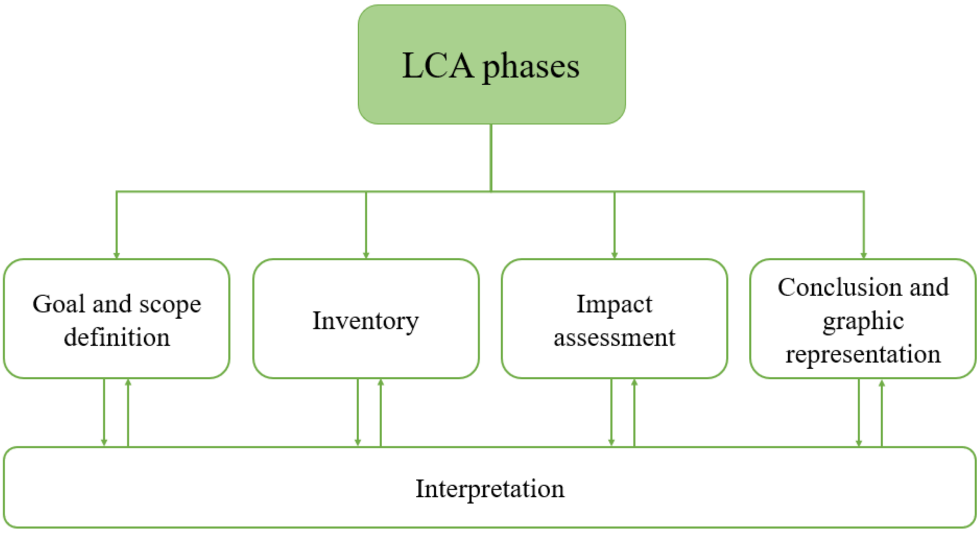

Figure 2: Interpretation process according to ISO 14040:2006

The results of the LCA evaluation must be interpreted in order to be able to draw conclusions and give indications of improvement. The ISO 14043 standard describes how to set the interpretation of the results. A strong criticism stems from the fact that interpretations of results, conclusions drawn and suggestions for improvement are often subjective.

The Life Cycle Assessment aims to improve the environmental quality of products through:

- Optimization of energy balances;
- Reduction of resource consumption;
- The reduction of polluting emissions;
- The reduction of the environmental load of waste.

Eco-design, or "environmental planning", is concerned with integrating the environmental factor into the product design and development addresses. The design strategies that give generic guidelines are not enough to guide project decisions: scientific data to support decisions and especially quantitative data are also needed.
The interpretation of the LCA evaluation, if used for comparative purposes between alternative products, is not simple since a product or an activity can have a reduced environmental load compared to some impact indicators and a high environmental load compared to other indicators of environmental impact. In the comparison of alternatives this can make it difficult to identify a better solution from an environmental point of view and therefore make the choice ambiguous. Moreover, the result of the evaluation must remain open to different reading possibilities and the value of the evaluation is precisely in the wealth of information it provides. Another open question is how to establish the "levels" of sustainability; in an absolute sense it is necessary to define the load capacity of the environment and to attribute a threshold of consumption and pollution admissible, with which comparing it at the time of construction, setting limits to the environmental load of the entire building.

It should be kept in mind that the assessment of environmental impacts as a tool to support decisions must be supplemented by an economic evaluation. The Life Cycle Assessment should therefore be accompanied by the Life Cycle Costing (LCC), that is the economic evaluation along the life cycle that allows to highlight the costs, in a global vision, of the entire life cycle.

1.7 Life Cycle Sustainable Assessment

A further step is to implement the LCA with economic (LCC) and social evaluation. The idea is therefore to be able to obtain a method of measurement of the total effective "sustainability" of a building project.

1.8 Environmental information tools

In the current proliferation of sustainability assessment criteria, the risk of confusion and circulation of non-scientifically proven information is high.

The need for product certification tools is expressed by different operators:

- Public Administrations need tools for Green Public Procurement, to introduce indications within building regulations, to insert environmental criteria in public tenders;
- Designers need tools to guide their choices based on the environmental performance of products and information media for product selection;
- Manufacturing companies need to effectively communicate their environmental policies to the market and to promote environmentally innovative products.

In order to convey environmental product information, environmental certification tools are required to certify compliance with certain environmental characteristics, defined differently by the different types of existing ecological labelling. The certification can have two types of user: it can convey environmental information from the producer to the consumer (*business to consumer*, B2C) or it can convey environmental information among the operators (*business to business*, B2B), for example from the producer to a professional (designer) or from one producer to another along the production chain. The type of suitable ecological labelling changes according to the use and the final recipient: the communication addressed to the final consumer must be direct and simple, so the brands are more effective, while the communication between operators must be of a technical nature and contains detailed information, for which environmental statements are more appropriate.

It is necessary in this sense to specify that in the building sector the purchases of construction products take place by operators (designers and construction

companies) and almost never by end users, so the type of communication suitable for the building sector is a technical information conveyed from environmental statements rather than an environmental brand affixed to products. Also, because the building product must then merge, through further processing, into the real finished product of the building sector, which is the building.
Talking about certifications, it is first of all necessary to distinguish between mandatory certifications, which are prescribed in regulations (for example the CE marking imposed by the construction products Directive) and which mainly concern safety and health aspects, and voluntary certifications (for example the Ecolabel or the EPD), which have the aim of highlighting levels of quality superior to those that simply comply with the regulatory requirements, for reasons of competitiveness on the market. The European Union stimulates the diffusion of voluntary ecological labels, disconnected from the logic of command and control, since they are more effective in encouraging the subjects involved to continuously improve the environmental performance of products.

The criteria for a correct environmental information are the credibility, which depends on the source, the objectivity, which depends on the tool used to perform the evaluation, the comparability, which depends on how the information is communicated, the univocity, which can be obtained by adhering to a national or international convention.

The standards of the ISO 14000 series give indications on a set of tools that can be applied at different levels, which allow to obtain environmental information that have the requisites that were sought before: credibility (in the case of third party verification), uniqueness (the ISO standard), objectivity (the life cycle analysis method, LCA) and comparability (labelling as an "information writing" system). There are synergies between the assessment and certification tools indicated by ISO 14000. Many information obtained from environmental audit (EMAS) can be useful for assessing the life cycle of products (LCA) and then, through a report, become commercial information of the product in the form of an environmental statement (EPD).

The implementation of these tools allows the company to pursue the objective of adapting to an environmental management system. This complex framework of tools should stimulate companies to compete in environmental matters and thus lead to the introduction of environmental innovations.

1.9 Ecological labelling

ISO 14020 establishes guidelines and principles for the development and application of voluntary environmental labels and declarations and defines three types of environmental labels:

- Type I environmental labels (IS0 14024) are based on a series of environmental criteria identified as relevant by an independent body, which also deals with the verification and certification issue. This label consists of a trademark to be affixed to products, which is only issued to products that exceed certain minimum requirements (threshold values). The Competent Body for the award of the trademark can be either a public body or a private organization. An example of type I labelling is the European Ecolabel;
- Type II environmental labels (ISO 14021) are environmental information based on self-declaration by the manufacturer. For them there is no certification of an independent body, nor a minimum threshold of acceptability. The manufacturer limits himself to declaring the environmental aspects of his own products that he considers useful to highlight. Among the numerous examples, the best known is the self-declaration of the percentage of recycled material (the "Mobius Cycle");
- Type III environmental labels (IS0 14025) provide quantitative data on the environmental profile of a product calculated according to the LCA procedures as codified by the body of ISO 14040 standards. For this type of labelling the verification of an independent body is necessary, but a minimum acceptability threshold is not required. Environmental

communication takes place through a document, the Environmental Product Declaration (EPD), which contains quantitative technical data related to the potential environmental impacts associated with the product life cycle. These impacts must be assessed in accordance with the Product Specifications and presented in a form that facilitates the comparison between products belonging to the same group or category, through the standardization of certain parameters.

In the building sector, apart from Type II labels (self-declarations) that have a low degree of reliability, the Ecolabel was firstly affirmed. But the work to define the requirements of the building product categories has stopped; it is in fact understood that the most effective instrument in the building sector is the Environmental Product Declaration, since it conveys a technical information on the environmental performance useful in the design phase.

1.9.1 Ecolabel

One of the first labelling tools spread nationwide in a spontaneous way was type I labelling, the Ecolabel. The German Ecolabel system, the Blue Angel (Der Blaue Engel), and the Scandinavian Ecolabel system, the White Swan (MiljérMrkt), were created to meet the buyers' need to identify the products with the least impact on the environment and producers to demonstrate the environmental impacts of their products in a credible and scientifically recognized manner.

Before examining the products and assigning the label, the product group must be defined, and a set of shared environmental criteria must be identified, overtime modelled in different ways according to the product category and therefore the performance characteristics’ use.

In 1993 the European Union, in the context of the activities of the Fifth Action Program, in order to harmonize the spontaneously born procedures within the various nations and to build a single reference system for the European market, introduced the European Ecolabel with an eco-label of European recognition. This did not actually delete the national brands.

In Europe, different types of Ecolabel developed at national level also concern building products. For example, the German Ecolabel system has defined the requirements for the certification of wood panels. Hard coatings for floors, varnishes and paints can be certified in the European Eco-label; all products aimed at final consumers. Other type I labelling systems were born in a widespread manner, promoted by some public and private organizations. Only a few products have been certified and therefore this tool does not constitute an adequate information base to be a firm reference when making design decisions.

The development of European Ecolabel criteria related to other categories of building products (for example insulating materials) has stalled because at European level it is understood that the Ecolabel is not a type of labelling appropriate to the building sector: it is a brand addressed to the final user (B2C), while in the building sector products are marketed among operators (B2B). Generally, the purchaser is the construction company or the designer, and therefore the transfer of more detailed technical information, conveyed by type III labelling (EPD), is required.

1.10 Environmental Product Declaration

The Environmental Product Declaration (EPD) is a technical document that arises from the manufacturer's will and, following a verification process of content by a certification body, accompanies the marketing of the product. The evaluation method is the Life Cycle Assessment, but it does not fall into the criticality of a generic LCA, since the EPD system guarantees an objective, verifiable and comparable procedure.

In order to make data contained in the environmental declaration comparable, common parameters must be defined for each product category: the "Product Specific Requirements" (PSR), renamed "Product Category Rules" (PCR), describes in a harmonized way for product or service categories, which are the data to be collected for the realization of the LCA, the method, the calculations and the results to be presented. The criteria are defined in a shared manner and are used to make EPDs comparable.

The EPD can be accessed by all products: there are no thresholds, as for the type I eco-labels, but it is simply the declaration of the impacts that the product generates throughout the life cycle. This system has the advantage of becoming a veritable vehicle of competition on the theme of environment between producers. Moreover, the fact that there is no "minimum threshold" to be reached, stimulates a continuous improvement of the products. The stimulus derives from the "comparability" of data, thanks to the uniformity of the procedures and the parameters adopted, so that the buyer can choose on the basis of precise information.

The environmental product declaration thus becomes an important tool also in the relationships between producers, especially in a field, such as the building one, in which the components and construction systems are often the result of the assembly of elements of different production origins and in which the traceability of the product tends to become difficult. In fact, a product can be considered a material, a component, a finished product or a processing. The EPD of a finished product is obtained by combining the EPD results of all materials, components and intermediate machining. The EPD must contain primary data related to a specific factory, so that, to certify a finished product, it is necessary to reconstruct the primary data of the supply chain. The EPD certification, as well as EMAS and ISO 14000, implies for producers the need to have a well-traced picture also of sub-suppliers and sub-contractors and can be an effective tool to stimulate all the operators in the production chain.

1.10.1 EPD: strengths and weaknesses

At this point it should be stressed that in the building sector the certification of building products is not sufficient to guarantee the eco-compatibility of the building product as a whole. To evaluate the eco-compatibility of products, the use of products must be contextualised: there is no more "ecological" material than another tout court, but it is only from the analysis of its application and its methods of use that can be determined the environmental characteristics of the building product. The assessment levels of eco-compatibility move from the material to the component and from the component to the building and it is not possible to disregard the comparison between these three levels. The assessment of the component can not be carried out without the knowledge of the materials and the evaluation of the building can not be carried out without the knowledge of the component. Therefore, in the building sector there is a double level of evaluation: on the scale of the component and on the scale of the building. The role of the EPD certification is therefore to support the building LCA evaluation. Finding environmental information is difficult and the construction of databases is one of the major problems of LCA, due on the one hand to the effort to gather the necessary information and on the other to the fact that data vary from region to region, because they depend on the production conditions and from the constructive methodologies, for which it is necessary to build databases at least nationally, but very often even at the regional level. Moreover, the fundamental doubt remains on the reliability of the information collected, often provided by the producers themselves, but not very formalized and based on statistical sampling whose methods of detection are not known. The collection of information is an operation that involves time and costs. Another problem is that even once a database has been built with enormous commitment, it must be continually updated to maintain its efficiency.

The difficulty of building a database through a detection operation, the impossibility of attributing the variety of building products on the market to product types whose environmental behaviour can be homologated and collectable in a statistical manner, the need for a continuous updating of data highlights the opportunity to transmit environmental data through the environmental certification tool, so that the information contained in it goes to implement a constantly updated database on building products.

An effective environmental certification system of products, based on EPD, could ensure that environmental information of product certifications can be used to build a database of building components. In this way data on building products would be more reliable, as the producer is a primary source and certification also guarantees data control. The database could in this way be automatically implemented and updated for producers' interest in providing updated information.

Unfortunately, there is a widespread tendency to try to define ecological materials in a sort of specific abacus to draw on for the construction of ecological buildings. This operation was carried out by various environmental assessment tools of buildings, including the Itaca Protocol, which, for example, recommended "*the use of insulators made of renewable or recyclable raw materials such as wood fiber, cork, cellulose fiber, linen, sheep's wool, wood-cement*» (although cement is not a renewable resource),«*the use of materials from renewable sources*». At this point it is necessary to understand what the criteria are to define if a material is ecological or not; but also, whether it is enough to adopt ecological materials within the project in order to define the whole building as ecological. In short, the hope is that, although it is necessary to bring the theme of the environment within the rules of the market, the theme of the environment does not become just another business tool, more "communicated" than "acted".

It is necessary to be aware that determining the ecological nature of materials and products is still a controversial and debated topic. Perhaps it is the still unresolved issue of environmental design. Even arguments such as the naturalness of products or the recyclability of materials is still the subject of contradictions. Furthermore, the durability and performance decay over time of natural and recycled products (but also non-recycled materials) is still not well documented. The non-toxicity of recycled products remains often little investigated, since these are new products whose material composition is "indefinite" (result of the aggregation of materials of different origins).

And so, some currents of thought support natural materials, such as wood and biofuels, without taking into consideration that these resources also determine impacts in terms of land consumption, water consumption, use of fertilizers, pesticides and herbicides. Not to mention the renewal times of these resources, which often exceed 10 years, and not to mention that the spread of monocultures attacks biodiversity (often certified forests are wooded areas "cultivated" with a single tree essence, a phenomenon that it does not happen in nature).

In conclusion, it should be carefully considered the projection of one material over another, one product over another, one constructive system over another, one technology over another. Above all, it appears unseemly to make comparisons out of a geographic context and without knowing the building within which the component is used.

1.11 Application of the LCA method in the building sector and its limits

The main objective of the application of the LCA method in the construction sector is to provide environmental information to support project choices, through an integral assessment of consumptions and of the pollutant emissions deriving, at the building level, from the choice of certain materials and building components, certain technical-constructive solutions and certain installation solutions. The LCA method is born in the industrial field, for the evaluation of industrial products, and the specificities of the building sector make the application of this tool in the construction sector very complex.

For example, a peculiar aspect of the building sector is the fact that the building product that leaves the factory does not constitute the final product, but only a component that must be integrated into the building system. Although a building may consist of prefabricated components (whose production can therefore be monitored at the factory), many "productive" operations take place on site, in places difficult to monitor and with semi-artisanal processing difficult to control, thus escaping from the environmental detection and implementation of the inventory (and especially the verification of the final "quality" of the system). Both the construction and the demolition phases contain processes that have an impact, but little control, which therefore tend to be omitted.

Furthermore, the building is not only a complex product, but above all it can not be replicated: although building products can always be the same, every building is different, depending on the geographical location, climate, the specifics of the site, the needs of project, methods of use, etc. This also determines a difficulty in assessing the role of the building components employed in the use phase.

Consequently, assuming to be able to collect reliable data relating to the production phase over time (the factory is a closed system that can be easily monitored), the environmental profiles of building products are not sufficient to make a complete and reliable assessment of the building. The sum of the impacts of the individual products may not correspond to the impacts of the assembled building system, especially if it is a building built on site. Furthermore, it is difficult to estimate the environmental impacts of the building use phase (energy management, maintenance, adjustments), depending on and varying according to the choices of the specific project. The assessment of the impacts along the life cycle of the individual components (which are considered in a certain sense as autonomous with respect to the building) and the assessment of the impacts throughout the life cycle of the entire building (where the individual components are an integral part) are two levels of analysis, distinct, but related. The responsibilities with respect to these two levels fall on different operators: manufacturers are responsible for the life cycle of building components (and any product certification), the designers and builders are responsible for the building system as a whole (and the eventually building certification). When designing materials and components, the interrelations of the component must be highlighted with respect to the building system and not only the environmental profile of the individual component, but also the environmental behaviour of the building system, before being able to express an opinion on eco-compatibility of a product and a technical solution. It follows that there are no materials, components, eco-compatible construction techniques in the absolute sense, but the eco-compatibility depends on the specific application and use: in fact, to make a life cycle assessment of a product it is necessary to know its use phase and the role of the component inside the building.

It should also be stressed that the LCA method, which is exhaustive in the analysis of the production process of building products, is less complete, on the other hand, if it is used as an environmental assessment tool for the entire building. The LCA method has very rigid boundaries, takes into consideration only some aspects and not the complexity of the themes that affect the design of buildings and concerns the objects that make up the building. For example, the LCA method does not include all those "macro-environmental" verifications that concern the correct relationship between the building and the context, the environmental quality of the settlement, the proximity to services, the permeability of soils, the use of materials to avoid the formation of heat islands, and so on. In this sense, the scoring tools are more complex and take into consideration qualitative aspects that are neglected in an LCA evaluation. The LCA method deals with the flows of material and energy: it is a method that quantifies the impact on the environment deriving from human activities and is linked to this informative contribution that must be used, without presumptions for the absolutization of results on design decisions. In fact, it is necessary to reconcile the control of environmental impacts with other aspects governed by the project. Being a quantitative method, it is an objective method, its strong point is also its weak point: it takes into consideration only the quantifiable elements, excluding all the qualitative aspects.

With respect to the limited field of investigation it is reliable, measurable and objectively determined and since the overall objective is the assessment of environmental sustainability, the LCA method highlights and quantifies the withdrawal and emission flows and therefore the actual environmental damage. The verification of the qualitative aspects of the project does not compete with the LCA method, which aims to evaluate a project with defined performances, quantifying the environmental impacts. The method in fact evaluates alternatives whose "performance parity" is defined. The environmental comparison is therefore based on the setting of this comparison, i.e. in the definition of performance: if a comparison is required with the same thermal resistance, it will be difficult even with the same thermal capacity and with the same sound resistance, etc. Moreover, even in the design choice the optimization of the technical solutions with respect to the different performances takes place as a "groping" procedure, made of adjustments and continuous compromises. The environmental assessment becomes a further aspect of performance verification.

The LCA method takes care of the entire life cycle, introducing an important variable in the building sector: the time. Many environmental assessments consider the environmental impacts of individual phases (for example the assessment of energy consumption in the use phase of the building), while the LCA method considers the environmental loads in a global scale extended to all the phases of the life cycle (essential issue in the construction sector, since buildings are durable goods over time).

Another interesting aspect is that, dealing with the "objects" of the construction, it also involves the operators upstream and downstream of the building process, determining various levels of responsibility that do not only concern the designer who makes design choices. In particular, the evaluation shifts the attention from the designer's choices to the possibilities and abilities of the producers of elements and building components. The latter manage a good share of the environmental impacts of the construction sector, not only in relation to the production phase, but also in relation to their ability to realize high performance products in use, durable and maintainable, their involvement is also extended to the phase of disposal and recycling, through their direct responsibility, in this way it is no longer just about designing eco-compatible buildings, but triggers a virtuous circle along all the building process.

1.11.1 The methodological approach in the building sector

The LCA method represents a multidisciplinary technical approach to environmental problems, the results of which are linked to the ability of analysts to break down, identify and measure the significant phases of the processes. These skills are acquired over years of experience and above all thanks to an effective multidisciplinary contribution in the course of the study. It often happens that LCA assessments relating to construction are carried out by environmental analysts, experts in the LCA method and physical and chemical phenomena specialists, but unaware of the specificities of the building sector (which is also a particularly complex sector for the variety of objects, phases, processes, operators that can be involved in the analysis). It also happens that LCA assessments relating to the construction sector are carried out by construction engineers, architects and designers, certainly experts in their field, but often lacking in terms of technical-disciplinary skills (in the physical, chemical, biological, environmental) that enter at stake in an LCA assessment. It would be also necessary (which, moreover, happens very rarely) that the LCA studies in the building sector envisaged a multidisciplinary participation of environmental analysts, expert in the LCA methodology and experienced operators of the specificities of the building sector. Multi-disciplinarity is particularly useful especially in the phases of defining the objectives of the study. Environmental analysts tend to identify "objects" of study, then products (materials, semi-finished products, buildings), while the usefulness of applying the LCA method in construction can find other levels of interest (construction systems, processes, services), hardly identifiable for those not in the sector. In particular, one of the interesting and valuable aspects of the method is the performance approach, which allows to reason on the role of technical-constructive choices in relation to the expected performance of the building and to find radically "alternative" solutions, not necessarily materials, the provision of a service or a service, thanks to project "ideas". By exploiting this feature, the LCA evaluation can become a real tool to support the design phase and to stimulate real environmental improvement.

1.11.2 LCA goals in the building sector

The LCA evaluation must be set starting from the definition of the objectives and purposes of the analysis. The purposes of the study greatly influence the initial choices and assumptions during the course. In particular, it is important to define who the evaluation is intended for and what the purpose of the evaluation is. In the construction sector, the possible recipients are manufacturers, builders, public administrations (as regulators and verifiers), designers, clients.

The multiplicity of possible subjects to which an LCA evaluation can be directed also derives a multiplicity of objectives, and consequently of possible levels of study. For example:

- LCA assessments can be aimed at producers and builders and have the objective of improving the environmental profile of a product or of a productive/constructive process or of technical-constructive procedures or be aimed at identifying which phases of the process are particularly impacting and on which aspects can be taken to reduce total energy and environmental loads;
- LCA assessments can be aimed at manufacturers and designers, and have the objective of communication and technical information (through environmental labelling), and therefore have the objective of promoting "green purchasing";
- LCA assessments can be aimed at Public Administrations, and have the objective of supporting institutional decisions and defining mandatory regulations (promoting, for example, environmental certifications for access to incentives or compliance with environmental criteria, based on LCA indicators, included in local regulations);
- LCA assessments can be aimed at designers and have the objective of supporting environmental design (eco-design), providing technical data on environmental performance to be used both in a comparative way between product alternatives, construction system, implementation methods, both to optimize a specific technical solution or service.

Depending on the recipients and the objectives of the assessment, the degree of depth changes and the types of data needed (primary or secondary) vary.

1.11.3 The functional unit and the weight

In setting up the study, once the objectives and the object of the analysis have been defined, the unit of measurement of the study must be defined, with respect to which data are gathered and the final results to be presented. Collecting the activated flows for the realization of a product, it is necessary to define what is the quantity of product that is being analysed. To define this unit of measurement ("reference flow") the performance expected from the product, i.e. the functional unit, must be defined. If the function of a product is the painting of a wall, the functional unit will be the m^2 of wall protected by paint and not the kilos of paint. The reference flow is the quantity of product needed to satisfy the performance: for example, if you need 1 kg of paint to paint a m^2 of wall, the quantity 1 kg is the reference flow of the LCA evaluation. The reference flow is the quantity of material that is being analysed, to which the consumption of raw materials, the energy spent for production, for transport, etc. can be associated.

Matching the quantity of material with an activity performed is particularly important when the objective of the evaluation is of a comparative nature. For example, setting up a comparative assessment between different insulation materials, the expected thermal insulation performance is achieved with a different amount of product, depending on the thermal conductivity (and density) of the different materials. Therefore, the comparison of environmental impacts should not take place at the same weight, but for the same performance. For this reason, it is appropriate to set up the study starting from the expected performance of the product, which is precisely the functional unit of reference for the entire study. "*Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis. It is important to determine the reference flow in each product system, in order to fulfil* *the intended function, i.e. the amount of products needed to fulfil the function.*" (UNI EN ISO 14040). The performance must therefore be identified by assuming the service deemed significant for the comparison.

For example, if different types of insulating material are compared, such as expanded polystyrene (EPS) and wood fibre, in the first case it might seem that polystyrene is a material with a high environmental impact, as chemical synthesis material, while wood fibre is a material with a low environmental impact because of natural origin. However, when the comparison is established in an LCA evaluation, defining an example of a building component, and therefore of application, the relationships between materials change considerably, depending on the fact that the materials are light or heavy. Comparisons between kg of EPS and kg of wood fibre can not be made, as the functional unit must first be defined. For example, the performance to compare two insulating materials can be thermal resistance: at this point it is necessary to define the thickness (in relation to the thermal conductivity) and the quantity of material in terms of weight (in relation to density) that are necessary to perform to the expected performance.

Compared to this example, it must also be said that when comparative assessments are made, it is essential to take into account the fact that the materials perform at the same time, so if we set the functional unit differently, the environmental result changes further. For example, if the performance considered to define the functional unit becomes thermal capacity, EPS would be disadvantaged compared to the wood fibre, since being a low-density material is also a material without thermal capacity; consequently the EPS must be combined with another capacitive material to guarantee both the thermal insulation performance and the thermal capacity performance, while the wood fibre performs both the thermal insulation performance and the thermal capacity performance.

In case of the evaluation of an intermediate product or a processing, whose final use is not yet known and for which the EPD contains only one LCA from the cradle to the gate and the end-of-life scenarios, the functional unit is replaced with the declared unit (declared unit). In this case the reference quantity may in general be a unit of weight (kg) or a unit of volume (m^3): for example, the incorporated energy can be expressed in MJ/kg or MJ/m^3. Very often, the EPDs of building products use the declared unit as a reference, specifying the product performances. This choice demonstrates the difficulty of setting an environmental assessment by selecting a "significant" performance without knowing the characteristics of the building in which the product will be used and therefore to which requirements the product will have to respond.

1.11.4 The boundaries of the system in the building sector

In the building sector there are various systems that can be considered, in relation to the objectives of the study. The object of the study can be the material, the product, the component, the technical-constructive solution, the building, the building process. It can also be a service: the heat supply service, the tourist-hotel service, the housing service etc. on the basis of the type of object to be analysed, it is necessary to identify the set of processes that are activated during the entire life cycle: this set of processes is the "system".

Once defined the "system" object of the study and the "reference flow" to be analysed, it is necessary to specify the "system boundaries" to be analysed. The "system" is the set of operations aimed at providing a specific function: this set of processes is considered bounded with respect to the "environmental system", with which it has exchanges in terms of input and output. Isolating and delimiting the "system" of the processes of an anthropic nature from the "system" of the natural environment is fundamental in order to detect flows entering and exiting the artificial "system", in order to draw up the inventory of withdrawals and emissions and to quantify the environmental impacts produced by man on nature.

To trace the boundaries, it is necessary to proceed to the description of the "system" by constructing a flow chart that describes the processes and sets the data collection.

For example, it is necessary to establish, in the construction of the production chain, which processes to take into consideration, with what level of detail it is possible to trace all the suppliers of semi-finished products and whether to acquire primary data for all processes.
If the systems are closed, like the factory, it is easier to monitor inputs and outputs. However, there are open systems, such as the construction and demolition site, but also the building during the entire life cycle, which are difficult to monitor and with respect to which it is difficult to realize a flowchart of the processes involved. The first approach to the flowchart and the boundaries of the system is actually reviewed several times during the study, as the relationships between the processes, their mutual role and importance are clarified for the purposes of the final evaluation, for which it is possible to decide to exclude processes that are not very important but burdensome to be censused and, instead, to investigate processes that have been omitted and that have a significant role. Obviously, the degree of detail with which the flowchart and the process chain are constructed depends on the type of LCA evaluation to be obtained, whether detailed or simplified.

Often, the problem is that the comparison is with evaluations that do not clearly specify the boundaries of the system or that data on available energy or potential acidification on the flow chart analysed are not precisely known. This is especially true when using data from databases, in which it is difficult to understand whether all processes have been taken into account or if some have been overlooked. Often it is not perfectly clear even if it is an eco-profile or an eco-balance.

It should also be said that in the building industry it is quite easy to find data on eco-balances and eco-profiles, but it is absolutely difficult to find data compared to other life-cycle stages. This makes it very difficult to carry out a "complete" evaluation and above all it is difficult to carry out an LCA building evaluation. Almost all assessments contain simplifications and limitations, to make the evaluation itself manageable. It is a matter of correctly delimiting the boundaries in relation to the objectives of the evaluation. This boundary work is referred to as the scope of the study and contains all the preliminary set-up assumptions.

1.11.5 The role of duration

Having to make an overall balance, and therefore count both energy and impacts caused by the production and construction of the building, and energy and impacts generated during the use phase of the building, it is necessary to define the duration to be considered in the evaluation of the use phase. The choice generally made is to estimate a scenario of 80-100 years, which is the expected duration of the building. But this duration does not coincide with the duration of the materials that make up the building, which in some cases are subject to a rather rapid performance decay over time and the need for maintenance and replacement (which must be computed as additional energy incorporated and impacts associated). It would then be necessary to assume the life cycle of products (a more reasonable life span from the point of view of quantification of primary energy spent in use, given that we do not know the evolution of energy plants and vectors that will characterize the next century), but at this point the problem concerns the definition of the durations of the materials, with respect to which very little scientific information is available. In particular, almost nothing exists with respect to the duration of the materials, also because most of the materials currently on the market are quite "recent" and therefore there is no history in this regard. But yet, from the environmental point of view, the parameter that affects most, since it can significantly change the final evaluation is that of durability: durable materials dilute the impacts caused to produce them over time. In fact, one way to take into account the duration as a rewarding factor is to "normalize" the impacts with respect to the expected years of life and then calculate the impacts/year.

To compare the energy consumption of production and of the use phase, a normalization can be made by dividing the impact indicators by the amount of time in which the product will be used and for the square meters of internal usable area, in this way can be made available an indicator that can be compared to the annual impacts during use, expressed with the same unit of measurement.

On the one hand, the importance of using durable products is emphasized, on the other it highlights the importance of the relationship between the durability of the building and the durability of the components: talking about a temporary building it is "useless" to do reference to durable products that have a high incorporated energy, while it is appropriate to select components with reduced energy incorporated. On the other hand, if we assume a long life of the building, it is advisable to choose durable products and avoid products that require maintenance and replacements over time. It should be stressed that the maintenance and replacement interventions must be counted in the built-in energy and therefore a building subject to continuous maintenance will increase its incorporated energy over time.

The duration is not always synonymous with sustainability. The replacement of products generated by the environmental improvement of new products is a dilemma from an environmental point of view. The paths of technological innovation on the one hand introduce better technologies from the environmental point of view, on the other they encourage a quick replacement of the existing, reducing the durations of the products (including buildings). Reasoning on durations is therefore an important step, essential but complex, for the multiple implications that it takes in the building sector. At the same time, it is an aspect that is still highly neglected in the LCA environmental assessments, where too often, scenarios of useful life of the building are assumed without any reflection on the service life of the materials in use.

1.11.6 Processing tools

Given the large amount of data contained in the inventory, data processing can be complex. For this reason, data processing software are available to facilitate the operations of collecting inventory data and assessing environmental impacts. Especially in the design of buildings, this software is an important reference, as they allow an approach even to non-experts, and therefore the possibility of processing data from the database to obtain information to support the project.

1.11.7 Databases

The choice of the type of data is fundamental for an LCA study. Based on the type of study, simplified or detailed, it is necessary to choose whether to use secondary data from databases or primary data collected directly in relation to a specific case. Even in the case of primary data collection, it is necessary to define whether they will be collected only for the main processes or if the entire production chain will be reconstructed.

Clearly, primary data collection takes place only for the realization of specific product studies, linked to a specific production plant, and for the purposes of product certification (such as EPD). On the other hand, if the study is intended to support design, it is enough to refer to databases and reasoning with respect to general project logics.

At the same time, using primary data, conveyed by product's EPD, could strongly modify the results of evaluations also used to support the design: using a specific product that applies the " Best Available Techniques" (BAT) obtaining a drastic reduction of environmental loads with respect to the products of its production sector can significantly change the results of an evaluation made with average data from the database.

Data contained in the databases used in the LCA studies, very often come from the trade associations and such data are considered reliable as they come from recognized and significant sources of the entire production sector. These data are certainly considered more reliable than those developed in relation to individual establishments (and specific LCA studies) or to the statistical data derived from the survey of a few establishments. Databases also often contain this type of data (data sources are generally declared transparently). The debate on the reliability of databases used to process LCA assessments remains open. And above all, remains the debate on the export that is made from the single case monitored to most cases and especially on the exportation of data coming from a specific country to all other nations.

This last operation presents the criticality of the diversity related to the energy mix: in fact, the production processes are almost similar in all countries, but the energy carrier changes, and above all the energy mix related to the production of electricity. These are all aspects that significantly affect the results of the evaluation: it is useless to be "detailed" in the definition of the processes if then we use little contextualized data.

Moreover, it is often difficult to understand how the data was constructed and therefore what aspects were considered: for example, it is not always easy to understand if the packaging was included, or which processes were included, and which were excluded. sometimes it is also difficult to understand the type of product and therefore the composition and the raw materials of the product (not always deductible from inventory). Furthermore, it should be stressed that it is difficult to navigate within databases, since there are actually few product categories compared to all types of building products on the market, taking into account that each nation has its own construction methods and each producer has its own production methods, in continuous evolution. Consequently, the selection of processes to construct the environmental balance is always "rough".

Once again, emerges the importance of using primary data and the importance of being able to access to specific environmental information in relation to the single product and the single production reality, thanks to the diffusion of environmental product certifications. Using "standard" data prevents to identify the peculiarities of the single product and to stimulate the single company to improve its production. Furthermore, the diffusion of environmental product certifications should generate a cascade effect so that the manufacturer of a construction system should demand environmental information from all suppliers and thus also encourage producers of components, semi-finished products and materials to orientate their production to environmental improvement. Therefore, if databases are a useful tool for accessing environmental data, it would be desirable to disseminate greater transparency and accessibility to specific environmental data related to specific products in specific contexts. In this direction, it is important to promote the environmental product labelling and in particular the EPD, which can constitute an environmental information tool integrated with traditional technical information tools.

Those who carry out an environmental assessment have the ambition to obtain a precise assessment. Dealing with quantitative numerical values, it seems clear that precise data are being expressed, but in reality, most of the ecological characteristics of materials and processes are inaccurate, due to the scarcity of data in this regard and therefore to the extent of the few cases detected in all cases. However, the current imprecision must not hinder the use of these values. On the one hand because it can still stimulate further studies and investigations that actually make the values available more precise, on the other because it is still possible to grasp some "trends" even from inaccurate data.

1.11.8 Data contextualization

To "simplify" the assessment operations on the scale of the building and due to the lack of diffusion of environmental information, designers appeal to "average" data on the incorporated energy or on the polluting emissions of materials or building products. The risk is that of not triggering environmental competitiveness within the same productive sector, but only a "fight" between different material and productive areas: nothing more wrong from an environmental point of view, which aims at "improving" current technologies available, a widespread improvement, without discrimination between material sectors. The current use of environmental data tends instead to operate "selections" and "discriminations" between ecological material fields and non-ecological materials, ignoring the fact that in the first place in each material sector there are more or less impacting production processes and whereas, secondly, the eco-compatibility of the materials depends on the adequacy of the project requirements.

The promotion of environmental product information and product environmental certification (EPD) in itself provides a fundamental contribution to the environment, as it stimulates individual producers to compete with the improvement of the quality of performance and eco-efficiency of their products, in this sense it is important not to "flatten" the environmental assessments made to the scale of the building by taking average data from databases or statistical surveys: each product must be in direct comparison with "similar" products, attesting the best environmental behaviour obtained from the adoption of the best available technologies, energy and material saving strategies, recycling strategies and attention to the end of life.

The dissemination of environmental product information related to specific products would also obviate the current difficulty of using average data derived from foreign databases, containing non-contextualised values (especially in terms of energy mix) and above all strongly conflicting values, as a result of detection of individual establishments in very different contexts. This shows how much the individual producer can do to "differentiate" their product from the point of view of the environmental performance, as it happens for other services.

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2 Life cycle phases

In this chapter life cycle phases of the building are described and analysed in particular stressing on the sustainability and environmental impact point of view, from raw material supply to the disposal to landfill or recycling and reuse. The various phases are summarized in the following table extracted from the BS EN 15978 standard:

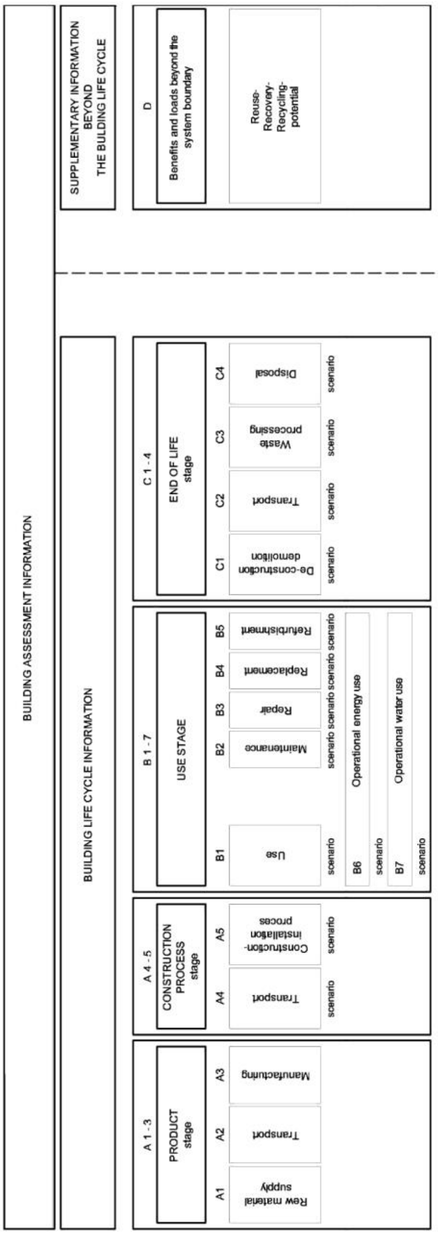

Figure 3: Display of modular information for the different stages of the building assessment [Source BS EN 15978:2011]

2.1 Product stage

Materials that make up the products and building components have changed considerably over time: from relatively simple, locally available, natural and with reduced transformation processes, to composites, coming from the entire globe, based on chemical and synthetic processes and derived from working processes and industrial processes.

The vernacular architecture consisted of local materials (such as wood, stone, clay and a few metals) and simple construction techniques, slowly evolving over the centuries to exploit local resources. Contemporary architecture, on the other hand, makes use of an infinite variety of materials, polymers and composites, and of advanced and industrialized construction techniques.

Repercussions on the environment are manifold. Composite materials are hardly separable in the original constituent components and therefore difficult to recycle. Materials and building components now refer to a global market, determining significant impacts from the transport point of view and also causing the export of construction methods and techniques far from the material culture sedimented over time and built on the basis of local climatic characteristics: the globalization of materials and technologies is leading to the construction of buildings that are decontextualized and therefore poorly efficient in responding to the characteristics of the context. The chemical synthesis substances used to improve the performance of the products alter its composition compromising its recyclability and sometimes even its wholesomeness. The industrial production processes generate considerable impacts in terms of consumption of energy, material resources and pollution on the environment, as well as determining soil degradation, landscape degradation and land use.

At the same time, it must be said that many new chemical synthesis materials have significant advantages from the performance point of view, while many natural or traditional materials can be characterized by deterioration in performance in use and easy perishability. Product innovation has led to improved mechanical resistance, thermal, acoustic and luminous behaviour of materials, often due to material contamination.

The contamination between materials and the creation of composite materials is generally the result of research and experimentation aimed at improving performance. Because of the difficulty of expressing an environmental opinion on materials in relation only to their appearance, their origin, their degree of prefabrication and processing, it is necessary to reduce the evaluation to performance data concerning both the qualities of the product in use and the impacts on the environment related to its life cycle. It is therefore necessary to evaluate the eco-efficiency of the various building materials and products in relation to the performance advantages based on the use and impacts caused during production and disposal.

The advent of accessible environmental information, drafting of new EU and international regulations that aim to make responsible all the actors of the process (designers, producers, construction companies, etc.) and the need to respond to mandatory environmental regulations relating to building production, are taking Italian companies to adopt as criteria for choosing their supplier network not only traditional quality/price requirements, but also environmental requirements. The qualification of the production offer has already started; now it is necessary to activate a quality demand able to orient the market towards environmental improvement.

2.2 "Natural" and industrial products

Currently, the debate around the theme of sustainability in architecture is often translated into the choice between natural products and industrial products. Often the classification of products is associated with the material: "natural" products are made of natural origin material and some of mineral origin, while industrial products are made of materials of mineral origin that require processes of industrial information and from chemical synthesis materials.

This articulation is not so simple and unambiguous; some consider "natural" only the materials of biological origin, while in reality also minerals are available "in nature", moreover some products made with "natural" materials such as wood are however integrated with chemical synthesis materials and therefore no longer catalogable as "natural". At this point it could be said that the different degree of eco-compatibility lies in the type of transformation process and in its energetic intensity, so it would also be necessary to distinguish between "noticeably" energy-consuming processes and low-energy processes, since some processes of industrial production can get closer to the category of craftsmanship and many processes of craftsmanship tend to approach industrial production. Consider, for example, the wood sector: there are various levels of "manipulation", which can go from simple wood cutting to create panels or solid wood profiles, to gluing strips in laminated wood, to panels in recomposed wood that begin to approach the industrial processes (even if at low energy) and above all open to a further sphere of environmental impacts, inherent in the use of products (paints, solvents, impregnating agents) that can be "toxic" and harmful. A further element of difficulty in the cataloguing of materials derives from the processes of hybridization and contamination between materials of different origins: more and more chemicals are used to form gluing and protective agents which on the one hand guarantee an extension of the durability of the materials, on the other allow to identify new innovative products, with improved performances. Faced with a performance and durability improvement, is it still appropriate to favour natural and non-treated materials?

Therefore the theme of the classification of materials does not appear to be the appropriate reference horizon for the identification of "sustainable" materials and products, instead it is necessary to make use of a life cycle assessment, to know the incorporated energy required for production and processing, putting it in relation to the duration guaranteed by the product and to the performances provided by the product during the use phase.

2.3 Raw material supply

Raw materials supply has a significant incidence on environmental impacts. On the one hand, for the question of "consumption" and therefore the progressive exhaustion of environmental resources; on the other hand, for the impacts that the areas of material extraction determine on the territory.

The problem can not be simply solved by directing the consumption of non-renewable resources towards renewable resources. Renewable resources, i.e. raw materials of plant and animal origin, only theoretically have better environmental behaviour. In fact, they have the advantage of not having such lasting impacts on the territory as a quarry, but if the harvesting and slaughtering is not planned and controlled, it can still have a landscape impact; moreover, even from the point of view of the depletion of resources, forests still have limits of renewability, so an excessive sampling can jeopardize the natural balances, knowing that "withdrawals" do not always take place at local level, so they operate "depletion" in distant territories and perhaps on valuable species.

To overcome this, the Forestry Stewardship Council tool has been introduced, which allows a balanced harvesting of the raw material to be guaranteed and not to take advantage of valuable species.

In any case it is known that renewable resources are also "infinite": from this point of view the tool of the ecological footprint allows to understand the quantities of land needed even simply to "produce" the wood, putting in evidence that there is not so much land available to support our current consumption.

One aspect to be taken into consideration is the availability of raw materials, regardless of whether they are renewable or non-renewable; it is also important to monitor the increasing presence of chemical synthesis materials. Until the Second World War the totality of building materials was 60-70% of mineral derivation (stone, bald, brick, cement) and 30-40% of vegetal and animal derivation. Today, however, almost all the materials on the market have a greater or lesser quantity of petrochemical origin substances.

2.4 Transport

That of transport, is a subject that is generally neglected, but the impact of which is not negligible. Unlike what happened in the past, when the only possibility was to make use of local materials, today designers have available a wide variety of materials coming from all over the world, thanks to the processes of globalization of the markets favoured by the economy and the ease of transport. Travels made by building materials and components cause an absolutely not negligible increase in environmental impacts: in any case transport is one of the most incident items in the generation of overall environmental impacts. It must be stressed that the theme of mobility does not only concern the impacts generated by motor vehicles, but also the use of territory that the construction of transport networks entails.

Often there is no mention of the long distance taken by each building component: during the entire product life cycle it is necessary to transport raw materials from the place of extraction to the place of production, the semi-finished products from an area of production to another, the finished products to the construction site and at the end of their life it is necessary to transport materials to the landfill or recycling plant. Currently the location of the plants is dictated by the low cost of energy or by the proximity of low-cost raw materials, this involves a separation between the production site and the construction site (in particular for the prefabricated components).

Furthermore, before arriving at the finished component, it is necessary to go through several semi-finished products that "travel" from one factory to another, sometimes with impacts higher than the processing.

Reconstructing the routes taken by raw materials and semi-finished products along the entire production chain is therefore an important aspect in the construction of an LCA budget and in the construction of the environmental profile of building products.

2.5 Manufacturing

Industrial activities produce and transform materials using raw materials and energy. Materials treatment can be aimed at a change in physical or chemical properties, in order to change its performance, or simply to a dimensional change. The expansion of industrial activities also coincided with an expansion not only quantitative, but also qualitative of materials and products on the market.

The current industrial production system uses natural resources and puts waste and pollution into the environment indiscriminately. Up to a certain point this behaviour has been absorbed by the planet, while today the consumption of resources and the production of waste has reached such an amount that it is not "sustainable" for the environment.

However, companies do not take on the environmental issue themselves and are even worried about the cost of environmental measures. Only in a global vision, which considers the cost-benefit ratio at national level, if not global, it emerges that environmental measures are an advantage also in economic terms: thinking about the cost of environmental disasters and ex-post interventions, the need to adapt prevention strategies is evident.

But the advantages, even in economic terms, can be perceived by the same companies: industries that have been oriented towards the adoption of environmental strategies have had advantages in competitiveness, innovation, energy saving and materials in the production phase.

If the question of saving resources and energy is intuitively perceived as both economic and environmental savings, a certain difficulty still remains in the solution of the downstream problems, the waste disposal. And yet, waste can also be a resource, and the same companies should act against the recovery of materials, giving rise to activities linked to recycling. Very little has been done so far and this undermines the closure of the production and consumption cycle.

Buildings are now 60-70% made up of subsystems and industrial provenance components; also, this often implies an adjustment of the duration of these components (and therefore of the entire building) to the average useful life of the other consumer goods, falling within the same production and consumption logic that allow the industry to continue production. This uncontrolled passage risks becoming a further strong impact on the environment.

The typical features of industrial production are:

- Need to guarantee a continuous production process;
- Reduction of the useful life of its products (scheduled duration);
- Need to guarantee a market (continuous demand);
- Competition on product quality (continuous improvement innovation).

An important open perspective is the transformation of industries from the manufacturing sector to the service sector. In fact, the production of tangible goods has experienced a period of overproduction, and consumerism has become the relief valve of an excess production. The conversion of the material goods production to the services production can be a sustainable prospect, both in terms of safeguarding jobs and in terms of reducing the impact on the environment. The conversion of production to services must be encouraged, however, by a different "planning", i.e. by a different way of designing and building the world.

But all these objectives can hardly arise spontaneously within individual companies: only a global environmental policy can formulate goals, incentives and environmental standards; and therefore regulate.

2.5.1 Energy consumption

Energy is the basis of all transformations: energy provides work and heat. During the production of materials, it is necessary a high energy consumption in relation to the thermal processes of raw materials transformation (thermal processes consume much more energy than mechanical ones).

Much of the energy used for production processes derives from fossil fuels, almost always used directly, and in some cases after conversion into electricity with an average European conversion efficiency of about 30%.

When electricity is used, environmental impacts of production vary a lot in relation to the national energy mix, i.e. how the electricity is produced in the specific country. In addition to fossil fuels, electricity is obtained from hydroelectric and nuclear generation, and from a small share of renewable sources (solar, wind). The contextualisation of production and the identification of the actual energy mix is one of the thorny issues of an environmental balance and an LCA evaluation.

However, it must also be stressed that, since the national energy networks of the European countries are interconnected, and energy is moved from one country to another according to the needs, it could be reasonable to speak in approximate terms of a European fossil fuel energy average per kilowatt of generated electrical power.

Of course, a factor of effective impact on the environmental balance, and which determines a discrepancy between database data and a specific case, is the adoption of alternative solutions for the production of energy. There are several alternative scenarios for energy production. Many plants that use fossil fuels are equipped with cogeneration systems, so as to produce "free" electricity along with the heat, for the same amount of fuel used. This allows for example to acquire green certificates to produce renewable energy. Furthermore, the use of biomass is becoming widespread, especially in contexts characterized by the high presence of forests and waste from wood production. Another very current topic concerns biofuels, fuels derived from plants; this is a topic of great interest for the purpose of identifying alternative scenarios of energy production that disengage us from dependence on foreign countries; in addition to the aspects of pollution reduction related to the CO_2 absorption of vegetation during growth. But a problem remains, the inefficiency: it is necessary to occupy large areas of land to produce few quantities of biofuel. For example, a strong conflict of territorial occupation between crops destined for biofuels and crops destined for food agriculture is emerging, with the risk of reducing agricultural land and raising grain prices (and therefore food). Once again it emerges that it is not easy to identify the virtuous paths towards sustainability; and the limitation of the territory available in the face of a continuously expanding population in the world and in terms of consumption, will open more and more conflicts in relation to ways of use of the soils.

2.5.2 Production scraps and post-production recycling

There is still little sensitivity among producers towards recycling their products at the end of their useful life cycle (post-consumption recycling). But yet, for many materials there is the possibility of being reintroduced in the production process. In fact, many manufacturers operate an internal recycling related to processing scraps that are generated during the production phase (post-production recycling).

This path, necessary to reduce raw materials consumption and solid waste production, should also involve the recovery of construction and demolition waste (post-consumption recycling), with economic benefits for both producers (who can recover raw materials) and for construction and demolition companies (which do not have to bear the costs of landfilling). Often the brake to this recovery is given by the distance of the site from the plant: once again the importance of the choice of materials coming from local production emerges, so that the building site is near the plant at the time of demolition and recovery of materials.

2.5.3 Quality and regulatory controls

The concepts of forecasting and prevention are introduced in industrial production after 1950: becoming aware of the diseconomies caused by the waste of products in the final verification, it has been started to understand that carrying out checks along the production chain, intervening on the causes of production defects, allows to reduce the production of waste in the final check and therefore save production time and costs.

Starting from the 1980s, a new approach to the theme of quality was established, based on the response of the good to predefined requirements. Even the legislation evolves from a descriptive-object to a demanding-performance: in 1985 the European Council’s Resolution entitled "Technical Harmonization and Standardization: The New Approach" overcomes the strategies based on the elaboration of specific product techniques, instead introducing strategies based on the definition of product performance levels.

The theme of quality has a further evolution in the nineties, shifting attention from the product quality to process quality through a systemic approach. In particular, with the ISO 9000 standard, system certification is introduced, in parallel with product quality certification.

The industrial production plants are "closed systems" and, as such, they can be monitored, from the point of view of the incoming and outgoing environmental flows, in a relatively simple manner. In addition, plants are already subject to regulatory controls and therefore most of the data that are useful to build an environmental product balance can be easily deduced from the monitoring documentation that the plant must in any case produce for regulatory compliance. If the company adheres to an environmental management system (EMS), and therefore is EMAS certified, a fortiori has available the environmental monitoring documents necessary for the realization of an environmental product balance.

As far as regulations are concerned, perhaps the most neglected theme is that of water pollution. In this regard it is particularly difficult to have factory monitoring available. On the other hand, concerning air pollution, there are many reference standards for the control of air emissions from the plants.

2.5.4 Emissions reduction

The Kyoto Protocol provided for voluntary participation programs to reduce CO_2 emissions based on carbon sales and purchase mechanisms. The procedure is based on the calculation of carbon dioxide emissions (kg of CO_2), determined by a certain activity and caused by the consumption of energy that the analysed activity requires. Once all the processes involved in the analysis have been described, possibly extending the analysis to the entire life cycle, through the appropriate calculation models it is possible to account for the equivalent CO_2 emissions of all the processes. Since carbon dioxide is absorbed by trees during the growth process, CO_2 emissions can be compensated by reforestation activities or the protection of growing forests, to absorb the emissions generated. Once the total value of emissions produced is obtained, the next step is to identify methods of compensation, which may range from reforestation or purchase of hectares of certified forests capable of absorbing the same amount of carbon dioxide for a certain period of time, until to initiatives to use renewable energy sources.

This operation allows to become aware of the impacts associated with the activities carried out and is therefore useful for approaching the environmental theme and making the individual operators responsible. At the same time, it can be simplistic to suggest that the impacts generated by an activity can be "compensated", since compensation-related activities also have an impact and above all because we only talk about compensating CO_2 emissions, but all the other types of impact generated are not considered. So, it is not true that to compensate CO_2 emissions is equivalent to "eliminate" the impacts, since all the types of impact associated with the activity are not considered. These actions therefore appear positive, but with a series of fragility from an environmental point of view, especially when a "monetization" of the compensated emissions is made.

2.6 Construction processes stage

"*Scenarios for the construction process stage cover the period from the factory gate of the different construction products to the practical completion of the construction work. The scenarios shall define for any elementary operation described within the boundaries of the construction stage"* (BS EN 15978:2011).

The aspects related to the construction of the building, although they concern a very limited temporal phase with respect to the life of the building, constitute a non-negligible phase of the life cycle from the environmental impacts point of view. First of all, an important incidence in the impact assessment is covered by the packaging and the transport of materials from the production plant to the site: materials are not always found locally and there is often a significant incidence of transport, both in relation to distances travelled and to the fact that building materials are generally heavy and bulky.

Another environmental impact important aspect concerns the construction site: the land occupation by the building under construction, the connection to the systems infrastructures, significantly alter the soils and above all greatly affect the overall impact. Finally, it should be noted how the implementation modalities have a significant incidence on the environmental impacts: water consumption for wet processes, soil and water pollution due to the spread of toxic and dangerous substances, harmful emissions for workers for the use of paints and adhesives, production of waste for scrap and waste of broken or damaged components. Not to mention that on-site works are exposed to greater risks of laying errors, approximation of execution, poor quality of construction. In relation to the design choice of the building system and the assembly methods (wet or dry), the incidence of the construction site waste, the installation errors, the toxicity risk of the workers' courses vary. And above all, the quality of the final product varies. The installation errors and the lack of professionalism of the operators on site make the design efforts of environmental improvement and performance excellence of the buildings useless. In this sense, the control of the realization constitutes a moment of considerable importance in a life cycle perspective. Surely it is possible to read on the building sites a progressive orientation towards prefabrication and dry assembly, motivated today by economy reasons and speed of realization. Thanks to this change it is possible to hope to obtain even higher quality of construction, which is essential in order to obtain buildings with high environmental performance, and the reduction of some types of impacts generally associated with the construction phase.

Fundamental element is the packaging, which serves to protect materials both during the period of storage in the factory and during the transport and storage phases on site before the installation, but constitutes an additional item of increase in the overall ecological balance: it is about "disposable" materials, normally polyethylene sheets, therefore plastic and of high impact, which become, after a very short life cycle, waste from the construction site. In addition to packaging, pallets are used for handling, usually in wood, and then burned on site (without energy recovery), thus producing polluting emissions.

2.7 Transport from the factory to the construction site

The incidence of materials and building components transport from the plant to the building site is not negligible, building materials are heavy and the weight increases the fuel consumption of the means of transport. Moreover, often the components, especially prefabricated, are bulky, of considerable size, requiring many trips. This is why the orientation towards the lightening of construction materials and the optimization strategies of the cargo space for transport appears to be important. In a prefabrication scenario, the trend is to create large elements, with an increase in transport impacts. It would instead be appropriate to choose small prefabricated elements to be assembled on site: linear elements transport allows a greater optimization of the transport load.

Another important choice concerns the means of transport: currently road transport is favoured, also because it allows with a single means to reach decentralized locations. But road transport is considerably more environmentally impactful, compared to transport by train and ship, around 10 times.

A further issue is the location of the plant with respect to the building site and therefore the distances to be covered. In general, the environmental assessment tools of buildings, and environmental criteria for sustainable design, promote the choice of local materials in order to reduce the impact on transport.

Important is the identification of the operator who "certifies" the origin of the materials: the designer generally provides the technical specifications relating to the products, but does not deal with the choice of suppliers, which is task of the construction company. Responsibility therefore falls on the construction manager, who is the supervisor of the supplies at the construction site.

Finally, it should be noted that the local origin is not synonymous with the reduction of environmental loads, because impacts also affect the weight of the materials and the overall dimensions of transport. In order to bring out at least the weight of the materials, in the LCA evaluations is used an indicator, not the simple distance, but the distance multiplied by the weight. This indicator's limit is not to bring out the advantage deriving from the compacting of the dimensions and the optimization of the load of the single mean of transport.

These considerations demonstrate once again the need for an LCA environmental balance linked to the specific case, which allows to compare alternatives in relation to the actual quantities to be transported, to the weights, dimensions, distances to the means of transport.

2.8 The use of soil

Environmental attention leads to particular caution to the inclusion of the building in the environmental context: it is necessary to insert the building in a site without altering it, integrating it into the local ecosystem, considering the topographical, hydrological and climatic aspects. The choice of site should also be balanced in relation to the proximity to infrastructure and services. This aspect leads to seek settlement locations as close as possible to the existing building and to favor the redevelopment of disused urban areas.

The building construction area should possibly be an already used area, to be cleared and "recycled" rather than a land still characterized by an ecological value. Even the land can be recycled. Moreover, in a logic of sustainability, in the case of the presence of a pre-existing building, the condition to be privileged is always that of recovery rather than the demolition and construction of a new building to reduce the use of resources and the production of waste.

A further aspect to consider is the respect of the soil during construction, both minimizing the "footprint" of the building, i.e. the portion of land occupied by the building, and minimizing the underground and paved parts, to maintain as much as possible the permeability of the land.

Land consumption is an environmental issue overlooked by the LCA method. The soil is a marginalized resource in the construction of inventory, compared to raw materials, water and energy. In some assessment methods, the synthetic land use indicator appears, but it is simply the land count occupied by the establishment, the building and the quarry. This "lack" perhaps depends on the fact that the LCA method was born to evaluate industrial products, which therefore do not determine the consumption of soil, if not for the supply of raw materials; on the other hand, it should be kept in mind that the consumption of soil in the building sector is highly relevant and an indicator that also counts this aspect should be introduced.

2.9 Construction-installation process

The building site is a place of work and, as such, a place in which consumption of resources and environmental impacts are determined, the impact of which is more or less substantial in relation to the types of operations performed. First of all, a significant incidence on the environmental impact is represented by the excavation operations, both for the construction of foundations and for the construction of underground parts. These operations require the handling of large quantities of land and the generation of a considerable amount of waste. The construction site also houses vehicles and machinery, which require energy consumption, and which generate noise and pollution in the surrounding area. In addition, in the construction site, means of transport arrive, which generate impacts in the loading/unloading/storage of materials.

During the management of the building site, especially if it is a traditional one, impacts are generated by the work in progress, which require energy and water and produce waste.

The environmental implications of construction activities are:

- consumption of resources for construction activities;
- waste produced by processing waste, packaging;
- dust and atmospheric pollution;
- pollution of soil or water by the payment of dangerous substances.

Environmental management (EMS) is also possible on site. An environmental management of the building sit can allow several advantages: the reduction of production costs, the reduction of consumption of natural resources, the reduction of waste, the optimal use of energy, the reduction of waste to be disposed of in landfills, the reduction of the possibility of incurring regulatory sanctions, reduction of the possibility of incurring damages for environmental damages. These "environmental" attentions can translate, for the construction companies, into savings also from an economic point of view and in a more rational management of construction activities.

2.9.1 Foundations

A first decisive impact produced by the building construction is the excavation for the realization of foundations or underground parts. The considerable movement of land that takes place for the construction of the underground parts is often underestimated, both for the foundation structures and for the construction of garages and cellars, and the alteration of the soils caused by the cementation for the underground space’s construction. It should also be noted that excavation earth, especially in urban environments, is often contaminated, and therefore requires special disposal for on-site treatments.

Preliminary operations for the construction of a building are therefore decisive in terms of environmental impact: on the one hand the excavation operations involve considerable movement of land, which must be transferred to landfill, on the other the realization of roads and plant infrastructures determines the colonization of additional portions of soil.

A further typical problem related to excavation operations is the alteration in the natural drainage network, which also risks causing ground subsidence.

On the one hand it is therefore necessary to limit the underground parts, both "lightening" the buildings and therefore limiting the load-bearing structures of the foundation and, above all, avoiding the creation of underground spaces; on the other hand, it is necessary to try to avoid that new achievements are "far" from the already existing infrastructural networks, in order to avoid the creation of new "specific" networks.

2.9.2 Construction machinery

The type of machinery necessary for the work and handling in the building site depends on the type of construction, on the size of the intervention, on the size and weight of the components to be moved. A first articulation depends on the type of site; if handmade or for prefabricated components. Wet working requires the presence of cement mixers and machines for on-site processing, while the prefabricated components must be simply moved and assembled.

A second articulation concerns the type of machinery necessary for the movement of prefabricated components, in relation to their dimensions. Prefabricated three-dimensional or two-dimensional components involve the need of lifting cranes and delegate to machinery most of the "work". Light and small components can even be handled and moved by the workers, avoiding the use of machinery.

2.9.3 Construction waste and toxicity

Construction waste can be classified as "clean" or "hazardous". "Clean" waste is inventories of various materials, processing waste, defective materials, packaging, excavated earth. "Hazardous" wastes are paint residues, waterproofing products containing tar, containers of dangerous substances.

Some building materials may cause damage to workers' health through contact during handling or inhalation. For example, fibrous insulating materials may release powders or fibres that may be inhaled and may be leaking if touched. In these cases, it is necessary to guarantee the safety conditions in the installation. Another important aspect is the use of adhesives, additives and substances that are dangerous for health. Workers must use protective gloves and masks and well ventilate after laying.

2.10 Wet processing management

Compared to the LCA evaluation, the traditional-artisanal construction site, still based on work on site, is a critical phase due to the impossibility of monitoring works and therefore due to the difficulty of compiling inventory data. The LCA method has always been applied to industrial products, so it is easily applicable if the building is made up of prefabricated components, made in the factory. On the other hand, construction in situ is difficult to control and "engineerable". The craftsmanship that still exists in widespread building sites makes it impossible to control a precise quantification of materials and energy consumption, emissions and waste. Not to mention that in wet processing it becomes difficult even to make an environmental assessment of the components used. Monitoring these processes is complex, as they are often based on the skills of the workers and companies. The executive project could be an adequate reference tool, but often the site differs from the indications contained in it. The monitoring of all these aspects should be carried out by the project manager, who should be involved and accountable with respect to data collection of this phase.

In particular, one of the most critical aspects is the production of scraps and construction waste. The production of scraps and the rejection of broken components during transport generates a fairly high amount of construction waste, which is almost never recovered by the manufacturing companies and sent for recycling, as it would be too expensive. In addition to a further impact on the environment, construction waste is also a financial loss for the construction company, which throws away some of the purchased material and has to pay the bill for the transfer of waste to landfill.

Also directing wet processes towards prefabrication reduces the possibility of loss of performance due to poor laying quality, reduces the production of waste and requires the designer to check the dimensions of the parts in relation to the size of the components used.

Orienting the project towards prefabrication would reduce waste from the construction site and above all the scraps. If the sizing of the elements takes place at the factory, the waste can be recovered and mostly recycled within the production process.

2.11 Building prefabrication

In a traditional construction, prefabricated elements make up 50-60% of the entire structure. The current orientation is an increase of this percentage, in order to move artisan works from the building site to the factory, industrializing and making them more monitorable. This orientation is prompted by the contraction of time and costs, by greater executive reliability and by the fact that skilled and specialized workers are scarce. The goal is to produce entire portions of building in the factory, delegating to the construction site only the assembly phase; examples of closed prefabrication, that is, of three-dimensional systems and therefore real building modules ready to be juxtaposed and stacked, also proliferate. The flexibility guaranteed by the production allows to manage these prefabrication scenarios without renouncing the variability and customization, coming out from the prefabrication prejudice that coincides with standardization and homologation. Clearly, even with high rates of prefabrication, the work related to the construction of foundations and plant connections remains.

One consideration to make is that the high prefabrication also leads to a lightening of the building, since it becomes essential to ensure easy handling of the parts of the building under construction and a reduced transport load. Prefabrication is therefore often associated with light prefabrication; this comes into conflict with the mass requirement for thermal comfort and also contrasts with the durability of the materials. Often light materials also have shorter durations. At the same time, from the building site point of view, the reduction of the in-situ operations makes it possible to contract material waste, production of construction waste and speed up construction times, with greater control over the overall quality of the work.

The prefabrication is also closely linked to implementation methods based on dry assembly, and therefore on reversible type connections that allow over time the removal and replacement of the elements for maintenance, and the selective demolition for components at the end of life.

Orientation towards prefabrication seems increasingly inevitable, also due to the difficulty of finding skilled workers to work on site. It is also about orienting this change in a direction that reconciles economic needs with environmental issues.

2.12 Use stage

"*The use stage covers the period from the practical completion of the construction work to the point of time when the building is deconstructed/demolished*" (BS EN 15978:2011).

The use phase is the phase of longer duration in buildings and consequently the one with greater impact on the environment. In particular, the greatest impacts are determined by the energy consumptions. However, impacts associated with adaptation, maintenance and retraining must not be neglected.

It should also be stressed that the long duration of buildings allows to "dilute" the impacts generated for the production and construction of them over time. The duration over time is therefore the aspect that has the greatest impact on the reduction of impacts on the environment, provided that is a building that guarantees well-being and comfort, that is low energy consumption and that is made of durable materials and components.

However, it should not be overlooked that sometimes, for specific needs of use, the duration of the building is reduced: it is therefore necessary to underline how the adequacy of the technical-constructive choices also depends on the expected use and replacement duration and that there is a design side linked to temporality that needs even more to be the object of a careful design to the environment.

2.13 Energy management

The emergence of problems related to energy supply and pollution caused by the consumption of energy produced by fossil fuels have led to the (obvious) importance of reducing energy consumption.

The energy efficiency of a production plant or a domestic plant is the relationship between energy input and the quantity of products or services supplied. Similarly, the energy intensity of a nation is the relationship between energy input and gross domestic product, which is the amount of energy consumed to produce a unit of gross national product.

The highest energy consumption is related to heating, but also cooling has an important share of it and is increasingly more and more relevant, not to mention the consumption related to lighting, especially in the tertiary and commercial sectors. This led to the activation of a series of strategies, such as incentives for energy saving, taxation on the use of energy, etc. The reduction of energy consumption is one of the most effective objectives toward the construction of sustainable buildings. The energy certification of buildings has this objective: to inform the end user about the building maintenance costs, stimulating a greater investment in the construction phase, aiming at high performance and reduced operating costs. There are different strategies to achieve consumption savings but can be grouped into some basic rules: designing "passive" buildings and using renewable energies.

Concerning the objective of environmental sustainability, it should always be checked that strategies to limit energy consumption, aimed at saving energy and reducing pollution during the use phase, achieve these objectives in a global budget, i.e. in the whole life cycle. In fact, all the current design guidelines take into consideration almost only the verification of the consumption reduction during the use phase, without checking what happens in the life cycle. The project choices should instead be supported also by the objective of eco-efficiency: the choice of materials, construction techniques and plants should guarantee the reduction of environmental impacts throughout the entire life cycle, in a global budget. To do this, it is necessary to have an adequate knowledge of the impacts of production and end of life, but also an adequate knowledge of the performances in use in terms of durability.

2.14 Healthiness and indoor air quality

People spend about 90% of their time indoors, at home, in the office, at school, in shopping centres, at the cinema, at the gym. Yet, until today, in the construction, little attention has been paid to the aspects related to the quality and healthiness of living spaces.

Since the early seventies, some research has shown high levels of toxicity in internal environments: the harmfulness of the materials with which buildings are built has been related to symptoms of malaise and common diseases. In 1984 the World Health Organization (WHO) indicated that the 30% of buildings, both newly built and refurbished, determined the onset of diseases related to indoor air quality: it was mostly of respiratory effects caused by the presence of chemicals, biological agents and particulates. It was estimated that direct and indirect costs for diseases related to the quality of buildings, including sick leave and loss of productivity by workers, exceeded $ 150 billion a year.

Recently, it has emerged that building-related health problems have increased: from simply air quality problems to health effects caused by light quality, noise, humidity, temperature management in the night, smells, vibrations. The term used today to understand all these aspects is Indoor Environmental Quality, which also includes Indoor Air Quality.

To remedy the pathologies related to unhealthy living environments, the strategies adopted are the ventilation control (natural and mechanical) to dilute the harmful substances potentially present in the interior spaces, the use of internal finishes that do not have releases of Volatile Organic Components (VOC), the control of dehumidification to prevent the proliferation of bacteria and mould, the verification of the sunlight entrance to ensure sterilization; this last requirement contrasts with the use of selective, low-emission glasses with "shielding" properties.

Once again emerges how the project is the result of an activity of mediation of conflicting needs and the importance of not to disregard any aspect. It should be emphasized that the LCA assessment method neglects the verification of indoor quality: the environmental impact indicators considered evaluate macro-environmental aspects. Moreover, the method was born in the field of design, to evaluate "objects", and its application in the construction sector makes it not always adequate to capture environmental issues between building and surrounding space relationship. Factors that determine the pollution of internal environments are various: emissions of harmful substances from building materials, furniture and consumption; plant activities and air conditioning methods; excessive artificialisation of the internal spaces and airtightness of the envelope; humidity or dryness of the air; use of chemicals and detergents; presence of tobacco smoke, biological activities and breathing; presence of microorganisms and moulds.

It should be noted that the pollutants are not only of chemical origin, but also of biological origin (moulds, bacteria and fungi developed by the humidity of the walls, furniture and carpets). In the latter case, responsible are not materials, but their use conditions.

It should be also emphasized that the internal quality is only influenced by materials of the internal coating, which are the ones with which the inhabitants come into effective contact, and therefore design attention should focus only on these ones. For other materials, attention must be paid to the protection of operators during production, construction, maintenance and disposal, but there are no dangers during the use phase.

It also important to pay attention on how to assemble and lay the finishing materials. In fact, about adhesives and glues, the harmfulness of emissions also depends on the release mode into the air.

Adhesives, sealants, paints and varnishes are many used during the realization of the finishes, without particular attention on dry time, during which solvents contained in these materials emit volatile organic substances, even for extended periods. Methods of release into the air can be directly or indirectly (when materials absorb and release, as in the case of textile materials, carpets, sofas).

The biggest problem is the emission duration over time. The type of pollutant emissions of building products can be: constant, if it is halved in one year or several years; slow, if it is halved in weeks or months; fast, if it is halved in minutes, hours, days. The least critical issue for the use phase is the rapid one, even if the one who suffers it is the tiler. It is therefore necessary to know the initial emission indexes and the decay ones. A material with a high initial emission level and a rapid decay may be healthier than a material with a low initial emission rate but with a slow rate of decay. The major problem is in fact given by low exposure, but for a prolonged time.

It can be concluded that the main causes of poor internal air quality are the misuse of certain materials, microclimatic factors and low levels of ventilation. Different solutions must be evaluated with an overall view of the problems, from the desing to use.

2.15 Use intensification and adaptability

Nowadays, if on the one hand the intended use, the ways of using spaces, the needs of inhabitants are changed so rapidly, that spaces must be able to adapt to uses in continuous development, becoming flexible and changeable, this need can not, however, be translated into a short-lived and "disposable" architecture. This is why it is important to design buildings that are adequate over time, "surviving" to changes: designing flexible buildings permits to make them suitable for changing needs and thus extending their useful life, reducing demolition, reconstruction operations and adaptations to new uses.

In recent decades, the division of space into different functional areas is replaced by an open, multifunctional space. Intensification of use and adaptability can involve not only the building, but the component. The intensification of the use of the component at the building scale can be pursued as integration of functions: while in the past the increase in building system components was a precise choice with the objective of increasing performance, today the trend is opposite and the number of parts that make up an object tends to shrink and the number of functions performed tends to increase. The motivation of this change is the economic cost of assembly operations and the consequent convenience to produce in a single operation pieces that integrate several functional sub-components.

2.16 Maintainability and requalification

Functional and technological obsolescence and rapid renewal rhythms, above all in the tertiary and commercial sectors, constantly test the ability of the building to remain "functional". Building management deals with two issues: on the one hand the image renewal, on the other hand the maintenance interventions that instead allow the performance and technological adaptation.

Long-term benefits of sustainable construction, such as lower maintenance and management costs and greater durability, are not immediately evident in the short term.

Extending the buildings life becomes a primary objective: if a building has a reduced life cycle, either because it loses its function and is abandoned or because building materials and components are of poor quality and have led to a rapid performance decay, the impact on the environment is high, since more production and construction cycles are needed to guarantee usable buildings. While if a building has a long-life cycle, maintaining its performance, the impact on the environment is reduced.

To allow the building to remain efficient over time it must be designed in such a way as to guarantee easy maintainability and adaptability. In this sense, the building maintenance becomes of primary importance.

2.17 Buildings and components durability

Designing in an environmentally responsible way means today dealing with the theme of duration and time, since the choice of the appropriate technology is strongly related to the life expectancy and the use conditions of the buildings. Sustainability is linked to the duration of the building and its components, since the reduction of substitutions and maintenance is itself a reduction of environmental impacts.

The theme of durability is a controversial topic from an environmental point of view. Surely a durable product is a product that "dilutes" its impacts over time and avoids new impacts related to the production of new products. At the same time the rapid evolution of technologies, increasingly energy efficient, calls for a continuous turnover to reduce energy consumption: increasingly high-performance windows and high-performance heating systems push to replace the "energy-consuming" parts of the building, but these substitutions have an environmental cost for the generated waste and the new resources used.

Also, in these choices, an LCA evaluation can help to define the replacement cost-benefit budget: the LCA evaluation allows to see if the savings obtained from the substitution compensate the impacts produced by the waste and the use of new resources. It also allows to estimate the "return times" of impacts of the production of a product.

What is certain, in relation to the theme of durations, is that products guarantee different durations in relation to their quality. Consequently, the responsibility of designers, but above all of builders, is that of shifting the criterion of choice from the economy towards the quality, guaranteeing a reduction of the costs in a balance of the life cycle.

2.18 End of life stage

"*The end-of-life stage of a building starts when the building is decommissioned and is not intended to have any further use. At this point, the building's demolition/deconstruction may be considered as a multi-output process that provides a source of materials, products and building elements that are to be discarded, recovered, recycled or reused. The scenarios for these end-of-life options for the products and materials determine the system boundary. These scenarios shall only model processes that have proven to be economically and technically viable*" (BS EN 15978:2011).

The architectural project is increasingly facing with the temporal dimension: the dismantling phase becomes therefore fundamental, linked to the controlled and programmed duration of the building components and of the building as a whole. But the innovation of the disposal scenario must go through the innovation of materials, components and assembly techniques. In order to favour end-of-life scenarios no longer linked to landfill disposal, but to recycling, a renewed planning and production are required.

Materials separability, assembly operations reversibility, the building decomposition and the selective demolition are all scenarios that favour the recycling of materials and the reuse of components, but these hypotheses require a design previously predisposed to market conditions that makes them economically favourable, to make it feasible.

Demolition and reconstruction processes involve the consumption of raw materials and energy for the new construction and production of waste. It is therefore necessary to try to prolong the life of the building and its parts as much as possible in order to avoid environmental impacts of dismantling and reconstruction. But if demolition is necessary, it is at least necessary to address the disposal towards the recycling of materials. However, a material is definable recyclable if, apart from the possibility of separating it during the demolition phase, a recycling market exists.

2.18.1 Buildings collective demolition

Wet processes during the building construction make materials indivisible, preventing the separation at the end of their life. In particular, waterproofing or bonding processes are irreversible: materials treated with bitumen or laid with glues and adhesives, even if potentially recyclable, become non-recyclable (they are no longer separable). All the parts that can not be separated, and therefore not recoverable and not recyclable, are demolished "collectively" and sent to the landfill.

2.18.2 Buildings selective demolition

"Closing the circle" means to make a process of use and consumption of the products in which, at the end of their useful life, materials are kept "productive" through reuse, identifying their residual qualities, or through recycling, avoiding landfilling and the production of waste. In order to implement this strategy of reducing environmental impact (in terms of resource consumption and emissions production), it is necessary to design building components easy to disassemble and whose constituent materials can be disaggregated and recyclable.
To talk about recovery and recycling of components, it is necessary to be able to make a selective demolition, i.e. the separation between materials that make up the building.

In fact, many finished components are recoverable: tiles, fixtures, stone elements, prefabricated panels, etc. What can not be removed as an integral component can at least be separated by type of material: aggregates, metal, glass, wood, plastic, etc.

The separability of different materials is favoured by the adoption of constructive methods based on the stratified construction (combination of different materials) and on the dry assembly, which allow at the end of life an easy disaggregation of the parts (easy dismantling).

Often, however, buildings are characterized by wet processes, at least of the load-bearing structure. In these cases, in order to operate a selective demolition, it is important that at least the completion and coating works can be disassembled, so as to "strip the structure" (with recovery of the materials) and proceed to the collective demolition of the single supporting structure.

The separability of materials depends therefore on how the building was designed and, on the choices related to the connection systems of the building components.

2.18.3 Redevelopment of buildings

The re-use of existing structures is a sustainable choice: in fact, if an LCA budget of environmental impacts is realized, the redevelopment of the existing is to be encouraged compared to demolition and construction, as the use of new materials and the production of waste is reduced. Even in the most “radical” interventions, the conservation of at least the load-bearing structure of the building constitutes a quantity of "maintained" energy of considerable entity (generally more than 50%).

Clearly the opportunity to redevelop or demolish must be assessed in relation to the new uses and the building's ability to be "adaptable". The redevelopment may concern only a performance improvement of the envelope, but often involves typological-distribution changes with respect to which the structural constraints may be very binding.

2.18.4 The end-of-life phase of materials and components

There is an "environmental" hierarchy of possible approaches to building products disposal (Passaro, 1993):

- The "reduction", i.e. Trying to reduce the production of waste;
- "Re-use", i.e. Using products and materials in a new context;
- "Recovery", i.e. Recycling, energy recovery of waste;
- Only if no previous "sustainable" approaches can be pursued, the ultimate solution is to start the landfill.

When demolishing the building is necessary, if it has been properly designed, it is possible to recover at least the materials, obtaining two environmental advantages: the reduction of waste and the recovery of still usable material. It should be emphasized that building waste does not come only from demolition activities. Conventional construction and the installation of semi-finished products involves the production of considerable quantity of waste and scraps.

The choices of demolition techniques depend above all on costs and speed of execution. So far, collective demolition has been favoured. It should however be stressed that the costs of landfilling will be increasingly higher, while the transfer of demolition materials to recycling plants in the future could even have economic recognition, giving value to waste. The “recycling culture” is starting to spread among construction industry operators.

2.18.4.1 Landfilling

The first European directive on waste is the Directive 91/156/CEE, which promotes recycling and introduces the European Waste Catalogue. The increasing presence of chemical substances in building materials and products entails the need for attention in the disposal of rubble, being harmful both to the environment and to health. For this reason, rubble is classified as "special waste": the nature of these wastes, which may contain dangerous substances such as lead, chromium and mercury, requires particular interventions. Waste from demolition is mixed waste of various kinds, consisting mainly of inert material (bricks, plasters, reinforced and non-reinforced concrete, stone material, bituminous conglomerate, etc.).

Waste resulting from recovery activities are very similar to those of demolition, but contain, in percentage, more quantities of materials for finishes and of stone material of large/medium size.

In the past, the Public Administration, because of environmental emergency created by urban and hazardous waste, with a greater impact on human health, has not given proper attention to construction and demolition waste. In recent years, however, under the pressure of the European Union, it is giving greater importance to the management of this type of waste. However, it is possible to see that considerable quantities of this waste are still abandoned illegally on public and private soils.

2.18.4.2 Energy recovery of building materials

An increasingly followed practice is that of "thermal recycling", i.e. energy recovery of materials, as the last possibility of "use" instead of landfilling. The combustion of waste in waste-to-energy plants produces thermal energy, allowing a further withdrawal of energy resources and reducing the amount of waste to be disposed of. This end-of-life scenario is favoured for wood and plastics, which have a good calorific value. In fact, plastics should be recycled rather than incinerated, since their combustion causes highly polluting emissions and because the embedded energy and waste of the non-renewable resource which is the raw material for their production are not taken into account.
The point of view of environmentalists towards waste-to-energy plants is controversial: although this is a favourable scenario compared to landfill disposal, it is disadvantageous compared to recycling.

2.18.4.3 Recycling of building materials

Recycling can be divided into two types of cycles (organic and technical) depending on the nature of the materials (natural and artificial). Organic recycling concerns those natural materials that have been subjected to few treatments and are still mono-materials. These materials can even fall within the natural cycle, requiring a reduced investment in energy for recycling. Biodegradable materials, totally of animal or vegetate origin, can be conveyed to “compost sites” where decomposition occurs by micro-organisms present in nature and reintegration into the ecosystem. It should however be stressed that building materials are rarely totally biodegradable, as for example fire retardant and anti-parasitic treatments make wood composting critical, but also recycling and even landfilling. Furthermore, many materials are mixed, due to the addition of synthetic fibres to improve their mechanical strength and durability. So, recycling in construction is almost always "technical", related to artificial materials. Technical recycling involves artificial materials that do not exist in nature and have been created by man. This category includes, for example, metal alloys, plastics, concrete and composite materials.

There are different approaches to "technical" recycling: direct recycling (without physical-chemical changes); indirect recycling (through phase changes but without changing the chemical composition); differentiated recycling (in the composition of new materials); undifferentiated recycling (for the production of goods using materials of inferior quality compared to those of the initial product). Only metals, glass and plastics are totally recyclable and can retain their properties over several cycles of use and reprocessing. Synthetic materials are recyclable, but generally require significant energy investment for reprocessing. Composite materials can not be recycled (the increasingly widespread use of mixed materials and composites is a major problem).

The most common building materials (brick, concrete, plaster, mortar and similar) are not completely recyclable for the same function, but can be recycled to a lower use, such as filling material or for road foundations. These traditional materials are composed of inert materials and therefore with reduced ecological toxicity. The analysis of the energy cost, that is the consumption of energy per unit of produced goods, shows that recycling allows, in addition to saving resources and reducing pollution, also to save energy. Recycling allows significant energy savings compared to the first process. Therefore, recycling allows to reduce the pollution caused by the introduction into the environment of waste, to reduce raw materials consumption by re-injecting materials into the process, to reduce energy costs due to refinement, but also to extraction and transport from the supply to the production area.

At the same time, recycling is not necessarily a waste reduction policy; for example, it is not entirely efficient from the thermodynamic point of view: it requires energy consumption, often an integration of raw materials and produces polluting emissions. It is therefore necessary to bear in mind that recycling implies impacts and therefore from the "sustainability" point of view it is more appropriate to reduce upstream the resource consumption rather than keeping on recycling to maintain the current high flow of material. Recycling should not be a strategy that puts less attention to the reduction target.

Furthermore, recycling activities can sometimes be more impactful than the production activity. It is therefore necessary to subject each recycling activity to a cost-benefit assessment and life cycle assessment and not to assume that it is always a positive operation for the environment.

To become successful, recycling must be supported by appropriate policies. A supply network, recovery and transformation processes are needed, but the current lack of organized activities, valorisation plants network and recycling market is strongly limiting the introduction of recycling in the construction sector. Yet the advantages are not only environmental, but also economic: the cost of recycling must be linked to that of taxes on waste collection, with that of landfill and with the costs of extracting raw materials.

2.19 References

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BS EN 15978, *Sustainability of construction works. Assessment of environmental performance of buildings*, 2011.

ISO 14044, *Environmental management - Life cycle assessment - Requirements and guidelines*, International Organization for Standardization, Geneva, Switzerland, 2006.

ISO 9000 Series standards:

- ISO 9001:2015: Quality management systems - Requirements
- ISO 9000:2015: Quality management systems - Fundamentals and vocabulary
- ISO 9004:2009: Quality management systems – Managing for the sustained success of an organization
- ISO 19011:2011: Guidelines for auditing management systems

A. Passaro, "*Attrezzature e impianti generali di cantiere*", Liguori, Napoli, 1993.

3 LCA Standards and Rating Systems overview

As we have already treated, the international standard's topic, by analysing the ISO 14040:2006 and ISO 14044:2006 with a specific view on their scopes, principles and structures, we need to set up a deeper overview on international standards for what it concerns the construction industry. It is possible to focus our attention to the building level standards and then try to criticize the development of reliable standards on the product side. Recently private and public organizations developed a great number of different standards and guidelines to create a sufficient network of cooperation among LCA technicians and a solid common framework approach on the study of Life Cycle Assessment. Those international standards, despite the efficiency effort made to share the same goal, creates an intricate system in which construction industry on an international level has a difficulty to find itself in relation to the differences among EU member state.

3.1 CEN/TC 350

The European Committee for Standardization has designated in 2004 the Technical Committee 350 to protect the construction industries and construction product to share a common language inside the international market in order to avoid technical and trade barriers. The CEN/TC350 purpose is the upgrade to a horizontal standardization method for the analysis of sustainability features related to LCA in new and existing construction works, focusing also into the development of a common rules for environmental product declaration (EPD).

This standards list had to be balanced to be harmonized, and for this reason, the Technical Committee decided to not include benchmarks and create a common levels setting: the creation of a core valuation method can not be so specific because each Member State in Europe has so many differences inside their construction industry from the point of view of framework and products availability and this divergence has to be take into account. The CEN/TC350 transparency is set in its inner technical instrument for decision making among Europe.

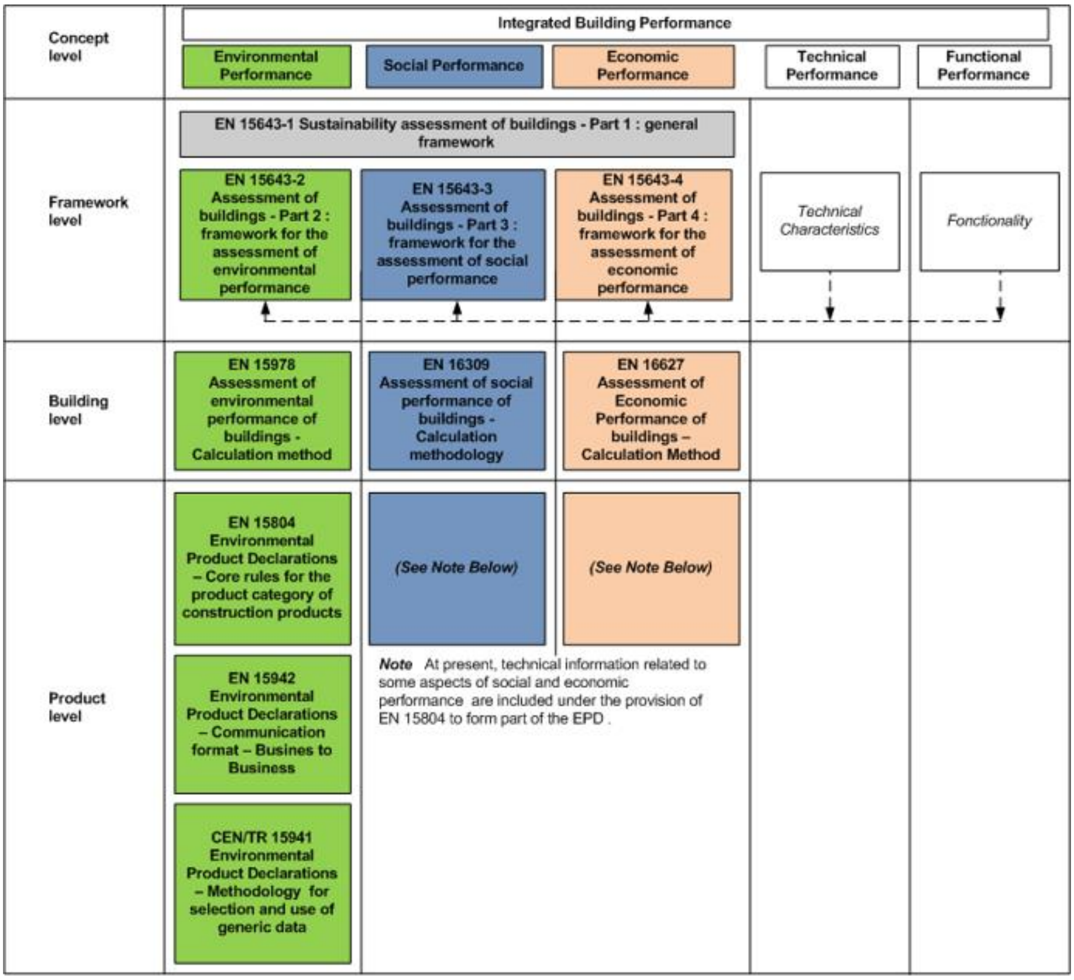


Figure 4: CEN TC/350 published Standards [Source: http://portailgroupe.afnor.fr/public_espacenormalisation/centc350/standards_overview.html]

The CEN/TC 350 works on sustainability perspective, called "ecological dimension", and their main standard published could be summarised as:

- EN 15643-2:2010
- EN 15978:2011
- EN 15804:2012+A1:2013

As we can see from the list below, the number of relevant standards to be taken into account during the harmonization process was huge and needed a great expenditure of time and effort.

ANNEX A: Relevant iso & CEN standards [CEN/TC 350, "*Business Plan",* CEN, 2018.]

A.1 Relevant standards of ISO/TC59/SC17:

- ISO 15392 Building Construction – Sustainability in building construction – General Principles
- ISO 21929-1 Building construction - Sustainability in building construction – Sustainability indicators - Part 1 - Framework for development of indicators for buildings
- ISO/DIS 21929-2 Building construction - Sustainability in building construction – Sustainability indicators - Part 2 - Framework for development of indicators for civil engineering works
- ISO 21930 Building construction - Sustainability in building construction – Environmental declaration of building products
- ISO 21931-1 Building construction - Sustainability in building construction – Framework for methods of assessment for environmental performance of construction works - Part 1 - Buildings
- ISO/TR 21932 Building construction - Sustainability in building construction – Terminology

A.2 Relevant standards of ISO/TC59/SC14:

- ISO 15686-1 Buildings and constructed assets – Service life planning – General principles
- ISO 15686-2 Buildings and constructed assets – Service life planning – Service life prediction procedures
- ISO 15686-3 Buildings and constructed assets – Service life planning – Performance audits and reviews

- ISO/DIS 15686-4 Buildings and constructed assets – Service life planning – Service life planning using Building Information Modeling
- ISO 15686-5 Buildings and constructed assets – Service life planning – Life cycle costing
- ISO 15686-7 Buildings and constructed assets – Service life planning – Performance evaluation for feedback of service life data from practice
- ISO 15686-8 Buildings and constructed assets – Service life planning – Reference service life and service life estimation
- ISO/TS 15686-9 Buildings and constructed assets – Service life planning – Guidance on assessment of service life data
- ISO 15686-10 Buildings and constructed assets – Service life planning – When to assess functional performance
- ISO/TR 15686-11 Buildings and constructed assets – Service life planning – Terminology

A.3 Relevant standards of ISO/TC59/SC2:

- ISO 6707-1 Building and civil engineering – Vocabulary – General terms

A.4 Relevant standards of CEN/TC89 and ISO/TC163:

- EN 15603 Energy performance of buildings - Overall energy use and definition of energy ratings
- EN 15217 Energy performance of buildings – Methods for expressing energy performance and for energy certification of buildings
- EN ISO 13790 Thermal performance of buildings – Calculation of energy use for space heating and cooling
- EN ISO 13791 Thermal performance of buildings - Calculation of internal temperatures of a room in summer without mechanical cooling - General criteria and validation procedures
- EN ISO 13792 Thermal performance of buildings - Calculation of internal temperatures of a room in summer without mechanical cooling - Simplified methods

- EN 13829 Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method
- EN ISO 15927 Hygrothermal performance of buildings – Calculation and presentation of climatic data
- EN ISO 12571 Hygrothermal performance of building materials and products - Determination of hygroscopic sorption properties
- ISO/DIS 10916 Calculation of the impact of daylight utilization on the net and final energy demand for lighting
- ISO 12655 Energy performance of buildings — Presentation of measured energy use of buildings

A.5 Relevant standards of CEN/TC156:

- EN 15251 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics
- EN 15243 Calculation of room temperatures and of load and energy for buildings with room conditioning systems
- EN 13465 Ventilation for buildings - Calculation methods for the determination of air flow rates in dwellings
- EN 15242 Ventilation for buildings – Calculation methods for the determination of air flow rates in buildings including infiltration
- EN 15241 Ventilation for buildings – Calculation methods for energy losses due to ventilation systems and infiltration in commercial buildings
- EN 13779 Ventilation for non-residential buildings - Performance requirements for ventilation and room conditioning systems

A.6 Relevant standards of CEN/TC169:

- EN 12665 Light and lighting - Basic terms and criteria for specifying lighting requirements
- A.7 Relevant standards of CEN/TC228:

- EN 15316 Heating systems in buildings – Method for calculation of system energy requirements and system efficiencies
- EN 15459 Energy performance of buildings - Economic evaluation procedure for energy systems in buildings

A.8 Relevant standards of CEN/TC229:

- CEN/TR 16110 Characterization of waste – Guidance on the use of eco-toxicity tests applied to waste
- CEN/TR 16376 Characterization of waste – Overall guidance document for characterization of waste from extractive industries
- EN 12920 Characterization of waste – Methodology for the determination of the leaching behavior of waste under specified conditions
- EN 13965-1 Characterization of waste – Terminology – Part 1: Material related terms and definitions
- EN 13965-2 Characterization of waste – Terminology – Part 2: Management related terms and definitions
- EN 14735 Characterization of waste – Preparation of waste samples for eco-toxicity tests

A.9 Relevant standards of CEN/TC247:

- EN 15232 Energy performance of buildings – Impact of building automation and controls and building management

A.10 Relevant standards of CEN/TC351:

- CEN/TS 16516 Construction products - Assessment of release of dangerous substances - A.11 Relevant standards of ISO/TC146/SC6 and CEN/TC264:
- ISO 16000-3 Indoor air -- Part 3: Determination of formaldehyde and other carbonyl compounds -- Active sampling method
- ISO 16000-4 Indoor air -- Part 4: Determination of formaldehyde -- Diffusive sampling method

- ISO 16000-6 Indoor air -- Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS/FID
- EN ISO 16000-9 Indoor air -- Part 9: Determination of the emission of volatile organic compounds -- Emission test chamber method
- EN ISO 16000-10 Indoor air -- Part 10: Determination of the emission of volatile organic compounds -- Emission test cell method
- EN ISO 16000-11 Indoor air -- Part 11: Determination of the emission of volatile organic compounds -- Procedure for sampling, storage of samples and preparation of test specimens
- ISO 16000-13 Indoor air -- Part 13: Measurement of polychlorinated dioxins/furans and polychlorinated biphenyls (PCBs)
- ISO 16000-15 Indoor air -- Part 15: Measurement of nitrogen dioxide (NO2)
- ISO 16000-17 Indoor air -- Part 17: Measurement of the concentration of airborne mould spores -- Sampling with gelatine/polycarbonate filters followed by a culture-based methodDetermination of emissions into indoor air

A.12 Relevant standards of ISO/TC205:

- ISO 16813 Building environment design -- Indoor environment -- General principles
- ISO 16814 Building environment design -- Indoor environment -- Methods of expressing the quality of indoor air for human occupancy

A.13 Relevant standards of ISO/TC207/SC5:

- ISO 14040 Environmental management - Life cycle assessment - Principles and framework.
- ISO 14044 Environmental management - Life cycle assessment - Requirements and guidelines

A.14 Relevant standards of ISO/TC207/SC3:

- ISO 14025 Environmental labels and declarations - Type III environmental declarations - Principles and procedures

ANNEX B: Relevant national standards [CEN/TC 350, "*Business Plan",* CEN, 2018.]

B.1 Relevant British standards:

- BS 6543:1985 Guide to use of industrial by-products and waste materials in building and civil engineering
- BS 7543:2003 Guide to durability of buildings and building elements, products and components

B.2 Relevant Dutch standards:

- NEN 8006:2004 Environmental data of building materials, building products and building elements for application in environmental product declarations – Assessment according to the Life Cycle Assessment (LCA) methodology

B.3 Relevant French standards:

- NF P 01-010 Environmental quality of construction products – Sanitary and environmental declaration of construction products
- NF P 01-020-1 Environmental quality of construction products and buildings – Part. 1: methodological framework for the description and the characterization of the environmental and sanitary performances of buildings
- GA P 01-030 (2003) Environmental quality of buildings - Environmental management system for the contracting authority: construction activities, adaptation or administration of buildings - Framework for design and implementation of high environmental quality approach

3.1.1 Framework level standards

EN 15643-1:2010 Sustainability of construction works - Sustainability assessment of buildings - General framework

In this standard, environmental, social and economic performance of buildings (both new constructions buildings or refurbishment) are assessed in general principles and requirements, while taking into consideration technical and functional features of a building.

EN 15643-2:2011 Sustainability of construction works - Assessment of buildings - Framework for the assessment of environmental performance

This more specific standard tends to harmonize the development of environmental performance for building in a life cycle perspective and for refurbishment process taking into consideration the potential remaining service life of the building. This standard has been developed under the more general frame of EN15643-1.

EN 15643-3:2012 Sustainability of construction works - Assessment of buildings - Framework for the assessment of social performance

As the previous standard, it set the framework for developing social performances under the EN 15641:1 structure and it is applicable for both new construction and existing buildings.

EN 15643-4:2012 Sustainability of construction works. Assessment of buildings. Framework for the assessment of economic performance

The economic performance, visible in quantitative specific indicators, for both new and existing buildings is assessed by this standard, under the general framework of EN 15643:1.

EN 15643-5:2017: Sustainability of construction works - Sustainability assessment of buildings and civil engineering works - Part 5: Framework on specific principles and requirement for civil engineering works

3.1.2 Building level standards

EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method

This standard, developed by CEN/TC 350, assessed the environmental performance of buildings giving the description of objectives to be evaluated, the system boundary that has to be applied in the building level, the inventory analysis description and its related procedure, environmental indicators to be calculated and its related calculation methodology. The data needed to fulfil the standard requirements are strictly correlated to the EPD information (EN 15804) and covers all the life cycle stages of an analysed building.

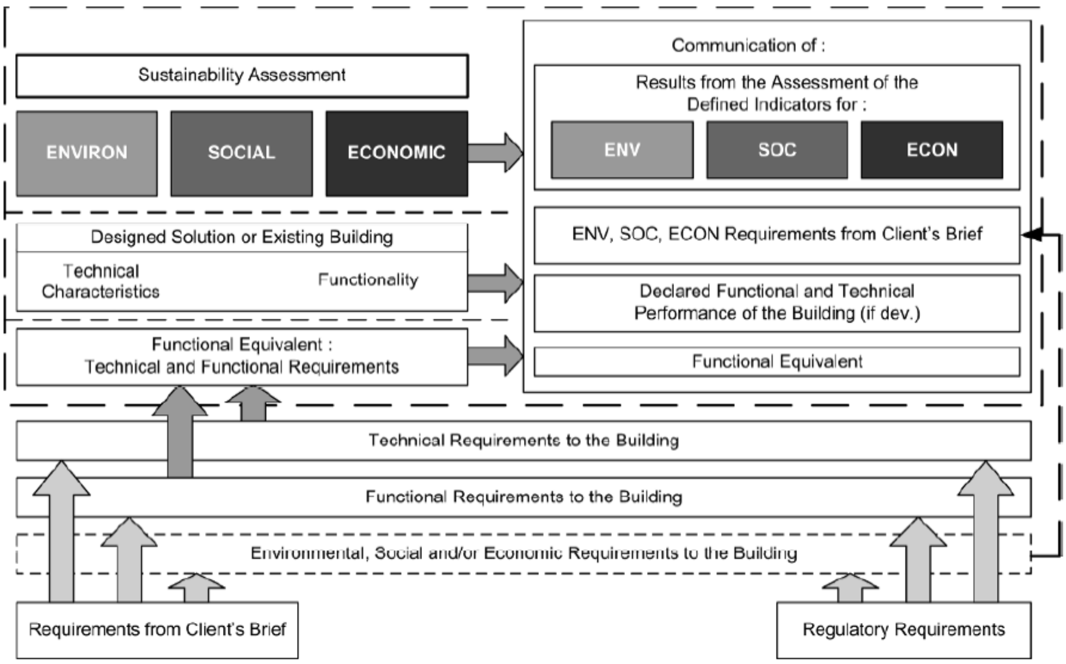


Figure 5: Concept of sustainability assessment for EN 15978:2011 [Source: BS EN 15978:2011, British Standard Institution]

The results that comes from this particular life cycle analysis are expressed by communication rules expressed in the standards itself, so that any evaluation on technological and functional requirements and their interpretations are outside the boundary of the system, but those are considered in functional equivalent, in order to create a dataset which can be useful to comparison's reasons. The deeper part of this standard debates the calculation methods of environmental indicators, and in order to have a general frame to be utilize it create a specific flowchart of process and requirements, expressed in the following table:

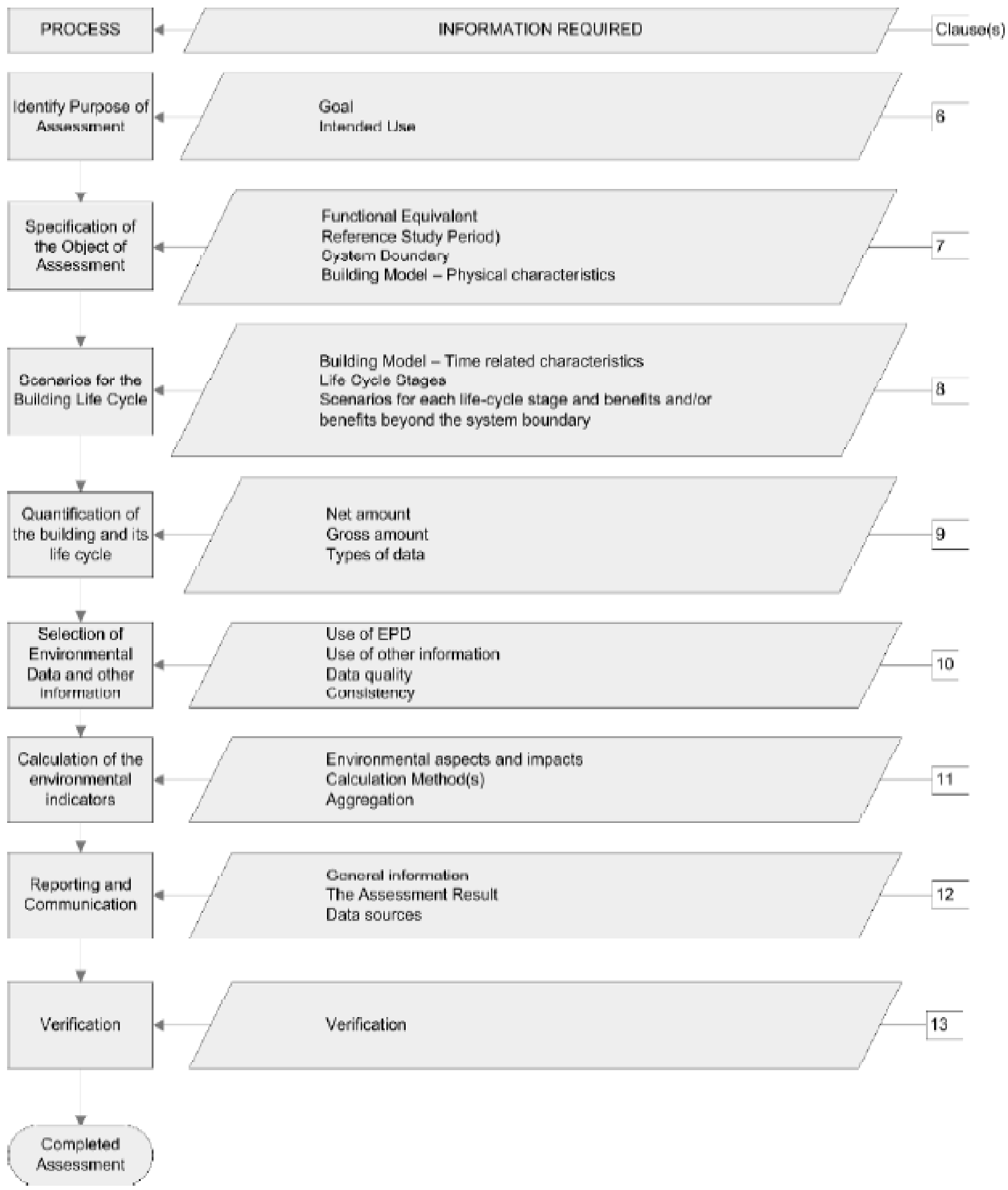


Figure 6: flowchart of the process for the assessment of the environmental performance by EN 15978 [Source: BS EN 15978:2011, British Standard Institution]

The intended use of the assessment is the first real step to be evaluated in order to produce a reliable LCA on environmental impact and the standard itself put some examples as aiming an LCA for decision making purpose or for certification release or conformance to legal requirements for specific buildings. Another important highlighted aspect is the definition of a functional equivalent as a representation of technical and functional features of the building: this is needed for clear and transparent comparison's reasons with other samples. The reference unit so it could be extracted by its functional unit.

The standard empathizes the reference study period in relation to the required service life of the building, identifying three different situations:

- Reference study period is equal to the required service life
- Reference study period is shorter than the required service life
- Reference study period is longer than the required service life (refurbishment, demolition or equivalent new building construction)

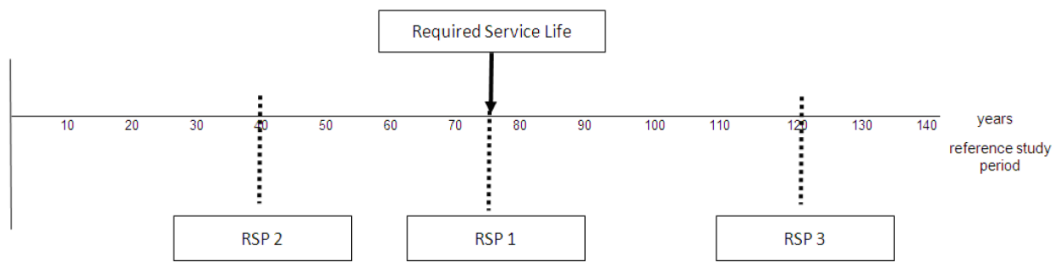


Figure 7: Required and Reference Service Life [Source: BS EN 15978:2011, British Standard Institution]

Excluding the first scenario, in which there a perfect match of reference and required s.l., in the other two we have to adjust the value of environmental impacts output per the factor RSP/ReqSL, taking in consideration which modules are independent or not by this choice and it can be summarized in this graphic representation:

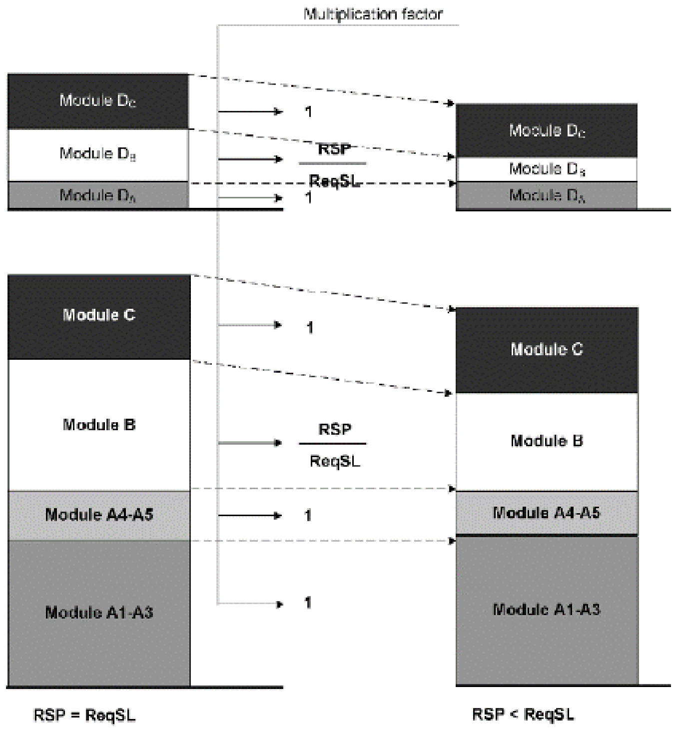


Figure 8: Multiplication factor for RSL<ReqSL [Source: BS EN 15978:2011, British Standard Institution]

Then it is required the definition of which process shall be included in the calculation of environmental impact, known as "boundary of the system": each process that is needed to maintain a relative function of the building must be included, within the building life cycle analysed. As has been made for the development of the communication model of EPD in the EN 15804, the boundary system follows the same "modularity principle":

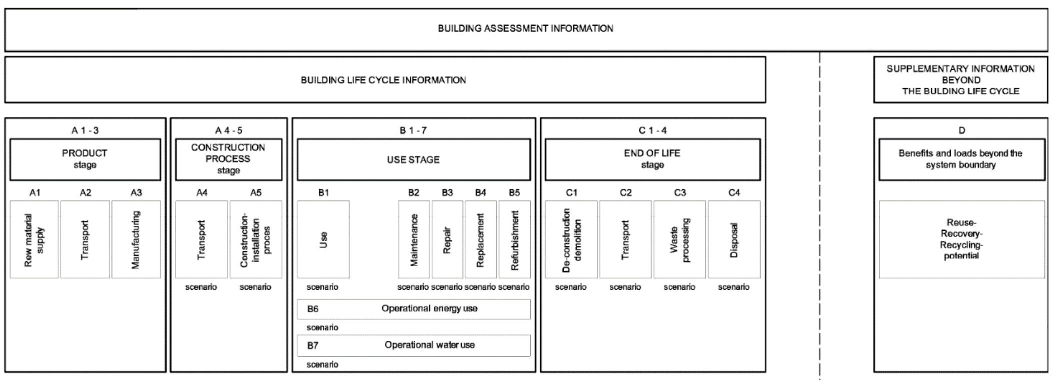


Figure 9: Boundary of the system modules [Source: BS EN 15978:2011, British Standard Institution]

Within the defined boundary of the system, it is necessary include all the time-related information for create a reliable building description: those will be used to assess the possible scenario for the models ranging from construction to end-of-life phase (A4 to C4). The maintenance, replacement and all the other scheduled and periodic operations must be included and had to be based on real-life data.
An important issue has been clarified in the standard: the number of replacements for products, components and elements used in the building, so that a function that rounds up the value (in order to obtain a full number) has been created:

$$NR(j) = E\,[ReqSL / ESL(j) - 1]$$

Furthermore, in this European Standard the environmental indicators for quantified impacts has been assessed, on the basis of factors agreed in the EN 15804, to create a relationship within information included in the EPD system development.

INDICATOR	***ACRONYM***	***UNIT***
Global warning potential	GWP	Kg CO_2 equiv.
Depletion potential of the stratospheric ozone layer	ODP	Kg CFC 11 equiv.
Acidification potential of land and water	AP	Kg SO^{2-} equiv.
Eutrophication potential	EP	Kg $(PO_4)^{3-}$ equiv.
Formation potential of tropospheric ozone photochemical oxidants	POCP	Kg Ethene equiv.
Abiotic Resource Depletion Potential for elements	ADP_elements	Kg Sb equiv.
Abiotic Resource Depletion Potential of fossil fuels	ADP_fossil fuels	MJ, net calorific value

Table 4: Environmental Indicators for EN 15804

The calculation method for each environmental indicator in the life cycle stages is set up on a matrix bases where each product quantified in a specific stage is multiplied with each environmental indicator value, as follow: $EP_i = \vec{a}_j \times M$

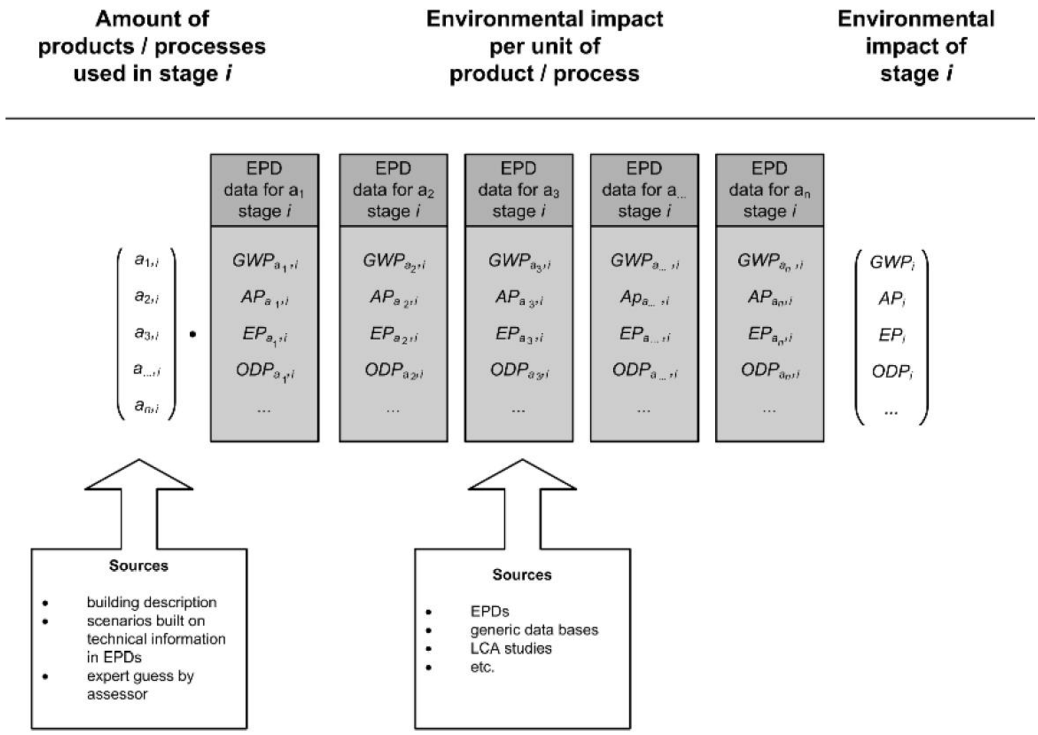


Figure 10: Calculation method for Environmental Indicators [Source: BS EN 15978:2011, British Standard Institution]

EP_i :is the indicator value of the module *i* of the building;

$\vec{a}_j$: is the vector containing the gross amounts of all products used in the module *j* of the building;

M : is the matrix containing in its columns the environmental indicator values per unit of all products and services used in the module *i* of the building.

All this calculation methods have to be reported in a standard way in order to create an information flow that could be applied for all the possible assessment purpose: the outputs have to be transparent and traceable. The final report has to contain all

the general information about general assumptions, the building features, objective of assessment, boundaries and possible scenarios used in the LCA development.
The environmental impacts results must be listed in a structured way, for each life cycle stage analysed and for every omitting information must be declared a reason. All those information requirements and structure is also needed for verification purposes, as the boundaries and scenarios used with respect the assessment reasons, the traceability of the data, conformity with EN 15804 requirements, and completeness and justification for quantification methods at the building level.

- EN 16309:2014 Sustainability of construction works - Assessment of social performance of buildings - Methods
- EN 16627:2015 Sustainability of construction works - Assessment of economic performance of buildings - Calculation methods
- CEN/TR 17005:2017 Sustainability of construction works - Additional environmental impact categories and indicators - Background information and possibilities

3.1.3 Product level standards

- EN 15804:2012+A1:2013 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products
- EN 15942:2011 Sustainability of construction works - Environmental product declarations - Communication format business-to-business
- CEN/TR 15941:2010 Sustainability of construction works - Environmental product declarations - Methodology for selection and use of generic data
- CEN/TR 16970:2017 Sustainability of construction works - Guidance for the implementation of EN 15804

3.2 EPD and PCR

3.2.1 EPD

In its legal framework, an EPD is a Type III environmental declaration in accordance to ISO 14025 and EN 15804, and so it can be categorized as a self-declaration of an LCA studies results. In the past years, there has been plenty of public and private association that developed Type III labelling in order to create an EPD programme in accordance to the ISO 14025, and at the same time their Product Category Rules started to overlap, so it comes with this international situation the necessity to harmonize those declaration and its related rating system. Furthermore, it is really important the process of mutual recognition within all those systems: right now, this approach is the one that can guarantee reduction in terms of cost time and effort, and can lead to different EPDs and PCRs systems, thanks to product categorization or geographical scope and communication's method to a standardized publication's way.

In the creation of a global common network, the International EPD system, the oldest programme started to provide PCR and an EPD system from 1998, has developed a specific path to create an EPD in accordance to the international standards. We want to analyse it to create a single images of a possible standard workflow system that can be shared outside its boundary.

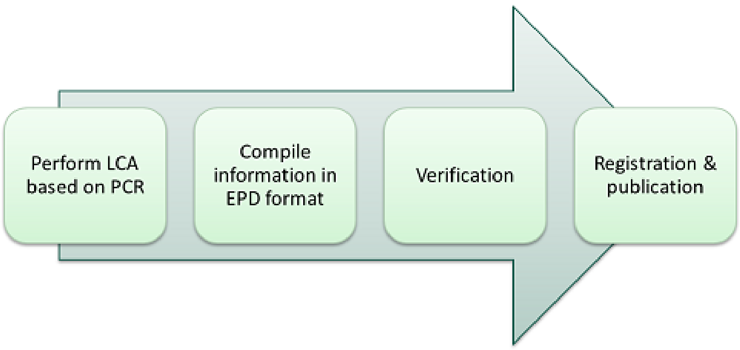


Figure 11: EPD approval path [Source:https://www.environdec.com/Creating-EPDs/Steps-to-create-an-EPD/]

The validation process goes through:

1) A third-party verification developed by an expertise of LCA has to be set up by the company who wants to create a specific EPD for one or more of their products. This LCA must comply with the Product Category Rules (PCR) which contains specification of LCA and EPD data divided by product category. All the data must be written in a correct English and with no personal implementation in terms of volume and consideration. The predefined form must be filled completely without missing information.

2) The results obtained must be compiled in a specific EPD format, which can vary for different products due to the flexibility of information that must be contained for such a variety of material that could be analysed.

PARAMETER		UNIT	A1	A2	A3	Total A1-A3	Add columns for add. modules
Global warming potential (GWP)	Fossil	kg CO_2 eq.					
	Biogenic	kg CO_2 eq.					
	Land use and land transformation	kg CO_2 eq.					
	TOTAL	kg CO_2 eq.					
Depletion potential of the stratospheric ozone layer (ODP)		kg CFC 11 eq.					
Acidification potential (AP)		kg SO2 eq.					
Eutrophication potential (EP)		kg PO43- eq.					
Formation potential of tropospheric ozone (POCP)		kg C2H4 eq.					
Abiotic depletion potential – Elements		kg Sb eq.					
Abiotic depletion potential – Fossil resources		MJ, net calorific value					
Water scarcity potential		m3 eq.					

Table 5: EPD Format (Potential Environmental Impact) [Source: https://www.environdec.com/Creating-EPDs/]

3.2.2 Product Category Rules (PCR)

The Product Category Rules, developed for each EPDs system by the International EPD System agency, are a set of rules, requirements and guidelines in terms of information and communication methods for each product category, and has to be in accordance with:

- ISO 14025:2006;
- ISO 9001, Quality management system;
- ISO 14001, Environmental management systems;
- ISO 14040, LCA – Principles and procedures;
- ISO 14044, LCA – Requirements and guidelines.

With respect construction product we can also add:

- ISO 15804, Sustainability of construction work, EPD;
- ISO 21930, Environmental declaration of building product.

Life cycle stages in the International EPD System	**Asset Life Cycle stages**	**Information module EN 15804**	**EPD type**	
			Declared unit: - Cradle-Gate - Cradle-Gate with opt.	**Functional unit: - Cradle-grave**
Upstream	A1) raw material supply	A1-A3) Product stage	Mandatory	Mandatory
Core	A2) Transport			
	A3) Manufacturing			
Downstream	A4) Transport	A4-A5) Construction process stage	Optional for a product and mandatory for a service	Mandatory
	A5) Construction installation			
	B1) Use	B1-B5) Use stage	Optional	Mandatory
	B2) Maintenance			
	B3) Repair			
	B4) Replacement			
	B5) Refurbishment			
	B6) Operational energy use			
	B7) Operational water use			
	C1) Deconstruction, demolition	C1-C4) End of life stage	Optional	Mandatory
	C2) Transport			

Life cycle stages in the International EPD System	Asset Life Cycle stages	Information module EN 15804	EPD type	
			Declared unit: - Cradle-Gate - Cradle-Gate with opt.	**Functional unit: - Cradle-grave**
	C3) Waste processing			
	C4) Disposal			
Other environmental information	D) Future, reuse, recycling or energy recovery potentials	D) Recovery stage	Optional	Optional
Inclusion of reference service life (RSL)	-	-	Mandatory if any module in B is included	Mandatory

Table 6: Life cycle of a building divided in 4 information modules according to ISO 21930 and 15804

A Life Cycle Assessment developed in the timeframe from cradle to grave is quite always the basis for the issuing of the EPD documentation, and in this case the scope of comparison within a limited product group permits the use of declared units, typically kg of product. While, if the scope of the LCA fall back into comparison across different material and services, a functional unit is required in order to guarantee a more equal judgement, so the International EPD system has developed sub-PCR with respect to particular product: Mortars, Synthetic carpet, Bricks, blocks, wood structures, acoustical systems solution, and so on.

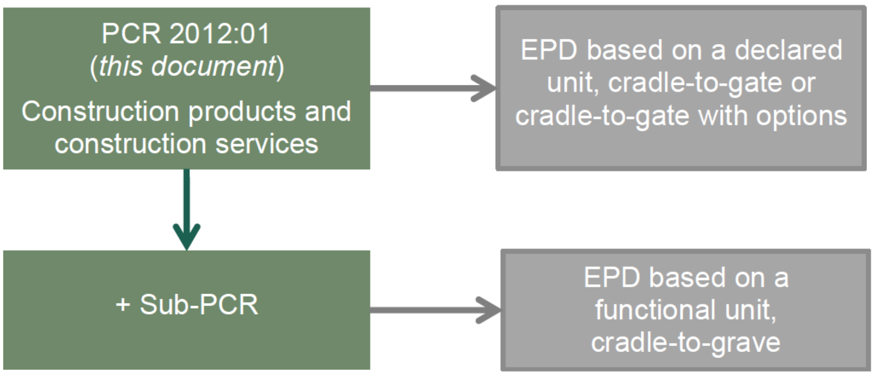


Figure 12: PCR structure development [Source: https://www.environdec.com/PCR/]

The latest version of PCR for construction product and construction services has been developed in 2012 and will be valid until 03/03/2019 when it will be revisited and issued the newest 3.0 version. This programme is addressed to all the construction product, and it recall the definition of it from the European construction product regulation: *"construction product' means any product or kit which is produced and placed on the market for incorporation in a permanent manner in construction works or parts thereof and the performance of which has an effect on the performance of the construction works with respect to the basic requirements for construction works".*

A very important aspect is its validity that has been classify as global but limited for what concern the timeframe for 5 years, passed that time the EPD must be revisited and reissued.

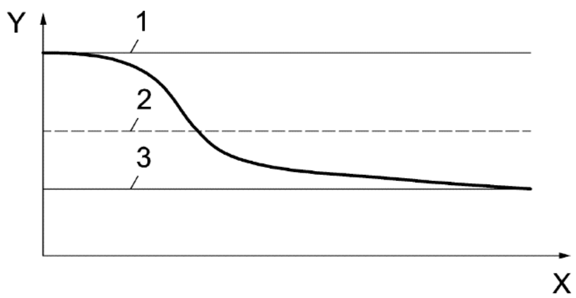
3.2.3 EN 15804:2012+A1:2013

This standard for the "Sustainability of construction works" has been issued to guarantee a central core to the PCR and create an EPD where they can easily give environmental information for buildings, in aggregated way. The Product Category Rules indicates, as already said, the parameters to be reported, which product stages had to be taken into account, calculation methods with respect specific inventory, boundaries and possible scenarios. In order to create a strick connection with EN 15978, the standards indicates the path in the same way as for building impact's evaluation: the primary step is the definition of a scope for a EPD, declearing that it shall be the identification of construction works that cause less environmental stress among possible different solutions, so that the structure has to facilitate the comparison among different construction programme.

This comparison has to be made for product that has same use and functions among all their life cycle, taking into the same amount of material and their relationship with operational aspects in the building to create similar scenarios. The EPD system has to use the same modularity chart expressed in the EN15978 so that the life cycle (cradle-to-grave) could be divided in stages and module groups (A1-A3, A4-5, B1-B5, B6-B7, C1-C4, and module D).

The standard analyses, as in the EN 15978, the difference between functional and declared unit in order to indicate the functions or performance characteristics of a product when it is identified or not, and it give us the possibility to normalized, in a mathematic way, the environmental data to create an expressed common basis. In the same way the Reference Service Life (RSL) expresses the performance of the product for a timeframe, taking into account the application of the product in the building context.

The RSL, as expressed in the Annex A of the standard, could be assessed in three different ways:



X = RSL

Y = Functional performance

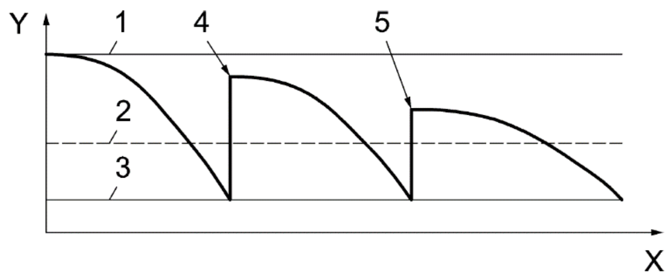
1 = Initial

2 = Average

3 = Minimum

Figure 13: Type of declared technical and functional performance and RSL [Source:15804:2012 + A1]

The RSL is strict correlated to the in-use conditions that, to estimate a reliable data, we have to take into account a multivariable scenario, in which internal and external environment, maintenance quality works plays a major role.



X = RSL
Y = Functional performance
1 = Initial
2 = Average
3 = Minimum
4 = Maintenance / Repair
5 = Maintenance / Repair

Figure 14: Type of declared technical and functional performance, repair/maintenance during RSL [Source:15804:2012 + A1]

The system boundaries describe which physical elements and their impact shall be assessed during the life cycle in order to have transparent and well-organized data to be compared. The LCA has to be based on that particular modular structure to which the boundaries have to match in a perfect way.

To set up the system boundaries we must follow two important principles:

- The “modularity principle”: if a process influences the environmental performance of a determined product, it has to be assigned to the stage in which it occurs;
- The “Polluter pays principle”: a waste process has to be assigned to the product system that generate the waste.

Furthermore, a very crucial aspect is the data availability to conduct a precise LCA and create reliable EPD, in order to do that, the standard prescribe firstly the use of specific data obtained from manufacturer production stage, then average data obtained from specific processes.

After the exclusions of those rules, we have to apply those following one:

Modules	Module A1 - A3		A4 - A5	B1 - B7	C1 - C4
	Production of commodities, raw material	Product manufacture	Installation processes	Use processes	End-of-life processes
Process type	Upstream processes	Processes the manufacturer has influence over	Downstream processes		
Data type	Generic data	Manufacturer's average or specific data	Generic data		

Table 7: Application of Generic and Specific data on EPD [Source EN 15804:2012 + A1]

The EN ISO 14044:2006, 4.2.3.6 deals with the quality requirements for data, crucial for the development of a reliable comparison system, but it has been also implemented with interior rules explained it this specific standard such as the update of data, that shall be as current as possible, or that data sets shall be based on 1-year average data. The calculation rules, that this standard try to apply, will determine specific predetermined parameters to be included in the EPD modules, and in order to do that is necessary create possible and scenario with the help of all the technical information derived from the product functions.

The elaborated scenario must be realistic and probable. The final calculation models and rules must be set up in accordance to the EN ISO 14044:2006. The allocation rules described in the standard EN ISO 14044 shall always be applied, but those have been implemented here in the EN 15804 in order to be more specific. The general rules, that the allocation process must be neglected whenever it is possible must be applied and then, when it is unavoidable it must be reasonably explained and justified. When we are in a situation of creation of co-product, we have to divide the process in sub-processes where we can allocate the co-product, everything included in our boundary system: if we have no input and output data about this sub-process, we have to allocate them in order to maintain their physical relationship. In all other cases we can start with an allocation based on their economic value. We have already seen how the EN 15978 developed a modular way for communication purpose, creating a precise system in which the information about environmental performance of the building should be assessed. In the same way the EPD information are divided in modules, for each stage of the product's life cycle, so that has been possible to set up a common communication format.

The environmental indicators in order to describe the impacts are the same as the EN 15978, even for the description of the resource's use.

Additional information on release of dangerous substances to indoor air, soil and water during the use stage			
Scenario title	**Parameter**	**Units**	**Result**
Release scenario Indoor air	Test results according to CEN/TC 351	*a*	
	Description of scenario 1	Text	
	Description of scenario *n*	Text	
Release scenario Soil	Test results according to CEN/TC 351	*a*	
	Description of scenario 1	Text	
	Description of scenario *n*	Text	
Release scenario Water	Test results according to CEN/TC 351	*a*	
	Description of scenario 1	Text	
	Description of scenario *n*	Text	
a	Emissions to indoor air and releases to soil and water according to the horizontal standards on measurement of release of regulated dangerous substances from construction products using harmonised testing methods according to the provisions of the respective Technical Committees for European product standards, when available.		

Table 8: Additional Information in the EPD structure [Source: EN 15978:2011]

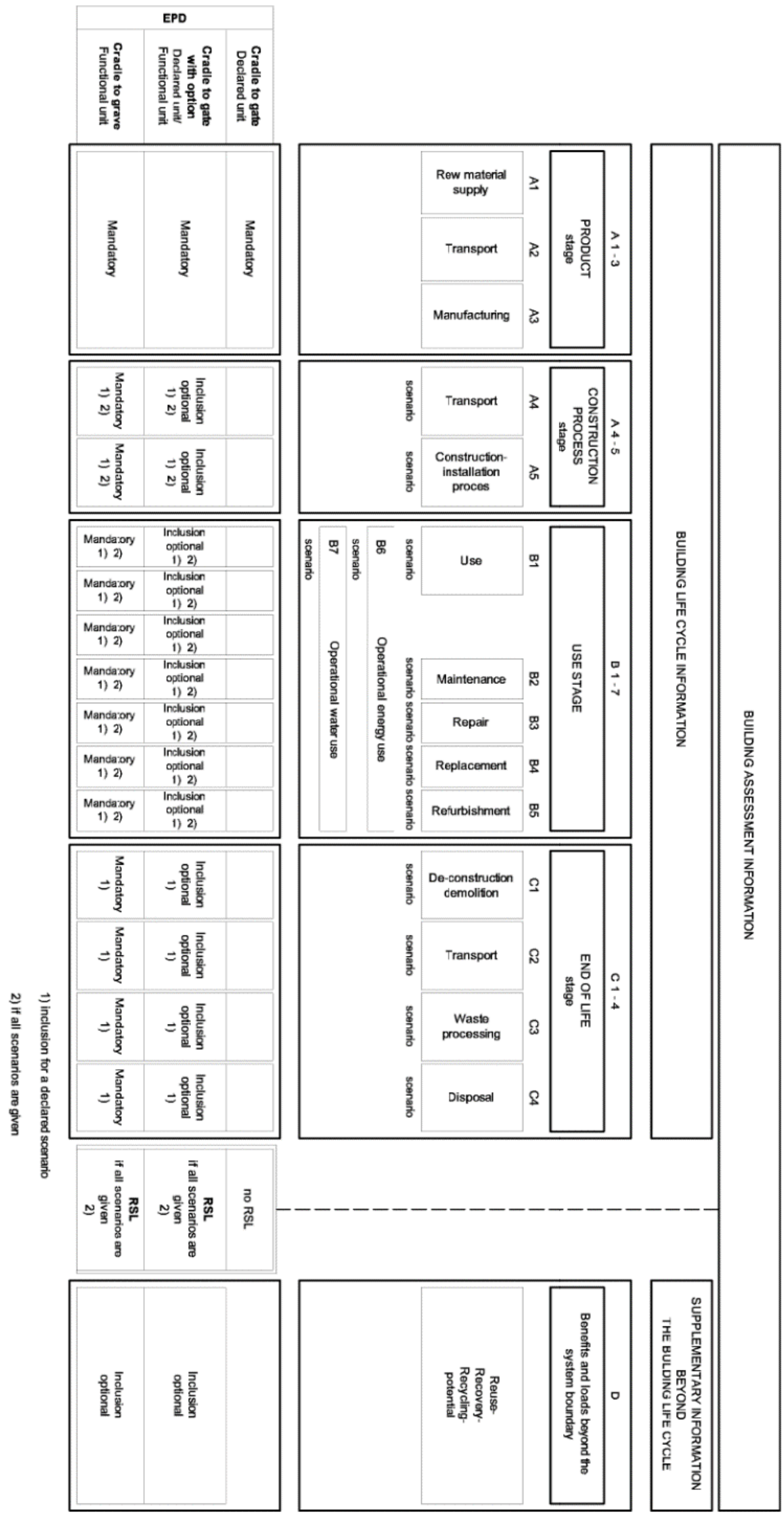


Figure 15:Types of EPD with respect to life cycle stages covered and life cycle stages and modules for the building assessment [Source: EN 15804:2012 +A1:2013]

3.2.4 Growing EPD data's importance

Thanks to the ISO 14025 and EN 15804:2012+A1:2013 has been possible to set up a common framework on the creation of shared EPDs database for construction products, despite the growing number of private associations that creates EPD programmes in accordance with the standards. As it is possible to see in the graph below the number of verified EPD has increased in the past three years for two main reasons:

- BREEAM, Greenstar and other Building assessment scheme introduced in their framework the recognition of EPD;
- Green Public Procurement increase interest in Environmental Product Declarations, and their implementation in its legal process.

Furthermore, some Member State introduce the EPD evaluations in their national regulations: France and Belgium started to require EPDs to implement environmental claims, while Germany utilizes them as requirements for some specific real estate investment for some particular construction asset.

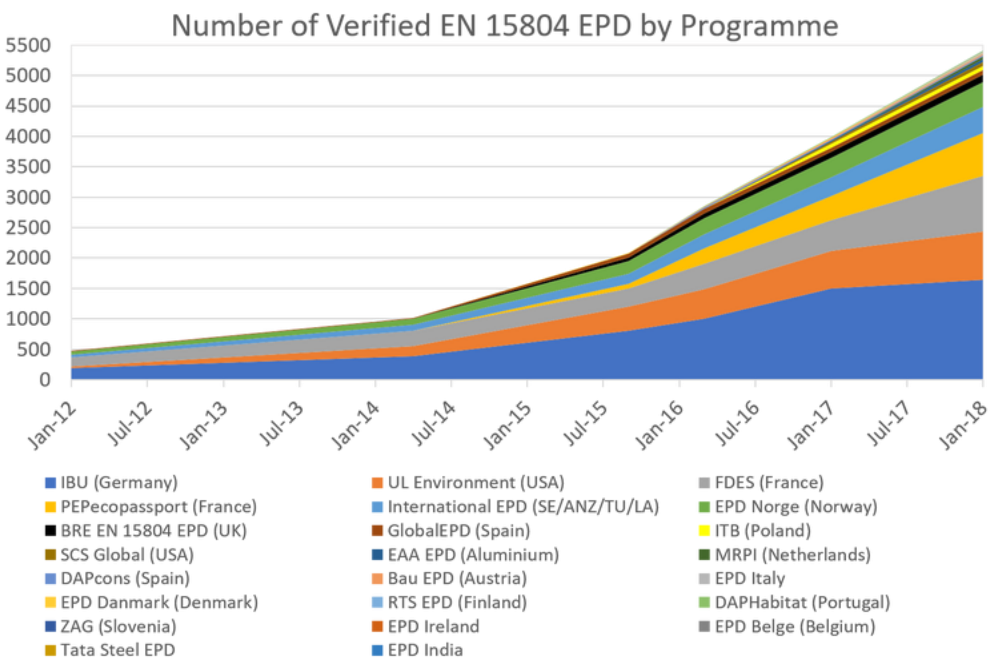


Figure 16: Number of verified EN 15804 EPD by Programme [Source: https://constructionlca.wordpress.com/2018/04/18/update-to-2018-epd-numbers/]

A huge problem in the harmonization process for the EPD system is the creation of an International EPD database, while nowadays the International EPD System based in Stockholm (Sweden), had collected until today more than 900 EPD from 41 different countries, while other EPD platform has been developed in France (Ines) and Germany (Oekobau) so there is a huge imbalance with respect data available from those States. In total we can count more than 5000 EPD registered today around the world and the number is going to increase as more legislations are going to be implemented in national regulation for what concern Life Cycle Assessment studies in the construction industries.

So, if all the EPD programme are going in the same direction for what concern a share methodology and mutual recognition for EPD scheme and framework, the number of Database in which the EPD have been collected during those years has become greater than what could be expected. This growth will increase the transparency of those programme and the possibility to share environmental performances for research, comparison, and critical analysis among Europe and in a world perspective, both for technicians and both final users.

While national and international agency works to standardize the EPD system format, they run on the same direction for what concern the PCR harmonization. The International EPD System is working closely with EPD Turkey Agency, Australasian EPD Programme, EPD Latin America, EPD Brazil and Regional hub in India in order to develop a world shared Guidance for PCR. To pursue this achievement, all the PCR databases need to collaborate and to operate in accordance with ISO 14025, such as IBU, ASTM, NSF International National Centre for Sustainability Standards EPD and others.

3.3 Study of the Most Adopted Rating Systems of Buildings

Rating systems aim to evaluate the environmental impact of buildings and construction projects. These schemes are designed to assist project management in making the projects more sustainable by providing frameworks with precise criteria for assessing the various aspects of a building's environmental impact. Given the growing interest in sustainable development worldwide, many rating systems for assessing the environmental impact of buildings have been established in recent years, each one with its peculiarities and fields of applicability.

The present work is motivated by an interest in emphasizing such differences to better understand these rating systems and extract the main implications to building design. It also attempts to summarize in a user-friendly form the vast and fragmented assortment of information that is available today.

The analysis focuses on the six main rating systems:

- The Building Research Establishment Environmental Assessment Methodology (BREEAM),
- The Comprehensive Assessment System for Built Environment Efficiency (CASBEE),
- The Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB),
- The Haute Qualit*é* Environnementale (HQE^{TM}),
- The Leadership in Energy and Environmental Design (LEED),
- The Sustainable Building Tool (sbtool).

This threefold depiction (Figure 14) is called the triple bottom line (TBL) of sustainability; it was first introduced by Elkington in 1994 and is still used nowadays.

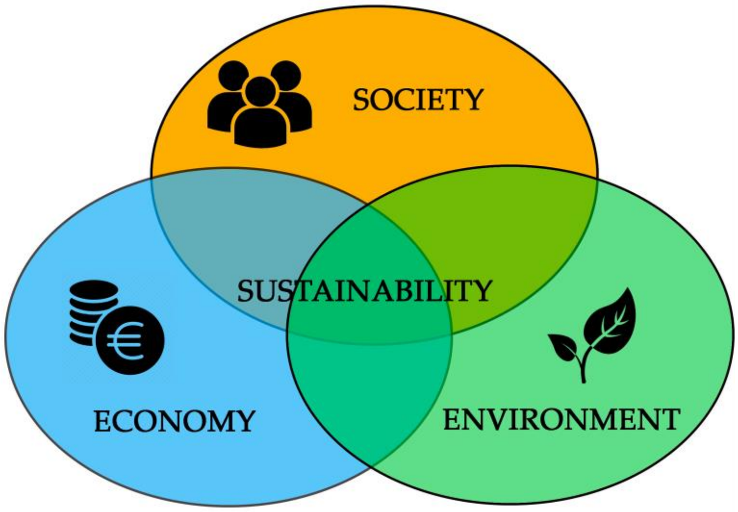


Figure 17: Triple bottom line of sustainability [Source: Elkington, J. Cannibals with Forks—The Triple Bottom Line of 21st Century Business; New Society Publishers:

The aim of the TBL is to consider the impact of resource consumption and the value creation in terms of integration among the three dimensions, assuming that each of them is equally important.

According to the Western Australia Council of Social Services, social sustainability is the capacity to provide a good quality of life by creating healthy and liveable communities based on equity, diversity, connectivity, and democracy. This moral capital requires the maintenance and the replenishment of shared values and equal rights. Human capital is accepted today as part of economic development. In this regard, it is necessary to define economic sustainability as the optimal employment of existing resources, so that a responsible and beneficial balance can be achieved over the long-term to reach the preservation of the capital. Economic sustainability concerns the real economic impact that a society has on its economic environment. The final definition to complete the triad of the TBL is environmental sustainability. It is defined as the capacity to use natural resources without exceeding their regenerative capacity and protecting the "natural capital" to prevent harm to humans and the environment; it is inherently linked with the concepts of sustainable production and sustainable consumption.

Going deeply on the TBL of sustainability, many rating systems currently available on the market, have been developed for assessing the environmental performance of buildings. They were introduced by different research institutions and have been modelled to respond to specific needs. With this work several information has been collected from official websites and technical manuals that deal with these assessment tools.

An interesting result of this work are the analysis of many building classification systems collected from different sources, their evolution reconstructed in chronological order and their geographical spread worldwide, and the comparison and in-depth analysis of the six rating systems most adopted and studied. Furthermore, the scoring mechanisms of these evaluation systems are presented.
The work is mainly divided into six sections. In the first one, the concepts underlying the environmental assessment schemes are described. In the second one the two most important approaches for assessing building sustainability performance are summarized: Life Cycle Assessment (LCA) and rating systems. In the last table are collected a huge number of tools and schemes, it provides information about their introduction year, promoting countries and administrators; even if this list may not be complete a wide range is included. In Section 3 are presented materials and methods adopted to conduct this work. Then in Section 4, six rating systems have been selected and presented in detail, after having established four selection criteria. These six selected schemes are deeply analysed and compared in a dedicated section, the 5th, according to various criteria such as the building and project types, life cycle phases, and scopes, arranged considering all the involved aspects in the evaluation of the environmental performance. The last section is dedicated to a summary of the work.

3.3.1 Overview of Environmental Assessment Schemes for Buildings

In the last 20 years there have been significant developments in investigating the impact of buildings on the environment. The purpose of these schemes is to measure the environmental sustainability of a built environment in a consistent and comparable manner, with respect to pre-established standards, guidelines, factors, or criteria. The two main approaches that have been used to design environmental assessment schemes for buildings are Life Cycle Assessment (LCA) and building assessment methods or rating systems. In some applications, both approaches have been combined.

3.3.2 Rating Systems for Assessing the Environmental Performance of Buildings

Classification systems for assessing the buildings environmental performance aim to establish an objective and complete method for evaluating a wide range of environmental performance. The goal of these schemes is to measure the building performance in a coherent and harmonized manner with respect to pre-established standards, criteria, factors, or guidelines.

Scoring methods have been mostly used to create rating systems for assessing buildings environmental sustainability and are based on four major elements:

1) Categories: they form a specific set of items relating to the building environmental performance considered during the assessment;
2) Scoring system: system of performance measurement that cumulates the possible points or credits number that can be earned by achieving a given level of performance in several aspects analysed;
3) Weighting system: represents the relevance assigned to each category within the overall scoring system;
4) Output: it aims at showing, in a comprehensive manner, the results of the environmental performance obtained during the scoring phase.

This structure is used by all rating systems for assessing the buildings' environmental impact, but once the details are examined, may diverge specific adaptations in several significant parts.

3.3.3 Rating Systems for Assessing the Buildings' Environmental Impact worldwide

The Building Research Establishment Environmental Assessment Method (BREEAM) firstly aimed at assessing the building's environmental impact. Introduced in 1990, and, since then, the field of the classification systems for assessing the building's environmental impact has been the subject to a rapid increase in the number of developed schemes and introduced on the market worldwide. This phenomenon seems to have reached a stability in recent years.

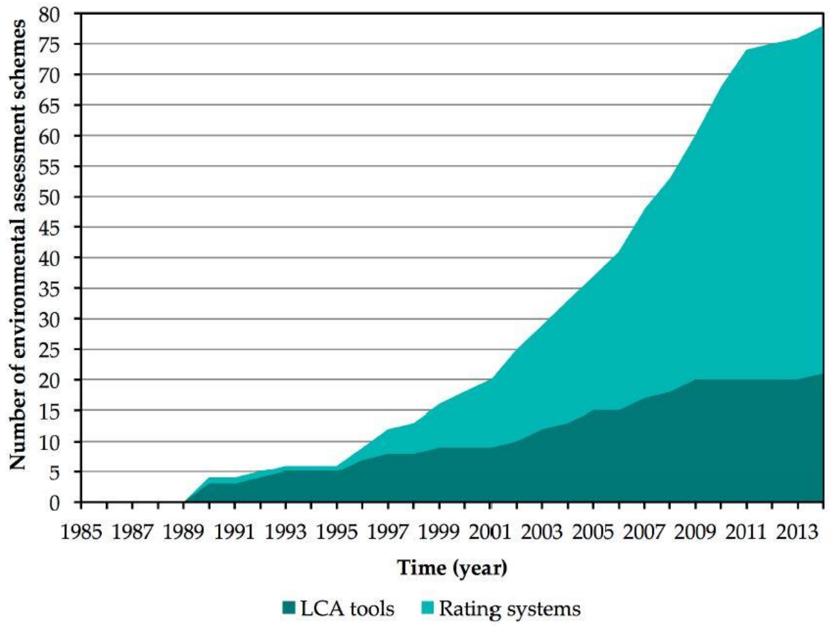


Figure 18: Trend of the schemes used for assessing the environmental impact of buildings presented worldwide from 1990 to 2014 [Source: Berardi, et al., 2017]

Table 18 lists more than 70 sustainable building assessment systems released worldwide, including LCA schemes and rating systems, providing additional information. The highest rate of introduction of new schemes, as can be observed, was registered between 1995 and 2010. After, the rate went down. Rating systems represent the largest share of all schemes presented worldwide and show a logistical growth. On the other hand, the trend of the LCA schemes develops rather linearly.

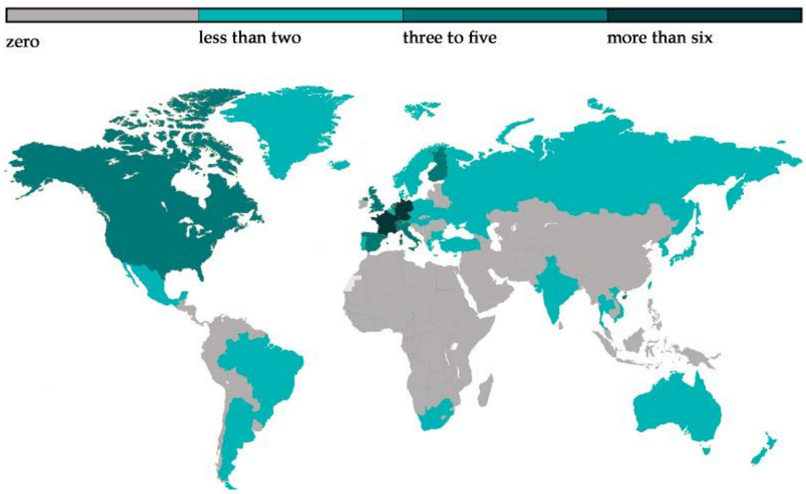


Figure 19: Number of rating systems for assessing the environmental impact of buildings available per country [Source: Berardi, et al., 2017].

The geographical distribution of the tools collected is as follows: 54 schemes in Europe, 15 in Asia, 8 in North America, 3 in both Oceania and South America, and almost 0 in Africa and Middle Eastern countries. Furthermore, some can't be attributed to a specific country or continent. However, the three schemes available in South America are only a personalization of tools originally developed in other continents.

3.4 Methodology

Literature about the schemes and their contents and structure is quite limited; the great part of data used have been acquired directly from rating schemes' official technical manuals. Additional material has been collected from the official homepages of the certification organizations or from scientific papers. In this research, the analysis focuses only on the evaluation and elaboration of the officially declared attributes of the frameworks. For this study, only environmental rating systems for assessing the buildings environmental performance have been considered; moreover, among all the worldwide existing rating systems, in the subsequent analyses have been considered only those that meet all the following four criteria:

1) Focus exclusively on buildings;
2) Of great scientific interest: cited in at least 20 papers present in the Elsevier's Scopus database.
3) Spread adoption: more than 500 projects certified;
4) Have to be a consolidated development: more than 5 years of service.

As shown in the following table, only six rating systems have been chosen because meet the four criteria, and will be described in Section 4:

1) Leadership in Energy and Environmental Design (LEED®), United States;
2) Building Research Establishment Environmental Assessment Methodology (BREEAM), United Kingdom;
3) Comprehensive Assessment System for Built Environment Efficiency (CASBEE), Japan;
4) SBTool, international;
5) Haute Qualit*é* Environnementale (HQE™), France;
6) Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB), Germany.

RATING SYSTEM	RESEARCH KEYS IN ELSEVIER'S SCOPUS (30TH OCTOBER 2018)	CITATIONS IN SCOPUS	CERTIFIED PROJECTS	YEARS OF DEVELOPMENT
LEED	leed OR "leadership in energy and environmental design" AND sustainable AND building AND (assessment OR evaluation)	256	89,600	19
BREEAM	breeam OR ("bre environmental assessment method" OR "building research establishment environmental assessment methodology") AND sustainable AND building AND (assessment OR evaluation)	132	>559,000	26

RATING SYSTEM	RESEARCH KEYS IN ELSEVIER'S SCOPUS (30^{TH} OCTOBER 2018)	CITATIONS IN SCOPUS	CERTIFIED PROJECTS	YEARS OF DEVELOPMENT
CASBEE	casbee OR "comprehensive assessment system for built environment efficiency" AND sustainable AND building AND (assessment OR evaluation)	47	>14,000 a	11
SBTOOL	sbtool AND sustainable AND building AND (assessment OR evaluation)	28	<2000	21
HQE™	hqe OR ("haute qualité environnementale" OR "High environmental quality") AND sustainable AND building OR (assessment OR evaluation)	24	380,000 b	23
DGNB	dgnb OR "deutsche gesellschaft für nachhaltiges bauen" AND sustainable AND building AND (assessment OR evaluation)	24	>718	8
GREEN STAR	"green star" AND sustainable AND building AND (assessment OR evaluation)	19	1450	9
GREENGLOBES	greenglobes OR "green globes" AND sustainable AND building AND (assessment OR evaluation)	10	1200	17
GREEN MARK	"green mark" AND sustainable AND building AND (assessment OR valuation)	6	3000	12
NABERS	nabers OR "national australian built environment rating system" AND sustainable AND building AND (assessment OR evaluation)	5	15,000	16
EEWH	eewh AND sustainable AND building AND (assessment OR evaluation)	5	4300	18
TERI-GRIHA	teri-griha OR "teri green rating for integrated habitat assessment" AND sustainable AND building AND (assessment OR evaluation)	0	875	10
BEAM PLUS	"beam plus" AND sustainable AND building AND (assessment OR evaluation)	6	467	21
LENSE	lense AND sustainable AND building AND (assessment OR evaluation)	4	N/A	9
PROMISE	promise AND Finland AND sustainable AND building AND (assessment OR evaluation)	0	N/A	11
ESCALE	escale AND sustainable AND building AND (assessment OR evaluation)	0	N/A	16
ØKOPROFIL	økoprofil OR ecoprofil AND sustainable AND building AND (assessment OR evaluation)	0	N/A	18
SICES	sices OR "sustainability index of a community energy system" AND sustainable AND building AND (assessment OR evaluation)	0	N/A	N/A
SPEAR®	spear OR "sustainable project appraisal routine" AND sustainable AND building AND (assessment OR evaluation)	3	N/A	17
LIDERA	lidera OR "liderar pelo ambiente para a construção sustentável" AND sustainable AND building AND (assessment OR evaluation)	5	24	12
CEPAS	cepas OR "comprehensive environmental performance assessment scheme" AND sustainable AND building AND (assessment OR evaluation)	1	N/A	15
SBAT	sbat OR "sustainable building assessment tool" AND sustainable AND building AND (assessment OR evaluation)	14	N/A	15

RATING SYSTEM	RESEARCH KEYS IN ELSEVIER'S SCOPUS (30TH OCTOBER 2018)	CITATIONS IN SCOPUS	CERTIFIED PROJECTS	YEARS OF DEVELOPMENT
GHEM	ghem OR "Green home evaluation manual" AND sustainable AND building AND (assessment OR evaluation)	0	N/A	N/A
GOBAS	gobas OR "green olympic building label" AND sustainable AND building AND (assessment OR evaluation)	0	N/A	14
ESGB	esgb OR "evaluation standard for green building" AND sustainable AND building AND (assessment OR evaluation)	12	N/A	11
LOTUS	lotus OR "sustainable building assessment system" AND sustainable AND building AND (assessment OR evaluation)	3	12	10

a updated in 2015; b updated in 2016; N/A: not available; LEED: Leadership in Energy and Environmental Design; BREEAM: Building Research Establishment Environmental Assessment Methodology; CASBEE: Comprehensive Assessment System for Built Environment Efficiency; HQE: Haute Qualité Environnementale; DGNB: Deutsche Gesellschaft für Nachhaltiges Bauen; SBTool: Sustainable Building Tool.

Table 9: Evaluation of rating systems against the identified four selection criteria [Source: Berardi, et al., 2017].

The six schemes are deeply analysed in Section 5, differences and similarities between them have been explored, the aim was to identify possible implications for the design of buildings. To this scope, the rating schemes that have been selected are grouped into homogeneous categories, and data is compared regarding design purpose and requirements, geographical coverage, etc. Finally, some general conclusions have been drawn.

3.5 Description of the Selected Rating Systems

In this section are described the six rating systems that have been selected. Here are presented the exploitation of categories, scoring, the structure, weighting and outputs, and the main features of each system.

3.5.1 Building Research Establishment Environmental Assessment Methodology (BREEAM)

Conceived in the UK in 1988 by the Building Research Establishment, the Building Research Establishment Environmental Assessment Methodology (BREEAM) was launched in 1990. It has currently been used in around 556,700 certified buildings around the world and, since its launch, more than two million buildings have been registered for assessment.

The main scheme is composed of ten categories which describe sustainability through 71 total criteria. To each category is assigned a percentage-weighting factor and is proportionally assigned the overall number of 112 available credits. However, there are some constraints on the credit assignment: indeed, a minimum achievement is required for the categories Energy and CO_2 and Water and Waste, which are reported in Table 7 where the categories for each scheme are listed.

RATING SYSTEM	CATEGORIES																		
	Energy and CO_2 emissions	**Water**	**Materials**	**Surface Water Run-Off**	**Waste**	**Pollution**	**Health and Wellbeing**	**Ecology**	**Management**	**Governance**	**Social and Economic Wellbeing**	**Resource and Energy**	**Land Use and Ecology**	**Transport and Movement**	**Innovation**	**Landscape and Heritage**	**Integrated Design**	**Stakeholders**	**Resilience**
Breeam communities 2012										X	X	X	X	X					
Breeam new construction 2016	X	X	X		X	X	X		X				X	X	X				
Breeam in-use 2015	X	X	X		X	X	X		X				X	X					
Breeam infrastructure 2016	X	X	X		X	X	X						X	X	X	X	X	X	X
Breeam nondomestic refurbishment 2015	X	X	X		X	X	X		X				X	X	X				
Ecohomes	X	X	X		X	X	X		X				X	X	X				
Code for sustainable homes	X	X	X	X	X	X	X	X	X										

Table 10: BREEAM: categories for each scheme [Source: Berardi, et al., 2017].

3.5.2 Comprehensive Assessment System for Built Environment Efficiency (CASBEE)

The Comprehensive Assessment System for Built Environment Efficiency, referred to by the abbreviation CASBEE, is a sustainability rating system for buildings from Japan. It was developed in 2001 by the Japan Sustainable Building Consortium (JSBC). In 2005, it was launched on the international market and, since 2011, it has become mandatory in 24 Japanese municipalities.

- CASBEE's structure has several schemes that depend on the size of a building and address the four main building life cycle phases:
- CASBEE for Predesign, for use in site selection and building planning;
- CASBEE for New Construction, to be used in the first three years after building completion;
- CASBEE for Existing Buildings, to be used after at least one year of operation;
- CASBEE for Renovation, which is intended to support a building refurbishment.

To fulfil the specific purposes, CASBEE moreover features lots of supplementary rating systems relevant when the basic version cannot be used, such as detached houses, temporary constructions, urban development, heat island effect, and cities and market promotions. CASBEE assesses a building project using a metric called building environmental efficiency (BEE), given by the ratio between the two metrics: built environmental quality (Q) and built environmental load (LR)

➔ BEE= Q/LR

Q calculates the "improvement in everyday services for the building users, within the virtual enclosed space boundary" and LR quantifies the "negative aspects of environmental impact that go beyond the public environment". Q and LR range between 0 to 100 and are computed based on three subcategories, tabulated on a score sheet, as reported in the next Table.

Scoring for Q	Scoring for LR
Q1: Indoor environment Q2: Quality service Q3: Outdoor environment on site	LR1: Energy LR2: Resources and materials LR3: Off-site environment

Table 11: CASBEE's score sheet [Source: Berardi, et al., 2017].

BEE is expressed as the gradient of a line on a graph that has LR on the x-axis and Q on the y-axis. Based on the BEE value, a level of performance (i.e., S, A, B+, B-, and C) is associated with a given project. On a radar chart are represented the values calculated in each category. The assessment results sheet analyses and applies weights, using coefficients for each item and the Q and LR values and produces, as a last step, an overall score conveyed through the BEE index. This index is used to assess the six categories covered by the CASBEE evaluation: indoor environment, quality of service, outdoor environment (on-site), resources and materials, energy, and off-site environment.

3.5.3 Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)

The Deutsche Gesellschaft für Nachhaltiges Bauen, usually referred to by the acronym DGNB, have been developed by the Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council), founded in 2007 with the collaboration of the Federal Ministry of Transport, Building and Urban Affairs. The DNGB was launched in 2009, its aim was to promote building sustainability in Germany and develop a German certificate for sustainable buildings.

The DGNB refers to the EPD (Environmental Product Declaration) developed according to the standards EN 15804 and ISO 14025 and is mainly based on quantitative measures calculated using the life cycle assessment approach. This system is flexible and applicable to national and international environmental assessment, including 13 different building types and (since 2011) entire urban districts. The evaluation is based on 63 criteria, subdivided into six categories that are weighted by a specific weighting factor (Table 9). The sum of the points obtained in all the categories provides the overall score for the building. Each of the 63 criterions can receive a maximum of 10 points. Four categories (ecological quality, economical quality, socio-cultural and functional quality, and technical quality) have equal weight in the assessment, while process quality is less important; therefore, the Deutsche Gesellschaft für Nachhaltiges Bauen system gives the same importance to the economic, ecological, sociological, and technical aspects of an intervention.

Category	**Weighting Factor**	**Description**
Ecological quality	22.5%	Ecological impacts on local and global environment of the building's construction, utilization of renewal resources, waste, water and land use.
Economical quality	22.5%	Life cycle cost and monetary values.
Socio-cultural and functional quality	22.5%	Health, comfort, user satisfaction, cultural backgrounds, functionality and assurance of design quality.
Technical quality	22.5%	Fire and noise protection, quality of the building shell and ease of maintenance.
Process quality	10.0%	Quality of planning and design, construction process, building use and maintenance and quality of the construction activities.
Quality of the location	Rated independently	Transport-related topics, risks and image of location.

Table 12: DGNB: categories, weights and category descriptions [Source: Berardi, et al., 2017].

We have to consider some specific requirements, such as the indoor air quality and the Design for all requirements included in the socio-cultural and functional quality criterion, and the legal requirements for fire safety and sound insulation included in the technical quality criterion. To obtain the evaluation it is necessary to achieve a minimum required level in each quality section.

3.5.4 Haute Qualité Environnementale (HQE™)

The Haute Qualité Environnementale standard, as known as HQE™, developed in 1994 by the HQE™ association, is the French certification awarded to building construction and management which aims to guarantee a high environmental quality of buildings and supports stakeholders, designers, developers, and users during the project life cycle phases. The HQE™ Association has developed many schemes; it is structured to have three organizations in charge of delivering national evaluations and one for supporting the evaluation across the world. HQE™ covers buildings throughout their design, construction, operation, and renovation, and so along their life cycle, it promotes best practices and sustainable quality in building projects. It is addressed to non-residential and residential buildings. Moreover, is available also a specific scheme for the management system of development and urban planning projects. The environmental performance requirements are organized into four topics that together include 14 categories. Topics are almost the same for all building types, but the targets are arranged differently for residential buildings and non-residential buildings (i.e., commercial, administrative, and service buildings) (Tables 10 and 11, respectively).

Environment	**Energy and Savings**	**Comfort**	**Health and Safety**
Target 1: Building's relationship with its immediate environment	Target 4: Energy management	Target 8: Hygrothermal comfort	Target 12: Quality of spaces
Target 2: Quality of components	Target 5: Water management	Target 9: Acoustic comfort	Target 13: Air quality and health
Target 3: Sustainable worksite	Target 7: Maintenance management	Target 10: Visual comfort	Target 14: Water quality and health
Target 6: Waste management		Target 11: Olfactory comfort	

Table 13: HQETM: distribution of targets for residential buildings [Source: Berardi, et al., 2017].

Environment	Energy	Comfort	Health
Target 1: Building's relationship with its immediate environment	Target 4: Energy management	Target 8: Hygrothermal comfort	Target 12: Quality of spaces
Target 2: Quality of components		Target 9: Acoustic comfort	Target 13: Air quality and health
Target 3: Sustainable worksite		Target 10: Visual comfort	Target 14: Water quality and health
Target 5: Water management		Target 11: Olfactory comfort	
Target 6: Waste management			

Table 14: HQETM: Distribution of targets for commercial, administrative and service buildings [Source: Berardi, et al., 2017].

For each target, expressed according to three ordinal levels (basic, performing, and high performing), a building project obtains an assessment. To achieve the certification, a building must have the high performing level in minimum three categories and the basic one in maximum seven categories. Each category is not weighted by a weighting factor in this system, because they are considered to have the same importance throughout the assessment framework.

3.5.5 Leadership in Energy and Environmental Design (LEED)

LEED, or Leadership in Energy and Environmental Design was launched in the USA in 1998 (LEED® version 1.0) by the US Green Building Council (USGB), a nongovernmental organization that includes representatives from industry, academia, and government. During the years, the LEED® system has undergone some revisions, integrations, and national customizations. The version currently used is the LEED® 4.0 and was released in 2016. The LEED Green Building Rating Systems are voluntary and are intended to evaluate the environmental performance of the whole building over its life cycle; it provides a framework to create healthy, highly efficient and cost-saving green buildings. Different schemes are designed for rating new and existing non-residential and residential buildings. Each scheme has the same list of performance requirements set out in five categories, but the number of prerequisites and available points changes a lot according to the specific area of interest and the building type. Table 12 provides a description of the categories included in the LEED environmental rating scheme.

Category	Description
Sustainable sites	This section examines the environmental aspects linked to the building site. The goal is to limit the construction impact and verify meteoric water outflow.
Water efficiency	The section is linked to the water use, management and disposal in the buildings. The reduction of water consumption and meteoric water reuse are promoted.
Energy and atmosphere	In this section building energy performance improvement, the use of renewable sources and the energy building performance control are promoted.
Materials and resources	In this area the environmental subjects associated to the material selection, the reduction of virgin material use, the garbage disposal and the environmental impact due to transport are considered.
Indoor environmental quality	The themes considered in this section cover indoor environmental quality, taking into account for example healthiness, comfort, air renewal and air pollution control.
Innovation in design	The aim of this section is to identify the design aspects that improve on the sustainability operations in the building construction.
Regional priority	This area has the objective of encouraging the design groups to focus the attention on the local characteristics of the environment.

Table 15: LEED®'s categories and description [Source: Berardi, et al., 2017].

Summing the points for each credit is given the evaluation outcome. All the credits receive a single weight following a precisely defined scoring system. It has a maximum score of 100 points, plus up to 10 additional bonus points if the building complies with two special categories. To pass the basic evaluation, a minimum of 40 points out of 100 should be obtained.

3.5.6 SBTool

With the aim of establishing energy and environmental performance standards suitable in both international and national contexts, in 1996, the international Green Building Challenge initiative (today the Sustainable Building Challenge) started to develop the today known as SBTool. It was necessary to identify assessment tools able to assess in the most objective way, the requirements of the environmental, economic, and social impacts of a building during its entire life cycle through different methodological bases. Thus, was born the so-called SBMethod, developed by the work of representatives from 20 countries, designed to offer, besides a common international standard, an easy customization with respect to individual national contexts. It is continuously updated by a technical committee managed by the International Initiative for a Sustainable Built Environment (iiSBE).

The SBMethod covers the three aspects of sustainability (environmental, economic, and social) under the building point of view and can be used to assess every design concept or existing building independently from its prevalent use and extension, in their four phases: predesign, design, construction, and use.

Originating from the SBMethod, was later renamed the Sustainable Building Tool (SBTool). It is a generic framework for rating the environmental performance of buildings and projects by assigning scores and credits to a certain number of areas. The method is structured in a way for which each parameter is defined by a weight; the weighting factors are different for each building types, such as new and existing buildings, residential and non-residential. The performance issues and the phases of the life cycle used for the assessment are listed in Table 13. Separate modules are provided for the site and building assessments, carried out respectively in the predesign phase, and the building assessments, done in the design, construction, or operation phases.

The performance framework of SBTool is organized into four levels:

1) performance issues,
2) performance categories,
3) performance criteria,
4) performance sub criteria.

Each performance issue contains categories that represent the domain in a more detailed and specific manner.

Issue area	Predesign	Design	Construction	Operation
Site location, available services and site characteristics	X			
Site regeneration and development. Urban design and infrastructure		X		X
Energy and resource consumption		X	X	X
Environmental loadings		X	X	X
Indoor environmental quality		X		X
Service quality		X	X	X
Social, cultural and perceptual aspects		X	X	X
Cost and economic aspects		X	X	X

Table 16: The SBTool's issue area expressed per each phase of a building's life cycle [Source: Berardi, et al., 2017].

3.6 Comparative Analysis of the Selected Rating Systems

Table 14 summarizes some information about the six rating systems for assessing the environmental impact of buildings selected. It is shown how the schemes' categories, similarities, and differences can be exploited.

In the following tables, the schemes are classified according to the following categories:

- Type of intervention (Table 15);
- Building type (Table 16);
- Phase of the building's life cycle (Table 17);
- Scopes (Table 18).

Rating System	Launch Year	Launch Country	Certification Body	International Versions and National Adaptations	Weighting System	Rating Levels
BREEAM	1990	UK	BRE	International versions: Non-domestic refurbishment In-use New construction: buildings National adaptations: United Kingdom USA Germany Netherlands Norway Spain Sweden Austria	Applied to each category	Unclassified Pass Good Very good Excellent Outstanding
CASBEE	2004	Japan	JSBC	N/A	Complex weighting system applied at every level	S A B+ B- C
DGNB 2014	2008	Germany	DGNB	International version Core 14 National adaptation: Austria Bulgaria China Denmark Germany Switzerland Thailand	Applied to each category	Bronze* Silver Gold Platinum
HQE™	1997	France	Certivèa Cerqual Cèquami Cerway	International versions Non-residential building in operation 2015 Infrastructures 2015 Habitat and environment Non-residential building under construction 2015 Residential building under construction 2015 Management system for urban planning projects 2016	N/A	Pass Good Very good Excellent Exceptional
LEED v.4	1998	USA	USGBC	International versions: LEED v3.0 for new construction and major renovations LEED for homes LEED for core and shell LEED for existing buildings: operations and maintenance LEED for commercial interiors LEED for schools LEED for retail LEED for healthcare LEED for neighbourhood development (in pilot stage) National adaptations: Argentina Brazil Canada Italy	All credits are equally weighted, but the number of credits related to each issue is different	Certified Silver Gold Platinum
SBTool 2016	2002	International	iiSBE	National adaptations: Czech Republic (SBToolCZ) Portugal (SBToolPT) Italy (Protocollo Itaca) Spain (Verde)	Applied to each category	-1 0 1 3 5

** Level available only for existing buildings*

Table 17: Summary of the main features of the selected rating systems [Source: Berardi, et al., 2017].

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The first assessment of the environmental impact of buildings have been made with respect to the type of intervention (Table 15). It can be noticed that BREEAM, CASBEE, DGNB, HQE™, and LEED® have dedicated modules to cover all the four types of intervention, while the SBTool does not provide assessment tools for building refurbishment and urban planning.

Rating System	New Buildings	Existing Buildings	Buildings under Refurbishment	Urban Planning Projects
BREEAM	X	X	X	X
CASBEE	X	X	X	X
DGNB	X	X	X	X
HQE™	X	X	X	X
LEED®	X	X	X	X
SBTool	X	X		

Table 18: Type of intervention [Source: Berardi, et al., 2017].

It can be seen in Table 16 that BREEAM, CASBEE, DGNB, and HQETM can be used to certify the environmental performances of all the different building types; while LEED® and SBTool do not have the industrial buildings in their evaluation. Concerning the life cycle phase of a building, each certification system covers all the four considered building's life cycle phases (pre-design and design, construction, post-construction and use/maintenance), except for the SBTool that does not cover the use/maintenance phase and LEED® that does not evaluate predesign or design.

Rating System	Residential Buildings	Office Buildings	Commercial Buildings	Industrial Buildings	Educational Buildings	Other Type of Buildings	Urban Planning
BREEAM	X	X	X	X	X	X	X
CASBEE	X	X	X	X	X	X	X
DGNB	X	X	X	X	X	X	X
HQE™	X	X	X	X	X	X	X
LEED®	X	X	X	N/A	X	X	X
SBTool	X	X	X	N/A	X	N/A	N/A

Table 19: Building type assessed by the selected schemes [Source: Berardi, et al., 2017].

Rating System	Pre-design and Design	Construction	Post-Construction	Use/Maintenance
BREEAM	X	X	X	X
CASBEE	X	X	X	X
DGNB	X	X	X	X
HQE™	X	X	X	X
LEED®	N/A	X	X	X
SBTool	X	X	X	N/A

Table 20: Life cycle phase of the building assessed by the selected schemes [Source: Berardi, et al., 2017].

As far the original categories, different elements in some schemes often refer to the same field and, sometimes, similar denominations do not evaluate same attributes. Therefore, eight major areas have been identified, in which the characteristic elements of all the categories are grouped together. According to this analysis, the categories most evaluated by the schemes are energy performance and solid waste management. Other important categories are materials, water, waste water management, and ecology and environmental quality, which are assessed by the vast majority of schemes. The areas that are less assessed are those related to resistance to natural disasters, which are considered only by CASBEE, DGNB, and HQE^{TM}. likewise, the olfactory comfort category is only considered by the HQE^{TM} schemes, while, in the other systems, it is included in the air quality, a more general category.

To conclude, the building information and users’ guidance are only considered by the BREEAM collection schemes and in some cases by a few sub-schemes in LEED, HQETM, and DGNB. The results have been presented also graphically in the next Figure.

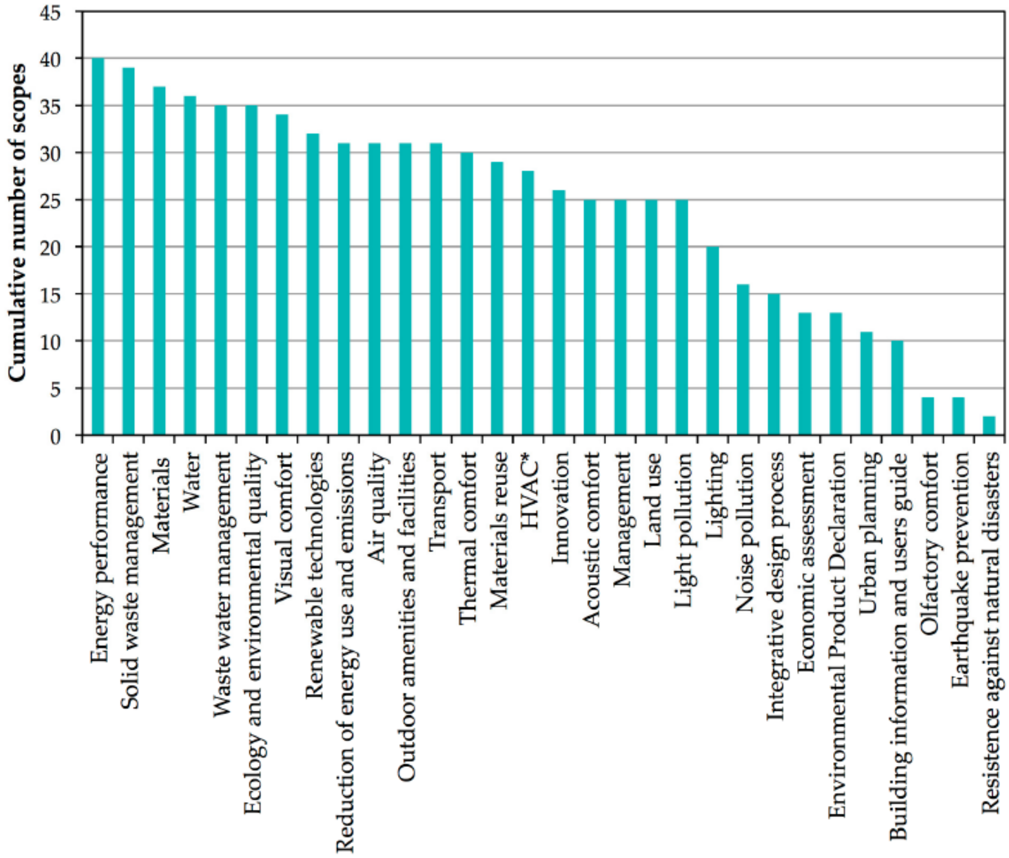

Figure 20: Scopes distribution among the analysed rating schemes (HVAC: heating, ventilation, and air-conditioning) [Source: Berardi, et al., 2017].*

Rating System	Energy Performance	Renewable Technologies	HVAC	Lighting	Reduction of Energy Use and Emissions	Olfactory Comfort	Visual Comfort	Thermal Comfort	Acoustic Comfort	Air quality	Innovation	Management	Building information and Users Guide	Economic assessment	Integrative Design Process	Materials Reuse	Environmental Product Declaration	Materials	Water	Land Use	Noise Pollution	Light Pollution	Waste Water Management	Solid Waste Management	Earthquake Prevention	Resistance against Natural Disasters	Outdoor Amenities and Facilities	Transport	Urban Planning	Ecology and Environmental Quality
BREEAM (B)																														
B Europe Commercial 2009	X	X	X	X			X	X			X	X	X	X		X		X	X	X	X		X	X			X	X		
B In-use international 2016	X	X	X	X	X		X	X	X	X			X		X			X	X				X	X			X	X		X
B New construction: infrastructure 2016 (pilot)	X										X	X		X	X	X	X	X	X		X	X	X	X				X		X
B International new construction 2016	X			X	X		X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X			X	X		X
B UK Domestic refurbishment 2014	X	X	X	X			X		X		X	X	X					X	X				X	X						X
B Nondomestic refurbishment 2015	X			X	X		X	X	X	X	X	X						X	X	X	X	X	X	X			X	X		X
B UK Datacenters 2010	X	X	X	X	X		X	X	X	X	X	X	X	X		X		X	X	X		X	X	X			X	X		X
B Communities 2012	X										X	X		X				X	X	X	X	X	X				X	X		X
B Code for sustainable homes 2010	X	X		X	X		X	X	X			X	X						X	X	X			X						X
CASBEE (C)																														
C for home (detached houses) 2007	X	X	X	X			X	X	X		X					X		X	X		X		X	X		X				X
C for building (new construction) 2014	X	X		X			X	X	X	X						X		X	X	X	X	X	X		X		X			
C for market promotion (offices and retail) 2014	X	X			X		X	X								X			X	X				X	X			X		X
C for urban development 2014	X				X							X		X		X		X	X	X			X	X	X		X	X	X	X
C for cities 2012														X					X	X				X			X		X	X

Rating System	Energy Performance	Renewable Technologies	HVAC	Lighting	Reduction of Energy Use and Emissions	Olfactory Comfort	Visual Comfort	Thermal Comfort	Acoustic Comfort	Air quality	Innovation	Management	Building information and Users Guide	Economic assessment	Integrative Design Process	Materials Reuse	Environmental Product Declaration	Materials	Water	Land Use	Noise Pollution	Light Pollution	Waste Water Management	Solid Waste Management	Earthquake Prevention	Resistance against Natural Disasters	Outdoor Amenities and Facilities	Transport	Urban Planning	Ecology and Environmental Quality
DGNB																														
DGNB Core 14	X	X	X	X			X	X	X	X		X	X	X		X			X	X	X		X	X	X	X	X	X	X	X
HQE™																														
NF Maison individuelle neuf 2013	X	X	X			X	X	X	X	X		X						X	X	X	X	X		X		X		X	X	X
NF Maison *rénovée* 2014	X	X	X	X		X		X	X									X	X		X		X	X		X			X	X
NF Logement habitat neuf	X		X	X	X	X	X	X	X	X								X	X		X			X					X	X
NF Qualit*é* envi-ronementale des b*â*timents 2015	X				X	X	X	X	X	X						X			X		X			X					X	X
NF B*â*timent durable 2014	X					X	X	X	X	X								X	X								X	X	X	X
HQE™ Non-residential building in operation 2015	X	X	X		X	X	X	X	X	X		X				X		X	X		X	X	X	X			X	X		X
HQE™ Infrastructures 2015				X	X				X			X		X				X	X	X	X						X	X		X
Habitat & Environnement	X			X			X	X	X	X		X	X	X		X		X	X					X				X	X	
HQE™ Non - residential building under construction 2015	X	X	X	X	X	X	X	X	X	X		X	X					X	X	X	X		X	X			X	X	X	X
HQE™ Residential building under construction 2015	X	X		X	X	X	X	X	X	X			X			X		X	X		X		X	X			X			
HQE™ Mana-gement system for urban planning projects 2016	X	X	X	X	X	X	X	X	X	X		X		X				X	X	X	X		X	X			X	X	X	X

Rating System	Categories																													
	Energy Performance	**Renewable Technologies**	**HVAC**	**Lighting**	**Reduction of Energy Use and Emissions**	**Olfactory Comfort**	**Visual Comfort**	**Thermal Comfort**	**Acoustic Comfort**	**Air quality**	**Innovation**	**Management**	**Building information and Users Guide**	**Economic assessment**	**Integrative Design Process**	**Materials Reuse**	**Environmental Product Declaration**	**Materials**	**Water**	**Land Use**	**Noise Pollution**	**Light Pollution**	**Waste Water Management**	**Solid Waste Management**	**Earthquake Prevention**	**Resistance against Natural Disasters**	**Outdoor Amenities and Facilities**	**Transport**	**Urban Planning**	**Ecology and Environmental Quality**
LEED®																														
LEED v4 for Homes Design and Construction																														
Multifamily mid-rise 2010	X		X		X					X		X			X			X	X	X			X	X			X			X
Homes and multifamily low-rise 2010	X	X	X	X	X					X		X			X			X	X	X			X	X			X			X
LEED v4 for Interior Design and Construction																														
Commercial interiors and hospitality	X	X	X	X	X		X		X	X	X	X			X	X	X	X	X			X		X			X		X	
Retail	X	X	X	X	X		X			X	X	X			X	X	X	X	X			X		X			X		X	
LEED v4 for Operation and Maintenance																														
Existing buildings and schools	X	X	X		X		X	X		X	X	X				X		X				X	X	X			X	X		X
Retail, data centres, hospitality, warehouses and distribution centres, multifamily	X	X	X		X		X	X		X	X	X				X		X				X	X	X				X		X
LEED v4 for Building Design and Construction																														
Schools	X	X	X		X		X	X	X	X	X				X	X	X	X	X	X	X	X	X	X			X	X		X
Healthcare	X	X	X		X		X	X	X	X	X				X	X	X	X	X	X		X	X	X			X	X	X	X
Core and shell	X	X	X		X		X	X	X	X	X		X		X	X	X	X	X	X		X	X	X			X	X		X
New construction, retail, data centers, warehouses and distribution centers, hospitality	X	X	X		X		X	X	X	X	X				X	X	X	X	X	X		X	X	X			X	X		X
Neighborhood development	X	X									X					X			X	X		X	X	X			X	X	X	X
SBTool																														
SBTool 2012	X			X	X		X	X	X	X				X				X	X		X		X	X			X	X	X	X

Table 21: Comparison of the scopes and criteria of the six selected rating schemes used for evaluating the sustainability of buildings [Source: Berardi, et al., 2017].

3.7 Conclusions

It has been presented an overview of the existing rating systems for assessing buildings' environmental impact. They are technical instruments developed with the purpose of evaluating the environmental performances of buildings.

It has been registered, in the last 10 years, a growing interest in the sustainable development due to the urgent necessity reduction in greenhouse gas emissions for the planet safety and the global society's health. This led to an important consequence on the building and construction industry and, therefore, to a wide spread of rating schemes with the purpose to enhance buildings' sustainability.

The core of this work is a comparative analysis of the most important and widespread six schemes for assessing the environmental impact of buildings, chosen after a survey of more than 70 schemes: the Building Research Establishment Environmental Assessment Methodology (BREEAM), the Comprehensive Assessment System for Built Environment Efficiency (CASBEE), the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB), the Haute Qualité Environnementale (HQE^{TM}), the Leadership in Energy and Environmental Design (LEED), and the Sustainable Building Tool (SBTool). It is interesting to point out that a systematic comparison of the schemes is not easy, sometimes even prohibitive. The fact is that, being different rating schemes developed for different purposes, a direct comparison of categories and subcategories is often not possible.

These are the outputs of the analysis, that has been conducted considering different aspects:

- All rating systems concern both new and existing buildings and, except the SBTool, cover also the refurbishment;
- BREEAM, CASBEE, DGNB, and HQETM are usable to assess all kind of buildings, while LEED does not include industrial buildings and the SBTool is the most limited since it does not consider urban planning

projects, and building typologies other than residential, office, commercial, and educational ones;

- Only BREEAM, CASBEE, DGNB, and HQETM embrace all the building's life cycle stages;
- SBTool is the only system that covers the certification of buildings with low-performance level;
- Concerning the assessed categories, energy performance, solid waste management, material, and water are the most considered under a quantitative perspective; while the ones less considered are resistance against natural disasters, earthquake prevention, and olfactory comfort.

To conclude, it should be stated that these schemes have been largely accepted and used in the building sector. For future developments, some suggestions of desirable features are completeness in the analysis of the building's elements and its life cycle; clearance in the representation of the weighting system and support of the scoring system with sound evidence.

Region	**Country**	**Name**	**Year**	**Type of Method**
Africa	South Africa	Green Star SA	2008	Rating system
		SBAT	2002	Rating system
Asia	China	GHEM	N/A	Rating system
		GOBAS	2003	Rating system
		DGNB	2009	Rating system
		ESGB	2006	Rating system
	Hong Kong	BEAM Plus	1996	Rating system
		CEPAS	2002	Rating system
	India	TERI-GRIHA	2007	Rating system
		LEED® India	2011	Rating system
	Japan	CASBEE	2004	Rating system
		NIRE-LCA	1996	LCA tool
	Korea	GBCC	1997	Rating system
	Singapore	Green Mark	2005	Rating system
	Taiwan	EEWH	1999	Rating system
	Thailand	DGNB	2010	Rating system
	Vietnam	LOTUS	2007	Rating system

Region	Country	Name	Year	Type of Method
Europe	Austria	BREEAM AT	N/A	Rating system
		DGNB	2009	Rating system
	Belgium	LEnSE	2008	Rating system
	Bulgaria	DGNB	2009	Rating system
	Czech Republic	DGNB	2011	Rating system
		SBToolCZ	2010	Rating system
	Denmark	BEAT 2002	2002	Rating system
		DGNB	2011	Rating system
	Finland	PromisE	2006	Rating system
		BeCost	N/A	LCA tool
		KCL-ECO	1992	LCA tool
	France	HQE™ Method	1997	Rating system
		ELODIE	2006	LCA tool
		TEAM™	1995	LCA tool
		EQUER	1995	LCA tool
		ESCALE	2001	Rating system
		PAPOOSE	N/A	LCA tool
	Germany	DGNB	2008	Rating system
		BREEAM DE	2011	Rating system
		GABI	1990	LCA tool
		GEMIS	1990	LCA tool
		LEGEP®	2001	LCA tool
		OpenLCA	2013	LCA tool
		Umberto	-	LCA tool
	Greece	DGNB	2010	Rating system
	Hungary	DGNB	2010	Rating system
	Italy	LEED® Italia	2006	Rating system
		Protocollo ITACA	2004	Rating system
		eVerdEE	2004	LCA tool
	Luxembourg	BREEAM LU	2009	Rating system
	Netherlands	BREEAM-NL	2011	Rating system
		SIMAPRO	1990	LCA tool
		Eco-Quantum	2002	LCA tool
	Norway	BREEAM-NOR	2012	Rating system
		Økoprofil	1999	Rating system
	Poland	DGNB	2013	Rating system
	Portugal	LiderA	2005	Rating system
		SBToolPT	2007	Rating system
	Russia	DGNB	2010	Rating system
	Spain	VERDE	2006	Rating system

Region	Country	Name	Year	Type of Method
		DGNB	2011	Rating system
		BREEAM ES	2010	Rating system
	Sweden	EcoEffect	2006	Rating system
		BREEAM SE	2008	Rating system
	Switzerland	BREEAM CH	N/A	Rating system
		DGNB	2010	Rating system
		Eco-Bat	2008	LCA tool
		REGIS	1993	LCA tool
	Turkey	DGNB	2010	Rating system
	Ukraine	DGNB	N/A	Rating system
	United Kingdom	BREEAM	1990	Rating system
		CCaLC Tool	2007	LCA tool
		Envest 2	2003	LCA tool
North America	Canada	LEED® Canada	2009	Rating system
		GreenGlobes	2000	Rating system
		Environmental Impact Estimator	2008	LCA tool
		ATHENA™	2002	LCA tool
	Mexico	SICES	N/A	Rating system
	United States	LEED®	1998	Rating system
		BEES 4.0	1998	LCA tool
		GreenGlobes	2004	Rating system
Oceania	Australia	Green Star	2003	Rating system
		NABERS	2001	Rating system
	New Zealand	Green Star NZ	2007	Rating system
South America	Argentina	LEED® Argentina	N/A	Rating system
	Brazil	LEED® Brazil	2007	Rating system
		HQE™	2014	Rating system
Generic		SBTool	2002	Rating system
		SPeAR	2000	Rating system

Table 22: Rating systems assessing the environmental impact of buildings in use worldwide. Adapted from Berardi, et al.

3.7.1 Which one is the best certification system?

Of course, is not possible to identify "the best" certification system, several studies have been made on the subject such as the one proposed below, in which the potential of the various methods are highlighted. It is not always possible to compare them on an equal footing, as some of them are environmental assessment systems, while others are energy certification systems.

3.7.1.1 Weighting of environmental aspects

A clear assertion points in the direction of the ecological criteria proportion in the overall result. BREEAM, with 33.6% and LEED with 31.1% are well ahead of the DGNB system with about 16%. Adding the energy sector, the outcome is the following ranking: LEED with 63.3% before BREEAM with 57.1% and DGNB with 30.7%. The DGNB is more like a system that assesses the building's market value and resale value, because its direct environmental impact.

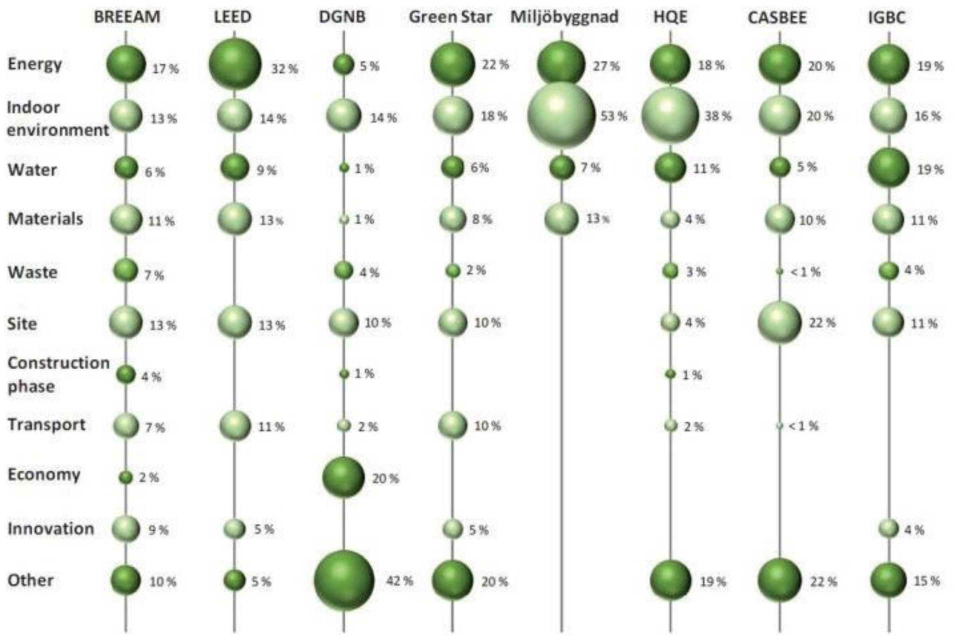

Figure 21: Weighting of environmental aspect for each certification system

3.7.1.2 Meaning of material choice

The DGNB system has not defined specific requirements or criteria in this field. At BREEAM, material influences are considered through a general life cycle analysis. LEED is the only system investigated that defines specific material requirements in terms of the use of low-emission and recycled materials, renewable raw materials or certified wood.

3.7.1.3 Importance of pre-chain

For BREEAM, upstream chains seem to have a specific focus, as life cycle considerations are limited to building materials according to the DETAIL study and do not refer to the use or reuse phase of the building. At the DGNB, upstream chains are not subject to specific criteria or considerations. Even at LEED, the environmental impact of building material production obviously does not matter.

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4 Life Cycle Costing

Conceptually similar to the LCA model is the criteria that guides the LCC model, with the substantial difference that the latter focuses on the analysis of the life cycle of a product from a purely economic point of view. In fact, the final aim of the LCC is to provide the company with a useful business management tool that allows it to understand where to intervene to reduce the costs related to a product. The LCC model developed seriously during the 1970s, especially with regard to the production and supply of weapons for the US military and the programme for the construction of public buildings in various US states. In Europe, too, in the mid-1970s, the LCC attracted the attention of the public sector in the construction, energy, transport and military sectors. The wide variety of applications is demonstrated, in part, by the many standards that have been applied over the years, for example: IEC 6030033 (International Electrotechnical Commission, 2004), ISO 15663 (International Standards Organization, 2000-2001), DoD 1973 (UD Department of Defense, 1973) and AS/NZS 4536 (Standards Australia and Standards New Zealand, 1999), to mention just a few (SETAC, 2008).

The number of key stages that can be identified depends considerably on the type of analysis to be carried out. In general, there are four main phases to consider (Ristimaki et al., 2013):

1) Raw material retrieval/acquisition;
2) The operational or use phase;
3) The phase concerning maintenance costs and possible replacements of components and spare parts for machinery, etc;
4) The phase of disassembly or disposal of the product.

There is no univocal way to proceed in the formulation of an LCC analysis, the four phases listed above are the result of a basic idea pursued in this writing, which is based essentially on the LCA model and on two other traditional approaches: The Total Cost of Ownership (TCO) and the Activity-Based Costing (ABC model). The first is defined as the "sum of the purchase cost of a product, plus all expenses incurred by the purchaser during its useful life, net of the settlement (or resale) price". As can be seen, the TCO method has its main focus in the acquisition phase and in the actual use phase (maintenance, support, etc.) while it tends to neglect the other typical phases of a product's life (Hunker et al., 2008).

The second approach (ABC model) calculates the cost associated with a given product by assessing the costs related to the activities carried out in the life cycle of the same product. In other words, the ABC model provides for the evaluation of all the activities that make up the company system, and then select those specific activities to be assigned to the product in question (Hunker et al., 2008).

However, both these approaches, which in some ways are similar to LCC, have significant limitations, mainly due to their lack of consideration of the product's life cycle.

4.1 Types of Life Cycle Costing

There are different types of LCC, which differ significantly from each other. The various models have been developed to meet the different needs of management over time. They are linked to the concept of TBL (Triple Bottom Line), which deals in an integrated way with business components from an economic, social and environmental point of view. The three types of LCC described below are: The Conventional LCC, the Environmental LCC and the Social LCC (UNEP/SETAC, 2011).

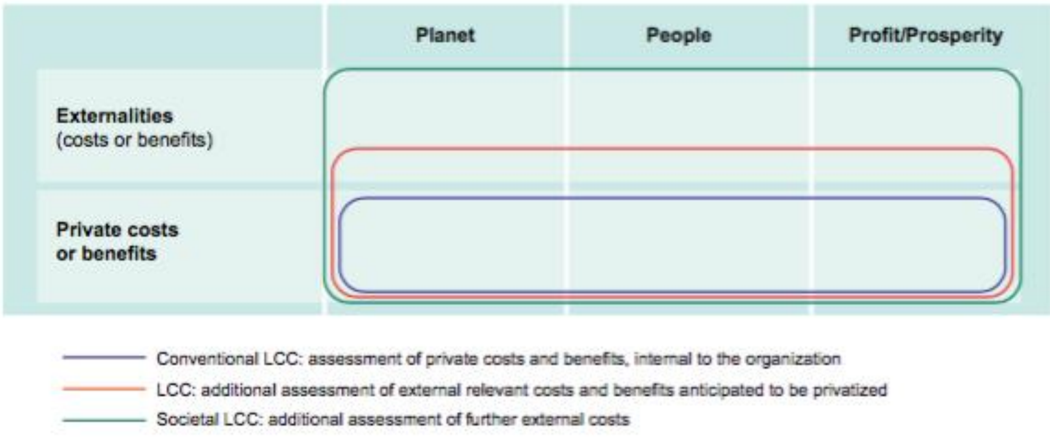

Figure 22: Le tre tipologie di LCC (UNEP/SETAC, 2012)

4.1.1 Conventional Life Cycle Costing (CLCC or LCC)

The first, in temporal terms, is the "Conventional LCC" which, by now, is commonly abbreviated as LCC and consists in the measurement and calculation of all the costs associated with a particular product during the various phases of its life cycle, following the logical thread of the "cradle to grave". The various cost items must be discounted using an interest rate that may correspond to the rate of inflation present at the time of drawing up the model, and consequently must have a predetermined reference time frame (UNEP/SETAC, 2011).

Usually, the LCC model, as well as the LCA model, is divided into four main phases that refer to the four most important cost items: the acquisition of raw materials (it can be decided, if it is worth it, to consider in a separate phase the costs of research and development, otherwise included in the process); the costs related to production, use of the product and its management; maintenance costs; and finally the costs related to the deconstruction or disposal of the product. The perspective of this type of LCC is addressed to the market, does not consider, in its typical structure, elements such as pollutant emissions caused in the production process (such as LCA or ELCC) or the cost of labour (such as SLCC), and for this reason is considered rather limiting, unable to provide an overview of the life process of a product (SETAC, 2008).

4.1.2 Environmental Life Cycle Costing (ELCC)

Not well known, this type of LCC represents a significant step forward compared to the traditional version. It combines elements of LCC with others belonging to the LCA model, thus considering both the costs related to the life cycle of a product and the externalities produced along the same, which are anticipated and then internalized later. In other words, the costs associated with the externalities resulting from the various phases are, in theory, considered within the business processes so as to be presented from an economic point of view. In order to achieve the internalization of externalities there are some models and theories that are also very different from each other that refer, for example, to external costs, eco-costs or the concept of "willingness to pay" which will be better explained in the chapter dedicated to ELCC (SETAC, 2008).

4.1.3 Societal Life Cycle Costing (SLCC)

The last model to be considered is the SLCC, which represents a further evolution of the LCC model. It includes, like the other two types, the evaluation of all costs associated with the life cycle of a product from an economic and environmental point of view, considering in addition the evaluation of impacts at the social level (using for example the method of "willingness to pay") (Hunker et al., 2008). In fact, Societal LCC aims to go beyond the concept of externalities at a strictly environmental level, including those related to human health damage and those considered difficult to assess from an economic point of view and that are only taken into account qualitatively (such as public health, quality of work, etc.). In other words, the SLCC is used to quantify the environmental impacts, resulting from the production of a given product, on society and in monetary terms. The SLCC analysis is particularly important if we take a Corporate Social Responsibility (CSR) perspective, a concept that is turning out to be more indispensable than ever for the correct management of a company, given the need to conduct increasingly responsible global corporate policies.

One of the most significant differences between the SLCC method and the other methods described above is the involvement of stakeholders. In other words, while interests and impacts on various stakeholders were not taken into account (or at least considered to a limited extent) in previous analyses, they play a major role in SLCC.

The different social impacts are assessed with respect to five main categories of stakeholders (UNEP/SETAC, 2009):

- Employees;
- Local community;
- Society;
- Consumers;
- Life cycle actors.

For each of these categories it is possible to identify different objectives and impacts that may vary the boundaries of the system initially chosen.

A further difference is the strong geographical connotation of the SLCC analysis. The analysis varies considerably when considering rural and urban geographical areas, just as it is certainly different to consider developed regions and regions with a high rate of poverty.

However, although the SLCC model is extremely interesting and has considerable potential, it is extremely underdeveloped due to its considerable difficulties of use. In fact, carrying out an analysis with almost exclusively qualitative survey techniques (as far as the social dimension is concerned) presents numerous pitfalls, such as the necessity for the interviewed persons (usually using direct or indirect interview techniques) to have a deep knowledge of the topics dealt with or to be morally free of prejudices towards company action (think of the difficulty of interviewing, and obtaining reliable answers, on a problem relating to human health, caused by a company operating in the territory, by people living with the discomforts caused by the company itself).

For these reasons, the type of SLCC analysis will not be discussed in depth in the course of this paper, although there may be interesting future developments related to it. This brief examination of the different types of LCC was intended to make it clear that this topic is extremely varied and presents many nuances. These themes will be taken up in a more specific way in the course of the writing.

4.2 The Life Cycle Costing (LCC) model

As already mentioned, the LCC model follows the guidelines that distinguish the LCA model and, more generally, the Life Cycle Thinking model, that is, the school of thought to which these types of analysis refer.

From a theoretical point of view, before starting the analysis, it is useful to pursue a reference scheme that consists of four main points (Ristimäki et al., 2013):

- Define the various strategies to be evaluated: to structure the analysis effectively it is necessary to establish various strategies to compare the results;
- Identify relevant economic criteria: each life cycle analysis takes into account certain variables that can be modified at will according to the objectives set. In this case, relevant economic variables such as: the discount rate chosen, the reference period, etc. should be defined;
    - Group costs into categories: each phase of the analysis will be characterised by a certain type of cost (for example, the cost of purchasing raw materials will be attributed to the first phase of the analysis). However, there are some cost items that can be attributed to different phases of the life cycle and you will need to choose carefully where to put them.

- Assess the degree of uncertainty: any analysis of future costs has a higher or lower degree of uncertainty. It will be necessary to establish a sensitivity analysis, which can take into account various scenarios, to reduce this risk.

Although the LCC is the oldest analysis in terms of application, it is not regulated by ISO standardisation, and is applied according to ISO 14040, to which the LCA refers.

There will therefore be the four steps described above for the LCA, which are briefly re-proposed for completeness:

- Definition of objectives: This phase defines the objectives of the analysis, the functional unit, the scope of application and the boundaries of the system. Unlike the LCA, it is advisable to define a structure of the costs to be analysed, dividing them into various categories and the appropriate process steps. In addition, the discount rate that can be recovered from the ECB inflation rate or chosen directly by management should be chosen.
- Inventory analysis (LCI): in the inventory phase, the cost data that will make up the analysis are retrieved.
- Cost assessment: costs are grouped into categories and broken down according to whether they belong to a particular stage of the analysis.
- Interpretation of results: The final stage of the analysis corresponds to the interpretation of the results of the analysis. This phase lends itself to various interpretations and can be freely performed according to the will of the management.

4.2.1 Elements of Life Cycle Costing

In order to conduct a properly conducted LCC analysis, it is particularly important to understand some basic elements of the analysis. In order to do this, some key elements for an accurate analysis will be provided below.

The main objectives of an LCC analysis, according to the Royal Institute of Chartered Surveyors (RICS), are:

- Enabling various investment options to be assessed more efficiently;
- Consider the impacts of all costs related to a product, rather than just the initial cost of an investment;
- Facilitate the efficient management of the management of the various projects implemented;
- Facilitate choices between different alternatives.

To achieve these objectives, it is necessary to identify the various main elements that make up an LCC analysis, among which the most important are (Ristimäki et al., 2013):

- The initial cost, or initial investment;
- The time period to be considered;
- The discount rate or interest rate;
- The operating and maintenance costs;
- The costs of disposal or disposal.

4.2.1.1 The initial investment

This investment cost may be broken down into other cost categories or items, the main of which may be:

- Purchase cost of materials, raw materials, etc.;
- Research and development (R&D) costs;
- Installation costs, transport of materials, etc.

These cost categories are by far the first items to be included in the analysis, since are the first step in the product's life cycle. The costs of R&D are, by usually, difficult to identify but can be estimated or inserted as percentages in other cost items.

4.2.1.2 The reference-period

The key to the analysis is to identify the correct reference time frame. It makes no sense to choose a period of 100 years if you are analysing the life cycle of a non-durable good with a useful life of five years. To avoid unreliable analyses, it is necessary to choose different time frames, in order to obtain a much more flexible analysis. Choosing different time periods can also be useful if you consider products that are subject to innovation, which could drastically change the parameters of the analysis.

4.2.1.3 The discount-rate

Analysing the life cycle of a product from a cost perspective means that these costs need to be discounted to their net present value. This can be identified in the inflation rate provided by the European Central Bank or alternatively chosen by management. The choice should not be random because choosing a high rate involves the emphasis on short-term forecasts, the exact opposite if you choose a modest discount rate. In general, the discount rate is chosen over a range of 2.00% to 4.00%. Usually, in addition to the discount rate, the inflation rate is also identified, which in most cases is also chosen over a range of 2.00-4.00%. Combined, you will get the real discount factor with which you can accurately calculate future discounted costs (calculated based on the SMART SPP5 guide).

Discount factor = 1/(discount rate inflation rate)n

For example, if you set a discount rate at 2% and an inflation rate at 3%, the discount factor for the twentieth year of the life cycle will be 1.21.

4.2.1.4 Operating and maintenance costs

As far as operating costs are concerned, in an LCC analysis they include almost exclusively the energy costs necessary for the production process and, more generally, for the operation of the company in all its aspects. Obviously, since the LCC is a flexible analysis and there is no unique way to conduct it, other cost items can be included in this particular category, such as, for example, direct or indirect labour costs, which are usually not included in the classic LCC analysis. Maintenance costs are another cost category that lends itself to many nuances. In general, there is a tendency to consider within this category those cost items that can be linked to maintenance on machinery or production equipment.

It is useful to divide this category into several sections that correspond to the frequency with which maintenance is carried out:

- Ordinary maintenance: this sub-category includes those small maintenance operations that can be carried out by personnel within the company or that in any case do not involve prolonged interruptions of production;
- Planned maintenance: planned maintenance operations, usually in several years' time, similar to overhauls;
- Extraordinary maintenance: these are those unexpected interventions that involve considerable loss of time in production.

Planning a good control and maintenance policy is essential to reduce the risk of facing significant losses of time and money related to extraordinary maintenance. For the purposes of the analysis, the possibility of such additional costs, which in most cases involve high costs, should be taken into account. However, it is very often difficult to obtain specific data to identify different maintenance operations because companies may also disregard these differences and account for the costs of such operations under a single cost item.

4.2.1.5 Disposal and disposal costs

This cost category is linked to the disposal of waste and scrap over the life cycle of the product and at the end of its useful life. These costs will be deducted from the residual value of the product at the time of decommissioning. In practice, as will be reiterated in the fourth chapter, calculating these costs solely on the basis of data provided by the company where the analysis is carried out is rather difficult. It is therefore necessary to rely on generic data provided by companies specialising in the disposal of the various types of cost. Referring to the C.E.R. (Catagolo Europeo dei Rifiuti, in english: European Waste Catalogue) codes of the various wastes, it is possible to find the unit price for each waste category and calculate (obviously it is necessary to provide data on the quantities of waste produced) the cost of the various wastes independently.

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5 BIM

"Construction of a model that contains the information about a building from all phases of the building life cycle." *ISO 16757-1: 2015*. The definition of the Building Information Modelling, acronym BIM, developed by the ISO standards encloses all the main components of this process. While a lot of specialist defines it as a type of software, and others refers to the mere 3D virtual model the main characteristic is to identify the definition of a specific process. In the BIM we have a digital representation of both geometrical and functional characteristics of all the construction elements that it is possible to identify in a construction process. All the data verge into a unique data source, ranging from early design conception to the demolition phase. This data-source has the main feature to be shared among all the parties involved in the facility during the life cycle: architects, engineers, construction project managers, facility managers and all the others: the BIM represents the integration of stakeholder's roles on a project.

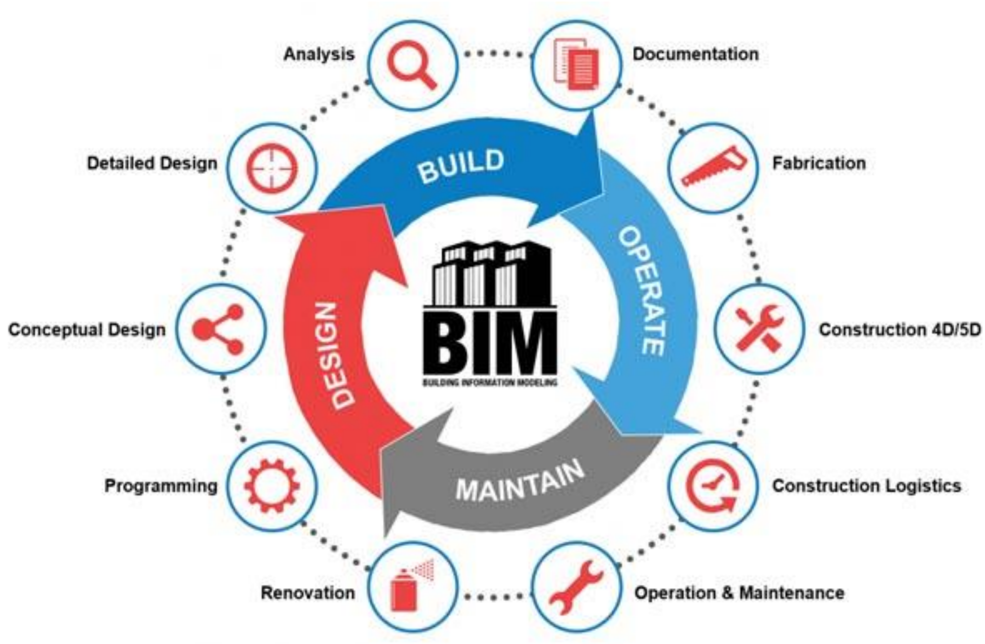

Figure 23: BIM process [Source: https://www.syspro.it/wordpress/services/bim/]

The Building Information Modelling has a wide range of technical application:

- Visual representation in 2D or 3D;
- Cost estimation
- Construction management;
- Conflict, interference and collision analysis;
- Facility management;
- Code validation;
- Material tracking
- Energy analysis
- Etc.

The BIM processes enables all the stakeholders to coordinate in a more efficient way all the project deliveries, thus it has been able to identify tangible advantage in terms of time and budget savings.

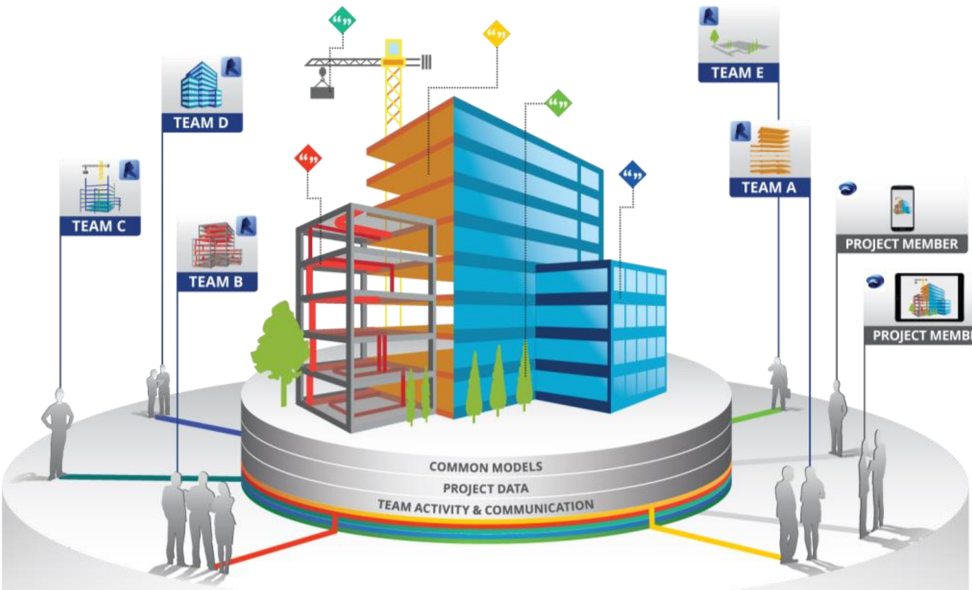

Figure 24: BIM coordination [Source: https://www.arketipomagazine.it/autodesk-amplia-il-bim-con-servizi-basati-su-cloud/]

5.1 BIM's levels

The process itself of implementation of the building information modelling in the construction industry has been a progressive one, so that it is possible to divide different stages of BIM maturity, the so called "BIM levels". The NBS annual National BIM report tries to identify yearly the maturity development of BIM processes, in order to understand its real adoption in the construction sector. Since the adoption of BIM levels definitions, that range from lv. 0 to lv. 3, we are still in debate on the exact meaning of each one and further implementation of new ones.

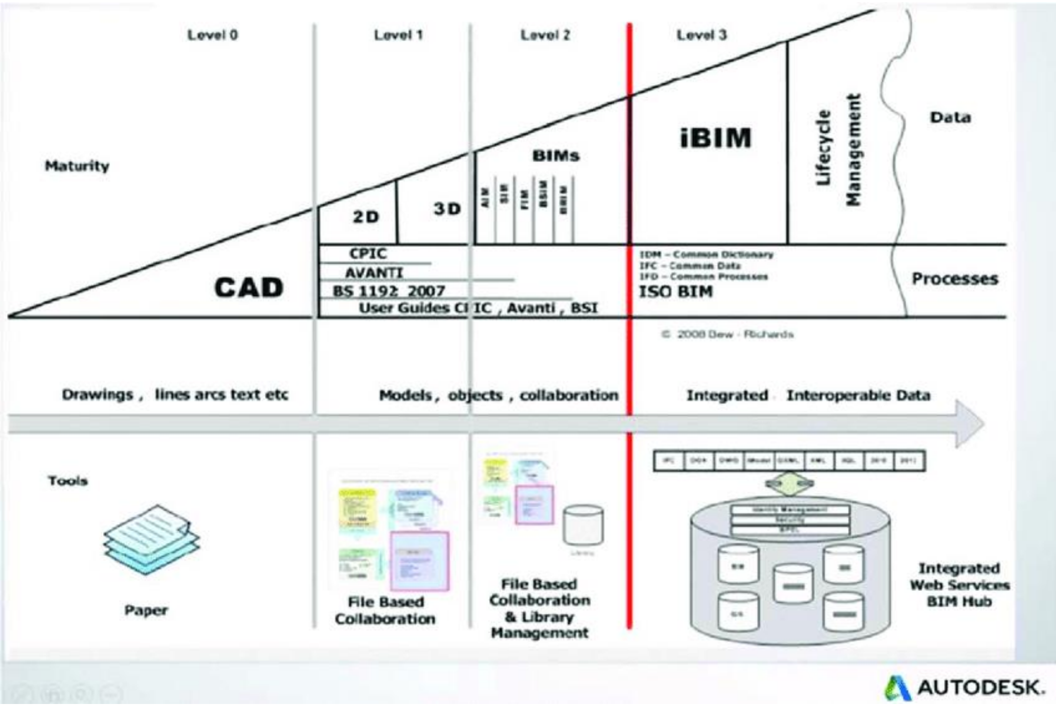

Figure 25: BIM level description [Source: http://www.bimplus.co.uk/analysis/explaining-levels-bim/]

The BIM levels can be defined as:

- The Level 0 is the entry level BIM in which it is possible to identify the main processes of collaboration among documents, but it only includes 2D drawings and separate papers or electronic prints as output. This level has already been surpassed quite by all the industries.
- In the Level 1 BIM the 3D drawings must be integrated in the construction processes, while in the BS 1192:2007 determines the principle guidelines to be followed in order to reach level 2. There is a more accurate collaboration among stakeholders and reliable information. The file collaboration is reached by the integration of a "Common Data Environment" so that a document management system is adopted by all the stakeholders.
- Level 2 of BIM processes could be reached just if an effective collaborative working flow is defined, so that every CAD drawing could be than exported in a standardised way that every participant to the project development is able to read it in a common way. The information exporting process must be adequate and specific to every single project.
- Level 3, even if its definition it is still under debate, could be identify as the process to create a sharing data system among Countries in order to achieve a common project development in the entire free market. The level aims to create a cultural environment based on learn and share approach.

5.2 Level of Detail (LOD)

Another important stage in the BIM maturity level is the definition of the Level Of Detail (LOD) in which it possible to assess the definition of 3D geometry and information of the building model, defined in six different stages. Every stage defines higher specification level of the model reliability, which follows the construction phases.

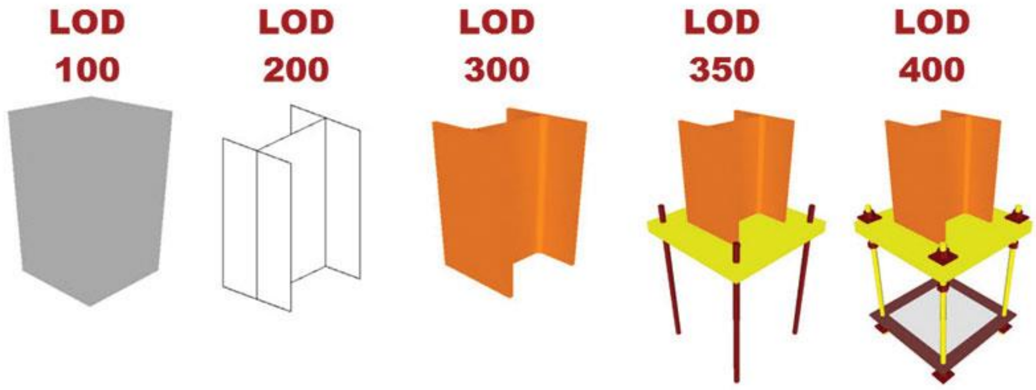

Figure 26: LOD from 100 to 400 level example. [Source: https://www.structuremag.org]

Each level of detail has been defined by the BIMForum as follow:

- LOD 100: the construction elements may be graphically represented in the Model with symbol or other generic ways, but it does not show actual size, shape or precise location.
- LOD 200: Generic representation in the model of building elements in generic object, with approximate quantities, size, shape and location. There could be also an integration of documents and no-information files.
- LOD 300: Graphical representation of object with appropriate size, shape, location and quantities and integrated with also no-graphical documents.

- LOD 350: In this level with have the integration of specific system, object or assembly represented in the Model with the interfaces with other building systems.
- LOD 400: The building system is identified in the model in terms of shape, size, quantity, location, orientation with high level of detail for fabrication, assembly and installation information.
- LOD 500: The building system are field verified in terms of LOD 400 specification.

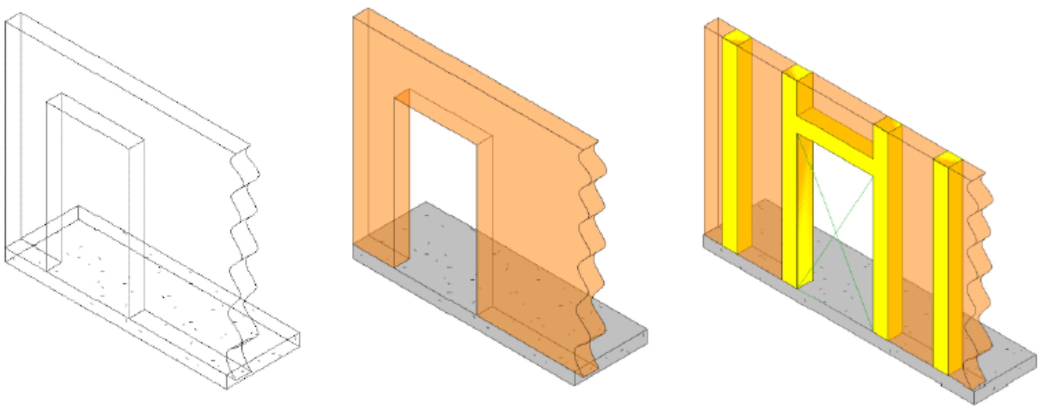

Figure 27:Example of LOD 200, 300, 350 for an Exterior wall [source: LOD Spec 2018 Part I, BIMForum]

5.3 Reference

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6 LCA-BIM in the early design stage

6.1 Phases of construction projects

In construction projects, three phases are usually identified:

- the preliminary phase (or technical and economic feasibility);
- the final project;
- the executive project.

The normative reference in Italy (in the context of public works) is the "Merloni Law" L.109/94 and subsequent amendments. The design thus divided is intended to ensure:

- the satisfaction of the needs of the community;
- the architectural and technical-functional quality in the context of the work;
- compliance with environmental, urban planning and protection of cultural heritage and landscape, as well as compliance with the provisions of the legislation on the protection of health and safety;
- limited land consumption;
- respect for hydrogeological, seismic and forestry constraints and other existing constraints;
- saving, efficiency and energy recovery in the construction (and subsequent lifespan of the work), as well as the assessment of the life cycle and maintainability of the works;
- compatibility with pre-existing archaeological sites;
- the rationalization of design activities and related checks through the progressive use of specific electronic methods and tools such as modelling for construction and infrastructure;
- the geological, geomorphological and hydrogeological compatibility of the work;

- accessibility and adaptability according to the provisions in force regarding architectural barriers.

In 2016, again with reference to public works, it was introduced in Italy the "nuovo Codice Appalti" i.e. the new Procurement Code of Legislative Decree 50/2016, whose novelty compared to the old one is the strengthening of the preliminary phase, enriched by a series of requirements based on the tender for the executive project to avoid unforeseen events, slowdowns and variations in the more advanced phases. The objective is, therefore, to ensure the quality of the process and the project, ensuring that there is the slightest deviation from reality.

6.1.1 Early design phase

As we have already pointed out, the construction phases among a single project may vary according to the design's nature in private or public sector, giving a high level of uncertainty during its development. The conceptual stage is a continuous dynamic flow in which a wide range of different operators must be aligned in the same project development. The ideas in the early stage of a design could flow in a linear and structured way or, at the same time, be expressed in a very chaotic and unstructured way, creating high level of uncertainty in the final design result.

The creation of a structure that can map all the design stage and organize them in a linear way has been under process for year, and it is not just a construction section problem but spread in all the industrial sectors. The need to create a common general and widely applicable process in the construction industry lays on the same need to align requirements of the different agents in order to choose the more balanced solution among the wide range of possibilities and solution, both in architectural and technical problems.

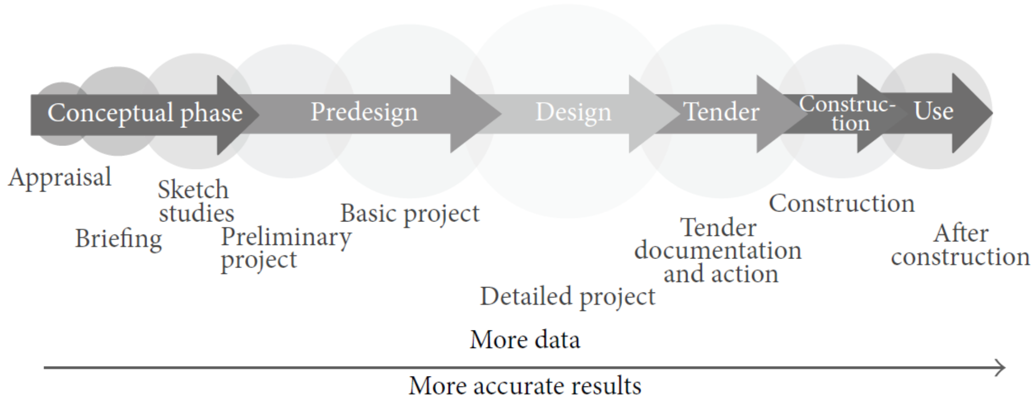

Figure 28: Project phase / information relationship [Source: van Dronkelaar et al. 2016]

The relationship between development and project phases lies on the amount of reliable data that each stage needs to accumulate and analyse in order to proceed in the project. Each stage requires more detailed information as the development is carried out: in the early design phase the agents involved in the project are already conscious about the general shape of the building (by sketches, plans and sections). Since we step forward in the development it is important to evaluate the actual link between initial requirement and chosen solution as every level of detail is align to the previous one.

Generally, in the predesign phase are identified hypothetical materials for the interior and exterior wall finishing, type of flooring and masonry, special mechanical or plumbing systems, windows and door features: that information will lead to an acceptable level of reliability on economic effort to be done.

Since the creation of a general accepted approach among the construction processes, the greater effort has been made by The Royal Institute of British Architects that published in the late 1963 the famous "Plan of Work" in which the structure of construction design is illustrated as a matrix format, and it has been revisited several times since its last update in 2013. It is one of the most important management schedule tools in the construction industry, dividing the project development in eight work stages (ranging from number 0 to 7), offering to the possible actors a core matrix in which their activities and responsibilities have been divided and organized so that every agent can find its connection among the others.

It has been used a sample in this discussion as it gives great importance to the early design stages, divided in the first three stages:

- 0: Strategic Definition
- 1: Preparation and Brief
- 2: Concept Design

Stage 0 identifies the relevant scope of the project by the client's Strategic and Business Brief in which it has been possibly understand principle needs and basic requirements and also the design context: in this stage is possible to evaluate the necessity to a refurbishment, a rationalization of space or if we require a completely new building.

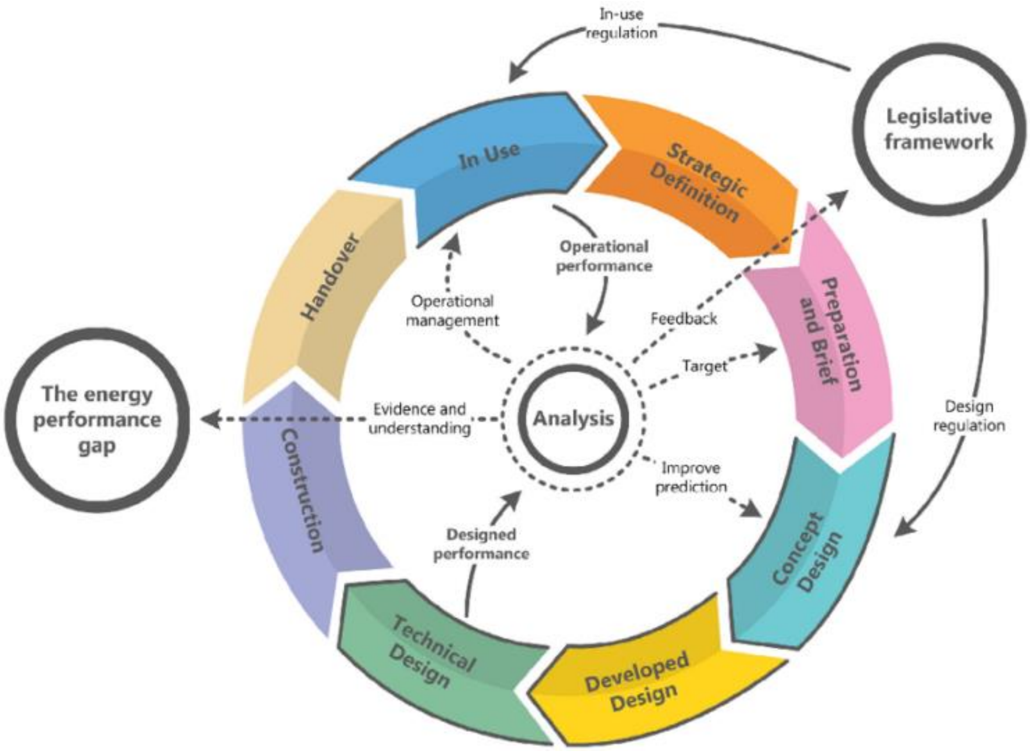

Figure 29: Feedback process in relation to the RIBA plan of work [Source: van Dronkelaar et al. 2016]

The Preparation and Brief stage have a heavy role in the project development because it is here that we can illustrate the Initial Project Brief and the team's selection and definition of each role and responsibilities. The Initial Project Brief is fundamental as it define the spatial requirements, the context of the projects and nevertheless the budget constraints. It is in this stage that for the first time the RIBA manage the communication among stakeholders with the help of Building Information Modelling systems.

The Concept Design should be carried out with all the previous requirements, and it is the combination of multiple parallel strategy as Sustainability, security, Cost information, Construction, maintenance and operational strategies, Health and Safety and project execution plan, in which each one is may have minimal or great impact on the Concept design developed at the end of this stage.

The Developed Design is the last part of the design stage in which it must be concluded with architectural, building services and structural design have been complete developed: it is in this final decision stage that all the possible solutions that could lead to the satisfaction of the client's needs and requirements must be processed, analysed and it must be chosen the more economical and technical feasible solution.

The great problem of the early design stage lies in the creation of possible alternatives with the right input of requirements that must be seat in a conscious way. The Plan of Work pointed out the complexity of the early design stage, with all the multi-disciplinary teams, organized in a flexible way. The real problem in the RIBA 2013 update, that can easily see in the other stages' matrix developed by academic and professional, is a real integration of BIM analysis and sustainability in this stage, where it is still predominant the economic and technical feasibility. In the early design stage is missing any reference to refurbishment and demolition or re-use or recycle of buildings and its related component and material as a reference of cradle-to-cradle approach. Furthermore, the sustainability aspects, which is fundamental for less impacting project in the overall construction industry, appears just in the Developed Design stage so that is not a remarkable requirement in the decision phase and completely unlinked in the planning phase.

“Instead of trying to “force fit” sustainable principles into an existing and often unreceptive manufacturing system, it may be useful to approach the subject from the opposite direction, and consider how functional objects might be designed and manufactured to be compatible with principles of sustainable development” [Quote by S. Walter, *Sustainable by Design—Explorations in Theory and Practice*, Earthscan, London, UK, 1st edition, 2006].

S. Walter in this quote, highlight the same problem that the RIBA tried to compensate in its final update: the sustainability could be reached lonely if in the predesign phase are collocated criteria of selection, among different solution, based on sustainability aspect in order to find long-term solution to the environmental impact reduction.

So, the goal of the thesis lies on the capability of integrate sustainability requirements in the early design phase thanks to Life Cycle Assessment in order to address environmental impacts as a dominant requirement in the building solutions choice. The main proposal is the integration of LCA in early design stages by BIM software in order to make collaborate the wide range of different roles involved in the project development.

6.2 LCA introduction in BIM environment

Sustainability is now recognised as one of the fundamental requirements for the development of contemporary society and cities. The concept of sustainability is evoked to characterize and define the optimal relationship between man and nature, in whatever form it takes place.

Within the challenge for the sustainable development of cities, a fundamental role is assumed by the construction industry. The weight of construction in generating the "unsustainability" of cities and territories or in general of the development of society is very high, because the value of construction in contemporary society is very high.

Too often, especially in construction, the requirement of sustainability is reduced and confused only with energy requirements (while it embraces economic, social and environmental plans). In fact, also because of a regulatory framework not yet defined and because of procedures and methods of sustainability assessment not yet established, often a building intervention is defined as sustainable only if it in some way determines energy savings in a phase of the useful life of the intervention itself. Sustainability, on the other hand, has to lie in achieving an optimal balance in meeting, at different times in time, economic, environmental and social requirements, often in conflict with each other.

It is therefore recommended that the decision-making process underlying the design be as "informed" as possible by data on the environmental, economic and social impacts determined by the choices made. In other words, the design must be able to consciously manage complex information related to the sustainability of the planned interventions. Often, however, such information is difficult to manage in an integrated way, because it is large, varied and complex, especially referring to buildings and infrastructures, which in themselves consist of the integration of different technological systems.

The Building Information Modelling (BIM) approach can therefore be a solution to this problem, offering the possibility of managing a complex information system in an integrated manner, referring to the various technological systems and components that make up the building or infrastructure object, and relating to different moments of its life cycle.

The BIM methodology is certainly suitable to manage a complex and varied amount of data such as that related to the environmental impact assessments through LCA analysis, thus helping to provide information about the sustainability of the choices made in the design phase, making aware and guiding the decision-making process. It should be noted that in this case, the integration of LCA analysis in BIM allows to analyse data related to environmental sustainability, which is therefore only one of the aspects of overall sustainability, as well as economic and social aspects.

The LCA analysis starts from the concept of life cycle and aims to analyse all the phases of the transformation process, from the raw material extraction, to their processing, transport and distribution, to the implementation, use and maintenance phase, up to the disposal at the end of the life cycle.

It is because of the complexity and high quantity of data that characterize building objects that BIM is becoming increasingly widespread, as a support for the storage and optimised management of all the information useful for design, realisation and management.

The BIM methodology potential in the management of information is therefore an interesting and valid support to implement LCA directly in the BIM environment with the aim of simplifying the evaluation procedures, the understanding and use of the results. The BIM also represents for many construction and design companies a valid decision-making tool in terms of costs, time and design solutions and extending this opportunity to LCA evaluations, can be used profitably as a tool for assessing the environmental sustainability of construction works.

Therefore, an analysis of the environmental impacts already in the preliminary phase is very important since the most fundamental decisions influencing the life cycle performance of a building are taken in the very beginning of the design process, as can be suggested by the following graph and as widely discussed above:

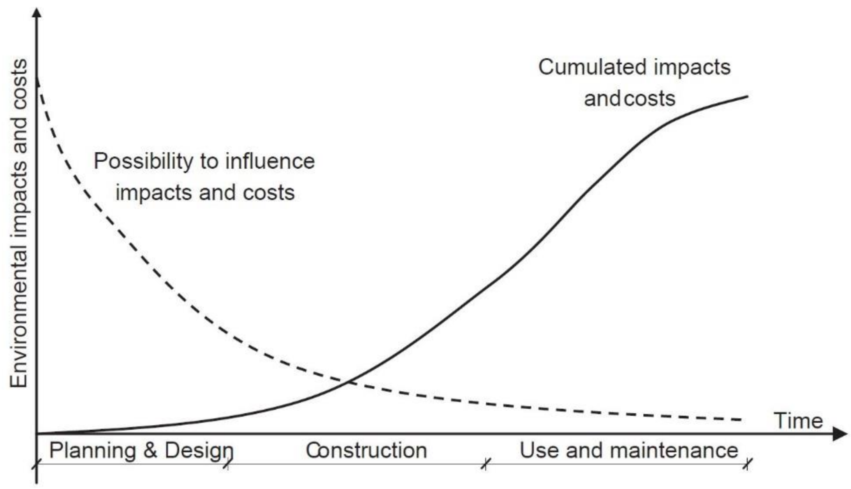

Figure 30: Design decision's influence on costs and environmental impacts [Source: UNEP. Life-cycle analysis of the built environment. UNEP Indust Environ 2003: 17e21.]

What the graph represents is that the earlier the assessment, the higher is the potential to effectively influence the life cycle performance of the building.

It is therefore logical to recognise the importance of introducing an LCA analysis already at the preliminary stage of the project, and then to make an analysis of the entire life cycle in order to make informed decisions on the design and choice of materials, a factor that naturally affects not only energy performance, but also issues such as the end of life of the building, so the recyclability or even the maintainability and durability, which can lead to choices such as the use of wood, stone or brick based on functional and environmental needs or the adoption of prefabrication that, reducing assembly and disassembly time, as well as reducing costs on site, reduces environmental impacts. What should be done, therefore, is to integrate these sustainability concepts from the preliminary phase, since, as already written, it would lead to considerable advantages. All this will of course be done at a low level of detail, both for a matter of time, because it is useless to make too detailed analyses in this phase and also because there is a limited availability of data; remember that the purpose of this analysis is to make design choices, without getting into the core of in-depth evaluations, so it will be done at a simplified level.

For this purpose, it has been developed a SWOT analysis, to highlight positive and negative aspects of LCA requirements in the early-design phase through use of BIM software.

6.2.1 SWOT analysis

	Helpful **To achieving the objective**	Harmful **To achieving the objective**
Internal origin **(attributes of the organization)**	**STRENGTHS** - Sustainable choices - Reliable analysis output - Adaptable and flexible - Integrated management of complex information - Minimal interference between operators	**WEAKNESSES** - More time needed - Cost increase - Higher workload - Wider data collection - Specialized LCA team addition - No unified standard
External origin **(attributes of the environment)**	**OPPORTUNITIES** - Creation of open-source plugin for BIM software - Open access among database - Cooperation with environmental certification systems	**THREATS** - Team management slows down - Small companies struggle in training and software investments - Legislative restriction - Errors in simplifying assumptions

Table 23: SWOT analysis

For what concerns strengths and opportunities of introducing the LCA analysis in the early design phase of the projects through the use of BIM it is important first of all to talk about the integrated management of complex information thanks to the use of BIM, this will permit to avoid errors that the "traditional" tools used for LCA analysis may present, this is given also by the fact that with BIM software there will be a minimal interference between the operators that will work on the project, because everyone will work on the same file through interconnected software; furthermore this leads to conduct LCA analysis in a flexible and adaptable manner, giving the possibility to change an aspect of the project and having immediate feedbacks on the outputs and so to compare the different solutions. This will permit, in an early-design phase, to make choices on the different project alternatives, about materials and technologies, to have an overview of the best solutions in a sustainable perspective along the whole life cycle of the building.

What is expected in the future is to have an open access among databases, giving to the user the possibility to choose the one more suitable for his project, but also to force companies to collaborate in the creation of reliable databases with the release of EPDs (nowadays few companies contribute); but also a creation of open-source plugins for BIM software, actually there are a lot of restrictions and limitations. In this scenario, the aim is also to be supported by the environmental certification systems, in a more precise parameters definition on the preliminary stage of the project, with indications and parameters.

The negative aspects related to the implementation of LCA solution within Building Information Modelling software range from weaknesses and threats, in the case we are concerned about internal organization or external environment scenarios. As already mentioned, the positive impact must be balanced with the negative one in order to provide an overall analysis of the BIM-LCA combination.

The weakness that has been found lies on the general great investment of time and money that should be achieved in the first implementation period: in the early design phase we deal with undetailed information where a wide range of assumption must be carried out in order to obtain reliable results and the new environmental requirement need a larger quantity of data.

Since we are dealing with the best choices among different technical solution, the overall cost for the implementation of LCA consideration in the BIM universe we are going to face higher project cost, with the addition of new LCA specialized team. This will create a higher time necessity within the early design stage, since new actors and information have been added to the general framework, with a correlated increment in the general workload.

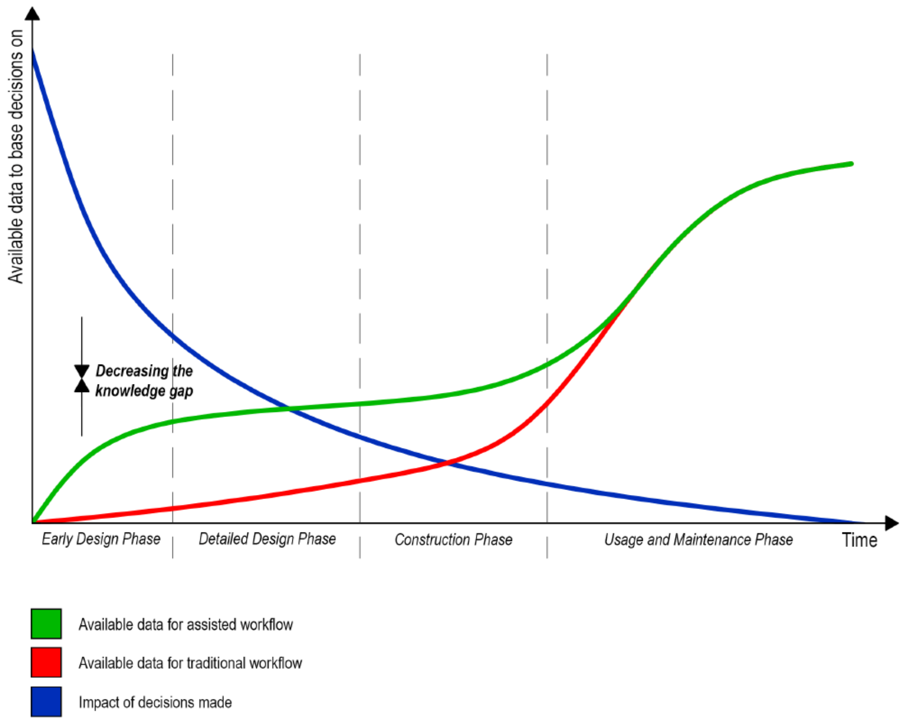

Table 24: Available data for integrated workflow [Source: Kohler, N.; Moffatt, S. Life-cycle analysis of the built environment]

Another important aspect to be taken into consideration is the data collection that in this phase is a critical point: normally the data collection and the data availability is very limited in this stage and while the data increases it reduces the knowledge gap in this phase, at the same time it will occur a greater effort in the data management system to do not create interference among different actors and responsibility for the data analysis. Furthermore, a unified standard is completely missing for what concern BIM and LCA analysis, so it could lead to a different methodologies or workflow among companies that could create misunderstanding between actors and clients.

The threats in the external environments are related firstly to the team management aspect, where companies must change their workflow in the project development to be able to create a reliable process. Also, the external restriction could be seen by the legislative power that could evaluate new environmental laws in the construction industries, creating new mandatory investments for the workers training and the software acquisition for the implementation of LCA in BIM. Finally, an easy error that could rise is the identification of simplified models that can really help the decision-making process in the early design phase: while the basic assumption that can be made in this stage need to be properly reported as if there are conceptually wrong in this stage, they can deeply affect the sustainability results.

6.3 SimaPro

In the study analysed, SimaPro software was used, developed by the Dutch company Pré Products Ecology Consultants, widely used in industrial and international practice and recognised by industry experts. It is the most widespread software in the world and over 80 countries use this type of program.

It is a reliable tool and, thanks to its marked interactive potential, allows to create, modify and adapt specific processes to those already existing in the database. It also allows interactive analysis of results, with large databases capable of examining most industrial processes. The software allows you to evaluate, monitor and analyze the environmental performance of products and services by analyzing in an orderly and clear even complex life cycles and following the guidelines of ISO 14040 and 14044.

Characteristics

1) The software has an intuitive interface and follows the indications of the ISO standards, dividing the study into the 4 main parts of the LCA study;
2) Possibility of modelling the various parameters, i.e. performing sensitivity analyses, uncertainty analyses, defining non-linear relations in such a way as to compare different scenarios;
3) Results available in data or table and full compatibility with Excel or ASP;
4) Possibility to have also national databases;
5) Evaluation of impacts at any time in the model;
6) Analysis of results with the possibility of immediately tracing the source of the data;
7) Graphical tree view of the study project to improve ease of reading and identify weak points in the system;
8) Possibility of analysis of disposal scenarios and complex recycling.

6.3.1 User Interface

The software has a simple graphical interface, the window that welcomes us is Explorer, which you can segment into 3 parts: the management part of the LCA, the part of the processes and the part of the description of these processes. A section follows us in the development of the LCA and proposes the classic subdivision of the study in: - Goal and Scope: where we can go to describe our study and our processes adding also all the part of the objectives and limitations of the analysis.

- Inventory: where we will set up, modify and evaluate all the components of our study;
- Impact assessment: where the program provides us with the processing of the data and its impacts;
- Interpretation: where we could go to manage the criteria for the interpretation of the study.

Another section is dedicated to processes and materials that include almost all of the subjects that can be found in nature. The main categories are 7 and are divided as follows: processes, Energy, Transport, Use, Processing, Waste Scenario, and Waste Treatment. With these categories, and the countless subcategories, we are able with due care to schematize any process of analysis.

The program allows us to select a process and set the inventory values necessary for the study, if necessary, given its flexibility, allows us to create an added process that starts from the settings of an existing process or from a new process completely empty.

6.3.2 Inventory data

The inventory data processed by the SimaPro program is contained in databases containing thousands of processes and materials.

6.3.2.1 Ecoinvent

Ecoinvent is a database containing key data on activities in Switzerland and Western Europe, covering energy, transport, building materials, chemicals, washing products, paper and board, agriculture and the treatment of pollutants. All processes are accompanied by extensive documentation, with the related data description (name, unit of measurement, data derivation, category and subcategory) and information about the uncertainty of the data.

6.3.2.2 US Input Output database

This database originates in the United States and its data are related to industrial and commercial elements of the U.S. economic sectors. Environmental data are processed with the most up-to-date sources in the U.S. states and one of the latest updates concerned the improvement of data on GHG emissions, soil emissions and land use.

6.3.2.3 Danish Input Output database

This is a database based on Danish data from the 1990s, modernised and modified for the purposes of LCA studies.

6.3.2.4 Ducth Input Output database

The creation of this database was allocated by the Dutch government with the desire to track the impacts of its policy on environmental loads related to private consumption at the national level. 105 Dutch industrial sectors were taken into account, as well as other sectors from other countries that were also members of the "Organisation for Economic Cooperation and Development", thus making the data usable outside the Netherlands.

6.3.2.5 LCA Food Database

This is a database that contains environmental data about processes related to food production chains. The data comes from Denmark.

6.3.2.6 Industry data

It contains data on data provided by industry associations evaluating products from birth to disposal.

6.3.2.7 ETH-ESU

The ETH-ESU database contains inventory data representative of the situation in Switzerland and some of these data are used to mediate and approximate European data. The specialisation of this database is in the fields of energy, energy carrier production, power generation, energy transmission, material production, transport and treatment of pollutants.

The characteristics of these data can be divided into three categories:

- Primary data: from direct surveys;
- Secondary data: derived from databases;
- Tertiary data: from estimates and average values. Impact assessment

The program, once entered the data from the inventory of our process, invites you to choose the method of assessment of the environmental impact that we have decided to analyze, listing the databases available. If it is not chosen, the method the program calculates the part of the inventory of emissions substance by substance, but if you choose a criterion for assessing the impact, the substances will be grouped with the required methodology and the program will provide the results in the form of tables, graphs or tree drawings.

6.3.3 Interpretation of results

SimaPro also offers the possibility of analysing the entire process or subdividing the assessment of impacts by impact categories, and by sub-processes. This allows us to provide much easier interpretation of data in a much quicker way. In addition to allowing the assessment of the impacts of the process, the program is able to compare two different processes in order to make a comparison of environmental impacts; this examination facilitates the degree of analysis and studies in order to better understand whether a process is more or less polluting. It should also be remembered that in comparative studies this procedure is essential. A useful feature of the program is the possibility of extrapolating the data into an Excel spreadsheet, thus giving the user the possibility of personalised management and thus helping him to interpret the results.

6.4 References

M. F. Ashby, “Materials and the Environment, Eco-Informed Material Choice”, Elsevier, 2nd Edition, Oxford, 2013.

M. F. Ashby, “Materials and sustainable development”, Elsevier, 1st Edition, Oxford, 2015.

M. Lavagna, “Life cycle assessment in edilizia: progettare e costruire in una prospettiva di sostenibilità ambientale”, Hoepli, Milano, 2008.

BS EN 15978, Sustainability of construction works. Assessment of environmental performance of buildings, 2011.

ISO 14044, Environmental management - Life cycle assessment - Requirements and guidelines, International Organization for Standardization, Geneva, Switzerland, 2006.

ISO 9000 Series standards:

- ISO 9001:2015: Quality management systems - Requirements
- ISO 9000:2015: Quality management systems - Fundamentals and vocabulary
- ISO 9004:2009: Quality management systems – Managing for the sustained success of an organization
- ISO 19011:2011: Guidelines for auditing management systems

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S. Walter, Sustainable by Design—Explorations in Theory and Practice, Earthscan, London, UK, 1st edition, 2006.

LCA software for fact-based sustainability – SimaPro: https://simapro.com/

RIBA Plan of work 2013: https://www.ribaplanofwork.com/

7 Case study

The study of the relationship between costs and environmental impacts is carried out through the use of a specific case study that will be useful for the realization of an LCA and an LCC. The results obtained will be the result of specific assumptions for the case study, therefore eliminating components and phases of the life cycle that are not interesting for the achievement of our goal. The results obtained will therefore be specific to the case study and cannot be interpreted in a general manner and thus determine objective conclusions regarding the construction technologies chosen. The building in consideration has a purely residential use, divided into three separate apartments, distributed on three levels of elevation: ground floor, first floor and attic with veranda.

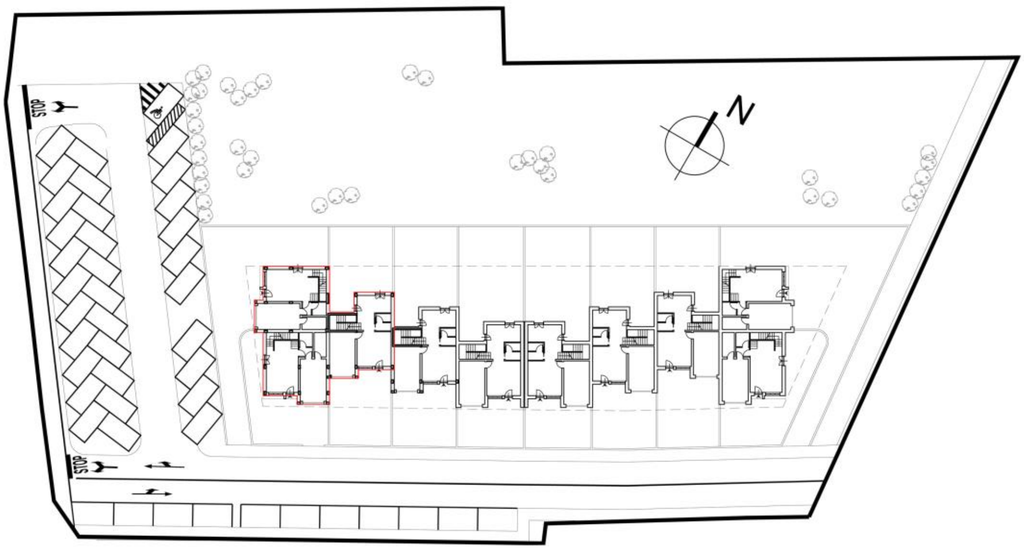


Figure 31: Building Planimetry, identification of case-study [D. Lorenzini "Il legno come alternativa costruttiva. Analisi energetiche, ambientali e costi del ciclo di vita".]

The subdivision of each apartment into living areas has not been analysed, as it does not affect the results; instead, the possibility of having radiant floors and heated and unheated areas has been considered, so as to be able to modulate the thermal performance of the building in a suitable way.

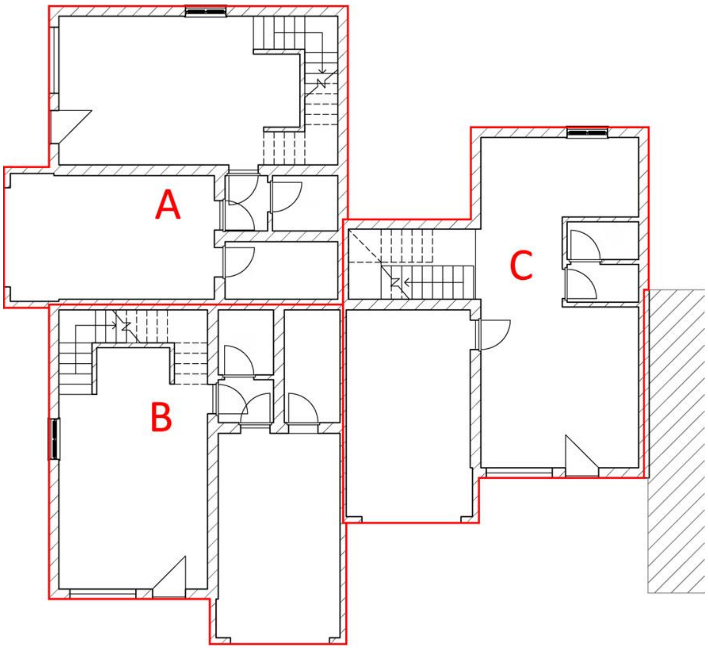


Figure 32: Ground floor plan [D. Lorenzini "Il legno come alternativa costruttiva. Analisi energetiche, ambientali e costi del ciclo di vita".]

The internal and external partitions, both vertical and horizontal, have been studied with regard to the levels of transmittance: each type of wall, floor or roof has a stratigraphy that allows them to stay within the minimum performance values required by the Italian and Austrian legislature. The project was located within the municipality of Graz, Austria (AT), without identifying a precise area. This allowed us to use general applicable scenarios for calculating the transport of materials and distances from disposal plants both for economic and environmental impact analysis in the construction and end-of-life phase of the building.

	Apartment A	Apartment B	Apartment C
Useful heated surface	108,80 m^2	105,00 m^2	158,60 m^2
Total surface	166,80 m^2	166,00 m^2	200,80 m^2
Reference surface	156,90 m^2	154,70 m^2	199,20 m^2
Useful heated volume	263,80 m^3	262,80 m^3	384,9 m^3
Total volume	482,00 m^3	493,50 m^3	601 m^3

Table 25: Surface and volume per apartment

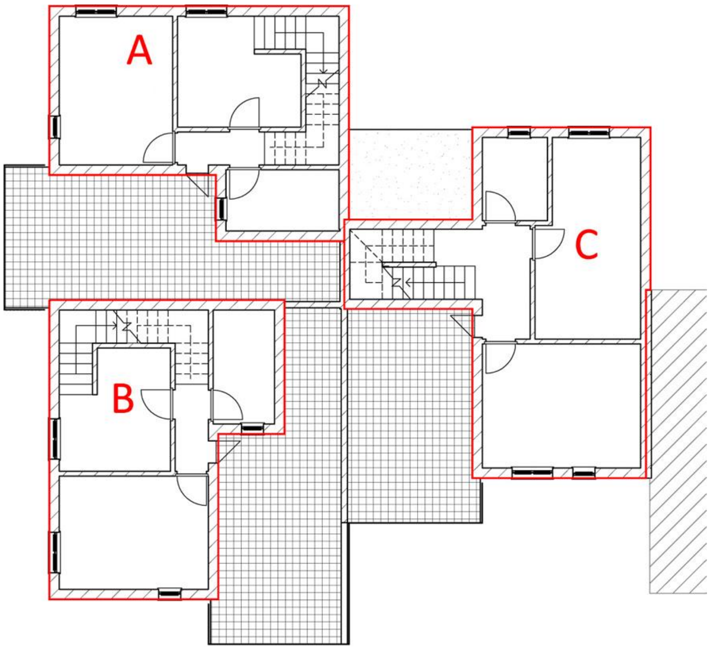


Figure 33: First floor plan [D. Lorenzini "Il legno come alternativa costruttiva. Analisi energetiche, ambientali e costi del ciclo di vita".]

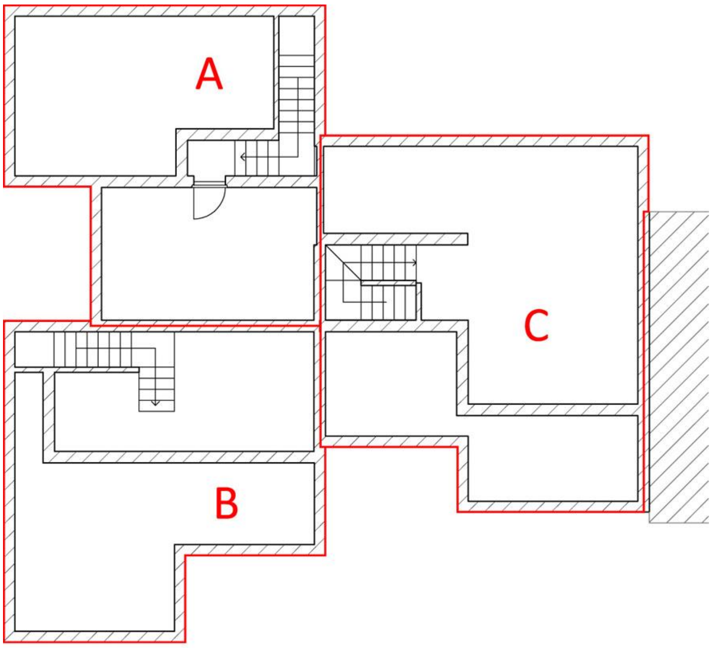


Figure 34: Second floor plan [D. Lorenzini "Il legno come alternativa costruttiva. Analisi energetiche, ambientali e costi del ciclo di vita".]

The case study has been the subject of four different construction techniques, in order to obtain economic analysis and comparable environmental performance. The choice of building materials used fell on the more classic use of brick, in the specific case Poroton, with an overlay system for the envelope and structural frame in reinforced concrete and slabs in brick cement. This typology is one of the most widespread building technologies used in the Italian building sector. From this standard case, we wanted to inspect the performance of a construction method atypical for the Italian landscape, but widely used in the Austrian construction industry, vertical partitions inside and outside reinforced concrete with full insulation coat, and slabs in brick cement as in the case of Poroton.

In order to be able to have a broader and more functional case study afterwards, wood was considered as the main building material: hence the choice for the use of the load-bearing wooden frame structure and the solid panels of cross laminated timber. In both cases the floors are built according to the methods of the two types, i.e. wooden frame and cross-laminated panels.

The four types identified are therefore:

- Poroton;
- X-lam
- Concrete
- Timber-frame.

The house has different solutions with regard to vertical and horizontal partitions, thus differentiating the relevant stratigraphy in order to meet the different thermal and performance requirements. Furthermore, the heated and unheated sides of the case study, enables us to identify different wall and flooring system per each situation, so that the thickness and material's choice determines the same functional unit for each technology analysed. A conceptual plan helps us to identify the different stratigraphy with respect the different required functions of each element.

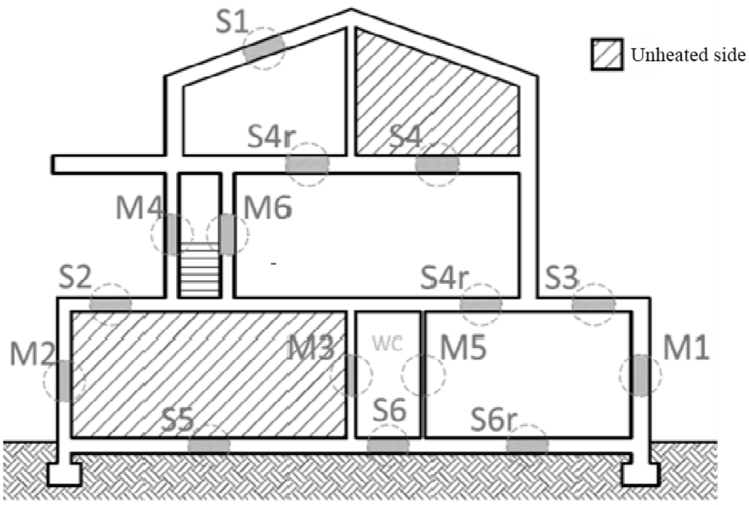


Figure 35: Conceptual scheme [D. Lorenzini "Il legno come alternativa costruttiva. Analisi energetiche, ambientali e costi del ciclo di vita".]

As shown in the figure we can identify different solutions for the realization of the partitions. Vertical partitions are divided into:

- M1: External envelope
- M2: External envelope on unheated internal side
- M3: Internal partition on unheated side
- M4: External stairwell core
- M5: Internal partition
- M6: Internal stairwell core

Regarding horizontal partitions we can identify:

- S1: Pitched roofing system
- S2: External roof on unheated side
- S3: External roof on heated side
- S4: Internal floor on unheated side
- S4r: Internal radiant floor
- S5: On ground floor system on unheated side
- S6: On ground floor
- S6r: On ground radiant floor

This breakdown structure allows us to identify the different solutions and their performance and functions so that we can process an ad hoc stratigraphy for each partition according to the various construction technologies adopted. The only elements that are univocally repeated for each of the case studies examined are the foundation structures and windows and doors, which do not present changes either in terms of surface area and volume, or in the materials used for their construction.

	nr	Name	s *cm*	λ *W/mK*	ρ *Kg/m³*	C *J/KgK*	μ *-*	*widht* *cm*	*Trasmit.* *U*
Poroton	1	Water-based paint	-	-	-	-	-	*36,1*	*0,256*
	2	Lime and gypsum plaster	1,50	0,700	1400	1000	10		
	3	POROTON 800	25,0	0,149	860	1000	10		
	4	Lime and gypsum mortar	1,00	0,900	1800	1000	20		
	5	EPS F insulation panel	8,00	0,040	25	1500	60		
	6	Lime and gypsum mortar	0,60	0,900	1800	1000	20		
	7	Water-based paint	-	-	-	-	-		
X-Lam	1	Double plasterboard + vapour membrane	2,50	0,320	1150	1100	13	*27,3*	*0,260*
	2	Hemp fiber Celenit LC/30	5,00	0,040	30	1700	2		
	3	X-LAM panels	14,2	0,130	500	1600	50		
	4	EPS insulation panels	5,00	0,040	25	1500	60		
	5	Mortar and plaster	0,60	0,900	1800	1000	20		
	6	Water-base paint	-	-	-	-	-		
Concrete	1	Water-based paint	-	-	-	-	*1*	*39,1*	*0,262*
	2	Lime and gypsum plaster	1,50	0,700	1400	1000	10		
	3	Reinforced concrete wall	22,0	1,480	2200	1000	100		
	4	Lime and gypsum mortar	1,00	0,900	1800	1000	20		
	5	EPS F insulation panel	14,0	0,040	25	1500	60		
	6	Lime and gypsum mortar	0,60	0,900	1800	1000	20		
	7	Water-based paint	-	-	-	-	1		
Timber frame	1	Double plasterboard + vapour membrane	2,50	0,320	1150	1100	13	*21,4*	*0,259*
	2	Wood fiber Thermoflex	16,0	0,040	45	2100	2		
	3	Wood frame structure	16,0	0,230	860	1000	10		
	4	OSB panles	1,20	0,130	650	1700	200		
	5	Waterproof mambrane	0,10	-	-	-	-		
	6	Insulation panels EPS F	1,00	0,040	25	1500	60		
	7	Mortar and plaster	0,60	0,900	1800	1000	20		
	8	Water-base paint	-	-	-	-	1		

Table 26: Material's features per technology

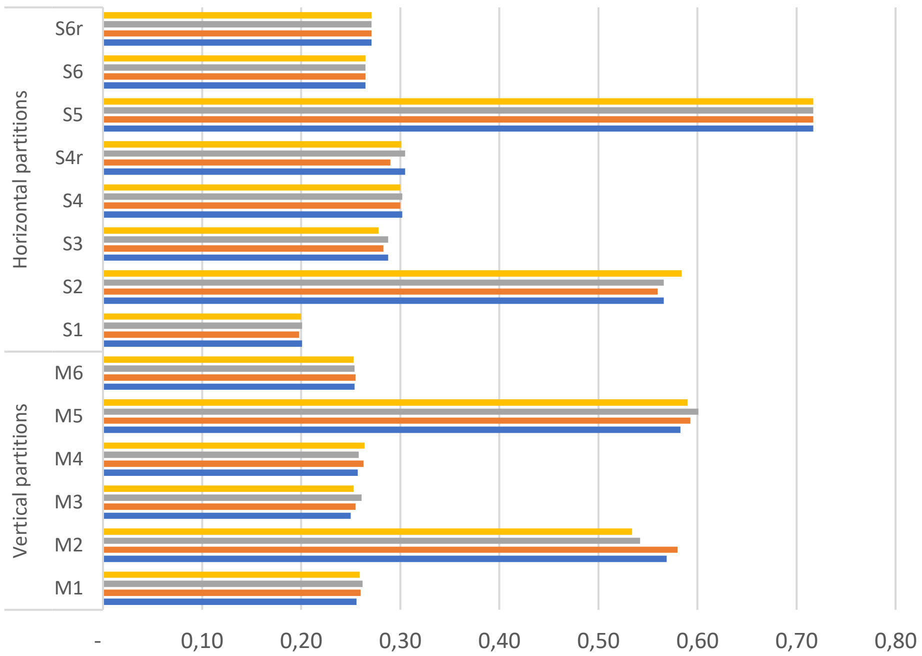
The challenge of comparing the economic and environmental performance of different technological solutions for the same building has led us to focus our attention on the performance of the building components, so that they are the same for each technology compared. In table "3" we notice how for each M1 wall all four technologies used remain within the same thermal performance range so that we can have a functional unit for each type of wall and/or floor.

		TRASMITTANCE			
		POROTON	**X-LAM**	**CONCRETE**	**TIMBERFRAME**
VERTICAL PARTITIONS	**M1**	0,256	0,260	0,262	0,259
	M2	0,569	0,580	0,542	0,534
	M3	0,250	0,255	0,261	0,253
	M4	0,257	0,263	0,258	0,264
	M5	0,583	0,593	0,601	0,590
	M6	0,254	0,255	0,254	0,253
HORIZONTAL PARTITIONS	**S1**	0,201	0,198	0,201	0,200
	S2	0,566	0,560	0,566	0,584
	S3	0,288	0,283	0,288	0,278
	S4	0,302	0,300	0,302	0,300
	S4r	0,305	0,290	0,305	0,301
	S5	0,717	0,717	0,717	0,717
	S6	0,265	0,265	0,265	0,265
	S6r	0,271	0,271	0,271	0,271

Table 27: Transmittance values per technology

The above table illustrates how the choice of materials for each component and its thickness has been of vital importance in order to have a unique reference unit for each component, so as to obtain comparable elements. Furthermore, it is important to note that the stratigraphy of the floors against the ground S5, S6 and S6r is the same for each construction technology, so as to be able to focus more on the different choices as regards the envelope and the internal partitions.

Trasmittance values for Walls and Floors per technologies



	Vertical partitions						Horizontal partitions							
	M1	M2	M3	M4	M5	M6	S1	S2	S3	S4	S4r	S5	S6	S6r
TIMBERFRAME	0,26	0,53	0,25	0,26	0,59	0,25	0,20	0,58	0,28	0,30	0,30	0,72	0,27	0,27
CONCRETE	0,26	0,54	0,26	0,26	0,60	0,25	0,20	0,57	0,29	0,30	0,31	0,72	0,27	0,27
X-LAM	0,26	0,58	0,26	0,26	0,59	0,26	0,20	0,56	0,28	0,30	0,29	0,72	0,27	0,27
POROTON	0,26	0,57	0,25	0,26	0,58	0,25	0,20	0,57	0,29	0,30	0,31	0,72	0,27	0,27

TIMBERFRAME   CONCRETE   X-LAM   POROTON

Table 28: Transmittance per components

7.1 References

D. Lorenzini ”*Il legno come alternativa costruttiva. Analisi energetiche, ambientali e costi del ciclo di vita”.* Politecnico di Milano, 2011.

Trasmittance values: https://www.ubakus.de/u-wert-rechner/index.php?

8 LCA Application

This chapter will describe the process that led to the LCA analysis, it is a standardized procedure that allows to record, quantify and evaluate the environmental impacts related to the life cycle of the building.

The 4 basic steps of an LCA were followed:

- Step 1: Definition of the goal and scope of the study
- Step 2: Life cycle inventory (LCI). It consists in making a model of the building life cycle with all the environmental inputs and outputs.
- Step 3: Life cycle impact assessment (LCIA). It mainly consists in understanding the environmental relevance of all the inputs and outputs.
- Step 4: interpretation of the study.

The analysis was carried out using the SimaPro software, a professional tool to collect, analyse and monitor the sustainability performance of products and services (for a more complete and detailed description see chapter 2).

8.1 Goal definition

The first step is the definition of the Functional Unit, that is the function on which to set the analysis and the comparison with the possible alternatives. The functional unit indicates the reference object of our study to which all the input and output data will be normalized.

It is thus defined by ISO 14040:

- Measurement of the performance of the functional output flow of the product system.
- The main purpose of the functional unit is to provide a reference to which to link the output and input flows.

It is a necessary reference to allow comparability of the LCA results and it's useful when evaluating different systems, it must be ensured that the comparison is made on a common basis. In the case study, a residential building was chosen with reference service life period of 50 years, in which the common elements between the 4 technologies, in addition to the dimensions, is the transmittance of all the internal and external walls, slabs and roof of the 4 technological solutions (Poroton, X-Lam, Cement and wood frame). In the analysis of the residential building chosen, surroundings are excluded. In the following table it is possible to see the comparison of the external load-bearing walls "M1", in the last column are shown the transmittances, in this case in a range between 0.25 and 0.26, which, in addition to being almost equal, respect the limits of Italian and Austrian law.

element	name	subelement	layer-nr.	ÖN B 1801-1	Material (Revit)	Material (DE	d [mm]	U W/m2K
POROTON								
M1	Exterior wall	facade	1	4C.01_claddings	Water-base paint		0,00	0,256
		facade	2	4C.01_claddings	External plaster		6,00	
		external	3	4C.01_claddings	EPS F Insulation		80,00	
		External	4	4C.01_claddings	Gypsum plaster		10,00	
		structural	5	2E.01_exterior wall st	POROTON 800		250,00	
		internal	6	4C.01_claddings	Internal plaster		15,00	
		internal	7	4D.02_wall coverings	Water-base paint		0,00	
X-LAM								
M1	Exterior wall	facade	1	4D.02_wall coverings	Water-base paint		0,00	0,260
		facade	2	4C.01_claddings	External plaster		6,00	
		external	3	4C.01_claddings	EPS F insulation		50,00	
		structural	4	2E.01_exterior wall st	X-LAM panels		142,00	
		internal	5	4C.01_claddings	Hemp fiber Celenit LC/30		50,00	
		internal	6	4C.01_claddings	Vapour barrier DELTA-FOV		0,30	
		internal	7	4D.02_wall coverings	Plasterboard metal structure			
		internal	8	4D.02_wall coverings	Plasterboard		12,50	
		internal	9	4D.02_wall coverings	Plasterboard		12,50	
CONCRETE STRUCTURE								
M1	Exterior wall	facade	1	4D.02_wall coverings	Water-base paint		0,00	0,262
		facade	2	4C.01_claddings	External plaster		6,00	
		external	3	4C.01_claddings	EPS F Insulation		140,00	
		external	4	4C.01_claddings	Gypsum plaster		10,00	
		structural	5	2E.01_exterior wall st	Reinforcing bars			
		structural	6	2E.01_exterior wall st	Reinforced concrete		220,00	
		internal	7	4C.01_claddings	Internal plaster		15,00	
		internal	8	4D.02_wall coverings	Water-base paint		0,00	

Table 29: Work Breakdown Structure

At this stage they will also be defined:

- Purposes of the LCA (what do you want to know?).
- The level of detail to achieve in the study.

8.1.1 Purposes of an LCA

In this module are defined the types of problems to respond to:

- Compare two products or compare the object of the study with a reference standard.
- Plan improvements to an existing product or design a new product.

In this study, the objective of the work is to compare 4 different construction technologies of the same residential building, thus leaving unchanged the dimensions and interior spaces, each element will have the same transmittance of the elements, which is our functional unit. Finally, the results will be compared with those obtained from the cost analysis and the final objective is to choose the best solution, making a weight between the results of the environmental and economic analysis.

8.1.2 Level of Detail

The Level of Detail (LoD) depends on the type of user for which the analysis is performed and the purpose. This LCA is carried out in the early design stage of the project, so it is not detailed and is characterized by assumptions and simplifications both on the level of detail of the stratigraphies of the construction elements themselves, and on the amount of material used, on which small approximations are made. The level of detail of the elements is in fact in line with the progress of the project, it would be inconsistent to make precise analyses, which involve a high expenditure of time and money, in this preliminary phase, considering among other things what is the objective of the project, as regards simplifications for example all environmental impacts and costs related to the systems of the house are neglected.

8.2 Inventory

Inventory is the most delicate and time-consuming phase of the LCA. It is the "accounting" part, the real eco-balance sheet, the heart of the LCA that forms the basis for the subsequent phases. It is at this stage that the inflows and outflows that cross the boundaries of the system are identified and quantified. The consumption of resources (raw materials and recycled products, water), energy (thermal and electrical) and emissions into the air, water and soil will therefore be identified and determined.

8.2.1 System Boundaries

It is at this stage that the system is defined more in detail:

- Qualitative and quantitative description of the process units;
- Categories of data associated with them;
- Hypotheses and assumptions (neglecting some inputs and outputs).

Before proceeding with the data collection, it is advisable to specify some information regarding the units of measurement used, their definition and the procedures for collecting data. The phases of the life cycle that are analysed in the project, according to European standard EN 15978 “Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method” (2011) are the following:

- Material production phase (A1-A3): "cradle to gate" processes for the materials and services used in the construction;
- Transport to and from site (A4): it shall include:
  - Transport of materials and products from the factory gate to the building site, including any transport, intermediate storage and distribution;
  - Transport of construction equipment (cranes, scaffolding, etc.) To and from the site;
- Boundary of the construction installation process (module a5): the construction process (in-situ construction, off-site construction assembly of pre-fabricated products or any combination of these);
- Use phase (b2-b5): considers the impacts that occur during the use phase due to the different components of the building, maintenance, repair, replacement and refurbishment operations;
- Use phase, boundary for replacement (b4): it "[...] Shall include:
  - The production of the replaced component and ancillary products;
  - The transportation of the replaced component and ancillary products, including production impacts and aspects of any losses of materials during transportation;
  - The replacement process of the replaced components and ancillary products;
  - Waste management of the removed component and of ancillary products;
  - The end of life stage of the removed component and of ancillary products".
- Boundary for the deconstruction (c1): it includes on-site operations and operations undertaken in temporary works located off-site as necessary for the deconstruction processes after decommissioning up to and including on-site deconstruction, dismantling and/or demolition.
- Boundary for transport (c2): it "shall include all impacts due to transportation to disposal and/or until the end-of-waste state is reached.

This includes transport to and from possible intermediate storage/processing locations".

- End of life (c3-c4): in particular, the module c3 is about "boundary for waste processing for reuse, recovery or recycling"; while c4 includes the final disposal and the possible post-transportation treatment that is necessary before disposal. "module c4 quantifies all the environmental loads resulting from final disposal of materials (neutralisation, incineration with or without utilisation of energy, landfilling with or without utilisation of landfill gases, etc)" (15978).

The LCA analysis has been set up starting from the creation of a WBS. In the following image (extracted from a table) is shown how it was set:

ele-ment	nam e	orien-tation	orientation exact	sub-element	layer-nr.	ÖN B 1801-1	Material (Revit)	d [mm]	U W/m2K	Square meter	Cubic meter	Density Kg/m3 - Resa Kg/m2	KG
POROTON													
			vertical	facade	1	4C.01_claddings	Water-base paint	0,00		463,95	0,00	0,30	139,19
			vertical	facade	2	4C.01_claddings	External plaster	6,00		463,95	2,78	1800,00	5010,66
			vertical	external	3	4C.01_claddings	EPS F Insulation	80,00		469,60	37,57	25,00	939,20
M1	Exterior wall	vertical		External	4	4C.01_claddings	Gypsum plaster	10,00	0,256	463,95	4,64	1800,00	8351,10
			vertical	structural	5	2E.01_exterior wall structures	POROTON 800	250,00		456,40	114,10	860,00	98126,00
			vertical	internal	6	4C.01_claddings	Internal plaster	15,00		418,40	6,28	1400,00	8786,40
			vertical	internal	7	4D.02_wall coverings	Water-base paint	0,00		418,40	0,00	0,30	125,52
			vertical	facade	1	4D.02_wall coverings	Water-base paint	0,00		72,40	0,00	0,30	21,72
			vertical	facade	2	4C.01_claddings	External plaster	6,00		72,40	0,43	1800,00	781,92
M2	Exterior wall	vertical	vertical	structural	3	2E.01_exterior wall structures	POROTON 800	250,00	0,569	72,10	18,03	860,00	15501,50
			vertical	internal	4	4C.01_claddings	Internal Plaster	15,00		67,30	1,01	1400,00	1413,30
			vertical	internal	5	4D.02_wall coverings	Water-base paint	0,00		67,30	0,00	0,30	20,19
			vertical	internal	1	4D.02_wall coverings	Water-base paint	0,00		142,65	0,00	0,30	42,80
			vertical	internal	2	4C.01_claddings	External plaster	15,00		142,65	2,14	1800,00	3851,55
			vertical	structural	3	2E.02_interior wall construction	Bricks	80,00		142,95	11,44	667,00	7627,81
M3	Interior wall	vertical	vertical	internal	4	4C.01_claddings	Rock-wool Rockacie	140,00	0,250	143,00	20,02	70,00	1401,40
			vertical	structural	5	2E.02_interior wall construction	Bricks	80,00		142,95	11,44	667,00	7627,81
			vertical	internal	6	4C.01_claddings	Internal plaster	15,00		142,65	2,14	1400,00	2995,65
			vertical	internal	7	4D.02_wall coverings	Water-base paint	0,00		142,65	0,00	0,30	42,80

Table 30: WBS with quantities expressed in m2, m3 and Kg

In the example we can see three different types of walls (M1, M2, M3) belonging to the construction technology of Poroton, consisting of a load-bearing structure in reinforced concrete and brick infills. Once the type of construction element and its sub-elements were defined, the stratigraphy of the wall was inserted in the "Material (Revit)" column, with the relative thicknesses and square metres that were exported by the Revit Software, then the cubic metres of each material were calculated. Each layer was then associated to its function (cladding, exterior/interior wall structure, wall covering, etc...) among those present in the standard ÖNORM B 1801 pt.2, as can be seen in the 7th column. The last step was to calculate the quantity in Kg of each material through its density and cubic meters. This is because the SimaPro Software for most materials, returns data on environmental impacts per kg of product.

Subsequently, a waste category was associated with each material present in the building and subsequently, through a dataset of the "IEA-EBC Annex 72: Assessment life cycle related environmental impacts caused by buildings", different types of scenarios were identified regarding the end of life of the material:

- Landfill: place where waste is deposited/removed and rotten in an unselected and permanent way, if it has not been possible to recycle or exploit it for the production of energy through incineration as a result of its collection.
- Incineration: where waste cannot be recycled or reused, it should be incinerated safely, leaving landfill only as a last resort in exceptional cases. The materials are then used as fuel in incinerators to produce energy. This practice requires careful and continuous monitoring due to the high potential for large environmental impacts.
- Reuse: all operations that allow products that have not yet become waste to be reused for the same purpose;
- Recycling: recovery operations that allow the materials of the waste we hold to be reprocessed, so as to obtain new products, substances or materials to be used both for new purposes and for the same purposes for which they were designed.

Each is weighted by a percentage value for each waste category; and, finally, the percentage of product sorted on collection point and sorted on building site. In the first, the reference table of Annex 72, the weight that is assigned to each waste scenario for each waste category assigned to the materials:

Product group/ Waste category	Description	Landfill [%]	Incineration [%]	Reuse [%]	Recycling [%]	sorted on collection point [%]	sorted on building site [%]
Stony & Glass	Bricks, roof tiles	5%	0%	0%	95%	25%	75%
	Bulk materials (e.g. sand, gravel, expanded clay grains)	5%	0%	95%	0%	10%	90%
	Concrete	5%	0%	0%	95%	25%	75%
	Flat glass	5%	0%	0%	95%	30%	70%
	Other stony waste (e.g. tiles, natural stone, slates, sand-lime bloc	5%	0%	0%	95%	25%	75%
	Porcelain and ceramics (e.g. toilet, bath, washbasin)	15%	0%	0%	85%	25%	75%
Wood	Chemically treated,impregnated wood (e.g. railway sleepers, outdoor playsets,garden screens)	0%	100%	0%	0%	60%	40%
	Composite wood products (e.g. fibreboards (like plywood, chipboard, OSB, MDF), veneer, laminate)	0%	95%	0%	5%	60%	40%
	Surface treated, solid wood (e.g. painted or varnished (like windo	0%	85%	0%	15%	60%	40%
	Untreated, uncontaminated wood (e.g. roofs, structures, formwo	0%	25%	0%	75%	60%	40%
Metals	Metals: iron, steel, non-ferro (copper, brass, aluminium, lead, zin	5%	0%	0%	95%	15%	85%

Table 31: Waste category identification

In the second we see the same data associated with each material of the project. In the specific case we can notice as an example the attribution of the waste category "Bricks, roof tiles" to the materials: Poroton 800, bricks and clay roof tiles:

Building technology & elements	Waste category	Landfill [%]	Incineration [%]	Reuse [%]	Recycling [%]	Sorted on collection point [%]	Sorted on building site [%]
Water-base paint	Finishing Layers|Finishing layer fixed to wood, plastic or meta	0%	100%	0%	0%	100%	0%
External plaster	Finishing Layers|Finishing layer fixed to stony waste (e.g. plas	5%	0%	0%	95%	100%	0%
EPS F Insulation	Insulation Materials|Synthetic insulation materials (e.g. polyu	5%	95%	0%	0%	100%	0%
Gypsum plaster	Finishing Layers|Finishing layer fixed to stony waste (e.g. plas	5%	0%	0%	95%	100%	0%
POROTON 800	Stony & Glass|Bricks, roof tiles	5%	0%	0%	95%	25%	75%
Internal plaster	Finishing Layers|Finishing layer fixed to stony waste (e.g. plas	5%	0%	0%	95%	100%	0%
Bricks	Stony & Glass|Bricks, roof tiles	5%	0%	0%	95%	25%	75%
Rock-wool Rockacier B soudable	Insulation Materials|Mineral insulation materials (e.g. stone v	50%	50%	0%	0%	100%	0%
Reinforcing bars	Metals|Metals: iron, steel, non-ferro (copper, brass, aluminiu	5%	0%	0%	95%	15%	85%
Reinforced concrete	Stony & Glass|Concrete	5%	0%	0%	95%	25%	75%
Clay roof tiles	Stony & Glass|Bricks, roof tiles	5%	0%	0%	95%	25%	75%
Wooden ventilation structure	Wood|Untreated, uncontaminated wood (e.g. roofs, structure	0%	25%	0%	75%	60%	40%
Wood fibre board	Wood|Composite wood products (e.g. fibreboards (like plywo	0%	95%	0%	5%	60%	40%
Waterproof membrane TYVEK® (	Bitumen|Bitumen (e.g. bituminous roofing, vapour barrier, w	85%	5%	0%	10%	100%	0%
Vapour barrier DELTA-FOV	Bitumen|Bitumen (e.g. bituminous roofing, vapour barrier, w	85%	5%	0%	10%	100%	0%
Concrete distributor	Stony & Glass|Concrete	5%	0%	0%	95%	25%	75%

Table 32: Waste categoy and end of life scenarios

At this point the SimaPro Software has been used. This is how we proceeded: we set up the Ecoinvent v3 database implemented in SimaPro, and then chosen among six dataset versions:

1) Allocation default, unit processes
2) Allocation default, system processes
3) Allocation recycled content, unit processes
4) Allocation recycled content, system processes
5) Consequential, unit processes
6) Consequential, system processes

Allocation default, unit" was chosen, which has the following characteristics: "an allocation dataset means that the principles of attributional modelling have been applied and default refers to the type of allocation employed i.e. mass or economic allocation, which in most cases is economic allocation (with some exceptions). A unit process version contains only emissions and resource inputs from one process step, plus references to input from other unit processes" (https://simapro.com/).

8.2.2 Data Collection

Once the process has been outlined, the data collection phase takes place. These will be of two types: those relative to the input flows and those corresponding to the outputs. The first refer to materials, transport and energy, the others to products and gases released into the air, water and soil. The aim will be to structure a real environmental balance sheet, for which the quality of the data will have to be checked. The data collection requires a very high effort, in terms of time and resources, because of the amount of information needed, which includes the various stages of the production process.

The data collected can be divided into three categories:

1) Primary data (from direct surveys).
2) Secondary data (from literature or specific software databases).
3) Tertiary data (from estimates and average values).

For this study, data used are those from the Ecoinvent v3 dataset, and are therefore secondary data.

8.2.3 Data Processing

Once data have been collected, they are related to all the process units that contribute to the production of the functional unit (e.g. the amount of electricity used in the production, kg per km of product and co-product that require transport, the amount of kg of raw materials used, etc.) where, for each process unit, an appropriate unit of measurement for the reference flow will be determined (e.g. 1 kg of material or 1 MJ of energy). Subsequently, data concerning the environmental impact are transformed and referred to the functional unit of product, through the definition of a contribution factor: it expresses, therefore, the contribution of each process with respect to the production of a functional unit, through the chosen unit of measurement. This procedure must be carried out for all the substances present in each process.

In this phase, dedicated software is often used:

- they provide a series of processes that have already been implemented and also allow new ones to be added.
- Presence of databases relating to various categories: materials, fuels and transport systems, in addition to waste disposal systems.
- Results are presented with inventory tables in which all data relating to input and output flows are collected.

In the case study a software was used, it was in fact possible to identify within the database the same materials that are present in the project, or those that are closest to them in terms of composition. A selection and collection of data was then made both for the production phase of the materials (A1-A3) and, following the same criterion, for the end of life phases (C3-C4), distinguishing the different scenarios of landfill, incineration, reuse and recycling.

The following image shows the SimaPro interface, the steps that led to the choice of data have been highlighted: Inventory → Processess from the drop-down menu of the processes, "Material" and "Waste treatment" were opened, within which the materials relating respectively to the production phases and the End-of-Life scenarios were identified.

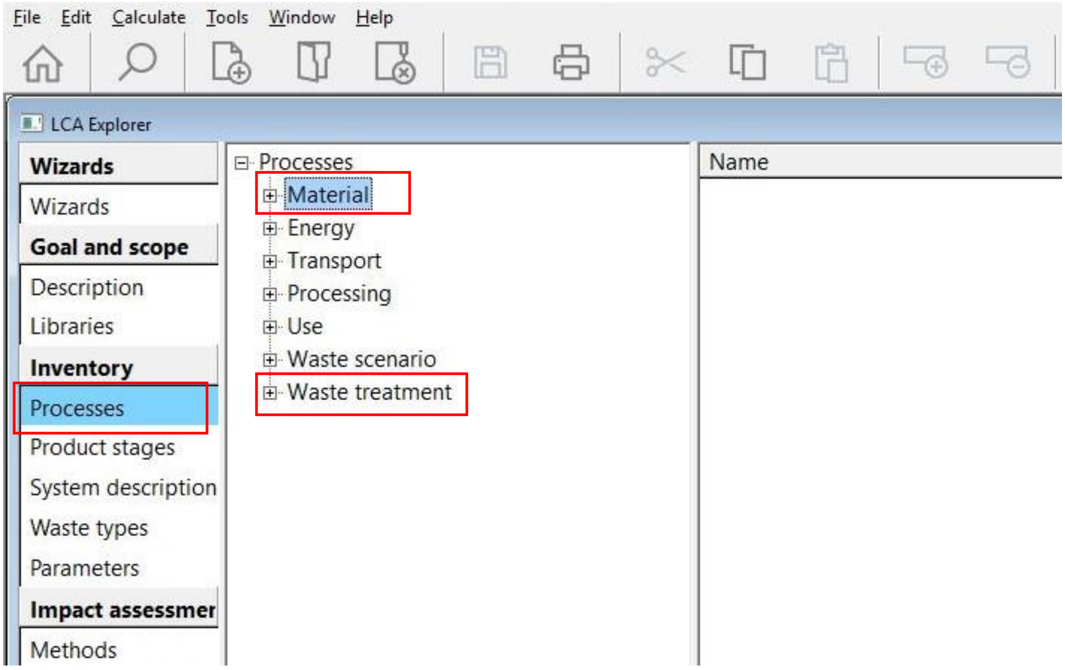


Figure 36: SimaPro interface [Source: https://simapro.com/]

Data related to the production phase have always found a matching with those present in the database of the Software, regarding the end of life phase instead, several times have been made approximations as there is no direct correspondence between the material of the project and the one present in Ecoinvent.

As can be seen in the following image in which the materials from the database for each scenario have been inserted, those left in white have a direct correspondence with the materials of the project, while some cells have been colored in blue because approximations have been made and in the database the choice fell on the most similar material among those present. For example, as can be seen, for the plaster, in the landfill and recycling scenarios, the concrete was used, being the material with the most similar properties. It can also be observed that in the end of life, there are never reuse scenarios, but there are many cases of recycling, this is because at the end of life the building materials will be treated before giving them a "new life".

Building technology & elements	Waste category	Landfill [%]	Incinera-tion [%]	Reuse [%]	Recycling [%]	Sorted on collec-tion point [%]	Sorted on buil-ding site [%]	Landfill [%]	Incineration [%]	Reuse [%]	Recycling [%]
Water-base paint	Finishing Layers|Finishing layer	0%	100%	0%	0%	100%	0%	Waste paint (CH	Waste paint (CH)	-	-
External plaster	Finishing Layers|Finishing layer	5%	0%	0%	95%	100%	0%	Waste concrete	-	-	Waste concrete, r
EPS F Insulation	Insulation Materials|Synthetic	5%	95%	0%	0%	100%	0%	Waste polystyre	Waste expanded	-	-
Gypsum plaster	Finishing Layers|Finishing layer	5%	0%	0%	95%	100%	0%	Waste gypsum (	-	-	Waste concrete, r
POROTON 800	Stony & Glass|Bricks, roof tiles	5%	0%	0%	95%	25%	75%	Waste concrete	-	-	Waste brick (CH) r
Internal plaster	Finishing Layers|Finishing layer	5%	0%	0%	95%	100%	0%	Waste concrete	-	-	Waste concrete, r
Bricks	Stony & Glass|Bricks, roof tiles	5%	0%	0%	95%	25%	75%	Waste concrete	-	-	Waste brick (CH) r
Rock-wool Rockacier B	Insulation Materials|Mineral ir	50%	50%	0%	0%	100%	0%	Waste mineral v	Waste expanded	-	-
Reinforcing bars	Metals|Metals: iron, steel, non	5%	0%	0%	95%	15%	85%	Waste aluminiur	-	-	Waste reinforcem
Reinforced concrete	Stony & Glass|Concrete	5%	0%	0%	95%	25%	75%	Waste concrete	-	-	Waste reinforced
Clay roof tiles	Stony & Glass|Bricks, roof tiles	5%	0%	0%	95%	25%	75%	Waste concrete	-	-	Waste brick (CH) r
Wooden ventilation stru	Wood|Untreated, uncontamin	0%	25%	0%	75%	60%	40%	-	Waste wood, untr	-	Waste core board
Wood fibre board	Wood|Composite wood produ	0%	95%	0%	5%	60%	40%	-	Waste wood, untr	-	Waste core board
Waterproof membrane	Bitumen|Bitumen (e.g. bitumi	85%	5%	0%	10%	100%	0%	Waste bitumen (	Waste bitumen (C	-	Waste mixed plas
Vapour barrier DELTA-F	Bitumen|Bitumen (e.g. bitumi	85%	5%	0%	10%	100%	0%	Waste bitumen (	Waste bitumen (C	-	Waste mixed plas
Concrete distributor	Stony & Glass|Concrete	5%	0%	0%	95%	25%	75%	Waste concrete	-	-	Waste concrete, r
Concrete-masonry slab	Stony & Glass|Concrete	5%	0%	0%	95%	25%	75%	Waste concrete	-	-	Waste reinforced
Gres tiles	Stony & Glass|Other stony was	5%	0%	0%	95%	25%	75%	Waste concrete	-	-	Waste brick (CH) r
Load distribution screed	Stony & Glass|Concrete	5%	0%	0%	95%	25%	75%	Waste concrete	-	-	Waste concrete, r
Lightweight concrete	Stony & Glass|Concrete	5%	0%	0%	95%	25%	75%	Waste concrete	-	-	Waste concrete, r

Table 33: Waste category choice from SimaPro

As for the transport phases A4 and C2, respectively belonging to the production stage and to the end of life, a different process was followed: in the following screenshot we can see how the impacts of the transport in the excel file were calculated. The light yellow indicates phase A4, the light green indicates phase C2. The procedure was as follows: according to standard ÖNORM B 1801 pt.2, each product was assigned to a material category (which is different for A4 and C2), all quantities were expressed in tonnes. Regarding A4, the objective is to calculate the ton/Km transported by each of the 4 means of transport that are: lorry 16-32 tons, lorry 7.5-16 tons, lorry 3.5-7.5 and lorry > 32 tons. Following the standard (whose data have been obtained through Austrian averages), for each material category, first of all the different percentages of product that are transported directly from factory to site and the ones transported via an intermediary supplier have been applied. Subsequently, the different routes: factory to site, factory to supplier and supplier to site, were identified for each of the different means of transport and in which percentage each is used. Finally, the distances for each of the routes, which are also Austrian averages, are attributed.

The same applies to the C2 scenario, where, however, the means of transport used is only one, i.e. lorry 16-32 tons. In this case, the estimated kilometres refer to the different end-of-life scenarios, so where each product is transported in order to be sorted and disposed of. The cells highlighted in yellow represent the tons per km attributed to each means of transport.

Product group/material category (A4)			% directly from factory to site (Arrangement of transportation)	% via an interedmediary supplier (Arrangement of transportation)	factory to site (Means of transport)			factory to supplier (Means of transport)	suppplier to site (Means of transport)			factory to site (Average transport distance of transportation from)	factory to supplier (Average transport distance of transportation from)	supplier to site (Average transport distance of transportation from)	[A4] Transport to building site				Means of transportation	[C2] Average transport distance of transportation from			C2
	quantity	[t]			Lorry 16-32 ton (Euro 5)	Lorry 7.5-16 ton (Euro 5)	Lorry 3.5-7.5 ton (Euro 5)	Lorry >32 ton (Euro 5)	Lorry 16-32 ton (Euro 5)	Lorry 7.5-16 ton (Euro 5)	Lorry 3.5-7.5 ton (Euro 5)	[km]	[km]	[km]	Lorry 16-32 ton (Euro 5) [tkm]	Lorry 7.5-16 ton (Euro 5) [tkm]	Lorry 3.5-7.5 ton (Euro 5) [tkm]	Lorry >32 ton (Euro 5) [tkm]	Lorry 16-32 ton (Euro5)	demolition site to sorting facility/	collection point/sorting	collection point/sorting facility to	TOT quantity weighted [tkm]
inishing products: pai	0,139	t	10%	90%	0%	100%	0%	100%	0%	80%	20%	100,00	100,00	35,00	0,000	4,899	0,877	12,527	100%	30	50	100	18,094
inishing products: plas	5,011	t	40%	60%	50%	50%	0%	100%	50%	50%	0%	100,00	100,00	35,00	152,825	152,825	0,000	300,640	100%	30	50	100	162,85
nsulation	0,939	t	40%	60%	100%	0%	0%	100%	85%	15%	0%	100,00	100,00	35,00	54,333	2,958	0,000	56,352	100%	30	50	100	119,75
inishing products: plas	8,351	t	40%	60%	50%	50%	0%	100%	50%	50%	0%	100,00	100,00	35,00	254,709	254,709	0,000	501,066	100%	30	50	100	271,41
IRICKS	98,126	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0	0,0	0,0	24531,500	0,000	0,000	0,000	100%	30	50	100	981,25
inishing products: plas	8,786	t	40%	60%	50%	50%	0%	100%	50%	50%	0%	100,00	100,00	35,00	267,985	267,985	0,000	527,184	100%	30	50	100	285,56
inishing products: pai	0,126	t	10%	90%	0%	100%	0%	100%	0%	80%	20%	100,00	100,00	35,00	0,000	4,418	0,791	11,297	100%	30	50	100	16,318
inishing products: pai	0,022	t	10%	90%	0%	100%	0%	100%	0%	80%	20%	100,00	100,00	35,00	0,000	0,765	0,137	1,955	100%	30	50	100	2,8236
inishing products: plas	0,782	t	40%	60%	50%	50%	0%	100%	50%	50%	0%	100,00	100,00	35,00	23,849	23,849	0,000	46,915	100%	30	50	100	25,412
IRICKS	15,502	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0	0,0	0,0	3875,375	0,000	0,000	0,000	100%	30	50	100	155,02
inishing products: plas	1,413	t	40%	60%	50%	50%	0%	100%	50%	50%	0%	100,00	100,00	35,00	43,106	43,106	0,000	84,798	100%	30	50	100	45,932
inishing products: pai	0,020	t	10%	90%	0%	100%	0%	100%	0%	80%	20%	100,00	100,00	35,00	0,000	0,711	0,127	1,817	100%	30	50	100	2,6247
inishing products: pai	0,043	t	10%	90%	0%	100%	0%	100%	0%	80%	20%	100,00	100,00	35,00	0,000	1,506	0,270	3,852	100%	30	50	100	5,5634
inishing products: plas	3,852	t	40%	60%	50%	50%	0%	100%	50%	50%	0%	100,00	100,00	35,00	117,472	117,472	0,000	231,093	100%	30	50	100	125,18
IRICKS	7,628	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0	0,0	0,0	1906,953	0,000	0,000	0,000	100%	30	50	100	76,278
nsulation	1,401	t	40%	60%	100%	0%	0%	100%	85%	15%	0%	100,00	100,00	35,00	81,071	4,414	0,000	84,084	100%	30	50	100	147,15
IRICKS	7,628	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0	0,0	0,0	1906,953	0,000	0,000	0,000	100%	30	50	100	76,278
inishing products: plas	2,996	t	40%	60%	50%	50%	0%	100%	50%	50%	0%	100,00	100,00	35,00	91,367	91,367	0,000	179,739	100%	30	50	100	97,359

Table 34: Transport calculation

Finally, as can be seen from the screen taken from the software, all the data collected relating to the project have been entered in the "Input/output" section. In particular, as you can see from the image, under the heading "Inputs from Technosphere: materials/fuels" the materials belonging to the production phase have been entered:

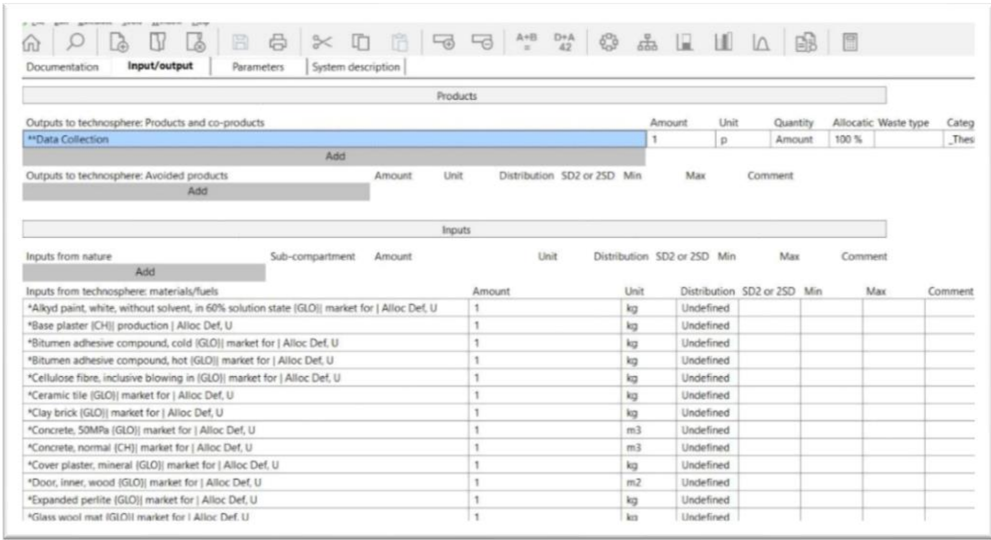


Figure 37: SimaPro interface, input data

While under "Outputs to technosphere: Waste and emissions to treatment" were entered the data on the end of life, as can be seen from the screen below:

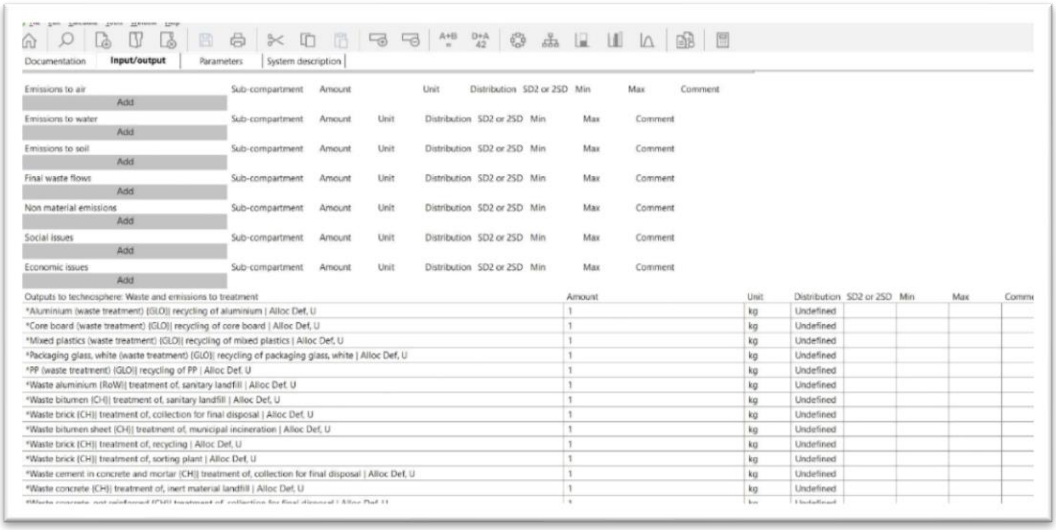


Figure 38: SimaPro interface, output data

8.3 Impact assessment

This assessment is a technical-quantitative and/or qualitative process to assess the effects of the environmental impacts of the substances identified in the inventory. Environmental impact is defined as the intervention of a substance on the environment and/or on man.

In order to have a return of the environmental impacts for each material, the following environmental indicators have been chosen:

- GWP (Global Warming Potential);
- PEDnr (Primary Energy Demand of non-renewable sources):
  - Fossil;
  - Nuclear;
  - Biomass;

- PEDr (Primary Energy Demand of renewable sources):
    - Biomass;
    - Solar, wind and geothermal;
    - Water;
- Land use.

Finally, the impact assessment methods were chosen, which are used to calculate impact assessment results. Each method deals with a certain type of environmental indicator. For the results related to GWP, as can be seen in the following image, which represents the interface of the SimaPro Software, the "IPCC 2013 GWP 100a" impact assessment method was chosen:

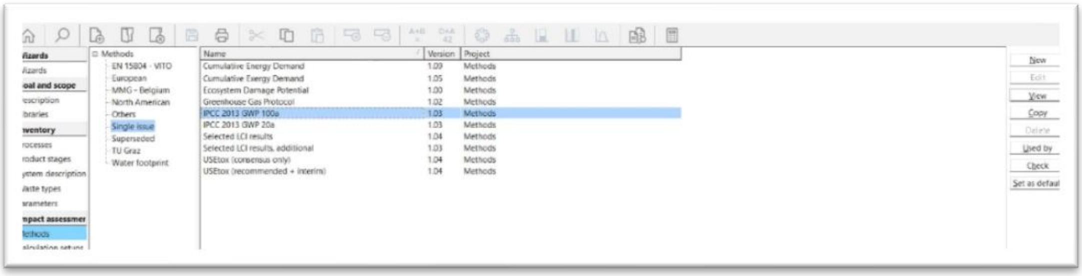


Figure 39: SimaPro interface, impact assessment method choice

The characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterization factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg carbon dioxide/kg emission.
The geographic scope of this indicator is at global scale. (cit. https://www.pre-sustainability.com/download/manuals/DatabaseManualMethods.pdf).

Cumulative Energy Demand V1.09" method was chosen for the impacts of PEDnr and PEDn; the CED represents the energy demand, valued as primary energy during the complete life cycle of a product; finally, the EF (Ecological Footprint) Method V1.07, for the land use data. Subsequently, once the environmental impacts of each material for a unit of product were obtained, they were included in the initial WBS, as shown in the following image.

Let's take once again the example of the Poroton construction technology, as can be seen, each SimaPro material has been associated to a layer of the stratigraphy in the table, then all data related to the environmental impacts per product unit (GWP, PEDnr, PEDr and land use) belonging to each of them were inserted and finally multiplied by the quantity of product, each with its own unit of measure (Kg, cubic meter or square meter), in general they are all expressed in Kg but elements such as the different types of concrete are expressed in cubic meters, while windows and doors are expressed in square meters.

In the columns TOT GWP, TOT PEDnr, TOT PEDr and TOT land use it is therefore possible to observe the final values of the impact of each layer for each environmental indicator.

element	name	subelement	layer-nr.	ÖN B 1801-1	Material (Revit)	d [mm]	U W/m2 K	Square meter	Cubic meter	Density Kg/m3 - Resa Kg/m2	KG	SIMAPRO MATERIAL A1-A3										
POROTON												Material (DB)	U.M.	GWP	TOT GWP	PEDnr	TOT PEDnr	PEDr	TOT PEDr	Land use	TOT	Mat
M1	Exterior wall	facade	1	4C.01_claddings	Water-base pain	0,00	0,256	463,95	0,00	0,30	139,19	*Alkyd paint, white, w	kg	6,5048	905,37	74,355	10349	24,07	3350	274.8	38254	*Wa
		facade	2	4C.01_claddings	External plaster	6,00		463,95	2,78	1800,00	5010,66	*Base plaster {CH}| pr	kg	0,2176	1090,2	1,441	7220,5	0,265	1329	2.548	12769	*Wa
		external	3	4C.01_claddings	EPS F insulation	80,00		469,60	37,57	25,00	939,20	*Polystyrene foam sla	kg	4.7017	4415,9	103,89	97570	1,595	1498	10.84	10181	*Wa
		External	4	4C.01_claddings	Gypsum plaster	10,00		463,95	4,64	1800,00	8351,10	*Base plaster {CH}| pr	kg	0,2176	1817	1,441	12034	0,265	2216	2.548	21282	*Wa
		structural	5	2E.01_exterior wall	POROTON 800	250,00		456,40	114,10	860,00	98126,00	*Clay brick {GLO}| ma	kg	0,3191	31309	3,6165	354872	0,195	19138	3.008	3E+05	*Wa
		internal	6	4C.01_claddings	Internal plaster	15,00		418,40	6,28	1400,00	8786,40	*Cover plaster, miner	kg	0,1506	1323,5	1,9743	17347	0,222	1952	3.011	26456	*Wa
		internal	7	4D.02_wall coverin	Water-base pain	0,00		418,40	0,00	0,30	125,52	*Alkyd paint, white, w	kg	6,5048	816,49	74,355	9333	24,07	3021	274.8	34498	*Wa
M2	Exterior wall	facade	1	4D.02_wall coverin	Water-base pain	0,00	0,569	72,40	0,00	0,30	21,72	*Alkyd paint, white, w	kg	6,5048	141,28	74,355	1615	24,07	522,8	274.8	5970	*Wa
		facade	2	4C.01_claddings	External plaster	6,00		72,40	0,43	1800,00	781,92	*Base plaster {CH}| pr	kg	0,2176	170,13	1,441	1126,8	0,265	207,5	2.548	1993	*Wa
		structural	3	2E.01_exterior wall	POROTON 800	250,00		72,10	18,03	860,00	15501,50	*Clay brick {GLO}| ma	kg	0,3191	4946,1	3,6165	56061	0,195	3023	3.008	46631	*Wa
		internal	4	4C.01_claddings	Internal Plaster	15,00		67,30	1,01	1400,00	1413,30	*Cover plaster, miner	kg	0,1506	212,88	1,9743	2790,3	0,222	313,9	3.011	4255	*Wa
		internal	5	4D.02_wall coverin	Water-base pain	0,00		67,30	0,00	0,30	20,19	*Alkyd paint, white, w	kg	6.5048	131,33	74,355	1501,2	24,07	486	274.8	5549	*Wa
M3	Interior wall	internal	1	4D.02_wall coverin	Water-base pain	0,00	0,250	142,65	0,00	0,30	42,80	*Alkyd paint, white, w	kg	6,5048	278,37	74,355	3182	24,07	1030	274.8	11762	*Wa
		internal	2	4C.01_claddings	External plaster	15,00		142,65	2,14	1800,00	3851,55	*Base plaster {CH}| pr	kg	0,2176	838	1,441	5550,2	0,265	1022	2.548	9815	*Wa
		structural	3	2E.02_interior wall	Bricks	80,00		142,95	11,44	667,00	7627,81	*Clay brick {GLO}| ma	kg	0,3191	2433,8	3,6165	27586	0,195	1488	3.008	22946	*Wa
		internal	4	4C.01_claddings	Rock-wool Rocka	140,00		143,00	20,02	70,00	1401,40	*Stone wool {GLO}| m	kg	1.372	1922,7	15,946	22347	0,853	1195	9.058	12694	*Wa
		structural	5	2E.02_interior wall	Bricks	80,00		142,95	11,44	667,00	7627,81	*Clay brick {GLO}| ma	kg	0,3191	2433,8	3,6165	27586	0,195	1488	3.008	22946	*Wa
		internal	6	4C.01_claddings	Internal plaster	15,00		142,65	2,14	1400,00	2995,65	*Cover plaster, miner	kg	0,1506	451,22	1,9743	5914,5	0,222	665,4	3.011	9020	*Wa
		internal	7	4D.02_wall coverin	Water-base pain	0,00		142,65	0,00	0,30	42,80	*Alkyd paint, white, w	kg	6.5048	278,37	74,355	3182	24,07	1030	274.8	11762	*Wa
M4	ior wall	facade	1	4D.02_wall coverin	Water-base pain	0,00	0,257	18,70	0,00	0,30	5,61	*Alkyd paint, white, w	kg	6.5048	36,492	74,355	417,13	24,07	135	274.8	1542	*Wa
		facade	2	4C.01_claddings	External plaster	6,00		18,70	0,11	1800,00	201,96	*Base plaster {CH}| pr	kg	0,2176	43,942	1,441	291,03	0,265	53,58	2.548	514,7	*Wa
		external	3	4C.01_claddings	EPS F insulation	140,00		18,70	2,62	25,00	65,45	*Polystyrene foam sla	kg	4,7017	307,73	103,89	6799,4	1,595	104,4	10.84	709,5	*Wa
		external	4	4C.01_claddings	Gypsum plaster	10,00		18,70	0,19	1800,00	336,60	*Base plaster {CH}| pr	kg	0,2176	73,236	1,441	485,05	0,265	89,31	2.548	857,8	*Wa

Table 35: Impacts calculation in excel

With regard to phases A4 and C2 relating to transport, the research on SimaPro was not carried out by material but by means of transport, so the emissions will refer to the type of vehicle, the quantity of material transported, and the distances covered, as seen above. Therefore, in order to have a return of the environmental impacts, the research on the Software has been carried out for each means of transport for each environmental indicator, these data have then been multiplied by the tons of product transported by each means for each km calculated previously.

The last phase analysed is B4, from standard (15978) includes: "The production of the replaced component and ancillary products; the transportation of the replaced component and ancillary products, including production impacts and aspects of any losses of materials during transportation; the replacement process of the replaced components and ancillary products; waste management of the removed component and of ancillary products and the end of life stage of the removed component and of ancillary products". Therefore, it has been easy to obtain this data because it has been enough, for each indicator, to sum up the phases A1-A3, A4, C2 and C3-C4, multiplying for each material the number of replacements foreseen by the maintenance plan. It can therefore be seen that some elements such as foundations, in this phase will have zero impacts because there are no replacements of any kind. With regard to the construction and demolition phases, respectively A5 and C1, literature data were used: in the first case it was assumed that phase A1 corresponds to 12.4% of the total emissions of the construction phase (Fröberg et al.). With regard to phase C1, the research conducted by M. Paleari and A. Campioli from Politecnico di Milano was taken as a reference "Construction and demolition waste: LCA of the demolition of 51 residential buildings" (translation of the original title: "I rifiuti da costruzione e demolizione: LCA della demolizione di 51 edifici residenziali", 2015) and therefore, with reference to the demolition phase, the average consumption of diesel fuel was taken into account for the operating machines, charging 0.044 MJ for each kg of demolished material and 0.002 MJ for each kg of crushed debris on site (Modulo Ecoinvent 3: Diesel, burned in building machine/GLO U); for transport, reference was made to a vehicle for transporting debris (Ecoinvent Module 3: Transport, lorry 16-32t, EURO4/RER U).

8.4 Assessment of improvements

It is a phase that allows to understand the result of the study, to contextualize it and to be able to indicate an improvement of the system through the identification of the components to which changes can be made so as to reduce the environmental impact of the entire system. It allows, where possible, an improvement of the environmental impact in issues such as lower energy demand, lower emissions, lower use of resources, etc.

In this module, all other information concerning the product studied, such as economic and financial information, must be combined with the technical and environmental results provided by the LCA in order to make a correct decision about the company's product policy and the environmental programmes that the company intends to develop in the future. It is important to underline that the LCA, like all methodologies based on comparison, does not propose an absolute solution, but identifies a set of alternatives from which those who will decide will then choose the best in their opinion.

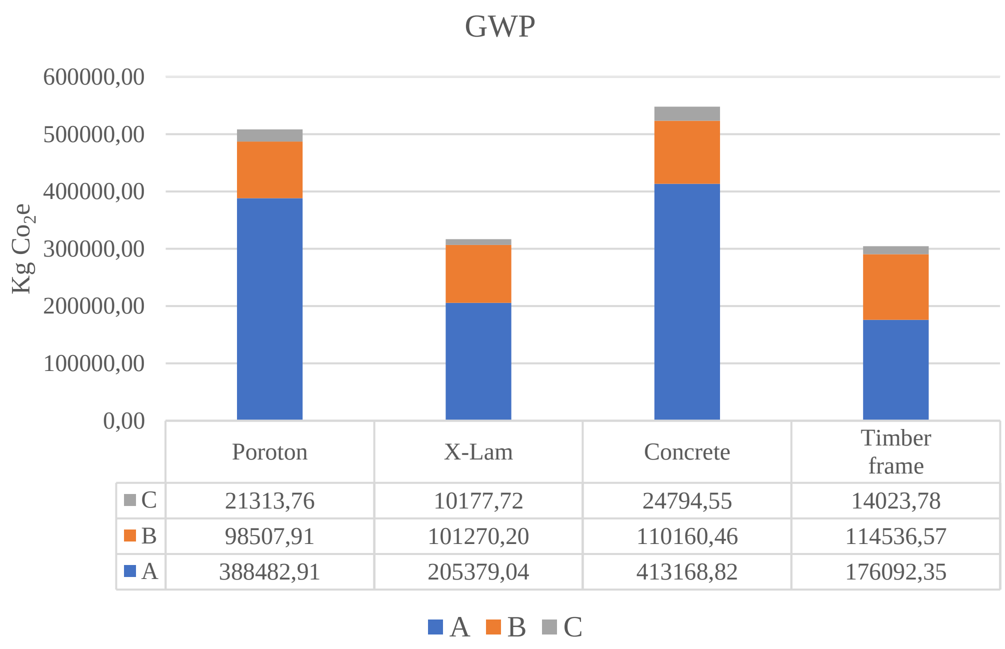
The objectives of this phase are the following:

- The definition of the objectives of the phase
- Translation and interpretation of the results.
- Verification of the achievement of the objectives of the study (iteration), the quality of the data and the limits of the system (sensitivity analysis)
- Compare the possible options.

Results should be interpreted and represented in such a way as to have a perception of the results that is easily usable, also trying to represent different scenarios from the one considered. Also, in this phase, the sensitivity analysis should verify the accuracy of the data and its influence on the final result. To represent the variability of the data, it is possible to initially make a comparison between the results obtained and those related to the best and worst situation; a more complex analysis would require the study of the variability interval of the input data.

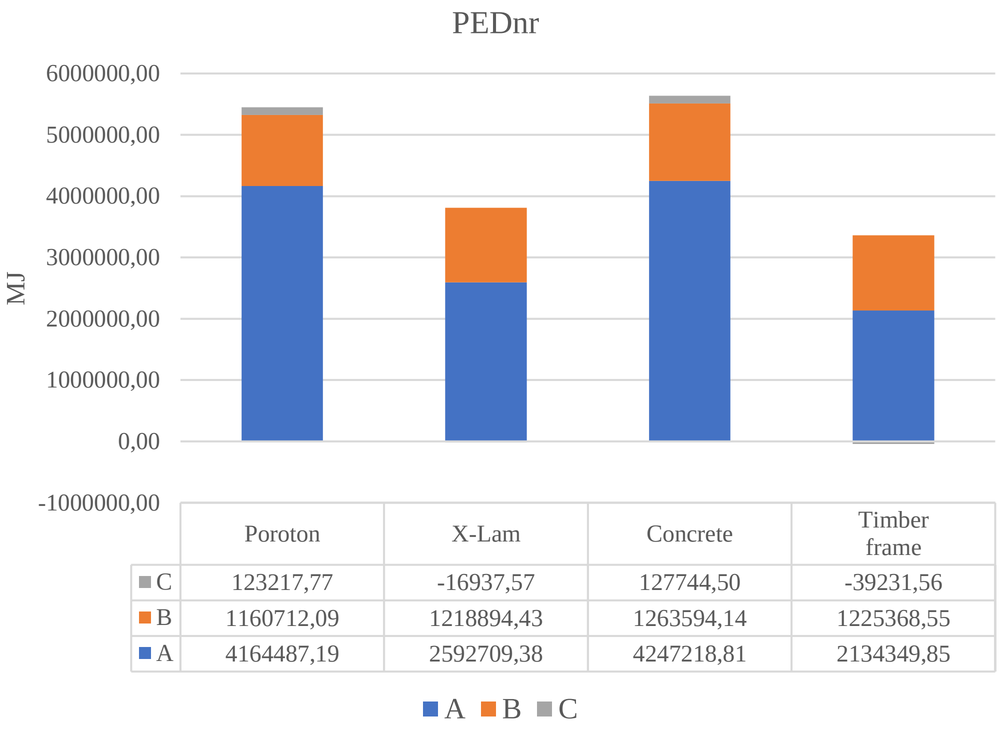
8.4.1 Analysis of the results

The following paragraph analyses the results obtained through the description of the relative graphs. Starting from an overall observation of the results, we observe the following graphs:



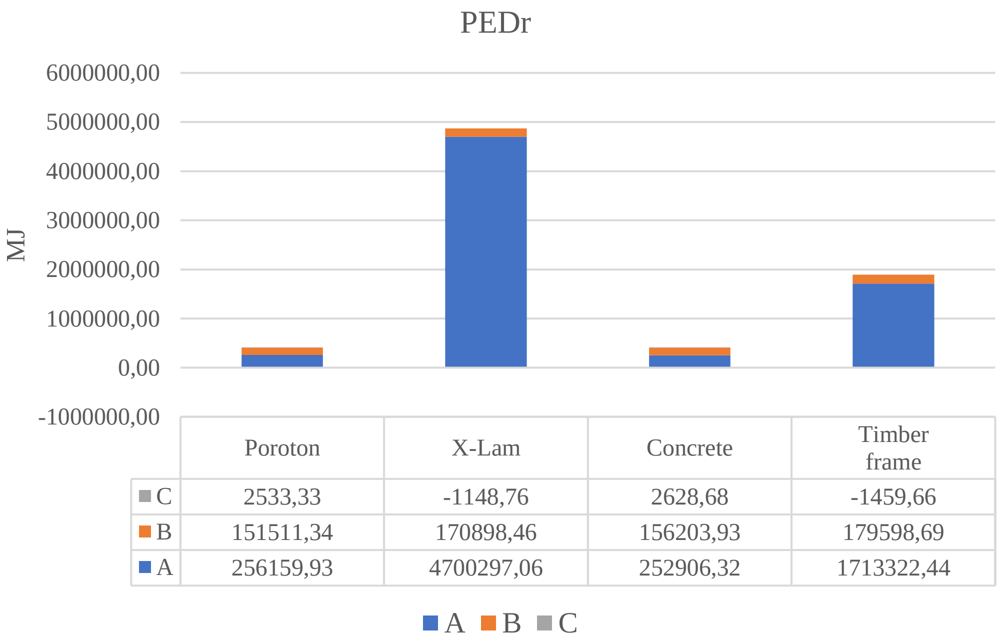
	Poroton	X-Lam	Concrete	Timber frame
C	21313,76	10177,72	24794,55	14023,78
B	98507,91	101270,20	110160,46	114536,57
A	388482,91	205379,04	413168,82	176092,35

Figure 40: Overall GWP results



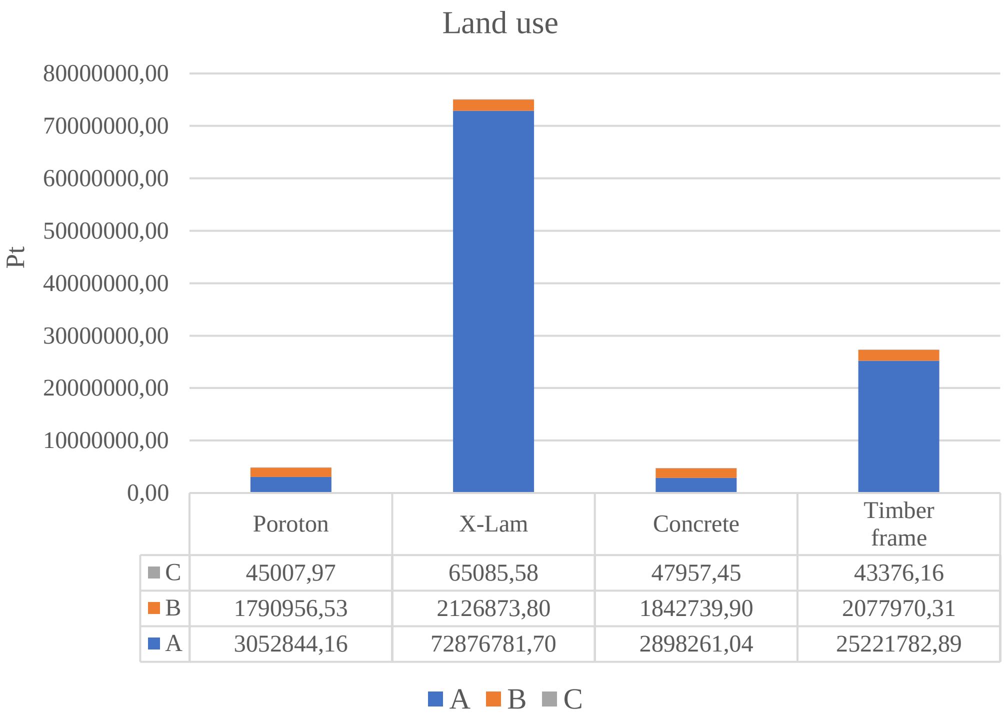
	Poroton	X-Lam	Concrete	Timber frame
C	123217,77	-16937,57	127744,50	-39231,56
B	1160712,09	1218894,43	1263594,14	1225368,55
A	4164487,19	2592709,38	4247218,81	2134349,85

Figure 41: Overall PEDnr results



	Poroton	X-Lam	Concrete	Timber frame
C	2533,33	-1148,76	2628,68	-1459,66
B	151511,34	170898,46	156203,93	179598,69
A	256159,93	4700297,06	252906,32	1713322,44

Figure 42: Overall PEDr results



	Poroton	X-Lam	Concrete	Timber frame
C	45007,97	65085,58	47957,45	43376,16
B	1790956,53	2126873,80	1842739,90	2077970,31
A	3052844,16	72876781,70	2898261,04	25221782,89

Figure 43: overall Land use results

The graphs show the stages A, B and C of the project, the A includes the phases A1-A3, A4 and A5, by B we mean the replacement, then the phase B4, finally the C indicates the phases C1, C2 and C3-C4. As can be seen, in all cases A is predominant, in particular, with regard to the environmental indicators GWP and PEDnr, the most impacting technologies are Poroton and concrete, while concerning PEDr and Land use indicators, the most impacting, as can be expected, are the X-Lam and timber frame, due to the large amount of wood used. In all cases, the end of life phase has the lowest impact in the life cycle, while the replacement phase has a considerable impact.

Let's now take a more detailed look at an example for each indicator. As far as GWP is concerned, let's consider Poroton technology:

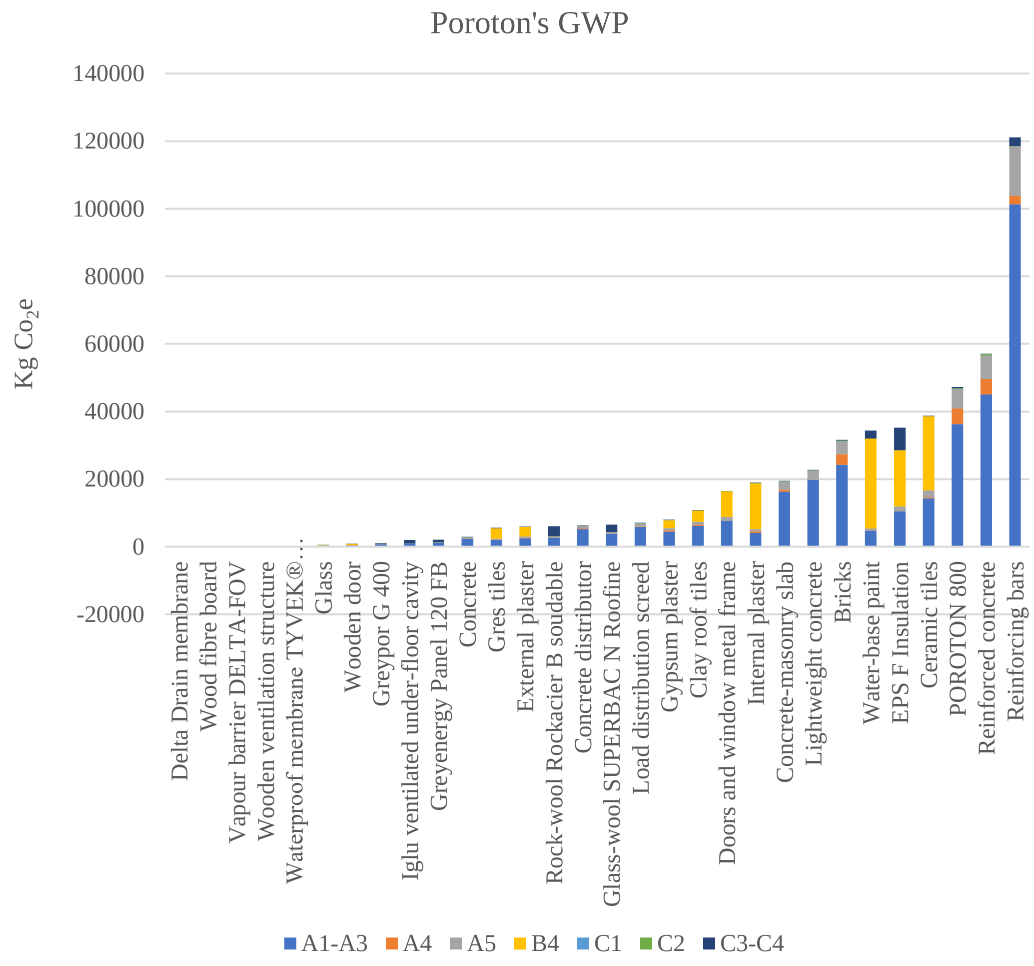


Figure 44: Poroton's GWP output for each material, highlighting the share of each phase

The graph represents in increasing order the impact of individual building materials throughout the life cycle, also in this case we can observe the subdivision into the 7 phases of the life cycle A1-A3, A4, A5, B4, C1, C2 and C3-C4, from production to end of life. It can be observed that the reinforced concrete structure is the most impacting, followed by the poroton walls. It is interesting to note that in materials such as water-based paint, EPS insulation, internal plaster and ceramic tiles, the use phase B4, highlighted in yellow, exceeds the production phase, because the maintenance activities are significant, especially in plaster and paint, where there are numerous replacements.

Let's now analyse the Primary Energy Demand of non-renewable sources in the concrete technology:

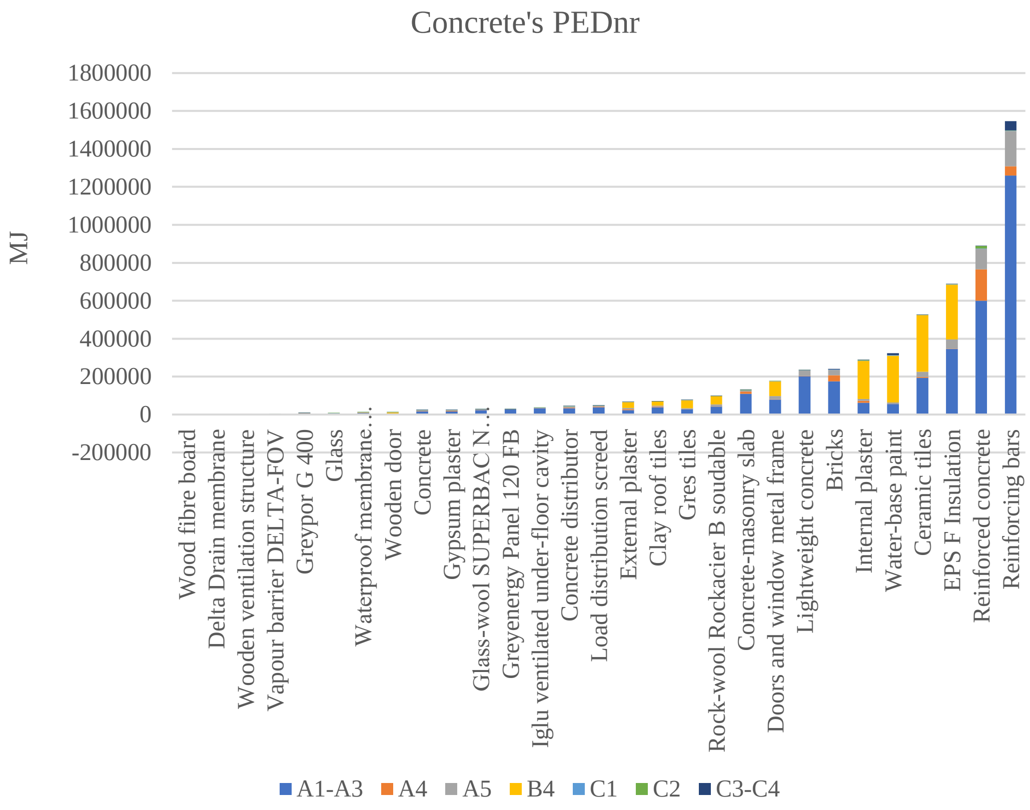


Figure 45: Concrete's PEDnr output for each material, highlighting the share of each phase

Also, in this case the most impacting is the reinforced concrete structure, with a very strong contribution of the reinforcing bars, followed by EPS insulation, ceramic tiles, paint and plaster, of the last three, also in this case the biggest contribution is given by the use phase B4.

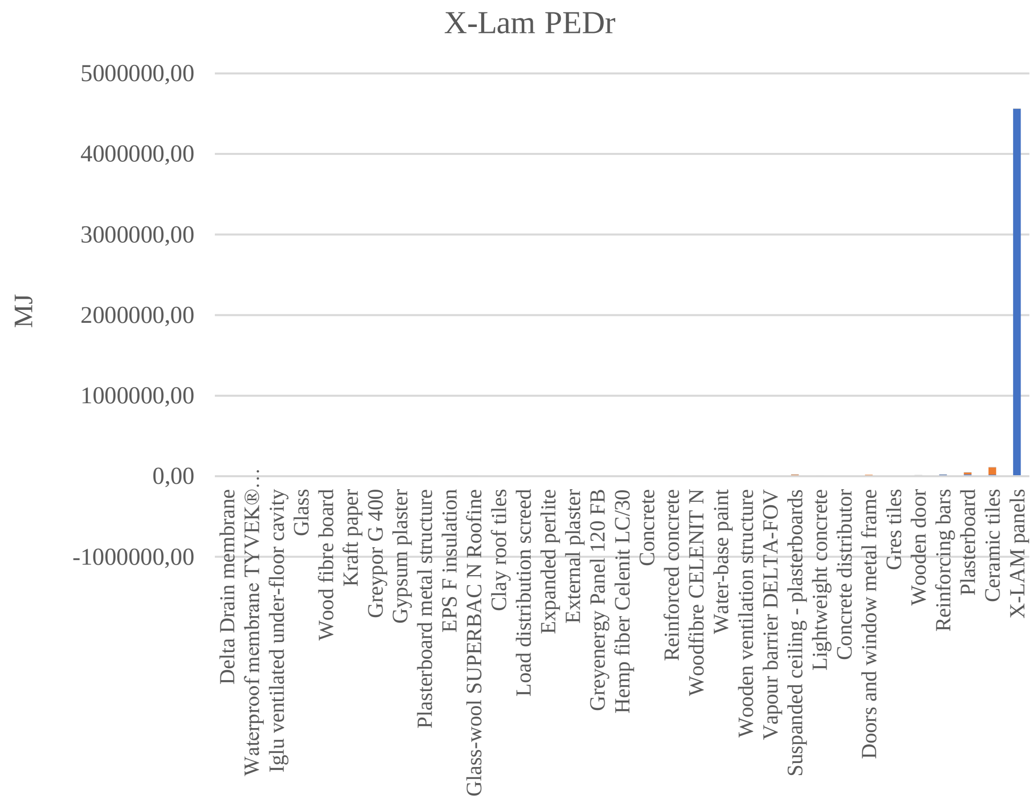


Figure 46: X-Lam's PEDr output for each material, highlighting share of each phase

In this case there is no space for many comments, it can be said, with a slight approximation, that the impacts are all generated by the material X-Lam, which is the horizontal and vertical load-bearing structure of the building and which represents 97% of the total impacts, the same situation applies to the Land use indicator.

Let's see what happens to timber frame technology in the case of Land use:

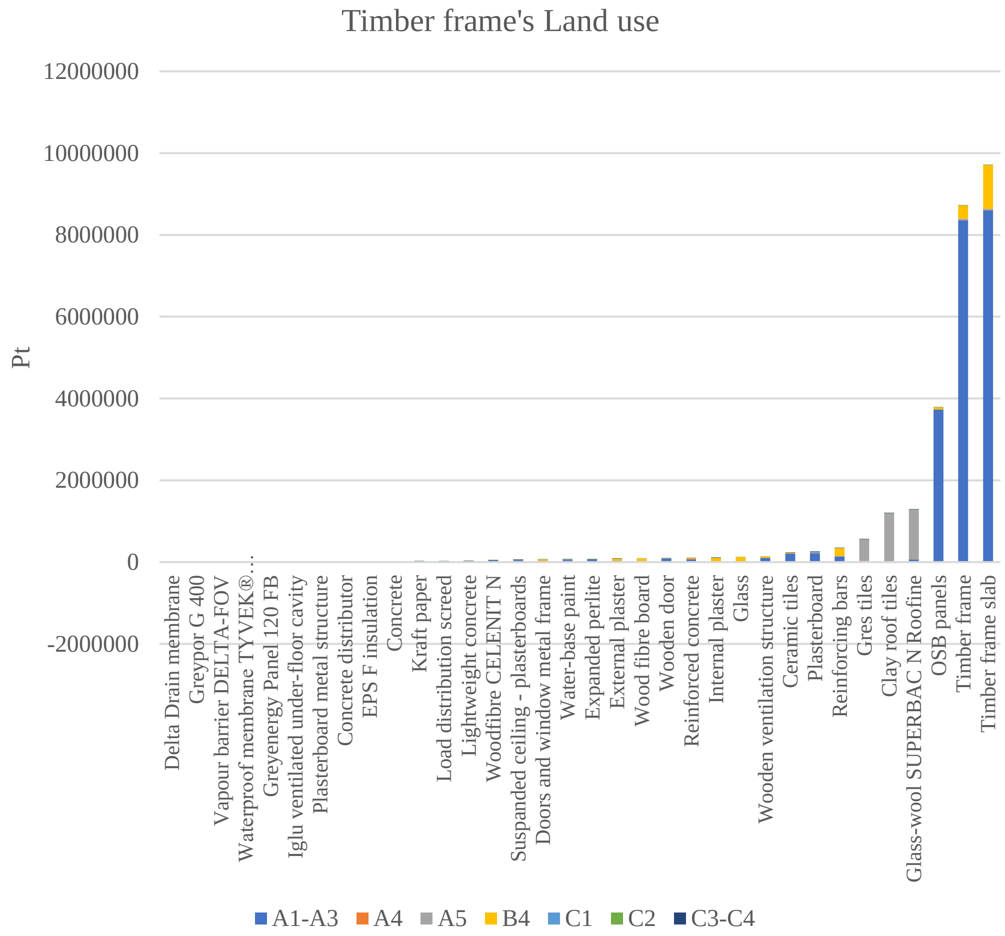


Figure 47: Timber frame's land use output for each material, highlighting share of each phase

As expected, the most impacting materials are those that make up the load-bearing structure in horizontal and vertical timber frames, followed in third place by the OSB panels, therefore the materials derived from wood.

Finally, let's see in detail what happens by comparing all the external and internal walls, the roof and the slabs of each technology, which, as we saw at the beginning of the chapter, as a common factor for each solution, have the same transmittance, but certainly different environmental impacts.

Let's see for example what happens with the environmental indicator GWP:

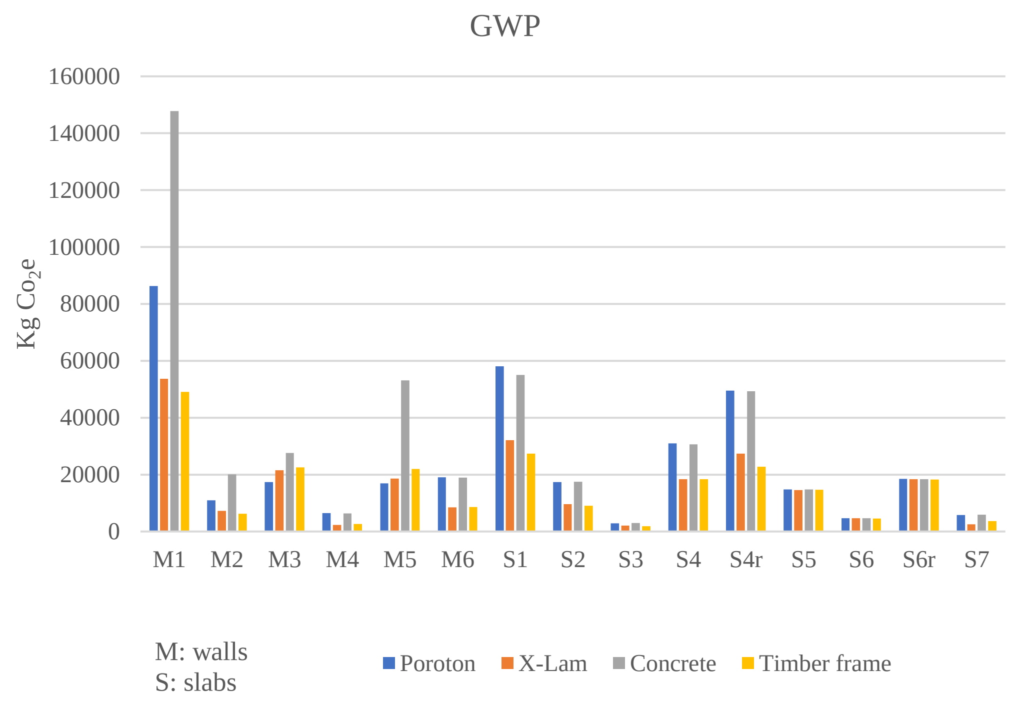


Figure 48: Comparison of GWP's outputs among the elements with the same transmittance

It can be observed that the M1, which is an external wall bordering the interior and the S1, which is the roof, are the most influential elements, in particular, in the M1 emerges the concrete, followed by the poroton, while in the S1 poroton and concrete, which are the most influential, have almost equal values. The elements S5, S6 and S6r have the same values because they are made of the same materials in the 4 technologies, they are the slabs against the ground.

The PEDnr indicator has a scenario very similar to that of the GWP. Let's look at the PEDr environmental indicator:

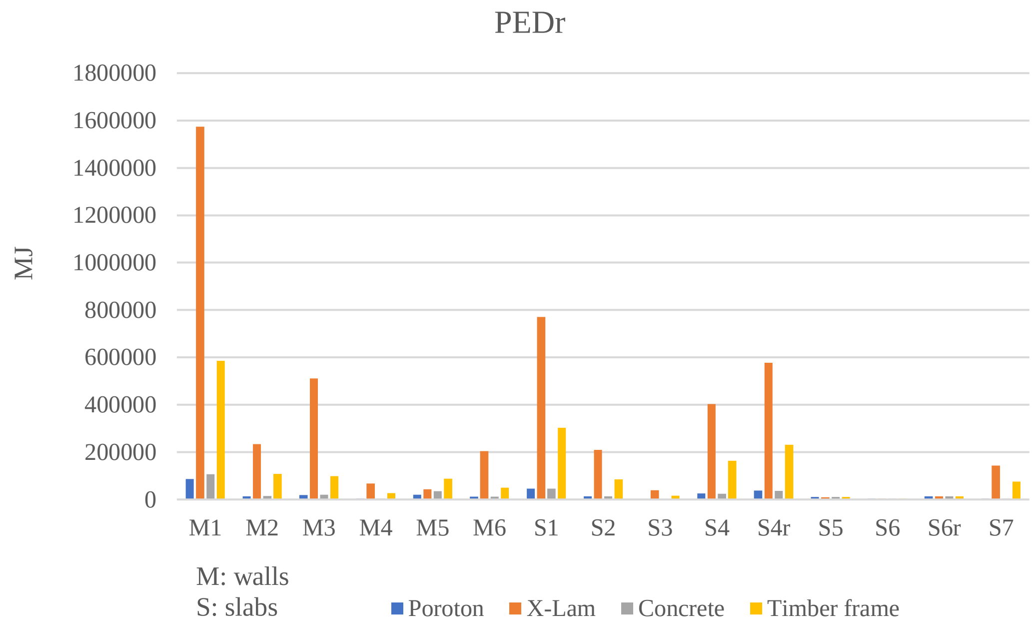


Figure 49: Comparison of PEDr's outputs among the elements with the same trasmittance

The X-Lam and Timber frame technologies dominate the graphic, being structures made of a renewable material, wood. The X-Lam in particular has much higher values because it has a massive structure, unlike the frame, which is punctual, and therefore has a lower use of wood. Also, in this case, the most impacting elements are the external wall M1 and the roof S1. The Land use environmental indicator gives a graph with results very similar to this one.

As a final analysis, we observe the same graph, representing the CO_2 emissions, which shows the impacts for each building technology, but in this case we have highlighted the phases of production, use and end of life and it is possible to see the incidence of each in each element, the production phase is always the most impacting, followed by the use phase and end of life.

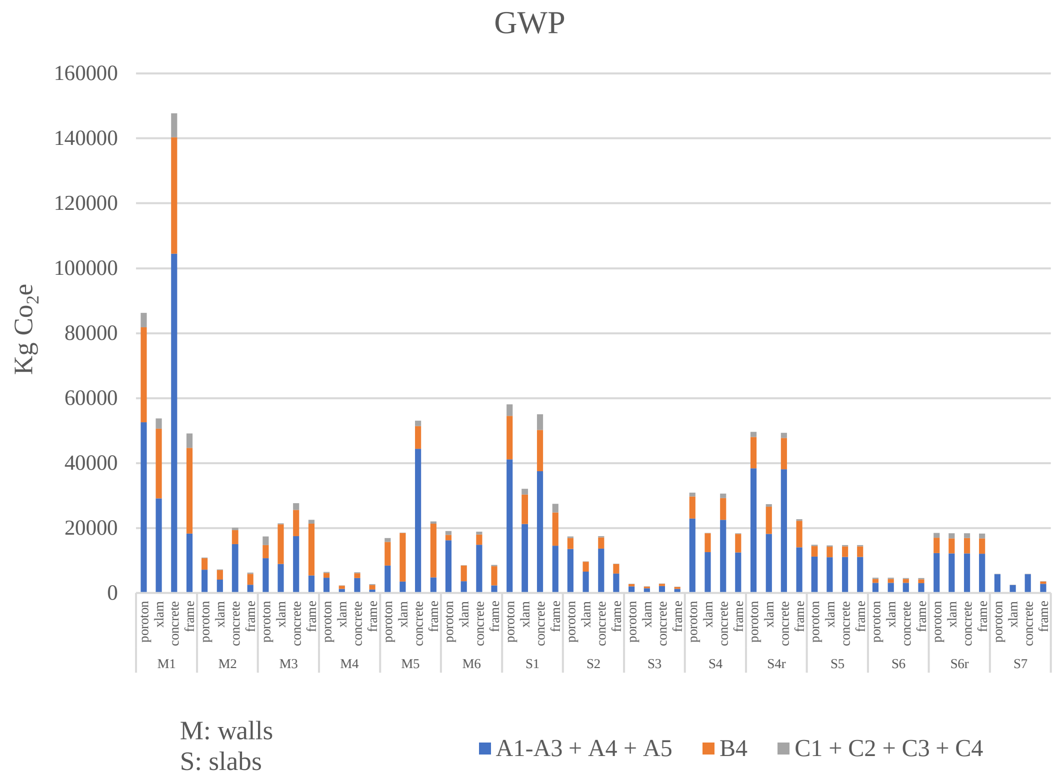


Figure 50: Comparison of GWP's outputs among the elements with the same trasmittance hilighting the different life cycle stages

The following graph shows the impact of the Land use indicator, how the production phase, consisting of the production of the material in the factory, transport to the construction site and construction stage, domains on the others and especially in X-Lam and timber frame technologies.

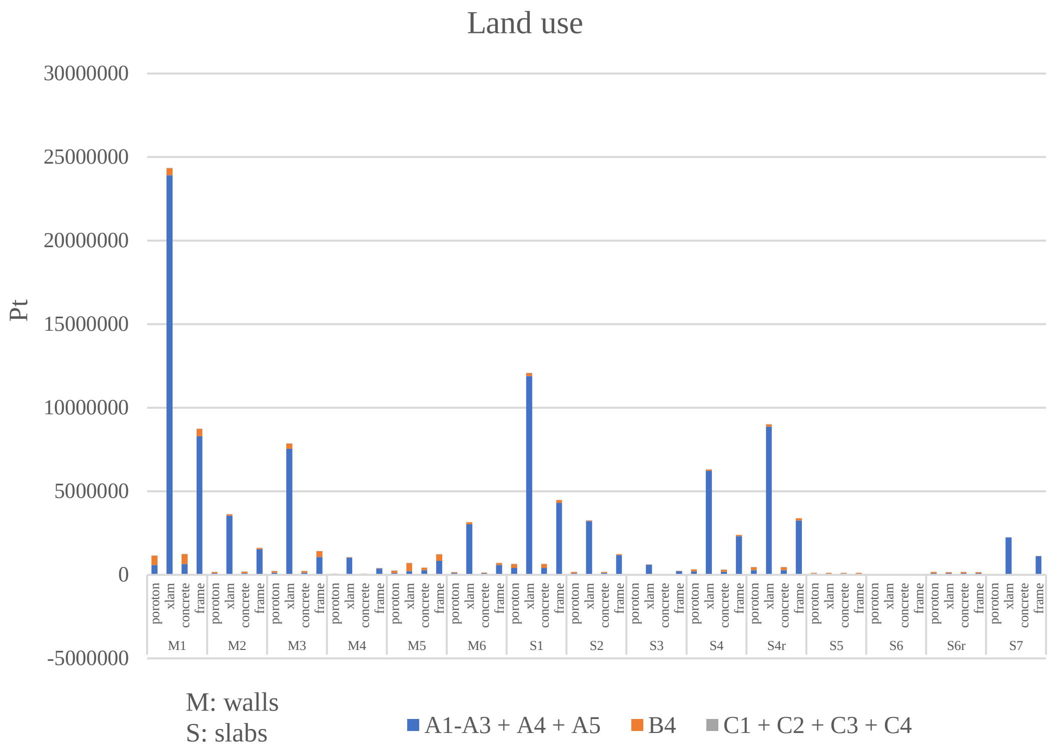


Figure 51: Comparison of Land-use's outputs among the elements with the same transmittance highlighting the different life cycle stages

8.4.2 Sensitivity analysis

Sensitivity analysis studies how the variation in the output of a system can be apportioned to different input parameters. In other words, it tries to determine how the change of input parameters would affect the change of the output. In this specific project it was useful to see how total emissions vary, assuming an initial error in the quantification of the quantity of the most environmentally impacting materials, respectively in the different technologies:

Poroton:

- Reinforcing bars;
- Reinforced concrete;
- Poroton;
- Ceramic tiles;
- EPS insulation panels.

X-lam:

- Plasterboard vertical panels;
- X-Lam panels;
- Ceramic tiles;
- Reinforcing bars;
- EPS insulation panels.

Concrete:

- Reinforcing bars;
- Reinforced concrete;
- EPS insulation panels;
- Ceramic tiles;
- Water-based paint.

Timber frame:

- Plasterboard vertical panels;
- Reinforcing bars;
- Ceramic tiles;
- Glass-wool panels;
- EPS insulation panels.

The following graphs show the effects on the environmental indicator GWP compared to the 4 construction technologies, in blue the quantity of CO_2 is indicated, in orange it is highlighted how much emissions would increase if the quantity of material had increased by 20%:

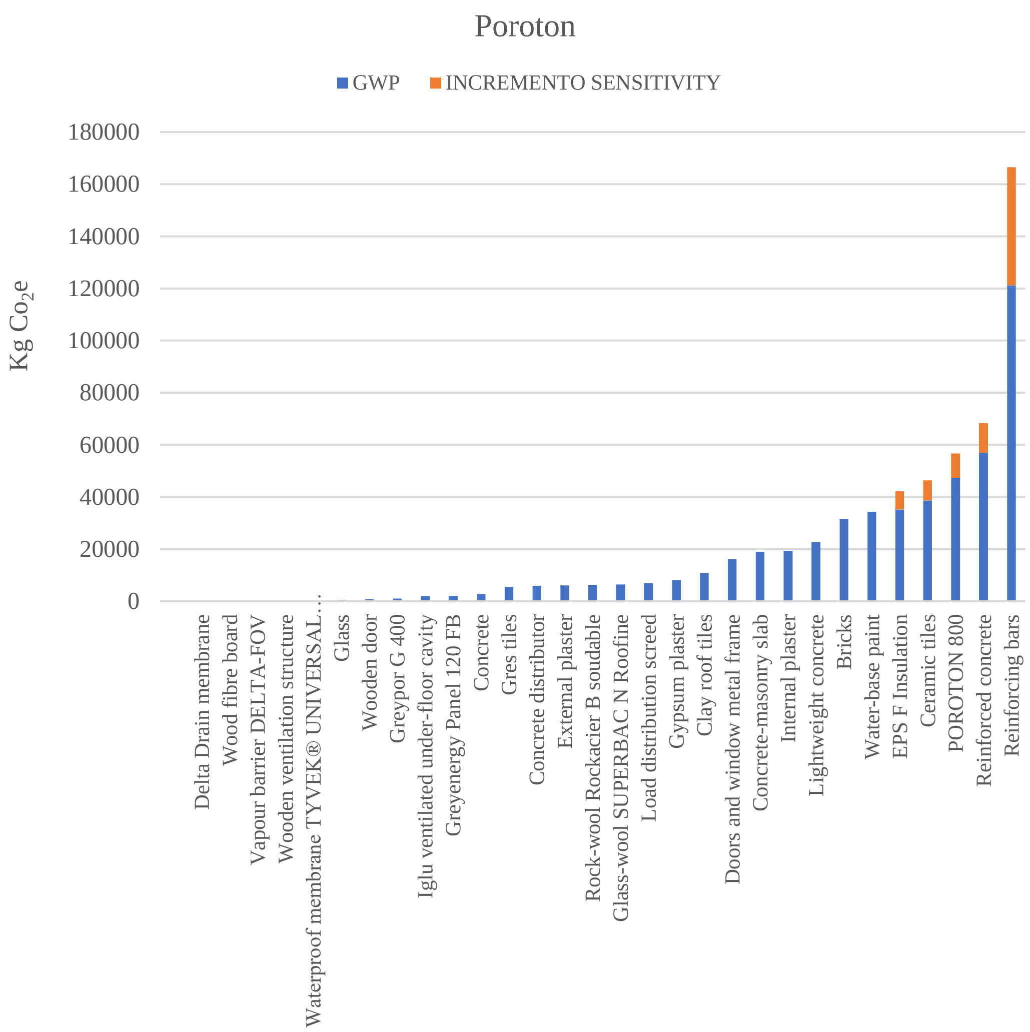


Figure 52: Poroton's GWP with the addition of a 20% to the 5 most impacting materials' quantities

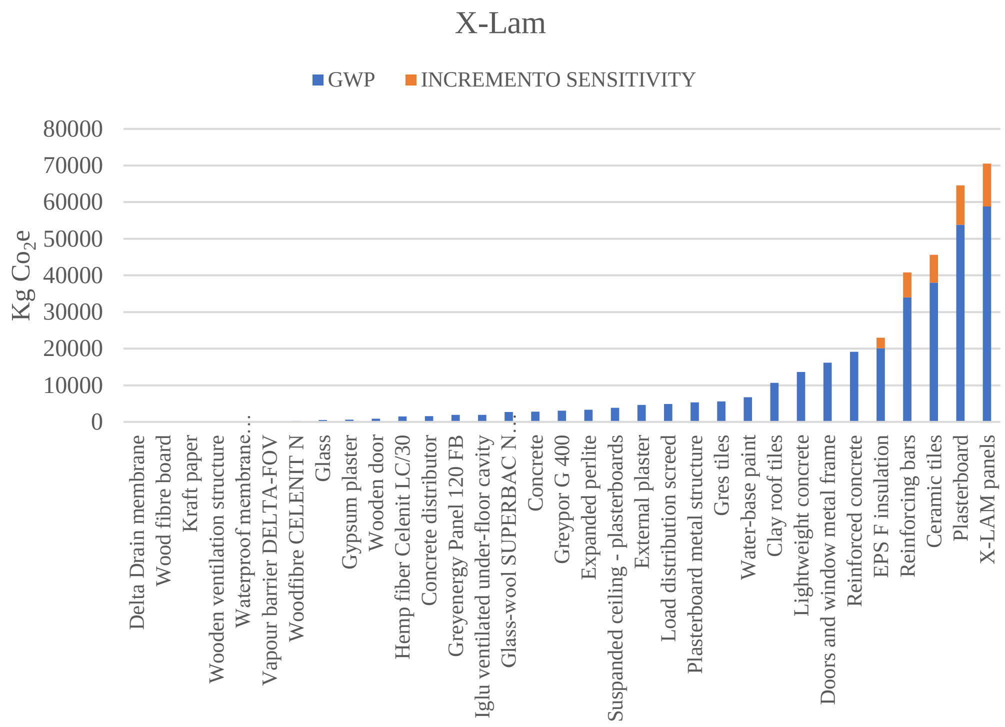


Figure 53: X-Lam's GWP with the addition of a 20% to the 5 most impacting materials' quantities

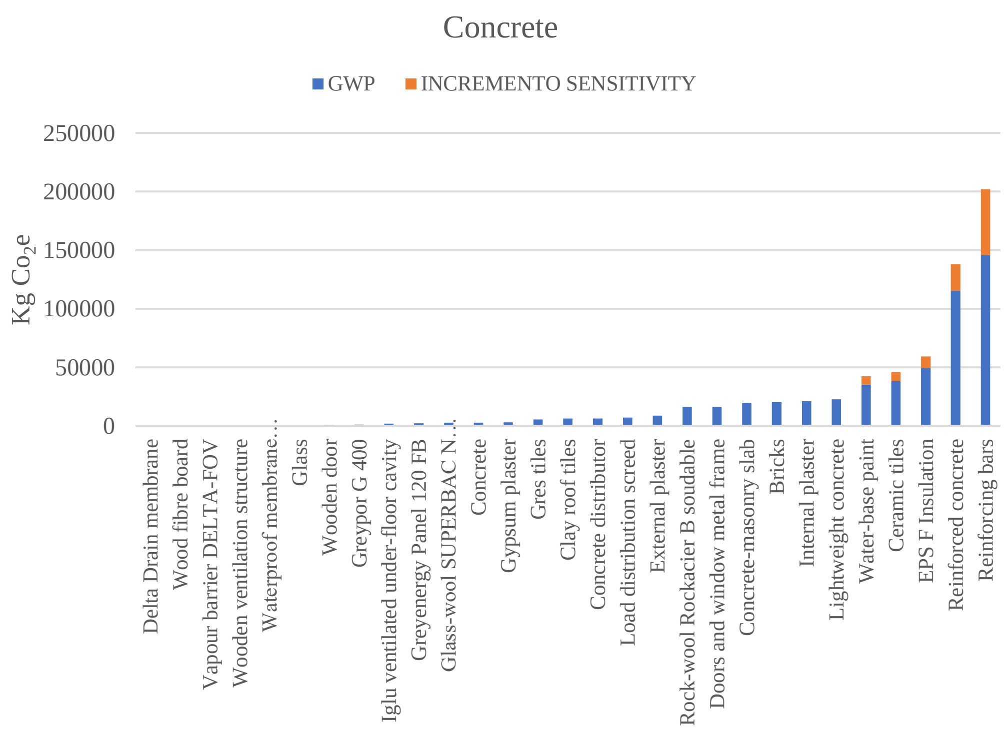


Figure 54: Concrete's GWP with the addition of a 20% to the 5 most impacting materials' quantities

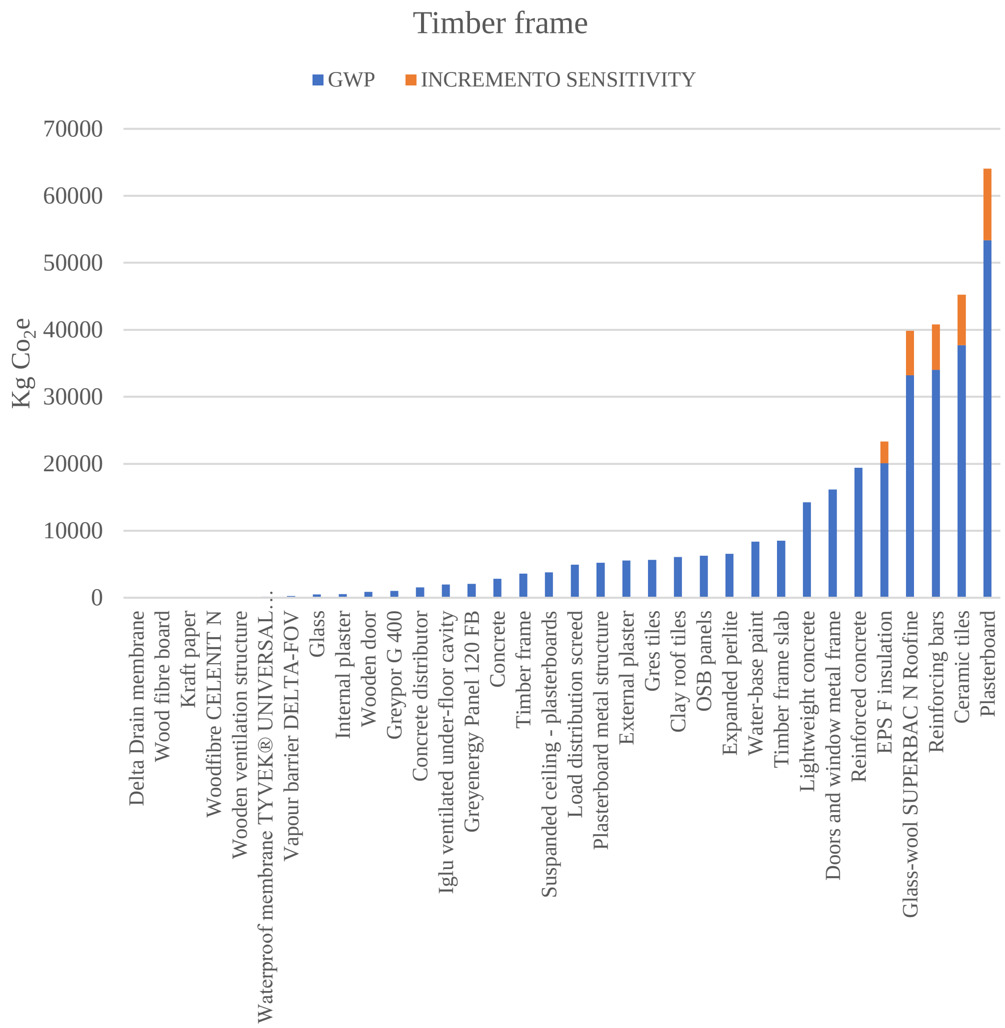


Figure 55: Timber frame's GWP with the addition of a 20% to the 5 most impacting materials' quantities

As a general comment we can say that it is essential to make a correct calculation of the quantity of reinforcing bars, as they have a very considerable impact in all the technologies analyzed, the same applies to the X-Lam and timber frames in wood technologies, but also in ceramic tiles and insulation panels, also present in all technologies.

The same analysis was then applied to the 5 most frequent maintenance activities, an error of 20% was hypothesized on the quantification of the number of replacements, this has therefore involved phase B4 "Use phase, boundary for replacement".

As in the previous analysis, let's see below the outputs on the environmental indicator of GWP in the 4 construction technologies; specifically, let's observe the most impacting materials for each of them:

Poroton:

- Water-based paint;
- EPS insulation panels;
- Ceramic tiles;
- Internal plaster;
- Doors and windows metal frame.

X-lam:

- Plasterboard vertical panels;
- Ceramic tiles;
- EPS insulation panels;
- Doors and windows metal frame;
- Water-based paint.

Concrete:

- EPS insulation panels;
- Water-based paint;
- Ceramic tiles;
- Internal plaster;
- Rock-wool insulation panels.

Timber frame:

- Plasterboard vertical panels;
- Ceramic tiles;
- Glass-wool panels;
- EPS insulation panels;
- Doors and windows metal frame.

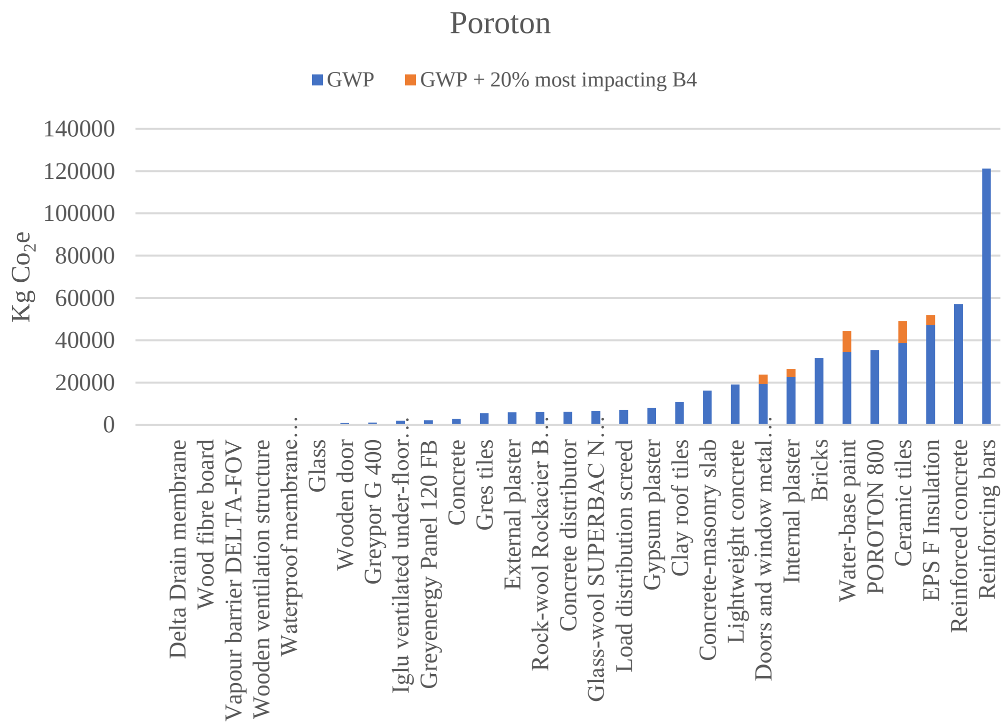


Figure 56: Poroton's GWP with the addition of a 20% frequency to the 5 most impacting maintenance activities

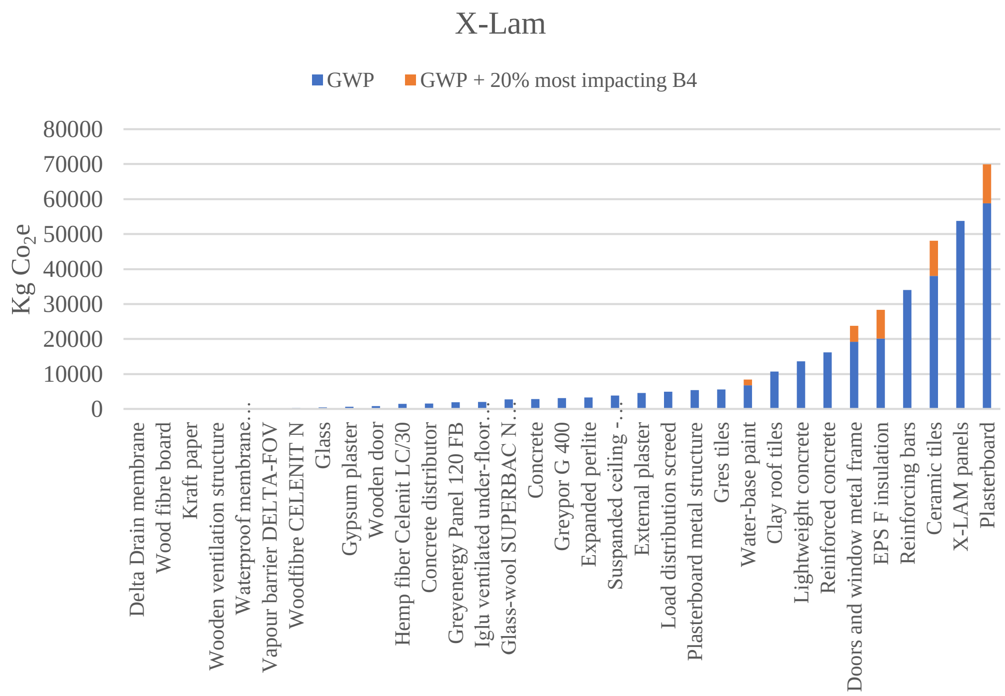


Figure 57: X-Lam's GWP with the addition of a 20% frequency to the 5 most impacting maintenance activities

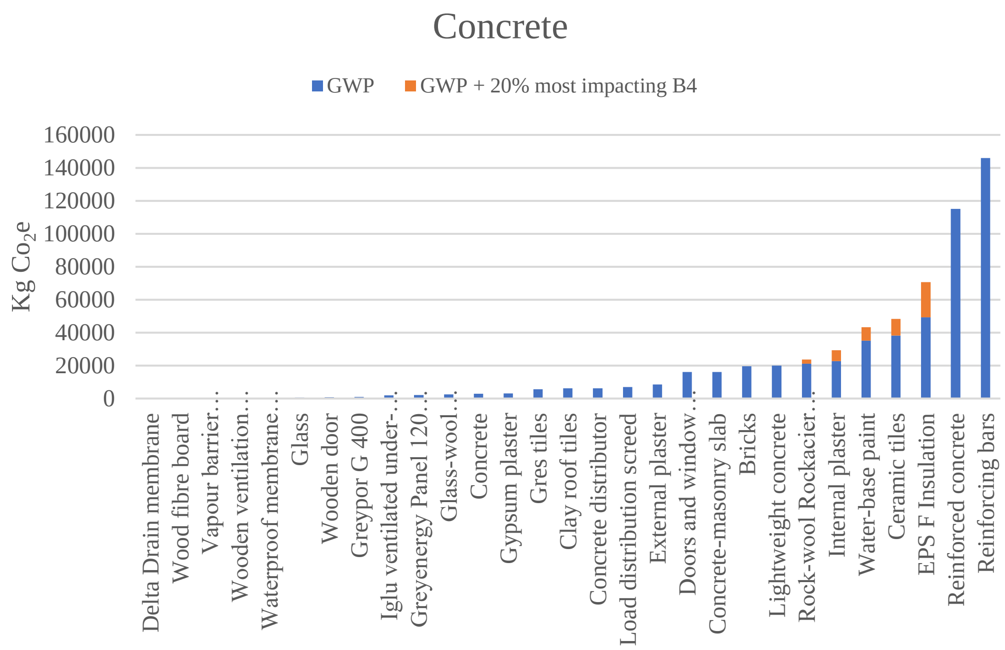


Figure 58: Concrete's GWP with the addition of a 20% frequency to the 5 most impacting maintenance activities

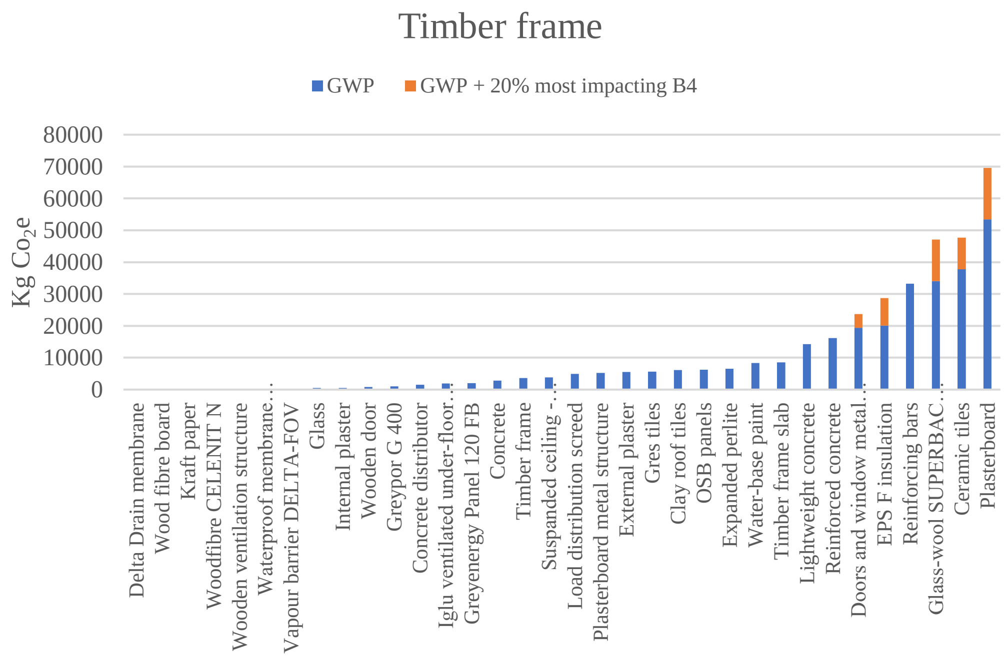


Figure 59: Timber frame's GWP with the addition of a 20% frequency to the 5 most impacting maintenance activities

These last graphs show that a 20% in the calculation of maintenance activities of materials such as plasterboard panels, insulation panels, water-based paint and ceramic tiles have a huge impact for what concerns the GWP indicator.

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9 Life Cycle Cost

9.1 Cost Estimation

The first important step in preparing the LCC analysis is to identify all relevant items that will form part of the boundary system. This definition will serve to create a unique correspondence with the environmental impact analysis, so as to be able to identify the relationship costs/impacts. The LCC calculation will identify construction costs, ordinary and extraordinary maintenance and final costs of destruction of the building and the subsequent generated waste treatment. As a database for the consultation of unit costs related to the construction of the building, we referred to the "Price List of the City of Milan", edition 2018: this list contains about 40,000 items divided into prices of completed works, supply of individual materials, manual work by specialized technicians, and rentals of construction equipment. The final price is also divided into the actual percentage of the cost of the material, of the workforce and of the freight rates, a very important tool for determining the major factors of incidence in the overall economic calculation of the work.

9.1.1 Bill of Quantities and Price List

For simplifying purposes of simplifying the design model, not all the works that could be found in the construction of a housing unit have been studied, but the costs only related to:

- Excavations and earthworks;
- Opaque structures;
- Windows;
- Reinforced concrete structures;
- Internal and external painting;
- Indirect costs

Therefore, the following are not included in the economic evaluation:

- Works of tinsmithing;
- Internal stairs;
- Construction charges

The estimate of the construction, maintenance and final disposal costs will be made for the four building technologies of reference: Poroton, X-lam, Concrete and Timber frame. The use of BIM modelling has allowed us to easily and quickly export the metric calculations for the various building components: from the abacus of materials to the calculations on opaque structures you can get files .xls to be used for the drafting of the economic calculation on Excel sheets.

Foundation	
Basic Wall: Insulated foundation	31.14 m²
Basic Wall: Foundation - 30 cm	21.87 m²
Basic Wall: Foundation - 37 cm	4.21 m²
_APP_A_	
Basic Wall: M1 - External Envelope	151.05 m²
Basic Wall: M2 - External Envelope	8.67 m²
Basic Wall: M3 - Internal partition	39.19 m²
Basic Wall: M5 - Internal partition	61.68 m²
_APP_A+B_	
Basic Wall: M3 - Internal partition	35.83 m²
_APP_A+C_	
Basic Wall: M2 -External Envelope	4.02 m²
Basic Wall: M6 - Internal stairwell core	18.08 m²
_APP_B_	
Basic Wall: M1 - External Envelope	140.30 m²
Basic Wall: M2 - External Envelope	7.76 m²
Basic Wall: M3 - Internal partition	41.67 m²
Basic Wall: M5 - Internal partition	65.00 m²
_APP_B+C_	
Basic Wall: M2 - External Envelope	42.71 m²
Basic Wall: M3 - Internal partition	6.72 m²
_APP_C_	
Basic Wall: M1 - External Envelope	175.05 m²
Basic Wall: M2 - External Envelope	5.85 m²
Basic Wall: M3 - Internal partition	24.10 m²
Basic Wall: M4 - External stairwell core	19.90 m²
Basic Wall: M5 - Internal partition	56.96 m²
Basic Wall: M6 - Internal stairwell core	41.95 m²

Table 36: Wall's abacus per building unit

As it is possible to obtain the metric calculation in an automated way, it is possible to obtain an abacus of the materials for the single building components: the calculation of the costs for each material used in each particular structure will allow us to obtain a cost per square metre that multiplied by the relative dimensions we will be able to obtain the total cost of the work (always taking into account the limitations already highlighted).

Family and type	*Material: Area*	*Material: Volume*
Delta-drain		
Basic Wall: Insulated Foundation	31,1 m²	0.0 m³
Basic Wall: Foundation - 30 cm	21,9 m²	0.0 m³
Basic Wall: Foundation - 37 cm	4,2 m²	0.0 m³
EPS F insulation		
Basic Wall: M1 - External envelope	472,2 m²	22.8 m³
Basic Wall: M4 - External stairwell core	19,9 m²	1.0 m³
EPS Greypor G 400		
Basic Wall: Insulated Foundation	30,7 m²	2.8 m³
External plaster		
Basic Wall: M1 - External envelope	473 m²	2.8 m³
Basic Wall: M2 - External envelope	68 m²	1.0 m³
Basic Wall: M4 - External stairwell core	19,9 m²	0.1 m³
Fermacell panel		
Basic Wall: M1 - External envelope	875 m²	10.6 m³
Basic Wall: M3 - Internal partition	582,9 m²	7.3 m³
Basic Wall: M4 - External stairwell core	39,8 m²	0.5 m³
Basic Wall: M5 - Partizione interna xlam	724,9 m²	9.1 m³
Basic Wall: M6 - Intenral stairwell core	230,4 m²	3.0 m³
Fiber wood insulation		
Basic Wall: M5 - Internal partition	182,6 m²	14.5 m³
Hemp-fiber insulation		
Basic Wall: M1 - External envelope	445,4 m²	21.5 m³
Basic Wall: M3 - Internal partition	291,9 m²	14.6 m³
Basic Wall: M4 - External stairwell core	19,9 m²	1.0 m³
Basic Wall: M6 - Intenral stairwell core	115,9 m²	5.9 m³
Internal plaster		
Basic Wall: M2 - External envelope	68,9 m²	0.4 m³
Reinforced concrete (Foundation walls)		
Basic Wall: Insulated Foundation	28 m²	5.7 m³
Basic Wall: Foundation - 30 cm	21,9 m²	5.4 m³
Basic Wall: Foundation - 37 cm	4,2 m²	1.3 m³
Vapour barrier		
Basic Wall: M1 - External envelope	473,4 m²	0.0 m³
Basic Wall: M4 - External stairwell core	19,9 m²	0.0 m³

Family and type	*Material: Area*	*Material: Volume*
Waterproof membrane		
Basic Wall: Insulated Foundation	31,1 m²	0.0 m³
Basic Wall: Foundation - 30 cm	21,9 m²	0.0 m³
Basic Wall: Foundation - 37 cm	4,2 m²	0.0 m³
XLAM panel		
Basic Wall: M1 - External envelope	465,4 m²	62.9 m³
Basic Wall: M2 - External envelope	68,9 m²	9.7 m³
Basic Wall: M3 - Internal partition	146,6 m²	20.7 m³
Basic Wall: M4 - External stairwell core	19,9 m²	2.8 m³
Basic Wall: M6 - Intenral stairwell core	58,7 m²	8.4 m³

Table 37: Material's abacus for walls component, X-lam

The use of BIM software has allowed us to break down the building in the most appropriate way for our purposes: from the useful surface of vertical partitions, horizontal partitions and other macro-components, to their internal subdivision and related materials. It has thus been possible to identify for each material present in the building its processing during construction and thus be able to combine a defined cost.

The abacus of the building materials allowed to analyse the individual construction costs of the materials for each specific perimeter and internal wall, the roof structures and floors, windows and doors specific to the housing unit. Concerning the cost calculation, a table has been created following this scheme: a resource analysis has been carried out, it is the list of resources (materials, workforce and equipment) needed to execute one quantity unit of a generic construction activity and their relative unitary costs. This independent unity entity is adaptable to each project, specifying and describing in detail the activity analysed.

Key points are:

- The computation of time work needed to execute an activity by the workforce; it is based on the average between probabilistic, optimistic and pessimistic time;

- The load cycle, the capacity and the yield of equipment;
- The calculation in percentage of materials, workforce and equipment to weigh their index of incidence in each activity.

The total costs for each activity have been calculated summing the unitary cost of each material multiplied for its incidence and the total surface, plus the cost of the workforce per each hour needed and the cost of the equipment.

Name a description	Unit of measurement (U.M.1)	Material	Unit of measurement U.M.2	Incidence on the U.M.1	Unitary cost €/U.M.2	Unitary cost €/U.M.1
Structure x-lam supply panels x-lam - not visible quality	mq	5 SHEETS thickness 150 mm. - five-layer (40+20+30+20+40), surface layers oriented according to the longitudinal axis of the panel	mq	1	103,2	103,2

Table 38: Material's cost estimation, X-lam

In this first part of the composition of a unit cost we would consider only the material used for the creation of a vertical bearing structure in X-lam as an example object. The primary unit of measurement will be the reference unit for the cost itself, while the description of the material used allows us to link the construction activity to a specific material, from which we can then identify a unit cost. Often the Milan price list uses units of measurement that do not correspond to our needs, so we have created an incidence factor that allows us to make a conversion from one measurement to another. In this specific case, both the unit cost provided by the City of Milan and our metric calculation refer to square meters: in this case we have created a unique system for the entries of building materials used.

Name a description	Unit of measurement (U.M.1)	Material	Unit of measuremen t U.M.2	Incidenc e on the U.M.1	Unitary cost €/U.M. 2	Unitary cost €/U.M. 1
Concrete for structures	mc	C25/30	mc	1,1	99,91	109,901
Wooden or metal formworks for structures	mq	Tavole in abete sottomisur a	mc	0,0008	225,4	0,192
		Travi in abete uso trieste		0,00006	194,3	
Steel for reinforced e concrete	mc	Fornitura e posa in opera di acciaio del tipo FEB44K	kg	234	0,5	117

Table 39: Load bearing structure material cost

An interesting and specific case was the creation of a unit cost for the creation of pillars and beams for the load-bearing concrete structure in the Poroton technology: the three main processes for their processing are the supply and installation of steel reinforcements, concrete and the provision of wooden formworks. As can be seen from the previous sheet, the prices of steel and formwork were supplied per kg and cubic metre respectively.

The conversion factor of 234 kg of steel reinforcement for each cubic metre of construction of a pillar was determined by using a 4% ratio between the volume of steel and concrete. Similar considerations for the boards in abbey and spruce beams used, which were provided at a cost of one cubic meter, later converted into square meter of surface area used for this processing. This conversion factor, if multiplied by the cost €/U.M2, will allow us to obtain the cost per reference unit of measurement U.M.1.

Description	workers	Interference index	h	Most probable execution time [a]	Pessimistic execution time [a] + 75%	Optimistic execution time [a] - 25%	Execution time	Activity duration	workforce cost €/h	Unit of measurement €/U.M.1	Worker €/U.M.	Tot workforce cost €/U.M.1
Specialised construction worker 3rd level	1	1	h	0,70	1,23	0,53	0,76	0,76	22,20	EUR/mq	16,84	31,40
1st level common construction worker	1		h	0,70	1,23	0,53	0,76		19,20	EUR/mq	14,56	

Table 40: Labour force cost estimation

As previously mentioned, the calculation of the labour cost using a probabilistic method allows us to identify the incidence of the human cost in the total computation of the construction activity. The labour costs, also in this case, have been provided by the price list of the Municipality of Milan. For each process a basic team of workers has been created, which varies in number and specialization with respect to the process itself. The interference factor, variable between the values 0 and 1, are used to represent the discomfort that each team can bring to others at the time they are working, both in spatial and temporal terms. For simplification we have hypothesized a site where there are no expected interferences between the various construction teams for which the factor 1 has been used for each processing. The most probable working time refers to the time used by the individual worker to complete the construction according to the general U.M.1. unit of measurement: in the example, 0.7 hours (42 minutes) are used to complete the installation of 1 square metre of X-lam load-bearing wall. The pessimistic performance is represented by 75% more time used than the most probable; the optimistic one is represented by 25% less time used.

Following the PERT (Program of Evaluation and Review Technique) technique, the processing time will be given by the formula: $T_e = \frac{a+4m+b}{6}$

Where:

- "a" represents the optimistic duration;
- “b" represents the pessimistic duration;
- “m” is the most likely duration.

Finally, you simply have to multiply the execution time obtained by the unit cost of the individual worker and thus obtain the total sum of the cost of the workforce for each individual processing.

Instead, the calculation of the equipment and machinery used for the single processes have been included in the calculation of indirect costs, when it was impossible to identify with certainty the incidence of a single process in the total cost of a rental of a machine.

Table 41: Equipment cost analysis

Description	N° tools	h	Most probable machine-execution time [a]	Pessimistic machine-execution time [a] + 75%	Optimistic machine-execution time [a] - 25%	Equipment required time to run a work unit	Hourly cost equipment €/h	Unit of measuremen €/U.M.1	Hourly cost equipment	Total cost equipment a €/U.M.1 unitary
Pump for subfloors, screeds and self-levelling	1	h	0,006	0,0045	0,0105	0,0065	1,03	-	0,007	0,007

The payment for construction machinery itself, which is time-chartered, is independent of whether or not the machinery is used in the production process, so that only in those processes in which it is possible to identify the relationship between machinery and activities has this item been taken into account.

The example identified is the use of a pump for subfloors, screeds and self-levelling, in the construction of a counter-ground floor in which it is possible to identify the single incidence of the machinery on the relative processing. The method used to identify the normal execution time for each individual machine is treated using the PERT method, already identified in the drafting of the costs concerning the workforce. From the pure sum of the unit costs of material, labour force and equipment it is possible to identify a unit cost per work: it is therefore now possible to create a unit cost for each macro building component and identify a total cost of the work.

Name a description	Unit of measuremen (U.M.1)	Unitary cost €/U.M. 1	Tot workforce cost €/U.M.1	Total cost equipment a €/U.M.1 unitary	Total Unit labour, material and equipment costs €	Material incidence	Labour incidence	Equipement incidence
Yawning of excavations	mq	2,882707	14,98	0,72	18,58	16%	81%	4%

Table 42: Total cost per work execution

9.2 Indirect cost

The indirect cost has been assessed for each technology, in order to sum it with the direct cost in order to obtain total construction cost. The items that have been considered are:

- the construction site fences;
- rent for locker room, office and other storages;
- Equipment rental;

- Scaffolding supply for the construction period;
- Connection to public and elettrical services
- Comsuption of public services;
- Personal equipment and PPE.

Each technology has been linked to a probable execution time of total construction given by literature, in order to obtain a reliable data. Each category has been assessed in each technology in order to have a complete dataset which enables us to create a comparison among different solutions.

DESCRIPTION	U.M.	Quantity	Cost [€]		TOT cost [€]	
Construction site fences						
Fence made of prefabricated wire mesh elements and galvanized tubular uprights with a height of 2 m, laid on concrete supports including installation and subsequent removal.	ml	70	€	9,50	€	665,00
Driveway gate made with a welded tube type scaffolding, covered with galvanized trapezoidal sheet metal, given on site with a resumption of anti-rust, opening device, including metal pillars supporting fixtures in a cast concrete.	ml	5,6	€	123,08	€	689,25
Shipbuilding shacks/changing rooms and toilets						
Hire of a barque for use as a locker room, office, infirmary, refectory, storage equipment and / or materials including base raised from the ground and insulated cover against temperature changes, simple lighting systems, electrical outlets and preparation for the necessary connections to the function, excluding furniture and operating costs.	€/Months	7,0	€	60,00	€	420,00
Prefabricated module for chemical toilets, including maintenance and emptying at least twice a week. Rental per month.	Months	7,0	€	125,00	€	875,00
Rental						
Circular Saw	Months	7,0	€	8,40	€	1.764,00
Truck					€	233,33
distance warehouse - site	Km	10				
Average urban speed	Km/h	30				
transport costs + driver	€/h	35				
number of trips	cad.	20,00				
Crane rental with electrically operated tower, in full efficiency conditions, already installed on site: working rental date including consumption f.e.m. and with crane operator.	Months	7,0	€	1.550,00	€	10.850,00

Table 43: Indirect costs analysis, part I

The indirect cost for the transportation of material has been identified by using the Austrian transportation scenario, used in the LCA analysis, so that it is possible to identified cost and relative environmental impacts. All the costs have been taken by the Price list of Municipality of Milan.

Scaffolding assembly and disassembly						
Rental of complete facade gantry scaffolding on site including transport, assembly and disassembly, grounding, lighting of the scaffolding, preparation of the worktops and their subpanels, design and calculation report, measured on the actual external surface of the scaffolding and all other charges. Up to 30 days.	mq	150	€	12,50	€	1.875,00
For each month over 30 days - xx months	Months	5,0	€	1.590,00	€	7.950,00
Internal scaffolding / scaffolding	mq	25	€	60,20	€	1.505,00
Connection to public and electrical services						
Electricity grid - building site control panel	cad.	1	€	3.500,00	€	3.500,00
Water supply network	cad.	1	€	1.000,00	€	1.000,00
Consumption of public services						
Electricity	€/Months		€	150,00	€	1.060,00
Water supply	€/Months		€	250,00	€	1.766,67
Personal equipment and PPE						
% of direct costs (CD)	%*CD	1			€	4.415,18
					Tempo (giorni)	212
					TOTAL INDIRECT COSTS	27.718,43
					TOTAL DIRECT COSTS	441.518,48
					% of Indirect costs	6,28%

Table 44: Indirect costs analysis, part II

9.3 Construction Costs

The direct costs for each single technology adopted are reported below, remembering that for each of them a breakdown of costs has been used from the single processing of materials to macro-components. In order to be able to use the costs obtained in an orderly and precise manner, a work breakdown structure was used in such a way as to be able to identify the total quantities requested and to be able to observe the respective differences for each technology.

	Level I			Level II			Level III			Level IV	Unitary cost	
											U.M.	€/U.M.
ATTIVITÀ PRELIMINARI												
0	Preliminary activities	01	0.01	Preliminary works	01	0.01.01	Earth movements excavations	01	0.01.01.01	Sculpture digging	mc	46,68
										General excavation	mc	46,68
										Yawning and digging	mq	17,86
LAVAORI CIVILI												
	Civil works	01	1.01	Foundation structures	01	1.01.01	Direct foundations: grade beam	01	1.01.01.01	Grade beams	mc	663,87
									1.01.01.02	Foundation 30 cm	mc	251,25
									1.01.01.03	Foundation 37 cm	mc	273,25
									1.01.01.04	Foundation + insulation	mc	273,25
											mq	15,86
							Foundations slabs		1.01.01.05	Iglu ventilated	mq	24,58
									1.01.01.06	Raft foundation	mc	105,80
				Elevation structure			ramps and landings		1.01.01.07	Staircase structure	mq	548,40
ENVELOPE												
2	Envelope	01	2.01	Vertical envelope	01	2.01.01	Perimeter walls	01	2.01.01.01	M1	mq	212,18
									2.01.01.02	M2	mq	195,95
									2.01.01.03	M3/M6	mq	167,84
									2.01.01.04	M4	mq	197,44
		02	2.02	Horizontal envelope	02	2.02.01	Perimeter floors	02	2.02.01.01	S1	mq	218,10
									2.02.01.02	S5	mq	91,40
									2.02.01.03	S6	mq	112,33
									2.02.01.04	S6r	mq	124,85
PARTIZIONI												
3	Partitions	01	3.01	Vertical partitions	01	3.01.01	Internal divider	1	3.01.01.01	M5	mq	141,00
		02	3.02	Horizontal partitions	01	3.02.01	Horizontal partitions	01	3.02.01.01	S2	mq	191,72
								02	3.02.01.02	S3	mq	202,30
								03	3.02.01.03	S4	mq	194,01
								04	3.02.01.05	S4r	mq	207,96
SERRAMENTI												
4	Windows and doors	01	4.01	External doors and windows	01	4.01.01	Gate				cad	905,14
							Security door 90*210				cad	1039,43
							Window 60*125				cad	451,98
							Double window 110*125				cad	466,23
							Double window 110*230				cad	545,24
							Quadruple windows				cad	665,23
							Skylight-Operable				cad	390,78
		02	4.02	Internal doors and windows	01	4.02.01	Door internal				cad	326,79
						4.02.02	Internal door 60*210				cad	937,48

Table 45: BOQ structure

9.3.1 Poroton

The vertical and horizontal closures and the elevation and foundation structures correspond to 87% of the direct costs of the building, excluding only the costs of excavation and deburring, and the costs of the windows and doors, which will be the same in all the identified four technologies.

Poroton		Quantities						Costs				
		€/U.M	U.M.	App. A	App. B	App. C	App. A+B+C	App. A	App. B	App. C	App. A+B+C	€
Foundations	Grade beams	663,87	mc				30,89				20506,82	**20.506,82 €**
	Foundation 30	251,25	mc				6,6				1658,24	**1.658,24 €**
	Foundation 37	273,25	mc				2,1				573,82	**573,82 €**
	Foundation +	273,25	mc				5,8				1584,84	**1.584,84 €**
	Insulation	15,858	mq				30,7				486,84	**486,84 €**
	Iglu ventilated	24,578	mq	61,40	61,39	63,08		1509,11	1508,86	1550,401		**4.568,37 €**
	Raft foundation	105,8	mc				19,44				2056,75	**2.056,75 €**
Elevation structures	Pillars 25x25	303,67	mc			2,38					722,74	**722,74 €**
	Pillars 40x25	303,67	mc			17,17					5214,08	**5.214,08 €**
	Beams 25x26	330,02	mc			12,86					4244,09	**4.244,09 €**
	Beams 40x26	330,02	mc			2,06					679,85	**679,85 €**
	Beams 50x26	330,02	mc			23,61					7791,83	**7.791,83 €**
Internal and external walls	M1	136,47	mq	149,29	142,96	178,71		20374,00	19510,13	24389,02		**64.273,14 €**
	M2	103,3	mq	10,72	9,38	7,22	45,09	1107,33	968,91	745,80	4657,60	**7.479,64 €**
	M3	133,38	mq	38,44	41,46	23,56	40,43	5127,07	5529,87	3142,40	5392,49	**19.191,84 €**
	M4	203,57	mq			18,69		0,00	0,00	3804,81		**3.804,81 €**
	M5	94,92	mq	61,29	63,89	55,74		5817,64	6064,43	5290,83		**17.172,91 €**
	M6	223,21	mq			42,55	18,6	0,00	0,00	9497,66	4151,74	**13.649,41 €**
Roof	S1	255,47	mq	72,87	72,87	85,88		18616,26	18616,26	21939,96		**59.172,49 €**
	S2	217,25	mq	20,21	20,31	20,58		4390,71	4412,44	4471,10		**13.274,24 €**
	S3	207,33	mq				11,37				2357,37	**2.357,37 €**
Floors	S4	200,83	mq	42,01	44,42	36,34		8436,71	8920,70	7298,03		**24.655,44 €**
	S4r	219,65	mq	48,54	45,86	79,96		10661,61	10072,96	17562,88		**38.297,45 €**
	S5	91,402	mq	27,87	27,22	21,06		2547,37	2487,96	1924,93		**6.960,26 €**
	S6	112,33	mq	6,47	6,35	14,32		726,76	713,28	1608,52		**3.048,55 €**
	S6r	125,76	mq	35,92	35,14	39,1		4517,15	4419,06	4917,06		**13.853,27 €**

Table 46: Poroton direct cost

In order to identify the most economically impacting items and see if there are patterns that are repeated in the analysis of other technologies, the metric computations have been divided into surfaces between the apartments A, B and C that make up the housing unit, with a further classification for shared components, such as apartment dividing walls or computations on the amount of material to be used for the construction of foundations.

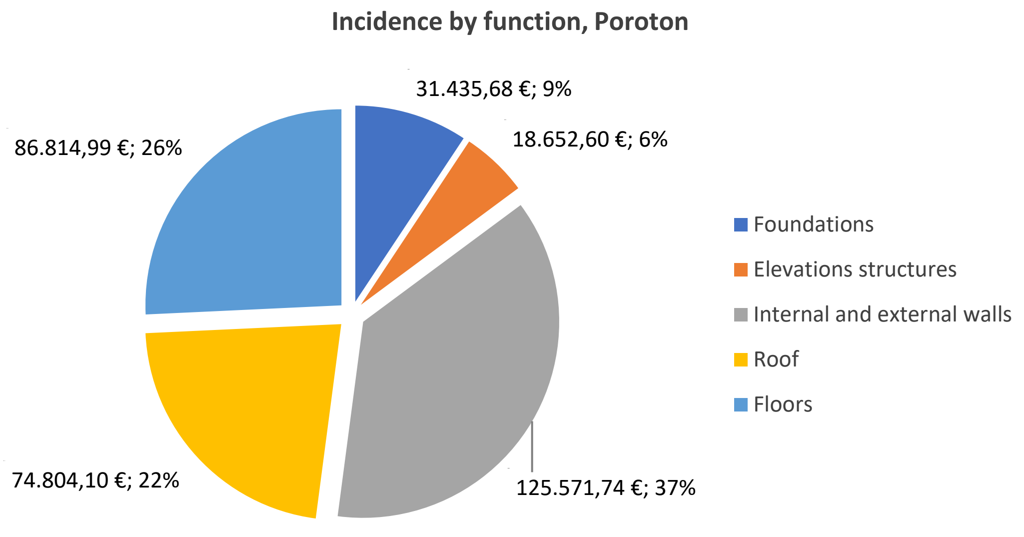


Figure 60: Cost incidence per functional elements, Poroton

The internal and external vertical partition accounts for the 37% of the overall cost of opaque surfaces due, more than to the cost per square metre of the individual processes, to the total surface area analysed. Coming into more detail on the individual works, the perimeter wall M1 and the pitched roofing system S1 are identified as the most economically impacting.

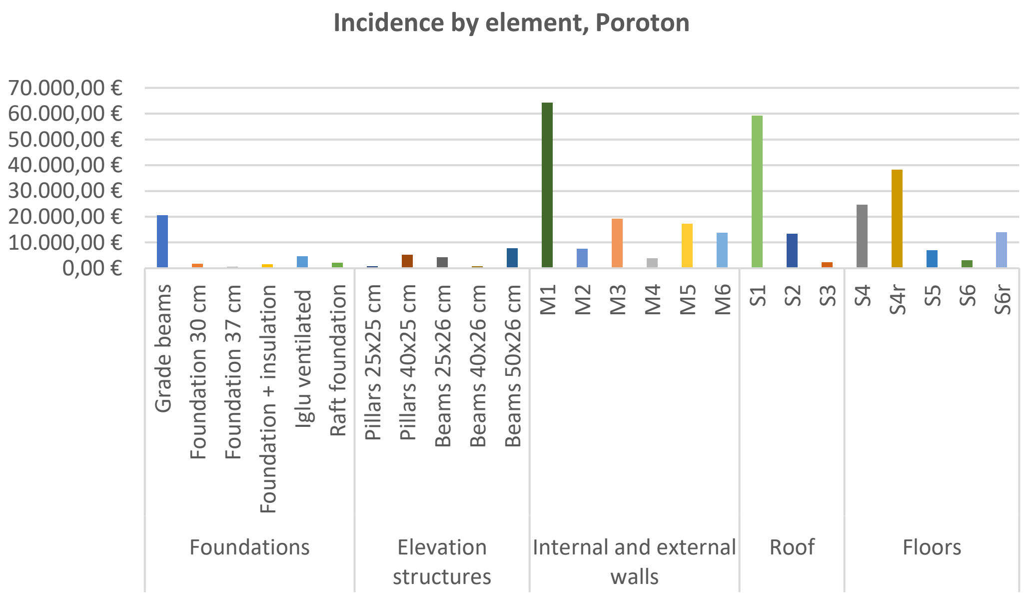


Figure 61: Cost incidence by elements, Poroton

It is interesting to note that the grade beams are the most expensive element, with its 20,506.82 €, among the category of foundations: this is due to the strong demand for both concrete and reinforcement and the demand for specialized staff.

9.3.2 X-lam

X-Lam				Quantities				Costs				
		€/U.M	U.M.	App. A	App. B	App. C	App. A+B+C	App. A	App. B	App. C	App. A+B+C	€
Foundations	Grade beams	663,87	mc				30,89				20506,82	**20.506,82 €**
	Raft foundation	105,80	mc				19,44				2056,75	**2.056,75 €**
	Foundation 30 cm	251,25	mc				6,60				1658,24	**1.658,24 €**
	Foundation 37 cm	273,25	mc				2,10				573,82	**573,82 €**
	Foundation + Insulation	273,25	mc				5,60				1530,19	**1.530,19 €**
		15,86	mq				27,70				439,27	**439,27 €**
	Igloo	24,58	mq	61,40	61,39	63,08		1509,11	1508,86	1550,40		**4.568,37 €**
Internal & xternal walls	M1	220,31	mq	151,05	140,3	175,05		33278,43	30910,06	38565,97		**102.754,47 €**
	M2	181,88	mq	8,67	7,76	5,85	46,73	1576,92	1411,41	1064,01	8499,36	**12.551,70 €**
	M3	194,11	mq	39,19	41,67	24,1	42,55	7607,34	8088,74	4678,16	8259,56	**28.633,81 €**
	M4	219,13	mq			19,9				4360,78		**4.360,78 €**
	M6	194,11	mq			41,95	18,08			8143,10	3509,59	**11.652,68 €**
	M5	70,15	mq	61,68	65,00	56,96		4327,07	4559,98	3995,94		**12.882,98 €**
Roof	S1	277,37	mq	71,75	71,75	85,63		19900,97	19900,97	23750,80		**63.552,75 €**
	S2	233,19	mq	20,66	20,09	21,19		4817,76	4684,84	4941,35		**14.443,95 €**
	S3	251,57	mq				11,65				2930,75	**2.930,75 €**
Floors	S4	246,93	mq	40,76	42,65	42,65		10065,05	10531,76	10531,76		**31.128,58 €**
	S4r	266,19	mq	47,6	45,19	78,13		12670,43	12028,92	20797,07		**45.496,41 €**
	S5	91,40	mq	27,52	26,02	21,42		2515,38	2378,28	1957,83		**6.851,50 €**
	S6	112,33	mq	6,42	6,4	14,27		721,14	718,89	1602,91		**3.042,94 €**
	S6r	124,85	mq	35,18	34,94	39,15		4392,18	4362,21	4887,83		**13.642,22 €**

Table 47: X-lam direct cost

The construction technology of the X-lam has similar characteristics with regard to the division of costs by technological functions, with a significant increase in vertical closures that cost up to 45% of this set. It should be specified that there are no processes for the creation of pillars and beams of reinforced concrete compared to Poroton technology, so that this category goes totally to raise the incidence of vertical and horizontal closures. It should be noted that the total construction costs of opaque closures have risen considerably, thanks to the striking example of the M1 perimeter wall, which costs 102,754.47 €.

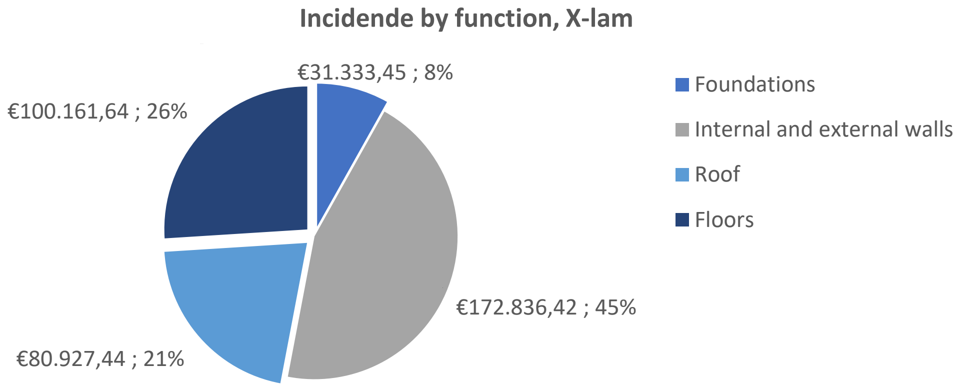


Figure 62: Cost incidence per functional elements, X-Lam

Also, in this case the most significant voices remain unchanged, with the pitched roofing system and the radiant floor as leading elements. The estimated costs for the construction of the grade beams remain unaltered because, as previously announced, the foundation structures are considered alike for the four technologies examined.

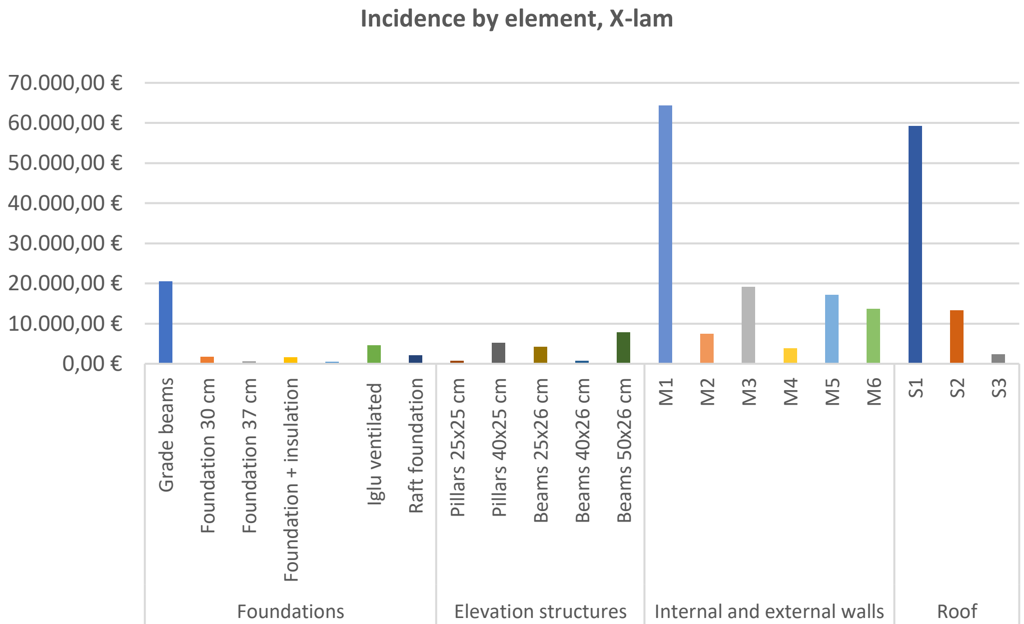


Figure 63: Cost incidence by elements, X-la,

9.3.3 Concrete

Concrete				Quantities				Costs				
		€/U.M	U.M.	App. A	App. B	App. C	App. A+B+C	App. A	App. B	App. C	App. A+B+C	€
Foundations	Grade beams	663,87	mc				30,89				20506,82	**20.506,82 €**
	Foundation 30 cm	251,25	mc				6,6				1658,24	**1.658,24 €**
	Foundation 37 cm	273,25	mc				2,1				573,82	**573,82 €**
	Foundation + insulation	273,25	mc				5,8				1584,84	**1.584,84 €**
		15,858	mq				30,7				486,84	**486,84 €**
	Iglu	24,578	mq	61,4	61,39	63,08		1509,11	1508,86	1550,401		**4.568,37 €**
	Raft found.	105,8	mc				19,44				2056,75	**2.056,75 €**
Internal and external walls	M1	222,71	mq	150,22	146,14	180,43		33454,98	32546,33	40182,94	0,00	**106.184,25 €**
	M2	180,45	mq	10,31	9,17	7,15	45,6	1860,47	1654,75	1290,24	8228,66	**13.034,13 €**
	M3	222,71	mq	38,97	41,52	23,96	41,23	8678,87	9246,78	5336,05	9182,19	**32.443,89 €**
	M4	204,03	mq			18,33		0,00	0,00	3739,85	0,00	**3.739,85 €**
	M5	155,6	mq	60,85	70,37	55,72		9468,25	10949,57	8670,03	0,00	**29.087,85 €**
	M6	190,51	mq			41,65	18,41	0,00	0,00	7934,81	3507,32	**11.442,12 €**
Roof	S1	249,99	mq	73,29	73,29	85,88		18321,99	18321,99	21469,40	0,00	**58.113,37 €**
	S2	213,92	mq	20,52	20,27	20,86		4389,73	4336,25	4462,46		**13.188,44 €**
	S3	208,54	mq				.1,64				2427,44	**2.427,44 €**
Floors	S4	180,15	mq	41,15	43,56	35,48		7413,33	7847,50	6391,86		**21.652,69 €**
	S4r	214,01	mq	48,24	45,22	78,70		10323,98	9677,66	16842,81		**36.844,46 €**
	S5	91,402	mq	28,04	26,83	21,08		2562,91	2452,32	1926,75		**6.941,98 €**
	S6	112,33	mq	6,34	6,28	14,22		712,15	705,41	1597,29		**3.014,86 €**
	S6r	124,85	mq	35,33	35,15	39,03		4410,91	4388,43	4872,85		**13.672,18 €**

Table 48: Concrete direct cost

The distribution of solid concrete is also in line with the previous ones, with a further increase in the percentage of vertical partitions, thanks to its 51%, while the roofing system, floors and foundation incidence remain unchanged. It should be noted that the use of concrete load-bearing walls increases the costs per square metre for its construction, compared to a technology such as poroton in which the concrete load-bearing skeleton is then buffered with much cheaper elements. Not to be underestimated is also its ineffectiveness from the point of view of thermal performance, which has been compensated for by a more marked use of insulating materials.

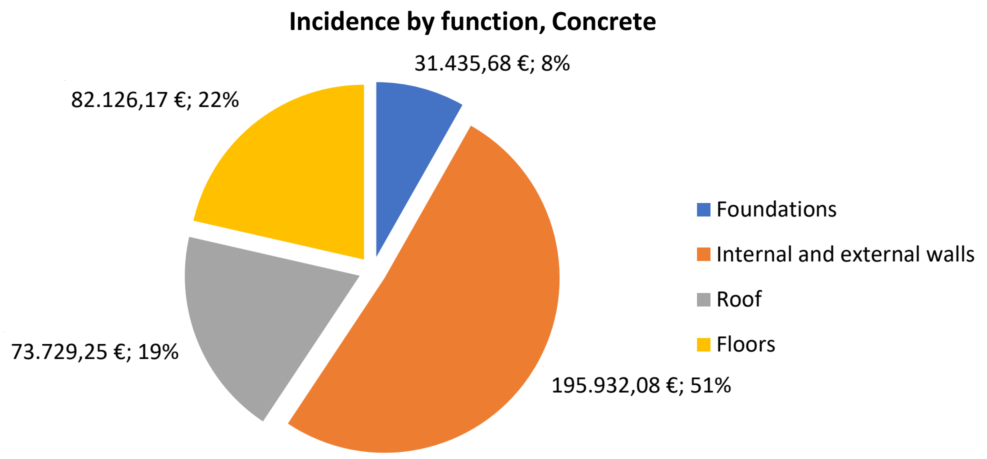


Figure 64 : Cost incidence per functional elements, Concrete

In the distribution of the costs referred to the various building components, the structure of the M1 perimeter-wall remains constantly the most marked item. However, it can be noted that the economic performance of the ground floor slabs has decreased, where S4, S4 radiant and S6 radiant occupy an important place in the analysis of horizontal partitions.

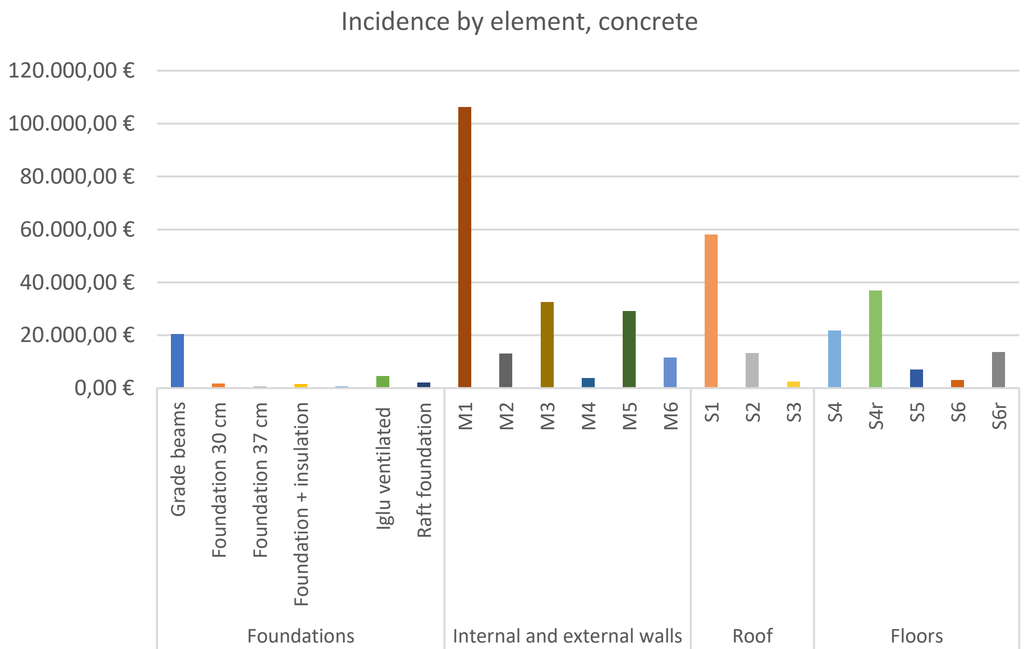


Figure 65: Cost incidence by elements, Concrete

9.3.4 Timber-frame

Timber frame				Quantities				Costs				
		€/U.M	U.M.	App. A	App. B	App. C	App. A+B+C	App. A	App. B	App. C	App. A+B+C	€
Foundations	Grade beams	663,87	mc				30,89				20506,82	**20.506,82 €**
	Foundation 30 cm	251,25	mc				6,60				1658,24	**1.658,24 €**
	Foundation 37 cm	273,25	mc				2,10				573,82	**573,82 €**
	Foundation + insulation	273,25	mc				5,80				1584,84	**1.584,84 €**
		15,86	mq				30,70				486,84	**486,84 €**
	Iglu ventilated	24,58	mq	61,40	61,39	63,08		1509,11	1508,86	1550,40		**4.568,37 €**
	Raft foundation	105,80	mc				19,44				2056,75	**2.056,75 €**
Internal and external	M1	212,18	mq	150,67	140,99	173,85		31969,27	29915,36	36887,62		**98.772,25 €**
	M2	195,95	mq	11,10	7,74	7,65	47,16	2174,99	1516,62	1498,98	9240,79	**14.431,38 €**
	M3/M6	167,84	mq	39,06	40,56	66,25	59,72	6555,87	6807,64	11119,48	10023,47	**34.506,46 €**
	M4	197,44	mq			20,70		0,00	0,00	4086,93		**4.086,93 €**
	M5	141,00	mq	61,67	66,91	57,43		8695,74	9434,60	8097,88		**26.228,23 €**
Roof	S1	218,10	mq	71,35	71,35	85,88		15560,45	15560,45	18730,56		**49.851,46 €**
	S2	191,72	mq	20,82	20,49	21,16		3991,63	3928,37	4056,82		**11.976,82 €**
	S3	202,30	mq				12,04				2435,66	**2.435,66 €**
Floors	S4	194,01	mq	40,09	42,27	35,59		7777,81	8200,75	6904,77		**22.883,33 €**
	S4r	207,96	mq	47,86	43,80	77,11		9953,07	9108,75	16035,97		**35.097,79 €**
	S5	91,40	mq	28,36	26,21	21,02		2592,16	2395,65	1921,27		**6.909,08 €**
	S6	112,33	mq	6,14	6,18	14,07		689,69	694,18	1580,44		**2.964,31 €**
	S6r	124,85	mq	34,55	35,31	38,85		4313,52	4408,41	4850,37		**13.572,30 €**

Table 49: Timber frame direct cost

The prefabricated wooden construction system is the second least expensive technology, behind Poroton alone. Even in the latter case, the costs per square metre for the processing of building components have been collected from the Price List of the Municipality of Milan, which, however, omits the item on the costs of the construction of the supporting structure in wood. This lack has been compensated by the 2018 Trento Price List, which includes many woodworking operations. As has been reported for the previous types, the wooden structure also has its heaviest item in the internal and external vertical closures, which covers 50% of the total of opaque closures and foundations, and in which the roofing system is the least expensive, compared to other cases.

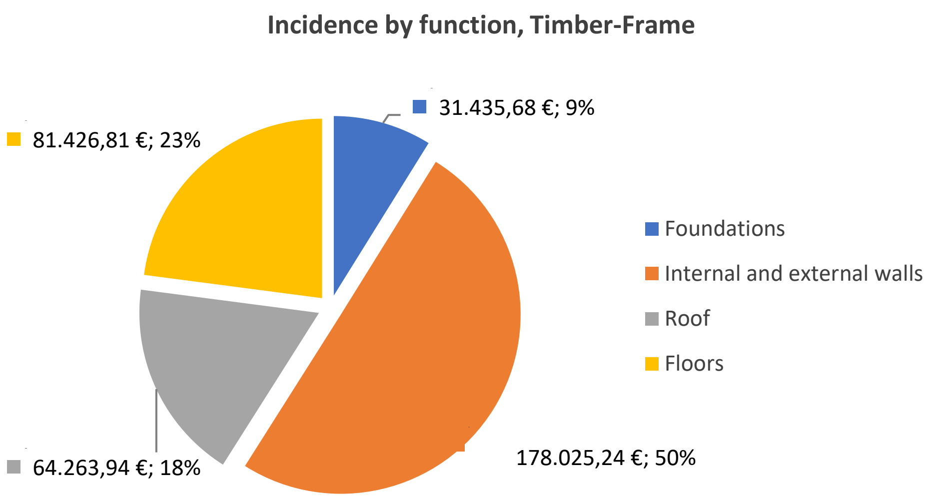


Figure 66 : Cost incidence per functional elements, Timber-Frame

As far as the single incidence is concerned, the vertical perimeter system M1 is also in this case the most expensive item, touching almost 100’000,00 € for its construction; subsequently we find the system of pitched roofing and the intermediate floor paving.

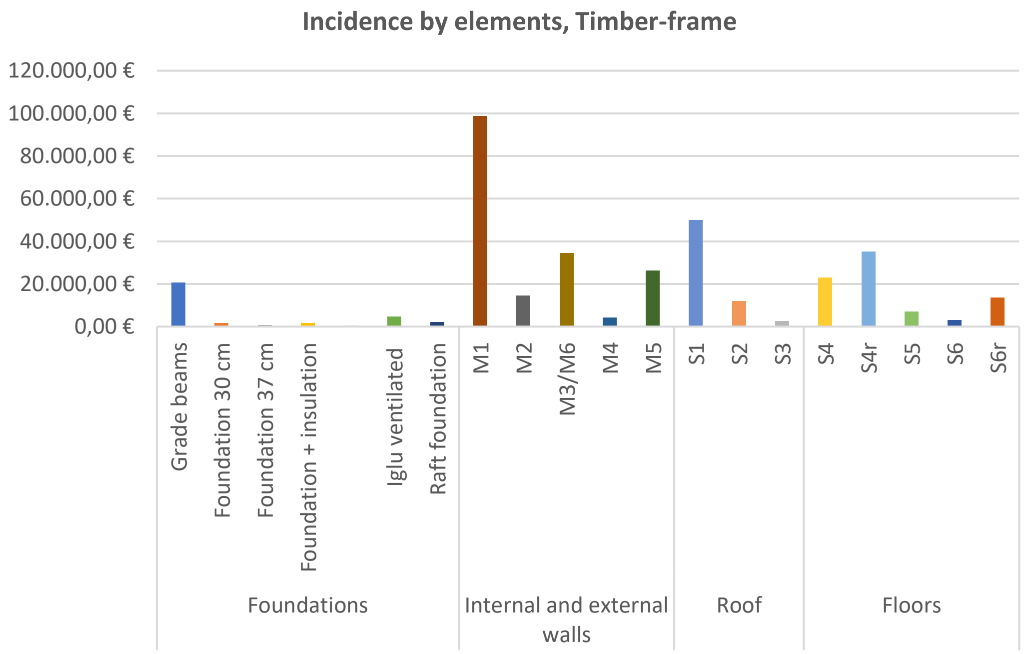


Figure 67: Cost incidence by elements, Timber-Frame

9.3.5 Comparison by technologies

	Windows and door	€/U.M	U.M.	Quantities App. A	App. B	App. C	App. A+B+C	Costs App. A	App. B	App. C	App. A+B+C	€
External windows and doors	Cancello autorimessa	905,14	cad	1,00	1,00	1,00		905,14	905,14	905,14		**2.715,43 €**
	Porta blindata appartamento 90*210	1039,43	cad	1,00	1,00	1,00		1039,43	1039,43	1039,43		**3.118,28 €**
	finestra singola 60*125	451,98	cad	2,00	2,00	2,00		903,95	903,95	903,95		**2.711,86 €**
	Finestra doppia 110*125	466,23	cad	2,00	2,00	2,00		932,45	932,45	932,45		**2.797,36 €**
	Finestra doppia 110*230	545,24	cad	1,00	1,00	1,00		545,24	545,24	545,24		**1.635,71 €**
	Finestra Quadrupla 180*1256	665,23	cad	1,00	1,00	1,00		665,23	665,23	665,23		**1.995,68 €**
	Skylight-Operable	390,78	cad	2,00	2,00	2,00		781,55	781,55	781,55		**2.344,66 €**
internal doors	Serramenti a porta 1 anta	326,79	cad	8,00	8,00	8,00		2614,29	2614,29	2614,29		**7.842,86 €**
	Serramenti a porta 60*210	937,48	cad	1,00	1,00	1,00		937,48	937,48	937,48		**2.812,44 €**

Table 50: Windows and doors direct cost

The transparent closures were considered identical for each type of dwelling, regardless of the technology analysed. The price list of the Municipality of Milan allowed us to identify costs per type of window, in relation to the type of material used for the frame and the useful surface. In a linear way with the previous process, the Revit model allowed us to export the total number of windows and doors for each housing unit, classifying them by different sizes.

	Excavations	€/U.M	U.M.	Quantities App. A	App. B	App. C	App. A+B+C	Costs App. A	App. B	App. C	App. A+B+C	€
Excavations	Sculpture digging	46,68	mc				58,32				2722,21	**2.722,21 €**
	General excavation	46,68	mc				452,00				21098,07	**21.098,07 €**
	Protection of excavation walls (yawning and digging)	17,86	mq				250,00				4464,95	**4.464,95 €**

Table 51: Excavation direct cost

The costs of excavations and earthmoving for the construction of the building were also considered equal for the four solutions adopted, and amount to a total of 28'285,23 € with a metric calculation of the excavation volume considered unique for the 3 housing units of the building.

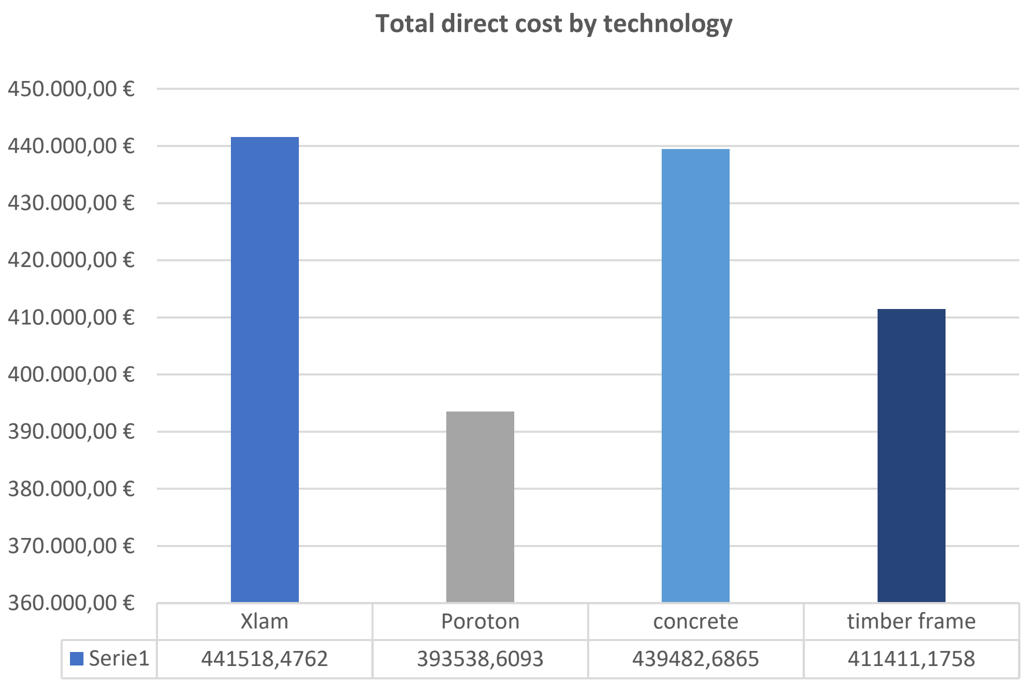


Figure 68: Total direct cost per technology

The analysis of the individual processes for macro building components, developed for each building technology used, has allowed us to identify the total direct costs of construction of the building. It should be noted immediately that the X-lam is the construction technology with the highest direct costs, 5% higher than the average construction cost, followed immediately by the concrete technology. Poroton's technology, on the other hand, is the only one that manages to contain direct costs below €400,000, with an average construction cost that is 7% lower.

We have taken into consideration the most impactful construction technology, the X-Lam, in order to identify and analyse the differential costs of the other 3 construction technologies. It should be noted that for each scenario the cost of construction of horizontal partitions, both for roofing and internal floors, are significantly lower than the technology of cross laminated timbers.

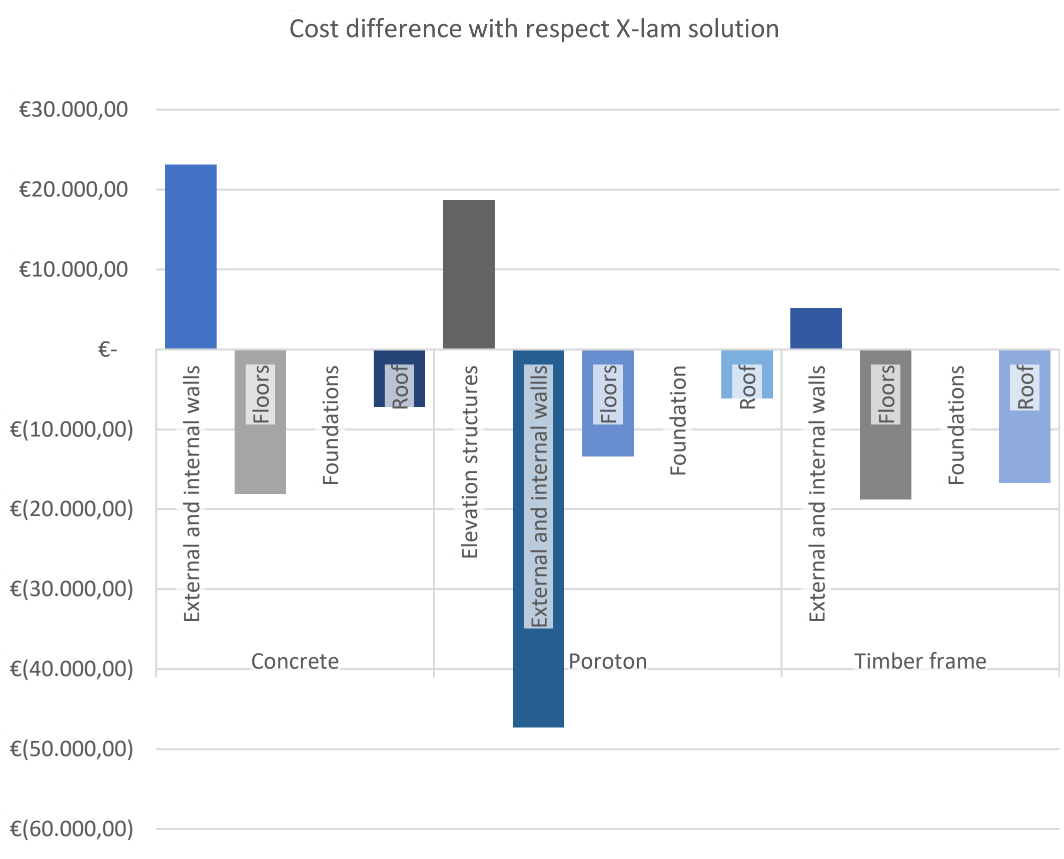


Figure 69: Differential cost, X-lam benchmark

On the other hand, it should be noted that the most fluctuating and least stable cost is the internal and external vertical partitions. As for the concrete, the total cost of this item differs by more than € 20000 more in direct cost, while in Poroton the more than € 45000 savings are mitigated by the costs of building a load-bearing structure, reducing the gain to 17% compared to the cost of walls in X-Lam. Different situation for the wood prefabrication system where the difference in the total direct costs is quantified almost only by the horizontal partition systems, with a slight increase in the construction costs of vertical walls of 3% compared to the reference case.

9.4 Use-phase analysis

9.4.1 Maintenance plan

The aim of this work is the development of a maintenance plan, providing the activities, the execution procedures and resources and the prediction of the costs during the all usage phase. The main steps that have been followed are: the collection of all the useful and necessary information about the building and its use and the information about the technical element that has been analysed, the decomposition of the latter in functional layers and constitutive materials, the definition of service life, requirements and performance parameters, the description of possible failures, agents that can cause some modifications of functional characteristics and finally, the scheduled maintenance plan.

- Maintenance schedule: programme that summarised all the interventions in a chronological way;
- Maintenance Cost: programme that summarised the associated costs that will occur in the analysed time-frame, so for the 60 years of expected service life of the building.

The main reason for a maintenance plan is that it is the most cost-effective way to maintain the value of assets.

The advantages of a plan are:

- The property is organised and maintained in a systematic rather than ad-hoc way;
- Building services can be monitored to assist their efficient use;
- The standard and presentation of the property can be maintained;
- Subjective decision-making and emergency corrective maintenance are minimised.

When building's maintenance is neglected, defects can occur which may result in extensive and avoidable damage to the building fabric or equipment. Neglect of maintenance can also give rise to fire and safety hazards, which could result in building owners being found legally liable for any injuries. In the images below is shown the relation between the preventive maintenance activity over time and the reparation costs.

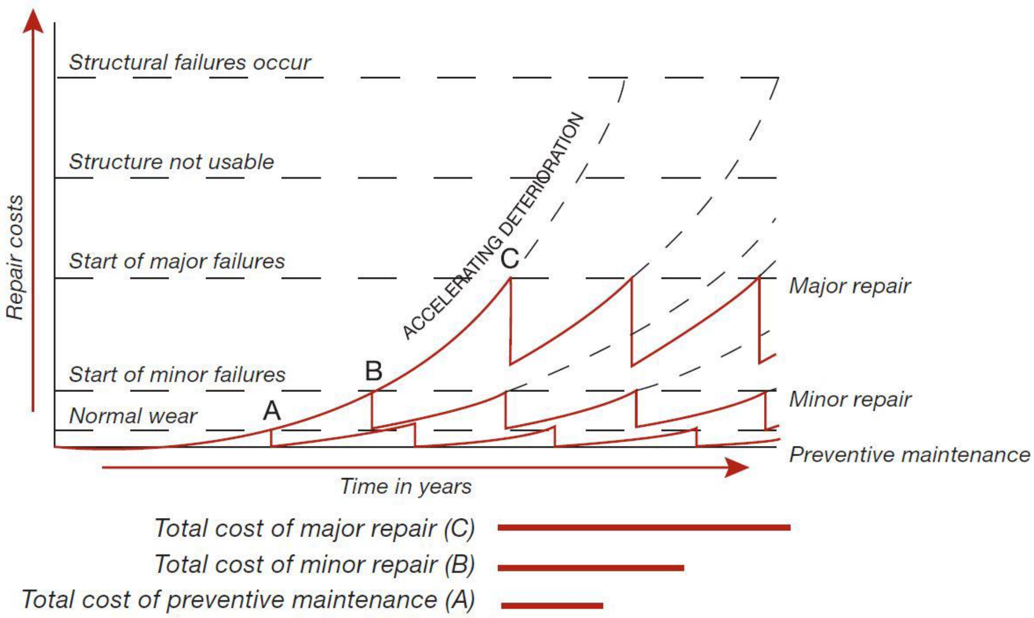


Figure 70: Cost-time relationship in maintenance [Source: Preventive Maintenance of Buildings, Van Nostrand Reinhold, New York, 1991]

We develop a chrono-program of every maintenance works that has to be done, in accordance to the operational plan framework, through the next 60 years. The intervention framework is divided in semester, distinguishing between preventive and opportunity maintenance and the aim is to provide a total cost budget per year. The schedule is divided for each type of intervention with a correspondence in the layer affected. The maintenance programme lay on the preventive maintenance activities, as inspection and partial and total and partial refurbishment/substitution of external layers of our technical components, in order to maintain the minimum requirements of the enclosure over its whole life, assessed in 60 years.

Three main categories of intervention have been identified with reference to the frequency of interventions with respect to the probability of failures:

- Preventive activities;
- Under condition based
- Opportunity

These categories thus make up maintenance activities for the building's macro-components: the vertical outer shell, the floors, the roofing system, the internal vertical partitions and maintenance activities on the windows and doors.

9.4.1.1 Preventive activities

Year				5		6		7		8		9		10		11		12		13		14		15	
Semester				1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
STRATEGY	INTERVENTION		COST (€)																						
PREVENTIVE MAINTENANCE	Layer Name Cost €/m^2 Extention	Mortar Plaster Inspection **0,15** 100%	150,00	■		■		■		■		■		■		■		■		■		■		■	
	Layer Name Cost €/m^2 Extention	Plasterboard Inspection **0,15** 100%	150,00	■		■		■		■		■		■		■		■		■		■		■	
	Layer Name Cost €/m^2 Extention	X-Lam struct. Ultrasonic test **0,55** 100%	550,00																					■	

Table 52: Preventive maintenance plan

The example of the Preventive maintenance programme can be easily read as all the operations that help the envelope enclosure to maintain its inner features with systematic operations by providing inspection, test and all the corrective activities on layers that do not developed yet failures and defects. In this specific example all the visual inspection that could be done in the external layers are scheduled for each year, while it has been proposed a ultrasonic test for structural evaluation of the timber X-lam, and, as it is a no-destructive test, it could be implemented in the maintenance programme a similar analysis every time a particular failure can be spread to the structural part.

The maintenance schedule offers a overlook to the different sequence of activities on a fixed sequence base, but at the same time a wide freedom to delete some overrated activities: in our case study, a total substitution of the external plaster layer every 15 years, allows us to turn down the refurbishment of the same layer that comes in the same year (because it has a pace of 5 year). This system is applied also to other components, i.e. for the Gypsum plasterboard, as confirmed by EPDs it can guarantee 30 years of service life before that mostly aesthetic features become to decay, and it implies that in the thirtieth year of service it does not require also reparation of possible damages like cracks, abrasion or detachment of the joints in the follow two years of use.

9.4.1.2 Under-condition activities

Year				20		21		22		23		24		25		26		27		28		29		30	
Semester																									
Strategy	Activities		Cost (€)	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Under condition	Layer Name Cost €/m Extention	Plasterboard Anti-mold **2,88** 15%	80,48	■								■								■					
	Layer Name Cost €/m Extention	Plasterboard Refurbishment **10,37** 10%	192,95	■								■								■					
	Layer Name Cost €/m Extention	Wood fiber Total sub. **10,26** 100%	1.907,86																					■	
	Layer Name Cost €/m Extention	Plasterboard Partial sub. **42,35** 8%	630,24									■													

Table 53: Under condition maintenance plan

The under-condition phase regards all the maintenance activities that should be scheduled after monitoring the actual condition of the component, with the help of predefined performance indicators that can help to evaluate possible failures. In this case, we have chosen the timber frame structure technologies and the under conditions activities determined for the internal wall solution. Here the anti-mold and anti-vegetative solutions have been adopted in order to decrease the growth of moisture and proliferation of vegetative factors in the external layer and in the internal structure of the plasterboards for high humidity spaces, with a frequency of 4 years each. Those activities and their relative range need to be updated with respect the real pace of failures appearance, so that the maintenance plan can be effectively correct and adoptable, thanks to the cyclical activities of inspection.

Furthermore, for what it concerns the partial substitution activity it is possible to analyse the activity extension with respect the total surface covered by the layer: the internal gypsum plasterboards of the timber frame could be affected by several agent, configuring an high rate of failure, so that activity such as partial refurbishment of joints and anchoring system or simple substitution have been identified. Unpleasant visual effect or fractures or cracks in the internal surface have been considered as the main probable failures.

9.4.1.3 Opportunity activities

Year				28		29		30		31		32		33	
Semester				1	2	1	2	1	2	1	2	1	2	1	2
Strategy	Activities		Cost (€)												
OPPORTUNITY	Layer	Concrete structure	359,58					■							
	Name	Endoscopic investigations													
	Cost €/m²	-													
	Extention	100%													

Table 54: Opportunity maintenance plan

The opportunity strategy represents all maintenance activities that can be carried out promptly by skilled workers, at a time when you are already carrying out maintenance on other elements that allow you to carry out restoration activities or the like without having to affect the building in the near future. In this case, the endoscopic tests that can be carried out in the load-bearing structure in concrete, both in the load-bearing skeleton of the Poroton and in the full concrete technology, have been taken as an example. These non-destructive study activities are carried out in order to locate and identify possible anomalies and structural damage to the building that could not be detected simply by observing the element from the outside. These tests can therefore be performed when the layers above are replaced during preventive activities such as the total replacement of the outer coat of the perimeter walls or the remake of the internal plaster.

9.4.2 Maintenance Schedule

The three different categories of intervention identified were used to create a complete and coherent maintenance schedule for the different technologies analysed, divided into macro-building components.

9.4.2.1 External vertical envelope

External envelope **M1, M2, M3, M4, M6** **Surface [m²]: 762,85**

Year				24		25		26		27		28		29		30		31	
Semester				1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Strategy	Activities		Cost (€)																
Preventive	Layer Name Cost €/m² Extention	Ext. Plaster Inspection **0,15** 100%	114,43	■		■		■		■		■		■		■		■	
	Layer Name Cost €/m² Extention	Plasterboard Inspection **0,15** 100%	114,43	■		■		■		■		■		■		■		■	
	Layer Name Cost €/m² Extention	X-Lam structure ultrasonic test **0,55** 100%	419,57													■			
	Layer Name Cost €/m² Extention	Ext. Plaster Part. Refurb. **29,04** 15%	3.323,45																
	Layer Name Cost €/m² Extention	Plaster & Ins. Total sub. **45,63** 100%	21.280,53													■			
	Layer Name Cost €/m² Extention	Ext. plaster Total sub. **13,28** 100%	2.096,76																
	Layer Name Cost €/m²	Paint total sub. 11,75 €	5.481,95													■			

External envelope **M1, M2, M3, M4, M6** **Surface [m²]: 762,85**

Year				24		25		26		27		28		29		30		31	
Semester				1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Strategy	Activities		Cost (€)																
	Extention	100%														■			
	Layer Name Cost €/m² Extention	Hemp ins. Total sub. **11,31** 100%	7.845,08													■			
	Layer Name Cost €/m² Extention	Plasterboard Total sub. **21,18** 100%	19.087,91													■			
Under condition	Layer Name Cost €/m² Extention	Ext. plaster Anti-vegetative **6,18** 5%	235,60			■								■					
Under condition	Layer Name Cost €/ m² Extention	Plasterboard Anti-mold treat. **2,88** 5%	110,02	■								■							
Under condition	Layer Name Cost €/ m² Extention	Plasterboard Refurbishment **10,37** 5%	395,65	■								■							
Under condition	Layer Name Cost €/ m² Extention	Plasterboard Partial sub. **21,18** 10%	1.615,44	■															
Opportunity	Layer Name Cost €/ m² Extention	X-Lam struct. Resistography t. **0,43** 100,00%	328,03													■			

Table 55: X-lam external envelope Maintenance schedule

For what concern an overall analysis on the different maintenance schedule adopted, we have reported the External partitions one, with respect to the X-lam technology. The reported time-frame, to the twenty-fourth to the thirty-first year of service life, so that it could be possible visualize as much activities as possible. In the preventive all the visual inspections and the total substitution have been considered, ranging from one to thirty year respectively. In the under-condition the most frequent activities of refurbishment and partial substitution can be found.

9.4.2.2 *Internal floors*

Horizontal partitions **S2, S3, S4, S4r** **Surface [m²]: 369.6**

Year				24		25		26		27		28		29		30		31	
Semester				1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Strategy	Activities		Cost (€)																
Preventive	Layer Name Cost €/m² Extention	Paint & mortar Inspection **0,15** 100%	55,44	■		■		■		■		■		■		■		■	
	Layer Name Cost €/m² Extention	Ext. floor tiles Cleaning and wax **1,51** 100%	558,03			■													
	Layer Name Cost €/m² Extention	Paint & mortar Clean & anti-mold **3,46** 15%	191,90													■			
	Layer Name Cost €/m² Extention	Water-based pain Total sub. **8,81** 100%	3.257,10													■			
	Layer Name Cost €/m² Extention	Ceiling mortar Total sub. **21,82** 100%	8.063,07													■			
	Layer Name Cost €/m² Extention	Ext. floor tiles Total sub. **22,57** 100%	1.635,61													■			
	Layer Name Cost €/m² Extention	Int. floor tiles Total sub. **28,20** 100%	8.379,81													■			
Under condition	Layer Name Cost €/m² Extention	Paint & mortar Partial sub. **30,63** 10%	1.132,02																
	Layer Name Cost €/m² Extention	Floor internal tiles Partial sub. **28,20** 5%	521,18																
	Layer Name Cost €/m² Extention	Int. & ext. tiles Part. Joint refurb. **15,24** 5%	281,68			■										■			

Table 56: Poroton horizontal partition maintenance schedule

In this example we could analyse the maintenance schedule for the horizontal partitions of the Poroton technologies and a particular timeframe has been chosen as it is possible to read the peculiar frequency of each activities. In the preventive, as already explained, we have assessed the total substitution of the main component of the flooring system and the visual inspection.

In order to avoid aesthetic damage in the flooring finishing as external and internal ceramic and gres tiles appropriate wax and anti-mold treatment have been added to the maintenance schedules, and those have been repeated for the different technologies that shares the same finishing features. The under condition expressed mainly the ordinary maintenance on the tiles and the refurbishment of their joints, in order to avoid moisture penetration and visible aesthetic damages. This framework has been applied also for the different technologies, with the necessary differences in terms of cost and frequency based on the analysis of the chosen materials.

9.4.2.3 Internal walls

Internal walls **M** **Surface [m²]:** **186,01**

Year				24		25		26		27		28		29		30		31	
Semester																			
Strategy	Activities		Cost (€)	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Preventive	Layer Name Cost €/m² Extention	Plasterboard Inspection **0,15** 100%	27,90	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
	Layer Name Cost €/m² Extention	Plasterboard Total sub. **42,35** 100%	7.878,01	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Under condition	Layer Name Cost €/m² Extention	Plasterboard Anti-mold treat. **2,88** 15%	80,48	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	Layer Name Cost €/m² Extention	Plasterboard Refurbishment **10,37** 10%	192,95	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0

	Layer Name Cost €/ m² Extention	Wood fiber Total sub. **10,26** 100%	1.907,86	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	Layer Name Cost €/ m² Extention	Gypsum Partial sub. **42,35** 8%	630,24	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 57: Timber frame internal wall maintenance schedule

The timber-frame structure of our study-case illustrates here the internal partition's wall maintenance schedule: the main activities identified were the substitution of the finishing layers of plasterboards it's related acoustic and thermal insulation over a thirty-year timeframe, as reported in the EPDs used to evaluate the reference service life of the material and construction products. Those type of ordinary maintenance have been used also in the other scenario in order to have a reasonable comparison over the different maintenance schedule.

9.4.2.4 Roof system

Roof S1 **Surface [m²]: 232,46**

Year				24		25		26		27		28		29		30		31	
Semester				1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Strategy	Activities		Cost(€)																
Preventive	Layer Name Cost €/m² Extention	Tile + Waterproof Inspection **3,00** 100%	697,38	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
	Layer Name Cost €/m² Extention	EPS insulation Total sub. **19,29** 100%	4.483,19	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	Layer Name Cost €/m² Extention	Waterproof membr. Total sub. **13,76** 100%	3.199,19	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	Layer Name Cost €/m² Extention	Ventilation struct. Total sub. **36,34** 100%	8.446,74	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	Layer Name Cost €/m² Extention	Paint Anti-mold treat. **5,88** 15%	205,12	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	Layer Name Cost €/m² Extention	Ceiling Mortar Total sub. **21,82** 100%	5.071,27	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

Roof **S1** **Surface [m²]:** **232,46**

Year				24		25		26		27		28		29		30		31	
Semester				1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Strategy	Activities		Cost(€)																
	Layer Name Cost €/m² Extention	Paint Total sub. **8,81** 100%	2.048,55	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	Layer Name Cost €/m² Extention	Vapour membr. Total sub. **3,38** 100%	785,69	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Under condition	Layer Name Cost €/m² Extention	Tiles Partial realignment **8,32** 10%	193,31	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Under condition	Layer Name Cost €/m² Extention	Tile Partial sub. **29,34** 15%	1.022,98	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
Under condition	Layer Name Cost €/m² Extention	Mortar Partial refurb. **21,82** 5%	253,56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Under condition	Layer Name Cost €/m² Extention	Wood fibre Partial refurb. **8,65** 5%	100,54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Opportunity	Layer Name Cost €/m² Extention	Cls structure Endoscopic test - 100%	359,58	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

Table 58: Roof system maintenance schedule

The pitched roofing system share quite all the elements within the different technologies, excluding the load-bearing structure and the internal finishing, in which we can identify a water-based paint on mortar or the ceiling, for concrete/Poroton and X-lam/Timber frame structures respectively.

The preventive category assumes the higher economic impact, even in terms of working hours labours, as we assume a total refurbishment of the external layers in order to avoid moisture and water penetration and the decay of thermal efficiency of the envelope. The under condition-based activities range from the realignment of the upper roof tiles every ten years and the refurbishment of the internal plaster.

The only opportunity activity identified was the endoscopic investigation to every thirty years accordingly to the total substitution of multiple layers, during this time-frame.

9.4.2.5 *Windows and doors*

Windows and doors **Number of doors and windows** **57**

Year				24		25		26		27		28		29		30		31	
Semester				1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Strategy	Activities		COST (€)																
Preventive	Layer	Wind./ door frames	57,00																
	Name	Visual inspection																	
	Cost €/m²	**1,00**																	
	Extention	100%		1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
	Layer	Window frames	176,91																
	Name	Joints lubrification																	
	Cost €/m²	**3,10**																	
	Extention	100%		0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Layer	Window joints	284,66																
	Name	Total substitution																	
	Cost €/m²	**5,26**																	
	Extention	95%		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Layer	Windows	27974,28																
	Name	Total sub.																	
	Cost €/m²																		
	Extention	100%		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Under condition	Layer	Window joints	14,98																
	Name	Partial sub.																	
	Cost €/m²	**5,26**																	
	Extention	5%		0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Layer	Door handle	311,56																
	Name	Partial sub.																	
	Cost €/ m²	**54,66**																	
	Extention	10%		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

Table 59: Windows and doors maintenance schedule

The ordinary and extraordinary maintenance’s activities for the windows and doors has been considered identical for all the four technologies, as has not been provided different scenarios for those specific components with respect different load-bearing features. It is possible to distinguish three different focuses: on the joints, on the frames and finally on the handle. With respect the expected service life of the doors and windows a total substitution has been provided after 30 years of use, while for the more fragile component, as joints and handle, we assessed precise measure of control and refurbishment: from the lubrification to the partial substitution under condition, for probable failures due to wear out or use after the guarantee period.

9.5 Demolition cost

The demolition costs, being part of the scenario also established in the LCA, have been studied and analysed. The first approach followed was characterized by the desire to separate the various building components according to normal demolition techniques, so as to be able to divide into similar categories of materials that will meet a similar disposal scenario. Unfortunately, this breakdown has not been completed because the price list of the City of Milan provides demolition costs for individual materials, but within them contain items that are continuously reordered for each material, thus creating a principle of double-counting. These items, such as rents of equipment and machinery for demolition and transport from the site to the waste management plant, cannot be separated from the final item as there is no data on the influence of these values on the total. These items, if taken individually and added together, will give a misleading result and certainly greater than the expected reality, since it excludes the concept of marginal cost that if the activities were calculated as a single action of demolition would certainly give a reliable result.

For these reasons it has been possible to consider demolition costs through a cost of euro per cubic meter compared to the useful volume of the building; this cost guarantees the total demolition of any residential type, with the appropriate mechanical means and including the load and transport to authorized landfills. If the supporting structure is made of reinforced concrete, as in the case of Poroton and Concrete, the cost will be 14.91€/ m^3, while for wooden structures it is cheaper, for a total of 10.67€/ m^3.

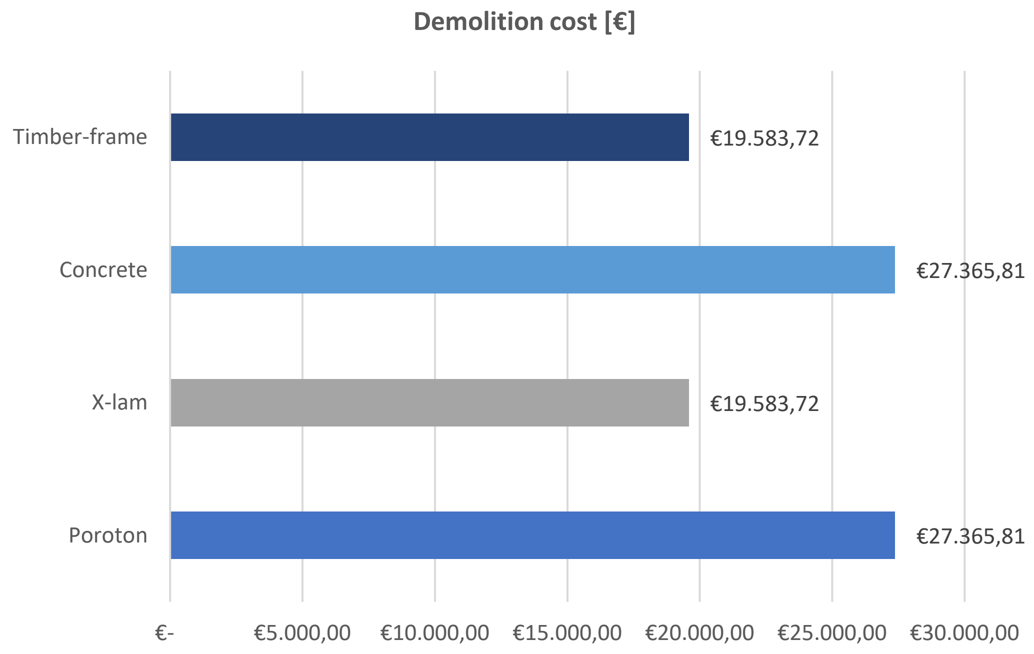


Figure 71: Demolition cost per Technology

9.6 Total LCC analysis

Being the economic perspective of crucial importance when it comes to determining the best course of action in a real estate operation, part of the decision-making process is based on an assessment of the cost related to the entire life cycle of the building and its planned modifications. The first step to accomplish this is to plan during a defined period what will be the necessary actions to take in order to maintain the proposed solution. Starting therefore from the maintenance plan each action had a value assigned and based on the frequency of recurring actions a yearly cost over the horizon for the cost estimation, which was defined as 60 years, has been calculated.

In order to compare to current cost to future ones a discounting is necessary. After the decision to use a 5% WACC (Weighted Average Cost of Capital) and a supposed yearly increase of 2% for activity costs based on the target inflation set by BCE for the next years the yearly discounted cost was calculated according to the formula

$$C_{adjusted} = C_y * (1 + 0{,}02)^y$$

used to increase the future costs due to inflation, and subsequently the following one to discount and make comparable to current costs where *y* is the year from today and C is the cost

$$C_{current} = C_{current} / (1 + 0{,}05)^y$$

After the discounting the obtained cost is a comprehensive idea of the maintenance portion of the entire life cycle cost, to which is to be added the construction cost and the disposal cost. The LCC method is useful not only to understand in advance what the long-term costs of an operation are going to be but also to help the decision-making process when more than one options are available. In the graphs below is represented the cumulative costs trend: this representation has been applied for the 4 different technologies scenarios in order to compare them.

9.6.1 Poroton

The first economic analysis will be develop over the Poroton scenario, in which it is possible to notice an important peak at the 30th year, that is because in that year occur the total replacements of different materials, such as: plaster, mortar and glass fibre reinforcing mesh; the vapour proof membrane, the gypsum boards and the rockwool panels, doors and windows. These activities involve a large expense in the same time, but it is the best and cheapest solution, to give an example, the rental of scaffolding (that is very expensive) is necessary only once, and it has been promoted also in order to reduce the discomfort over the house-owners for the shortest amount of time.

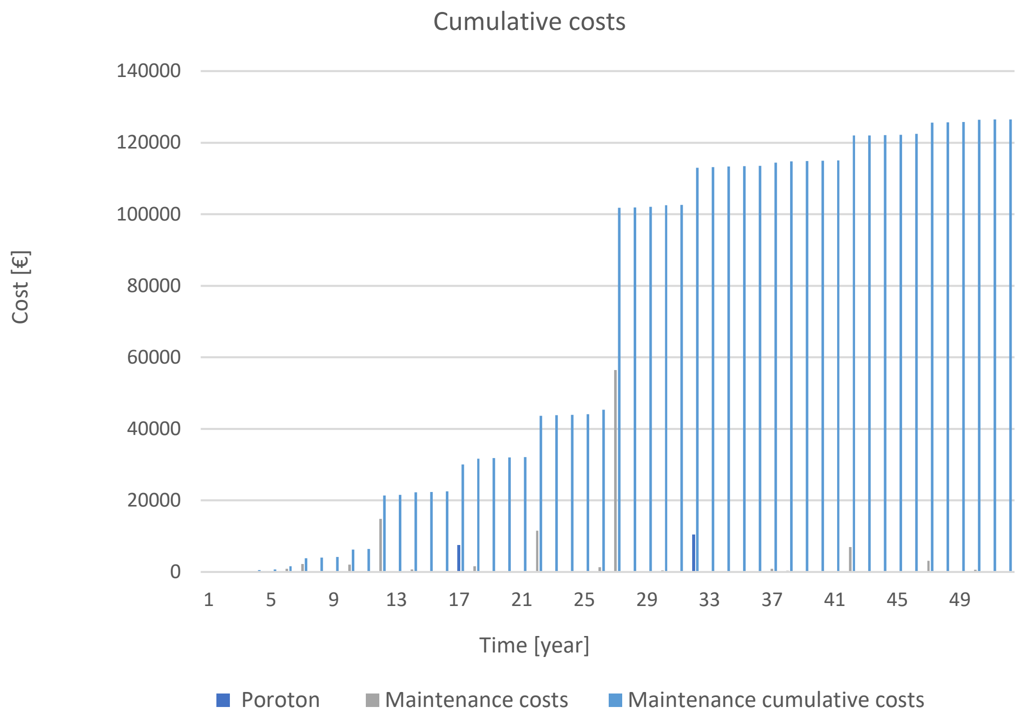


Figure 72: Cumulative cost, Poroton

In the graph it has been included all the maintenance activities regarding the preventive, under-condition and opportunity activities and the demolition activities for the final disposal scenario, which can be seen as the last great expenditure in the sixtieth year. The cumulative cost curve can help us in understanding how the total refurbishment in the thirtieth year had the greater influence on the use-phase cost and from the financial point of view those activities could be allocated in the closest years in order to reduce the great economic outflow.

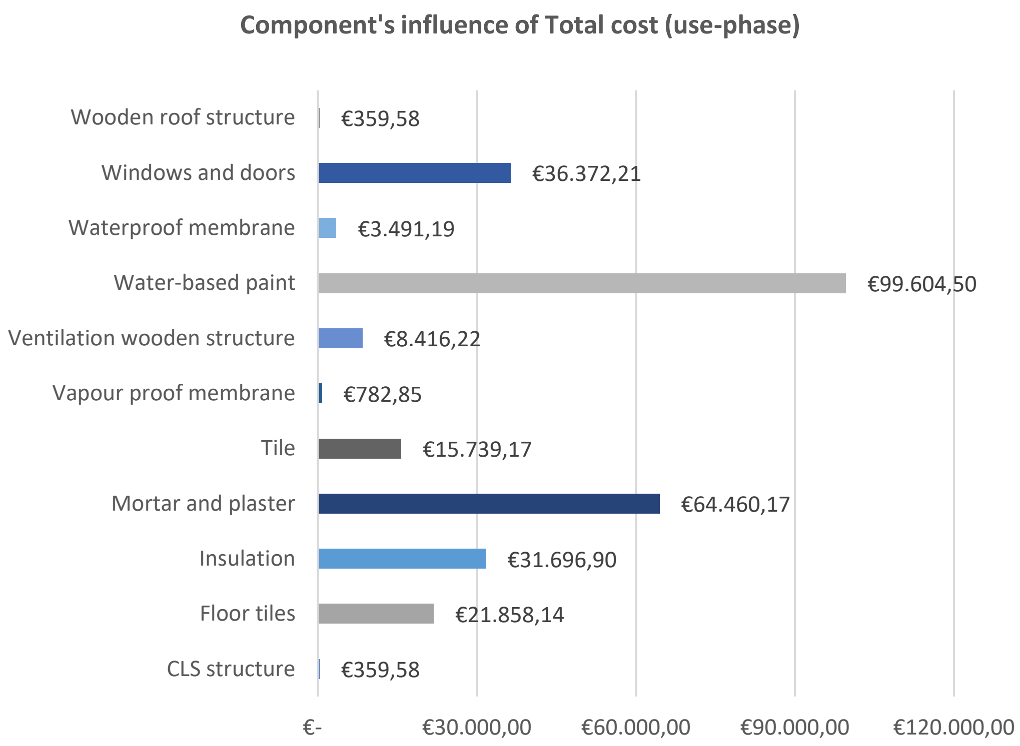


Figure 73: Component influence, Poroton

In the previous graph it is possible to see the incidence of single component on the overall cost of maintenance on the building, the data have been reported without actualization with respect inflation rate and Weighted Average Cost of Capital, as it still creates a good view on the proportions. The water-based paint it's by far the heaviest cost (39% of incidence on the total cost), and it can be expected as it has been used in all the vertical partition for the internal and external finishing layer and for the internal finishing of the flooring system. The plaster and mortar with the insulation panels accounts for the 19% and 11% respectively, due to the activities of total substitution at the end of their probable service life. Furthermore, the roof and floor tiles combined represent the 14% of the total use-phase costs. As expected, the waterproof and vapour-proof membrane have a very small influence on this particular analysis.

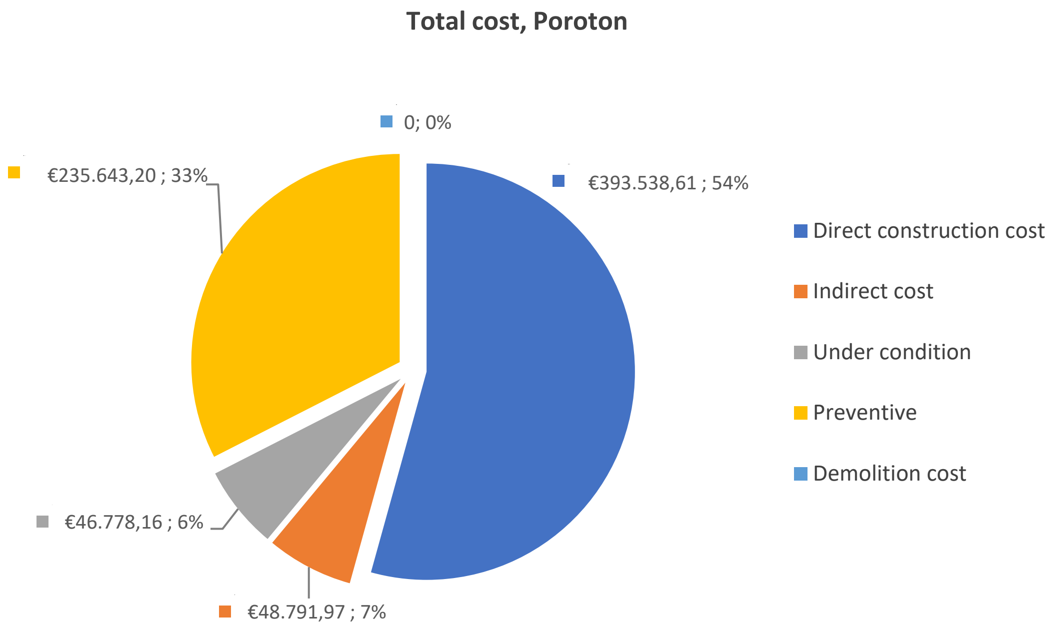


Figure 74: Total cost, Poroton

This pie-chart illustrates us a total overview of the economic outcomes during a 60-year period of investigation: exactly 52% of them represent the initial investment for the construction (reported as direct cost), while the preventive maintenance activities accounts for a total 35%. The opportunity costs have been omitted as their influence was under a 1% threshold. The under-condition maintenance activities account for a 6% on the total, as their use has been limited by a wide range of operation on the preventive schedule. Furthermore, the indirect cost lies on a 6% value, as the greater longevity of the construction activities, with respect the wooden prefabrication ones, is expected to drop down in the following analysis.

9.6.2 X-Lam

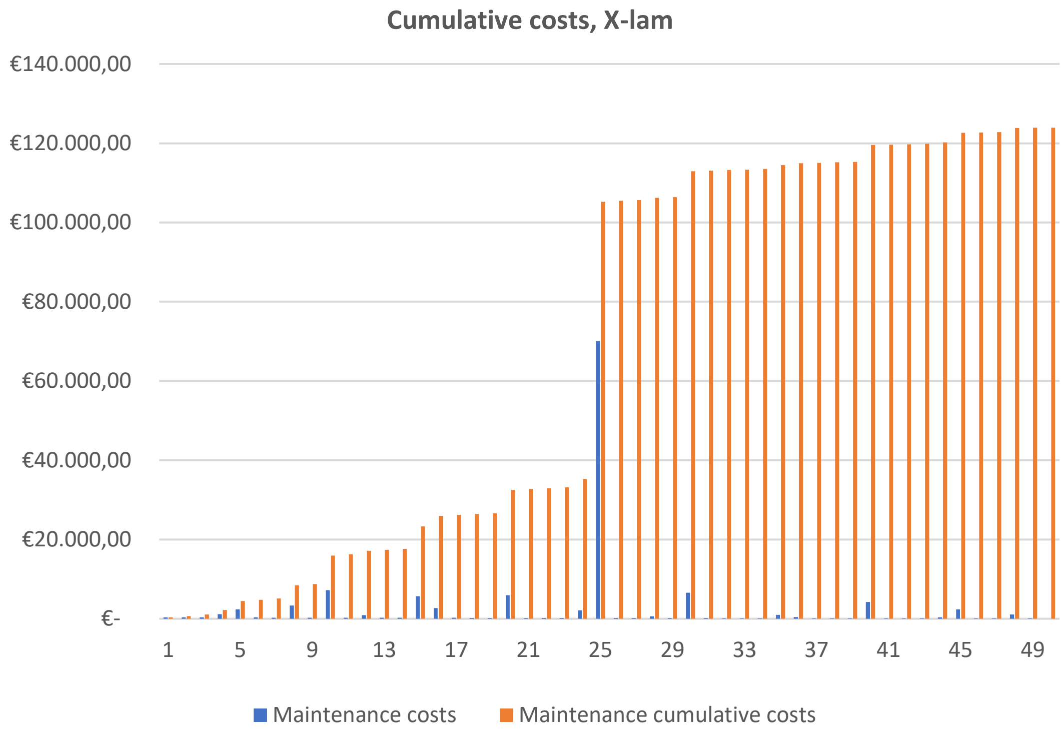


Figure 75: Cumulative cost, X-lam

The yearly and cumulative cost of the Cross Laminated Timber solution use-phase accounts for a total of €74.389,31, slightly lower with respect the Poroton solution. Furthermore, the pattern of their allocation during years defines the solution's differences: in the first thirty years the yearly running cost for the ordinary and extraordinary maintenance activities drop down and, at the end of this time-frame, those cumulative costs accounts less than the total refurbishment for the substitution of multiples component of the envelope. A great difference with respect the Poroton maintenance costs.

The overall maintenance schedule has been impacted mostly by gypsum plasterboard's maintenance activities, as it was chosen as the finishing layer on internal vertical, while the internal plasterboards ceiling accounts for a total of 10%.

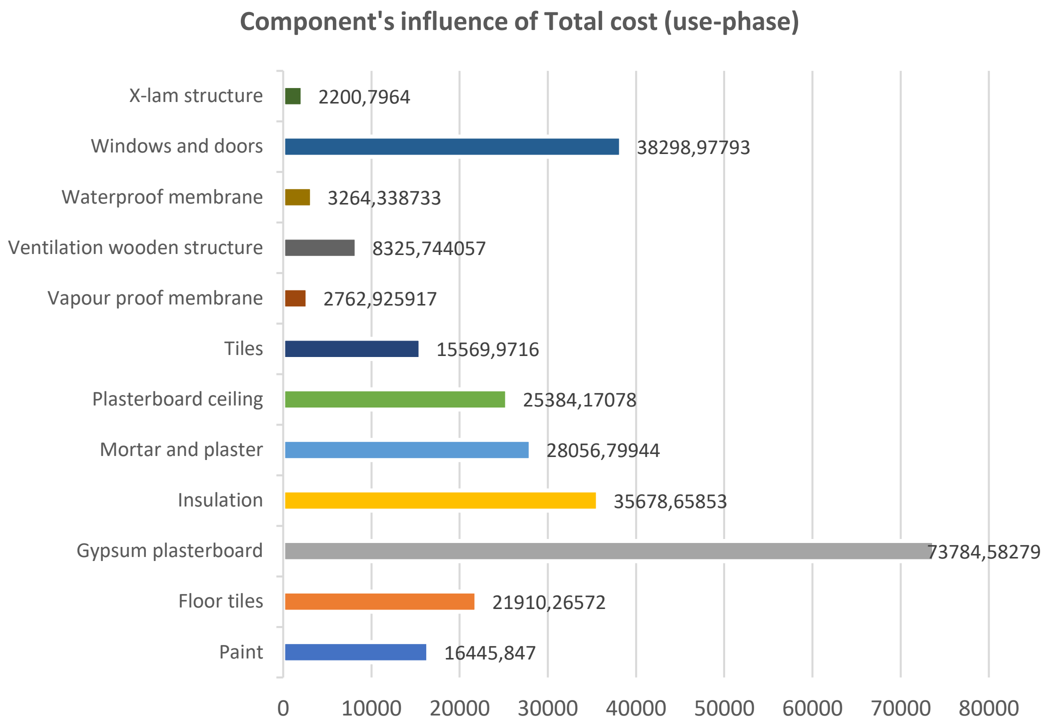


Figure 76: Component influence, X-Lam

Furthermore, the insulation substitution, required every thirty years in order to avoid thermal performance decay, accounts for a 13% and it is possible to determine also the relation with the upper layer of mortar and plaster component that need the same treatment. The windows and doors, as have been considered equal for all the solution, accounts here for a 14% of the overall cost. The activities that are linked with the water-based paint accounts for just 16445,88€, thus marking a great drop with respect the Poroton solution: this is just the effect of using a plasterboard system with respect paint as finishing layer. While, if we consider the total impact of non-destructive test, the X-lam solution shows a greater influence with respect the structural test to be developed for concrete structure.

The pie-chart illustrates the total cost dissected as the single influence of the most important cost-categories: in an overall analysis it is visible the wide impact of the construction cost, 58%, with respect the maintenance activities that account for a

35% combined (under-condition and preventive maintenance ranging from 18% to 17% respectively).

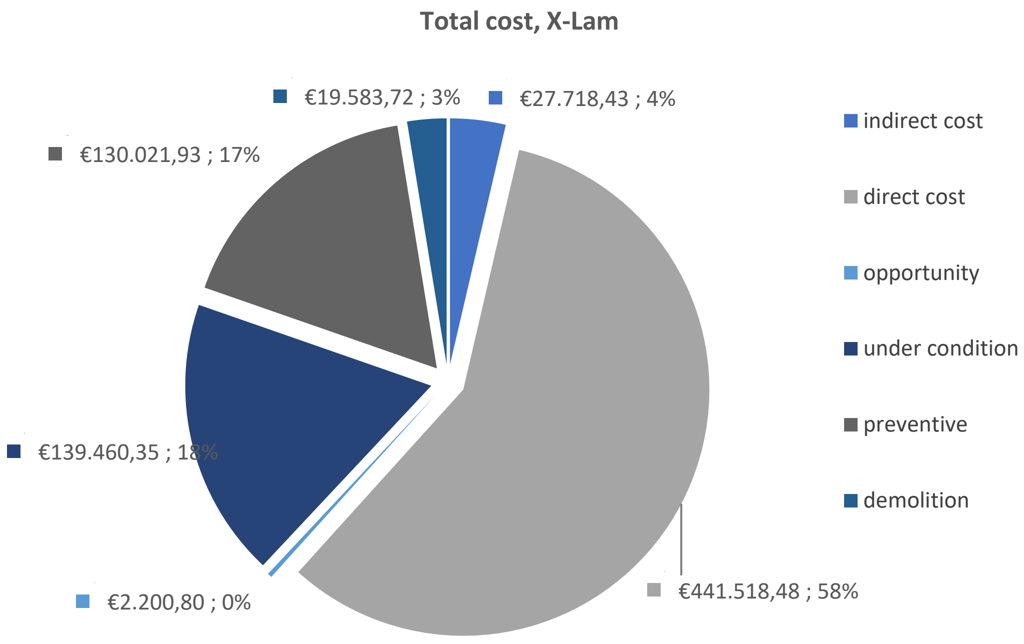


Figure 77: Total cost, X-Lam

The concrete structure, as already mentioned, reflects the greater use-phase costs with respect the other solutions, while it is cumulative cost pattern reflects similarities with the Poroton solution. The graph shows as the preventive maintenance takes a huge impact over the decades, but the cumulative costs will not overlook the total refurbishment planned in the middle of the service life of the building. In the thirtieth year the huge economic effort amount for a total of at least 140’000,00 € due to the replacement of components, in particular the adopted insulation panels at the end of their expected service life. The pattern of under condition and preventive activities continues over the years, until reaching the point of demolition and related waste management.

9.6.3 Concrete

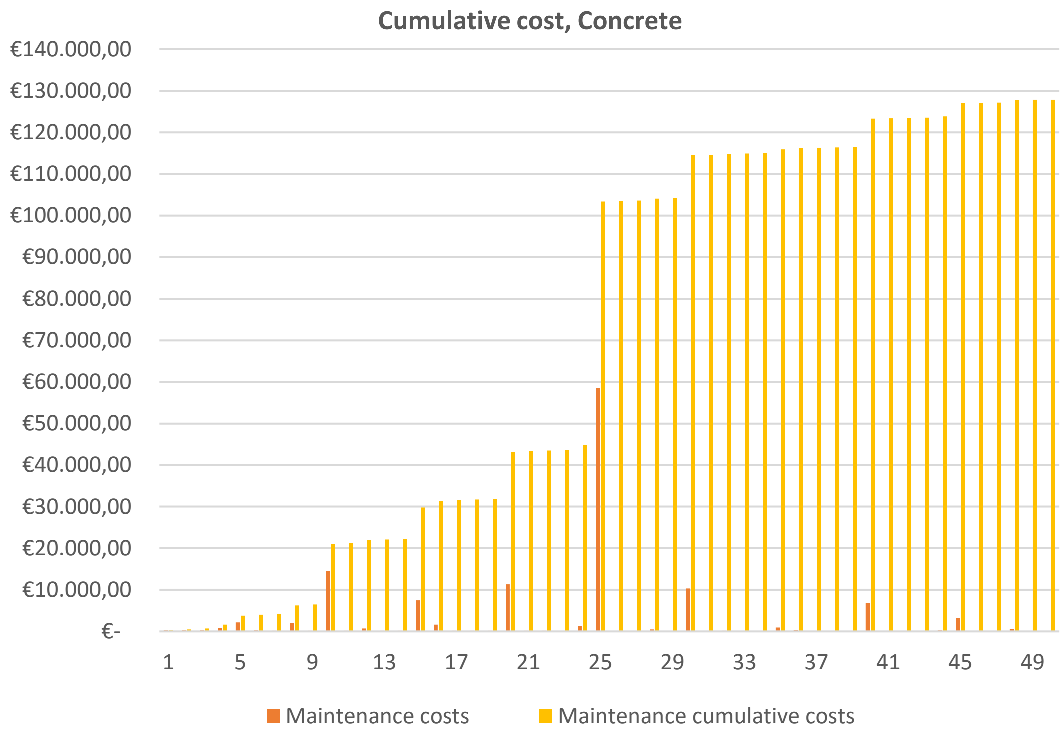


Figure 78: Cumulative cost, Concrete

With respect the previous examples, the concrete technology had a less effective distribution of the material's influence over the total cost in the use-phase. The water-based paint accounts for the 34%, with a total expenditure of more than 90'000 € over the sixty-year timeframe, while the linked mortar and plaster layers accounts for the 24% percent. The remaining cost have been distributed with and adequate proportion: insulation panels, windows and doors and floor tiles contribute the most, with a 11%, 13% and 8% respectively. The bituminous membrane with vapour/water roofing effects and non-destructive test are the less impacting.

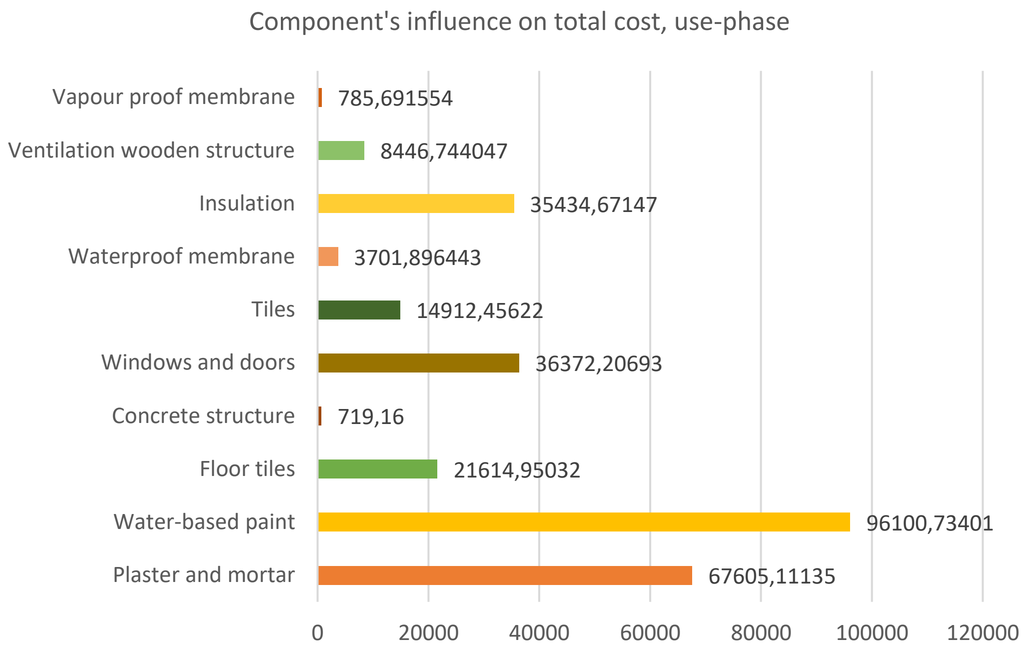


Figure 79: Component influence, Concrete

The distribution of the total cost, illustrated in the next pie-chart, allows us to notice its breakdown, with a very similar features already explained in the previous case-studies.

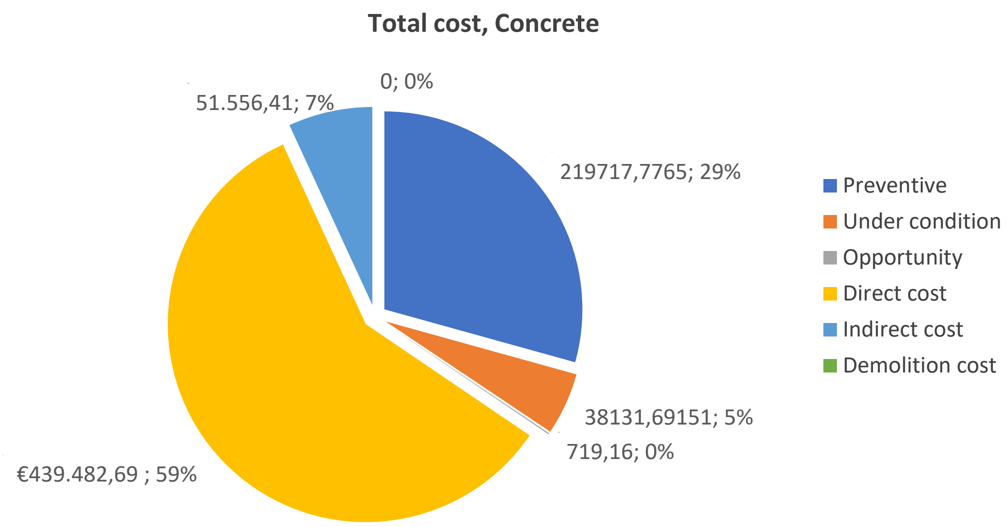


Figure 80: Total cost, Concrete

9.6.4 Timber Frame

Figure 81: Cumulative cost, Timber frame

Here illustrated the cumulative cost for what concern the timber-frame technology, in which it possible to analyse the deep economic outflow foreseen in the thirtieth year, with all the similar features already explained.

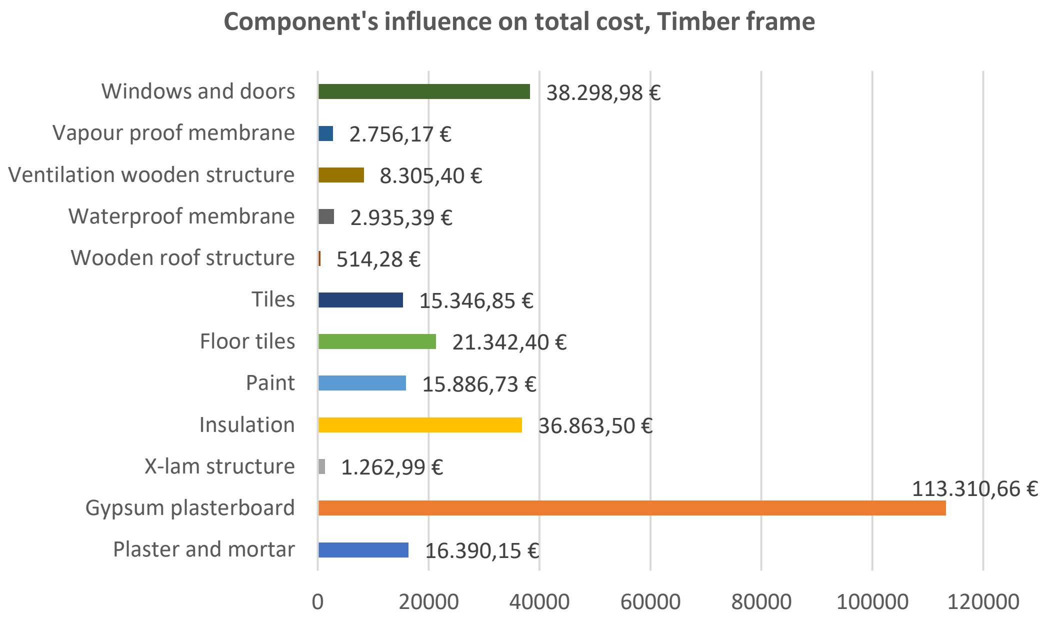


Figure 82: Component influence, Timber Frame

The plasterboard has been used in this case-study for the internal vertical partition as finishing layer and also in the internal horizontal partition as ceiling: due to this widely use, it accounts for the 41% of the total maintenance cost. Furthermore, the other components that complete the vertical envelope categorized other heavy cost: insulation, plaster and paint (use in the external façade), if combined, account for the 26%.

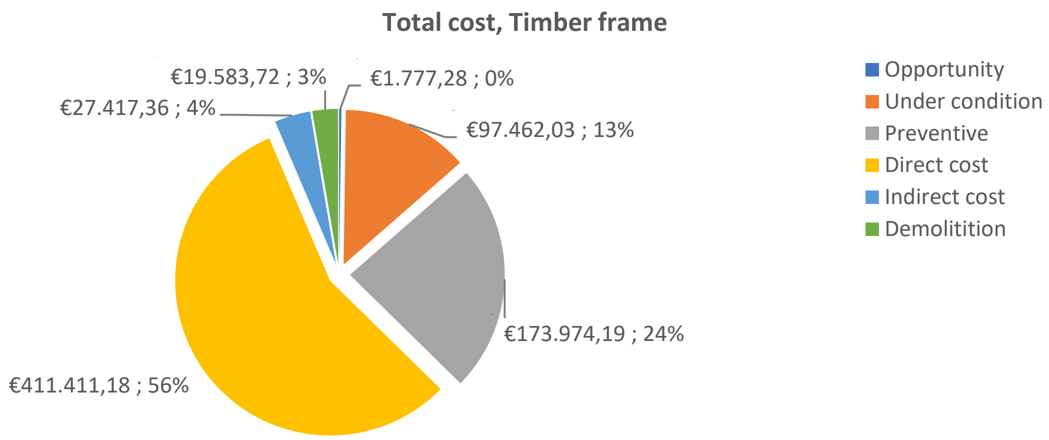


Figure 83: Total cost, Timber Frame

9.7 LCC comparison

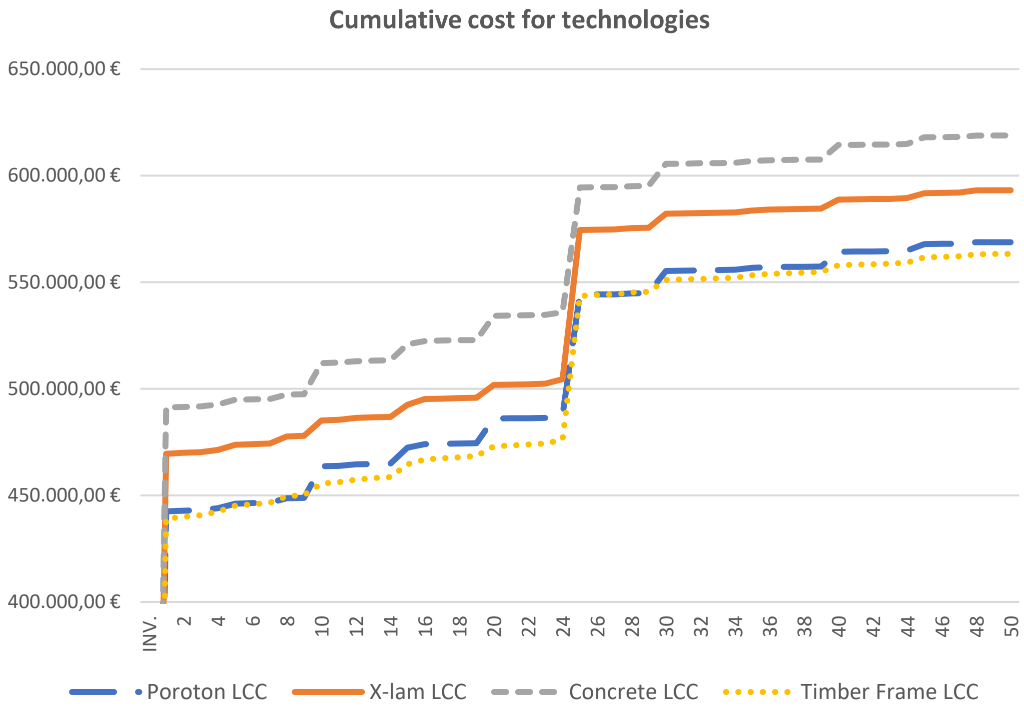
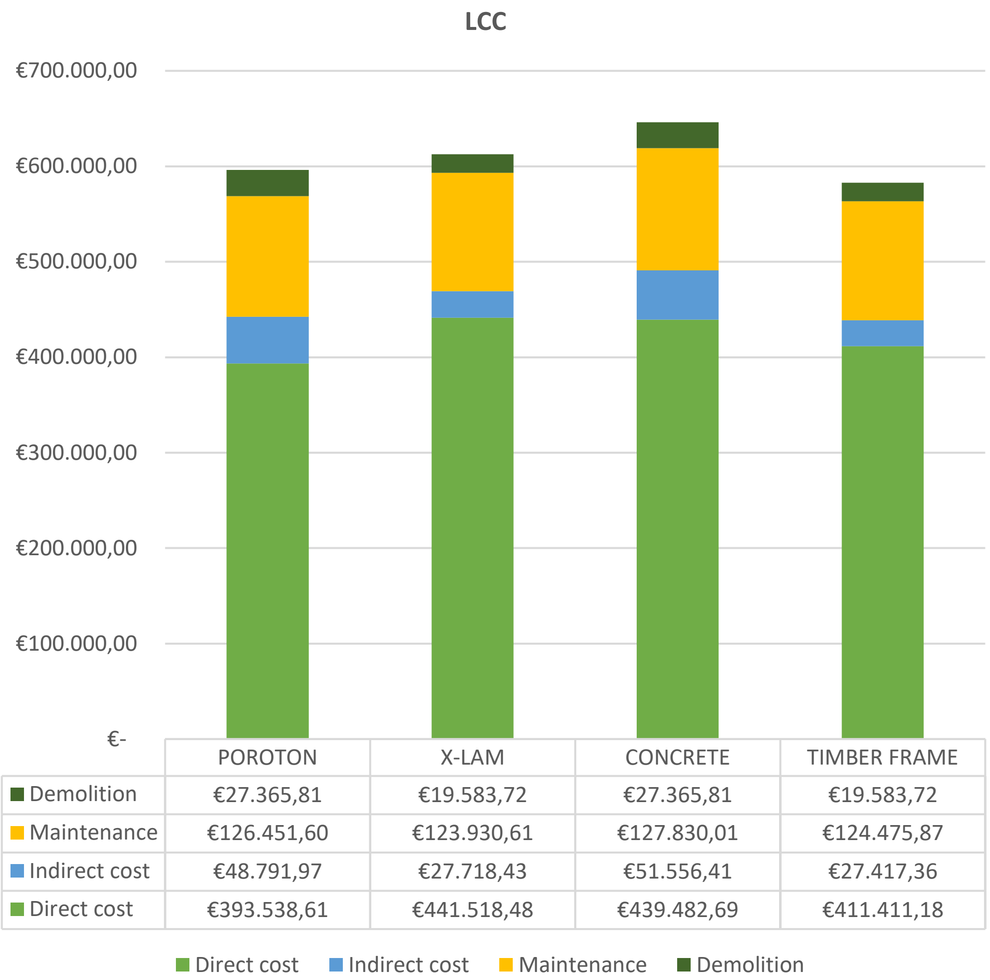


Figure 84: Cumulative Life Cycle Cost per Technology

The life cycle cost analysis enables us to allocate different cost category in order to understand the contrasting features for each technology used. The cumulative cost graph, illustrated above, allow us to identify the cost cycle with respect of time. Timber frame is the technology that requires the lowest initial investment for the building construction activities, and its planned maintenance enables it to maintain the lowest economic effort during its life cycle. In the same way, the concrete structure has the worst economic performance in all the cost categories: significant that the direct indirect cost overtakes the second most expensive construction budget by 5%. Unfortunately, this investment will not give better results for the maintenance plan, in which we can evaluate the maximum slope in cumulative cost line. The Poroton solution follows quite similarly the Timber-frame pattern, while the X-lam reflect the average results of cost allocation.



	POROTON	X-LAM	CONCRETE	TIMBER FRAME
Demolition	€27.365,81	€19.583,72	€27.365,81	€19.583,72
Maintenance	€126.451,60	€123.930,61	€127.830,01	€124.475,87
Indirect cost	€48.791,97	€27.718,43	€51.556,41	€27.417,36
Direct cost	€393.538,61	€441.518,48	€439.482,69	€411.411,18

Figure 85: Life Cycle Cost division per technology

9.7.1 Sensitivity analysis

Sensitivity analysis studies how the variation in the output of a system can be apportioned to different input parameters. In other words, it tries to determine how the change of input parameters would affect the change of the output. In this specific project it was useful to see how, in the maintenance plan, the variation of some costs and the choice of determined inflation rate and WACC data, may affect the total cost.

The table below illustrates the variation of the whole maintenance cost for the Poroton schedule, and the correlation between simultaneous variation of the chosen inflation rate and the Weighted Average Cost of Capital. The chromatic scale serves to identify the more divergent data: it ranges from the red to the green scale, in which the first represent the bigger variation, while the green establishes advantageous scenarios. The worst scenario it is the condition in which we are operating with a very high inflation rate but, in the same time a very low cost of capital, while vice versa if we operate with a very low inflation rate (0,5%) and a very high cost of capital our maintenance cost will drop to 27’000 €.

		WACC VARIATION							
	79.662 €	4%	5%	6%	7%	8%	9%	10%	11%
INFLATION RATE VARIATION	0,5%	112.824 €	88.088 €	69.901 €	56.313 €	46.009 €	38.086 €	31.913 €	27.043 €
	1,0%	129.020 €	99.971 €	78.766 €	63.030 €	51.172 €	42.109 €	35.088 €	29.579 €
	1,5%	148.044 €	113.825 €	89.029 €	70.754 €	57.073 €	46.680 €	38.675 €	32.429 €
	2,0%	170.463 €	130.026 €	100.944 €	79.662 €	63.835 €	51.887 €	42.738 €	35.640 €
	2,5%	196.967 €	149.030 €	114.818 €	89.963 €	71.604 €	57.832 €	47.351 €	39.265 €
	3,0%	228.406 €	171.393 €	131.022 €	101.909 €	80.554 €	64.638 €	52.600 €	43.367 €
	3,5%	265.823 €	197.792 €	150.005 €	115.803 €	90.892 €	72.451 €	58.589 €	48.021 €
	4,0%	310.506 €	229.059 €	172.311 €	132.009 €	102.867 €	81.441 €	65.439 €	53.312 €

Table 60: Sensitivity analysis for WACC and IR

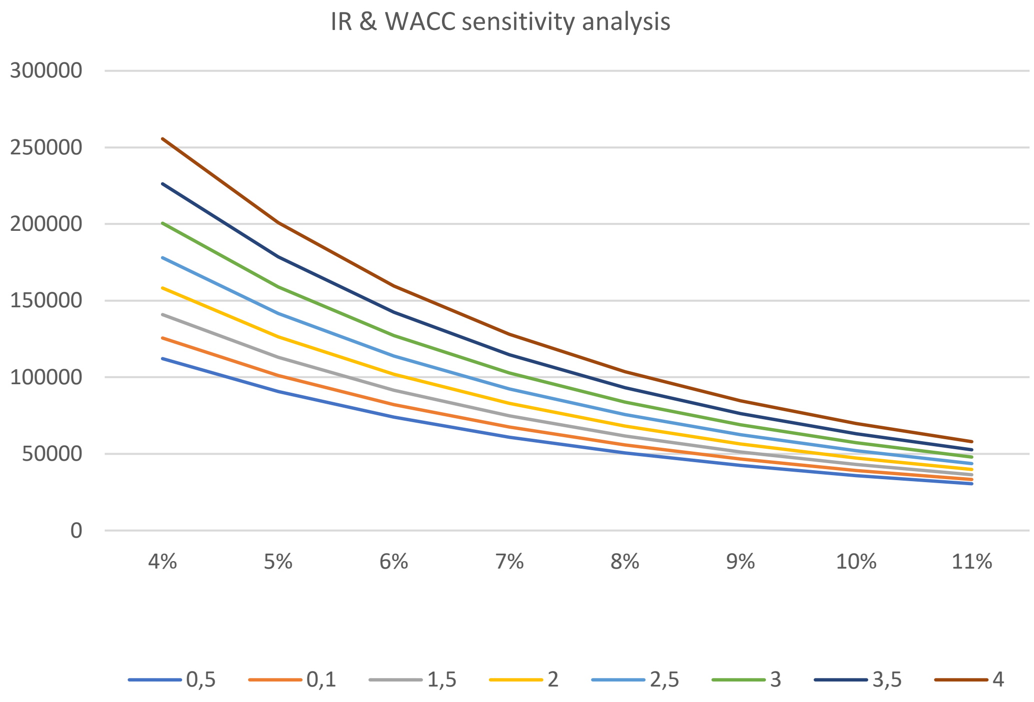


Figure 86: WACC and IR variation

The combination of WACC and Inflation rate data could lead us to very different results: the relationship between the extreme values of the table it is almost eleven to one. This analysis should lead to take caution when we have to estimate those kinds of parameters.

Furthermore, we have developed a sensitivity analysis on the marginal errors on the maintenance activities data, such as the cost and frequency required for each maintenance schedule that have been set up. In order to understand what maintenance activities could have a huge influence on the overall cost of use-phase. In order to study this incidence, we have taken the most expensive activities and the most frequent ones, that can be found in the maintenance schedule, and then we have tried to identify the relationship between percentual variation of those activities in term of cost or frequency on the total cost.

In the following example we can identify a sensitivity analysis on the concrete scenario, in which the total refurbishment of the external coat has been varied for range of 25% of activity cost and on range of 5 years frame in the activity frequency.

Frequency variation [year]	Cost variation [€]							
€ 80.169	€ 6.362	€ 12.723	€ 19.085	€ 25.447	€ 31.809	€ 38.170	€ 44.532	€ 50.894
10	83.532 €	92.951 €	102.369 €	111.787 €	121.205 €	130.623 €	140.042 €	149.460 €
15	79.470 €	84.825 €	90.181 €	95.536 €	100.892 €	106.247 €	111.603 €	116.958 €
20	77.495 €	80.876 €	84.257 €	87.638 €	91.019 €	94.400 €	97.781 €	101.162 €
25	76.618 €	79.123 €	81.627 €	84.131 €	86.636 €	89.140 €	91.644 €	94.149 €
30	75.628 €	77.142 €	78.655 €	80.169 €	81.683 €	83.197 €	84.711 €	86.224 €
35	75.306 €	76.497 €	77.689 €	78.881 €	80.072 €	81.264 €	82.456 €	83.647 €
40	75.052 €	75.990 €	76.928 €	77.866 €	78.804 €	79.742 €	80.680 €	81.619 €
45	74.853 €	75.591 €	76.329 €	77.068 €	77.806 €	78.545 €	79.283 €	80.022 €
50	74.695 €	75.277 €	75.858 €	76.439 €	77.021 €	77.602 €	78.183 €	78.764 €

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Table 61: Concrete external coat refurbishment sensitivity analysis

Here we can find the variation of the total maintenance cost with respect the possible combination on the variation of cost and frequency: this tool enables us to identify the range in which our errors in the cost/frequency evaluation could be considered acceptable, and, on the red zones, all the range in which our mistakes could have a huge impact on the economic analysis.

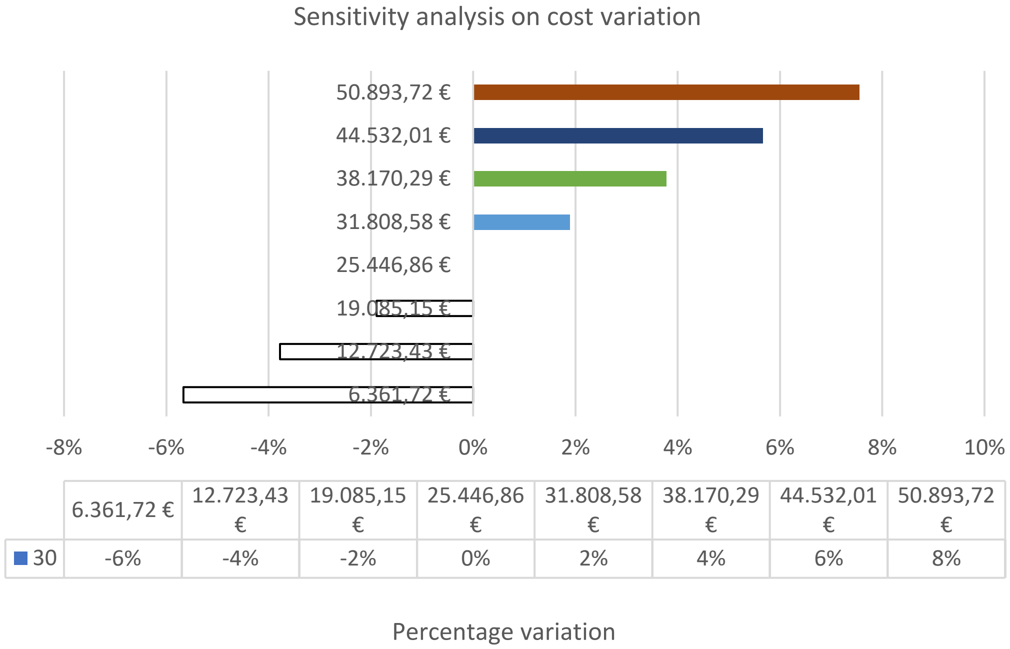

Figure 87: Sensitivity analysis graph, variation on total cost

If we base our sensitivity analysis on the hypothesis that we could have done an error in the cost estimation, while the refurbishment frequency remains the same (30 years) is it possible to identify the percentage of variation of total cost.

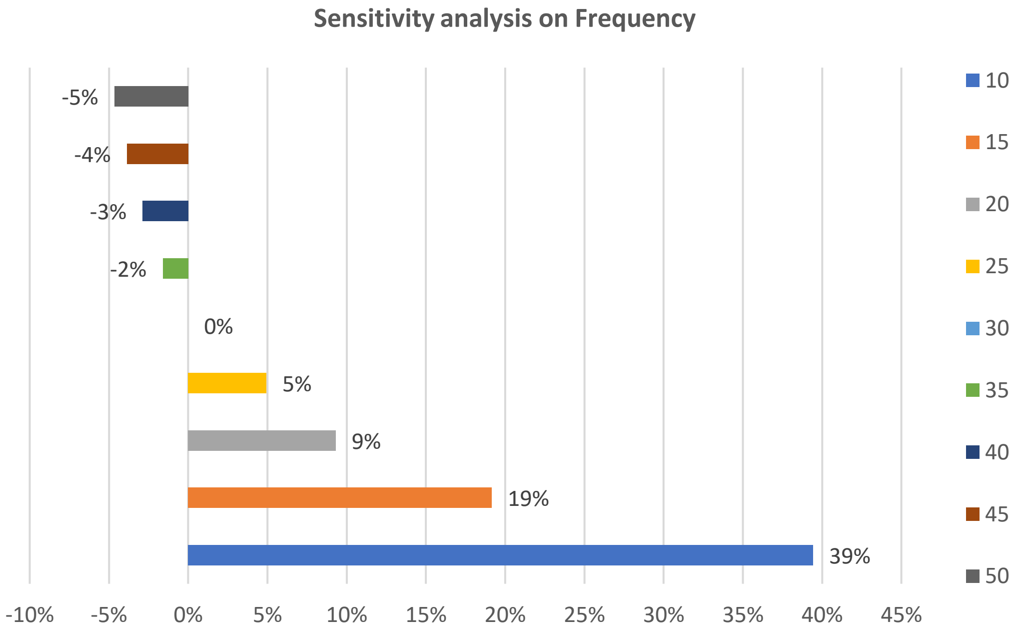

Figure 88: Sensitivity analysis graph, frequency variation

In the same way, we could understand how much the activity frequency has a much more influence on the total expenditure with respect the cost estimation deviation. If we double the maintenance cost for the external coat, we obtain an 8% variation on the total cost, while if we had to change the frequency, this operation will cost us much more than expected.

In order to have a total overview on the actual reliability on our study case, we create a sensitivity analysis on the five most expensive items and the five most frequent for every construction technology in order to understand similarities and significant differences.

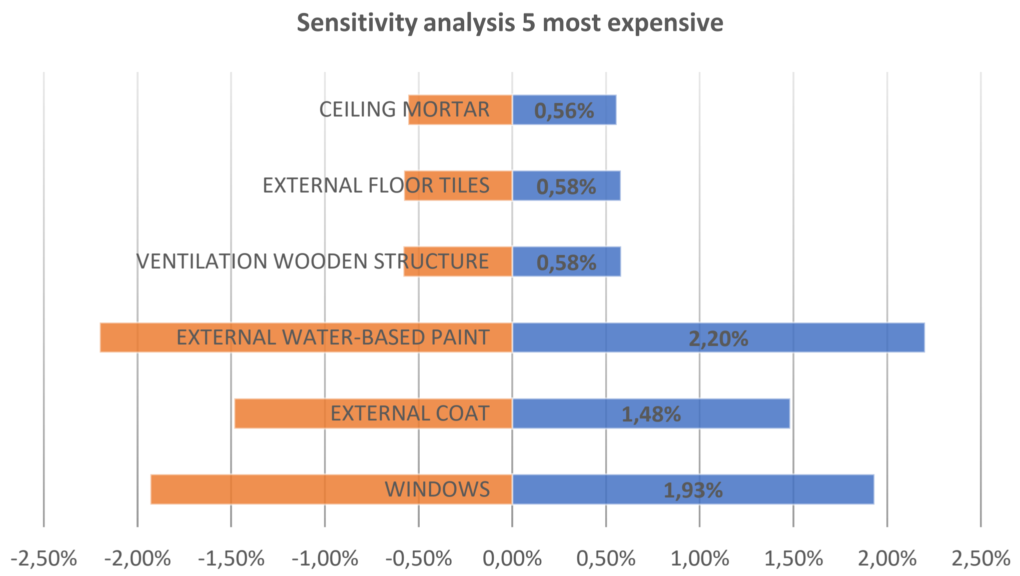

Figure 89: Sensitivity analysis, 5 most expensive activities

In this representation the five most expensive activity in the Poroton technology have been taken into analysis with a sensitivity method. Here we can see how the most impacting categories could lead to a maximum of 2,20% of influence on the total cost of the maintenance phase.

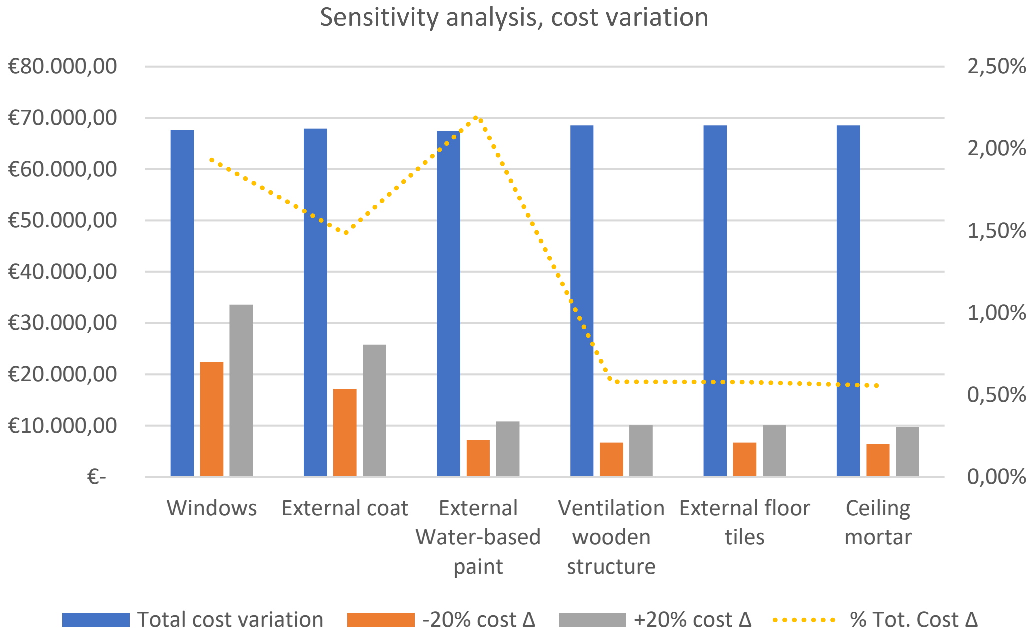

Figure 90: Sensitivity analysis graph, 5 most expensive

In a different situation the most frequent activity and their incidence on total cost:

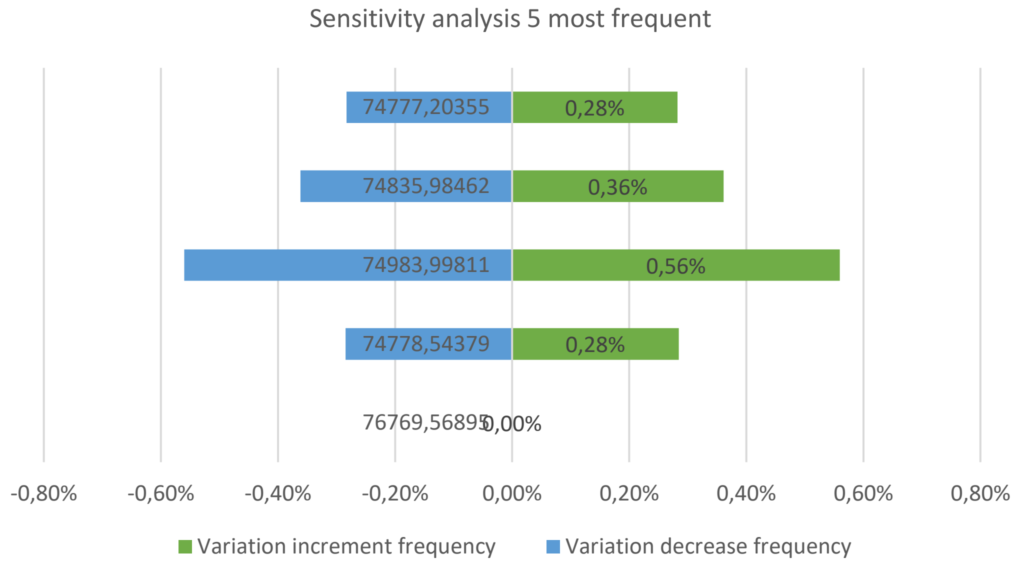

Figure 91: Sensitivity analysis, 5 most frequent activities

The actual most important parameter to consider and to periodically check is the real frequency to be linked to each category: if we take the most frequent activities in the Timber-Frame technologies as reported in the table:

Buil. component	Maint. activity	Frequency		Act. cost	Frequency var.	Total cost
Mortar and plaster (external)	Visual Inspection	12	M	114,82 €	9 M	76.769,54 €
Gypsum plasterboard	Anti-mold treatment	4	Y	129,43 €	3 Y	75.203,28 €
External floor tiles	Cleaning and floor wax	5	Y	545,39 €	4 Y	77.667,77 €
Window frames	Joints lubrification	5	Y	352,07 €	4 Y	76.568,45 €
Int. and ext. floor tiles	Joints refurbishment	5	Y	275,30 €	4 Y	76.131,88 €

Table 62: Sensitivity analysis, 5 most frequent

The activities reported are shows us the incidence of the frequency if it is been estimated with a range of 20% in excess or defect in the maintenance schedule. The total variation of total cost increase for a maximum of 0.56%, so it is possible to assume the maintenance frequency in our project has not a huge impact on the overall analysis, also because the more frequent activities are also the less expensive ones, as it effects partially the total area of the building. The most effective analysis should be made on single activities taking into account a double variable as frequency and cost combined.

74.566 €	136 €	273 €	409 €	545 €	682 €	818 €	954 €	1.091 €
3	73.520 €	74.345 €	75.170 €	75.996 €	76.821 €	77.647 €	78.472 €	79.298 €
4	73.267 €	73.839 €	74.412 €	74.984 €	75.556 €	76.129 €	76.701 €	77.274 €
5	73.162 €	73.630 €	74.098 €	74.566 €	75.035 €	75.503 €	75.971 €	76.439 €
6	73.073 €	73.452 €	73.831 €	74.210 €	74.589 €	74.968 €	75.347 €	75.726 €
7	73.013 €	73.332 €	73.652 €	73.971 €	74.290 €	74.609 €	74.928 €	75.247 €

Table 63: Sensitivity analysis, cleaning activities

After understanding the most impacting variables, such as the cleaning and wax protection on the previous example, among the activities it is possible to set up a new a sensitivity analysis to estimates the rang between cost/frequency parameters for this specific activity. As critical review on this particular analysis could be assessed that the choice of the components and relative parameters and their variable over time is crucial to identify significant results, so that a hotspot analysis to evaluates the major impacting categories is required.

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10 LCC & LCA: Carbon tax and Eco-cost

10.1 LCA and LCC results comparison

After a detailed and complete analysis of the environmental impacts and life cycle costs associated with the case study, compared to the four types used, the scientific research focused on finding an effective methodology to compare the results of the LCA and the LCC, although so different. As has been pointed out in the previous chapter, the environmental performance of the two wood technologies were the least impacting compared to Poroton and concrete, and the cumulative growth of tons of CO_2 equivalent coherently followed the cumulative trend of costs. The direct relationship created between the results of environmental and economic impacts can give us a total view of performance, but without being able to give a clear answer between the various types on which is the most optimal

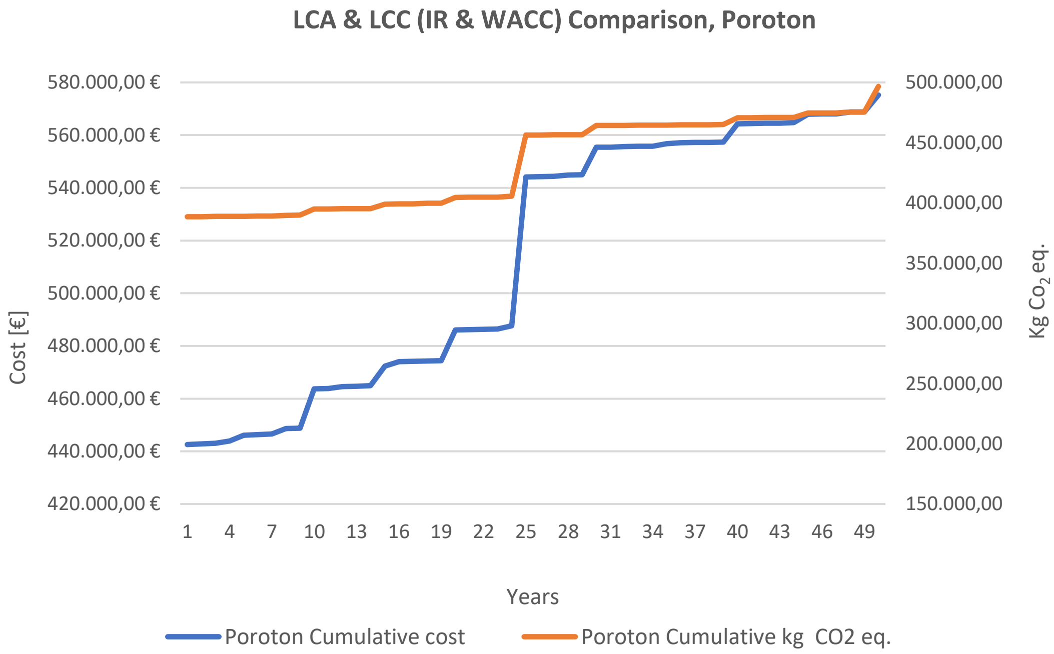


Figure 92: LCA & LCC comparison, Poroton

The previous graph can define two different cumulative curves in units of measurement, thanks to the help of a secondary vertical axis, so as to identify the cumulative costs in the main axis, and the kilograms of CO_2 equivalent of the second.

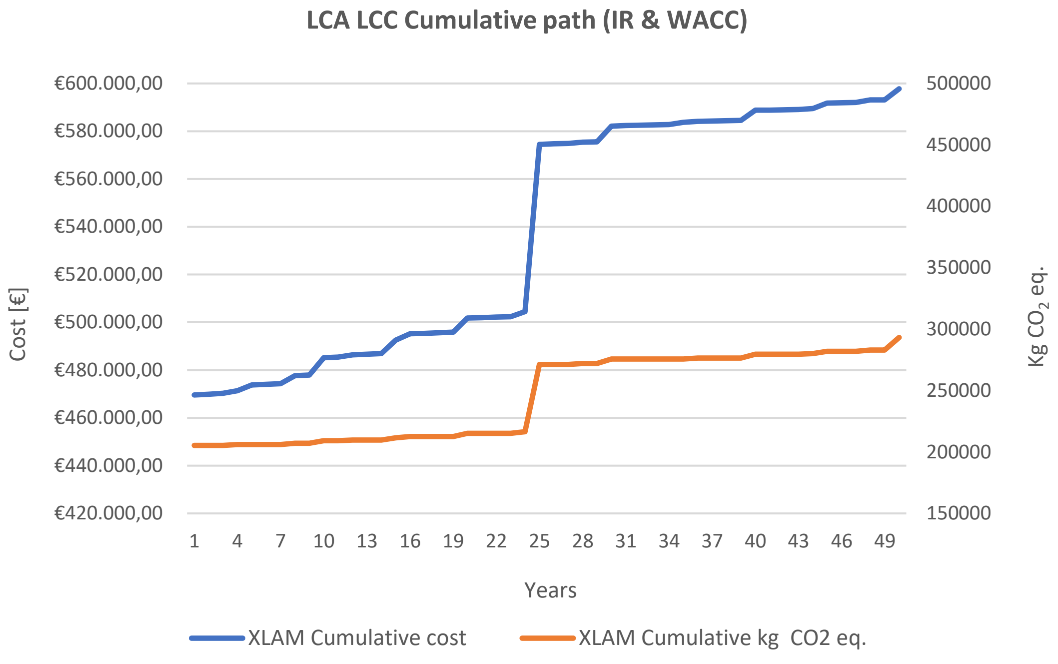


Figure 93: LCA & LCC comparison, X-Lam

The graphic representations of the trends, especially in the Poroton technology, highlight how there are some recognizable recurring patterns:

- The close relationship between CO_2 emissions and construction costs;
- The use phase is the crucial phase for both economic and environmental outflows;
- End of life with a considerable increase in both LCA and LCC valuations.

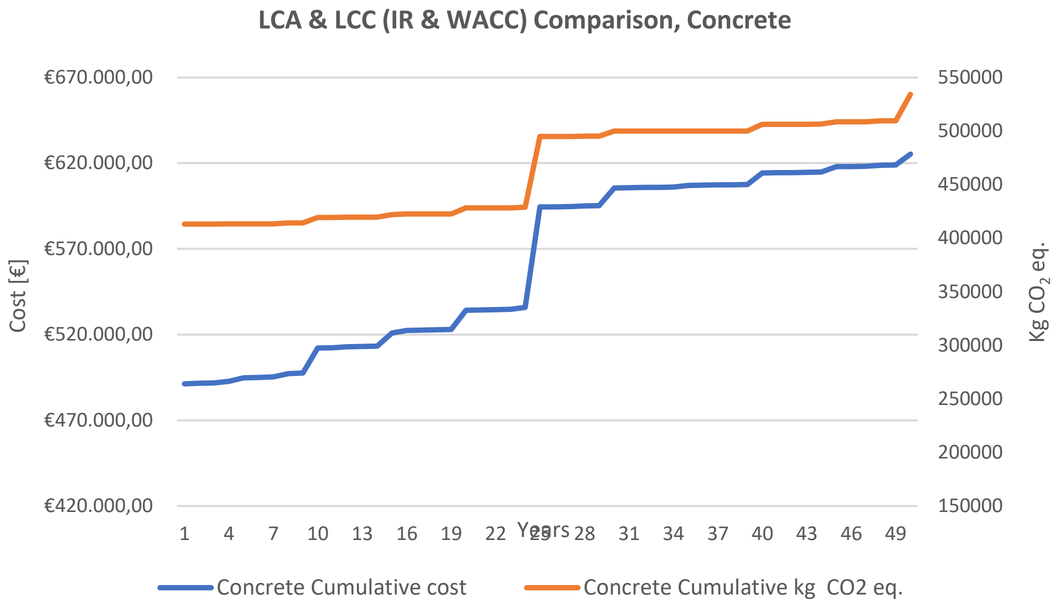


Figure 94: LCA & LCC comparison Concrete

The concrete, as previously pointed out, is the building technology studied with the greatest economic and environmental impact during the life cycle. The situation is diametrically opposed as far as the wooden load-bearing structure is concerned, in which the data are among the lowest in both categories.

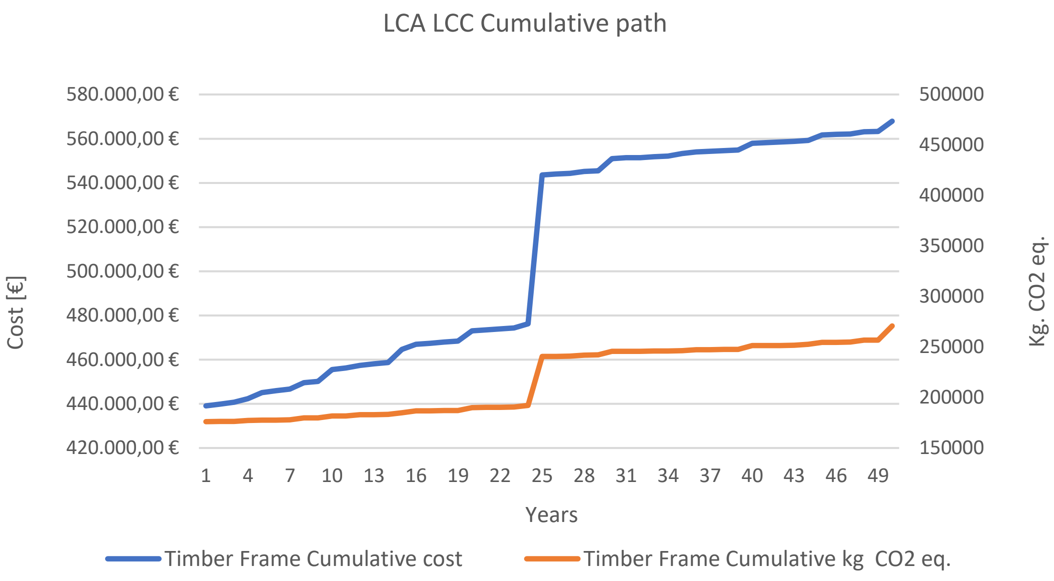


Figure 95: LCA & LCC comparison Timber-frame

In order to unambiguously identify economic performance and environmental impacts with respect to the various technologies examined, it is necessary to use a single indicator that allows the results of LCA and LCC to be systematized: The Carbon Tax has been identified in order to achieve this goal. This new tool, adopted in international markets, allows to price CO_2 emissions for the various sectors of industry. The use of the Carbon Tax will allow us to univocally sum up the costs related to the life cycle of the building and the taxation related to emissions, so as to have a single comparable value and determine the best economic/environmental performance. This methodology has the limitation of being able to be applied only to the GWP data per technology used, thus leaving out of the analysis the results relating to the Land-use and Primary Energy Demand.

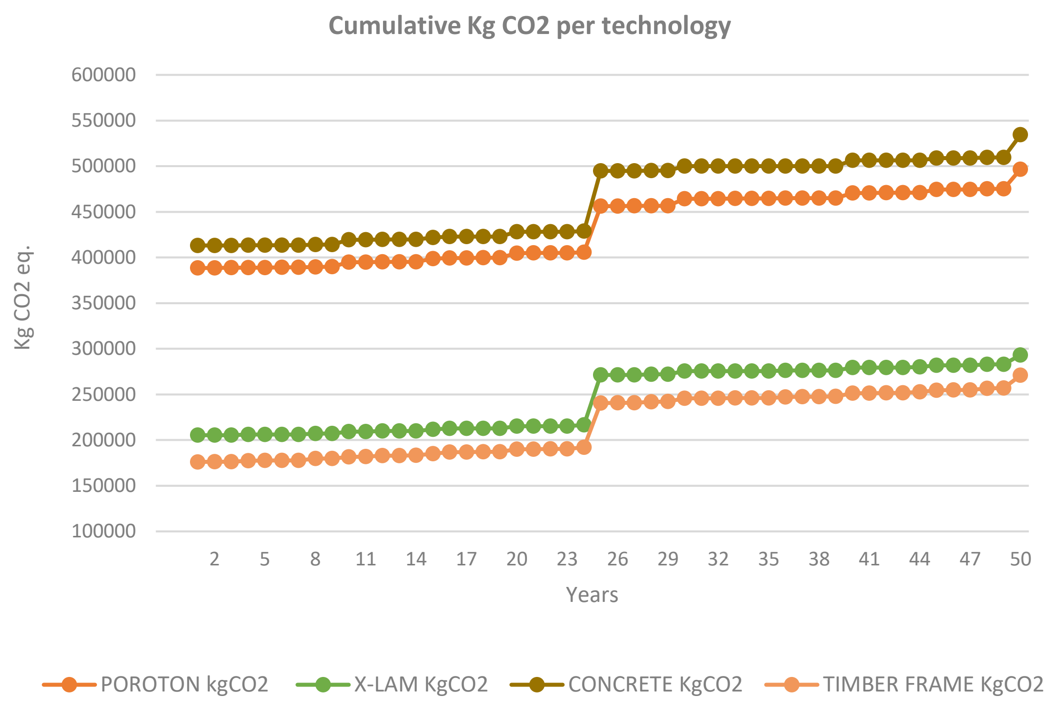


Figure 96: Cumulative CO_2 quantities per technology

From the representation of the cumulative kilograms of carbon dioxide for each technology, during the 50 years of service life, it is possible to unequivocally highlight the ability of the X-lam and Timber-Frame to generate almost half of the impacts caused by Poroton and Concrete. For the purposes of our research, we have therefore decided to evaluate the weight given to the pollution (in this case the Kg CO_2 eq.) in the decision-making process. In order to be able to compare costs and impacts, we needed a unique language that expressed these data in the same unit of measurement.

The choice to use the Carbon-Tax was dictated by the desire to express the GWP in economic value, so that it can be compared with the cumulative costs and analyse the impact. The question is therefore whether the carbon tax is able to compensate for the different initial investment values, thanks to a more impactful taxation for the most polluting technologies. The limitation of this model lies in the impossibility of monetarizing all the indicators, but only the GWP, thus ensuring a partial analysis of the cost/impact ratio.

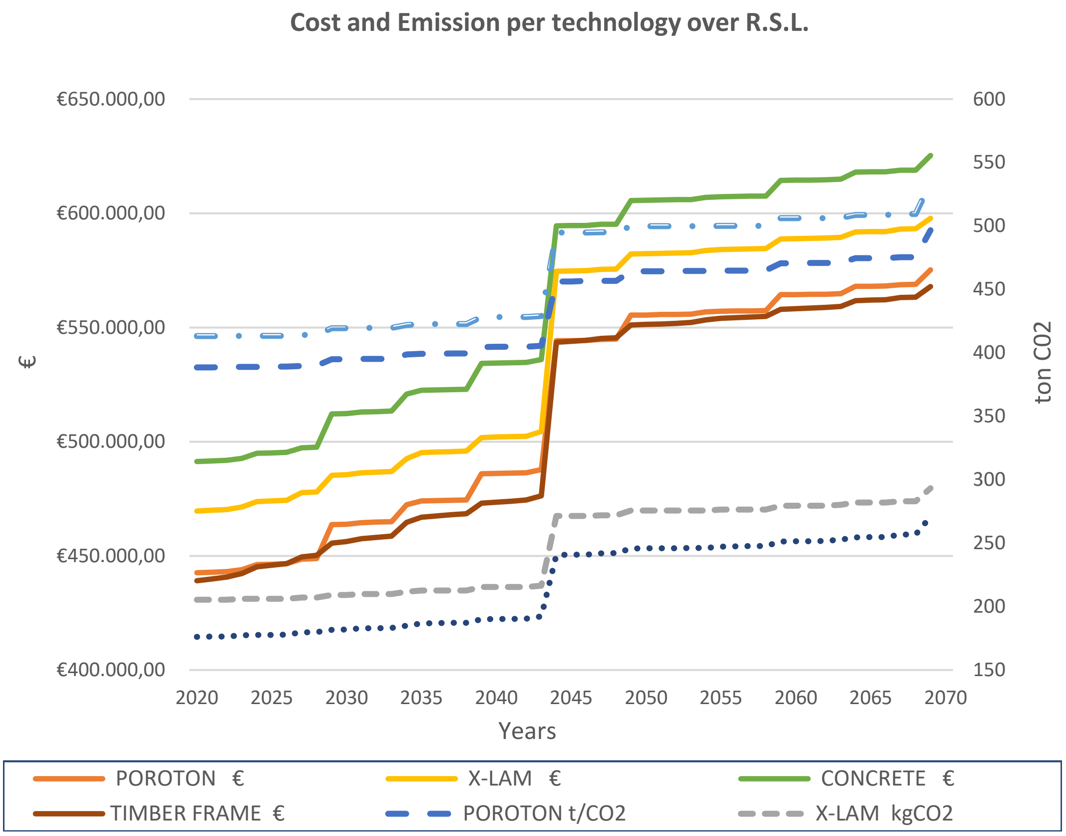


Figure 97: Cumulative cost and CO_2 ton per technology

10.2 Carbon tax

The carbon-tax is a policy to limit CO_2 emissions into the atmosphere and reduce the increase in temperatures of the planet in the horizons of 2030-2050. The thesis will not give a merit assessment on the methodology of taxation between Countries, on the search for the most appropriate price and on how the money and funds that would result from it should be invested. The thesis uses instead the various scenarios created by the scientific community for the expected increase in the price of coal between now and 2050, in order to be able to economically stimulate the development and implementation of less polluting technologies.
The implementation of this taxation tool in our case study will focus on the use of the Austrian scenario, so that we can analyse its applicability with respect to the building model. Even today, the methodology with which the right value of taxation can be calculated, and the best use of the funds that will be generated, is still under discussion.

The carbon-tax is above all a system of incentives for companies to develop technologies that allow to reduce the costs of cutting emissions, thanks to financial incentives that allow to reduce carbon emissions into the atmosphere.

10.2.1 Austrian scenario

Austrian climate policies, determined on the basis of the United Nations Climate Change Conference (COP 21 or CMP 11), held in Paris in 2015, seek to identify future GHG greenhouse gas emissions and methods for reducing them. This scenario seeks to achieve the goal of reducing Austria's GHG emissions by 40% by 2030 and 80% by 2050, compared to the levels identified in 1990. The new Austrian energy scenario includes several targeted interventions, such as increasing energy efficiency, lifestyle changes, increased use of renewable energy sources and especially the implementation of a system of taxation of CO_2 emissions. These policies will thus allow to limit the increase in temperatures, by 2050, to only 1.5 - 2 ° C below pre-industrial levels.

The Carbon Tax identified by Austria and its increase during the years, is reported as follows:

- 8 €/ton CO_2 in 2020;
- 40 €/ton CO_2 in 2030;
- 200 €/ton CO_2 in 2050.

Prices are identified on the value of the Euro in 2013, so that the effects of inflation can be taken into account.

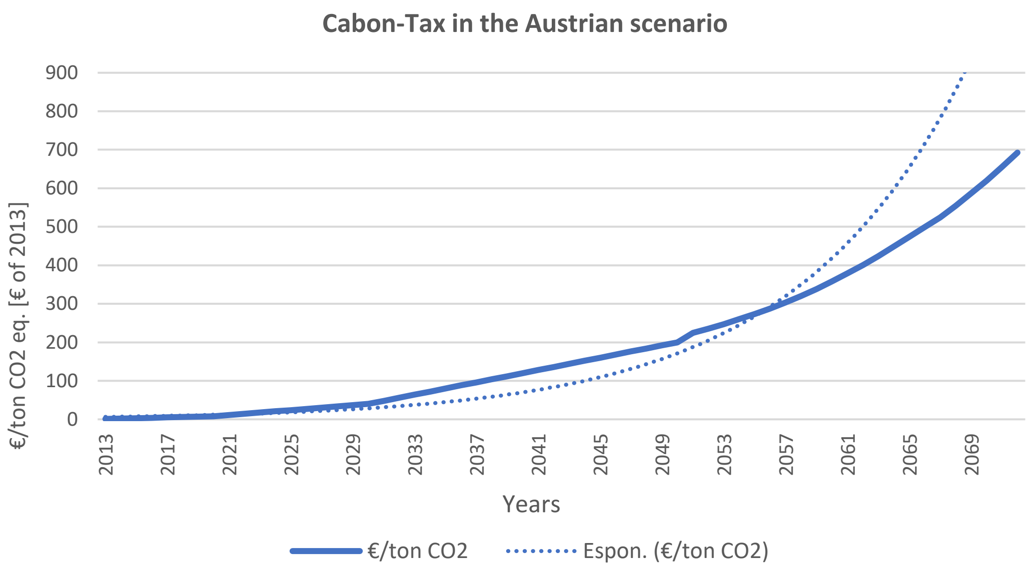


Figure 98: Carbon Tax in the Austrian scenario [Source: Ina Meyer, "Energy Scenarios 2050", 2013]

In order to identify the carbon-tax applicable to our project, 2020 was considered as the year of construction of our case study, and then be able to identify the annual and cumulative fees for each individual technology, add them to the results of LCC and get a representation in which the environmental performance is included. In order to identify a likely, estimate of the carbon-tax values from 2050 onwards, the likely trend from 2050 to 2070 has been estimated.

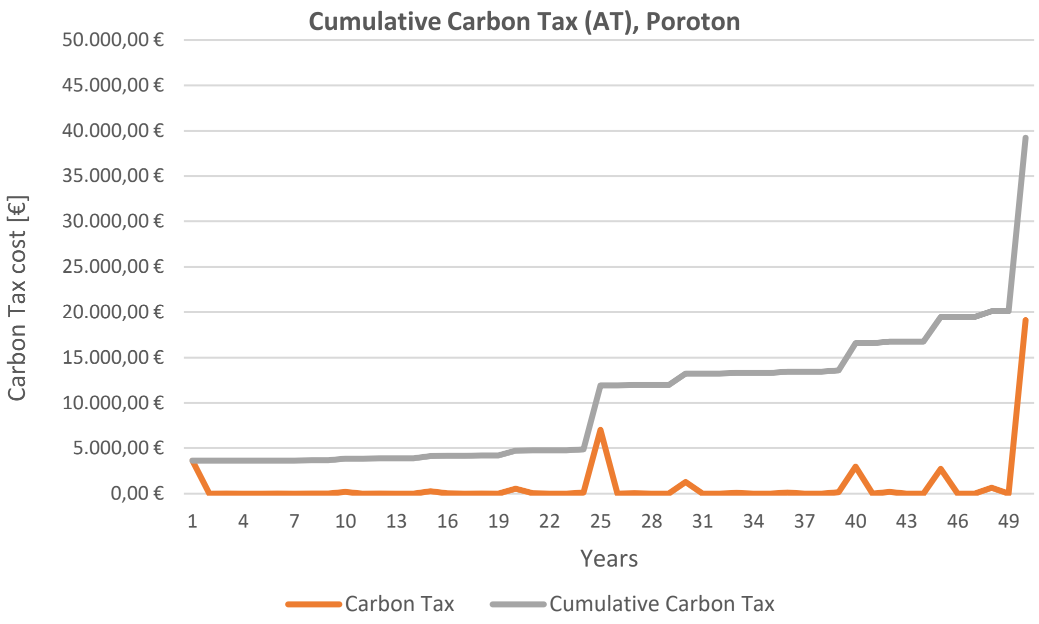


Figure 99: Carbon Tax outflows in Poroton

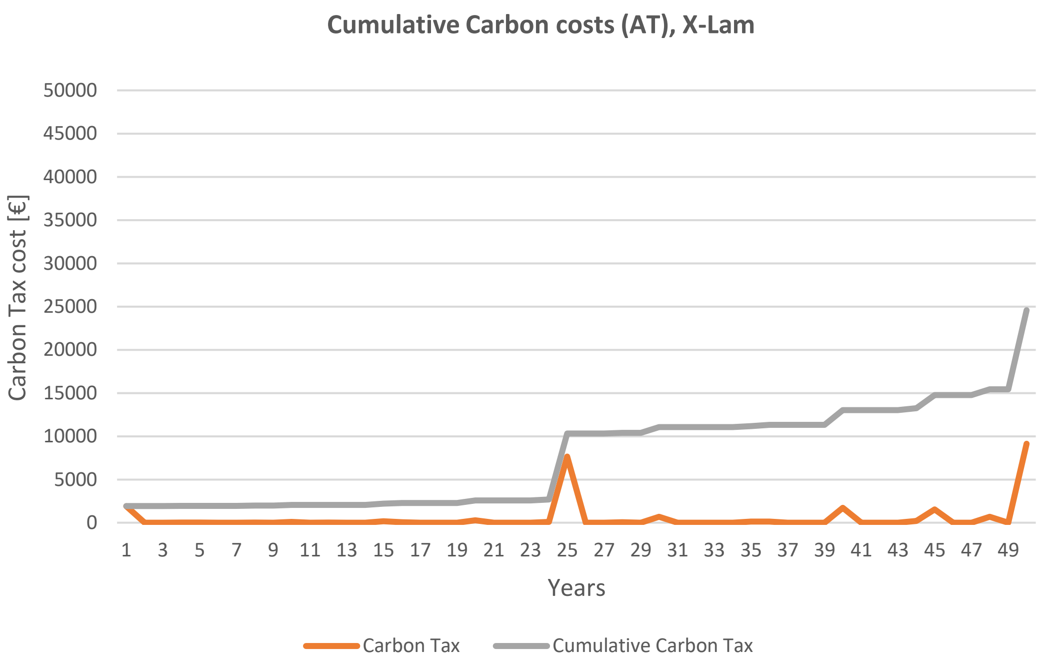


Figure 100: Carbon Tax outflows in X-Lam

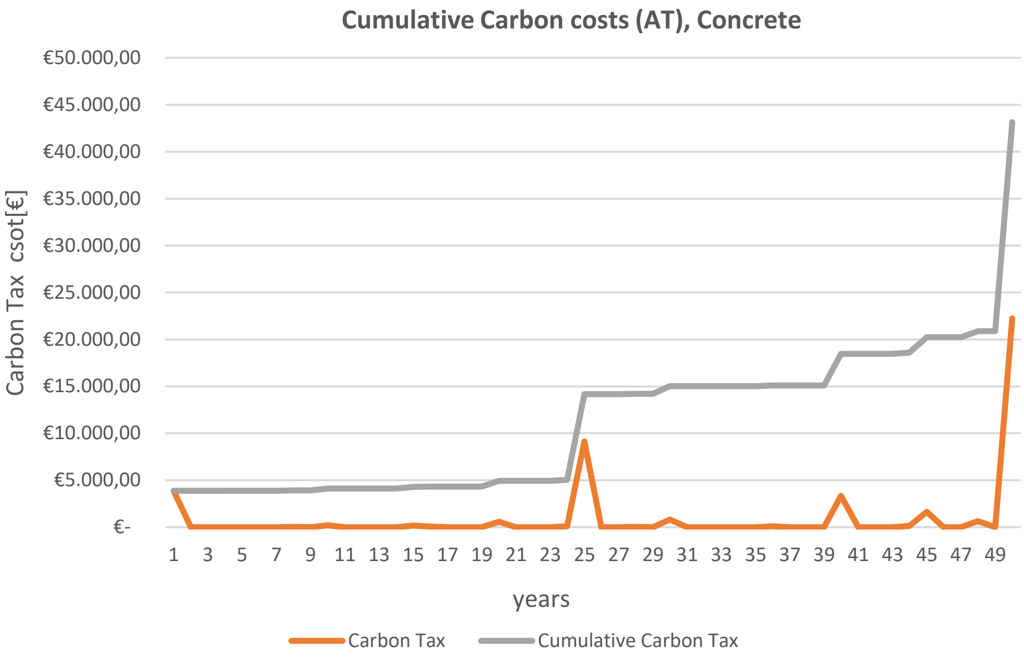


Figure 101 : Carbon Tax outflows in Concrete

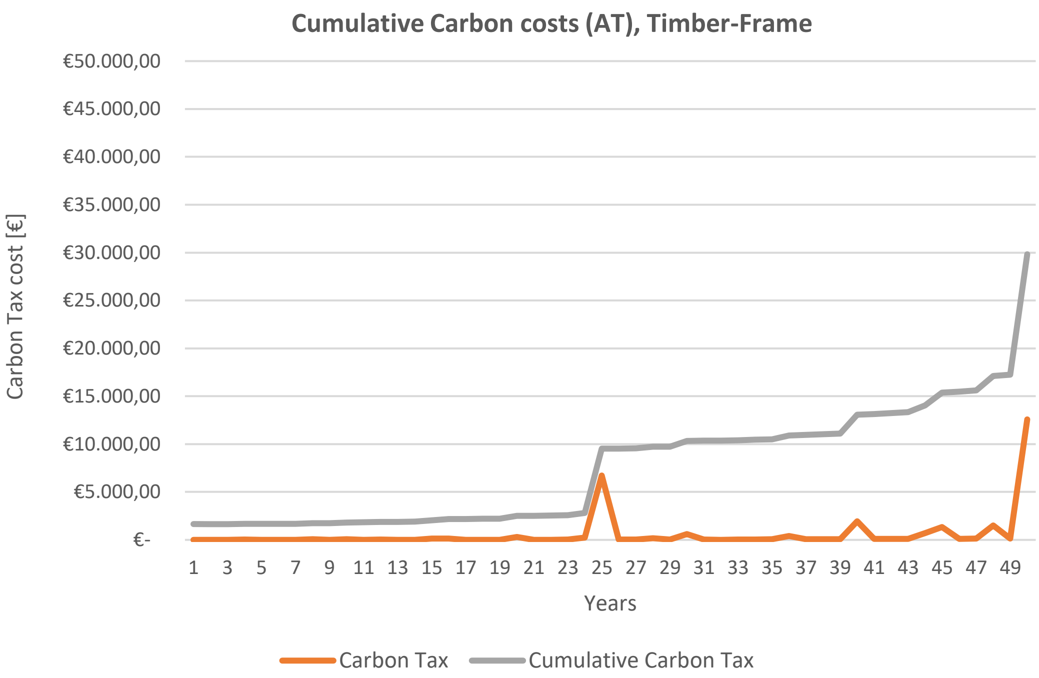


Figure 102: Carbon Tax outflows in Timber Frame

With the help of the Carbon Tax it was been possible to identify a cost expressed in Euro for each CO_2 emission during the life cycle, but with an exponential increase in the unit price over the years. It can be seen that in the year of construction 2020, taxation still remains very low given the gradual implementation of this financial instrument. As ordinary and extraordinary maintenance activities are carried out, the relative annual cost increases, as the growth of the Carbon Tax increases. Its most evident effect can be seen in the analysis of the additional expenditure to be considered in the end of life phase, where taxation has reached its peak.

In the following graph you can identify the four cumulative cost curves related to the implementation of the Carbon-Tax and shows more clearly its distribution. Poroton technology, together with Concrete technology, have the highest taxation, while technologies with wood as the main material have a much lower taxation.

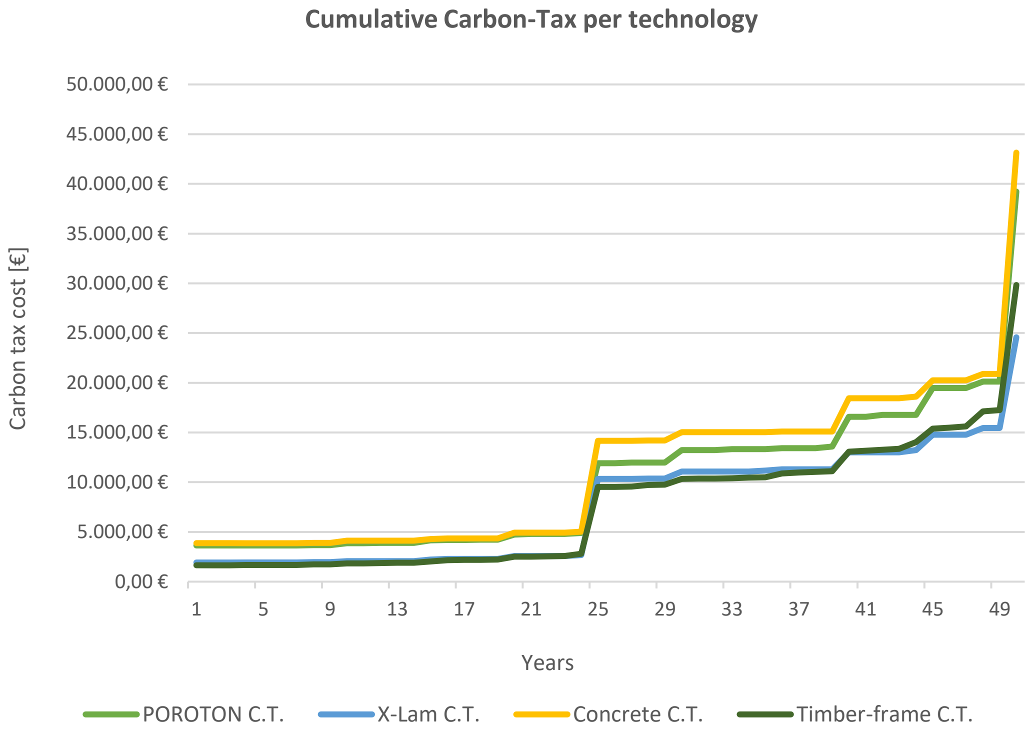


Figure 103: Cumulative Carbon Tax per each technology

The application of Carbon-Tax for each type allows to identify CO_2 emissions in costs, following the principle now adopted of "Polluters pay". But what impact does the application of this eco-tax guarantee in the total cost evaluation?

In the next graphic representation, we take the case of Concrete technology, where we have both the direct, indirect, maintenance and demolition costs higher, but it is also the technology with the highest impacts of the GWP indicator. In this case, it is expected that the Carbon-Tax will have a noticeable relevance, when the costs of the building and the tax itself are combined.

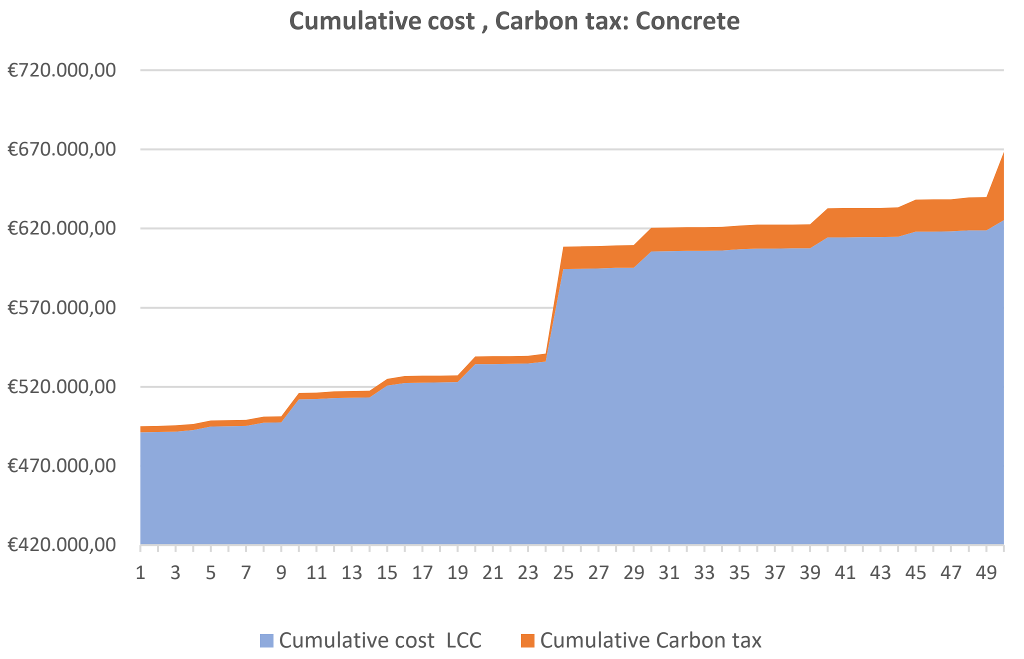
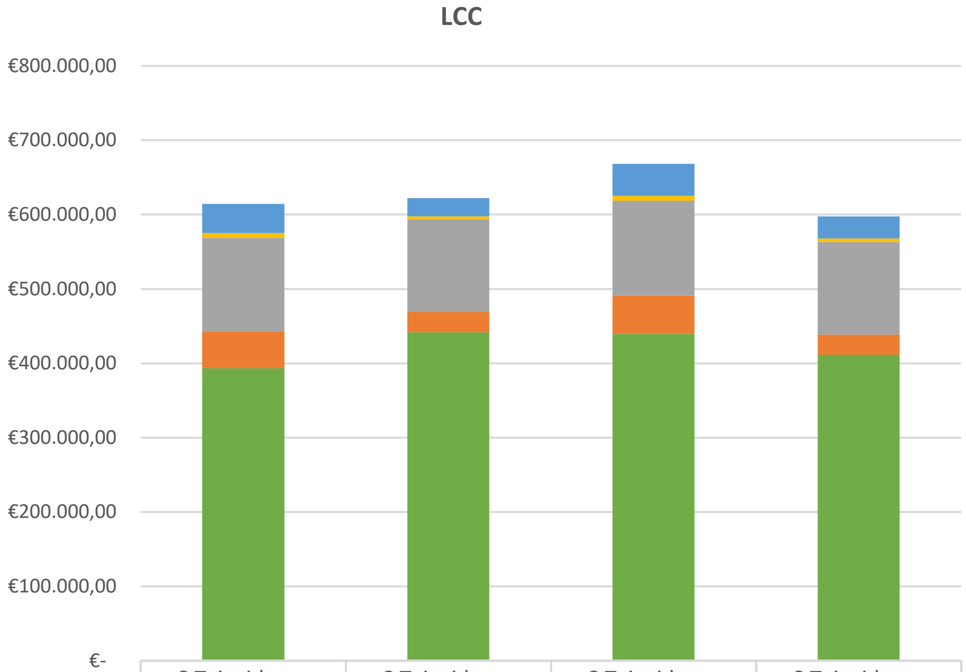


Figure 104: LCC, Carbon-tax influence

The graph shows in a simple visual way, how the carbon-tax does not have a significant incidence in the total cost of the work, but above all it can be seen how the most impacting phase, A1-A3 and A4, are not compensated by a high tax, when this begins to become relevant from the thirtieth year on.



AUSTRIAN SCENARIO	C.T. incidence POROTON	C.T. incidence X-LAM	C.T. incidence CONCRETE	C.T. incidence TIMBER FRAME
Carbon Tax	€39.227,14	€24.574,83	€43.141,81	€29.830,36
Demolition	€6.423,21	€4.596,62	€6.423,21	€4.596,62
Maintenance	€126.451,60	€123.930,61	127830,0107	124475,8653
Indirect cost	€48.791,97	€27.718,43	51556,4082	27417,35976
Direct cost	€393.538,61	€441.518,48	439482,6865	411411,1758

Figure 105: Life Cycle Cost, including C.T.

The carbon-tax therefore amounts to between thirty-nine and forty-three thousand euros, over the 50 years of life of the building, for the most impactful technologies such as Poroton and Concrete, while X-lam and Timber frame pay about 40% less than their competitors. This difference in taxation therefore allows the Timber-Frame to be both the most economical and the least impactful technology, but it is essential to emphasize that the choice of wood technology is determined by its economic impact on the initial investment and not by the lower eco-tax resulting.

In fact, it is important to analyse the incidence of the carbon tax in relation to the total cumulative costs of the various technologies: in the following graph it is possible to see how X-lam and Timber-Frame include a tax that impacts on the total from 3.95% to 4.99%% respectively, while concrete and Poroton go beyond 6% each. These results certainly do not meet the initial hypothesis that emissions taxation would lead to a strong propensity towards less impactful technologies.

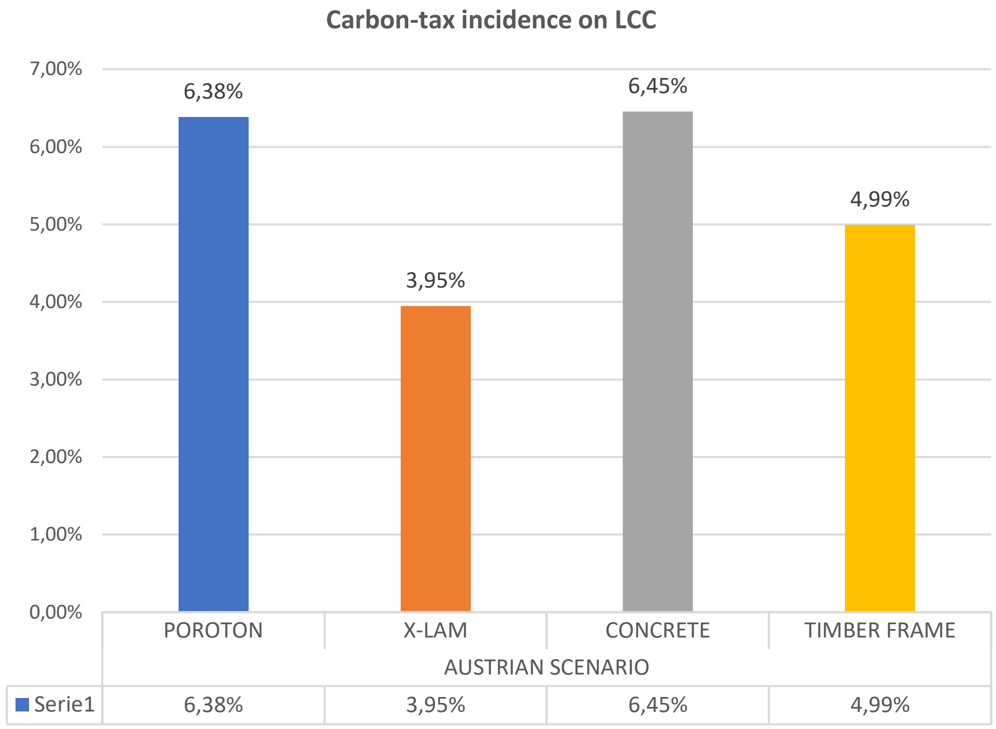


Figure 106: Carbon-tax incidence on LCC

The eco-tax applied to our project is not able to affect and have a strong relevance in the process of choice as it does not have a significant economic impact in the estimation of total costs.

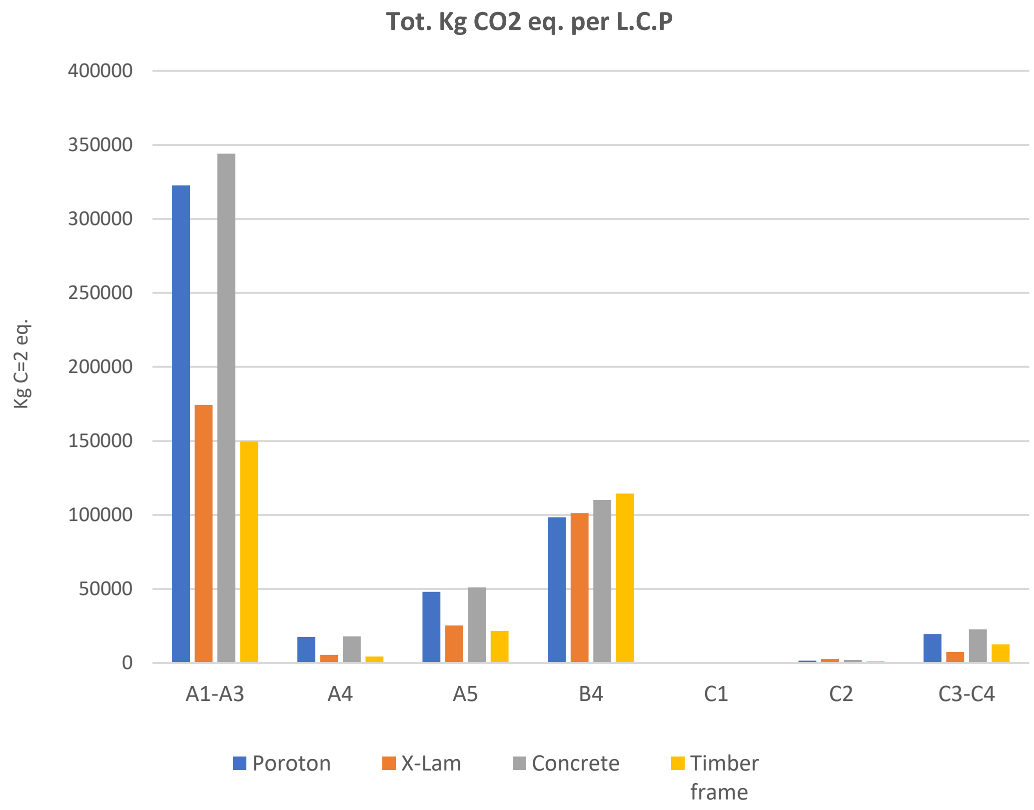


Figure 107: Total GWP per Life Cycle Phases

The carbon-tax, as previously pointed out, has a continuous growth from 2020 to 2070, but at the moment any new construction will not be affected immediately by the imposition of taxation, as the production phase A1-A3 is the most influential but at the same time the least taxed.

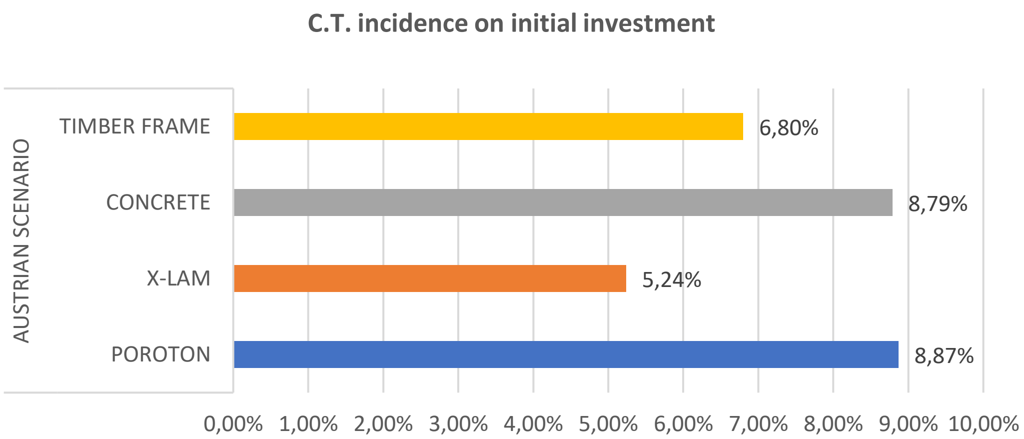


Figure 108: Incidence of Carbon Tax on Initial investment

If we consider the mere initial investment, the carbon tax will have an impact on this outflow that reaches a maximum of 8.87% (Poroton scenario). This ratio, although very relevant, does not seem to alter the economic hierarchy previously analysed, so it still has no effect in terms of choice for future constructions.

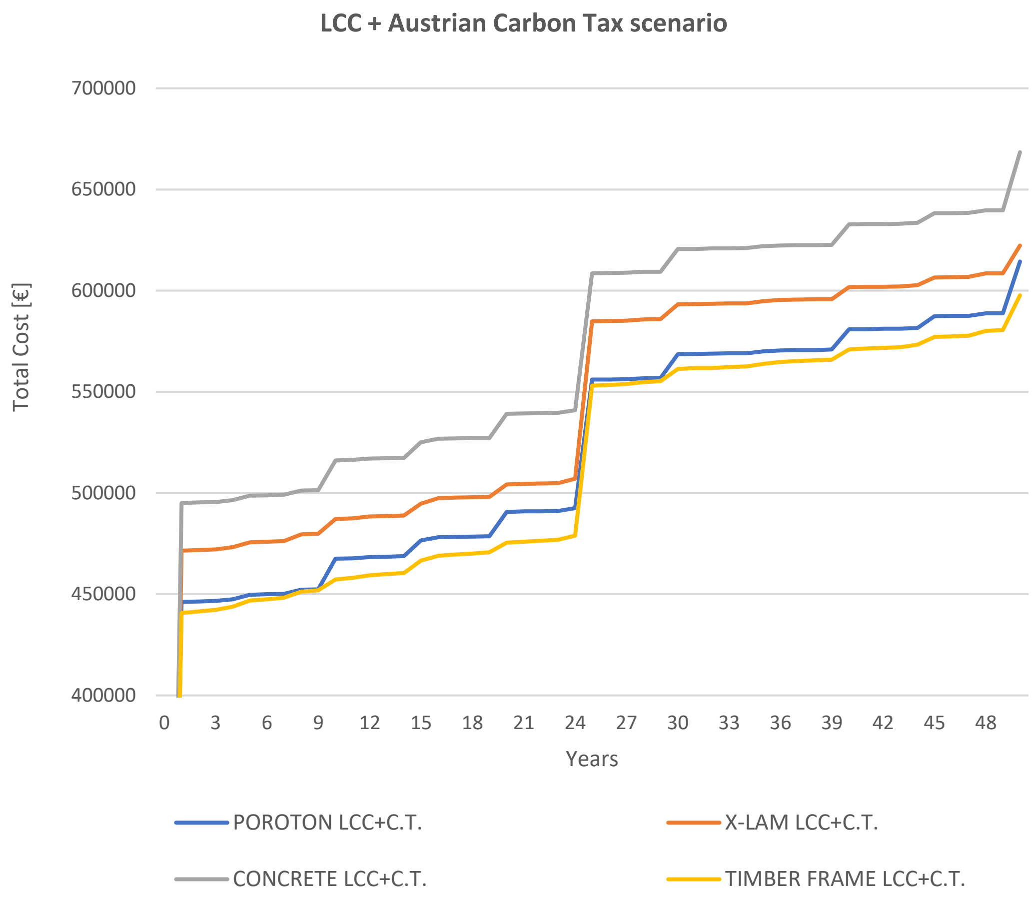


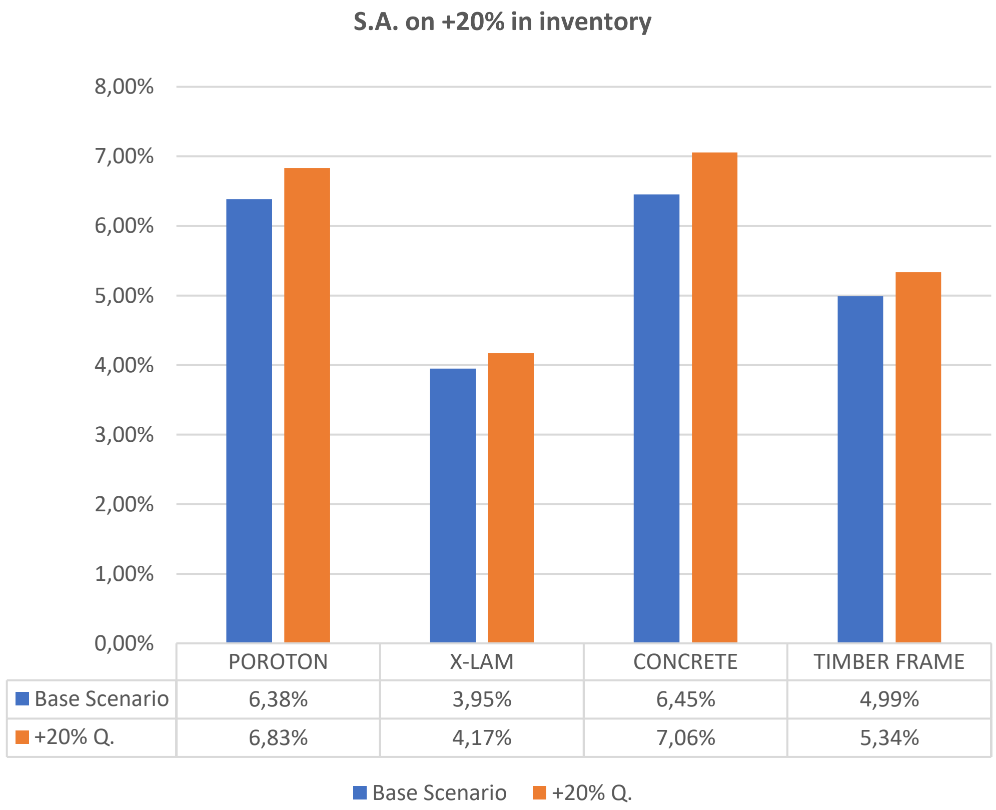
Figure 109: LCC + Carbon Taxation for technologies

The final results show that, if we add the total cumulative costs and the Carbon tax, the Timber-frame is the least impacting and for the same energy performance, the optimal solution in terms of costs and air emissions. The concrete, at the other extreme turns out to have both the emissions and higher costs, so it is the worst solution among those analysed.

A more in-depth analysis would deserve the case of Poroton and X-lam, as Poroton has lower costs and far greater impacts than X-lam: The Carbon-Tax fails to compensate for the difference in initial investment, 5.73% between Poroton and X-lam, to obtain a building with 47.13% less CO_2 emissions. This case makes us reflect on the real ability of the Carbon Tax to move choices in the short term.

10.2.2 Sensitivity Analysis

A fundamental part of being able to analyse the data obtained is the development of a subsequent sensitivity analysis that reports the variation of the final results with respect to predetermined variables. The following analyses will concern the variation of quantity in the inventory, the frequency of maintenance activities and the possible price variations imposed by the carbon-tax.



	POROTON	X-LAM	CONCRETE	TIMBER FRAME
Base Scenario	6,38%	3,95%	6,45%	4,99%
+20% Q.	6,83%	4,17%	7,06%	5,34%

Figure 110: Sensitivity analysis on inventory

The first case analysed is the implementation of sensitivity analysis with regard to the five most influential materials for the indicators of GWP, and increase the quantities, and thereby going to operate on the likely errors in the inventory. The analysis is based on a 20% increase in the quantities in the inventory of the five most impactful materials for each technology, as far as GWP is concerned. The total change in impacts, given the increase in the assumed materials, will correspond to a proportional increase in Carbon Taxation. The results show that a 20% increase in inventory quantities, limited to 5 important items, then influences the incidence of minimum coal taxation, with a growth that never exceeds even 0.5% change from the base case.

The second case study investigated is the analysis of changes in environmental impacts in phase B4, relating to the phase of use of the building, so as to investigate the error on data relating to maintenance activities.

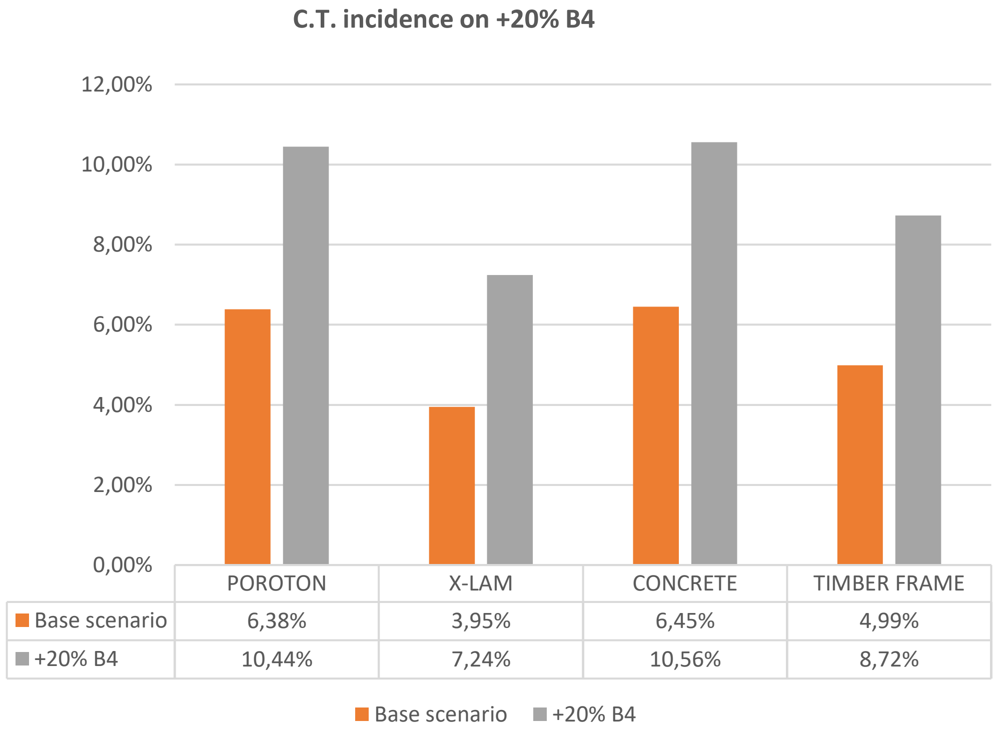


Figure 111: Sensitivity analysis on B4 phase

This analysis confirms the concept that phase B4 alone can bring about a significant change in the total carbon-tax: the study of partial and total replacement frequencies has important effects for the change in total impacts. However, this influence does not allow us to define alternative maintenance activities for which there could be changes of choice with respect to the base case.

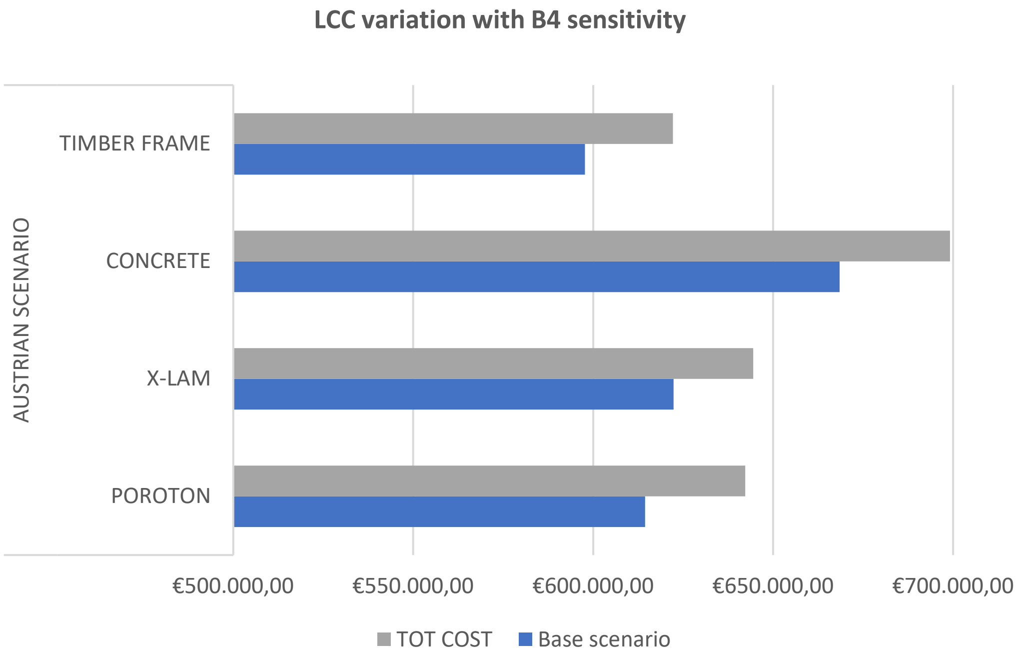


Figure 112: LCC variation, B4 sensitivity

The total variation with a variation of 20% of the impacts of phase B4 manages to increase the incidence to a maximum of 10.56%, in the case of concrete, with an increase that exceeds 4% for all technologies. The sensitivity test applied to the maintenance activities allows us to understand the greater relevance of maintenance schedule and cost estimation with respect the initial inventory creation, as it could lead to greater errors in terms of carbon taxation estimation.

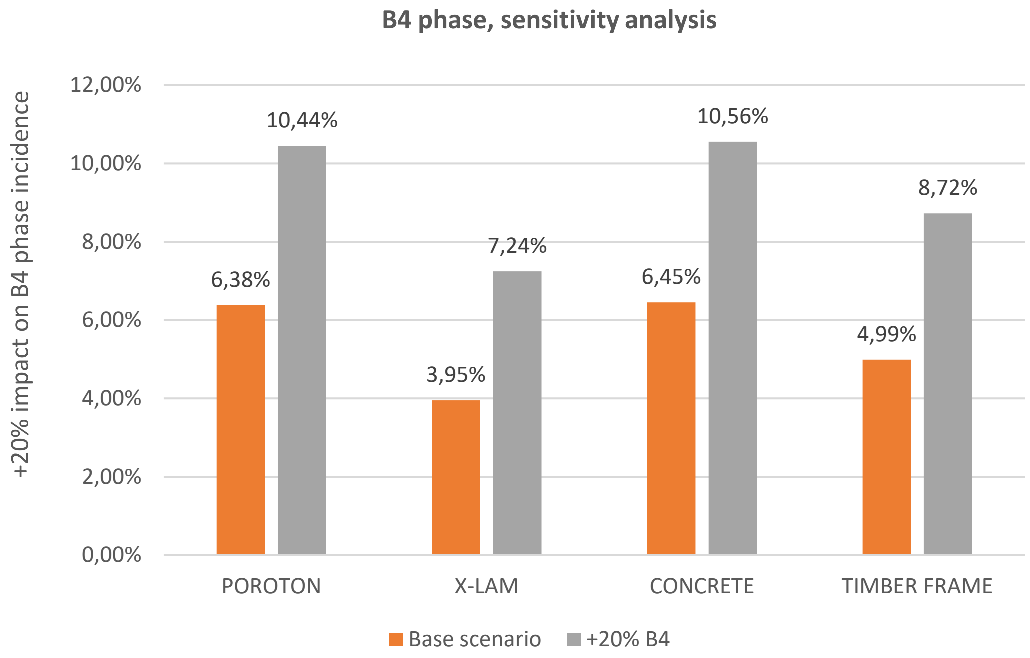


Figure 113: Sensitivity analysis on B4 phases per technologies

The last sensitivity analysis carried out concerns the possible variation of the carbon-tax in the Austrian scenario, with a variation of +25%, +50%, +75% and 100% of the annual unit cost. This analysis allows us to identify how much the Carbon-Tax can affect the total change in costs, and we can identify the change of +100% compared to the Austrian scenario as a significant change.

With a variation in incidence shifted to 12%, as far as the two most impacting technologies are concerned, the carbon tax manages to have a very significant impact in terms of choice. Even in this extreme case, where the carbon tax actually applied is twice as much as the base case, the extreme results remain unchanged, with Timber frame still being the best solution and Concrete clearly the worst.
While limiting the boundary system to the cases of Poroton and X-lam, the choice of the most performing technology remains unchanged, with Poroton still in advantage.

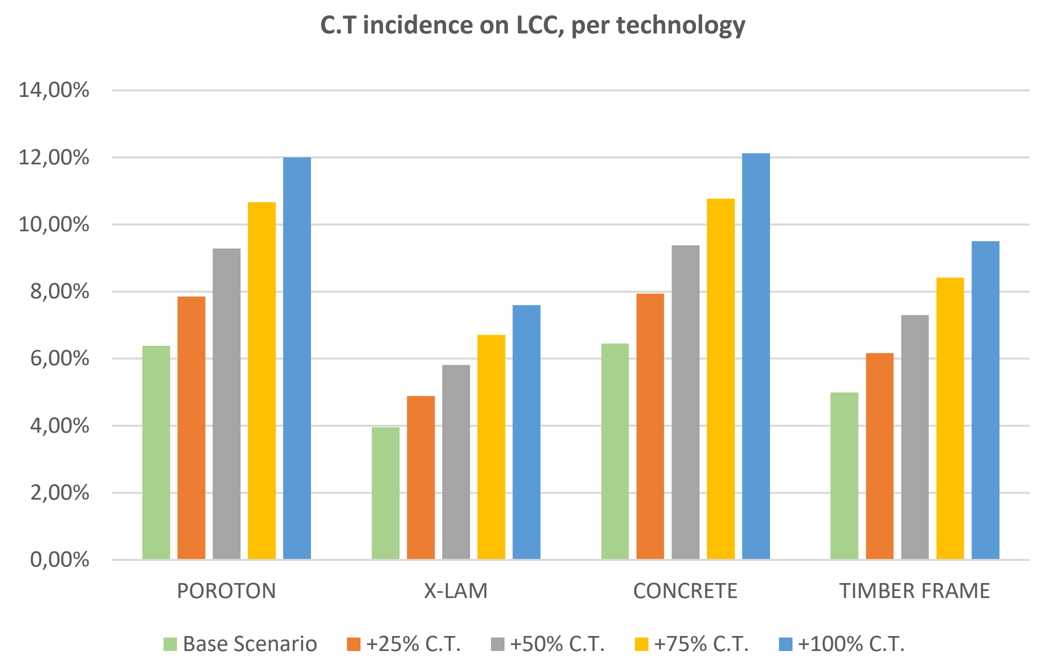


Figure 114: Sensitivity analysis on Carbon Tax variation

The sensitivity analysis allowed us to identify the areas where the detection of an error would have the greatest influence on the total result, and even in extreme cases of errors and estimates, the classification of technologies does not change. The only real source of evaluation error to keep an eye on is the choice of the methodology used to develop the Life Cycle Cost, and the inflation and WACC data for the Net Present Value.

10.3 Eco cost

The application of an eco-tax such as the Carbon Tax fails in obtaining significant results in terms of incidence on total costs as it is not yet able to tax in a decisive way the most impactful phase of the life cycle, i.e. production. The Carbon Tax will only find a significant place in the parameters of choice between various types when it is able to cover the greater investments required in the face of clearly reduced emissions. This type of situation is dictated by the fact that the rising costs forecast by the carbon tax do not reflect the real monetary value of the ecological impacts generated.

The World Council for Sustainable Development, WBCSD, defines the eco-efficiency as: “the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity, throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity." This definition gives us an overview on the actual model to be followed in order to reduce air pollution and the other environmental impact. This purpose could be achieved by the introduction of the concept of Eco-cost, that allows us to measure the environmental load of the LCA indicators in monetary terms: for CO_2 emissions an eco-cost of 135€/t CO_2 has been expressed. Thanks to an investment equal to the eco-cost, linked to each production chain in different sectors, on technologies systems and other prevention measures for reducing CO_2 emissions, stratospheric results can be obtained for our planet. This cost is not a real indicator that is part of the cost estimate in the production and trade phase but must be seen as a hidden cost. The eco-cost is expressed in monetary value in order to create comparisons between different technologies and materials used and expressed with respect to the monetary value of 2007. The indicator can therefore also be used in a panorama of LCC and combination with LCA to compare alternatives.

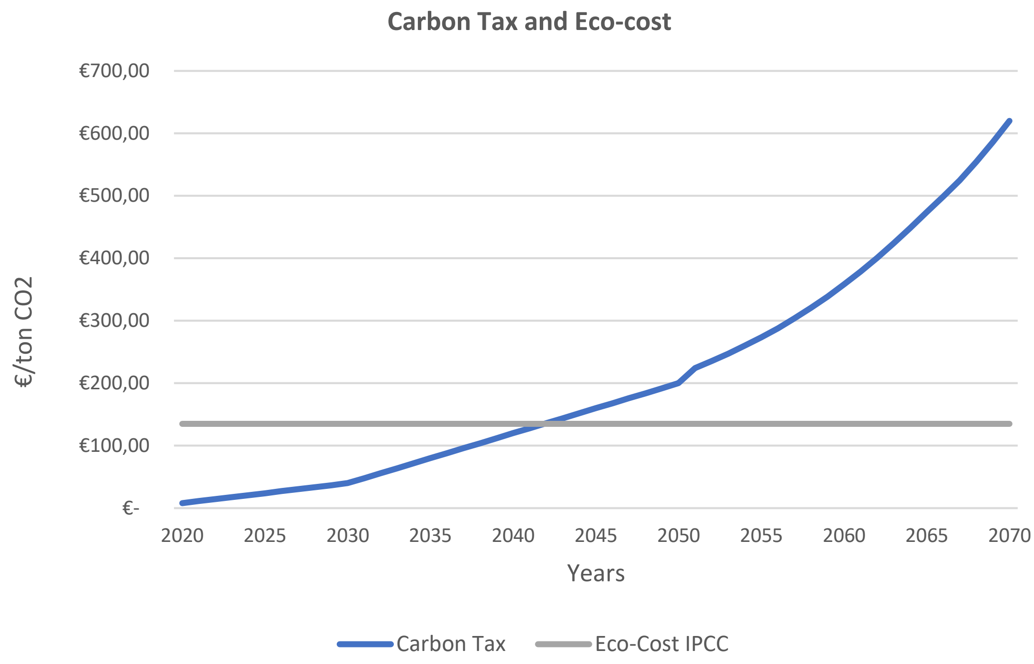


Figure 115: Carbon Tax and Eco-cost estimation [based on data provided by J.G.Vogtlander "LCA-based assessment of sustainability: The Eco-costs/Value Ratio (EVR)"]

If we applied the Eco-cost of 135 €/ton CO_2 to our case study, it would lead us to consider the Carbon Tax no longer as a mere instrument of taxation to be added to the cumulative cost of the work, but rather with a view to increasing the intrinsic value of the building, through greater weight to the least impactful technologies.

As already explained, the eco-costs linked to the various environmental indicators are expressed in monetary value in 2007, so considering the same rate of inflation used in the LCC methodology, the costs have been discounted to 2020 so that they can be integrated into the LCC and LCA evaluation of our case study. Compared to the application of the carbon-tax, where cost growth starts from values that are still too low to change the economic perception of companies, the Eco-Cost represents a stable average value over time. Therefore, if we consider that the phase with the greatest impact remains the production phase, the IPCC evaluation responds exactly to the question of how to have a greater impact on the evaluation of materials with the least impact.

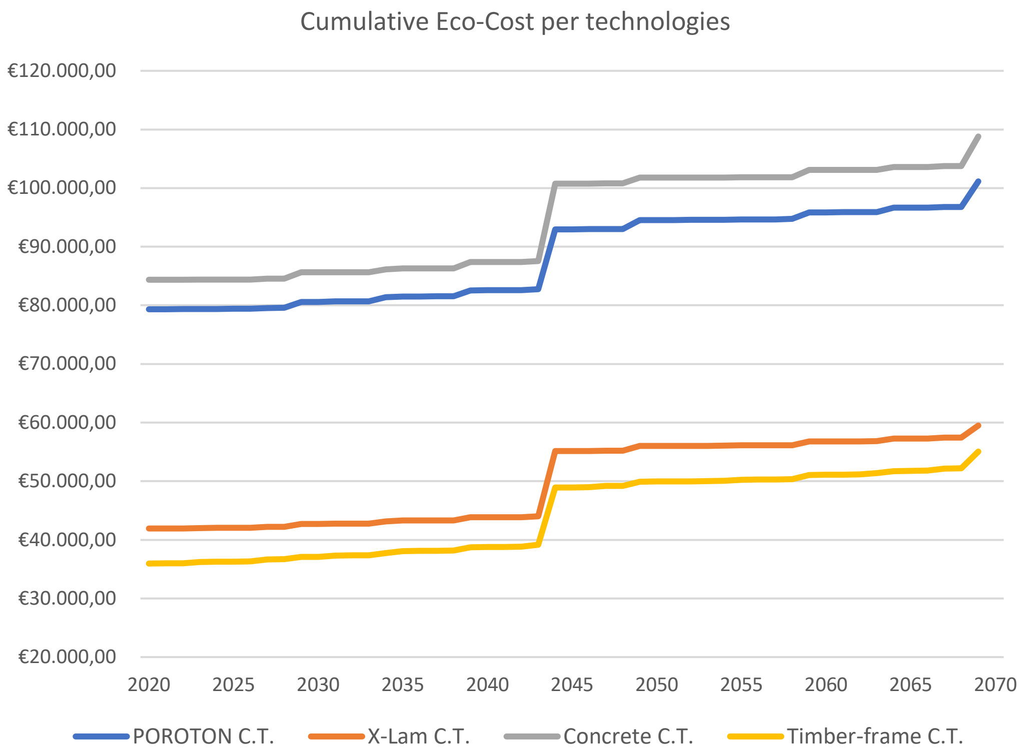
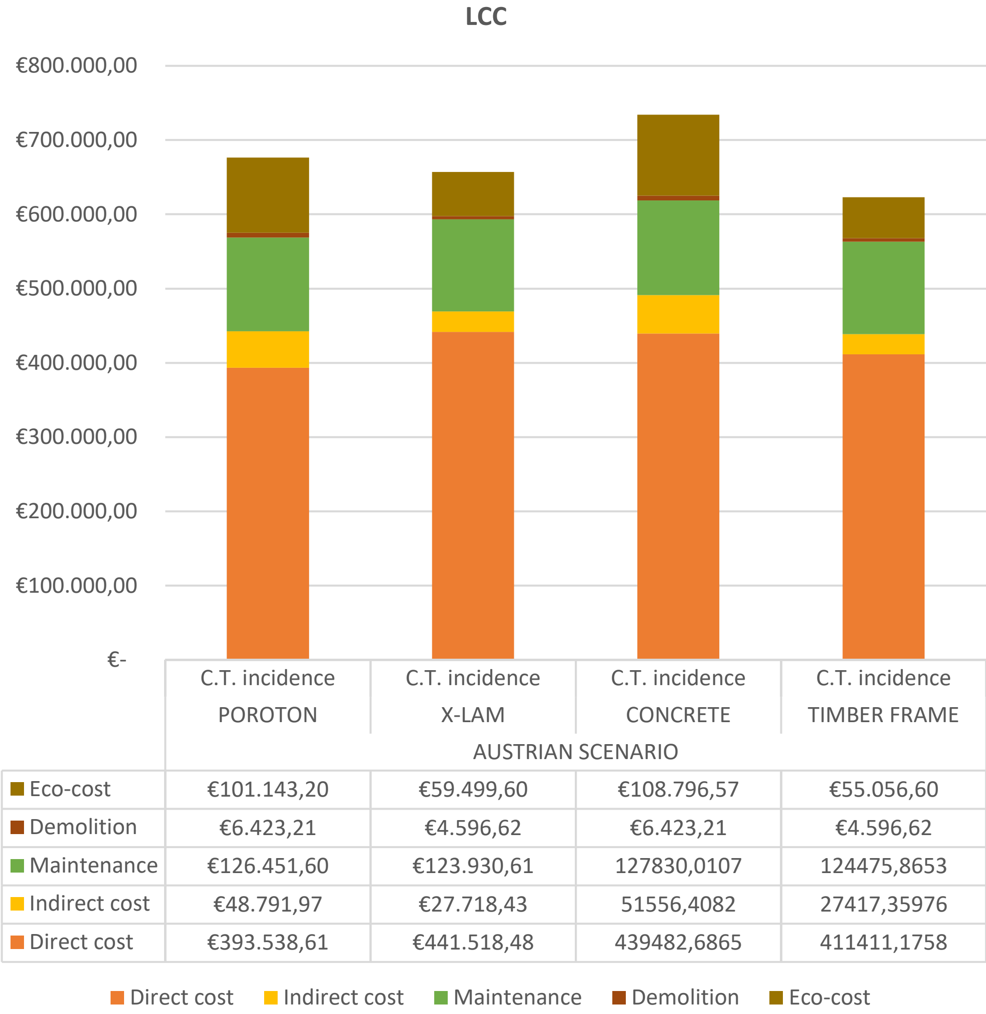


Figure 116: Cumulative Eco-cost per technologies

The evaluation therefore identifies, with a different monetary weight to the Carbon Tax, a hidden cost that companies would have to face to cover the emissions generated by their operational chain. The relationship between economic and environmental assessment is therefore fundamental in order to obtain an ever-increasing eco-efficient ratio



	C.T. incidence POROTON	C.T. incidence X-LAM	C.T. incidence CONCRETE	C.T. incidence TIMBER FRAME
Eco-cost	€101.143,20	€59.499,60	€108.796,57	€55.056,60
Demolition	€6.423,21	€4.596,62	€6.423,21	€4.596,62
Maintenance	€126.451,60	€123.930,61	127830,0107	124475,8653
Indirect cost	€48.791,97	€27.718,43	51556,4082	27417,35976
Direct cost	€393.538,61	€441.518,48	439482,6865	411411,1758

Figure 117: LCC with Eco-cost application

The cost analysis with the inclusion of the eco-cost relating to CO_2 emissions for each technology used in the scenario, shows that the eco-cost identified for the technologies Poroton and Concrete are 45% higher than that relating to wood technologies. This is a clear indication of how eco-cost can comprehensively identify the relationship between technologies with very different environmental impacts. Furthermore, the eco-cost impacts more sharply than the carbon tax, especially as regards the impact of the eco-cost on the total cumulative costs, both with respect to the initial investment. The major problem encountered in the taxation of carbon has been identified in the inability to tax adequately the environmental impacts generated in phase A1-A3, the opposite consideration in the application of eco-cost.

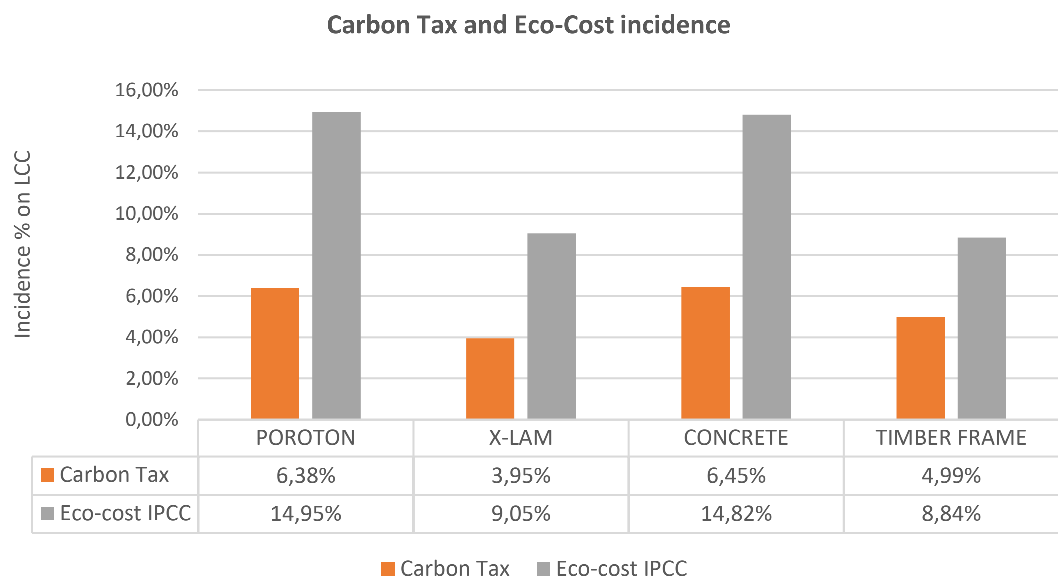


Figure 118: Eco-cost incidence on LCC with respect Carbon Tax

The eco-cost, although it should not be considered a real cost but a hidden economic value, can have a much greater influence than the total cumulative costs, thus managing to direct the choice and perception of the least impacting solutions as the equally most advantageous solutions to be used.

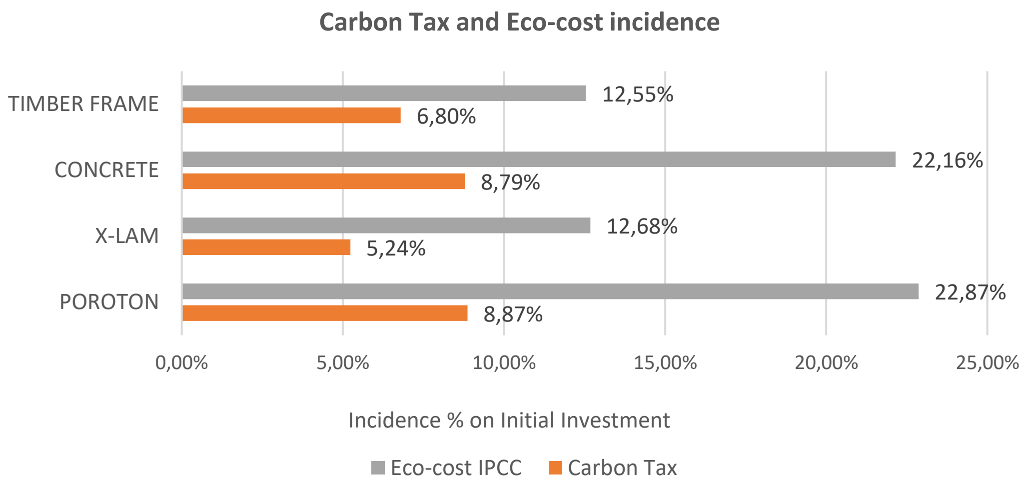


Figure 119: Eco-cost incidence on Initial Investment with respect Carbon Tax

The incidence of eco-cost compared to the mere initial investment is an indicator that allows us to identify the most impactful difference between the two systems, in which the eco-cost manages to identify a much higher cost for investments that generate more air pollution. The Poroton and Concrete finally are identified with an initial investment to which must be summed up a more then 20% more hidden cost related to the environmental emissions. The eco-cost succeeds in give a very high influence in the decision-making process and change the perception of building values, in which the environmental impacts has a strong relevance.

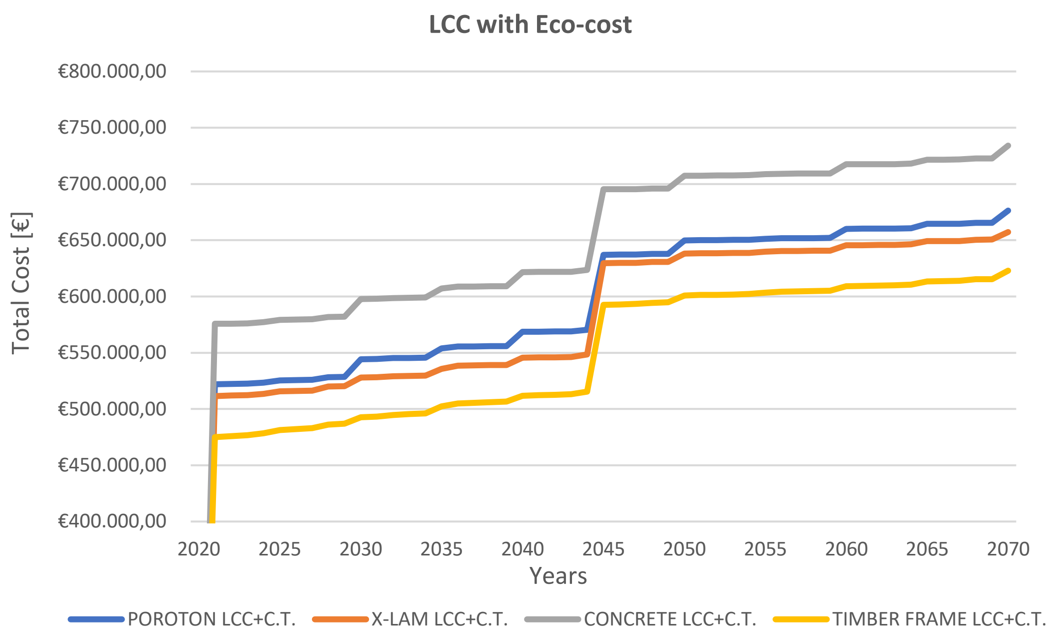


Figure 120: LCC including Eco-Cost

It is important to note that since the outflow generated by the initial investment, the eco-cost allows the two technologies with the least impact to be the two best choices from the point of view of economic performance, thanks to their intrinsic characteristic of causing less air pollution.

10.4 Reference

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J.G. Vogtländer, "*LCA-based assessment of sustainability: the eco/costs/Value Ratio(EVR)",* Sustainable Design Series of Delf University of Technology, 2007. Available at: http://www.vssd.nl/hlf/b004.htm

11 Conclusions

The primary aim of this work was to analyse evaluation methods of the life cycle of a residential building among 4 different technological solutions through LCA ed LCC analysis, in order to make the best choice in an early-design phase. The main goal was to identify a single unit of measurement to be able to compare environmental and economic aspects, to this purpose, it was decided to attribute a monetary value also to the LCA, an aspect that is often neglected; therefore, two types of proposals were made with the aim of encouraging companies to implement eco-sustainable corporate behaviours and policies. The first is the so-called carbon-tax, a policy to limit CO_2 emissions into the atmosphere and reduce the increase in temperatures of the planet in the horizons of 2030-2050. It is a solution that turns out to be interesting and impacting from a decision point of view only in the future, when taxation will be increasingly consistent, but currently has an impact of about 5% on total costs during the life cycle.

It was therefore decided to propose an alternative solution, that is the application of eco-cost, the IPCC was able to demonstrate how, for some types of pollution, it is possible to obtain a corresponding estimate of future costs incurred by those responsible for the negative impact. In practice, the IPCC calculates the amount needed to remedy the environmental damage caused, based, for example in the case of climate change, on the index measuring the warming potential of greenhouse gases (GWP). It is an interesting measure that manages to monetarise the negative externalities caused by CO_2 emissions into the environment, it can be called as "hidden" cost, being not really paid, but used in a sort of cost-benefit analysis aimed at making the best design choice and then to give a higher value to the more environmentally friendly option, unlike the carbon-tax, which is instead a real fee to be paid. Through this policy, the results are considerable, so we see that the environmental impact has a strong weight on the initial investment, about 20%, a substantial figure and certainly has a strong relevance in terms of decision-making.

However, it is necessary to find a way to measure the other environmental indicators in monetary terms, even if the GWP is certainly the most discussed. There is a lot of research going on, but it is not easy to find a unified method, especially at a global level. We believe that the method proposed by the IPCC must be a real input that raises awareness and pushes for a change at a political level on the weight to be attributed to the environmental impact caused by products, not only in the world of construction, over the life cycle, and that also leads to the introduction of standards, as well as in recent years progress has been made with regard to economic analysis based on the life cycle that is now becoming recognized also at the Italian level, as demonstrated by recent regulatory developments introduced for example by D.Lgs n. 50 of 18 April 2016, which regulates the procurement code and requires companies participating in public tenders to formulate a life cycle cost analysis (art. 96 of the aforementioned decree).

Another aspect we would like to comment on concerns the availability of data for carrying out the LCA analysis. In our case we used the database Ecoinvent v.3, ecoinvent can be defined as a global leader in creating the most transparent life cycle inventory databases, but despite this, we found many difficulties in finding the materials that were present in our project, even if they were very common building materials, especially in end-of-life scenarios. In this regard, it would be necessary to force industries to produce EPDs, as happens in France for example, because the current situation allows for analysis with a large margin of error.

Regarding the end of life, a subject widely discussed in recent times, currently there is not much documentation. Often, in fact, for both economic and environmental analysis, percentage values referring to the entire life cycle are taken as a reference, in general they impact about 3%, which is why it is not given particular weight. But on this subject, it is essential to investigate in a perspective of "from cradle to cradle", especially when it comes to prefabrication. Unfortunately, in this thesis the end of life of materials has been treated in the same way in the 4 scenarios analysed, no distinction has been made between prefabricated technologies (the wooden ones) and others because we had to stick to datasets. This is a limit in terms of environmental impacts and certainly costs as the prefabricated elements at the end of their life can be recovered more easily than in cases where there is an undifferentiated demolition, even giving rise to scenarios of reuse and not only recycling.

A brief comment on the outputs of our work: wooden buildings were the most environmentally friendly. In the current building industry, the aim should be to create projects that are not only aesthetically beautiful, but also functional and respectful of the ecosystem, through the recycling of materials, adopting technologies that exploit renewable and non-polluting energy. The wood in this context is the most suitable to achieve the defined technical characteristics, both from an environmental and from a technological point of view; indeed, it has considerable advantages: a reduction in consumption (for example energy) and emissions (CO_2) has been the principle underlying the mitigation of environmental impacts so far. By optimizing the weak points (high energy incorporated) and maximizing the strengths (environmental benefits), the increased use of wood can improve the environmental profile of a building. Moreover, it is easily available thanks to the sustainable management of forests, which in Europe increases their surface every year.

Attachments

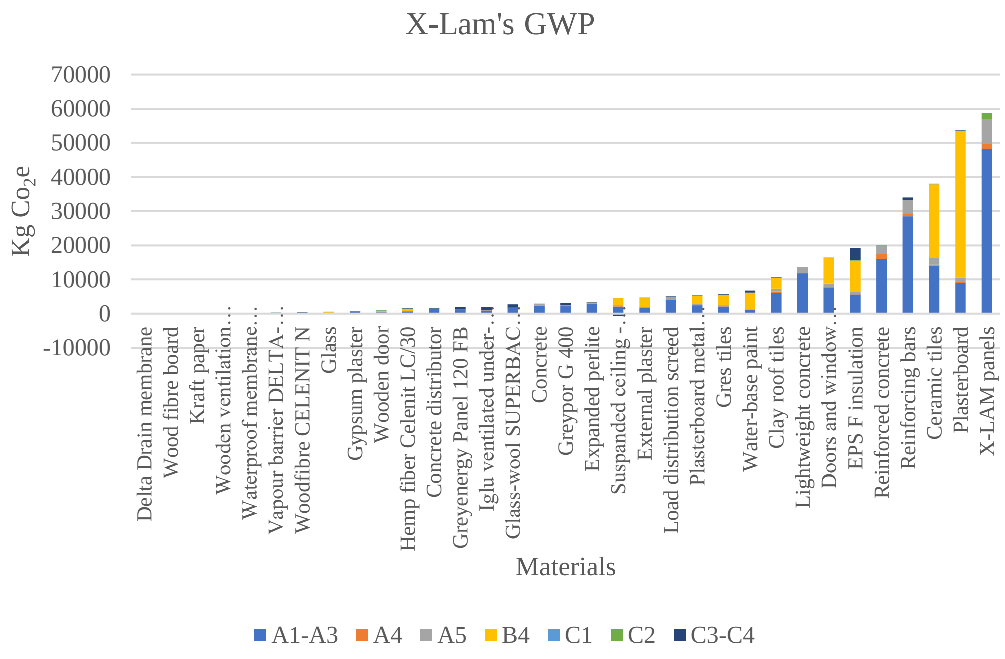

Figure 121: X-Lam's GWP output for each material, highlighting share of each phase

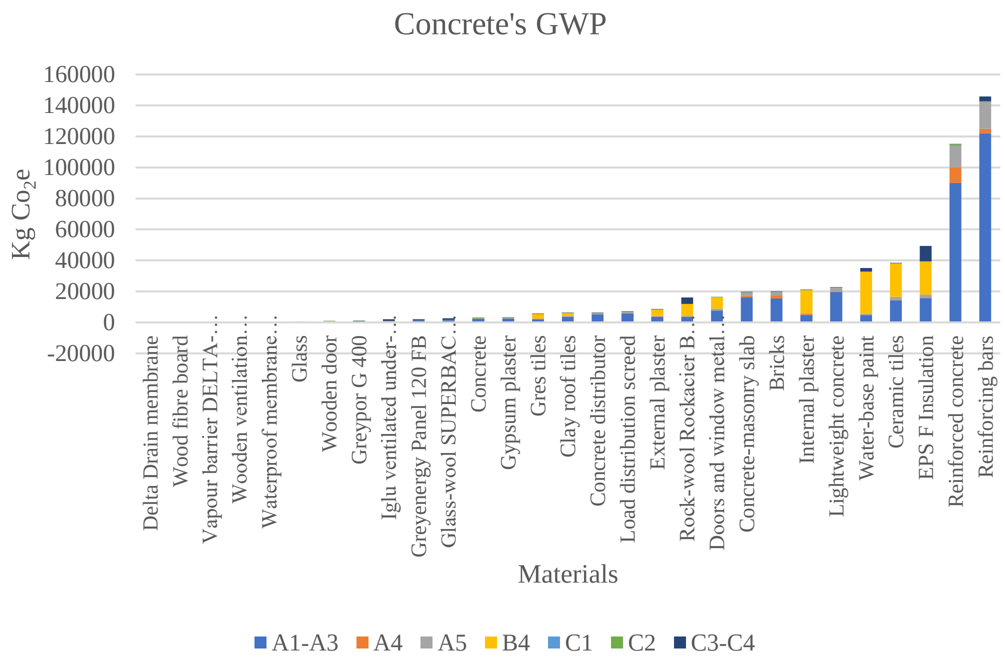

Figure 122: Concrete's GWP output for each material, highlighting share of each phase

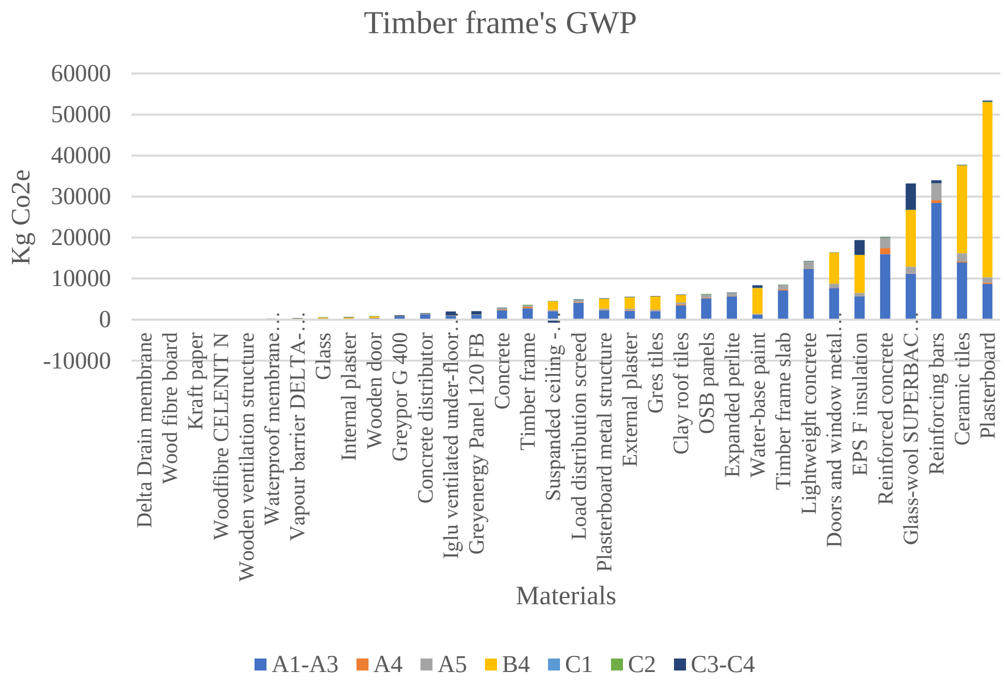

Figure 123: Timber frame's GWP output for each material, highlighting share of each phase

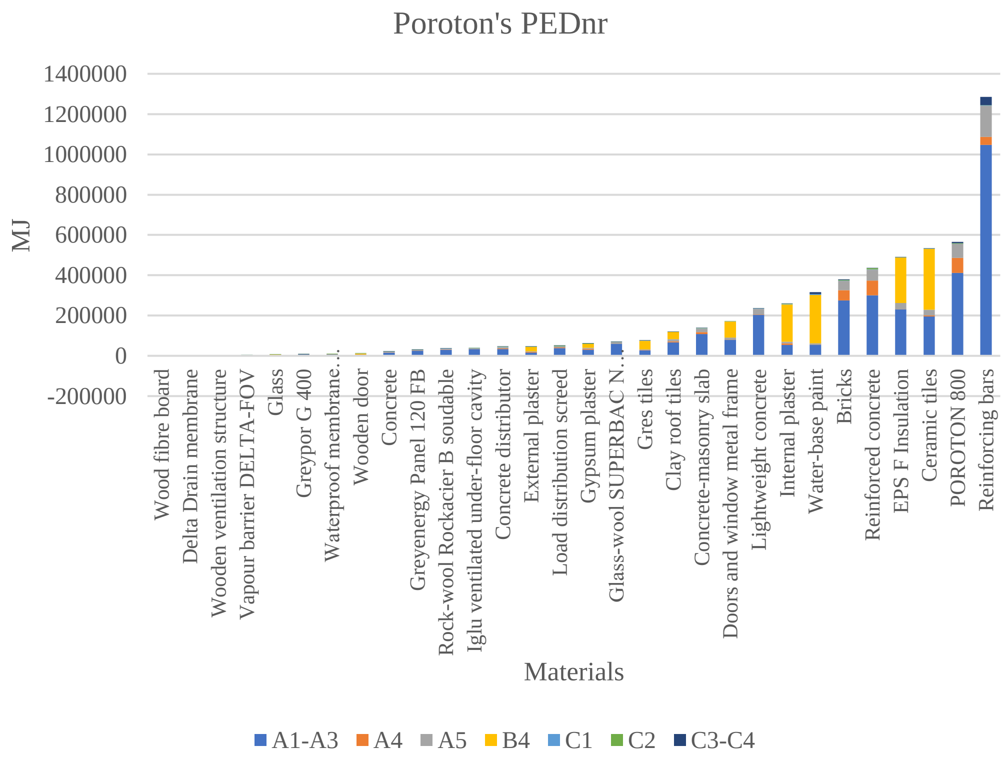

Figure 124: Poroton's PEDnr output for each material, highlighting share of each phase

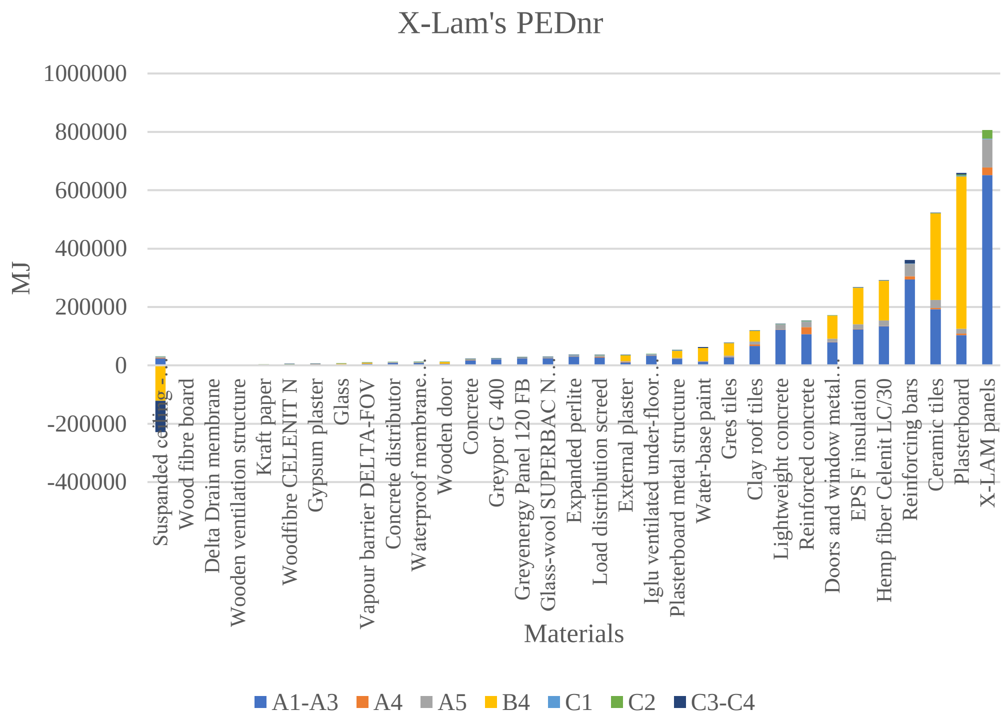

Figure 125: X-Lam's PEDnr output for each material, highlighting share of each phase

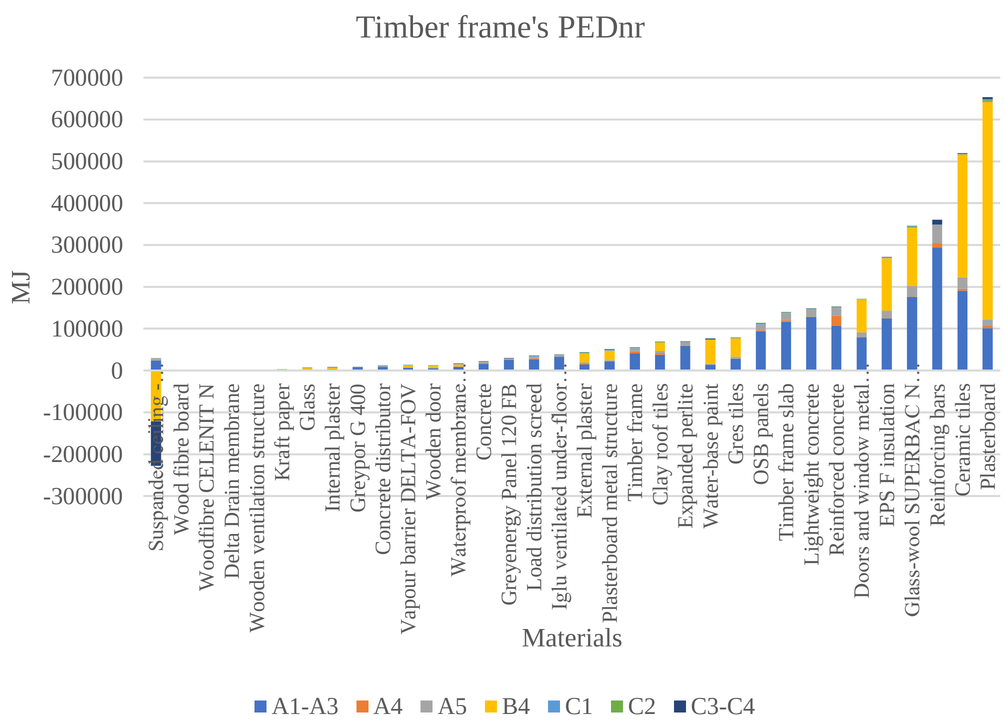

Figure 126: Timber frame's PEDnr output for each material, highlighting share of each phase

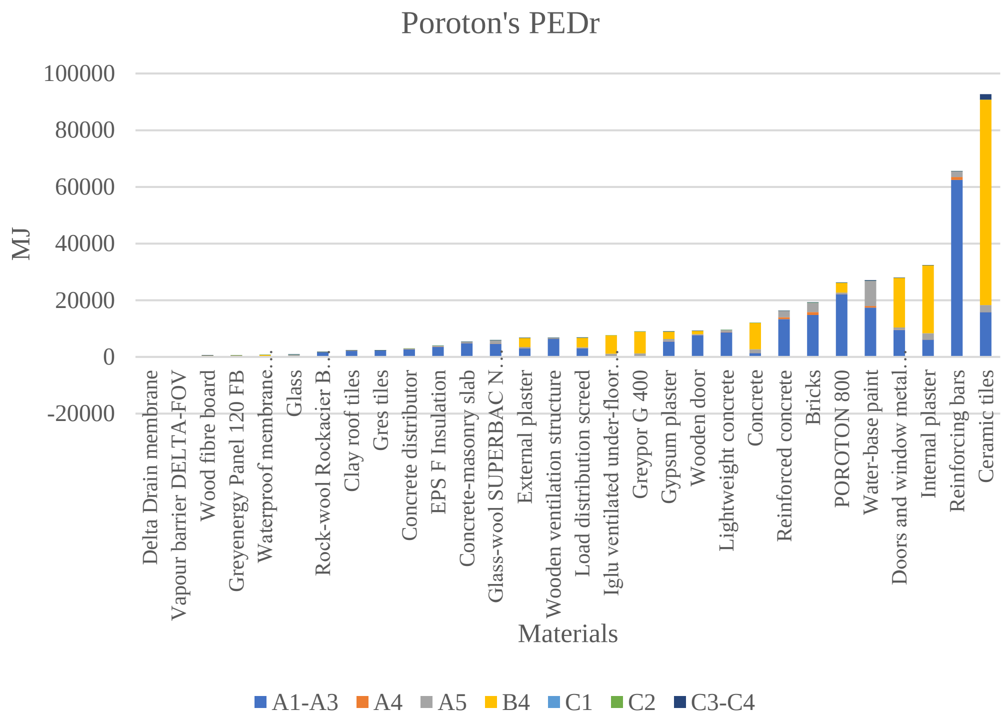

Figure 127: Poroton's PEDr output for each material, highlighting share of each phase

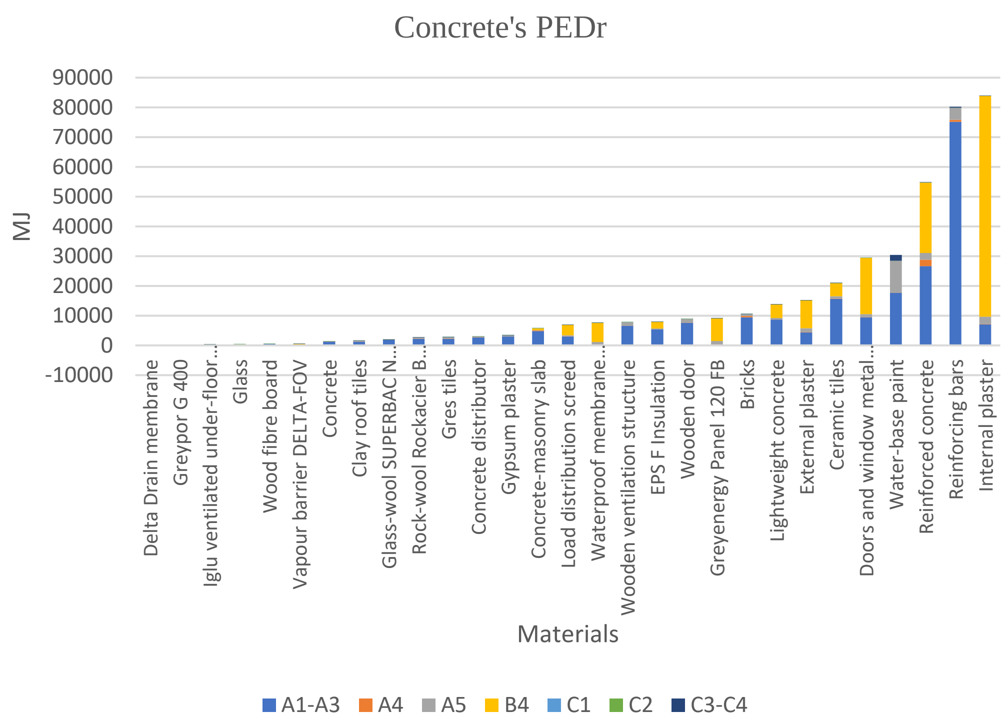

Figure 128: Concrete's PEDr output for each material, highlighting share of each phase

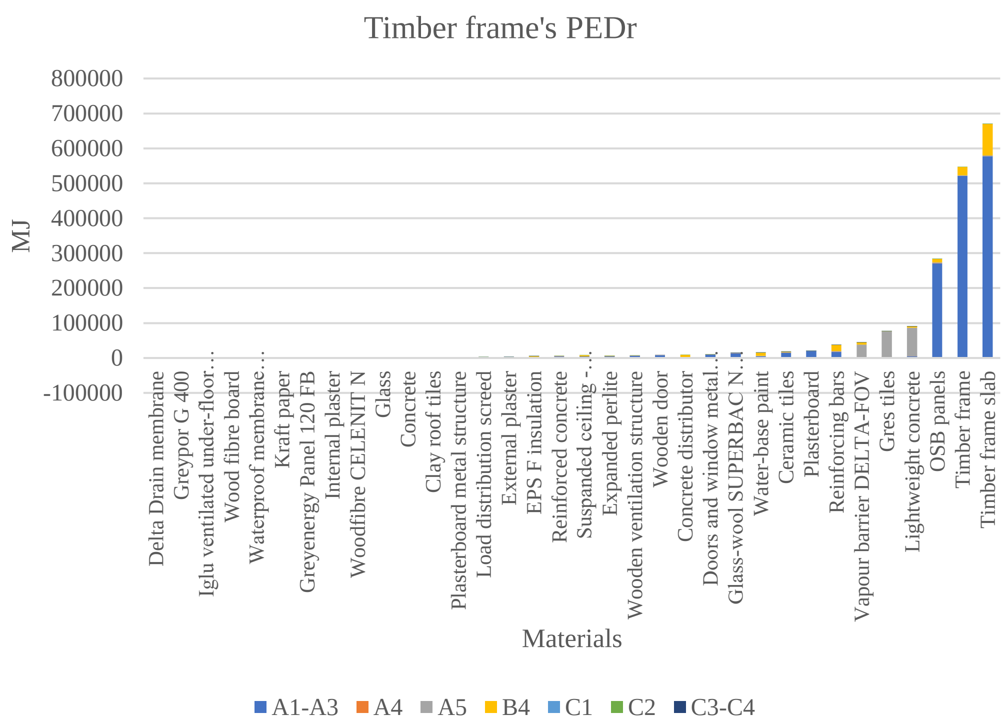

Figure 129: Timber frame's PEDr output for each material, highlighting share of each phase

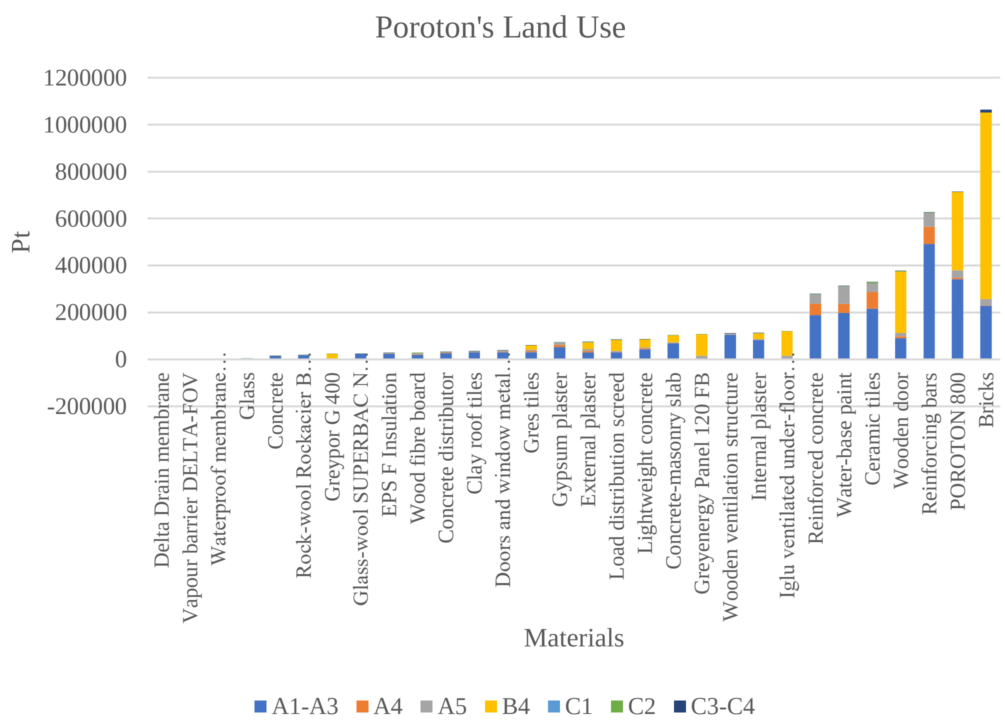

Figure 130: Poroton's Land Use output for each material, highlighting share of each phase

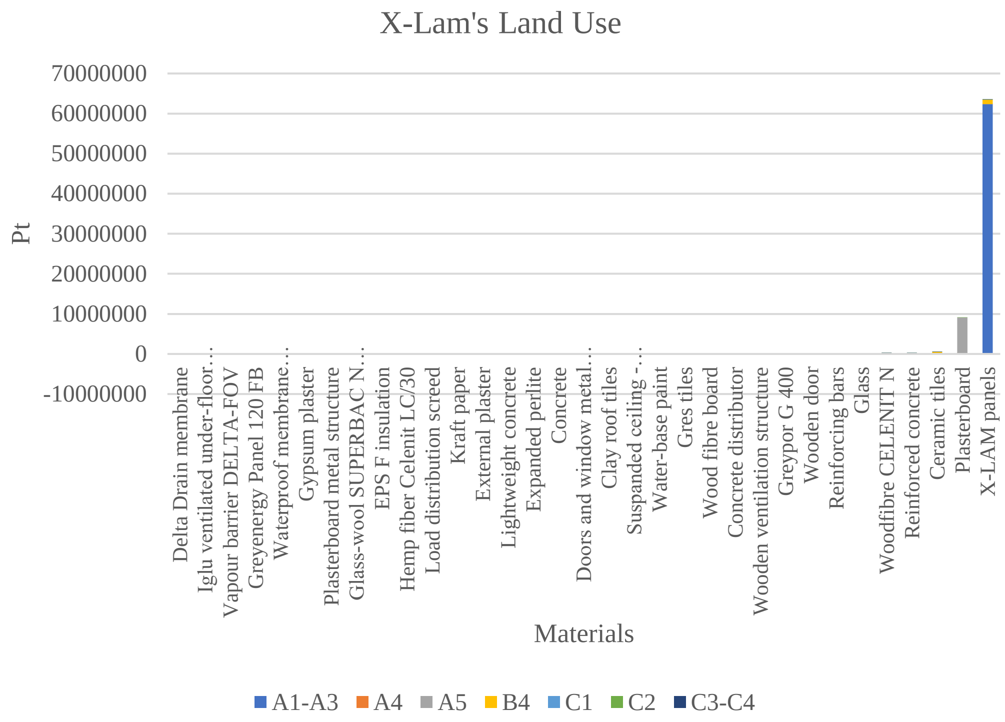

Figure 131: X-Lam's Land Use output for each material, highlighting share of each phase

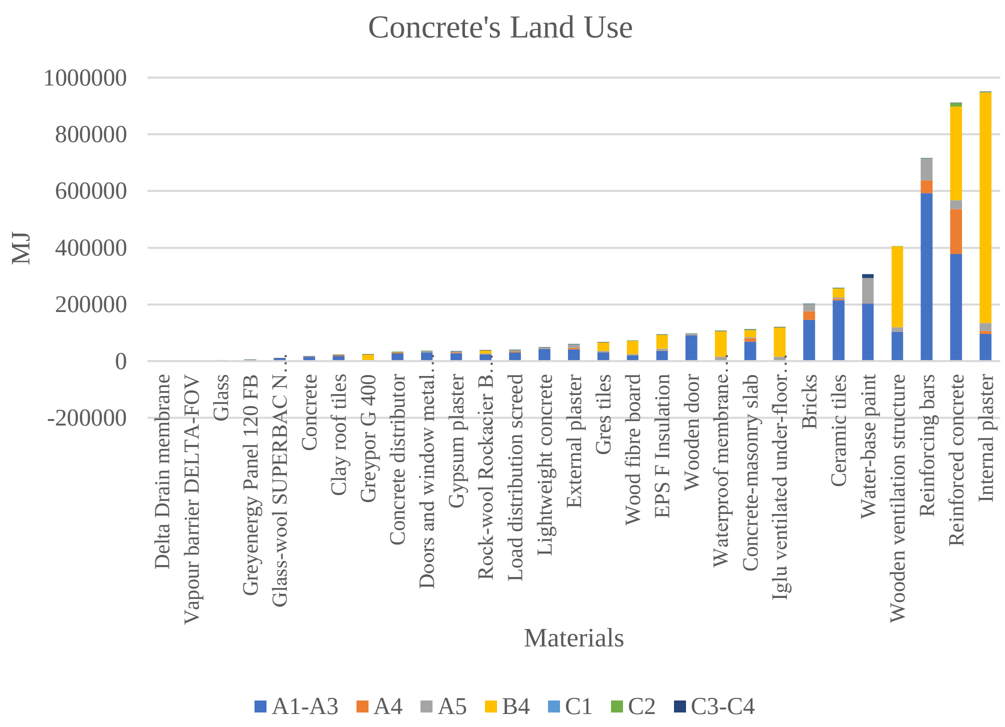

Figure 132: Concrete's Land Use output for each material, highlighting share of each phase

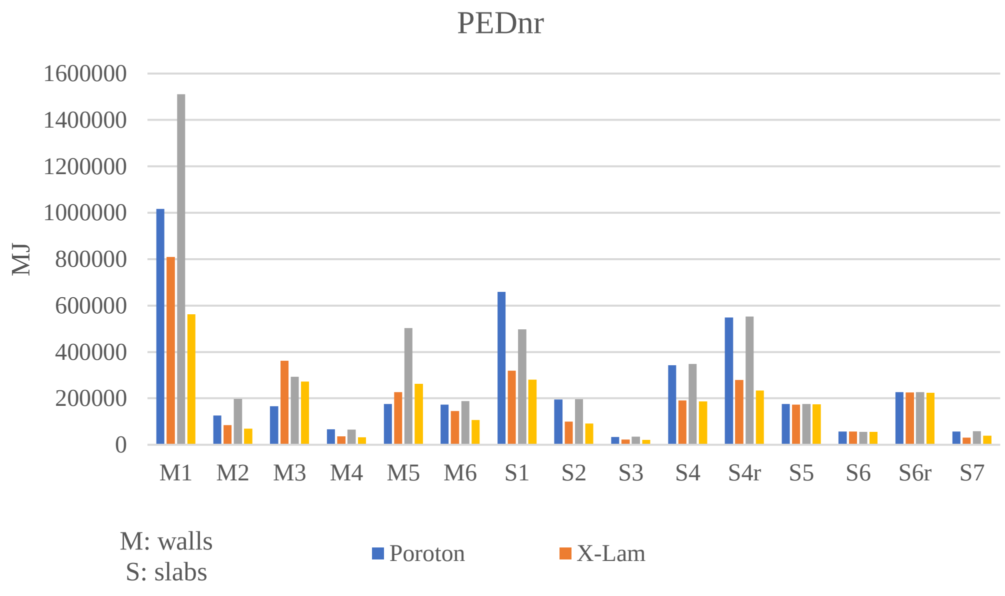

Figure 133: Comparison of PEDnr's outputs among the elements with the same transmittance

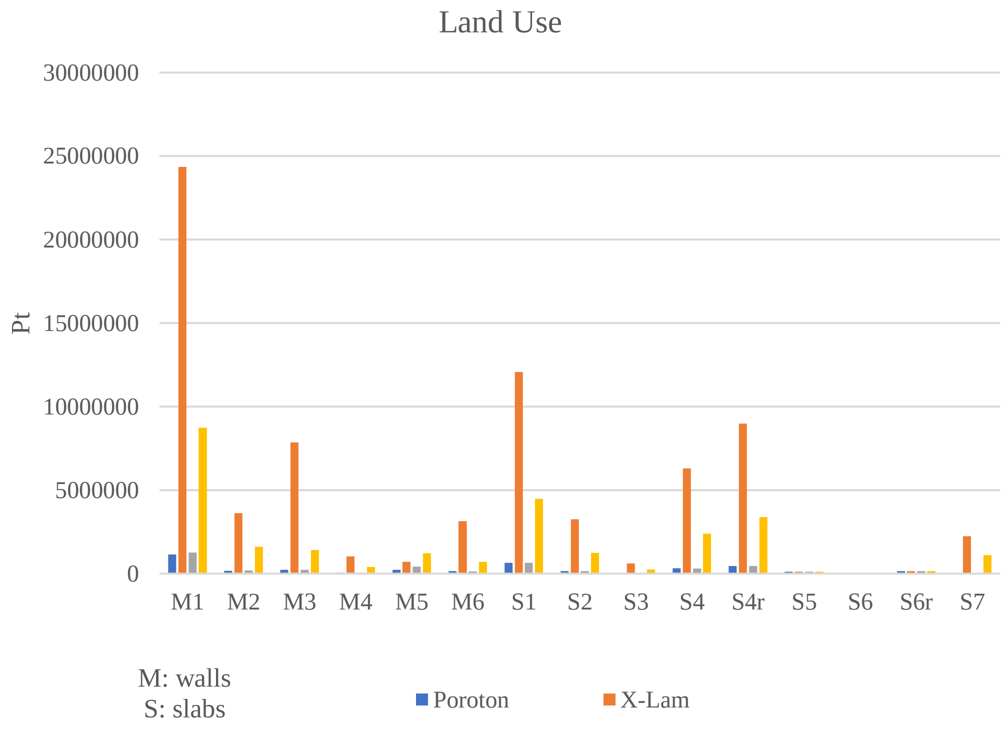

Figure 134: Comparison of Land user's outputs among the elements with the same transmittance

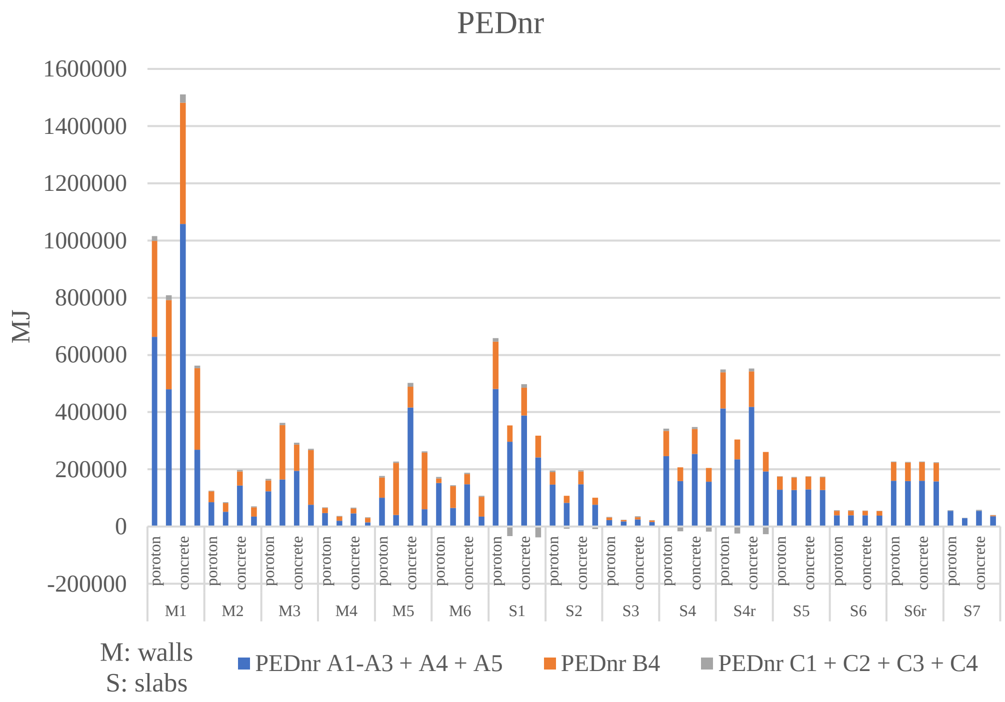

Figure 135: Comparison of PEDnr's outputs among the elements with the same transmittance highlighting the different life cycle stages

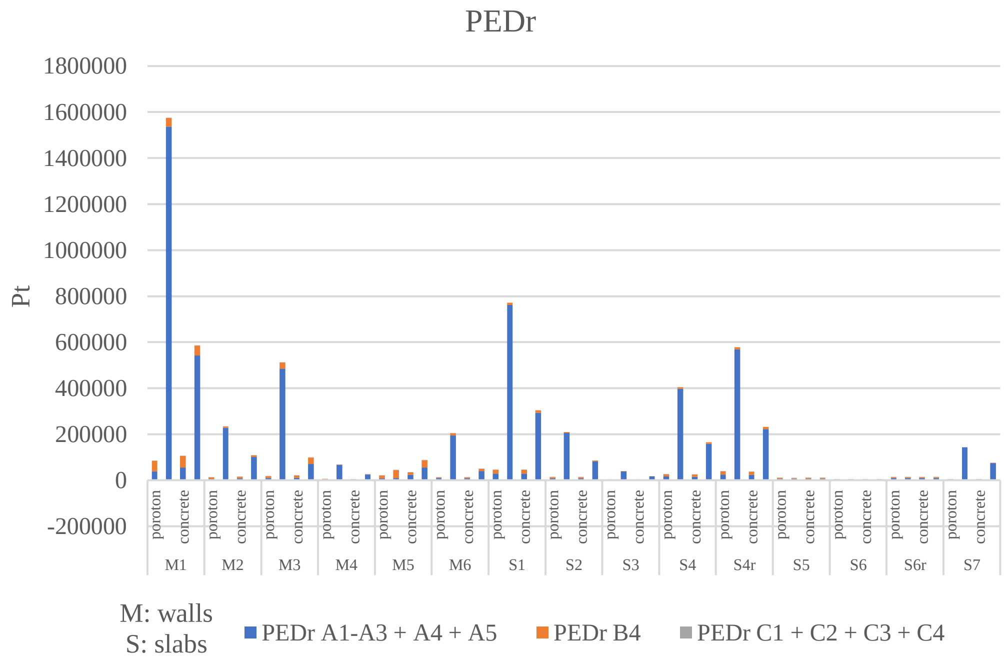

Figure 136: Comparison of PEDr's outputs among the elements with the same transmittance highlighting the different life cycle stages

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