The sustainable approach to structural and thermal design in buildings

Autors:

Bernardino Chiaia

Alessandro Pasquale Fantilli

Oscar Mancinelli

Andrea Cutrupia

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1. Aims

The use and sustainability of cement in housing construction is a concern due to the considerable amount of carbon dioxide generated in the manufacturing process [1], with most recent reporting indicating that clinker burning accounts for approximately 4% of all global CO2 emissions." [2]
In response to the problem, the use of more ecologically sound alternatives such as wood is increasing [3], however the determining factors and efficacy of such materials on environmental impact is still an open debate. Further generalized environmental impact assessment (E.I.A.) of these building materials is necessary.

In this regard, the goals of this work are to answer the following questions:

- To what extent is the sustainability of a construction influenced by the construction techniques, and by location?
- What are the results obtained by Life Cycle Assessment (LCA) when only the materials are taken into consideration?
- How are the results influenced by the use of the building?

In order to answer these questions, it was decided to carry out two studies on two different types of building: a single-family house and a condominium. The first case focuses on a small 3-story building with a total area of 120 m^2 (Fig. 1); the second on a multistory building. The study of the first building has been completed and the evaluation of the second building has just begun. Therefore, only the analysis of the family house will be discussed at present.

The structure of this house consists of:

- Reinforced concrete frame with cast-in-situ beams, columns and one-way slabs;
- Precast reinforced concrete vertical panels and horizontal one-way slabs.
- Timber CLT structure.

The climatic influence on the use of the building was taken in account by analyzing three different scenarios: building in Catania, Turin and Oslo. Therefore, the family house reported in Fig.1 was evaluated 9 times. For each structural typology a FEM analysis was conducted using dedicated software (CDM Dolmen [4]).

Fig. 1: EMA Haus, Arch. Bernardo Bader.

2. Design of structural and non-structural elements

Because an existing building (Fig. 1) is investigated, the shape and the geometrical dimensions of the structure are fixed. Only the thickness of the panels and the size of the frame cross-sections are modifiable, which have been designed to satisfy all requirements for proper performance.
All structural analysis and design were performed using *CDM Dolmen*, which is a Finite Element software.
The stratigraphy of the envelope was chosen according to the construction technology and the local weather conditions. Each type of construction is characterized by a specific stratigraphy, which remains the same in the three locations; only the thickness of the insulating layer changes according to the required thermal performances.
Instead, the stratigraphy design of different building types was carried out to ensure the same thermal transmittance values.

2.1. Reinforced concrete frame

As mentioned above, the design of the structure was made in accordance with current shape and dimension of the building (Fig.2).
Pre-dimensioning was conducted by referring to ACI code [5] and Eurocode 2 [6], which establish the minimum size of the structural element. An appropriate stratigraphy was provided for envelope elements and internal partitions (external and internal walls, slabs, and roof). Fig.3 shows the cross-section of external walls, which are composed of a plaster layer, bricks, mineral wool isolating panels, and another plaster layer (internal to external ordering). Table 1 shows the layers thickness of this type of wall.

Fig. 2: Reinforced concrete structure.

Table 1: Layers of the external wall in RC frame.

External walls		
	Material	**Thickness [m]**
1	Plaster	0.015
2	Thermal insulation -	0.05
3	Bricks	0.25
4	Plaster	0.015
	Total thickness [m]	0.33

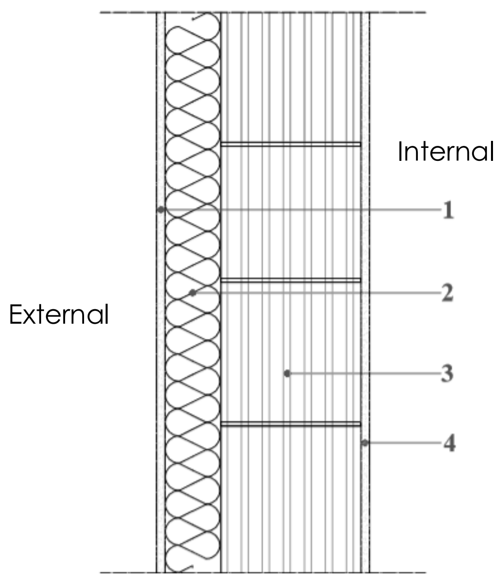

Fig. 3: Stratigraphy of the external wall of R.C. frame.

2.2. CLT structure

Cross Laminated Timber structure, also known as C.L.T., was developed by an Austrian timber manufacturing company in 1990. C.L.T. structuring consists of three to nine cross laminated softwood board plies with different orientation, which form precast panels. The layers are composed of wooden slats which are crossed and glued by a specific type of glue.

In this project, CLT Dolomiti was chosen [7].

CLT consists of good structural, thermal and fire resistance properties and is made from sustainable material with a low carbon footprint, because it is derived from re-planted trees. The ecological issue resulting from C.L.T. is the adhesive glue used in production and its effect on the environment.

In order to guarantee the connection between CLT panels, self-drilled screws were used. To connect vertical and horizontal elements, L angular (to transfer shear forces) and hold – down (to transfer vertical forces and moment) anchors were chosen. The skeleton of CLT structure is made up of precast panels whereas the element in direct contact with the soil, such as foundations and slab on grade, are made with concrete. Due to different structural and thermal requirements, stratigraphy changes.

An example of the external wall is shown in Fig. 4. Table 2 indicates the layers' thicknesses.

Table 2: Layers referred to external wall in CLT structure.

External walls		
	Material	**Thickness [m]**
1	Plaster	0.015
2	Thermal insulation	0.160
3	CLT panel	0.090
4	Thermal insulation	0.050
5	Gypsum Plasterboard	0.015
6	Gypsum Plasterboard	0.015
	Total thickness [m]	0.345

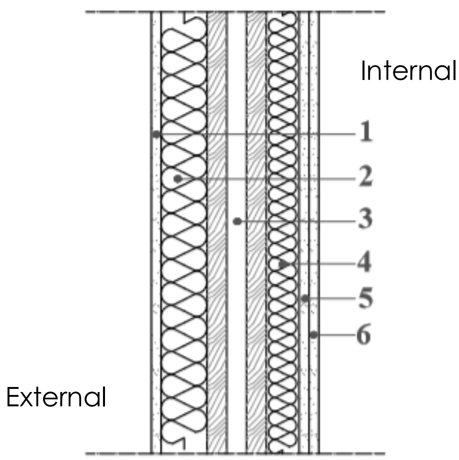

Fig. 4: Stratigraphy of the external wall in CLT structure.

2.3. Precast RC Panels Structure

The use of Precast RC Structures allows the combination of concrete with industrial fabrication. Hence, versatile and fire-resistant structures can be obtained with structural elements that are precast in a plant under controlled boundary conditions and then assembled on site. The construction of the building with precast RC panels is faster than with traditional cast-in-situ frame. Precast elements can be beams, columns and panels. In this project, sandwich precast exterior wall panels were employed with respect to time efficiency and to improve the thermal insulation. These panels consist of an insulation core, in XPS, between two layers of normal-weight concrete (Fig. 5). The thickness of insulation layer is in accordance with the local thermal requirement. See Fig. 5 and Table 3.

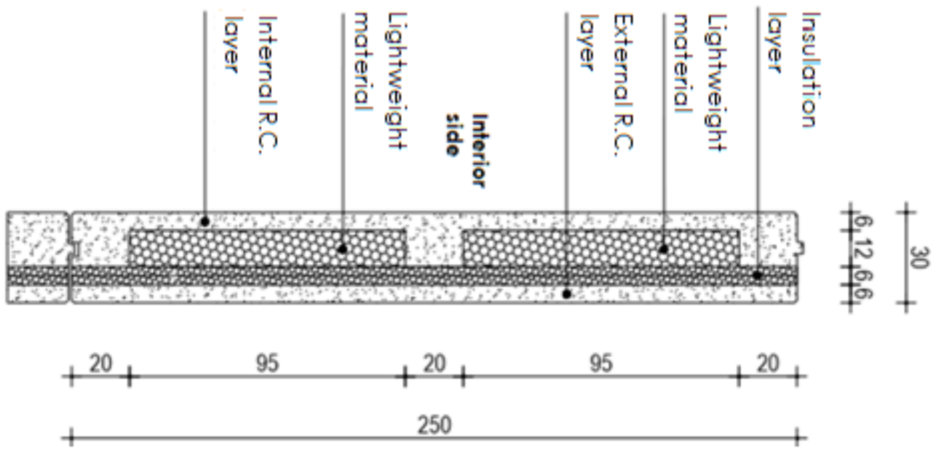

Fig. 5: Precast RC external panel.

Table 3: Layers of external wall shown in precast construction

External walls		
	Material	Thickness [m]
1	Reinforced concrete panel	0.340
2	Thermal insulation - Rockwool	0.120
3	Plaster	0.015
	Total thickness [m]	0.48

2.4. Structural Assessment

CDM Dolmen is the software used for finite element analysis [4]; Through this software, self-load and live load was computed and combined in accordance with Eurocode 2 [6] in the case of concrete structures.

Two phases of computation were made. A pre-dimensioning of the structural elements was conducted in the first phase, then the software computed the necessary reinforcement according to the stresses provided by the static and dynamic analyses. Fig. 6 shows the 3D model created in CDM Dolmen in the case of reinforced concrete structure, whereas an example of Rebar cutting list of a column is illustrated in Fig. 7.

When a building is composed by CLT panels, the structure must be modeled with shell elements (Fig.8), rather than beam elements found in the R.C. frame. In CLT structure, the thickness and the number of layers of which the timber panel is composed were chosen in reference to similar cases. The performance of the panels provided by the producers was compared with the stress values computed by CDM Dolmen. Fig.9 shows this state of stress of one shell structure.

Finally, in the RC. Precast structure the panels and the insulation layer thicknesses were established in accordance with the satisfaction of both thermal and mechanical performance. The amount of reinforcement within the panel was determined from literature [8]. As in the case of CLT structures, structural check is based on the comparison between calculated stresses and the mechanical strength of the materials. For this reason, the FEM model used in this case is the same of the CLT structure (Fig. 8).

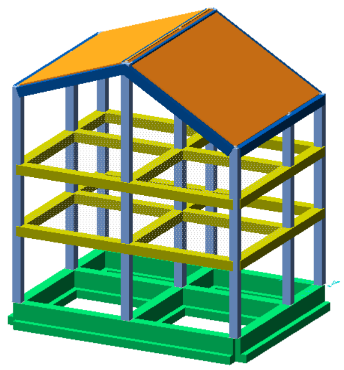

Fig. 6: Structural model of R.C. frame.

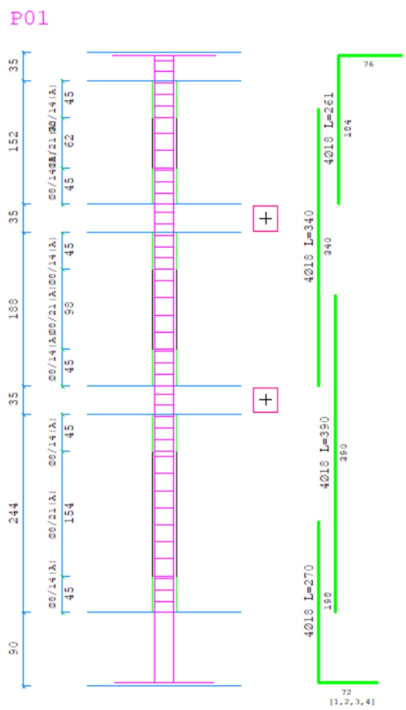

Fig. 7: Example of the rebar cutting list in a column of the R.C. frame structure.

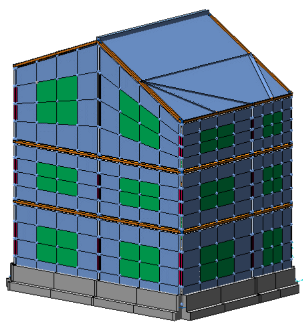

Fig. 8: Model with shell elements valid both for the CLT and precast R.C. structures.

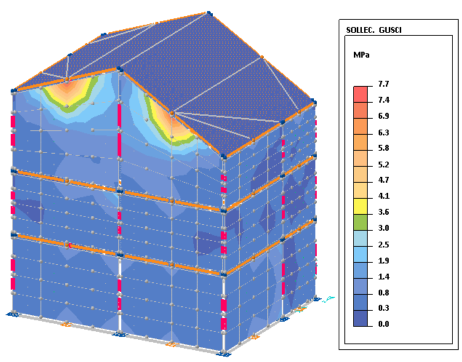

Fig. 9: State of stress in the shell structure.

3. LCA

3.1. Introduction

LCA (Life Cycle Assessment) is an environmental impact evaluation tool. It considers the complete life cycle "from cradle to grave"; from materials production to the end-of-life and management of waste disposal (Fig. 10).
In relation to the LCA, the analysis may be performed at the product level (according to EN 15804 [9]) and at the building level, according to EN 15978 [10].
EN 15978 considers in the LCA process (Fig. 11):

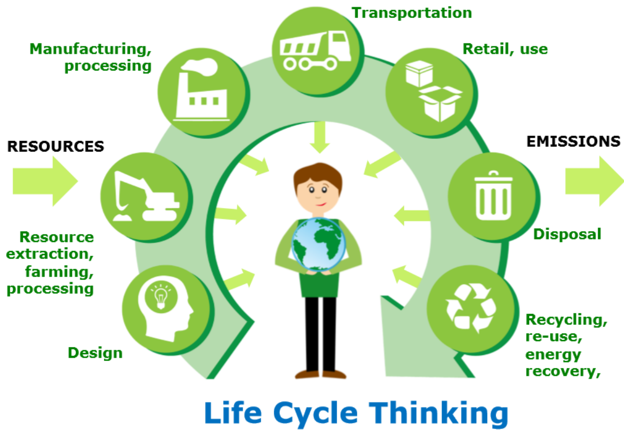

Fig. 10: Life Cycle Assessment basic principles [11]

- Material production (Modules A1 to A3).
- Construction stage (Modules A4 and A5).
- Use stage (Modules B1 to B7).
- End – of – life stage (Modules C1 to C4).
- Benefits and loads due to recycling, recover or reuse of materials (Module D).

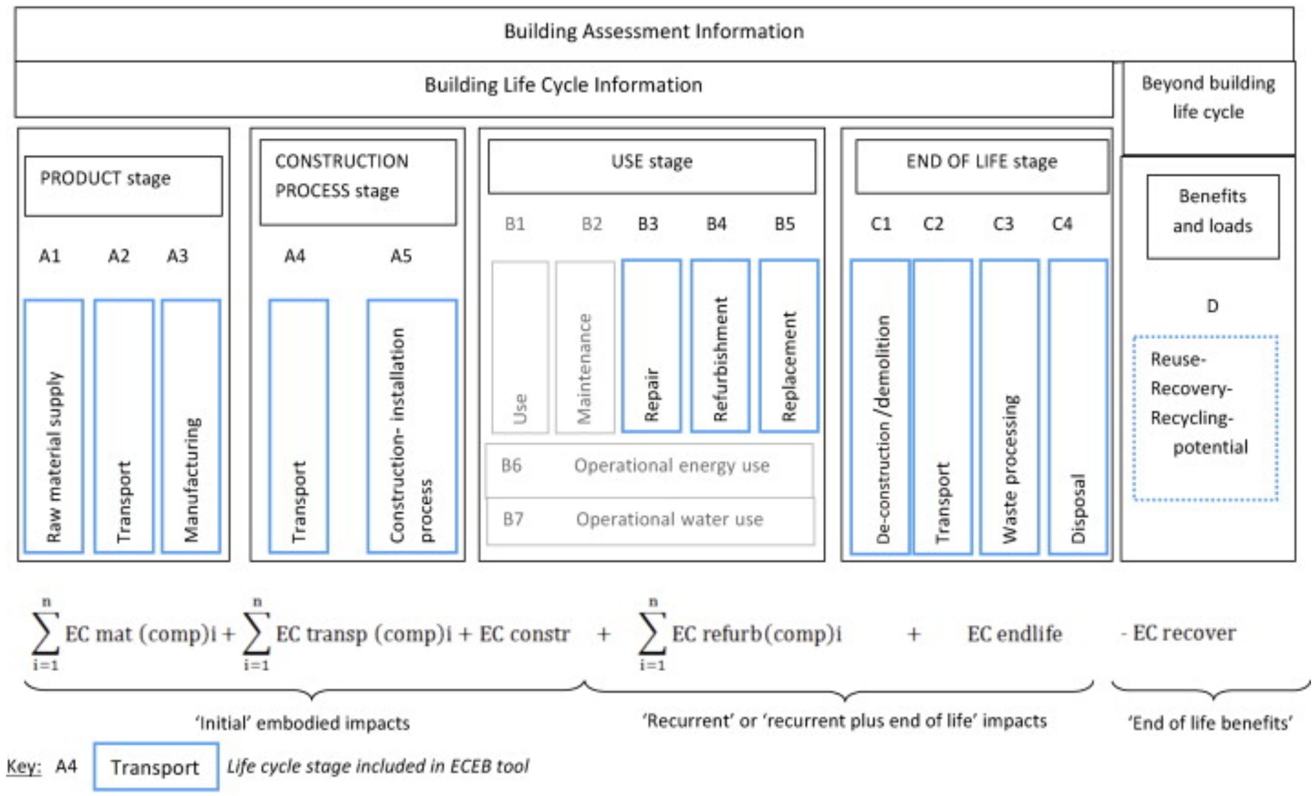

Fig. 11: Life cycle stages from EN 15978:2011 [10].

According to ISO standards 14040-44 [12, 13] and to the ILCD Handbook guidelines, the LCA structure is divided into four phases (Fig. 12):

- Goal and scope definition.
- Life Cycle inventory (LCI).
- Life Cycle Impact Assessment (LCIA).
- Interpretation

In the goal and scope definition phase, the objectives of the study, the reasons that led to carry it out and the expected audience have to be clearly declared. This phase requires also methodological choices, such as the definition of the Functional Unit and of the System Boundaries. The Functional Unit is a reference parameter to which results of LCA are related. The choice of the Functional Unit is arbitrary, but it has to be consistent with the goal of the study and the function of the product analyzed with the LCA. The identification of the system boundaries consists in deciding the boundaries of the study and the processes that will be included in the LCA.

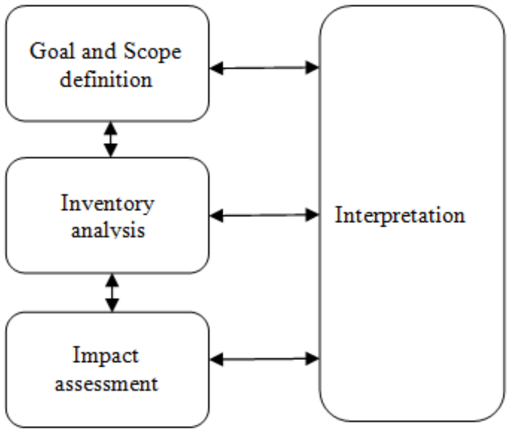

Fig. 12: Life Cycle Assessment Framework [12].

The identification of data quality requirements is also part of this phase: it is important to define, according to the goal of the study, the data characteristics, in terms of time, geographical and technology coverage, precision, completeness and representativeness of the data, uncertainty of the information, source of the data (primary or secondary data), gaps and cut-off criteria.
The **Life Cycle Inventory** phase consists in the quantification of inputs and outputs throughout the life cycle of the studied product, according to the methodological decisions taken in the first phase. Data on raw materials, energy and emissions have to be collected. The data inventory is the most time and resource consuming phase of the LCA and, according to the expected data quality, it can be carried out mostly though on-site data collection and measurements (primary data) or through data based on literature or on already existing databases (secondary data).
The **Life Cycle Impact Assessment** is the phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system (ISO 14044:2006). In this phase, data concerning emissions and resource consumption, coming from the LCI phase, are employed to build some indicators in different Areas of Protection (AoPs) (classified in "Human Health", "Natural Environment" and "Natural Resources").
To this aim, scientific methods based on environmental mechanisms have been developed in order to convert the input/output quantities of LCI into indicators that quantify the impacts, according to different impact categories. The assessment can be done at midpoint or endpoint level. Indicators at midpoint level define impact categories such as acidification, climate change, ozone depletion, ecotoxicity; while at endpoint level the impacts quantified at the midpoint level are converted into categories that quantify the final effects on the AoPs, such as the damage to human health, damage to ecosystem quality and the damage to resources. As a consequence, indicators at endpoint level have a higher degree of uncertainty than midpoint indicators. The results of LCIA are expressed as impact scores in a unit common to all contributions within the impact category by applying the so called "characterization factor". Figure 13 shows the relationship between midpoint indicators and endpoint indicators according to Recipe2016 method (Huijbregts et al., 2017).
The **interpretation phase** is transversal to all the three previous phases and it is essential in order to derive robust conclusions and recommendations. In this phase it is verified the consistency between the stated goal and scope and the findings of the Inventory and of the Impact Assessment. The Interpretation has to evaluate the completeness, the consistence and the sensitivity of the LCA study.
Regarding the phase following the End of Life (EoL) stage (Module D), a material con be:

- **Reuse**: when it is used again instead throwing it away, without modifying its form and function (e.g. a timber panel could be reuse in another building, even if it is usually not possible due to the loss of mechanical performance following demolition).
- **Recycle**: when it is subject to a mechanical process to change its form and function. This is only recommended when reusing are not possible. (e.g. a timber panel could be transformed in another wooden object).

- **Recover:** when it is converted from waste into resources through thermal and biological means (e.g. a timber panel could be burnt down to produce energy, such as electricity and heat). Resource Recovery occurs after reuse and recycle have been attempted.

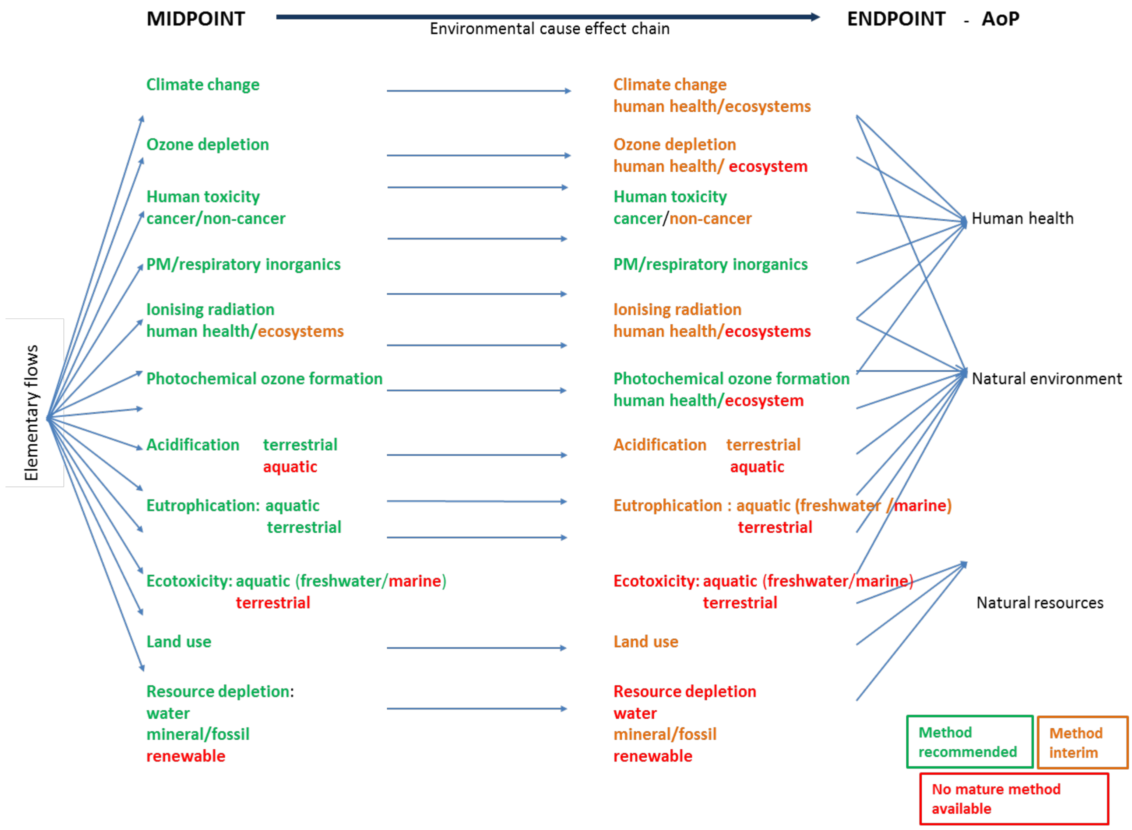

Fig. 13: Overview on the recommended methods (Sala et al., 2012 [11])

Impact factors

Impact category: climate change - GWP 100a

Flow	Category	Flow property	Factor	Unit	Uncertainty
Carbon dioxide, fossil	Emission to air/high populati...	Mass	1.0	kg CO2-Eq/kg	none
Carbon dioxide, fossil	Emission to air/low populatio...	Mass	1.0	kg CO2-Eq/kg	none
Carbon dioxide, fossil	Emission to air/low populatio...	Mass	1.0	kg CO2-Eq/kg	none
Carbon dioxide, fossil	Emission to air/lower stratosp...	Mass	1.0	kg CO2-Eq/kg	none
Carbon dioxide, fossil	Emission to air/unspecified	Mass	1.0	kg CO2-Eq/kg	none
Carbon dioxide, land transfo...	Emission to air/high populati...	Mass	1.0	kg CO2-Eq/kg	none
Carbon dioxide, land transfo...	Emission to air/low populatio...	Mass	1.0	kg CO2-Eq/kg	none
Carbon dioxide, land transfo...	Emission to air/low populatio...	Mass	1.0	kg CO2-Eq/kg	none
Carbon dioxide, land transfo...	Emission to air/lower stratosp...	Mass	1.0	kg CO2-Eq/kg	none
Carbon dioxide, land transfo...	Emission to air/unspecified	Mass	1.0	kg CO2-Eq/kg	none
Carbon dioxide, to soil or bi...	Emission to soil/agricultural	Mass	-1.0	kg CO2-Eq/kg	none
Carbon dioxide, to soil or bi...	Emission to soil/forestry	Mass	-1.0	kg CO2-Eq/kg	none
Carbon dioxide, to soil or bi...	Emission to soil/industrial	Mass	-1.0	kg CO2-Eq/kg	none
Carbon dioxide, to soil or bi...	Emission to soil/unspecified	Mass	-1.0	kg CO2-Eq/kg	none
Carbon monoxide, fossil	Emission to air/high populati...	Mass	1.9	kg CO2-Eq/kg	none
Carbon monoxide, fossil	Emission to air/low populatio...	Mass	1.9	kg CO2-Eq/kg	none
Carbon monoxide, fossil	Emission to air/low populatio...	Mass	1.9	kg CO2-Eq/kg	none
Carbon monoxide, fossil	Emission to air/lower stratosp...	Mass	1.9	kg CO2-Eq/kg	none
Carbon monoxide, fossil	Emission to air/unspecified	Mass	1.9	kg CO2-Eq/kg	none
Carbon monoxide, from soil...	Emission to air/high populati...	Mass	1.9	kg CO2-Eq/kg	none
Carbon monoxide, from soil...	Emission to air/low populatio...	Mass	1.9	kg CO2-Eq/kg	none
Carbon monoxide, from soil...	Emission to air/low populatio...	Mass	1.9	kg CO2-Eq/kg	none
Carbon monoxide, from soil...	Emission to air/lower stratosp...	Mass	1.9	kg CO2-Eq/kg	none
Carbon monoxide, from soil...	Emission to air/unspecified	Mass	1.9	kg CO2-Eq/kg	none
Chloroform	Emission to air/high populati...	Mass	20.0	kg CO2-Eq/kg	none
Chloroform	Emission to air/low populatio...	Mass	20.0	kg CO2-Eq/kg	none
Chloroform	Emission to air/low populatio...	Mass	20.0	kg CO2-Eq/kg	none

Fig. 14: OpenLCA internal database about elementary flows, impact factor and impact category (in this case climate change – GWP 100A) of each process.

3.2. Assumptions

In this study the life cycle of the building was considered by the phases of production (modules A1 to A3), transportation (modules A4 and A5) and End of Life (modules C1 to C4 and D) of materials. The use phase will be assessed in chapter 4.

The assessment is mainly based on secondary data from literature and from available Life Cycle databases, which are evaluated in relation to some necessary estimates & assumptions. These include:

- -the distance between materials' production plans and the construction, which has been estimated of 50 km for all the materials;
- the materials' End of Life (EoL), which have been assumed as follows:
    - Steel rebars: 70% recycled and 30% landfilled
    - Concrete, cementitious materials: 70% recycled and 30% landfill.
    - Wood of CLT panels: 100% recycled.
    - Other materials (such as plastic materials): 100% landfill.

The percentages of the EoL scenarios for Steel rebars and concrete were based on JRC Technical Report [14].

These assumptions are consistent with the goal of this LCA study, which is to provide a first general assessment of the building environmental impacts. For a more specific assessment, further primary data collection is needed.

3.3. Sustainability of materials

3.3.1. Timber

Timber is generally considered a material with low environmental impacts. Mainly, this is due to the renewability of this resource, but also to the capacity of trees (across its growth) to uptake carbon dioxide and to the recyclability and reusability of wood [15, 16]. However, CLT panels are a composite material due to the glue presence. Therefore, the environmental performance of the panels depends not just on the wood material, but also on the other non-organic components.

Since no primary data were available for the timber panel production, a secondary data from an Environmental Product Declaration (EPD) [17] that is supplied by a CLT panels producer has been used in the Life Cycle model.

3.3.2. Concrete

Different environmental impacts correspond to different concrete types. Mainly, the impact per unit volume of concrete depends on the following two factors:

- the type and quantity of materials of which the concrete is made up. Therefore, the use of alternative materials as substitutes for the clinker (for instance the blast-furnace slag and the fly ash) could probably reduce the environmental impact per unit volume of the concrete. In fact, most of dioxide emissions derive from the chemical reactions that occur during the raw materials cooking in order to transform these in clinker. Through the replacement of these materials with others coming from industrial waste, it is possible to reach two results: on one hand, part of emissions due to the cooking of materials are avoided; on the other hand, a reuse of waste materials is obtained that leads to a waste disposal reduction.
- the specific production chain of the concrete (involving the use of energy, the use of resources, emissions and waste production).

According to the Roussel relationship [18], there is an empirical relationship between the CO_2 eq. emissions of concrete and the compressive strength of the concrete. The relationship is as follows:

$$f_c \approx \left(CO_2^{m^3}\right)^2 \tag{1}$$

In other words, the compressive strength is proportional to the square of the CO_2 emitted during the production of concrete. Nevertheless, the total CO_2 decreases also when compressive strength increases, because high performance concrete leads to a net reduction of the concrete volume. In the case of the family house, this strategy is not effective, because the cross sections sizes of the structural element are close to the minimum ones for the Normal-Strength Concrete [6].

In the family house project, C25/30 class concrete composed by Portland Cement (Cem I) was assumed.

A secondary data from Ecoinvent 3.1 database has been considered for the cement assessment. Specifically, the dataset "concrete production 25MPa, RNA only, cut-off,S" has been employed. This data set covers the production of North American 25 MPa ready-mix concrete. Density: 2'409 kg/m³. Ingredients (for 1 m³): Cement 206 kg, Water 123 kg, Gravel 1100 kg, Sand 910 kg, Fly ash 69 kg, Admixtures (air-entrainers and superplasticizers) 1,2kg. The dataset includes the whole manufacturing processes to produce ready-mixed concrete, internal processes (material handling and mixing) and infrastructure.

This cement results have an impact of 0,808 kg CO_2-equivalent per kg of product. To reduce the CO_2 – equivalent, part of Portland cement can be replaced by more sustainable binders such as

- CEM III/A (in which 35 to 65% of clinker is replaced by blast furnace slag);
- CEM III/B (in which 66 to 80% of clinker is replaced by blast furnace slag);
- CEM III/C (in which 81 to 95% of clinker is replaced by blast furnace slag).

However, the current study only considers the use of CEM I, because further analysis is necessary to understand how new cements can reach the same compressive strength the CEM I.
IIn addition to the concrete, cement - based materials, mortar and plaster, are included

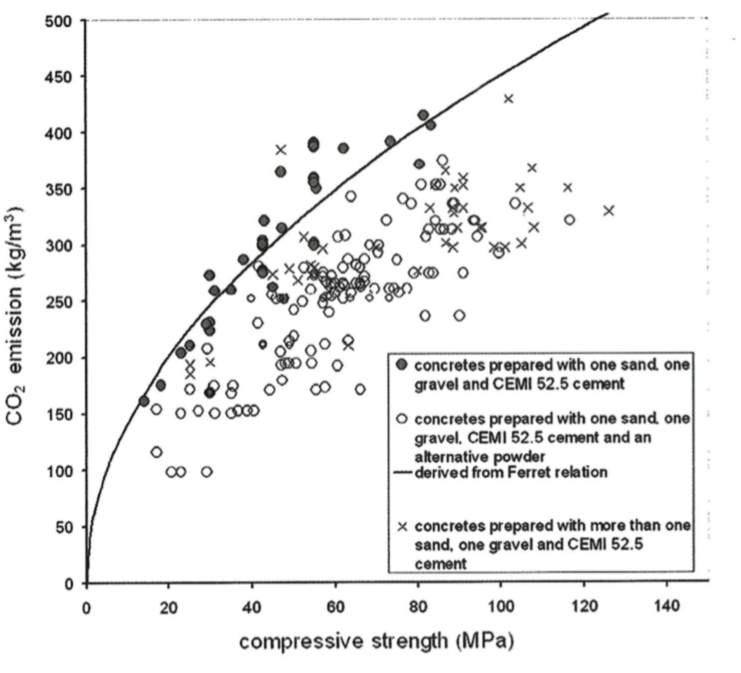

Fig. 15: G. Relationship between 28 - days compressive strength and CO_2 emissions per cubic meter of concrete [18].

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3.4. Carbonation

The carbonation is a chemical process during which concrete adsorb CO_2 from the atmosphere, according to the following chemical reaction:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{2}$$

It is the reverse reaction that occurs during the cooking of the raw materials to produce clinker. This reaction covers the entire life of almost all cement-based materials: it begins when the construction is finished, passing through the life cycle of the structure, and continues during the demolition process. However, this phenomenon has advantages and disadvantages.

- Advantages: the CO_2 uptaken allows to balance part of CO_2 released during the concrete productive process. From this point of view, this chemical reaction makes the concrete more sustainable. Furthermore, in the cases of un-reinforced concrete, the product of the carbonating reaction ($CaCO_3$) has larger volume than $Ca(OH)_2$, leading to filling of the concrete pores and, thus, increasing its strength.
- Disadvantages: Carbonation contributes to the degradation of reinforced concrete, because the chemical reaction leads to a de-passivation of the reinforcement due to the reduction of pH. The steel is susceptible to corrosion, as can be seen in Fig. 16, and the spalling concrete occurs.

The amount of the uptaken CO_2 was determined in accordance with EN 16757: 2017 [20], which provides the compute of the CO_2 in kg per m^2 of concrete structure:

$$CO_2\ uptake = k \cdot (\sqrt{t}/1000) \cdot U \cdot C \cdot D_c \tag{3}$$

Where:

- k = factor given in the Table BB.1 from on EN 16757: 2017 [20] (Fig. 17).
- U = is the maximum theoretical uptake in kg CO_2 / kg cement; 0.49 is the value for Portland cement (CEM I).
- C = is cement content in kg per m^3 of concrete. In this report, the value is 300 kg / m^3.
- D_C = factor given in the Table BB.1
- t= exposition time of the concrete's surface. In the family house case, it coincides with the life expectancy of the building (i.e. 50 years).

This approach has been used to calculate the carbonatation of the structural and non-structural element containing cement.

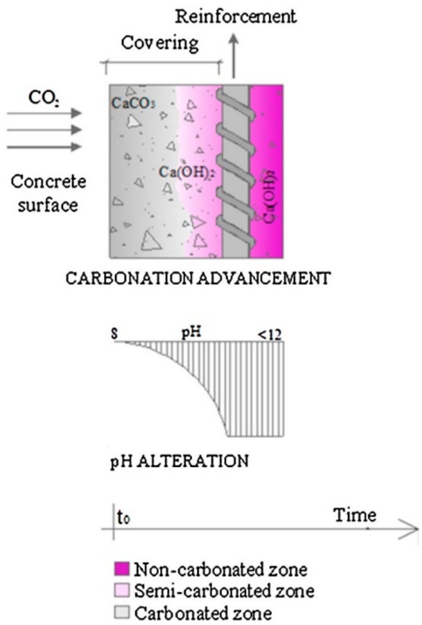

Fig. 16: Effects of carbonation and pH change in concrete [19].

Table BB.1 — k-factors [mm/year^{0,5}]for calculation of depth of carbonation for different concrete strength classes (cylinder) and exposure conditions and also degree of carbonation for different exposure conditions. (Derived from [25])

Concrete strength	< 15 MPa	15 to 20 MPa	25 to 35 MPa	> 35 MPa	Degree of carbonation (D_c)
Parameters	Value of k-factor, in mm/year^{0,5}				Percentage
Civil engineering structures					
Exposed to rain		2,7	1,6	1,1	85
Sheltered from rain		6,6	4,4	2,7	75
In ground [a]		1,1	0,8	0,5	85
Buildings					
Outdoor					
Exposed to rain	5,5	2,7	1,6	1,1	85
Sheltered from rain	11	6,6	4,4	2,7	75
Indoor in dry climate [c]					
With cover [b]	11,6	6,9	4,6	2,7	40
Without	16,5	9,9	6,6	3,8	40
In ground [a]		1,1	0,8	0,5	85

[a] Under groundwater level k = 0,2.

[b] Paint or wall paper. (Under tiles, parquet and laminate k is considered to be 0.)

[c] Indoor in dry climate means that the RH is normally between 45 % and 65 %.

Fig. 17: Table BB.1 given by: EN 16757:2017 [20]

3.5. Observation on the results

Table 4 shows the values of CO_2 emitted and uptaken by the whole of the material used in the three buildings in reference to the different phases of life cycle of materials. All the values are derived from the OpenLCA database, except in the cases of the CLT panels [17] and of the steel rebars [14].

Table 4: Global Warming Potential impacts of the main phases considered in the buildings' life cycle.

Material	U.o.M.	Production stage	Construction stage	EoL stage	Total [kg]
		A1, A2, A3	A4, A5	(C1, C2, C3, C4, D)	
Brick	kg -CO2 eq./kg	0.2315	0.0078	0.0042	0.2434
Thermal isolation - Rockwool	kg -CO2 eq./kg	1.1746	0.0102	0.0042	1.1890
Plaster	kg -CO2 eq./kg	0.2257	0.0078	0.0042	0.2376
Mortar	kg -CO2 eq./kg	0.2032	0.0244	0.0042	0.2318
Paint	kg -CO2 eq./kg	1.9414	0.0244	0.0042	1.9699
Tiled roof	kg -CO2 eq./kg	0.3449	0.0078	0.0042	0.3568
Waterproof membrane	kg -CO2 eq./kg	0.7375	0.0244	0.0042	0.7660
Vapour barrier	kg -CO2 eq./kg	2.5171	0.0244	0.0042	2.5456
Ceramic tiles	kg -CO2 eq./kg	0.5465	0.0078	0.0042	0.5585
Adhesive mortar	kg -CO2 eq./kg	1.1040	0.0005	0.0042	1.1086
Screed - Portland	kg -CO2 eq./kg	0.8269	0.0078	0.0042	0.8389
Thermal insulation - XPS	kg -CO2 eq./kg	3.7577	0.0244	0.0042	3.7862
Crawl space	kg -CO2 eq./kg	1.9114	0.0244	0.0042	1.9400
Acoustic pad	kg -CO2 eq./kg	1.8899	0.0244	0.0042	1.9184
Gypsum Plasterboard	kg -CO2 eq./kg	0.1618	0.0102	0.0042	0.1762
Reinforcing-Steel	kg -CO2 eq./kg	1.9624	0.0078	-0.5860	1.3842
Concrete	kg -CO2 eq./m3	237.94	19.48	-44.7700	212.65
CLT	kg -CO2 eq./m3	-685.53	55.21	810.23	179.91

In the cases of reinforced concrete structures, the negative values of the uptaken CO_2 for carbonation is due to EoL scenarios, whereas the uptaken CO_2 for carbonation that occurs during the use stage has not been considered yet because this assess is reported in the paragraph 5.2. Instead, in the CLT panels structures, the negative value is due to the biogenetic CO_2, which is the capacity of wood to absorb carbon dioxide during the growth of the tree.

The End of Life stage of the CLT structure highly influence the Global Warming Potential (GWP) results. Therefore, different scenarios should be considered. Specifically, a total recycling of the panels is hypothesized.

It is important to underline that the results obtained derive from input data taken from Ecoinvent 3.1 database or literature (as in the case of CLT panels and steel rebars). These data often refer to average situations, therefore they are plausible, but it is not strictly related to the specific case study. Therefore, it is clear that, in order to obtain accurate results, precise data related to each case are necessary.

With respect to the values reported in Table 4, following remark is necessary: to calculate the CO_2 equivalent for precast RC Panels, a specific Ecoinvent dataset was considered. In addition to the concrete, also the thermal insulation (XPS) must to be taken into account. However, since no specific data were available, the resources necessary to obtain the final panel was not considered.

4. Thermal analysis

The aim of the thermal analysis is to compute the energy consumption for heating or cooling the three construction typologies in according to the weather conditions. Particular attention was paid to the greater contribution of the thermal inertia that concrete offers compared to timber panels.
DesignBuilder is the software used to carry out this evaluation, which is an interface of the EnergyPlus calculation engine.

4.1. Energy modeling

The thermal transmittance of the building envelope elements of each of the nine buildings was taken into account by including information on the relative stratigraphy.
The openings were modeled as timber profile and double glazing filled with argon gas in order to obtain high-performance thermal doors and windows.
To reduce the solar loads during the warmer seasons, external window shading systems were provided, which also provide solar heat gains during the cold season.
The weather conditions were considered using the internal database of Design builder.
The building was divided into two thermal zones: in one, all of the living space was enclosed, and in the second the ground floor was considered as an un-heated zone. According to the standards on thermal comfort [21], heating setpoint temperature is 20 °C, whereas the cooling setpoint temperature is 26°C.
Regarding the HVAC (Heating, ventilation and air conditioning) system, an ideal system (CoP=1) powered with electricity was provided for both heating and cooling needs.
Since usually there is no mechanical ventilation system in a family house, only natural ventilation has been provided.

5. Results and discussions

The total amount of kg CO_2 – equivalent can be determined by multiplying the volume of each material, deriving from the design, by the unit emission. This calculation was performed for each building type and for each location. See tables 5, 6, 7, 8 ,9,10, 11, 12, 13.

Table 5: Bill of quantities and CO_2 total emissions of the Reinforced Concrete frame structure in Catania.

R.C. frame structure			
Catania			
Material	Quantity [kg]	Unit emission [kg CO_2 eq./kg]	Total emission [kg]
Bricks	36927.54	0.243	8989.97
Thermal insulation - Rockwool	1242.92	1.189	1477.78
Plaster	11371.57	0.238	2702.44
Mortar	2392.41	0.232	554.48
Paint	85.42	1.970	168.27
Tiled Roof	2081.40	0.357	742.64
Waterproof membrane	348.49	0.766	266.96
Vapour Barrier	13.22	2.546	33.65
Ceramic tiles	2249.56	0.558	1256.28
Adhesive mortar	340.75	1.109	377.76
Screed - Portland	3042.13	0.839	2551.98
Thermal insulation - XPS	99.15	3.786	375.40
Crawl space	195.30	1.940	378.87
Acoustic pad	7.66	1.918	14.68
Reinforcing steel	6519.00	1.384	9023.66
Concrete	36927.54	0.099	3661.14
		TOT. [kg]	32576.02

Table 6: Bill of quantities and CO_2 total emissions of the Reinforced Concrete frame structure in Turin.

R.C. frame structure			
Turin			
Material	Quantity [kg]	Unit emission [kg CO_2 eq./kg]	Total emission [kg]
Bricks	36927.54	0.243	8989.97
Thermal insulation - Rockwool	1993.10	1.189	2369.71
Plaster	11371.57	0.238	2702.44
Mortar	2392.41	0.232	554.48
Paint	85.42	1.970	168.27
Tiled Roof	2081.40	0.357	742.64
Waterproof membrane	348.49	0.766	266.96
Vapour Barrier	13.22	2.546	33.65
Ceramic tiles	2249.56	0.558	1256.28
Adhesive mortar	340.75	1.109	377.76
Screed - Portland	3042.13	0.839	2551.98
Thermal insulation - XPS	148.73	3.786	563.11
Crawl space	195.30	1.940	378.87
Acoustic pad	7.66	1.918	14.68
Reinforcing steel	6519.00	1.384	9023.66
Concrete	36927.54	0.099	3661.14
		TOT. [kg]	33655.65

Table 7: Bill of quantities and CO_2 total emissions of the Reinforced Concrete frame structure in Oslo.

R.C. frame structure			
Oslo			
Material	Quantity [kg]	Unit emission [kg CO_2 eq./kg]	Total emission [kg]
Bricks	36927.54	0.243	8989.97
Thermal insulation - Rockwool	2194.91	1.189	2609.66
Plaster	11371.57	0.238	2702.44
Mortar	2392.41	0.232	554.48
Paint	85.42	1.970	168.27
Tiled Roof	2081.40	0.357	742.64
Waterproof membrane	348.49	0.766	266.96
Vapour Barrier	13.22	2.546	33.66
Ceramic tiles	2249.56	0.558	1256.29
Adhesive mortar	340.75	1.109	377.77
Screed - Portland	3042.13	0.839	2551.98
Thermal insulation - XPS	223.09	3.786	844.67
Crawl space	195.30	1.940	378.87
Acoustic pad	7.66	1.918	14.69
Reinforcing steel	6519.00	1.384	9023.67
Concrete	36927.54	0.099	3661.14
		TOT. [kg]	34177.15

Table 8: Bill of quantities and CO_2 total emissions of the Precast R.C. panels structure In Catania.

Precast R.C. panels structure			
Catania			
Material	Quantity [kg]	Unit emission [kg CO_2 eq./kg]	Total emission [kg]
Thermal insulation - XPS	975.26	3.786	3692.54
Thermal insulation - Rockwool	1513.95	1.189	1800.03
Plaster	6055.22	0.238	1439.02
Tiled Roof	2081.40	0.357	742.64
Waterproof membrane	348.49	0.766	266.96
Vapour Barrier	9.39	2.546	23.91
Paint	41.16	1.970	81.08
Thermal insulation - Glass Wool	28.52	1.189	33.91
Ceramic tiles	2249.56	0.558	1256.29
Adhesive mortar	340.75	1.109	377.77
Screed - Portland	3042.13	0.839	2551.98
Crawl space	195.30	1.940	378.87
Acoustic pad	7.66	1.918	14.69
Concrete 25/30	97080.00	0.099	9624.88
Gypsum Plasterboard	3001.38	0.176	528.81
Reinforcing steel	1745.88	1.384	2416.66
		TOT. [kg]	25230.03

Table 9: Bill of quantities and CO_2 total emissions of the Precast R.C panels structure in Turin.

Precast R.C. panels structure			
Turin			
Material	Quantity [kg]	Unit emission [kg CO_2 eq./kg]	Total emission [kg]
Thermal insulation - XPS	1024.83	3.786	3880.24
Thermal insulation - Rockwool	1993.10	1.189	2369.71
Plaster	6055.22	0.238	1439.02
Tiled Roof	2081.40	0.357	742.64
Waterproof membrane	348.49	0.766	266.96
Vapour Barrier	9.39	2.546	23.91
Paint	41.16	1.970	81.08
Thermal insulation - Glass Wool	28.52	1.189	33.91
Ceramic tiles	2249.56	0.558	1256.29
Adhesive mortar	340.75	1.109	377.77
Screed - Portland	3042.13	0.839	2551.98
Crawl space	195.30	1.940	378.87
Acoustic pad	7.66	1.918	14.69
Concrete 25/30	97080.00	0.099	9624.88
Gypsum Plasterboard	3001.38	0.176	528.81
Reinforcing steel	1745.88	1.384	2416.66
		TOT. [kg]	25987.42

Table 10: Bill of quantities and CO_2 total emissions of the Precast R.C panels structure in Oslo.

Precast R.C. panels structure			
Oslo			
Material	Quantity [kg]	Unit emission [kg CO_2 eq./kg]	Total emission [kg]
Thermal insulation - XPS	1099.20	3.786	4161.80
Thermal insulation - Rockwool	2157.38	1.189	2565.04
Plaster	6055.22	0.238	1439.02
Tiled Roof	2081.40	0.357	742.64
Waterproof membrane	348.49	0.766	266.96
Vapour Barrier	9.39	2.546	23.91
Paint	41.16	1.970	81.08
Thermal insulation - Glass Wool	28.52	1.189	33.91
Ceramic tiles	2249.56	0.558	1256.29
Adhesive mortar	340.75	1.109	377.77
Screed - Portland	3042.13	0.839	2551.98
Crawl space	195.30	1.940	378.87
Acoustic pad	7.66	1.918	14.69
Concrete 25/30	97080.00	0.099	9624.88
Gypsum Plasterboard	3001.38	0.176	528.81
Reinforcing steel	1745.88	1.384	2416.66
		TOT. [kg]	26464.30

Table 11: Bill of quantities and CO_2 total emissions of the CLT panels structure in Catania.

CLT Panels structure			
Catania			
Material	Quantity	Unit emission [kg CO_2 eq./kg]	Total emission [kg]
Gypsum Plasterboard	9132.28	0.176	1609.01
Thermal insulation - Rockwool	1753.23	1.189	2084.52
Plaster	3080.23	0.238	732.01
Tiled roof	2081.40	0.357	742.64
Waterproof membrane	348.49	0.766	266.96
Vapour Barrier	5.57	2.546	14.17
Thermal insulation - Glass Wool	28.52	1.189	33.91
Ceramic tiles	2253.43	0.558	1258.45
Adhesive mortar	340.75	1.109	377.77
Screed - Portland	3643.05	0.839	3056.08
Thermal insulation - XPS	99.15	3.786	375.41
Crawl space	195.30	1.940	378.87
Acoustic pad	7.66	1.918	14.69
CLT	11690.34	0.428	5007.64
		TOT. [kg]	15952.11

Table 12: Bill of quantities and CO_2 total emissions of the CLT panels structure in Turin.

CLT Panels structure			
Turin			
Material	Quantity	Unit emission [kg CO_2 eq./kg]	Total emission [kg]
Gypsum Plasterboard	9132.28	0.176	1609.01
Thermal insulation - Rockwool	1943.10	1.189	2310.27
Plaster	3080.23	0.238	732.01
Tiled roof	2081.40	0.357	742.64
Waterproof membrane	348.49	0.766	266.96
Vapour Barrier	5.57	2.546	14.17
Thermal insulation - Glass Wool	28.52	1.189	33.91
Ceramic tiles	2253.43	0.558	1258.45
Adhesive mortar	340.75	1.109	377.77
Screed - Portland	3643.05	0.839	3056.08
Thermal insulation - XPS	148.73	3.786	563.11
Crawl space	195.30	1.940	378.87
Acoustic pad	7.66	1.918	14.69
CLT	11690.34	0.428	5007.64
		TOT. [kg]	16365.57

Table 13: Bill of quantities and CO_2 total emissions of the CLT panels structure in Oslo.

CLT Panels structure			
Oslo			
Material	Quantity	Unit emission [kg CO_2 eq./kg]	Total emission [kg]
Gypsum Plasterboard	9132.28	0.176	1609.01
Thermal insulation - Rockwool	2110.06	1.189	2508.78
Plaster	3080.23	0.238	732.01
Tiled roof	2081.40	0.357	742.64
Waterproof membrane	348.49	0.766	266.96
Vapour Barrier	5.57	2.546	14.17
Thermal insulation - Glass Wool	28.52	1.189	33.91
Ceramic tiles	2253.43	0.558	1258.45
Adhesive mortar	340.75	1.109	377.77
Screed - Portland	3643.05	0.839	3056.08
Thermal insulation - XPS	223.09	3.786	844.67
Crawl space	195.30	1.940	378.87
Acoustic pad	7.66	1.918	14.69
CLT	11690.34	0.428	5007.64
		TOT. [kg]	16845.63

It is possible to note that the global amount of concrete in the precast R.C. structures is greater than the one of R.C. frame structure. Nevertheless, the highest values of total CO_2 equivalent emissions occur in the R.C. frame structure because there are larger quantities of other materials that constitute the building envelope (such as bricks), which have a greater environmental impact.

5.1. Comparison of CO_2 emissions with respect to location and type of construction.

To assess the influence of the climate location on the global emissions of CO_2, the impact of the types of structure is evaluated in the different place of Europe (Catania, Turin and Oslo). See table 14 and Fig. 18

Table 14: Summary table of GWP impact for a family house evaluated in Tables 5, 6, 7, 8, 9, 10, 11, 12 and 13.

Location / Building type	Catania [kg]	Turin [kg]	Oslo [kg]
R.C. frame	32576.02	33655.65	34177.15
Precast R.C panels	25230.03	25987.42	26464.30
CLT panels	15952.11	16365.57	16845.63

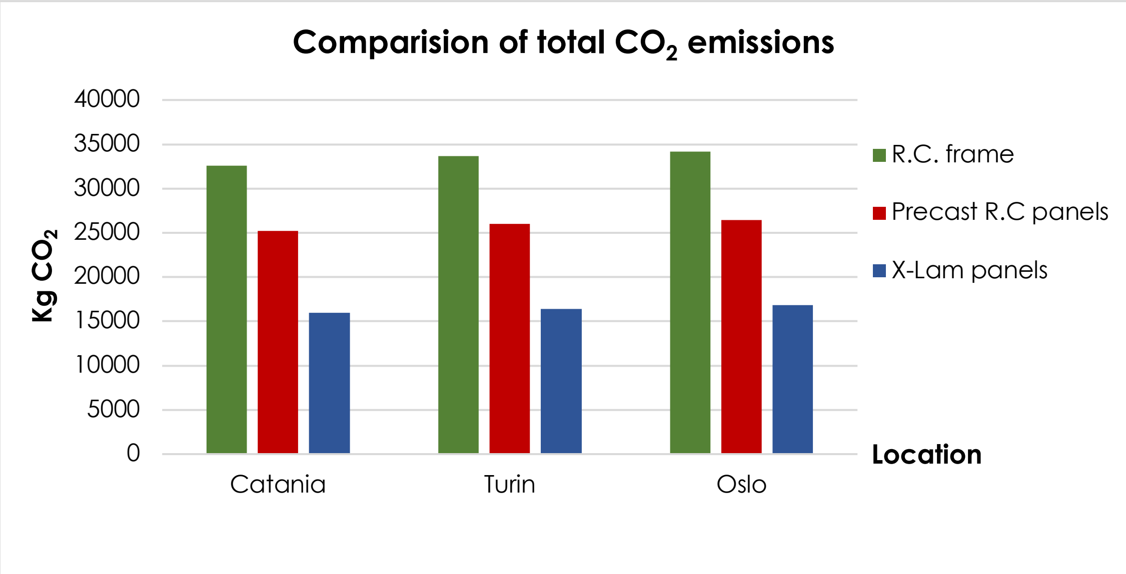

Fig. 18: Comparison of total CO_2-eq emission

As a result, R.C. frames structures are on average responsible for the higher impact of the GWP impact category (about 52% more than RC precast panels structures, and about 1,4 times more than CLT panels structures).

In all locations, there is a difference of about 58% between the two precast structures, made with timber and concrete respectively.

In all the cases a family house built in Oslo is responsible for higher GWP impacts than those of other cities: these yield between 2,8% and 4,2% more GHGs for R.C. frame structure, between 2,6% and 5,6% more GHGs for CLT panels structures and between 4,9% and 3% more GHGs for R.C. precast structures. Thus, the "location" variable produces little variation to the LCA of the materials.

5.2. Carbonation

The amount of CO_2 uptake due to carbonation effects during the use stage (Module from B1 to B7) was evaluated through the eq. (3) in cement – based materials. As the degree of carbonation depends on the degree of the exposure, an evaluation on each side of all structural elements was carried out.
From a quantitative point of view, it should be noted that only the insulation thickness varies in the buildings of the same type. Accordingly, the CO_2 of both concrete and cementitious materials is the same for these constructions. Therefore, the CO_2 uptaken by all the construction are valid in all the three cities.

Table 15: Comparison between total CO_2 emitted (Table 14) and CO_2 uptaken

Building Type	Location	CO_2 uptake [kg]	CO_2 eq. emitted [kg]	Difference [%]	Global CO_2 eq [kg]
Frame structure	Catania	6842.54	32576.02	21.0	25733.48
	Turin		33655.65	20.3	26813.11
	Oslo		34177.15	20.0	27334.61
Precast RC Panels	Catania	3846.996	25230.03	15.2	21383.04
	Turin		25987.42	14.8	22140.42
	Oslo		26464.30	14.5	22617.30

Therefore, the values of the global CO_2 equivalent shown in the last column of the table 15 include the carbonation of the concrete both in the use stage and during the storage of the cementitious waste materials in landfills.
Table 15 also shows the comparison between total CO_2 eq emitted and CO_2 uptaken. For all the cities, the carbonation reduces global CO_2 eq of about 20%, for R.C. fame structures, and of about 15%, for precast R.C. panels structures, with respect to that emitted for materials production.
This is a relevant result, because the emissions of global CO_2 eq. of precast R.C. (Table 15) panels and CLT structure (Table 14) are quite similar, as reported in Fig. 19.

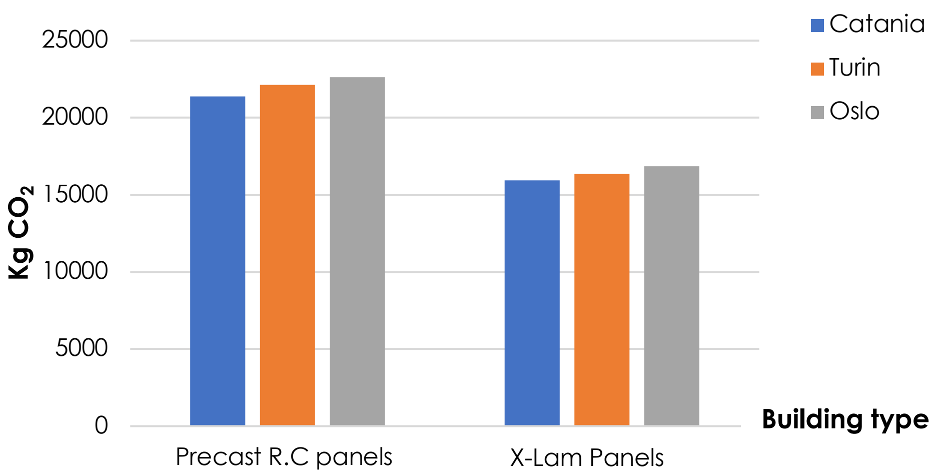

Fig. 19: Comparison between global CO_2 emissions related to Precast R.C. panels structures and CLT panels structures

5.3. End of Life (EoL)

In this paragraph, the CO_2 equivalent emitted or uptaken during the last phase of the materials life (Module C1, C2, C3, C4, D) is taken into account. The values depend on the treatment of materials during the building's demolition. For instance, recycling waste materials (but also recover and reuse ones) could assume negative values if the greenhouse emissions saved due to the avoided use of raw materials exceed those produced during the recycling process.
The tables 16, 17 and 18 below show the result in terms of CO_2 equivalent to the last stage of materials life related to each structure type and each city.

Table 16: GWP impact of materials EoL R.C. frame structures

R.C. frame structure				
Materials	U.M	Catania	Turin	Oslo
Concrete	kg CO_2-Eq	-688.85	-688.85	-688.85
Steel	kg CO_2-Eq	-3820.13	-3820.13	-3820.13
Other materials	kg CO_2-Eq	251.19	254.52	255.67

Table 17: GWP impact of materials EoL Precast R.C. panels structures

Precast R.C. panels structure				
Materials	U.M	Catania	Turin	Oslo
Concrete	kg CO_2-Eq	-1810.83	-1810.83	-1810.83
Steel	kg CO_2-Eq	-1023.09	-1023.09	-1023.09
Other materials	kg CO_2-Eq	82.60	84.80	85.80

Table 18: GWP impact of materials EoL C.L.T. panels structures

C.L.T. panels structure				
Materials	U.M	Catania	Turin	Oslo
CLT	kg CO_2-Eq	22552.05	22552.05	22552.05
Other materials	kg CO_2-Eq	95.53	96.52	97.53

From these table, it is possible to observe that:

- Concrete wastes have negative values: as previously said, it is due to the carbonation that entails the CO_2 absorption by the concrete. About this point, the opportunity to consider the CO_2 uptaken by concrete has to be carefully evaluated accordingly to the specific disposal conditions.
- Steel rebars waste have negative values too. However, this time it depends on the assumption made in the paragraph 3.2, according to which the 70% of timber waste is recycled.

In the three types of building, only the values corresponding to the entry "other materials" change. Specifically, this item involves the insulation layer, which is characterized by a variation in thickness according to the city climate conditions. However, more accurate data could lead to more appropriate hypothesizes. As a consequence, more in-depth knowledge, for instance about the waste treatment methods used in each city for the different analyzed materials, could lead to more detailed results about the EOL assessment.

5.4. Results of thermal analysis

DesignBuilder is used to estimate the heating and cooling needs of the buildings in terms of daily and annual consumption (kWh) and in peak, measured as the seasonal maximum values (kW). Because the aim is to assess the CO_2-equivalent emissions that occur over the life of the building for heating and cooling needs, attention has been paid only to the evaluation of annual consumption. The value of energy obtained has been multiplied by the years of life assumed for the building (100 years) and converted in terms of CO_2-equivalent depending on the type of energy that is expected to be used (in this case electricity).

The following tables (19 and 20) and graphs (Fig. 20 and 21) show the annual consumption for heating and cooling needs in regard to the average weather condition of each considered city.

Table 19: Annual energy consumed for heating needs.

Annual heating needs			
Location	R.C. frame [kWh]	Precast R.C. panels [kWh]	CLT panels [kWh]
Catania	193.506	292.879	167.179
Turin	2577.677	2612.111	2524.760
Oslo	4835.872	4854.198	4257.247

Table 20: Annual energy consumed for cooling needs.

Annual cooling needs			
Location	R.C. frame [kWh]	Precast R.C. panels [kWh]	CLT panels [kWh]
Catania	5969.277	5929.161	6221.813
Turin	4092.854	4132.948	4174.705
Oslo	2524.469	2579.792	2775.447

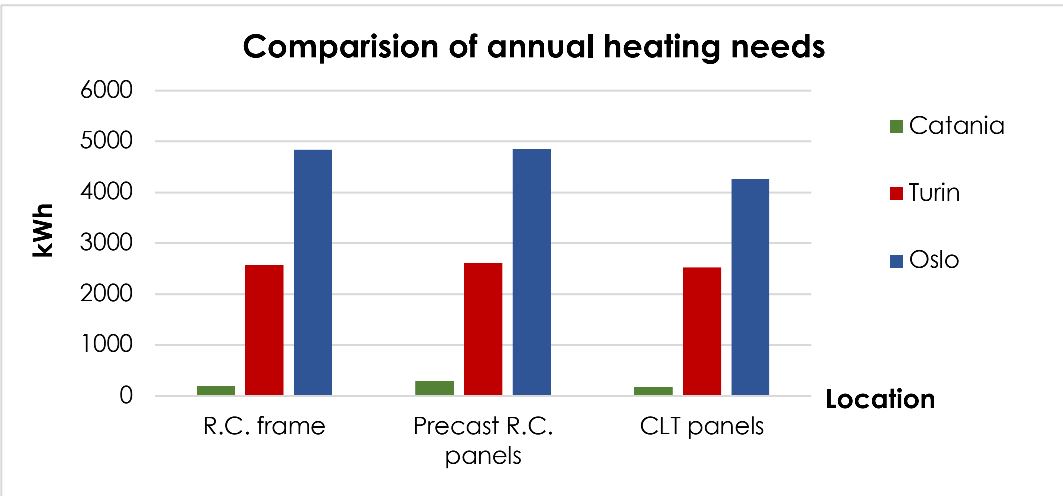

Fig. 20: Comparison of the energy values consumed for the heating needs.

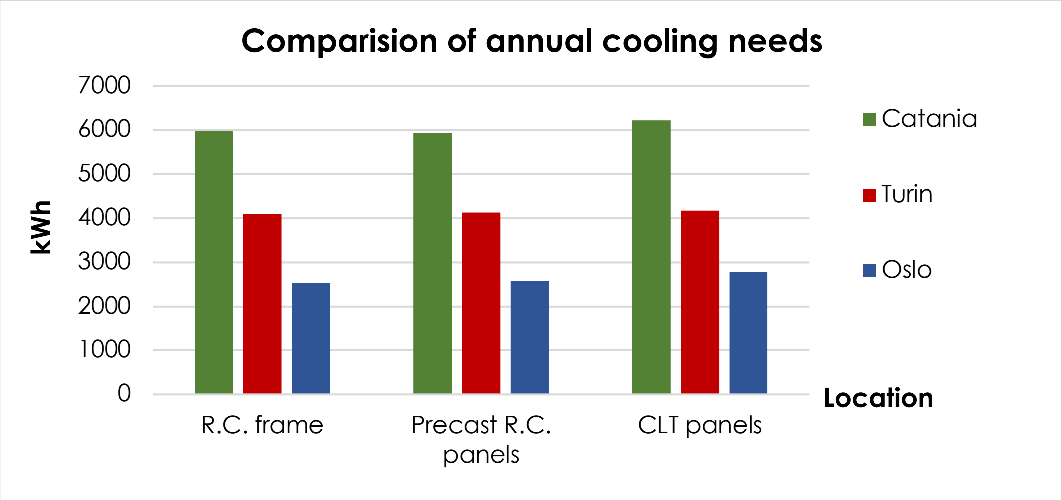

Fig. 21: Comparison of the energy values consumed for the cooling needs.

It is clear from this data that the weather conditions are the factor that most influences energy consumption, especially in the case of heating needs. To heat the family house built in Catania, only 4% to 6% of the energy required to the buildings in Oslo is needed, whereas slightly more than half of the energy required in the case of Oslo is necessary for the heating needs of the Turin building. Substantial differences, even if to a lesser extent, occur in summer cooling, which are obviously linked to the degree of climate variance. The cooling needs in Catania are more than twice that of Oslo for all the structural types, whereas in Turin 62% to 66% of the energy employed in Catania is used.
These results strongly imply the importance of thermal insulation of the building envelope.
Finally, it is notable that the house in Catania has both the maximum and minimum values of energy spent, for cooling and heating needs respectively.

Conversely, the "structural type" factor generally has a low incidence of energy consumption, particularly in regard to summer cooling. The difference between the consumption that occurs between the timber structure and the other two buildings in Turin for summer cooling is only 2-3%, and only 12% for the same structures in the case of Oslo. Similarly, the values of energy consumed in the three different structures are almost the same in both Catania and Turin, whereas, in the CLT panel structure, consumption is about 10% higher than the other two structures. Only in the case of the heating needs in Catania is there an appreciable difference, in which the consumption in the timber structure is just under half of the prefabricated structure in R.C.
These differences between the structural types are unexpectedly low and not considered of character [22]. Probably, the choice to assume the use of natural ventilation in this study did not permit the material properties to be maximized. For example, the alternative use of mechanical ventilation would make it possible to make greater use of the thermal mass of concrete buildings, especially in summer cooling in hot climates such as Catania. Despite this, the data still shows the greatest difference to occur between timber buildings and concrete buildings in extreme climates (Catania and Oslo), which was to be expected; the results indicating that, in general, it is better to lean for buildings with large thermal mass in Mediterranean climates (Catania), while the choice falls on light and well insulated buildings in Nordic climates (Oslo).

5.5. Overall results

In order to obtain the total calculation of the CO_2 - equivalent emissions, it is first necessary to estimate the energy spent to satisfy the heating and cooling needs throughout the lifetime of each family house, which is done by multiplying the annual values for the estimated lifespan of the buildings (100 years).Secondly, it is necessary to convert the results into energy thermals in terms of values of the produced CO_2. To achieve this, conversion factors are used to determine the emissions of carbon dioxide associated with energy use [23].

Table 21: Total values of needs and CO_2 emissions.

Total needs and CO2 emissions								
Location	Structural type	heating needs	cooling needs	total needs	lifespan	total needs	conv. factor	kg CO_2 -needs
		kWh/year	kWh/year	kWh/year	years	kwh	kg CO_2 / kWh	kg CO_2 eq.
Catania	R.C. frame	193.51	5969.28	6162.78	100	616278	0.43	265000
	Precast R.C. panels	292.88	5929.16	6222.04	100	622204	0.43	267548
	CLT panels	167.18	6221.81	6388.99	100	638899	0.43	274727
Turin	R.C. frame	2577.68	4092.85	6670.53	100	667053	0.43	286833
	Precast R.C. panels	2612.11	4132.95	6745.06	100	674506	0.43	290038
	CLT panels	2524.76	4174.71	6699.47	100	669947	0.43	288077
Oslo	R.C. frame	4835.87	2524.47	7360.34	100	736034	0.43	316495
	Precast R.C. panels	4854.20	2579.79	7433.99	100	743399	0.43	319662
	CLT panels	4257.25	2775.45	7032.69	100	703269	0.43	302406

From table 21 it is possible to observe once again how the parameter that most affects consumption, and therefore emissions, is the weather climate.
Lastly, the total emissions that occur during the life cycle of buildings are evaluated in Table 22 by summing the contributions coming from the LCA of the materials (tables 14 and 15) with those due to the just calculated energy needs (table 21).

Table 22: Global CO2 – eq. emissions from both LCA of materials and heating and cooling needs.

Total needs and CO_2 emissions				
Location	Structural type	CO_2 eq. (LCA)	CO_2 eq. (needs)	Global CO_2 eq.
		[kg]	[kg]	[kg]
Catania	R.C. frame	25733.48	264999.65	290733.13
	Precast R.C. panels	21383.04	267547.72	288930.75
	CLT panels	15952.11	274726,67	290678.79
Turin	R.C. frame	26813.11	286832.83	313645.95
	Precast R.C. panels	22140.42	290037.54	312177.96
	CLT panels	16365.57	288077.00	304442.56
Oslo	R.C. frame	25733.48	316494.66	342228.14
	Precast R.C. panels	22617.30	319661.57	342278.87
	CLT panels	16845.63	302405.84	319251.47

From the Table 22 it is clear that the emissions due to the estimated consumption of energy for the heating and cooling needs of the environments are about one order of magnitude greater than those evaluated in the LCA of the materials. The difference is even more evident when moving from R.C. to CLT buildings and from hot climates to the harsh ones.
As a result, it is always important to provide the buildings with a good layer of insulation in order to increase energy efficiency, especially in buildings with low thermal inertia and in cold climates.

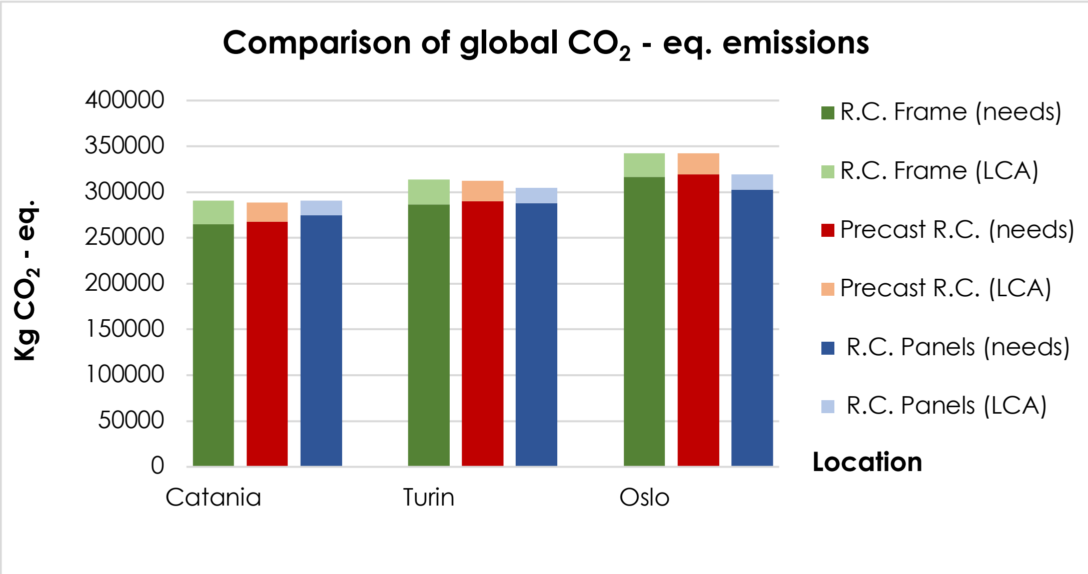

Fig. 22: Comparison of global CO2 - eq. emissions

Finally, Fig. 22 shows the comparison between the CO2 equivalent values emitted during the entire life cycle of the three structures in the three hypothesized cities. The histogram in Fig. 22 also highlights the low incidence of LCA on greenhouse gas emissions compared to emissions due to consumption for heating and cooling. Accordingly, the parameter that, in general, most affects the level of CO2 emissions is the weather condition. This result also depends on the type of ventilation adopted during the thermo-dynamic analysis: the natural ventilation. The natural ventilation is performed randomly by the occupants; therefore, it is usually not aimed at fully exploiting the thermophysical propriety of the building materials in view of the energetic optimization.
A programmed ventilation based on the daily climatic conditions (e.g. mechanical ventilation or free-cooling during the warm season) would better utilize the proprieties of the materials.
However, this choice is more realistic for larger buildings.

6. Cost analysis

Certainly, cost valuation plays a crucial role because it often determines the choice of the structural type to be realized.
There are many parameters that affect the cost assessment. A lot of these refer to the specific location, i.e. the real estate market, the local cost of labor, the materials price list, the urban context and so on. However, some simplifications are necessary in order to standardize the building cost with the aim of conducting a comparison. For this reason, a single price list based on construction projects in Turin were used. Each entry considers the following component costs:

- Labour
- Freight and transport
- Materials

In order to evaluate the overall cost of the three types of building, the following procedure was employed:

- Redacting of the bill of quantities
- Quantification of the workings
- Multiplication of the materials quantities from bill of quantities for the unit cost, deduced both from regional price list, and from commercial catalogues.

The prices are listed without VAT (Value – Added Tax) and the total cost does not include the prices related to the fee of the professional.
The results obtained are shown in the following Fig. 23.

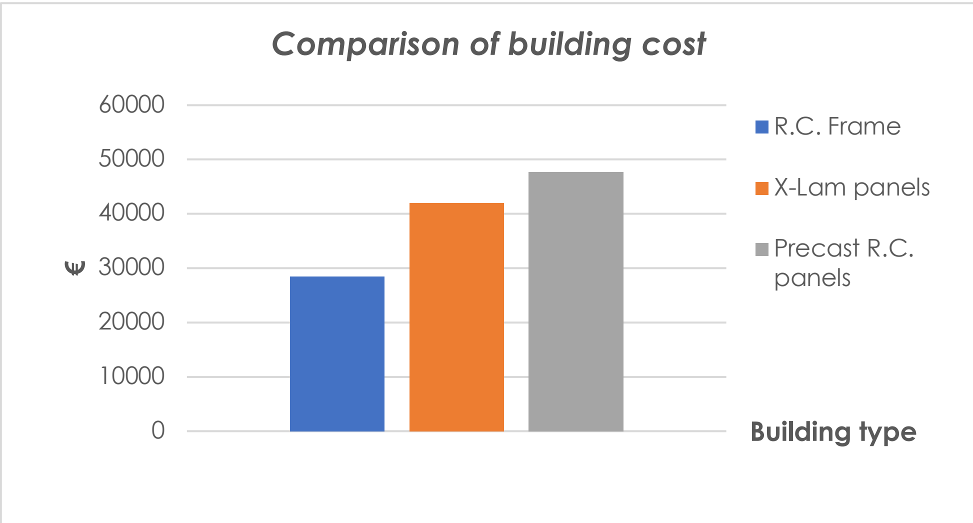

Fig. 23: Comparison of building cost

From the cost assessment, it is possible to observe that the reinforced concrete precast structures are the most expensive one (at least in the family house case), whereas the frame structure entails lower costs. This result is borne out by reality because the reinforced concrete frame structures are the most common construction type.

7. Conclusions

The previous results throw light on the overall environmental impact that a building causes during its life based on the used materials. It is possible to state the following observations:

- CLT structures is the more sustainable in every city. This result is due to lower greenhouse emissions occurring during the processing of the raw material (with respect to cement) and to the absorption capacity of CO_2 by the trees, from which the wood derives.
- The structures with precast R.C. panels have lower CO_2 equivalent emissions then the R.C. frame ones. In fact, the construction of a precast building requires less materials than a usual house in reinforced concrete frame structure and bricks. This is made possible because, unlike made-in-site concrete structures, plasterboard linings (which has a lower environmental impact) are preferred over plaster or mortar layers in precast panels structure.
- Referring only to the LCA of the materials, it should be noted that the building located in Oslo has the largest environmental impact in terms of CO_2 equivalent; this is mainly due to the amount of thermal insulation needed to guarantee the required performance
- Carbonation processes that occur both during the life of the concrete-made buildings and after disposal in landfills of concrete materials could enable the reduction of the GWP impact.
- The greatest contribution to emissions derives from energy consumption for heating and cooling needs.
- In the case of the family house, the parameter that most affects the CO2 emissions is the climatic condition, whereas the type of structure plays a marginal role. This result is also due to the choice of adopting natural ventilation in the thermal analysis, which is better suited to this type of building
- From an economic standpoint, reinforced concrete precast structures are most expensive (at least in the family house case), whereas the frame structure entails lower costs.

7.1. Further method development

A more in-depth analysis should be carried out in order to improve the results of the GWP impacts. In particular, clarifications should be provided about the biogenetic CO_2 effect. Nevertheless, it is important to underline that this is a preliminary LCA, referred to generic data and still based on important assumptions. To obtain more robust results, primary data on materials processes and EoL treatments would be necessary.

Furthermore, a similar simulation on a building of a larger scale is being carried out because it could lead to interesting result. In fact, a study previously conducted on three buildings with R.C. frame structure of different heights (12, 30 and 60 floors) shown how the unitary environmental impact decreases with the increase in the number of floors of the building [24]. In addition, a mechanical ventilation system could be provided for the taller building, as this could allow benefit from the greater thermal inertia of the concrete buildings (especially during the warmer season), thus reducing the use of energy and, therefore, the emissions of greenhouse gases.

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Further notes

To answer to your comments regarding the email dated 2019-01-16, the following clarification is reported:

- "POROTON" is a specific clay brick brand, produced by "Consorzio POROTON". The POROTON bricks (clay-only composed, thus without the presence of concrete) are characterized by high thermal insulation performance, and these was used in the envelope walls of the frame structures made of reinforced concrete. For this reason, the term "POROTON**"** was initially used to indicate this type of structure. Nevertheless, as it was misleading, it has been replaced by "R.C. frame structure".