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The sustainable approach to structural and thermal design in a family house

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1.Abstract

The building is responsible for a high global share of environmental, economic and social impacts.

For this reason, the theme of sustainability plays a leading role and, during the last years many safety measures have been taken to reduce the emissions of greenhouse gases: the final goal is to make all new buildings nZEB, that is Nearly Zero Energy Building.

In this direction, building materials are becoming increasingly more important for resource efficient construction.

In particular, if on the one hand there is a research of new sustainable materials and on the other hand it is necessary to study new technologies in order to improve and make more sustainable the traditional materials, such as concrete.

Thanks to this work, we compare three types of construction:

- Building in bricks (Poroton)
- Cross Laminated Timber (CLT) or XLAM building
- Building with precast concrete panels

For all cases, we analyse the structural behaviour through the definition of stresses thanks to FEM (Finite Element Method) program, the construction cost and the carbon footprint, which is expressed in terms of CO_2 equivalent.

To evaluate the buildings' emissions, we choose the LCA (Life Cycle Assessment) method.

In this way, we evaluate the whole life cycle of the building, that is "from cradle to grave".

In fact, we consider not only the production of materials, but also their transport to building site and their end – of – life since each material can be recycled, reused or sent to the landfill.

Furthermore, each type of building is located in three European cities (Torino, Catania, Oslo) with very different climate in order to test their thermal behavior.

In this case, it is necessary to respect the transmittance values required by Code rules and so we must design we designed specific stratigraphies which differ mainly in insulation's thickness.

Finally, for our checks and calculations, it is also important to underline that we refer to a family house, particularly EMA House, designed from 2005 to 2006 by Architect Bernardo Bader.

The house spread over 3 levels with a total area of 120 sqm and includes a garden.
On the ground floor a “summer-studio” directly links to the garden, bath and bedrooms are located on the second floor, while kitchen, dining and living area are situated on the top floor.

Figure 1.1 - EMA Haus, Arch. Bernardo Bader [18]

2. Building sustainability

The building sector is responsible for environmental, economic and social impacts.

The theme of environmental sustainability joined the building sector for two fundamental reasons: on the one hand, the building sector turns out to be the main cause of environmental impacts, such as energy consumption and greenhouse gas emissions; on the other hand, man wants to find comfortable and healthy buildings.

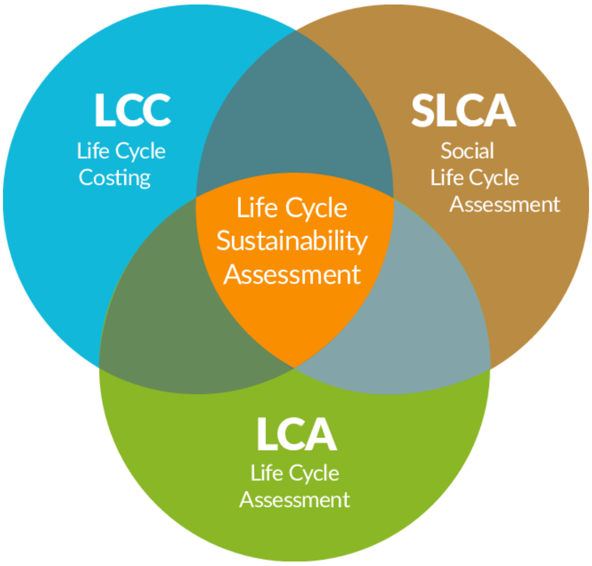

Figure 2.1 - Life Cycle Sustainability Assessment
Source: ESR10: "Life Cycle Sustainability Assessment of transportation infrastructure"

In particular, the environmental sustainability takes care of relationships between building - environment and building - citizens.

In fact, building produces environmental impacts not only with the construction, but with the whole process, from procurement of raw materials to disposal of ruins.

The factor that generates the greatest impacts consist of energy consumptions: huge efforts have been made over the last years towards the efficient use of energy in buildings during the use stage due to heating and cooling needs. The aim of the European Union is to make all new buildings zero-energy by 2020.

The concept of "sustainable development" was used, for the first time, inside the Brundtland Report, entitled "Our Common Future". It was drawn up in 1987 from the World Commission on Environment and Development, known as Brundtland Commission (by the name of its Norwegian president, Gro Harlem Brundtland), that had investigated the environmental situation from 1983 to 1987.

The term sustainable development means the will to guarantee the development of society and the wealth of people, putting as limit the environment's capacity to support this development. In fact, the sustainability refers to the carrying capacity of the environment, or its capacity to provide resources and to absorb waste.

In Europe, according to the strategies focused on promoting sustainable development, the design undergone an evolution over the years.

The goal is to promote a sustainable building, understood as a process in which all involved subjects try to make buildings, new or renovated, functional, accessible, comfortable, energy efficient in a long-term perspective.

In particular, dwelling upon environmental protection, it's necessary to guarantee the efficiency of resources and the reduction of environmental impacts.

In this way the design follows the principle of "life cycle thinking", which considers the whole life cycle of the buildings from "cradle to grave" or "from cradle to cradle".

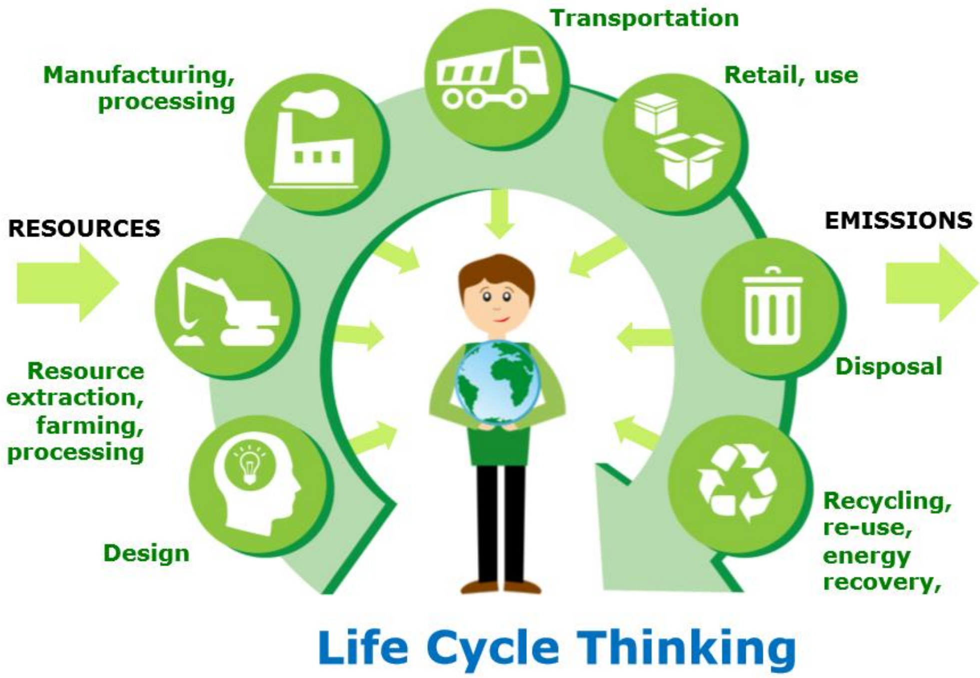

Figure 2.2 - Life Cycle Thinking
Source: ESR10: "Life Cycle Sustainability Assessment of transportation infrastructure"

The most important instrument of life cycle thinking is LCA, Life Cycle Assessment, which provides the best framework for assessing the potential environmental impacts of products.

It considers the complete life cycle, from materials production to the end-of-life and management of waste disposal.

LCA initially was referred to simple products with specific functions and analyzed their short period of life. This is not the case of buildings, which have usually a very long life and are multi – functional.

The application of LCA is a complex problem, especially during the design process when the most important decisions regarding the building design are taken. In fact, they will influence the building performance over its whole life.

It is also essential to refer to the interaction between environmental criteria and structural criteria: the structural engineers have the ability to decide, during the design, about which materials and structural systems to adopt in order to reduce the environmental impacts of the constructions satisfying structural requirements.

Therefore, in the concept of sustainable building, the materials are very important, since the transformation of raw materials into building products implies a great energy consumption and the consequent introduction of pollutants and waste into the environment, related, for example, to the production, transport and method of use.

Finally, the performance of the building will depend on the chosen materials, such as thermal and acoustic wellness.

In relation to the life cycle assessment, the analysis may be performed at the product level, according to EN 15804 and at the building level, EN 15978.

EN 15978 considers in the LCA process:

- 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)

The analysis of Modules A1 to A3 corresponds to a cradle – to – gate analysis.

In order to fulfil the building design’s requirements, mainly related to sustainability, efficient use of resources and structural safety, we consider quantifiable environmental indicators, such as CO_2 equivalent, which measure the performance of the building during their whole life cycle.

3. Reinforced concrete building

3.1 Introduction

3.1.1 Historical Outline

Concrete is a stonelike material obtained by permitting a proportioned mixture of cement, sand, gravel or other coarse aggregate, and water.
The time period during which concrete was first invented depends on how one interprets the term "concrete."
Ancient materials were crude cements made by burning gypsum or limestone and when sand and water were added to these cements, they became mortar, used to adhere stones to each other.
Over thousands of years, these materials were combined with others, until it was created the modern concrete.
The first concrete structures were built by the Nabataea traders who occupied a series of oases and developed a small empire in the regions of southern Syria and northern Jordan in around 6500 BC.
They discovered the advantages of hydraulic lime and by 700 BC, they were building kilns to supply mortar for the construction of rubble-wall houses, concrete floors, and underground waterproof cisterns, which permitted them to thrive in the desert.
In making concrete, they understood the need to keep the mix as dry or low-slump as possible, because an excess of water introduces voids and weaknesses into the concrete.
Around 3000 BC, the ancient Egyptians used gypsum and lime mortars in building the pyramids:
the Great Pyramid at Giza required about 500,000 tons of mortar.
Finally, in 1824, an Englishman named Joseph Aspdin invented Portland cement by burning finely ground chalk and clay in a kiln until the carbon dioxide was removed. It was named "Portland" cement because it resembled the high-quality building stones found in Portland, England.
During the 19th century, concrete was used mainly for industrial buildings while the first use of Portland cement in civil construction was in England and France between 1850 and 1880 by Frenchman Francois Coignet, who added steel rods to prevent the exterior walls from spreading, and later used them as flexural elements.

However, in this period, concrete was considered socially unacceptable as a building material for aesthetic reasons.

In 1902, August Perret designed and built an apartment building in Paris using steel with reinforcement for concrete.

The building had no bearing walls, but it did have an elegant façade, which helped make concrete as a building material socially acceptable.

In 1904, the first concrete high-rise building was constructed in Cincinnati, Ohio. It stands 16 floors or 210 feet tall.

Figure 3.1 - The Ingalls Building in Cincinnati, Ohio [15]

In our days, the world's tallest structure (as of 2011) was built using reinforced concrete. The Burj Khalifa in Dubai in the United Arab Emirates (UAE) stands 2,717 feet tall.

Here some characteristics:

- The structure consists of hotel, office and retail space, restaurants, nightclubs, swimming pools, and 900 residences.
- The construction of the structure used 431,600 cubic yards of concrete and 61,000 tons of rebar.
- The building has an empty weight of about 500,000 tons.
- Burj Khalifa can hold 35,000 people at a time.

Figure 3.2 - The Burj Khalifa in Dubai [15]

3.1.2 Reinforced concrete – general characteristics

There are a lot of factors that make concrete a universal building material.
Its facility to be modeled in order to obtain the wanted shape is, for example, one of these factors. Others are its high fire and weather resistance. Moreover, most of the constituent materials are usually available at low cost locally or at small distances from the construction site.
It has high compressive strength (like natural stones) while its tensile strength is low.
For this reason, it was introduced, in the second half of the nineteenth century, the use of steel, a material with high tensile strength, to reinforce concrete.
The result of the combination of two materials is the so-called reinforced concrete, which combines many of the advantages of each, in particular, the good compressive strength and formability of the concrete and the high tensile strength, ductility and toughness of steel.
In this way, reinforced concrete has unlimited range of use, from buildings to bridges.
This material also shows adaptability to a great variety of one-dimensional (beams, columns), two-dimensional (slabs) and three-dimensional (shell) structures and so the engineers have wide possibilities for aesthetically satisfying structural solutions.
In order to understand reinforced concrete's behaviour, it's necessary to briefly describe its components.

3.2 Concrete's ingredients

3.2.1 Cement

A cementitious material is one that has the adhesive and cohesive properties necessary to bond inert aggregates into a solid mass of adequate strength and durability.

For making structural concrete, it's important that hydraulic cements are used. Water is needed for the hydration, a series of chemical processes which permit to cement paste to first set and then harden.

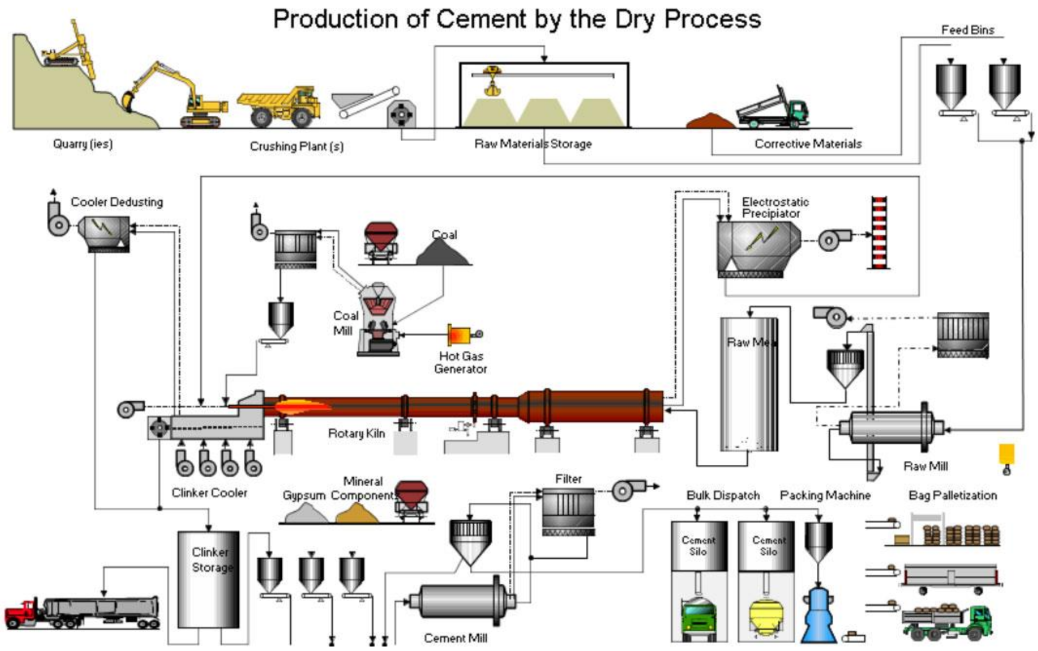

Figure 3.3 Cement manufacturing process
Source: Engineering intro

The most common hydraulic cement is Portland cement, which was first patented in England in 1824.

Portland cement consists of calcium and aluminium silicates: it is made by limestones, which provides CaO, and clays or shales, which furnish SiO_2 and Al_2O_3.

Gypsum and additional unreacted limestone are added, and the mixture is ground to the required fineness.

Over the years, five standard types of Portland cement have been developed.

In particular, concrete is made up of Portland cement Type I, normal Portland cement (in our project, all calculations refer to Portland cement Type I). The other types of

Portland cement increase its performance and they are used to speed construction when needed.

Tipi di cemento	Denominazione	Sigla	Clinker K	Loppa d'altoforno granulata S	Micro silice D	Pozzolana Naturale P	Pozzolana Industriale Q	Cenere Volante Silicica V	Cenere Volante Calcica W	Scisto Calcinato T	Calcare L	Costituenti Secondari
I	Cemento Portland	I	95-100	-	-	-	-	-	-	-	-	0-5
II	Cemento Portland alla loppa	II-A/S	80-94	6-20	-	-	-	-	-	-	-	0-5
		II-B/S	65-79	21-35	-	-	-	-	-	-	-	0-5
	Cemento Portland alla microsilice	II-A/D	90-94	-	6-10	-	-	-	-	-	-	0-5
	Cemento Portland alla pozzolana	II-A/P	80-94	-	-	6-20	-	-	-	-	-	0-5
		II-B/P	65-79	-	-	21-35	-	-	-	-	-	0-5
		II-A/Q	80-94	-	-	-	6-20	-	-	-	-	0-5
		II-B/Q	65-79	-	-	-	21-35	-	-	-	-	0-5
	Cemento Portland alla cenere volante	II-A/V	80-94	-	-	-	-	6-20	-	-	-	0-5
		II-B/V	65-79	-	-	-	-	21-35	-	-	-	0-5
		II-A/W	80-94	-	-	-	-	-	6-20	-	-	0-5
		II-B/W	65-79	-	-	-	-	-	21-35	-	-	0-5
	Cem. Port. allo scisto calcinato	II-A/T	80-94	-	-	-	-	-	-	6-20	-	0-5
		II-B/T	65-79	-	-	-	-	-	-	21-35	-	0-5
	Cem. Portland al calcare	II-A/L	80-94	-	-	-	-	-	-	-	6-20	0-5
		II-B/L	65-79	-	-	-	-	-	-	-	21-35	0-5
	Cem. Portland composito	II-A/M	80-94	←	←	←	←	6-20	→	→	→	→
		II-B/M	65-79	←	←	←	←	21-35	→	→	→	→
III	Cemento d'altoforno	III-A	35-64	36-65	-	-	-	-	-	-	-	0-5
		III-B	20-34	66-80	-	-	-	-	-		-	0-5
		III-C	5-19	81-95	-	-	-	-	-	-	-	0-5
IV	Cemento pozzolanico	IV-A	65-89	-	←	←	11-35	→	-	-	-	0-5
		IV-B	45-64	-	←	←	36-55	→	-	-	-	0-5
V	Cemento composito	V-A	40-64	18-30	-	←	18-30	→	-	-	-	0-5
		V-B	20-39	31-50	-	←	31-50	→	-	-	-	0-5

Figure 3.4 - Types of cement in accordance to UNI - EN 197/1 [3]

For complete hydration of a given amount of cement, an amount of water equal to about 25 percent of that of cement is needed chemically (a water-cement ratio of 0.25).
An additional amount of water provides the necessary workability of the concrete mix.
For normal concretes, the water-cement ratio is in the range of about 0.40 to 0.60. In the high-strength concretes, the ratio is 0.21 and so the workability is guarantee by the use of admixtures.
The strength of the cement paste depends on the water-cement ratio and in particular it decreases directly with an its increasing.
In fact, if the quantity of water increases, during the chemical reaction, there is the production of pores in the cement paste.
The strength of the hardened paste decreases in inverse proportion to the fraction of the total volume occupied by pores since only the solid paste resists stress.

3.2.2 Aggregates

In ordinary structural concretes the aggregates occupy 65 to 75 percent of the volume of the hardened mass.

It is important that the aggregate has good strength, durability and weather resistance; that its surface be free from impurities and that no unfavourable chemical reaction take place between it and the cement.

Natural aggregates are classified as fine and coarse. Fine aggregate (natural sand) is any material that will pass a No. 4 sieve, that is, a sieve with four openings per linear inch. Material coarser than this classified as coarse aggregate.

Requirements for satisfactory aggregates are found in ASTM C33 "Standard Specification for Concrete Aggregates".

The unit weight of normalweight concrete varies from 140 to 152 pounds per cubic foot (2244.58 to 2434.81 kg) and it can be assumed 145 pcf (2322.68 kg).

3.2.3 Admixture

In addition to the main components of concretes, admixtures are used in order to improve concrete performance.

There are admixtures to accelerate or retard the process of hydration (accelerating admixtures and set-retarding admixtures), improve workability and durability (such as air – entraining agents) and increase strength (such as superplasticizers), reducing water-cement ratio.

Finally, we use fly ash and silica fume. They are pozzolan materials which are used as supplementary cementitious materials in place of part of the Portland cement in concrete mixes.

In particular, fly ash tends to increase the strength of concrete at ages over 28 days, while silica fume contributes to strength gain at early ages, from 3 to 28 days, both fly ash and silica fume are used in the production of high-strength concrete.

It's very important to underline how the use of mineral admixtures, as fly ash, reduces the energy usage and greenhouse gas production.

For this reason, these materials have the potential to further improve the sustainability of concrete construction when used as a partial replacement for Portland cement.

In these way, we can take the advantages of reinforced concrete structures, which come from concrete's thermal mass. In fact, differently from other materials, concrete's thermal mass reduces the energy and CO_2 needed for heating and cooling.

3.3 Proportioning and mixing concrete

The components of concrete mix are proportioned to obtain the required strength, proper workability for placing and low cost.
The size of aggregates has to reduce the volume of voids while water is added not only for the process of hydration, but also for wetting the surface of the aggregate.
This caused, on the one hand, an increasing of the plasticity and fluidity of the mix (that is, its workability improves), on the other hand, a decreasing of the strength because of the larger volume of voids created by the free water.
In order to reduce free water while retaining the workability, cement must be added and so the water – cement ratio, as already said, becomes the most important factor to control the strength of the concrete.
For a given water – cement ratio, to reduce cost, it is necessary to select the minimum amount of cement that will secure the wanted workability.

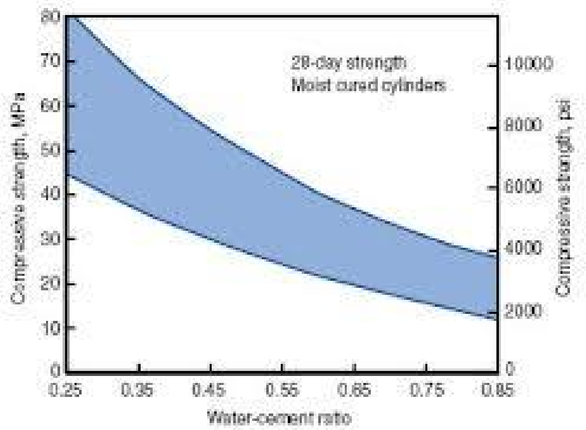

Figure 3.5 - Effect of water-cement ratio on 28-day compressive
Source: Engineering intro

If we consider a proportioned mix design, 1 m^3 of concrete is made up of:

- about 300 kg of cement
- about 120 l of water
- 0.4 m^3 of sand (included voids)
- 0.8 m^3 of coarse aggregates (included voids)

Air content is 4 to 7 percent when air is deliberately entrained in the mix and 1 to 2 percent when it is not.

The weights of the fine and coarse aggregates depend on material in the saturated dry condition.

Concrete consistency is measured by the slump test.

It is used to check that correct amount of water has been added to the mix.

The test is carried out in accordance with EN 12350 – 2, *Testing fresh concrete. Slump test.*

The steel slump cone is placed on a solid, impermeable, level base and filled with the fresh concrete in three equal layers.

Each layer is rodded 25 times to ensure compaction. The third layer is finished off level with the top of the cone. It is carefully raised and the concrete slumps.

The upturned slump cone is placed on the base to act as a reference, and the difference between its top and the top of concrete is measured.

When the cone is removed, the slump may take one of three forms.

- In a true slump, the concrete keeps the shape.
- In a shear slump, the top portion of the concrete shears off and slips sideways
- In a collapse slump the concrete collapses completely

A collapse slump will mean that the mix is too wet, and it is a high workability mix.

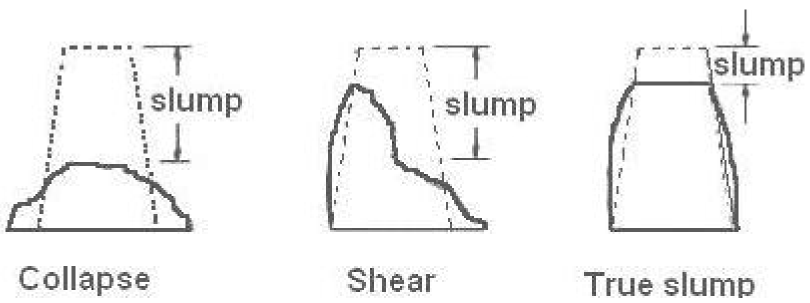

Figure 3.6 - Types of slump
Source: Wikipedia

Fresh concrete gains strength most rapidly during the first few days and weeks. Structural design is generally based on the 28 – day strength, about 70 percent of which is reached at the end of the first week after placing.
Placing is the process through which the fresh concrete is transferred from the conveying device to its final place in forms.
The final concrete strength depends on the conditions of moisture and temperature during the initial period.
In this way, it is important to maintain appropriate conditions during this time (that is, the process of curing).
To prevent damage, concrete should be protected from loss of moisture and so it is necessary to keep exposed surfaces continually wet.
Moreover, to protect concrete against low temperatures during cold weather, the mixing water is heated, and thermal insulation is used where possible such special admixture.

3.4 Properties in compression

Performance of a structure subjected to loads depends on the stress – strain relationship of the material from which it is made.
About concrete, as known, its compressive stress – strain curve is important.
We can see (Figure 3.7) an initial straight elastic portion in which stress and strain are closely proportional, then the curve begins to curve to the horizontal, reaching the maximum stress, that is, the compressive strength. Finally, the curve shows a descending branch after the peak stress is reached.
The compressive strength f_c' is in the range from 3000 to 6000 psi (from 21 MPa to 42 MPa) for normalweight cast – in – place concrete, and up to about 10000 psi (69 MPa) for precast prestressed concrete.
The modulus of elasticity E_C, that is, the slope of the initial straight portion of stress – strain curve depends on the concretes' strength and it is can be calculated through the empirical equation found un ACI Code

$$E_c = 33{w_c}^{1.5}\sqrt{f_c'} \quad (3.1)$$

where w_c is the unit weight of the hardened concrete in pcf and f_c' is its strength in psi.
For normalweight concrete, with $w_c = 145$ pcf, E_C can be expressed as:

$$E_c = 57000\sqrt{f_c'} \quad (3.2)$$

For compressive strengths in the range from 6000 to 12000 psi (from 42 MPa to 83 MPa), the ACI Code may overestimate E_C by as much as 20 percent.
For this reason, we use the following equation to calculate E_C:

$$E_c = \left(40000\sqrt{f_c'} + 1000000\right)\left(\frac{w_c}{145}\right)^{1.5} \quad (3.3)$$

In this way, we can clearly see how it is important to measure E_C rather than estimated since the modulus of elasticity becomes a key design criterion.
Information on concrete strength properties is obtained through tests made 28 days after placing. However, cement continues to hydrate, and concrete continues to harden.

When compressed in one direction, concrete expands in the direction transverse to that of the applied stress.

The ratio of the transverse to the longitudinal strain is known as Poisson' ratio and particularly depends on strength.

At stresses lower than about 0.7 f_c', Poisson's ratio for concrete is between 0.15 and 0.20.

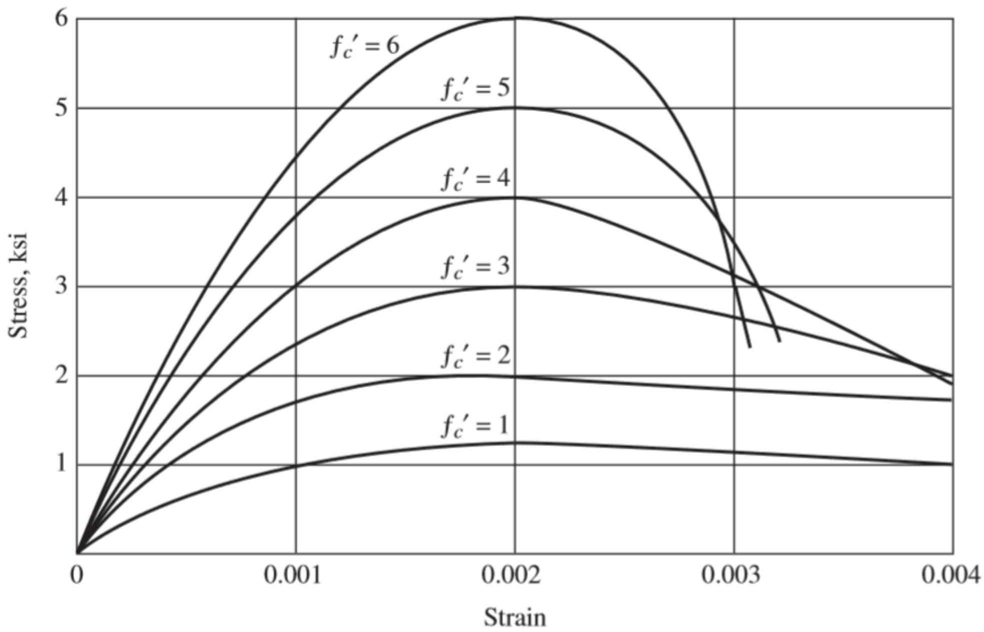

Figure 3.7 - Typical concrete stress-strain curve, with short-term loading
Source: Design of Reinforce Concrete, ninth edition

3.5 Precast concrete building

The concrete structural elements, such as slabs, columns, beams, are combined to constitute structural systems for building.

The structural engineer must select, from many alternatives, the best structural system in relation to the given conditions.

The use of reinforced concrete as building material has the following advantages:

- Versatility of form. The material can satisfy a lot of architectural and functional requirements.
- Durability. With adequate protection for steel reinforcing, the structure has a long life and resists even adverse climatic and environmental conditions
- Fire resistance. With adequate protection for the reinforcement, a reinforced concrete structure provides the maximum in fire protection
- Speed of construction. A concrete building can often be completed in less time than a steel structure. In fact, in this last case, it's necessary the prefabrication of all parts in the shop
- Cost. Concrete buildings have low cost.
- Availability of labor and material. It is possible to use local labour and building materials so that only the cement and reinforcement could come from a remote source.

However, cast – in – place reinforced concrete structures require a significant amount of skilled on-site labor.

For this reason, precast concrete building is a class of concrete construction for which the structural members are made off site in precasting yards, under controlled boundary conditions, and assembled on site.

In this way, the construction of the building is faster and more economic.

Precast concrete construction involves the construction of repetitive and standardized units: columns, beams, floor and roof elements, and wall panels.

Advantages of precast construction include less labor per unit because of mechanized series production; use of unskilled local labor; shorter construction time; better quality control and higher concrete strength; greater independence of construction from weather and season.

There are also disadvantages, such as the greater cost of transporting precast elements and the technical problems and costs of site connections of precast elements.

Precast constructions are used in all types of structures, from industrial building to bridges and stadiums.
In our case, we adopted precast concrete panels to build a family house.
In particular, we used precast exterior wall panels.
Wall panels are made in a variety of shapes, depending on architectural requirements: because of the examined building is located in three cities with very different climate, in order to improve thermal insulation, sandwich panels are used.
They, as figure below shows, consist of an insulation core, in XPS, between two layers of normalweight concrete.
The two layers must be adequately interconnected through the core to act as one unit.
Stresses in wall panels are more severe in handling and during the erection than in finished structure, and the design must provide for these temporary conditions.
Moreover, to control cracking that is very important in wall panels, the maximum tensile stress in the concrete should not exceed the modulus of rupture with a margin of safety.
For normalweight concrete panels, the tensile stress is limited to $5\sqrt{f_c'}$.

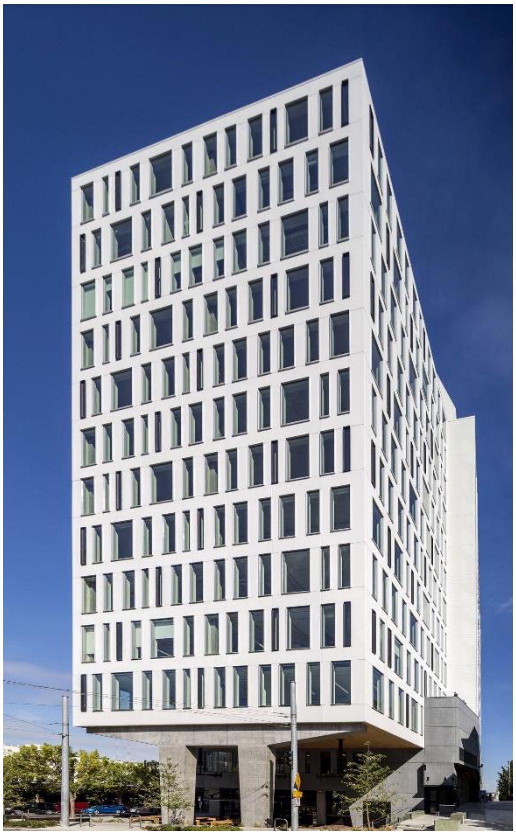

Figure 3.8 - 400 Fairview: example of precast concrete modules
Source: Archello

4. Cross Laminated Timber (CLT) or XLAM Building

In the beginning of the 20th century, all the building sector focused on the development of reinforced concrete, which enable the construction of buildings with complex shapes and geometry thanks to its adaptability to every field.

Nowadays concrete is the most widely used construction material, but because of the recent concerns about the climate change, other sustainable materials are taken in account.

One of these new technologies is Cross Laminated Timber also known as CTL or XLAM.

In the beginning of the 1990, what is now known as Cross Laminated Timber was developed by a timber manufacturing company in Austria.

However, it took several years for the product to be used in the building construction, mainly due to the lack of technical knowledge in the field.

After studies on the performance of CLT and on its sustainability, XLAM gained popularity especially in the Northern Europe.

In particular, its success depends on the ease to be handle and on the possibility to have precast elements.

Cross Laminated Timber panels consist of several layers of timber boards with different orientation, some of them longitudinally and others transversally as shown in figure 3.9

The basic CLT element is made up of at least three layers glued together in order to provide a substantial structural response to the structural stresses.

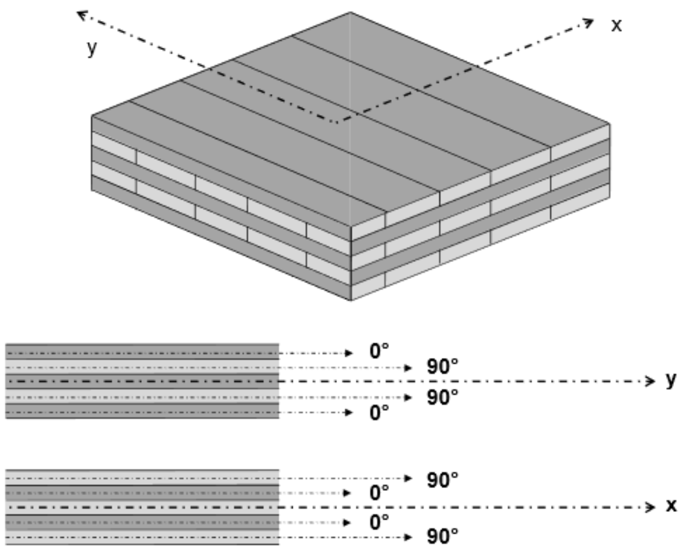

Figure 4.1 - Cross Laminated Timber (CLT) panel [17]

XLAM is obtained by assembling two basic raw materials: lumber and adhesive glue. Laminated timber modules depend essentially on the manufacturing company.

A key factor in the raw material choice is the importance of a product coming from an eco-labelled, certified forest PEFC (Programme for the Endorsement of Forest Certification).

A PEFC label assures that the timber is cut from a forest that follows the reforestation standards and respects the environment.

In our project we choose XLAM Dolomiti, which is considered a leader in this sector.

The initial phase of the manufacturing consists of the planing of the board surface to remove possible impurities, to refresh the wood to reduce oxidation, and to improve the gluing efficient.

The second phase is the adhesive application. In particular there are three main wood adhesives used for Cross Laminated Timber production:

- PRF (phenol-resorcinol-formaldehyde)
- EPI (emulsion polymer isocyanate)
- PUR (one-component polyurethane).

XLAM Dolomiti uses PUR, produced by the Swiss company Purbond, a product with good gluing strength and without formaldehyde.

After a quality check, the panel is put inside an automatic machine that cuts out the openings for windows and doors according to project’s requirements.

XLAM has good structural, energy saving and insulation properties, fire resistance, as well as fast and easy prefabrication.

Moreover, CLT is also a sustainable material with a low carbon footprint since it is possible to recreate it by planting new trees.

The only problem is linked to the adhesive glue used in the production and its effect on the environment.

Another important aspect is the possibility of assembling panels in the factory, creating real prefabricated house.

Figure 4.2 - Example of XLAM panel [17]

This not only reduces constructing times but also the risk of accidents on the job site area. In fact, there is a small number of on-site workers and the equipment needed for the installation is simple.

Finally, Cross Laminated Timber has an excellent resistance against earthquakes better than other building materials.

This depends on the elasticity of the raw materials which prevent the structure to collapse in case of seismic forces.

The problem is the correct and safe design of connection between the elements.

In order to guarantee the connection between XLAM panels, we hypothesized to use self-drilled screws (HBS ϕ 10mm, *Rothoblaas company*), while for the connection between vertical and horizontal elements, we used:

- L angular to transfer shear forces
- Hold – down to transfer vertical forces caused by overturning moment

In particular, for L angular, we decided to use TITAN TCN 200 (looking at the attached related *Rothoblaas company*) for the connection between XLAM panels and slab's reinforced concrete beams of the ground floor and TITAN TTN 240 between XLAM panels and XLAM slab.

For the hold – down project, we used WHT 340 (*Rothoblaas company*) profiles to absorb the tensile forces.

5. Design of a family house

5.1 Introduction

Design is the determination of the general shape and specific dimensions so that a structure will perform the function for which it was created and will safely withstand the influences that will act on it throughout its useful life.

These influences are the loads and other forces to which it will be subjected, as well as other detrimental agents, such as temperature fluctuations and foundation settlements.

The basic form of the structure is defined by its intended use. The design of concrete structures follows the same general sequence.

First, an initial structural system is defined, the initial member sizes are selected, and a mathematical model of the structure is generated.

Second, gravity and lateral loads are determined based on the selected system, member sizes and external loads.

Third the loads are applied to the structural model and the load effects calculated for each member. This step may be done by using computer modelling software. This step is more complex if we considered earthquake loads.

Fourth, maximum load effects at critical member sections are identified and each critical section is designed for moment, axial load, shear, and torsion as needed.

At this step, the process may become iterative. For example, if the member initially selected is too small, its size must be increased, load effects recalculated for the larger member and the members redesigned. If the initial member is too large, a smaller section is selected; however, loads are usually not recalculated as gravity effects are most often conservative. Fifth, each member is checked for serviceability.

Sixth, the reinforcement for each member is detailed, that is, the number and the size of reinforcing bars are selected for the critical sections to provide the required strength. Seventh, connections are designed to ensure that the building performs as intended. Finally, the design information is incorporated in the construction documents.

The term member refers to an individual portion of the structure, such as a beam, column, slab.

5.2 Reinforced Concrete Structure

5.2.1 Design of structural elements

Joists

In order to define the geometry of structural elements, we referred to ACI Code and NTC 2018.

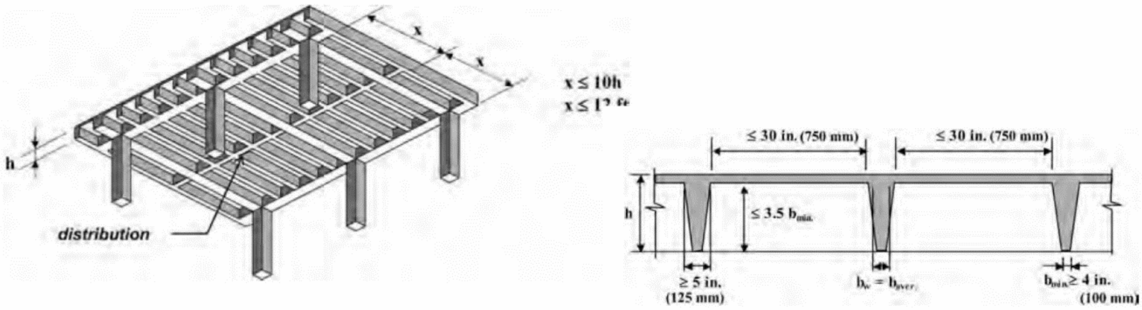

Figure 5.1 – Design of Joist [6]

- The distance between joists must not exceed 750 mm
- The minimum width b_{min} of a joist must not be less than 100 mm
- The internal height must not exceed 3.5 times b_{min}
- The distance between rompitratta joists must be less than 10 times the height h and 4 m
- The height h depends on the type of floor's restraint and on the span l_s

The height of the slab was used the table below in reference to the "one end continuous" structural scheme:

Continuity across the supports	Minimum depth h
Simply supported	$\ell_s/16$
One end continuous	$\ell_s/18.5$
Both ends continuous	$\ell_s/21$
Cantilever	$\ell_s/8$

Figure 5.2 - Height of slab [6]

In this case, the greater span l_s measures 4 m and so:

$$h_{min} = \frac{l_s}{18.5} = \frac{400}{18.5} = 21.6\ cm \quad (5.1)$$

The height *h* of slab that we chose is 28 cm > 21.6 cm.

Beams

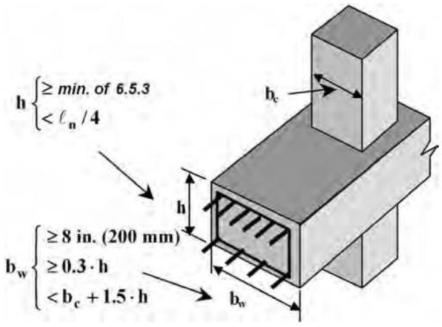

Figure 5.3 – Design of beam [6]

- The height *h* must not be greater than ¼ of the span l_n
- The width b_w must not be less than 200 mm; (> 200 mm)
- The width b_w must not be less than 0.3 h; (> 0.25 h)
- The width b_w must not exceed 1.5 h + b_c (width of the column)

The beams' design satisfies the relationship:

$$h_{min} = \frac{l_n}{18} = \frac{385}{18} = 21.4\ cm \quad (5.2)$$

In our building, the main beams have the following dimensions:

- h = 30 cm
- b_w = 40 cm

In the case of secondary beams, there are not precise rules for their design and for this reason we assume the same dimensions of the main ones:

- h = 30 cm
- b_w = 40 cm

Columns

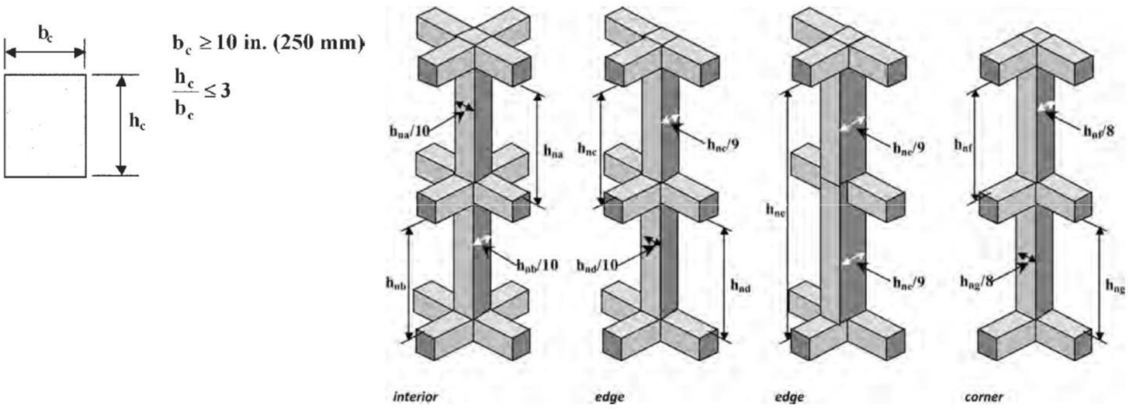

Figure 5.4 – Design of column [6]

- If the column is rectangular, the smaller side must be more than 250 mm
- In a rectangular column, one side must not exceed 3 times the other
- There are limitations depending on the position of the column in the frame (internal, end or corner column)

In this project, each column is (30 x 30) cm regardless of its position.

5.2.2 Structural Skeleton of the building

In order to achieve greater clarity, we provide the three-dimensional skeleton of the structure.
It is obtained by using Revit 2018 software.

Figure 5.5 - Structural skeleton of the building (Revit 2018)

We also represent the model floor plan, the main frame and the secondary frame.

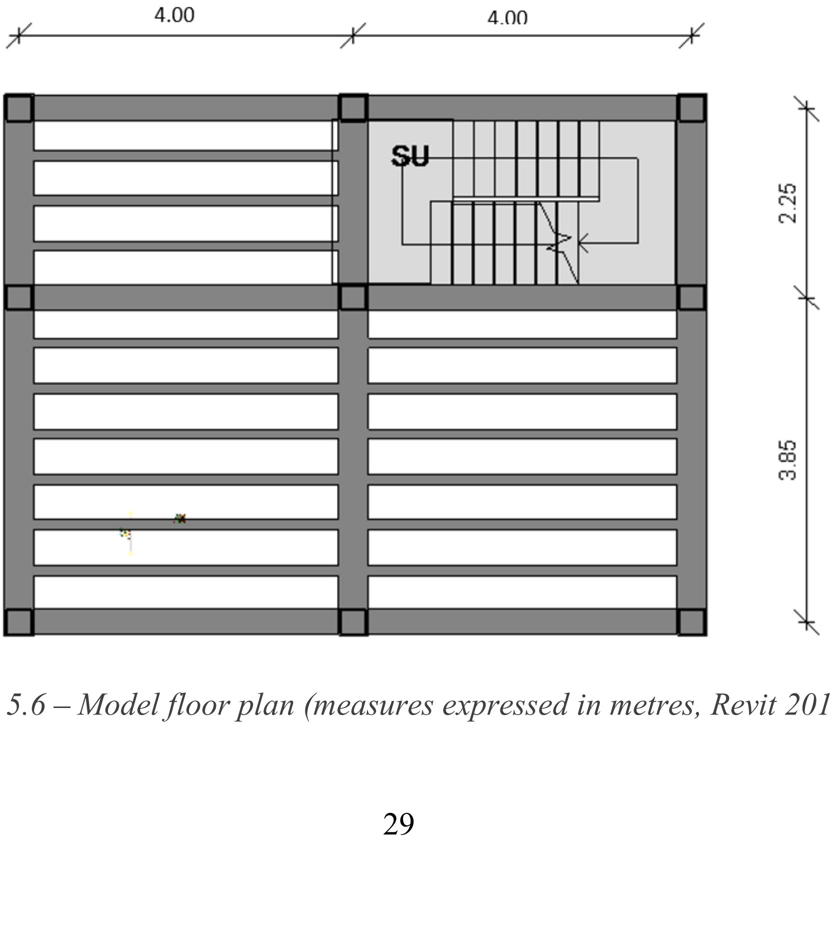

Figure 5.6 – Model floor plan (measures expressed in metres, Revit 2018)

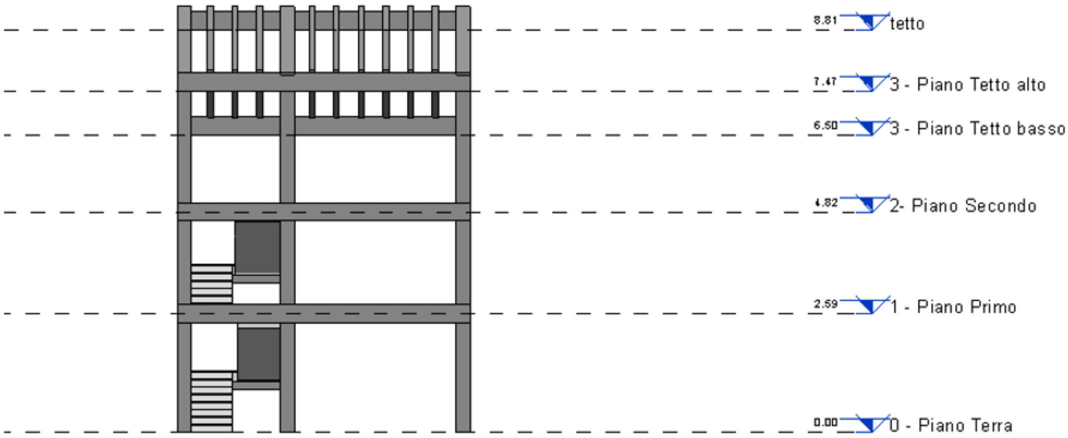

Figure 5.7 - Main Frame (measures expressed in metres, Revit 2018)

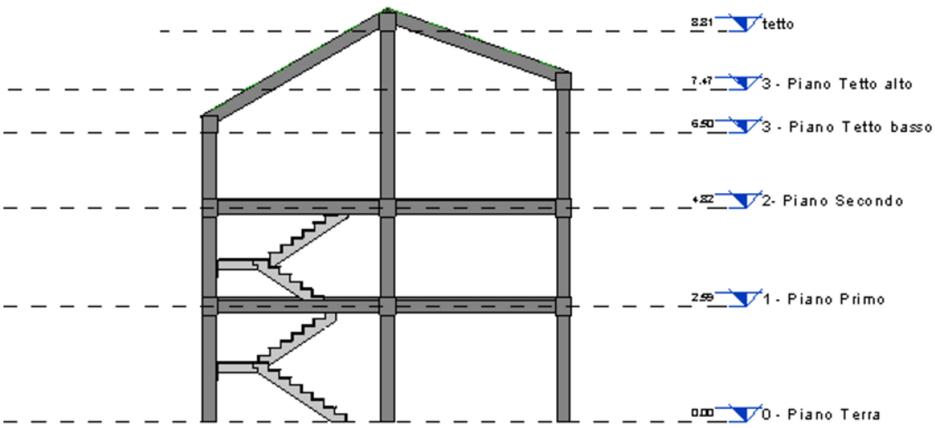

Figure 5.8 - Secondary Frame (measures expressed in metres, Revit 2018)

5.2.2 Definition of loads

Loads can be divided into three categories:

- Dead loads
- Live loads
- Environmental loads

Dead loads

Dead loads are constant in magnitude and fixed in location throughout the lifetime of the structure.
Usually the major part of the dead load is the weight of the structure itself, which depends on the dimensions of the elements and the density of material.
For building, dead loads also include the structural or non-structural permanent loads, such as external walls, internal walls, roof, slabs…
In order to define the weight of the elements, we hypothesized different stratigraphy depending on the locality (Torino, Catania, Oslo) and the type of construction (structure in bricks, XLAM structure or prefabricated reinforced concrete panels).
Moreover, the chosen stratigraphy must satisfy thermal demands and for this reason, they differ particularly in thermal insultation’s thickness.
We defined the weight of each building material through catalogues.
In particular, in this RC building, we use for external walls Poroton bricks in order to increase thermal performance and, consequently, to reduce insulation’s thickness.

Stratigraphies of RC Structures

- ***Torino***

Floor on the ground				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	-
2	Regularization layer	0.065	-	-
3	Thermal insulation - EPS	0.120	-	-
4	Waterproof membrane	0.004	-	-
5	Screed for systems	0.100	-	-
6	Reinforced concrete slab	0.040	-	-
7	Crawl space	0.350	-	-
8	Lean Concrete	0.100	-	-
			Total thickness [m]	***0.79***

Table 5.1 - Stratigraphy of floor on the ground. The Table show structural features (thickness and weight) - Torino

External walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Plaster	0.015	15.00	0.225
2	Poroton	0.250	-	2.280
3	Thermal insulation - Rockwool	0.100	0.59	0.059
4	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.38***
			Total weight [kN/m^2]	***2.789***

Table 5.2 - Stratigraphy of external walls. The Table show structural features (thickness and weight) - Torino

Inside walls				
	Material	Thickness [m]	Density [kN/m3]	Weight [kN/m2]
1	Plaster	0.015	15.00	0.225
2	Poroton	0.080	-	1.150
3	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.11***
			Total weight [kN/m^2]	***1.600***

Table 5.3 - Stratigraphy of inside walls. The Table show structural features (thickness and weight) - Torino

Interfloor				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	0.190
2	Regularization layer	0.040	17.65	0.706
3	Acoustic pad	0.003	0.29	0.001
4	Screed for system	0.060	4.00	0.240
5	Vapour barrier	0.003	-	0.001
6	Slab	0.280	-	3.089
7	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.41***
			Total weight [kN/m^2]	***4.453***

Table 5.4 - Stratigraphy of interfloor. The Table show structural features (thickness and weight) - Torino

Roof				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Tiled roof	0.015	-	0.374
2	Ventilated Air Gap	0.060	-	-
3	Waterproof membrane	0.004	-	0.039
4	Thermal insulation - Rockwool	0.140	1.52	0.213
5	Vapour Barrier	0.003	-	0.001
6	Roof	0.240	-	2.648
7	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.48***
			Total weight [kN/m^2]	***3.500***

Table 5.5 - Stratigraphy of roof. The Table show structural features (thickness and weight) - Torino

- ***Catania***

Floor on the ground				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	-
2	Regularization layer	0.065	-	-
3	Thermal insulation - EPS	0.080	-	-
4	Waterproof membrane	0.004	-	-
5	Screed for systems	0.100	-	-
6	Reinforced concrete slab	0.040	-	-
7	Crawl space	0.350	-	-
8	Lean Concrete	0.100	-	-
			Total thickness [m]	***0.75***

Table 5.6 - Stratigraphy of floor on the ground. The Table show structural features (thickness and weight) – Catania

External walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Plaster	0.015	15.00	0.225
2	Poroton	0.250	-	2.280
3	Thermal insulation - Rockwool	0.05	0.59	0.030
4	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.33***
			Total weight [kN/m^2]	***2.759***

Table 5.7 - Stratigraphy of external walls. The Table show structural features (thickness and weight) - Catania

Inside walls				
	Material	Thickness [m]	Density [kN/m3]	Weight [kN/m2]
1	Plaster	0.015	15.00	0.225
2	Poroton	0.080	-	1.150
3	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.11***
			Total weight [kN/m^2]	***1.600***

Table 5.8 - Stratigraphy of inside walls. The Table show structural features (thickness and weight) - Catania

Interfloor				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	0.190
2	Regularization layer	0.040	17.65	0.706
3	Acoustic pad	0.003	0.29	0.001
4	Screed for system	0.060	4.00	0.240
5	Vapour barrier	0.003	-	0.001
6	Slab	0.280	-	3.089
7	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.41***
			Total weight [kN/m^2]	***4.453***

Table 5.9 - Stratigraphy of interfloor. The Table show structural features (thickness and weight) – Catania

Roof				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Tiled roof	0.015	-	0.374
2	Ventilated Air Gap	0.07	-	-
3	Waterproof membrane	0.004	-	0.039
4	Thermal insulation - Rockwool	0.1	1.52	0.152
5	Vapour Barrier	0.003	-	0.001
6	Roof	0.240	-	2.648
7	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.45***
			Total weight [kN/m^2]	***3.439***

Table 5.10 - Stratigraphy of roof. The Table show structural features (thickness and weight) - Catania

- ***Oslo***

Floor on the ground				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	-
2	Regularization layer	0.065	-	-
3	Thermal insulation - EPS	0.180	-	-
4	Waterproof membrane	0.004	-	-
5	Screed for systems	0.100	-	-
6	Reinforced concrete slab	0.040	-	-
7	Crawl space	0.350	-	-
8	Lean Concrete	0.100	-	-
			Total thickness [m]	***0.85***

Table 5.11 - Stratigraphy of floor on the ground. The Table show structural features (thickness and weight) - Oslo

External walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Plaster	0.015	15.00	0.225
2	Poroton	0.250	-	2.280
3	Thermal insulation - Rockwool	0.120	0.59	0.071
4	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.40***
			Total weight [kN/m^2]	***2.801***

Table 5.12 - Stratigraphy of external walls. The Table show structural features (thickness and weight) - Oslo

Inside walls				
	Material	Thickness [m]	Density [kN/m3]	Weight [kN/m2]
1	Plaster	0.015	15.00	0.225
2	Poroton	0.080	-	1.150
3	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.11***
			Total weight [kN/m²]	***1.600***

Table 5.13 - Stratigraphy of inside walls. The Table show structural features (thickness and weight) - Oslo

Interfloor				
	Material	Thickness [m]	Density [kN/m³]	Weight [kN/m²]
1	Ceramic tiles	0.009	-	0.190
2	Regularization layer	0.040	17.65	0.706
3	Acoustic pad	0.003	0.29	0.001
4	Screed for system	0.060	4.00	0.240
5	Vapour barrier	0.003	-	0.001
6	Slab	0.280	-	3.089
7	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.41***
			Total weight [kN/m²]	***4.453***

Table 5.14 - Stratigraphy of interfloor. The Table show structural features (thickness and weight) - Torino

Roof				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Tiled roof	0.015	-	0.374
2	Ventilated Air Gap	0.060	-	-
3	Waterproof membrane	0.004	-	0.039
4	Thermal insulation - Rockwool	0.140	1.52	0.213
5	Vapour Barrier	0.003	-	0.001
6	Roof	0.240	-	2.648
7	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.51***
			Total weight [kN/m^2]	***3.500***

Table 5.15 - Stratigraphy of roof. The Table show structural features (thickness and weight) - Oslo

Graphic Representation of Stratigraphies

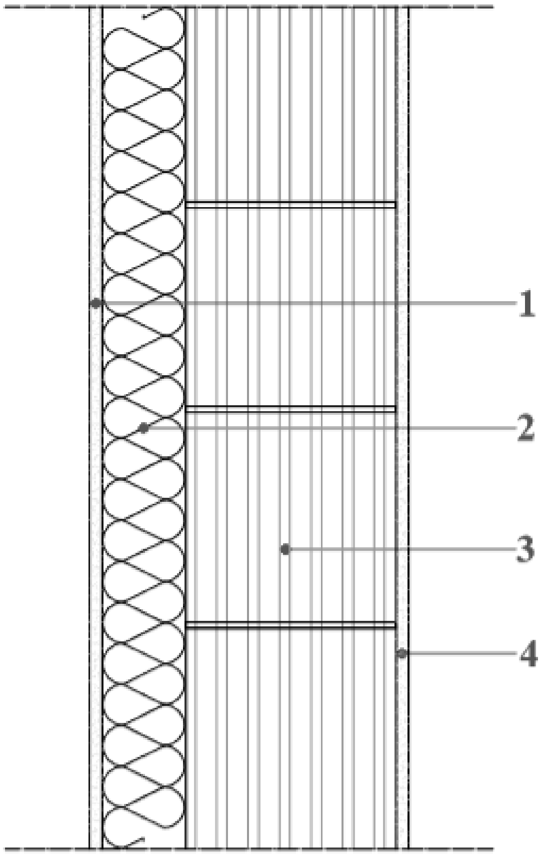

Figure 5.9 - Stratigraphy of External Walls (measures in cm)

1. Plaster (th. 1.5 cm)
2. Thermal Insulation – Rockwool (th. X cm)
3. Poroton (th. 25 cm)
4. Plaster (th. 1.5 cm)

"X" refers to insulation thickness and its value depend on the location where the building is situated.

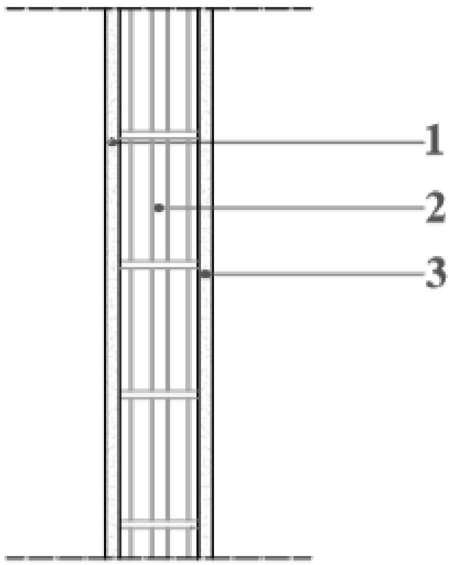

Figure 5.10 - Stratigraphy of Internal Walls (measures in cm)

1. Plaster (th. 1.5 cm)
2. Poroton (th. 8 cm)
3. Plaster (th. 1.5 cm)

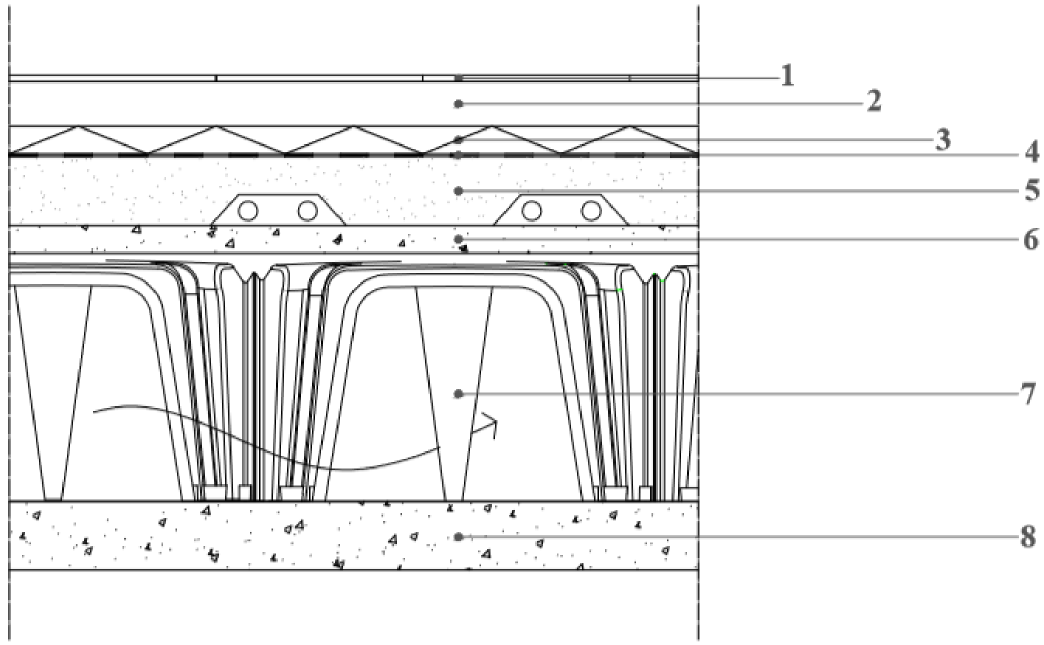

Figure 5.11 - Stratigraphy of floor on the ground (measures in cm)

1. Ceramic Tiles (th. 0.9 cm)
2. Regularization Layer (th. 6.5 cm)
3. Thermal Insulation – XPS (th. X cm)
4. Waterproof membrane (th. 0.4 cm)
5. Screed for systems (th. 10 cm)
6. Reinforced concrete slab (th. 4 cm)
7. Crawl space (th. 35 cm)
8. Lean concrete (th. 10 cm)

"X" refers to insulation thickness and its value depend on the location where the building is situated.

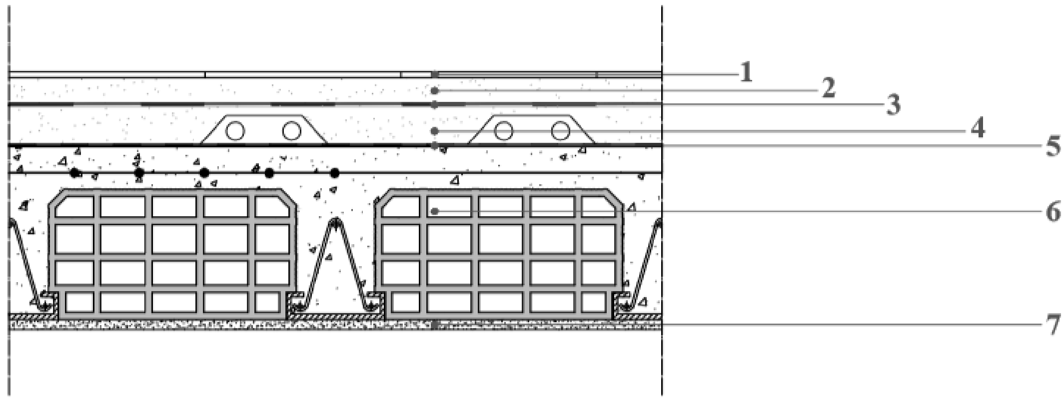

Figure 5.12 - Stratigraphy of Interfloor (measures in cm)

1. Ceramic Tiles (th. 0.9 cm)
2. Regularization Layer (th. 4 cm)
3. Acoustic Pad (th. 0.3 cm)
4. Screed for systems (th. 6 cm)
5. Vapour Barrier (th. 0.3 cm)
6. Floor (th. 24 + 4 cm)
7. Plaster (th. 1.5 cm)

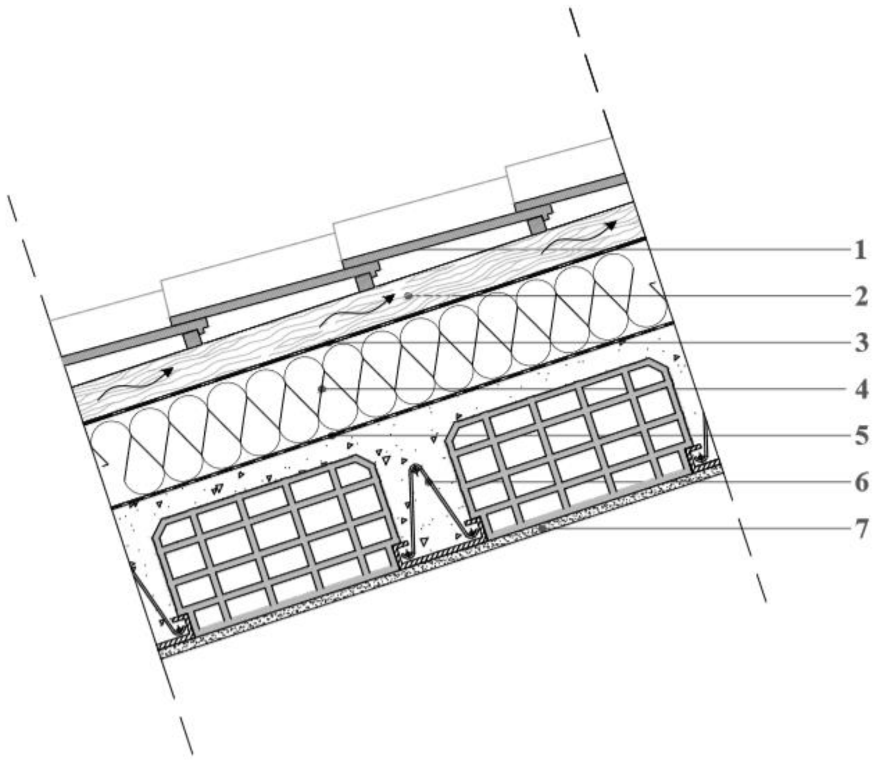

Figure 5.13 - Stratigraphy of roof (measures in cm)

1. Tiled roof (th. 1.5 cm)
2. Ventilated Air Gap (th. 6 cm)
3. Waterproof membrane (th. 0.4 cm)
4. Thermal insulation – Rockwool (th. X cm)
5. Vapour Barrier (th. 0.3 cm)
6. Floor (th. 20 + 4 cm)
7. Plaster (th. 1.5 cm)

Observations:

From the above tables, we can observe how the thickness of thermal insulation changes according to the climatic differences.

In this way, we can reduce the thermal thickness in Catania, while we have to increase its value in Oslo in order to guarantee the required performance.

Live loads

Live loads consist of occupancy loads in building. They may be either fully or partially in place or not present at all and may also change in location. Their magnitude and distribution are uncertain and their maximum intensities throughout the lifetime of the structure are not known with precision.
In particular, their value is established by table 3.1.II of NTC 2018.

Cat.	Ambienti	q_k [kN/m²]	Q_k [kN]	H_k [kN/m]
A	**Ambienti ad uso residenziale**			
	Aree per attività domestiche e residenziali; sono compresi in questa categoria i locali di abitazione e relativi servizi, gli alberghi (ad esclusione delle aree soggette ad affollamento), camere di degenza di ospedali	2,00	2,00	1,00
	Scale comuni, balconi, ballatoi	4,00	4,00	2,00
B	**Uffici**			
	Cat. B1 Uffici non aperti al pubblico	2,00	2,00	1,00
	Cat. B2 Uffici aperti al pubblico	3,00	2,00	1,00
	Scale comuni, balconi e ballatoi	4,00	4,00	2,00
C	**Ambienti suscettibili di affollamento**			
	Cat. C1 Aree con tavoli, quali scuole, caffè, ristoranti, sale per banchetti, lettura e ricevimento	3,00	3,00	1,00
	Cat. C2 Aree con posti a sedere fissi, quali chiese, teatri, cinema, sale per conferenze e attesa, aule universitarie e aule magne	4,00	4,00	2,00
	Cat. C3 Ambienti privi di ostacoli al movimento delle persone, quali musei, sale per esposizioni, aree d'accesso a uffici, ad alberghi e ospedali, ad atri di stazioni ferroviarie	5,00	5,00	3,00
	Cat. C4. Aree con possibile svolgimento di attività fisiche, quali sale da ballo, palestre, palcoscenici.	5,00	5,00	3,00
	Cat. C5. Aree suscettibili di grandi affollamenti, quali edifici per eventi pubblici, sale da concerto, palazzetti per lo sport e relative tribune, gradinate e piattaforme ferroviarie.	5,00	5,00	3,00
	Scale comuni, balconi e ballatoi	Secondo categoria d'uso servita, con le seguenti limitazioni		
		≥ 4,00	≥ 4,00	≥ 2,00

Figure 5.14 - Table 3.1.II
Source: NTC 2018

Environmental loads – Snow Load

Environmental loads consist of snow loads, wind pressure and earthquake load effects. The snow load is a variable load and it only acts on the surfaces in contact with external environmental.

The snow load q_s, acting on the roof with a vertical direction, is calculated through this equation:

$$q_s = \mu_i \cdot q_{sk} \cdot C_E \cdot C_t \quad (5.3)$$

In particular:

- q_{sk} = characteristic value of snow load on the ground
- μ_i = shape coefficient of roof
- C_E = exposure coefficient
- C_t = thermal coefficient

The characteristic value of snow load on the ground

The characteristic value of snow load on the ground depends on the geographic area where the building is located, in terms of local conditions of climate and exposure and so we have a different value for the three cities.

Torino

Torino is located in *Zona I – Alpina* and it has an altitude a_s of 239 metres above sea level. In this way, q_{sk} is calculated with the expression (section 3.4.2 of NTC 2018):

$$q_{sk} = 1.39 \cdot \left[1 + \left(\frac{a_s}{728}\right)^2\right] = 1.54\ \frac{kN}{m^2} \quad (5.4)$$

Catania

Catania is located in *Zona III* and it has an altitude a_s of 7 metres above sea level (section 3.4.2 of NTC 2018):

$$q_{sk} = 0.60 \frac{kN}{m^2}$$

Oslo

The characteristic value of snow load on the ground is defined in reference to the Eurocode 1.

In particular, hypothesizing an altitude between 75 and 200 metres above sea level, we have:

$$q_{sk} = 2.5 \frac{kN}{m^2}$$

Municipalità della provincia di Oslo	Carico della neve al suolo [kN/m^2]
Oslo:	
per 0 - 75 m o.h.	1,5
per 75 - 200 m o.h.	2,5
oltre 200 m o.h.	3,5

Figure 5.15 - Characteristic value of snow on ground - Oslo

It’s possible to see how the characteristic value of snow load depends on the geographic area and its probability of snowfall. The greatest value is in Oslo, in northern Europe, with a cold climate, while the minor value is in Catania, where there is a very hot climate and the snowfall is practically absent.

The exposure coefficient

The exposure coefficient C_E can be used in order to consider the characteristic of the area where the building is situated. Its value is given by table 3.4.I of NTC 2018, but, without specific information, we assume $C_E = 1$.

Topografia	Descrizione	C_E
Battuta dai venti	Aree pianeggianti non ostruite esposte su tutti i lati, senza costruzioni o alberi più alti.	0,9
Normale	Aree in cui non è presente una significativa rimozione di neve sulla costruzione prodotta dal vento, a causa del terreno, altre costruzioni o alberi.	1,0
Riparata	Aree in cui la costruzione considerata è sensibilmente più bassa del circostante terreno o circondata da costruzioni o alberi più alti	1,1

Figure 4.16 - Table 3.4.I: exposure coefficient
Source: NTC 2018

The thermal coefficient

The thermal coefficient considers the decrease of snow load due to the melting of the snow thanks to the heat losses of the building.
This coefficient depends on the thermal insulation properties of the materials used and so, in absence of a specific study, $C_t = 1$.

The shape coefficient

The shape coefficient depends on the shape of the roof and its incline α, expressed in sexagesimal degrees (table 3.4.II of NTC 2018).

Coefficiente di forma	$0° \le \alpha \le 30°$	$30° < \alpha < 60°$	$\alpha \ge 60°$
μ_1	0,8	$0{,}8 \cdot \frac{(60-\alpha)}{30}$	0,0

Figure 5.17 - Table 3.4.II: shape coefficient
Source: NTC 2018

In this case, because we have a double pitch roof (21° and 33° of incline), we must consider three load conditions, named *Caso I, Caso II* and *Caso III.*

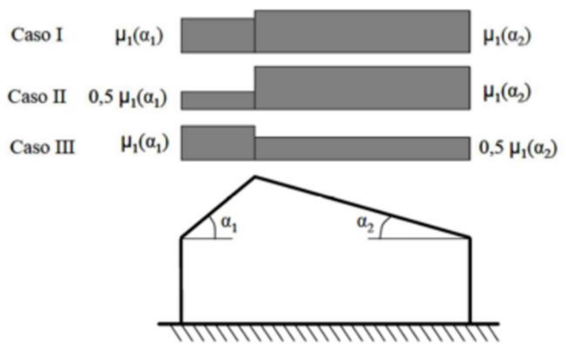

Figure 5.18 - The figure shows the load conditions
Source: NTC 2018

We obtain the following shape coefficients:

- μ_1 (α = 21°) = 0.8
- μ_2 (α = 33°) = 0.72

The results about snow loads are:

Snow load - Torino		
α = 21°	1.11	kN/m^2
α = 33°	1.23	kN/m^2

Table 5.16 - Snow load - Torino according to incline angle

Snow load - Catania		
α = 21°	0.48	kN/m^2
α = 33°	0.43	kN/m^2

Table 5.17 - Snow load - Catania according to incline angle

Snow load - Oslo		
α = 21°	2	kN/m^2
α = 33°	1.8	kN/m^2

Table 5.18 - Snow load - Oslo according to incline angle

Environmental loads – Seismic Load

Earthquake result from the sudden movement of tectonic plates in the earth's crust. The movement takes place at fault lines, and the energy released is transmitted through the earth in the form of waves that cause ground motion many miles from the epicenter. Regions adjacent to active fault lines are the most prone to experience earthquakes.
As experienced by structures, earthquake consist of random horizontal and vertical movements of the earth's surface. As the ground moves, inertia tends to keep structures in place, resulting in the imposition of displacements and forces that can have catastrophic results. The purpose of seismic design is to proportion structures so that they can withstand the displacements and the forces induced by the ground motion.
Seismic design has emphasized the effects of horizontal ground motion because the horizontal components of an earthquake usually exceed the vertical component and because are usually much stiffer and stronger in response to vertical loads.
Designers of structures that may be subjected to earthquakes, therefore, are faced with a choice:

- Providing adequate stiffness and strength to limit the response of structures to the elastic range
- Providing lower – strength structures, with lower initial costs, that have the ability to withstand large inelastic deformations while maintaining their load-carrying capability.

The hazard definition refers to the Probabilistic Seismic Hazard Analysis (PSHA): the seismic design parameters are linked to the Limit States (LS), which measure the performance of the structures.
Each Limit State is defined through the exceedance probability P_{VR} in a given period V_R. V_R is expressed in years and represents the period during which the structure maintains its functionality (design life of the structure).

V_R is calculated as the product between the design life of the structure V_N and a coefficient C_u, depending on the importance class defined in the section 2.4.3 of NTC 2018.

CLASSE D'USO	I	II	III	IV
COEFFICIENTE C_U	0,7	1,0	1,5	2,0

Figure 5.19 - Value of C_u coefficient
Source: NTC 2018

$$V_R = V_N \cdot C_u \quad (5.5)$$

There are two categories of LS: Serviceability Limit State (SLS) and Ultimate Limit State (ULS).
SLS indicates the condition after which there is loss of functionality for the structure, while the ULS are associated with the collapse or with structural failure.
In particular, in NTC 2018, four different LS are identified:

- Operational Limit State (OLS)
- Damage Limitation State (DLS)
- life Safety Limit State (SLS)
- Collapse prevention Limit State (CLS)

The table 3.2.I of NTC 2018 reports the value of exceedance probability in reference to Limit State.

Stati Limite	P_{V_R}: Probabilità di superamento nel periodo di riferimento V_R	
Stati limite di esercizio	SLO	81%
	SLD	63%
Stati limite ultimi	SLV	10%
	SLC	5%

Figure 5.20 - Table 3.2.I: value of exceedance probability
Source: NTC 2018

The seismic actions are defined with respect to the hazard at the reference site.
Thus, we can calculate the value of T_R, the return period:

$$T_R = -\frac{V_R}{\ln(1 - P_{VR})} \quad (5.6)$$

The seismic hazard is expressed in terms of maximum expected ground acceleration (a_g) in free field condition on horizontal and rigid surface and in terms of elastic horizontal and vertical spectral acceleration for the same conditions.
INGV provides the hazard map of Italy, in which the maximum ground accelerations corresponding to a exceedance probability of 10% in 50 years are defined with respect to 50th percentile.
Particularly four different zones are identified depending on the a_g value.

Seismic zone	***a_g [g]*** ***P_{VR} = 10% in 50 years***
1	$a_g > 0.25$
2	$0.15 < a_g \leq 0.25$
3	$0.05 < a_g \leq 0.15$
4	$a_g \leq 0.05$

Table 5.19 – a_g Value in accordance to Seismic zone

For regular and small size structures the seismic action can be defined using a given response spectra.
If T_{ref} is the period of interest of the structure, the Sa ($T=T_{ref}$) will be the spectral acceleration to be used in the analysis.
The mathematical expressions of the Design Spectrum (DS) proposed in NTC 2018 depend on three coefficients: a_g, F_0, and T_c (they are reported in the Annex B of the NTC 2018) that modify the shape and the amplitude of the spectrum at a given site.
Since the three coefficients refer to the condition of flat and rigid surface, it's important to consider the amplification phenomena due to the stratigraphy effects and topographic effects.
The real soil stiffness induces an amplification of the ground motion that depends on the shear wave velocity measured 30 meters deep (V_{S30}). There are five different soil categories.

Categoria	Caratteristiche della superficie topografica
A	*Ammassi rocciosi affioranti o terreni molto rigidi* caratterizzati da valori di velocità delle onde di taglio superiori a 800 m/s, eventualmente comprendenti in superficie terreni di caratteristiche meccaniche più scadenti con spessore massimo pari a 3 m.
B	*Rocce tenere e depositi di terreni a grana grossa molto addensati o terreni a grana fina molto consistenti,* caratterizzati da un miglioramento delle proprietà meccaniche con la profondità e da valori di velocità equivalente compresi tra 360 m/s e 800 m/s.
C	*Depositi di terreni a grana grossa mediamente addensati o terreni a grana fina mediamente consistenti* con profondità del substrato superiori a 30 m, caratterizzati da un miglioramento delle proprietà meccaniche con la profondità e da valori di velocità equivalente compresi tra 180 m/s e 360 m/s.
D	*Depositi di terreni a grana grossa scarsamente addensati o di terreni a grana fina scarsamente consistenti,* con profondità del substrato superiori a 30 m, caratterizzati da un miglioramento delle proprietà meccaniche con la profondità e da valori di velocità equivalente compresi tra 100 e 180 m/s.
E	*Terreni con caratteristiche e valori di velocità equivalente riconducibili a quelle definite per le categorie C o D,* con profondità del substrato non superiore a 30 m.

Figure 5.21 – Soil Categories
Source: NTC 2018

In particular, the stratigraphy amplification is considered through the coefficient S_s which depends on soil category.

Categoria sottosuolo	S_S	C_C
A	1,00	1,00
B	$1{,}00 \le 1{,}40 - 0{,}40 \cdot F_o \cdot \frac{a_g}{g} \le 1{,}20$	$1{,}10 \cdot (T_C^*)^{-0,20}$
C	$1{,}00 \le 1{,}70 - 0{,}60 \cdot F_o \cdot \frac{a_g}{g} \le 1{,}50$	$1{,}05 \cdot (T_C^*)^{-0,33}$
D	$0{,}90 \le 2{,}40 - 1{,}50 \cdot F_o \cdot \frac{a_g}{g} \le 1{,}80$	$1{,}25 \cdot (T_C^*)^{-0,50}$
E	$1{,}00 \le 2{,}00 - 1{,}10 \cdot F_o \cdot \frac{a_g}{g} \le 1{,}60$	$1{,}15 \cdot (T_C^*)^{-0,40}$

Figure 5.22 - Value of S_s coefficient in accordance to soil category
Source: NTC 2018

The amplification phenomena due to the site topography is considered by a coefficient S_T

Categoria topografica	Ubicazione dell'opera o dell'intervento	S_T
T1	-	1,0
T2	In corrispondenza della sommità del pendio	1,2
T3	In corrispondenza della cresta di un rilievo con pendenza media minore o uguale a 30°	1,2
T4	In corrispondenza della cresta di un rilievo con pendenza media maggiore di 30°	1,4

Figure 5.23 - Value of ST coefficient
Source: NTC 2018

Thus, the total amplification is expressed with the coefficient

$$S = S_S \cdot S_T \quad (5.7)$$

The design horizontal response spectrum is defined considering four period ranges identified by T_B (initial value of constant acceleration range), T_C (initial value of constant velocity range) and T_D (initial value of constant displacement range) with a fixed damping ratio.

The equations of the Italian design horizontal spectrum are:

- $0 \leq T < T_B : S_a(T) = a_g \cdot S \cdot \eta \cdot F_0 \cdot \left[\frac{T}{T_B} + \frac{1}{\eta \cdot F_0}\left(1 - \frac{T}{T_B}\right)\right] \quad (5.8)$
- $T_B \leq T < T_C : S_a(T) = a_g \cdot S \cdot \eta \cdot F_0$
- $T_C \leq T \leq T_D : S_a(T) = a_g \cdot S \cdot \eta \cdot F_0 \cdot \left[\frac{T_C}{T}\right] \quad (5.9)$
- $T_D \leq T : S_a(T) = a_g \cdot S \cdot \eta \cdot F_0 \cdot \left[\frac{T_C T_D}{T^2}\right] \quad (5.10)$
-

Regarding the vertical spectral components, NTC 2018 defines a coefficient F_V as maximum amplitude factor for vertical acceleration.

In particular, the stratigraphy amplification coefficient is equal to the unit ($S_s = 1$) while the topography amplification coefficient S_T is the same of the horizontal components.

$$F_V = 1.35 \cdot F_0 \cdot \left(\frac{a_g}{g}\right)^{0.5} \quad (5.11)$$

5.2.3 Dolmen modelling

<u>Introduction</u>

The structural design of the buildings was carried out using “DOLMEN”, a FEM (Finite Element Method) software.

The finite element method allows to define the condition of stress-strain under loads for which it is not possible to obtain an analytical solution.

In order to avoid the writing of a manual, we only describe the fundamental aspects instead of each singular step.

The most important elements that we use during building modelling are the following:

- *Aste: elements that allow to represent objects with a size greater than the other two, such as beams and columns.*
- *Gusci: elements that allow to model elements with two predominant dimensions. This component was largely used in XLAM building's modelling in order to represent the external panels.*
- *Solai: represent the namesake structural elements. They permit to specify the framework and so the stressed beams.*
- *Nodi: represent beams' intersection. It is possible to block one or more motions to simulate external constraint.*

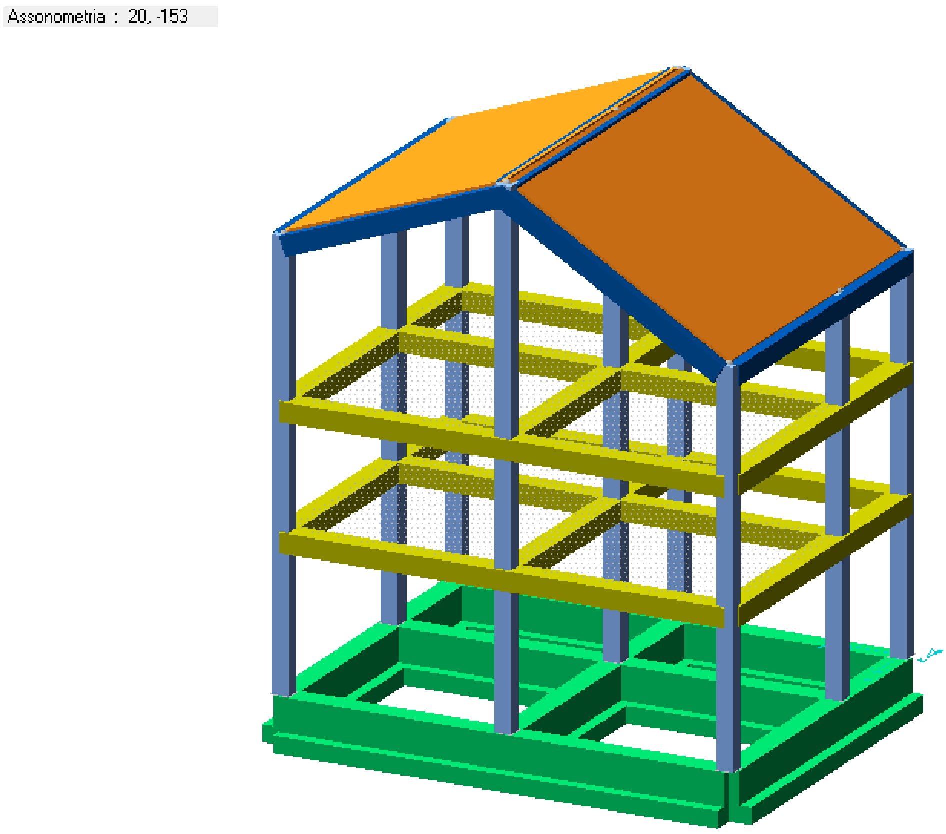

Figure 5.24 - Dolmen 3D model

Load application

In all considered cases, the loads analysis is lead in accordance with section 2.5.3 of NTC 2018.

The software, through a specific command, allows to give at each element its own weight.

Moreover, as already mentioned in this paragraph, we conferred on the floors, the load of civil building (Cat A).

It's also important to define the geological characteristics of the soil.

Since we had not data coming from specific seismic geotechnical tests, we took the information from previous studies in Torino and Catania.

Nel caso specifico, i risultati della prova sismica realizzata nell'area di intervento, hanno evidenziato che la categoria del suolo di fondazione è di **tipo B** (Rocce tenere e depositi di terreni a grana grossa molto addensati o terreni a grana fina molto consistenti

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Figure 5.25 - Soil Category of Torino.
Source: Technical Report

Parametro	Valore	
Classe d'uso	II	
Vita nominale	50 anni	
Categoria topografica	T1	
Categoria Sottosuolo	C	
Coefficiente di struttura	1	
Smorzamento	5%	
Coefficiente di amplificazione topografica S_T	1.0	
Coordinate Topografiche	Lat N	37.2783
	Long E	14.6110

Figure 5.26 – Soil category of Catania.
Source: Technical report

About Oslo, the question is more complicated: soil characteristics are fundamental to define the response spectra in seismic checks. However, DOLMEN software considers only the Italian territory and so we compared Oslo to Torino because Norway has low seismicity.

Static and dynamic calculation

After loads application, we proceed with the calculation of strains. It is a static calculation that only considers the size, the distribution and the different load combinations both SLS and ULS.
In this way we can evaluate axial force, shear force and bending moment acting on each structural element.

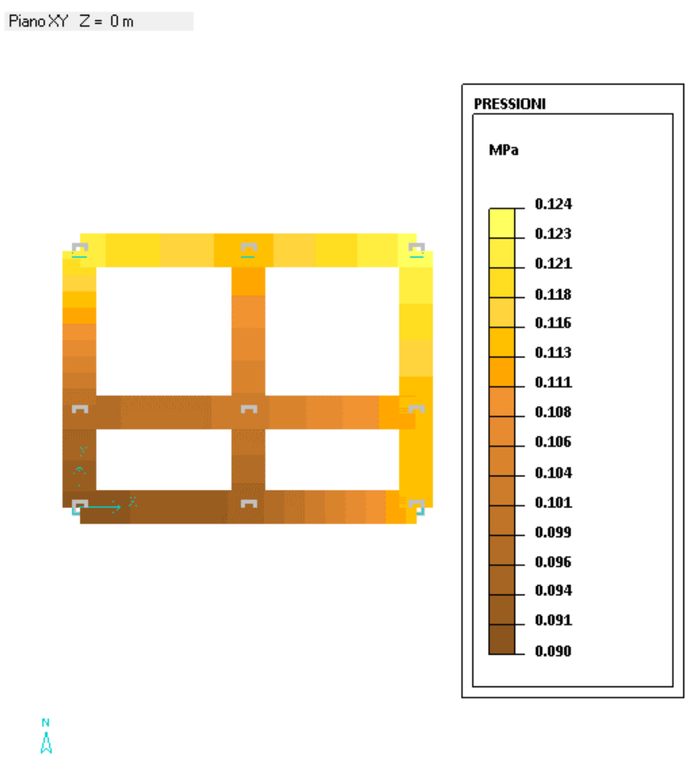

Figure 5.27 - Example of pressure diagram (Torino)

In addition to static calculation, a dynamic one is carried out in order to consider the seismic force.

Inserting the appropriate input data, we obtain the response spectra in reference to NTC 2018.

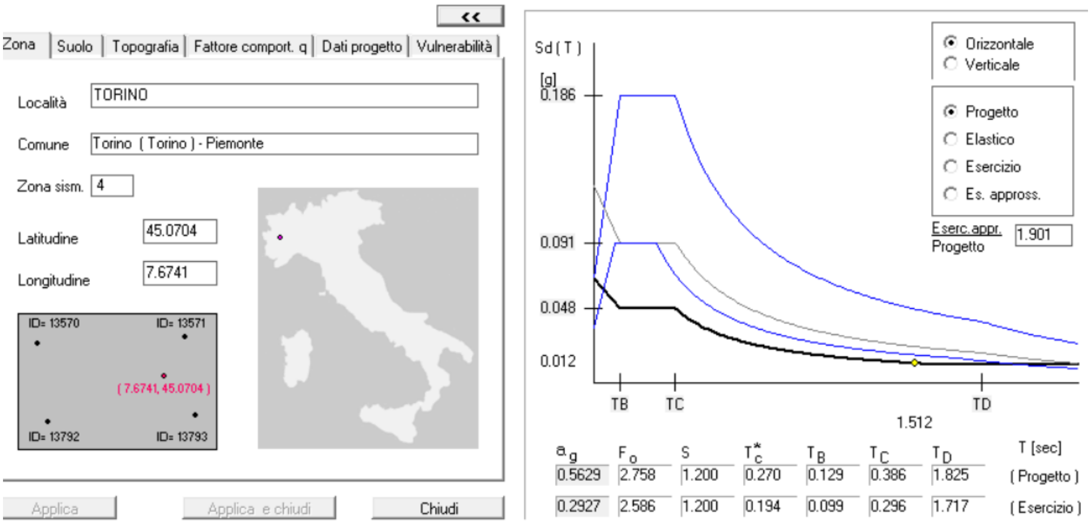

Figure 5.28 - Example of seismic input and response spectra (Torino)

Thanks to these information, Dolmen is able to calculate the fundamental vibrational modes so that the total participating mass is greater than 85 percent of total building mass.

In particular if we pay attention on the fundamental period, which is linked to the first vibrational mode, the value that we obtain is 0.42 s.

This value is comparable to that calculated by NTC 2018 (Linear Static Analysis) through the following equation:

$$T_1 = C_1 \cdot H^{\frac{3}{4}} = 0.40\ s \quad (5.5)$$

Where:

- C_1 is a coefficient which depends on the structural typology. C_1 = 0.075 for reinforced concrete structures
- H represents the height of the structure expressed in meters (measured from the foundation level)

This allows to verify the reliability of Dolmen results.

Design of structural elements in Dolmen

In this way the software produces stresses for each structural element.

Thanks to these calculated stresses and the size of structural elements, steel reinforcement can be calculated.

In particular, Dolmen itself allows this calculation and it also checks the designed sections.

In fact, the program is not able to design autonomously the structural element, but it can calculate their quantity of steel reinforcement in reference to NTC 2018.

There is a specific module related to columns, beams, joists, shells, etc…

If the necessary amount of reinforcement is more than that imposed by NTC 2018, we must increase the size of the structural element: in this case, the calculation must be repeated because the volume and consequently the weight of structural element is changed.

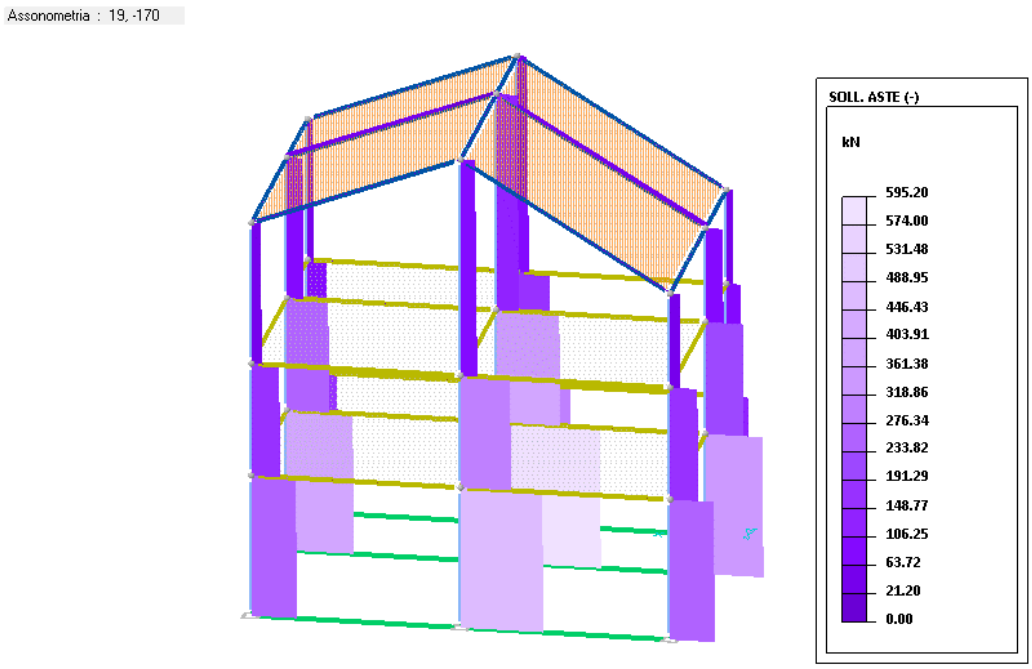

Figure 5.29 - Example of Axial Forces. As expected, only the columns show these strains and their value is negative in accordance to sign rule

RC structures – Columns

Once stress analysis and dynamic analysis finished, we can use Dolmen "COLUMN" module to carry out the automatic calculation of the reinforcement according to all load cases.

As output, we also obtain a reinforcement exploded and a report, contained the results of the checks.

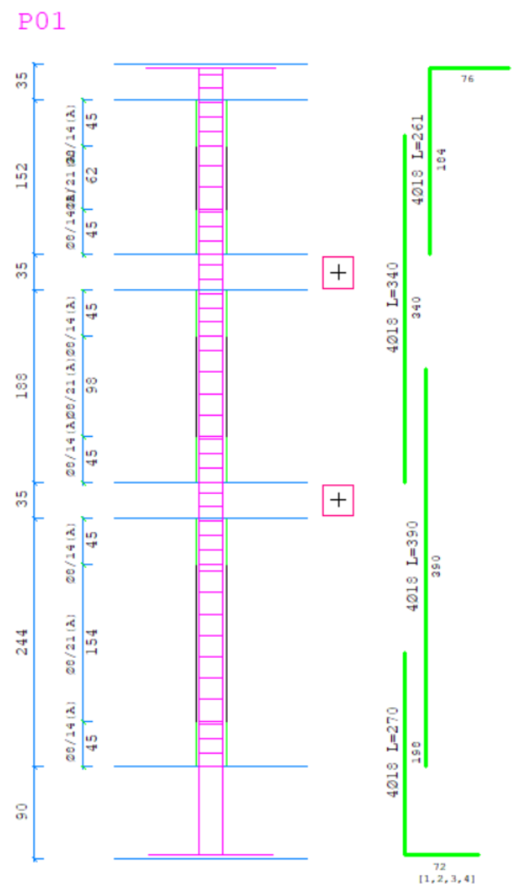

Figure 5.30 - Example of Reinforcing Steel representation

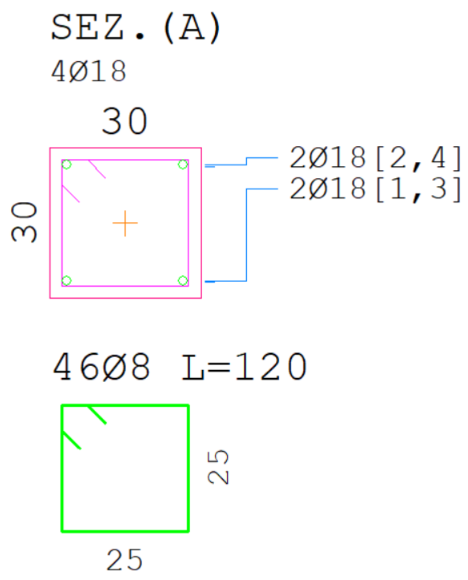

Figure 5.31 - Examples of column section

RC structures – Beams

Like columns, there is a specific module “CONTINOUS BEAMS” which provides reinforcement calculation.
The program, in addition to show a report similar to that of the columns, also creates the stresses diagram and the graphs concerning resistance shear and moment. In this way, we can do a visual check.

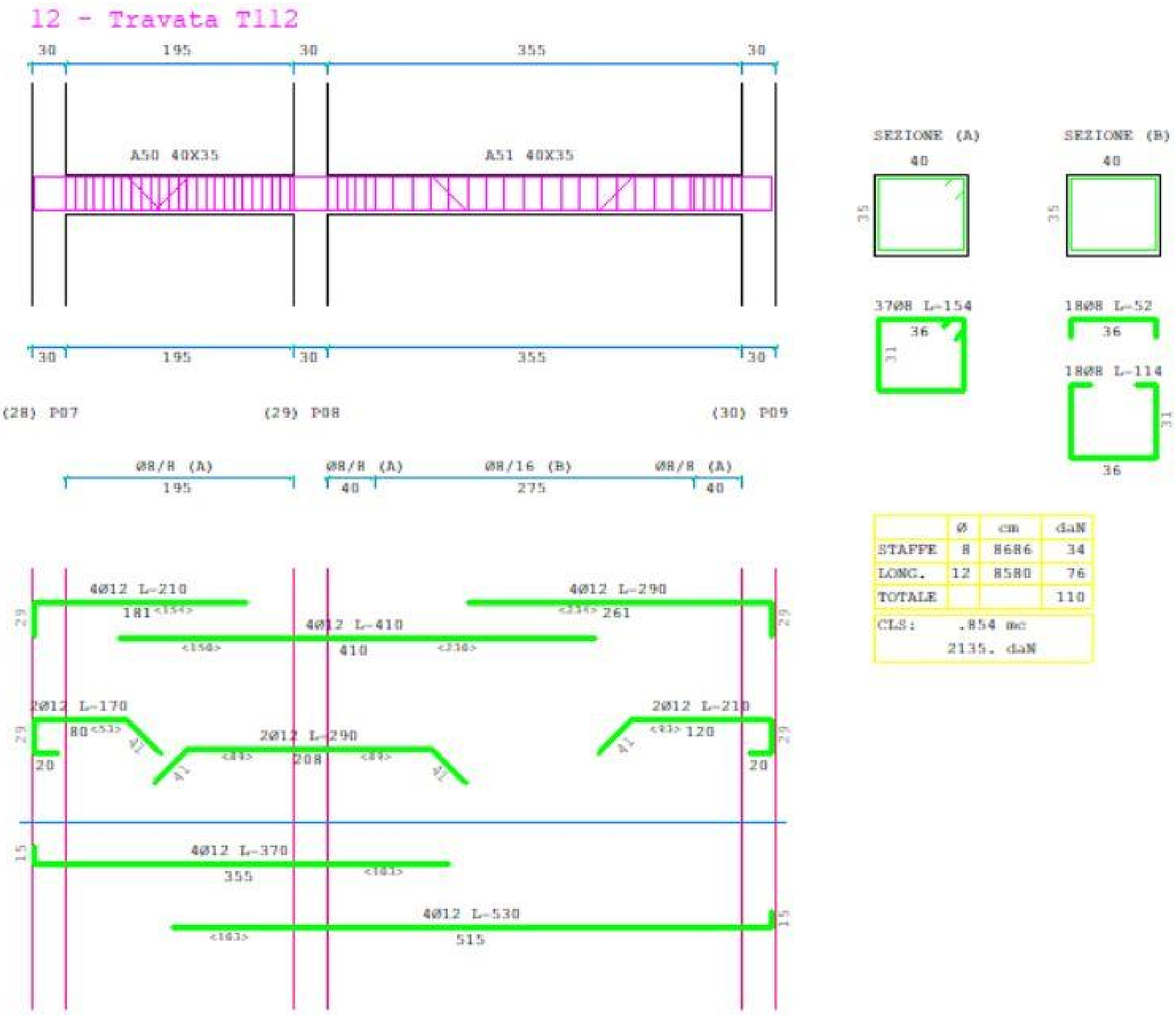

Figure 5.32 - Example of beams. In the figure we can see the section of the beam, the amount of concrete and steel and the steel scheme

RC structures – Joists

During the construction of three-dimensional model in Dolmen, we define the frame and the joists size, and afterward proper weights, permanent weights and accidental weights were applied.
Also in this case, the specific module “CONTINOUS BEAMS” allows to calculate steel reinforcement and shows resistance shear and moment graphs.

5.3 XLAM Structure

5.3.1 Definition of loads

Differently from Reinforced Concrete structures, the skeleton of XLAM structure is made up of precast XLAM panels.

In particular, the connection between XLAM panels themselves and between XLAM panels and slabs is guaranteed by self-drilled screws in the first case, by L angular in the second case. In this way, the only structural elements made up of reinforced concrete are the grade beams (we hypothesized the same sized like the case of RC structures) and the slab on the ground.

For these reasons, if the live and environmental loads are unchanged, we must define new dead load. In fact, not only timber and concrete frames have different weight, but also the stratigraphies change.

Stratigraphies of RC Structures

- ***Torino***

Floor on the ground				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	-
2	Regularization layer	0.065	-	-
3	Thermal insulation - EPS	0.120	-	-
4	Waterproof membrane	0.004	-	-
5	Screed for systems	0.100	-	-
6	Reinforced concrete slab	0.040	-	-
7	Crawl space	0.350	-	-
8	Lean Concrete	0.100	-	-
			Total thickness [m]	***0.79***

Table 5.20 - Stratigraphy of floor on the ground. The Table show structural features (thickness and weight) - Torino

External walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Gypsum Plasterboard	0.015	-	0.151
2	Gypsum Plasterboard	0.015	-	0.151
3	Thermal insulation - Rockwool	0.050	0.69	0.034
4	XLAM panel	0.090	4.12	0.371
5	Thermal insulation - Rockwool	0.070	0.88	0.062
6	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.26***
			Total weight [kN/m^2]	***0.994***

Table 5.21 - Stratigraphy of external walls. The Table show structural features (thickness and weight) - Torino

Inside walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Gypsum Plasterboard	0.0125	-	0.151
2	Gypsum Plasterboard	0.0125	-	0.151
3	Thermal insulation - Glass Wool	0.045	0.13	0.006
4	Gypsum Plasterboard	0.0125	-	0.151
5	Gypsum Plasterboard	0.0125	-	0.151
			Total thickness [m]	***0.10***
			Total weight [kN/m^2]	***0.610***

Table 5.22 - Stratigraphy of inside walls. The Table show structural features (thickness and weight) - Torino

Interfloor				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	0.190
2	Regularization layer	0.04	17.65	0.706
3	Screed for system	0.060	4.00	0.240
4	Acoustic pad	0.003	0.29	0.001
5	XLAM panel	0.137	4.12	0.564
6	Gypsum Plasterboard	0.013	-	0.151
			Total thickness [m]	***0.38***
			Total weight [kN/m^2]	***1.852***

Table 5.23 - Stratigraphy of interfloor. The Table show structural features (thickness and weight) - Torino

Roof				
	Material	Thicknes s [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Tiled roof	0.015	-	0.374
2	Ventilated Air Gap	0.050	-	-
3	Waterproof membrane	0.004	-	0.039
4	Thermal insulation - rockwool	0.060	1.47	0.088
5	Vapour Barrier	0.003	-	0.001
6	XLAM panel	0.100	4.12	0.412
7	Thermal insulation - rockwool	0.050	0.49	0.025
8	Gypsum Plasterboard	0.013	-	0.151
			Total thickness [m]	***0.29***
			Total weight [kN/m^2]	***1.090***

Table 5.24 - Stratigraphy of roof. The Table show structural features (thickness and weight) - Torino

- ***Catania***

Floor on the ground				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	-
2	Regularization layer	0.065	-	-
3	Thermal insulation - EPS	0.080	-	-
4	Waterproof membrane	0.004	-	-
5	Screed for systems	0.100	-	-
6	Reinforced concrete slab	0.040	-	-
7	Crawl space	0.350	-	-
8	Lean Concrete	0.100	-	-
			Total thickness [m]	***0.75***

Table 5.25 - Stratigraphy of floor on the ground. The Table show structural features (thickness and weight) - Catania

External walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Gypsum Plasterboard	0.015	-	0.151
2	Gypsum Plasterboard	0.015	-	0.151
3	Thermal insulation - Rockwool	0.030	0.69	0.021
4	XLAM panel	0.090	4.12	0.371
5	Thermal insulation - Rockwool	0.060	0.88	0.053
6	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.23***
			Total weight [kN/m^2]	***0.971***

Table 5.26 - Stratigraphy of external walls. The Table show structural features (thickness and weight) – Catania

Inside walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Gypsum Plasterboard	0.0125	-	0.151
2	Gypsum Plasterboard	0.0125	-	0.151
3	Thermal insulation - Glass Wool	0.045	0.13	0.006
4	Gypsum Plasterboard	0.0125	-	0.151
5	Gypsum Plasterboard	0.0125	-	0.151
			Total thickness [m]	***0.10***
			Total weight [kN/m^2]	***0.610***

Table 5.27 - Stratigraphy of inside walls. The Table show structural features (thickness and weight) - Catania

Interfloor				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	0.190
2	Regularization layer	0.04	17.65	0.706
3	Screed for system	0.060	4.00	0.240
4	Acoustic pad	0.003	0.29	0.001
5	XLAM panel	0.137	4.12	0.564
6	Gypsum Plasterboard	0.013	-	0.151
			Total thickness [m]	***0.38***
			Total weight [kN/m^2]	***1.852***

Table 5.28 - Stratigraphy of interfloor. The Table show structural features (thickness and weight) - Catania

Roof				
	Material	Thickness [m]	Density [kN/m³]	Weight [kN/m²]
1	Tiled roof	0.015	-	0.374
2	Ventilated Air Gap	0.050	-	-
3	Waterproof membrane	0.004	-	0.039
4	Thermal insulation - rockwool	0.060	1.47	0.088
5	Vapour Barrier	0.003	-	0.001
6	XLAM panel	0.100	4.12	0.412
7	Thermal insulation - rockwool	0.030	0.49	0.015
8	Gypsum Plasterboard	0.013	-	0.151
			Total thickness [m]	***0.28***
			Total weight [kN/m²]	***1.080***

Table 5.29 - Stratigraphy of roof. The Table show structural features (thickness and weight) - Catania

- ***Oslo***

Floor on the ground				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	-
2	Regularization layer	0.065	-	-
3	Thermal insulation - EPS	0.180	-	-
4	Waterproof membrane	0.004	-	-
5	Screed for systems	0.100	-	-
6	Reinforced concrete slab	0.040	-	-
7	Crawl space	0.350	-	-
8	Lean Concrete	0.100	-	-
			Total thickness [m]	***0.85***

Table 5.30 - Stratigraphy of floor on the ground. The Table show structural features (thickness and weight) - Oslo

External walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Gypsum Plasterboard	0.015	-	0.151
2	Gypsum Plasterboard	0.015	-	0.151
3	Thermal insulation - Rockwool	0.050	0.69	0.034
4	XLAM panel	0.090	4.12	0.371
5	Thermal insulation - Rockwool	0.160	0.88	0.141
6	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.35***
			Total weight [kN/m^2]	***1.073***

Table 5.31 - Stratigraphy of external walls. The Table show structural features (thickness and weight) - Oslo

Inside walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Gypsum Plasterboard	0.0125	-	0.151
2	Gypsum Plasterboard	0.0125	-	0.151
3	Thermal insulation - Glass Wool	0.045	0.13	0.006
4	Gypsum Plasterboard	0.0125	-	0.151
5	Gypsum Plasterboard	0.0125	-	0.151
			Total thicknes s [m]	***0.10***
			Total weight [kN/m^2]	***0.610***

Table 5.32 - Stratigraphy of inside walls. The Table show structural features (thickness and weight) - Oslo

Interfloor				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	0.190
2	Regularization layer	0.04	17.65	0.706
3	Screed for system	0.060	4.00	0.240
4	Acoustic pad	0.003	0.29	0.001
5	XLAM panel	0.137	4.12	0.564
6	Gypsum Plasterboard	0.013	-	0.151
			Total thickness [m]	***0.38***
			Total weight [kN/m^2]	***1.852***

Table 5.33 - Stratigraphy of interfloor. The Table show structural features (thickness and weight) - Oslo

Roof				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Tiled roof	0.015	-	0.374
2	Ventilated Air Gap	0.050	-	-
3	Waterproof membrane	0.004	-	0.039
4	Thermal insulation - rockwool	0.080	1.47	0.118
5	Vapour Barrier	0.003	-	0.001
6	XLAM panel	0.100	4.12	0.412
7	Thermal insulation - rockwool	0.050	0.49	0.025
8	Gypsum Plasterboard	0.013	-	0.151
			Total thickness [m]	***0.32***
			Total weight [kN/m^2]	***1.120***

Graphic Representation of Stratigraphies

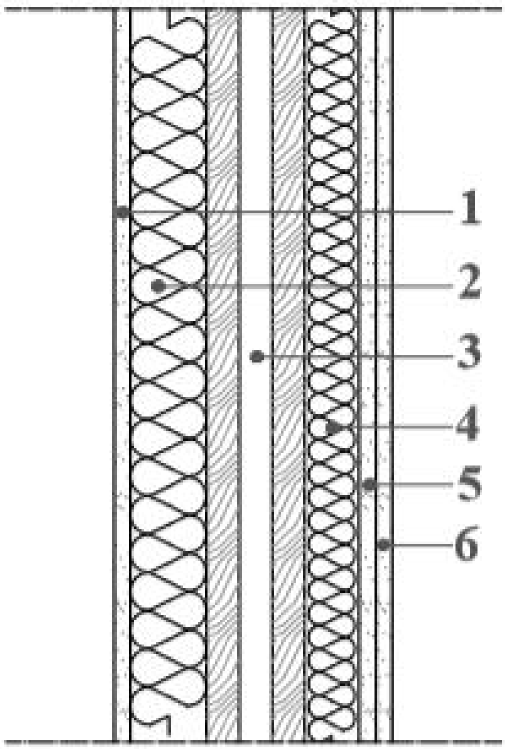

Figure 5.33 - Stratigraphy of External Walls (measures in cm)

1. Gypsum Plasterboard (th. 1.5 cm)
2. Gypsum Plasterboard (th. 15 cm)
3. Thermal Insulation – Rockwool (th. X cm)
4. XLAM panel (th. 9 cm)
5. Thermal Insulation – Rockwool (th. X cm)
6. Plaster (th. 1.5 cm)

"X" refers to insulation thickness and its value depend on the location where the building is situated.

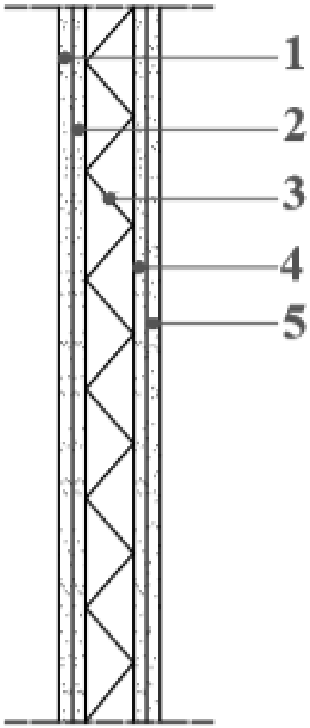

Figure 5.34 - Stratigraphy of Inside Walls (measures in cm)

1. Gypsum Plasterboard (th. 1.25 cm)
2. Gypsum Plasterboard (th. 1.25 cm)
3. Thermal Insulation – Glass Wool (th. 4.5 cm)
4. Gypsum Plasterboard (th. 1.25 cm)
5. Gypsum Plasterboard (th. 1.25 cm)

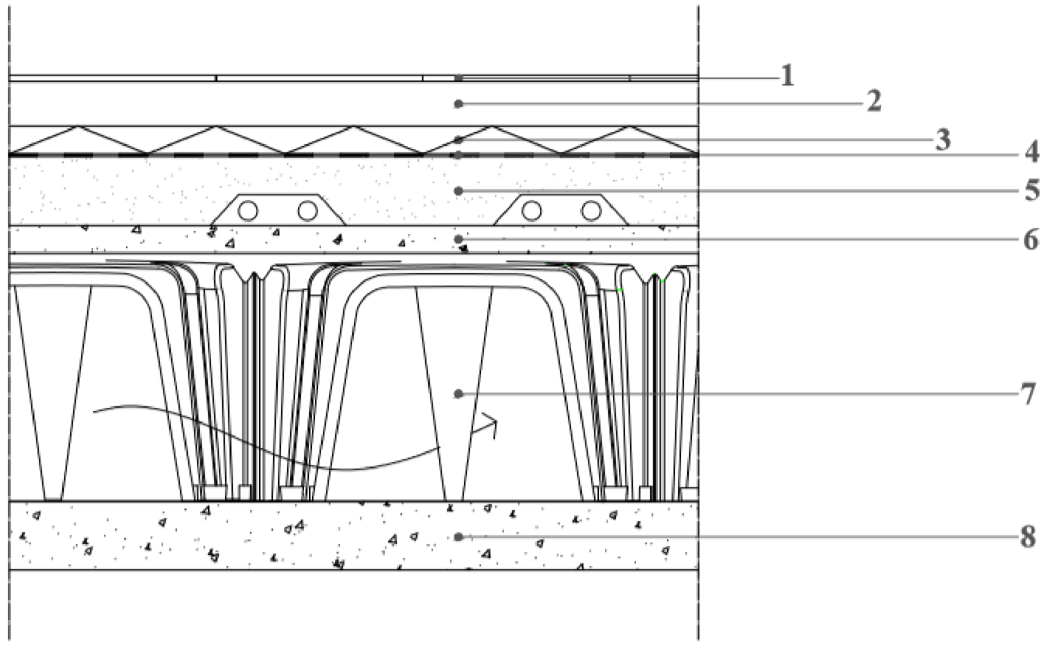

Figure 5.35 - Stratigraphy of floor on the ground (measures in cm)

1. Ceramic Tiles (th. 0.9 cm)
2. Regularization Layer (th. 6.5 cm)
3. Thermal Insulation – XPS (th. X cm)
4. Waterproof membrane (th. 0.4 cm)
5. Screed for systems (th. 10 cm)
6. Reinforced concrete slab (th. 4 cm)
7. Crawl space (th. 35 cm)
8. Lean concrete (th. 10 cm)

“X” refers to insulation thickness and its value depend on the location where the building is situated.

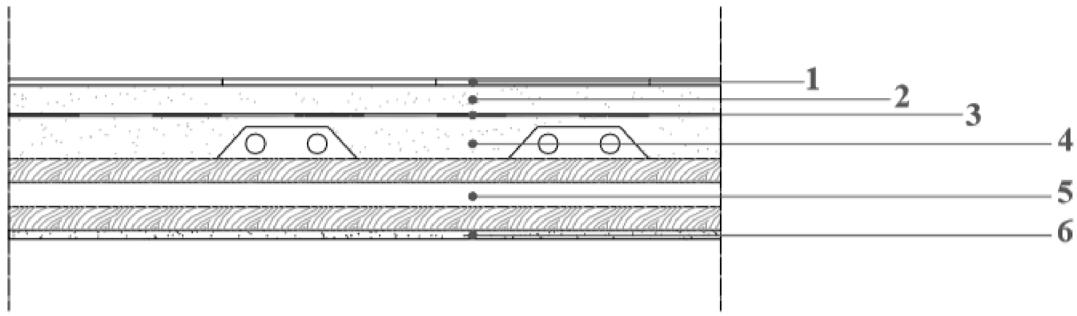

Figure 5.36 - Stratigraphy of Interfloor (measures in cm)

1. Ceramic Tiles (th. 0.9 cm)
2. Regularization Layer (th. 4 cm)
3. Acoustic Pad (th. 0.3 cm)
4. Screed for systems (th. 6 cm)
5. XLAM Panel (th. 13.7 cm)
6. Gypsum Plasterboard (th. 1.25 cm)

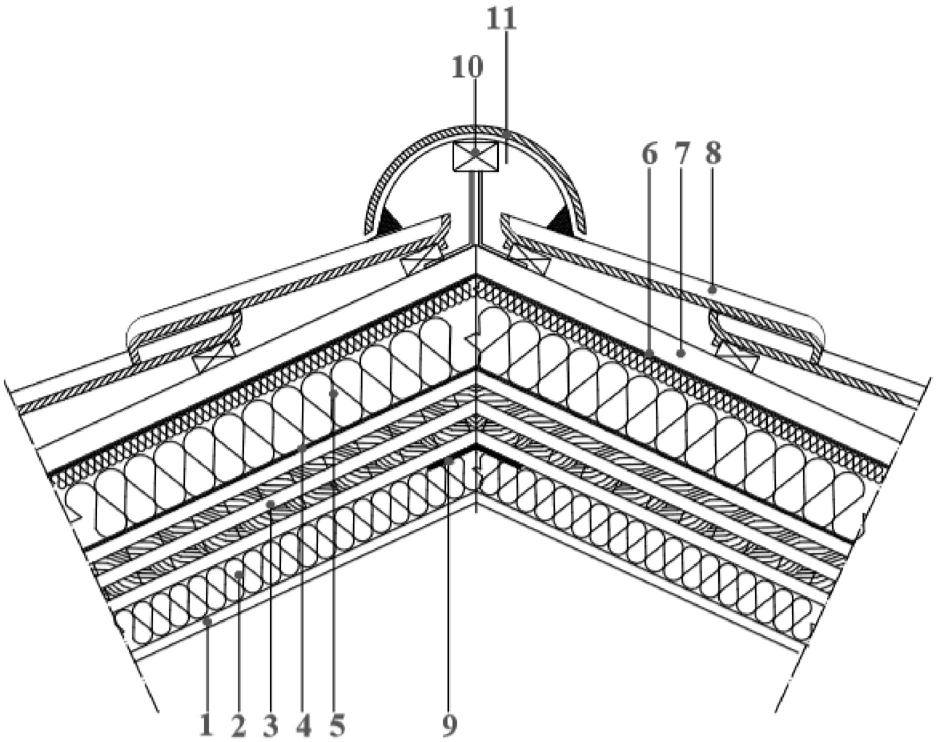

Figure 5.37 - Stratigraphy of roof (measures in cm)

1. Gypsum Plasterboard (th. 1.25 cm)
2. Thermal Insulation – Rockwool (th. X cm)
3. XLAM Panel (th. 10 cm)
4. Vapor Barrier (th. 0.3 cm)
5. Thermal Insulation – Rockwool (th. X cm)
6. Waterproof membrane (th. 0.4 cm)
7. Ventiled Air Gap (th. 5 cm)
8. Tiled Roof (th. 1.5 cm)
9. Taping for Airtight
10. Batten under – ridge
11. Ridge

"X" refers to insulation thickness and its value depend on the location where the building is situated.

5.3.2 Dolmen Modelling

In this case, the sizes of the structural elements are fixed because we used prefabricated XLAM panels which have a specific thickness and weight.

For this reason, unlike concrete structure, we do not need to design the structural element, but we must check that the applied stresses are lower than the shear resistance of the shell, which is provided by the manufacturer of the XLAM panels (in this case it is equal to 4 Mpa).

In fact, in three-dimensional model, CLT panels are represented as shells with a thickness equal to that of real panel.

It is important to underline two assumptions:

- Since timber mechanical behaviour depends on the tree spatial directions (that is, the timber is an orthotropic material), it is important to reduce the value of the elastic modulus.
- XLAM panels are linked each other and to the slab on the ground thanks to two types of elements: clamps to transmit axial forces and hold-down to transmit shear forces.

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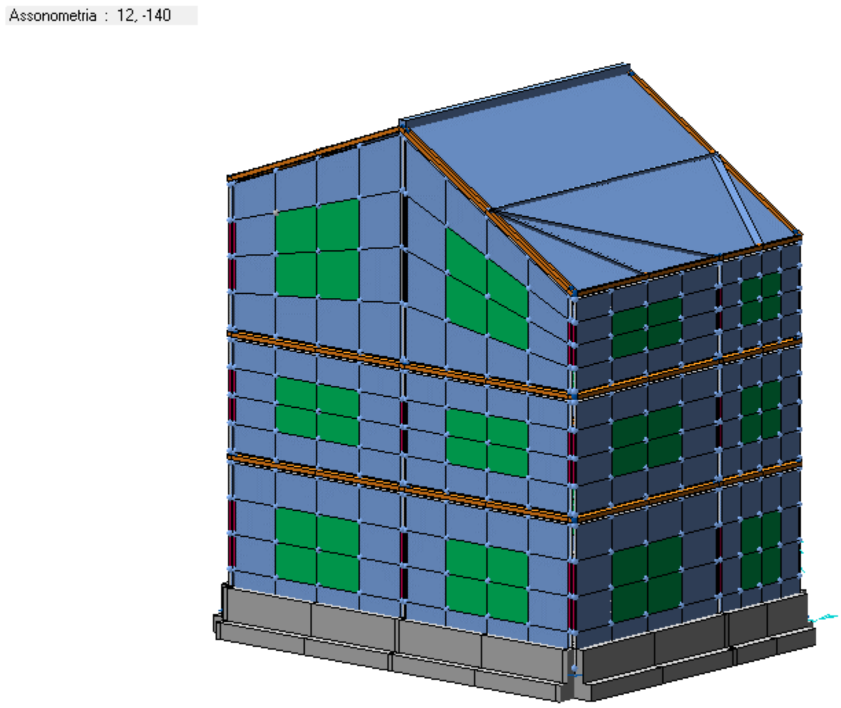


Figure 5.38 - Dolmen 3D Model

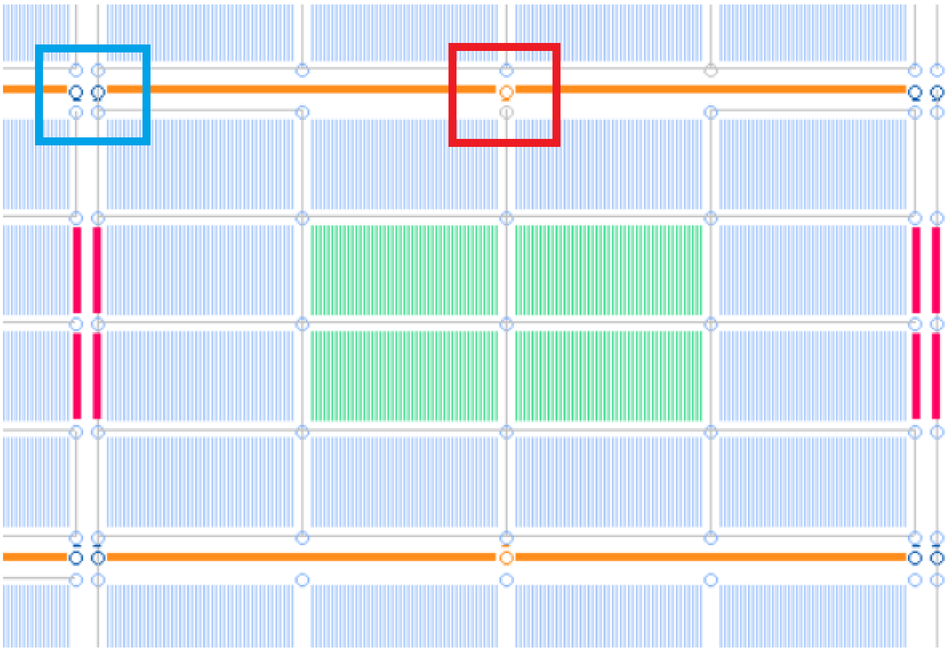


Figure 5.39 - Connection between XLAM panels. We can see hold - down (blue rectangle) and clamps (red rectangle)

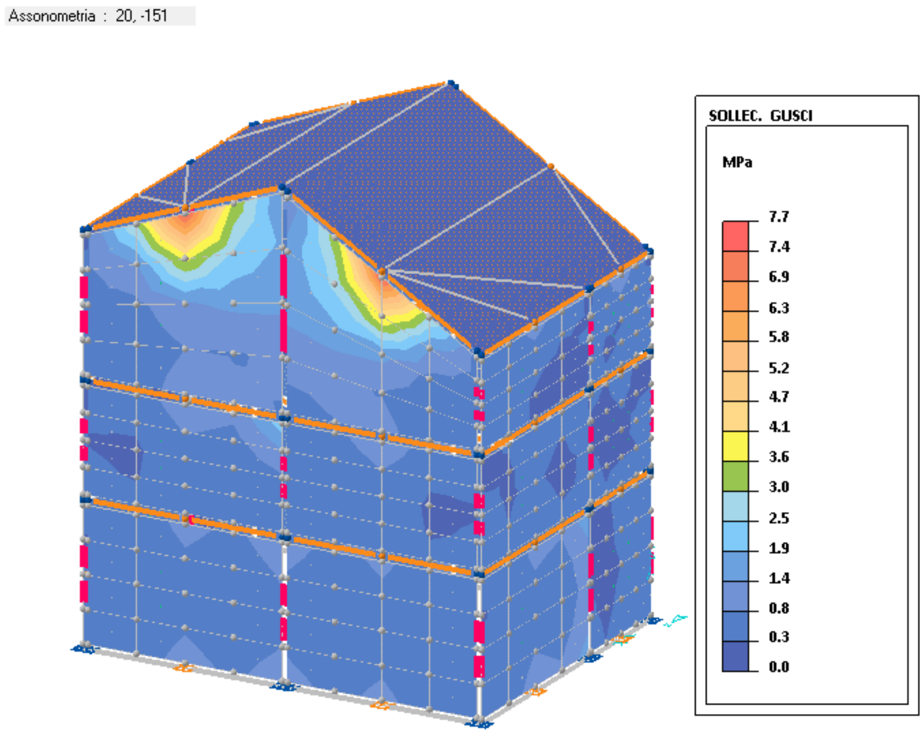


Figure 5.40 - Strains of shells. We can see how the strains are lower than the shear resistance (4 MPa)

5.4 Precast Reinforced Concrete Panels

5.4.1 Definition of loads

In order to evaluate concrete's behaviour, we also designed a precast concrete building. The main advantages are a shorter construction period and a better architectural quality. In fact, precast buildings are made up of reinforced concrete modules, which are manufactured off site and then assembled on site.

In this way, the building designers must guarantee the required performances.

So, unlike the previous RC structure, we define new stratigraphies to calculate the loads acting on the structure.

In particular, if the live and environmental loads are the same since the boundary conditions and the intended use of the building did not change, it is important to define new dead loads, which depends on the density of the materials.

Stratigraphies of Precast RC Panels

- ***Torino***

Floor on the ground				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	-
2	Regularization layer	0.065	-	-
3	Thermal insulation - EPS	0.120	-	-
4	Waterproof membrane	0.004	-	-
5	Screed for systems	0.100	-	-
6	Reinforced concrete slab	0.040	-	-
7	Crawl space	0.350	-	-
8	Lean Concrete	0.100	-	-
			Total thickness [m]	***0.71***

Table 5.35 - Stratigraphy of floor on the ground. The Table show structural features (thickness and weight) - Torino

External walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Reinforced concrete panel	0.340	25.10	8.533
2	Thermal insulation - Rockwool	0.100	0.59	0.059
3	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.46***
			Total weight [kN/m^2]	***8.82***

Table 5.36 - Stratigraphy of external walls. The Table show structural features (thickness and weight) – Torino

Inside walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Gypsum Plasterboard	0.0125	-	0.151
2	Gypsum Plasterboard	0.0125	-	0.151
3	Thermal insulation - Glass Wool	0.045	0.13	0.006
4	Gypsum Plasterboard	0.0125	-	0.151
5	Gypsum Plasterboard	0.0125	-	0.151
			Total thickness [m]	***0.10***
			Total weight [kN/m^2]	***0.610***

Table 5.37 - Stratigraphy of inside walls. The Table show structural features (thickness and weight) - Torino

Interfloor				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Ceramic tiles	0.009	-	0.190
2	Regularization layer	0.040	17.65	0.706
3	Acoustic pad	0.003	0.29	0.001
4	Screed for system	0.060	4.00	0.240
5	Vapour barrier	0.003	-	0.001
6	Slab	0.280	-	3.089
7	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.41***
			Total weight [kN/m^2]	***4.453***

Table 5.38 - Stratigraphy of interfloor. The Table show structural features (thickness and weight) - Torino

Roof				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Tiled roof	0.015	-	0.374
2	Ventilated Air Gap	0.060	-	-
3	Waterproof membrane	0.004	-	0.039
4	Thermal insulation - rockwool	0.140	1.52	0.213
5	Vapour Barrier	0.003	-	0.001
6	Roof	0.240	-	2.648
7	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.48***
			Total weight [kN/m^2]	***3.500***

Table 5.39 - Stratigraphy of roof. The Table show structural features (thickness and weight) - Torino

In order to avoid the repetition of the same tables, now we only report the stratigraphies of the external walls. In this way, we can observe how the insulation's thickness change according to the city.

- ***Catania***

External walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Reinforced concrete panel	0.340	25.10	8.533
2	Thermal insulation - Rockwool	0.04	0.59	0.024
3	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.40***
			Total weight [kN/m^2]	***8.78***

Table 5.40 - Stratigraphy of external walls. The Table show structural features (thickness and weight) – Catania

- ***Oslo***

External walls				
	Material	Thickness [m]	Density [kN/m^3]	Weight [kN/m^2]
1	Reinforced concrete panel	0.340	25.10	8.533
2	Thermal insulation - Rockwool	0.120	0.59	0.071
3	Plaster	0.015	15.00	0.225
			Total thickness [m]	***0.48***
			Total weight [kN/m^2]	***8.83***

Table 5.41 - Stratigraphy of external walls. The Table show structural features (thickness and weight) - Oslo

Panel transverse section

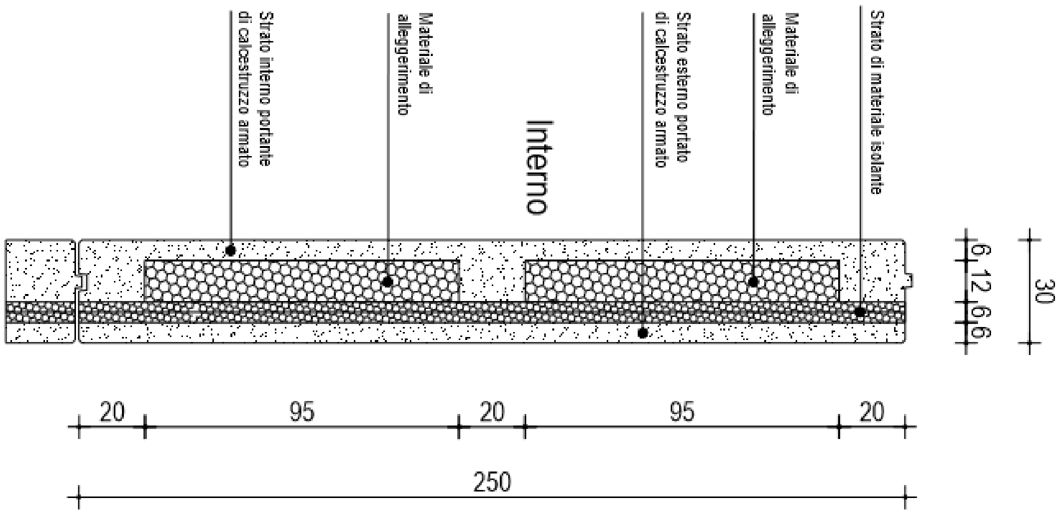


Figure 5.41 - Section of Precast Reinforced Concrete Panel

As Figure 5.41 shows, we used a sandwich panels, which are made up of layers of precast with insulation in between.

The insulation is attached to the panel during the manufacturing phase and the connection parts inside of the panel makes strong adhesion between the concrete layers and the insulation.

This is very important since insulation material and concrete have different thermal characteristics.

5.3.2 Dolmen Modelling

About Dolmen modelling, like XLAM structure, we use “shell” command in order to represent reinforced concrete panel.

The other elements are modelled like the previous RC structure even if there are not columns since the concrete panels are load-bearing structures.

Finally, even if the program Dolmen allows to calculate the amount of steel in order to satisfy structural checks, for reinforced concrete panels, we use a value of steel given by the literature: 13 kg/m^2 of panel.

6.Technological Disarticulation

6.1 Introduction

The building system can be considered as the interaction of different levels, each of them with specific degrees of complexity.

According to UNI 8290, the fist level concerns the classes of technological units, the second one concerns the technological units, the third one concerns the classes of technical elements.

In addition to these three levels defined by UNI 8290, we also consider another level which concerns the technical elements.

In particular, for each project, we can do:

- Functional - spatial disarticulation
- Technological disarticulation
- Disarticulation for work items

The functional – spatial disarticulation consists in identifying homogeneous spatial elements.

This disarticulation takes place with the study of the project’s plan and the various spatial elements are organized according to specific criteria and requirements of the project.

The technological disarticulation is the so - called WBS (Work Breakdown Structure) of the building.

It allows to break up the building in its elementary components and so it is possible to make the best choices during the design phase.

In particular, the technological disarticulation allows to examine the project with an increasing degree of detail.

Until this moment, the two type of disarticulation permits to identify all technical elements.

However, excluding precast elements, generally the technical elements don’t arrive in building site complete in all their parts.

For this reason, it is important the disarticulation for work items because the elements are divided according to their realization processes.

In this way, we can improve the organization of the construction yard since we are able to know the involved building companies and their arrival order.

In our project we mainly focused on the technological disarticulation.

Each element is clearly identified with a code so that we can quickly know its structural and thermal features, in addition to its quantity and emissions.
So technological disarticulation is important to define the bill of quantities and the CO_2 equivalent emissions.
In the disarticulation we did not consider the building systems because they were not studied in depth.

Example: External walls on first floor – RC structures (Torino)

This technical element is identified by the code: 2.1.1.2 where:

- the first number, “2”, refers to “Envelope” category;
- the second number, “1”, refers to the type of envelope, in this case “Vertical Envelope”;
- the third number, “1”, is linked to “External Walls”;
- the last number, “2”, characterizes the floor of the building (in this case the first floor).

In this way, we can quickly know all its features, such as the following ones:

External walls - 2.1.1.2				
	Material	λ [W/mK]	Thickness [m]	Resistance [(m² K) / W]
1	Plaster	0.550	0.015	0.027
2	Poroton	0.193	0.250	1.295
3	Thermal insulation - Rockwool	0.035	0.100	2.857
4	Plaster	0.550	0.015	0.027
Internal laminar layer (1/hi)				0.130
External laminar layer (1/he)				0.040
Total Resistance [(m² K) / W]				***4.38***
Transmittance U [W/(m² K)]				***0.23***
Internal thermal capacity [kJ/(m² K)]				***39.90***
External thermal capacity [kJ/(m² K)]				***21.80***
Thermal lag [h]				***13.11***

Figure 6.1 - Thermal features of external walls 2.1.1.2

External Walls - 2.1.1.2.			
Material	Quantity	U.M.	Weight [kg]
Poroton	26.99	m^2	6272.53
Thermal insulation - Rockwool	26.99	m^2	162.32
Internal plaster	26.99	m^2	619.00
External plaster	26.99	m^2	619.00
Mortar	395.38	kg	395.38
Paint	53.98	m^2	12.59

Figure 6.2 - Bill of quantities of external walls 2.1.1.2

6.2 Reinforced Concrete Structures Disarticulation

Figure 6.3 - Technological disarticulation of RC structure

6.3 XLAM Structures Disarticulation

TECHNOLOGICAL DISARTICULATION - XLAM STRUCTURE

1. LOAD - BEARING STRUCTURE

- **1.1. Foundation**
  - 1.1.1. Grade beams
- **1.2. Elevation**
  - *1.2.1. Vertical*
    - 1.2.1.1. External walls Xlam (X cm)
    - 1.2.1.2. External walls Xlam (X cm)
    - 1.2.1.3. External walls Xlam (X cm)

2.ENVELOPE

- **2.1. Vertical envelope**
  - *2.1.1.External doors and window frames*
- **2.2. Lower horizontal envelope**
  - *2.1.1.Floor on the ground*
    - 2.2.1.1. Floor on the ground (X cm)
- **2.3. Upper envelope**
  - *2.3.1.Roof*
    - 2.3.1.1. Slanted roof (X cm)

3.PARTITION

- **3.1. Internal and vertical partition**
  - *3.1.1.Inside walls*
    - 3.1.1.1.Inside walls (X cm)
    - 3.1.1.2.Inside walls (X cm)
  - *3.1.2.Internal doors frames*
- **3.2. Internal and horizontal partition**
  - *3.2.1.Interfloor*
    - 3.2.1.1.Interfloor Xlam (X cm)
    - 3.2.1.2.Interfloor Xlam (X cm)

NOTE:
"X" refers to element's thickness and its value changes according to the location where the building is situated.

Figure 6.4 - Technological disarticulation of XLAM structure

6.4 Precast Concrete Panels Disarticulation

Figure 6.5 - Technological disarticulation of precast concrete panels

7. Life Cycle Assessment – LCA

7.1 Introduction

To evaluate the building sustainability, we consider the LCA (Life Cycle Assessment) method.

If we look at an LCA structure, this is divided into four main moments:

- Goal and scope definition
- Inventory analysis (LCI, Life Cycle Inventory analysis)
- Life Cycle Impact Assessment (LCIA)
- Results' interpretation (Life Cycle Interpretation)

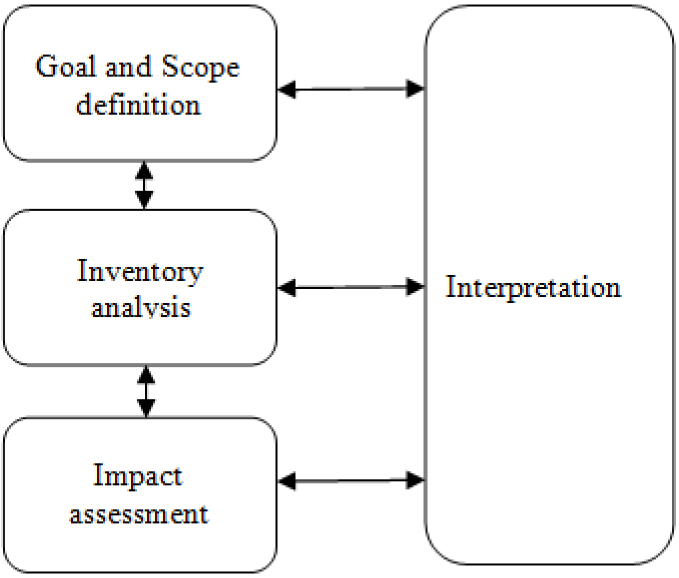


Figure 7.1 - Life Cycle Assessment Framework.
Source: ISO 14040

The first one is the preliminary phase, but it's the more important because the case study and the level of detail are defined. In this phase, we also chose the functional unit, or the function on which to set up the analysis and the comparison with the possible alternatives.

The inventory analysis is the core of LCA method. In particular, during this phase, we identify and quantify both elementary input output flows. Therefore, the consumptions of resources, energy and emissions are determined.

The inventory is made up of:

- Process flowchart, which consists of a graphic and qualitative representation of all phases and processes involved in the life cycle.

- Data collection. Data can be primary if they come from direct surveys or secondary if they are obtained from literature or software database.
- Boundary conditions which define the interaction between the studied system and the environment.

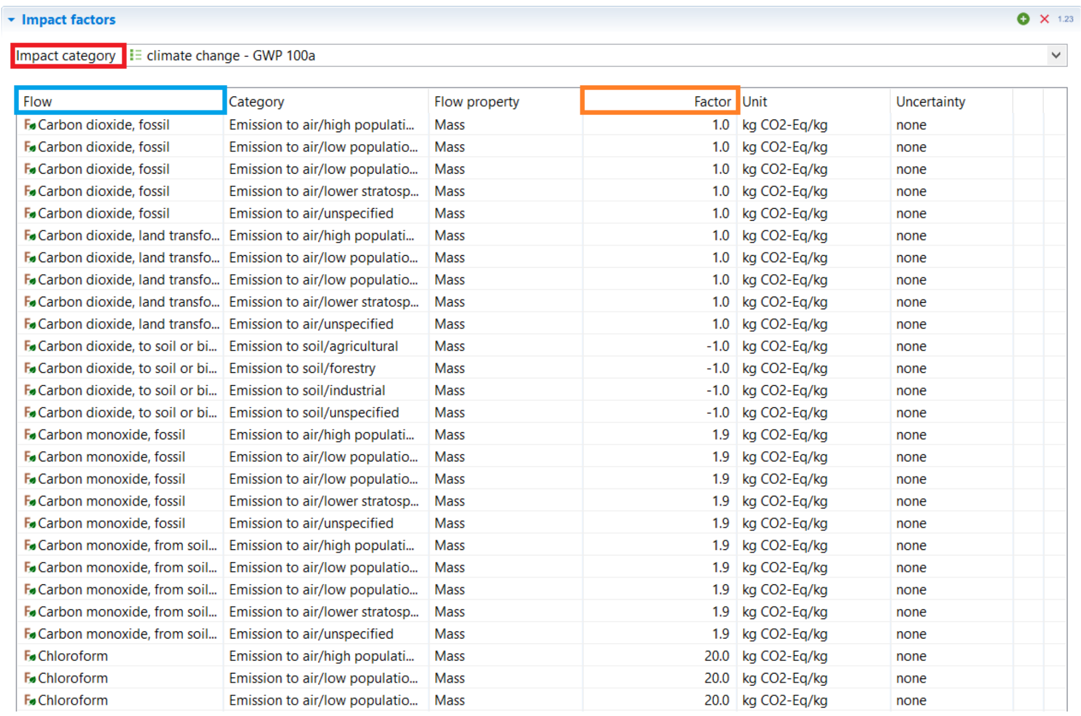
During the third phase, we evaluate the product effects towards environment.

In particular, according to ISO 14040 – 44, we must choose the impact assessment method and then the impact categories.

It is also important to pay attention to classification and characterization.

The classification allows to know the elementary flows at the base of each building product system while characterization involves the impact factor, which expresses the contribution of each process in relation to the chosen functional unit.

For example, if we consider as impact category the climate change, the functional unit is CO_2 equivalent (kg CO_2 – Eq / kg). The impact factor is a value that transforms and refers each data concerning environmental impact (such as methane) to the functional unit.



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

Figure 7.2 - The Figure shows the elementary flows that are considered in each process, the impact factor and the impact category (In this case climate change - GWP 100a)
Source: OpenLCA

Finally, during the results' interpretation, we can define product development and improvement and strategic planning in order to guarantee sustainability.
In the examined project, we chose the Carbon Footprint (CF) as environmental indicator. It is expressed in terms of CO_2 equivalent and it allows to measure the whole of greenhouse gas emissions, associated directly or indirectly with a product, an organization or a service.
In particular this indicator analyzes the emissions deriving by the following greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), perfluorocarbons (PFCs).
Each gas has a different environmental behavior, and, for this reason, it is important to use an indicator, the GWP (Global Warming Potential), a ratio that describes the warming impact of each gas relative to over a set period, usually hundred years.
In order to calculate CO_2 equivalent, we use the software *openLCA* and we chosen to use data relevant to a GWP 100a.
Finally, the data are provided by IPCC (Intergovernmental Panel on Climate Change) 2013.
The IPCC is the main international organization for the evaluation of climate changes.
Since the Carbon Footprint is a very important indicator, its SWOT analysis might be interesting.
The SWOT analysis is a strategic management tool used to specify the object of the project and to identify its internal (Strengths and Weaknesses) and external (Opportunities and Threats) factors.
We underline some key points.

Strengths of Carbon Footprint

- It is easy to understand since it is based on physical units which do not require specific knowledge.
- It is of global interest since climate change affects everybody.
- The Carbon Footprint allows to implement specific and effective strategies.

Weaknesses of Carbon Footprint

- The insufficient accuracy of the data
- The Carbon Footprint indicator considers climate change as a single and unique impact category. This restrictive environmental assessment may limit the effectiveness of the sustainability assessment since it does not consider resource depletion, acidification, toxicity and so on.

Opportunities of Carbon Footprint

- In the LCA method, Carbon Footprint can be considered as an instrument to analyze the interactions between man and environment.
  In particular, it offers savings opportunities from energetical, economic and environmental point of view.

Threats of Carbon Footprint

- System boundaries are often among the greatest threats in CF quantification.
  In particular the mainly difficulty is to obtain the data related to the all elements involved in the product life cycle.

Strengths	**Weaknesses**
Easy to understand and communicate globally, of global interest, broadly applicable and easy to implement	Insufficient accuracy of the data and methods to permit disaggregated product CF
Simplify the process to obtain CF of products and help to prioritise the reduction of emissions	Variability of the supply chains in addition to local environmental uniqueness
Multiplier effect on the value and supply chain	Different ways of dealing with CF and LCA issues increases the differences between the existing methodologies
Capacity for social and economic immersion	Climate change as a single impact category
Opportunities	**Threats**
Growth in the number of investors and in green economic sectors	Subjective system boundaries and thresholds
Free methods and databases	Lack of convergence between Product Carbon Footprint and Corporate Carbon Footprint
Audit CF by independent agencies	
Solid future value. Good for differentiating and opening new	Proliferation of methods and communication programmes

Figure 7.3 - The summary diagram of SWOT analysis of CF
Source: [12]

As previously said, we consider the whole the whole cycle of life: not only the production of materials (modules A1 to A3), but also their transport (Modules A4 to A5) and their end – of – life (Modules C1 to C4 and D)
However, we made the following assumptions:

- the production site is 50 km away for each material
- in reference to the eof, some materials (i.e., concrete, steel) can be recycled, whereas others (i.e., insultations) are sent to landfill. We also considered the electricity and the fuel used during the deconstruction process and the transport to the landfill.

In this way, we consider a specific scenario for the demolition:

- Steel: 100% recycled
- Concrete, cementitious materials and ceramic materials: 100% recycled
- Wood: 100% recycled
- Other materials (such as plastic materials): 100% landfill

In particular, 70 percent of recycling takes place during a controlled demolition phase, while the remaining 30 percent after wreckage's treatment.
Finally, we provide some information about the sustainability of the two most used materials in the project: concrete and cross laminated timber (XLAM).

7.2 Concrete Sustainability

For the concrete, it is important to focus on the Figure 7.1.

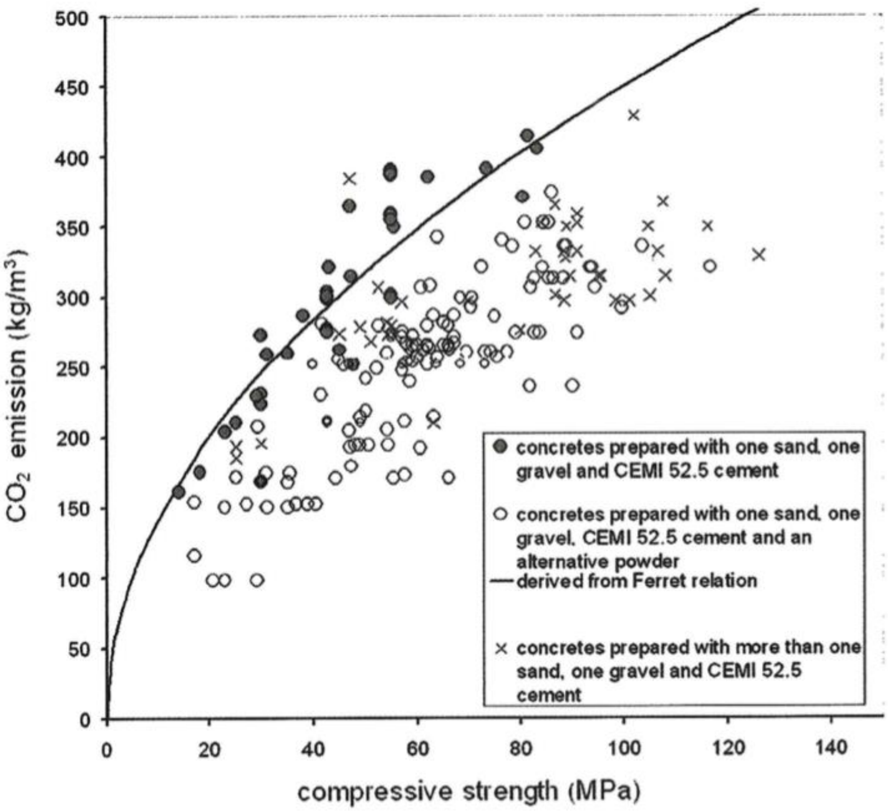


Figure 7.4 - Relationship between concrete 28 - days compressive strength and CO2 emissions per cubic metre of materials m3.
Source: Cement & concrete composites n°31, "study of two concrete mix-design strategies to reach carbon mitigation objectives", G. Halbert, N. Roussel, 2009.

This Figure shows the relationship between concrete mechanical resistance and CO2 emissions.
The mechanical resistance is proportional to the square of the amount of carbon dioxide (CO2) per cubic metre of materials, according to the following expression:

$$f_c \approx \left(CO_2^{m^3}\right)^2 \quad (7.1)$$

It is important to underline as high strength concretes are the most sustainable even if their unit impact is greater.
This mainly depends on the possibility to change the transverse section of structural elements, such as columns, according to the applied load, thanks to relation:

$$V = \frac{P}{f_c} \cdot H \quad (7.2)$$

Where:

V is the volume of structural element

H is the height of structural element

P is the applied load

fc is compressive strength

In this way, it is clearly that, if fc increases and the height H is fixed, the volume decreases under the effect of the same load.

However, an increasing of compressive strength involves consequently an increasing of steel reinforcement (like the other materials, steel causes CO_2 emissions).

For these reasons, in order to evaluate the sustainable of the building, it is important the choice of the concrete which is able to satisfy the requirements.

7.3 Cross Laminated Timber Sustainability

On the other hand, timber is certainly an ecological material that has no impact on the environment and that can be reused and recycled.

What is not really known is the behavior of timber and an adhesive glue together.

To analyze the effective impact in terms of emissions in the atmosphere it is necessary to investigate three phases, i.e. the production of the adhesive, the application to produce CLT, and the disposal of the product. During these three steps in the materials life, the adhesive might emit different substances.

For this reason, some companies, such as XLAM Dolomiti, study in order to find possible alternative solutions.

It is already possible to find bio-based wood adhesives on the market. They are bio resins obtained from plants and animal wastes or wax.

The benefit of using a bio-based adhesive is the same as using timber in the construction, i.e. they can be recycled, and they have no carbon footprint.

The reason why none of the CLT producers uses them is because of the weak adhesive strength and the higher costs.

Finally, waste parts or disposed modules of CLT could be used for indoor residential heating or it is also possible to convert the CLT waste into construction products.

8. Carbonation

8.1 Introduction

As said previously, the demand for sustainability in production processes increases in these last years and it especially includes the construction industry, considered one of the biggest consumers of natural resources.
It is also highly responsible for global warming, since the cement industry accounts for about 5% to 7% of the annual global emissions of carbon dioxide (CO_2).
Sixty percent of these emissions are caused by the calcination process of calcinate ($CaCO_3$) to obtain calcium oxide (CaO):

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (8.1)$$

It is the major component of clinker.
The other percent comes from the production process itself, due to the reactions of limestone calcination in clinker production.
In order to support sustainability, it is possible to use recycled materials to produce concrete, such as slag and fly ash.
They are considered industrial waste product, which can replace up to 80% of cement weight.
In this way, there is a visible reduction of CO_2 consumption and emissions.
The concrete has the property to absorb CO_2 from environmental through the carbonatation.

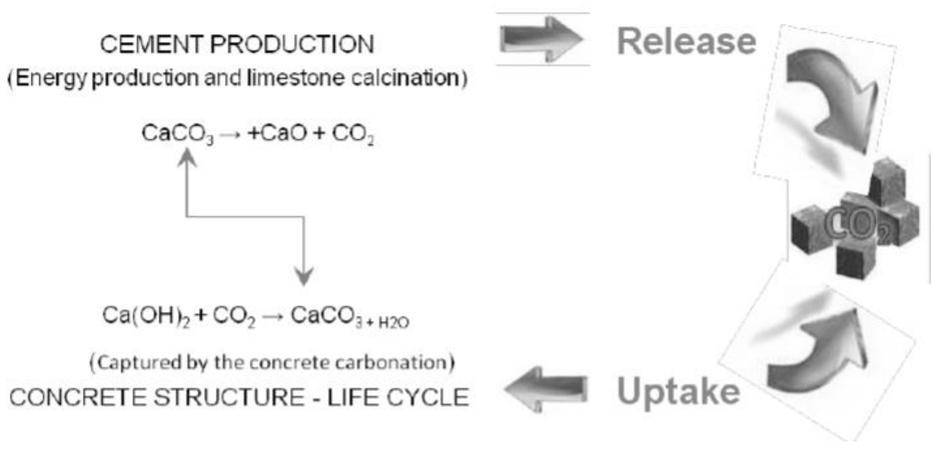


Figure 8.1 - CO_2 emission and uptake in concrete structure.
Source: [16]

Almost all of cement-based materials have a carbonation reaction during their lifespan due to the presence of carbon dioxide in Earth atmosphere.
This process begins at construction, passing through the life cycle of the structure, and continues during demolition process.
Carbonation is a chemical reaction, described by the following reaction:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (8.2)$$

So, thanks to this reaction, CO_2 from the atmosphere is consumed.
The equation shows a reaction between an acid gas (CO_2) with alkali of concrete, especially $Ca(OH)_2$.

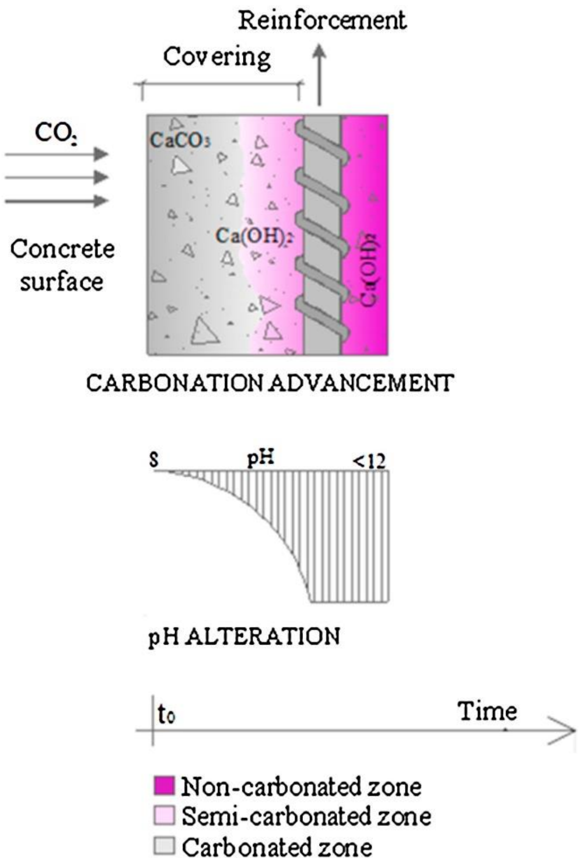


Figure 8.2 - Representation based on the advance of carbonation and pH change in concrete over time.
Source: Modeling of carbonation and the service life prediction of concrete structures

Starting from the surface, carbonation progressively moves into the concrete structure and forms a carbonate layer.
In reinforced concrete, this process can be harmful because leading the reinforcement de-passivation, leaving the steel susceptible to corrosion due to lowered pH-value.
For this reason, it is important to take into account this phenomenon during concrete design.
In particular, the risk of steel corrosion is avoided by consider adequate cover to reinforcement (this is described in Eurocode 2).

When there is no reinforcement, the carbonation process is beneficial since the product of the carbonating reaction ($CaCO_3$) has larger volume than $Ca(OH)_2$, leading to filling of the concrete pores and increasing its strength.

Cement content and type, water/binder ratio, moisture and CO_2 concentration are the main factors that affect this process and so we must consider them during the calculations.
The main compound carboned is calcium hydroxide ($Ca(OH)_2$).
However, chemical reaction also involves silicates (Equation 8.3) and aluminates (Equation 8.4)

$$3CaO.2SiO_2.3H_2O + 3CO_2 \rightarrow 3CaCO_3 + 2SiO_2 + 3H_2O \quad (8.3)$$

$$4CaO.2Al_2O_3.13H_2O + 4CO_2 \rightarrow 4CaCO_3 + 2Al(OH)_3 + 10H_2O \quad (8.4)$$

The main results of this reaction are the reduction of concrete pH to a value less than 9 and CO_2 uptake from atmosphere due to formation of calcium carbonate ($CaCO_3$).
Carbonation process depends on diffusivity and CO_2 reactivity with concrete.
Thus, the greater this gas concentration and the lower compressive strength of concrete are, the greater carbonation depth of concrete.
Moreover, the carbonation depth is higher in an inside environment, followed by outside protected from the rain and outside unprotected from the rain.
It can be also observed an exponential relationship between CO_2 uptake and the surface area concerning the structure exposed to the air according to the graphical representation of CO_2 absorbed amount during carbonation process.

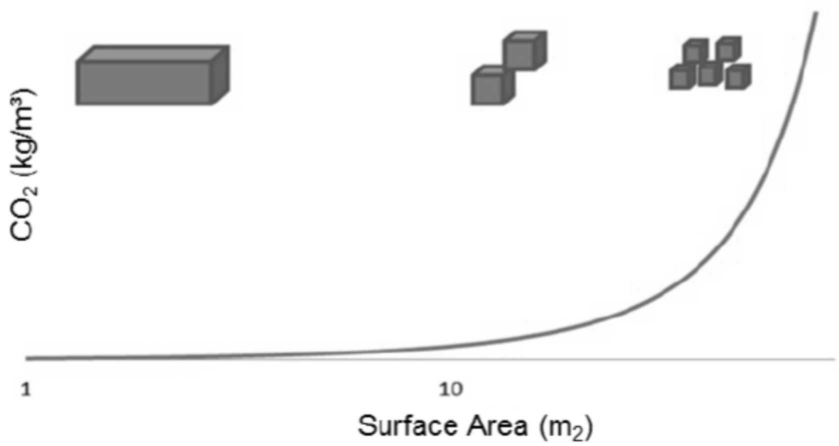


Figure 8.3 - Co2 uptake x Surface area
Source: [16]

In this way, slender structures tend to present grater CO_2 uptake indicators than robust structures.

In our project, to calculate CO_2 uptake, we used EN 16757: 2017.

The CO_2 uptake in kg per m^2 concrete surface during t years can be calculated as:

$$CO_2\ uptake = k * \left(\sqrt{t}/1000\right) * U * C * D_c \quad (8.5)$$

Where:

- k = factor given in the Table BB.1
- U = is the maximum theoretical uptake in kg CO_2 / kg cement. The value is 0.49 for Portland cement (CEM I).
- C = is cement content in kg / m^3 of concrete. The value is 300 kg / m^3 in our case.
- D_C = factor given in the Table BB.1

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 %.

Figure 8.4 - Table BB.1 Source: EN 16757:2017

8.2 Carbonation - RC Structures

8.2.1 Torino

Columns		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
Indoor in dry climate with cover		
k	4.6	mm / year$^{0.5}$
D	40	%
Ground floor - surface concrete	20.088	m^2
First floor - surface concrete	16.056	m^2
Second floor - surface concrete	22.707	m^2
CO_2 uptake concrete	*1.913*	*kg CO_2 / m^2*
	112.557	*kg CO_2*
Outdoor - sheltered from rain		
k	4.4	mm / year$^{0.5}$
D	75	%
Ground floor - surface concrete	10.044	m^2
First floor - surface concrete	8.028	m^2
Second floor - surface concrete	9.585	m^2
CO_2 uptake concrete	*3.430*	*kg CO_2 / m^2*
	94.868	*kg CO_2*
Total CO_2 uptake concrete	**207.426**	***kg CO_2***

Table 8.1 - Total CO_2 uptake of Columns - Torino

Beams		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
Indoor in dry climate with cover		
k	4.6	mm / $year^{0.5}$
D	40	%
First floor - surface concrete	5.64	m^2
Second floor - surface concrete	5.64	m^2
Roof	2.44	m^2
CO_2 uptake concrete	***1.913***	***kg CO_2 / m^2***
	26.241	***kg CO_2***
Outdoor - sheltered from rain		
k	4.4	mm / $year^{0.5}$
D	75	%
First floor - surface concrete	32.43	m^2
Second floor - surface concrete	32.43	m^2
Roof	34.62	m^2
CO_2 uptake concrete	***3.430***	***kg CO_2 / m^2***
	341.217	***kg CO_2***
Total CO_2 uptake concrete	***367.457***	***kg CO_2***

Table 8.2 - Total CO_2 uptake of Beams - Torino

Grade Beams		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
In ground		
k	0.8	mm / year$^{0.5}$
D	85	%
Surface concrete	93.06	m^2
CO_2 uptake concrete	***0.707***	***kg CO_2 / m^2***
	65.777	***kg CO_2***
Total CO_2 uptake concrete	***65.777***	***kg CO_2***

Table 1.3 - Total CO_2 uptake of Grade Beams – Torino

Co2 uptake of cement-based elements		
Portland cement (CEM I)		
Value		U.M.
0.49		kg CO_2 / kg cement
Material	Quantity [kg]	CO_2 uptake [kg Co$_2$]
External walls - cement mortar	2189.057	1072.638
Inside walls - cement mortar	317.347	155.500
Plaster	10150.494	4973.742
Total		***6201.880 kg CO_2***

Table 8.4 - Total CO_2 uptake of cement-based elements - Torino

8.2.2 Catania

Columns		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
Indoor in dry climate with cover		
k	4.6	mm / year$^{0.5}$
D	40	%
Ground floor - surface concrete	20.088	m^2
First floor - surface concrete	16.056	m^2
Second floor - surface concrete	22.707	m^2
CO_2 uptake concrete	*1.913*	*kg CO_2 / m^2*
	112.557	*kg CO_2*
Outdoor - sheltered from rain		
k	4.4	mm / year$^{0.5}$
D	75	%
Ground floor - surface concrete	10.044	m^2
First floor - surface concrete	8.028	m^2
Second floor - surface concrete	9.585	m^2
CO_2 uptake concrete	*3.430*	*kg CO_2 / m^2*
	94.868	*kg CO_2*
Total CO_2 uptake concrete	**207.426**	***kg CO_2***

Table 8.5 - Total CO_2 uptake of Columns - Catania

Beams		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
Indoor in dry climate with cover		
k	4.6	mm / $year^{0.5}$
D	40	%
First floor - surface concrete	5.64	m^2
Second floor - surface concrete	5.64	m^2
Roof	2.44	m^2
CO_2 uptake concrete	***1.913***	***kg CO_2 / m^2***
	26.241	***kg CO_2***
Outdoor - sheltered from rain		
k	4.4	mm / $year^{0.5}$
D	75	%
First floor - surface concrete	32.43	m^2
Second floor - surface concrete	32.43	m^2
Roof	34.62	m^2
CO_2 uptake concrete	***3.430***	***kg CO_2 / m^2***
	341.217	***kg CO_2***
Total CO_2 uptake concrete	***367.457***	***kg CO_2***

Table 8.6 - Total CO_2 uptake of Beams - Catania

Grade Beams		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
In ground		
k	0.8	mm / $year^{0.5}$
D	85	%
Surface concrete	93.06	m^2
CO_2 uptake concrete	***0.707***	***kg CO_2 / m^2***
	65.777	***kg CO_2***
Total CO_2 uptake concrete	***65.777***	***kg CO_2***

Table 2 - Total CO_2 uptake of Grade Beams – Catania

Co_2 uptake of cement-based elements		
Portland cement (CEM I)		
Value		U.M.
0.49		kg CO_2 / kg cement
Material	Quantity [kg]	CO_2 uptake [kg Co_2]
External walls - cement mortar	2189.057	1072.638
Inside walls - cement mortar	317.347	155.500
Plaster	10150.494	4973.742
Total		***6201.880 kg CO_2***

Table 8.8 - Total CO_2 uptake of cement-based elements - Catania

8.2.1 Oslo

Columns		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
Indoor in dry climate with cover		
k	4.6	mm / $year^{0.5}$
D	40	%
Ground floor - surface concrete	20.088	m^2
First floor - surface concrete	16.056	m^2
Second floor - surface concrete	22.707	m^2
CO_2 uptake concrete	*1.913*	*kg CO_2 / m^2*
	112.557	*kg CO_2*
Outdoor - sheltered from rain		
k	4.4	mm / $year^{0.5}$
D	75	%
Ground floor - surface concrete	10.044	m^2
First floor - surface concrete	8.028	m^2
Second floor - surface concrete	9.585	m^2
CO_2 uptake concrete	*3.430*	*kg CO_2 / m^2*
	94.868	*kg CO_2*
Total CO_2 uptake concrete	**207.426**	***kg CO_2***

Table 8.9 - Total CO_2 uptake of Columns - Oslo

Beams		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
Indoor in dry climate with cover		
k	4.6	mm / year$^{0.5}$
D	40	%
First floor - surface concrete	5.64	m^2
Second floor - surface concrete	5.64	m^2
Roof	2.44	m^2
CO_2 uptake concrete	***1.913***	***kg CO_2 / m^2***
	26.241	***kg CO_2***
Outdoor - sheltered from rain		
k	4.4	mm / year$^{0.5}$
D	75	%
First floor - surface concrete	32.43	m^2
Second floor - surface concrete	32.43	m^2
Roof	34.62	m^2
CO_2 uptake concrete	***3.430***	***kg CO_2 / m^2***
	341.217	***kg CO_2***
Total CO_2 uptake concrete	***367.457***	***kg CO_2***

Table 8.10 - Total CO_2 uptake of Beams - Oslo

Grade Beams		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
In ground		
k	0.8	mm / year$^{0.5}$
D	85	%
Surface concrete	93.06	m^2
CO_2 uptake concrete	***0.707***	***kg CO_2 / m^2***
	65.777	***kg CO_2***
Total CO_2 uptake concrete	***65.777***	***kg CO_2***

Table 8.11 - Total CO_2 uptake of Grade Beams - Oslo

CO_2 uptake of cement-based elements		
Portland cement (CEM I)		
Value		U.M.
0.49		kg CO_2 / kg cement
Material	Quantity [kg]	CO_2 uptake [kg Co_2]
External walls - cement mortar	2189.057	1072.638
Inside walls - cement mortar	317.347	155.500
Plaster	10150.494	4973.742
Total		***6201.880 kg CO_2***

Table 8.12 - Total CO_2 uptake of cement-based elements – Oslo

Observations:

In our calculations, we considered a concrete with 25/30 MPa compressive strength and we assumed 50 years since they are the useful life of structures.
The surface area was given from the study of the three – dimensional geometric model.
We obtain the same carbonatation in all the three cities because the variation is only due to the thickness of the insulation.

Finally, it is also important to underline how the total amount of CO_2 uptake does not only include concrete, but also each cement – based material, such as mortar.
This allows an increase of CO_2 uptake.

8.3 Carbonation – Precast concrete panels

Here again, like RC structures, the results are the same for the three cities.

Precast Concrete Panels		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
Indoor in dry climate with cover		
k	4.6	mm / year$^{0.5}$
D	40	%
Ground floor - surface concrete	65.208	m^2
First floor - surface concrete	26.988	m^2
Second floor - surface concrete	42.102	m^2
CO_2 uptake concrete	***1.913***	***kg CO_2 / m^2***
	256.856	***kg CO_2***
Outdoor - exposed from rain		
k	1.6	mm / year$^{0.5}$
D	85	%
Ground floor - surface concrete	65.208	m^2
First floor - surface concrete	26.988	m^2
Second floor - surface concrete	42.102	m^2
CO_2 uptake concrete	***1.414***	***kg CO_2 / m^2***
	189.850	***kg CO_2***
Total CO_2 uptake concrete	***446.706***	***kg CO_2***

Table 8.13 - Total CO_2 uptake of Columns

Beams		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
Indoor in dry climate with cover		
k	4.6	mm / year$^{0.5}$
D	40	%
First floor - surface concrete	5.64	m^2
Second floor - surface concrete	5.64	m^2
Roof	2.44	m^2
CO_2 uptake concrete	***1.913***	***kg CO_2 / m^2***
	26.241	***kg CO_2***
Outdoor - sheltered from rain		
k	4.4	mm / year$^{0.5}$
D	75	%
First floor - surface concrete	32.43	m^2
Second floor - surface concrete	32.43	m^2
Roof	34.615	m^2
CO_2 uptake concrete	***3.430***	***kg CO_2 / m^2***
	341.217	***kg CO_2***
Total CO_2 uptake concrete	***367.457***	***kg CO_2***

Table 8.14 - Total CO_2 uptake of Beams

Grade Beams		
Material	concrete	25/30
time [t]	50	years
U [CEM I]	0.49	kg CO_2 / kg cement
C	300	kg/m^3
In ground		
k	0.8	mm / year$^{0.5}$
D	85	%
Surface concrete	93.06	m^2
CO_2 uptake concrete	***0.707***	***kg CO_2 / m^2***
	65.777	***kg CO_2***
Total CO_2 uptake concrete	***65.777***	***kg CO_2***

Table 8.15 - Total CO_2 uptake of Grade Beams

CO_2 uptake cement		
Portland cement (CEM I)		
Value		U.M.
0.49		kg CO_2 / kg cement
Material	Quantity [kg]	CO2 uptake [kg Co_2]
Plaster	6055.220	2967.056
Total		**6201.880 kg CO_2**

Table 8.16 - Total CO_2 uptake of cement-based elements

*<u>Observations</u>***:**

In this case we have a low CO_2 uptake of cement-based materials since we use RC panels and so the only cement-based material is the plaster.

9. Cost analysis

In the building production, each product differs from the one previously built.

In fact, every time, building (volume, materials, etc…) and construction yard (climate, spaces, etc…) change and this involves characteristic prices.

For these reasons, for each building, it is necessary to quantify costs related to construction, production and global costs through the so-called evaluation input data, such as the reference period, the real estate market, cost scale and, particularly, the representative unit parameter, which can be physical (square metre) or functional (for examples, student place, used for schools and universities).

In this way, we define the ordinary unit cost thanks to which we can do the prices analysis and the bill of quantities.

In particular, to calculate building cost, we use price list for building types or price list of the construction projects, depending on the considered phase.

The first one reports, as the name says, the cost for building types with annual update.

It is used during the planning phase when we only know the type and the volumes of the building: the only way to define the cost is comparing with similar cases and the method is the parametric estimate.

The second one is used during the phase of detailed and final proposals when it is possible to establish analytically building cost.

Each cost considers the following components:

- Manpower
- Freight and transport
- Materials

In our project, to define the cost of the building, we followed a clear and detailed scheme:

- Technological disarticulation (see chapter 5)
- Quantification of the workings
- Multiplication of the quantities of materials for the unit cost, deduced not only from regional price list, but also from commercial catalogues (for example, Rockwool catalogue).

It is important to underline that the prices are without VAT (Value – Added Tax) and the total cost does not include the prices related to fee of the professional.

The definition of the bill of quantities was made for all three buildings (Poroton, XLAM and precast concrete), situated in Torino.

This permitted us to compare the costs and understand cost – performance ratio

10. Analysis of results

10.1 Introduction

In order to make the results clearer and more comprehensible even for non – experts, the numerical results, obtained from the previous analysis, are represented through graphs.
In particular, we decide to pay attention about three aspects considered the most important:

- Construction cost
- CO_2 – equivalent emissions
- Carbonation

The comparisons take place both between the three types of construction (Poroton, XLAM and Precast concrete panels) maintaining the location fixed and between the three locations (Torino, Catania and Oslo), maintaining the type of construction fixed.

10.2 CO_2 equivalent comparisons

In order to understand the environmental behaviour of the building types (Poroton, Xlam, Precast RC Panels) in all cities (Torino, Catania, Oslo), we report the following tables.
In particular, it is clear how the Xlam structure is the more sustainable in every city: this depends on the features of the timber, which allows to reduce gases emissions.
The structure with precast RC panels has reduced CO_2 -Equivalent emissions too: in fact, the construction of a precast building requires less materials than a usual house in bricks (Poroton).
In this way, it is correct the Poroton structure causes the highest CO_2 -Equivalent emissions. In fact, cement is one of the main responsible of CO_2 production and, in this case, cement is used not only for its structural skeleton, but also in materials as mortar.
Moreover, if we pay attention on building type in reference to all cities, we can see how the building located in Oslo has the major environmental impact in terms of CO_2 -Equivalent; this mainly depends on the amount of thermal insulation necessary to guarantee the required performance.

Torino	
Building Type	CO_2 - Eq Emissions [Kg CO_2]
Poroton	40422
Xlam	17811
Precast RC Panels	22732

Table 10.1 – CO_2 Equivalent Emissions in Torino in reference to all building type

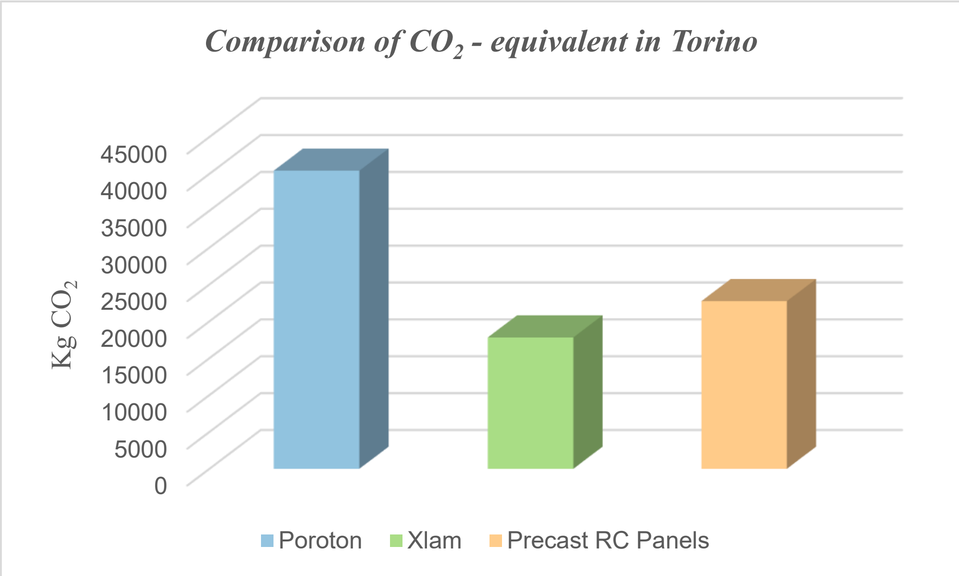


Figure 10.1 - Comparison of CO_2 - equivalent in Torino

Catania	
Building Type	CO_2 - Eq Emissions [Kg CO_2]
Poroton	39346
Xlam	17399
Precast RC Panels	21977

Table 10.2 – CO_2 Equivalent Emissions in Catania in reference to all building type

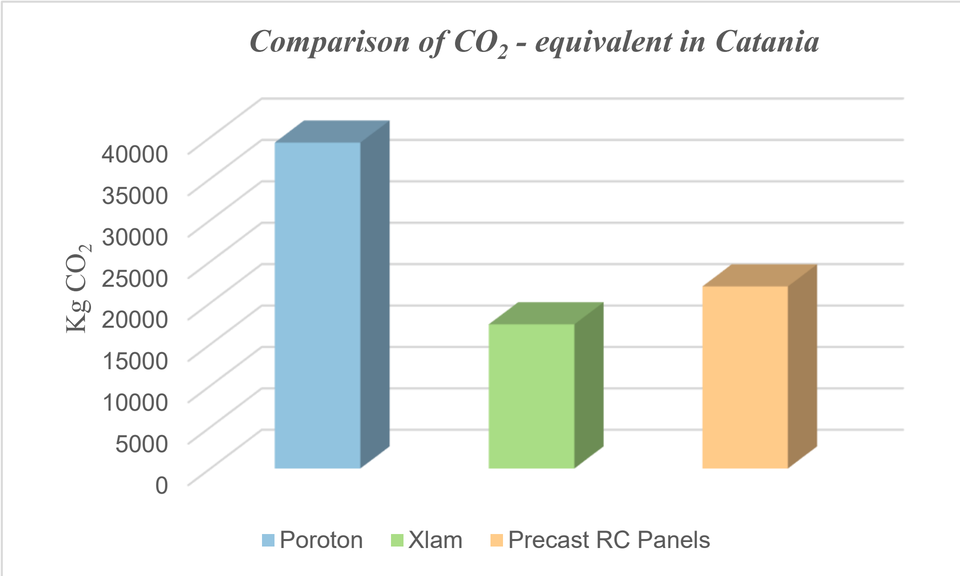


Figure 10.2 - Comparison of CO_2 - equivalent in Catania

Oslo	
Building Type	CO_2 - Eq Emissions [Kg CO_2]
Poroton	40422
Xlam	18290
Precast RC Panels	22830

Table 10.3 – CO_2 Equivalent Emissions in Oslo in reference to all building type

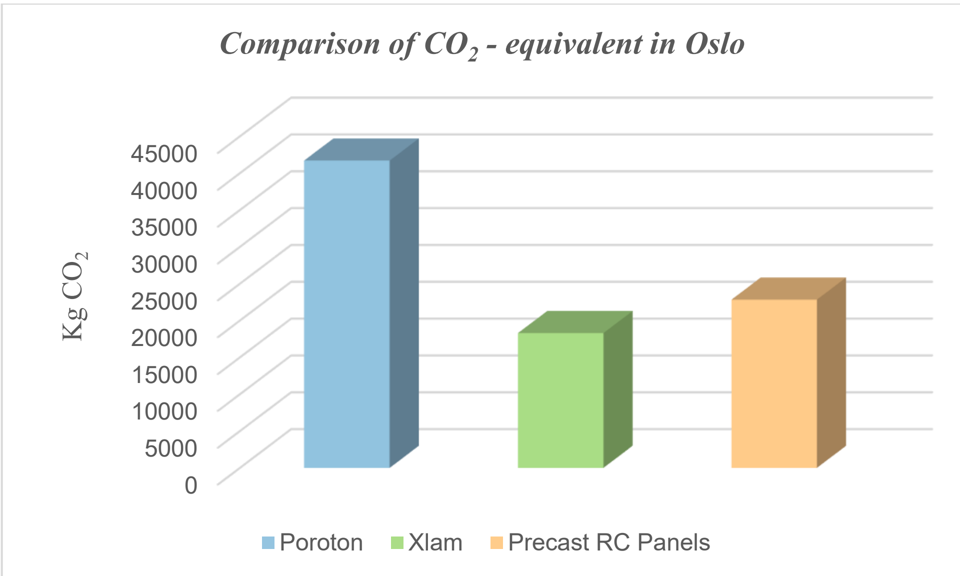


Figure 10.3 - Comparison of CO_2 - equivalent in Oslo

Poroton	
Building Type	CO_2 - Eq Emissions [Kg CO_2]
Torino	40422
Catania	39346
Oslo	41704

Table 10.4 – CO_2 Equivalent Emissions of RC structure in Poroton in reference to all cities

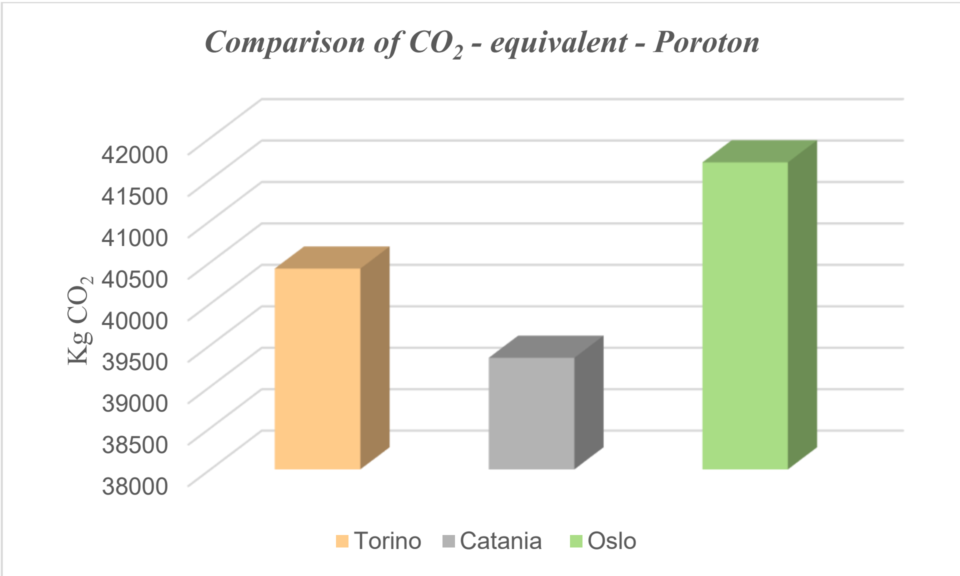


Figure 10.4 - Comparison of CO_2 - equivalent RC structure

Xlam	
Building Type	CO_2 - Eq Emissions [Kg CO_2]
Torino	17811
Catania	17399
Oslo	18290

Table 10.5 – CO_2 Equivalent Emissions of Xlam structure in reference to all cities

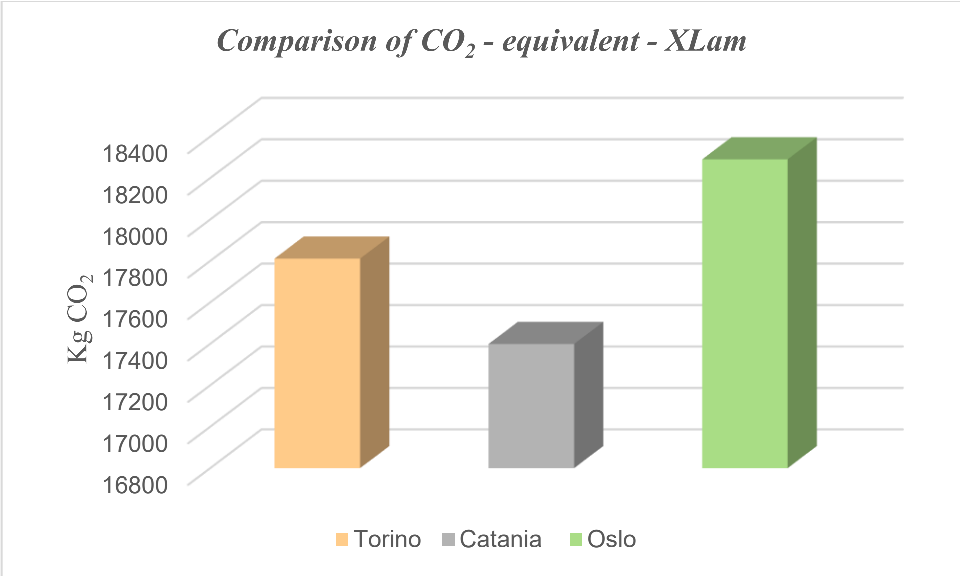


Figure 10.5 - Comparison of CO_2 - equivalent Xlam structure

Precast RC Panels	
Building Type	CO_2 - Eq Emissions [Kg CO_2]
Torino	22732
Catania	21977
Oslo	22830

Table 10.6 – CO_2 Equivalent Emissions of Precast RC Panels in reference to all cities

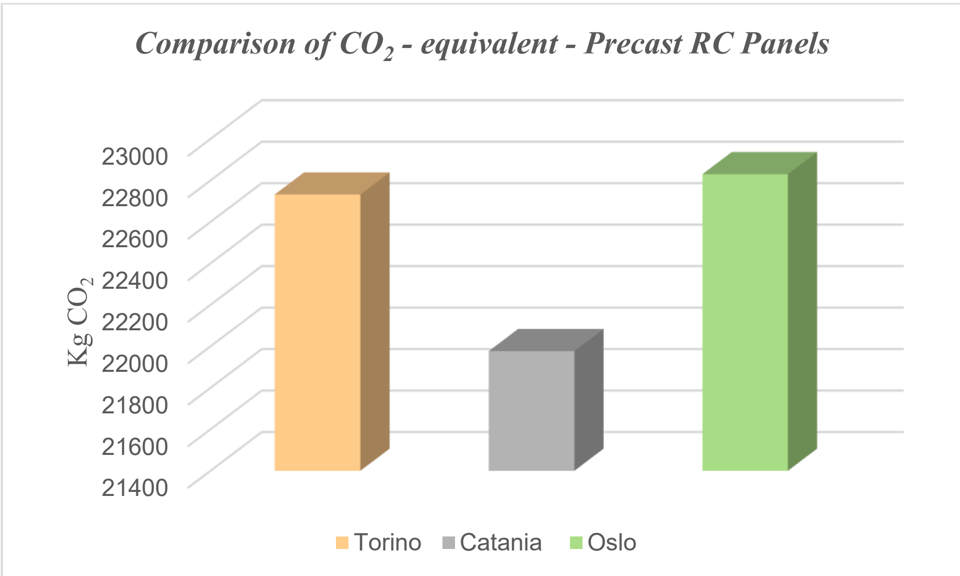


Figure 10.6 - Comparison of CO_2 - equivalent Precast RC Panels

10.3 CO_2 – uptake Comparison between Poroton and Precast Concrete Panels

In order to compare reliable results, we exclude Xlam structure. In fact, in reference to stratigraphies, we did not use cement – based material (according to EN 16757 we must not consider screeds or regularization layers) and so CO_2 uptake is only linked to grade beams.

However, if we observe numerical results, we understand how the CO_2 uptake of grade beams has the minor influence.

Building Type	CO_2 uptake
Poroton	6842.540
Precast RC Panels	3846.996

Table 10.6 – Comparison of CO_2 uptake

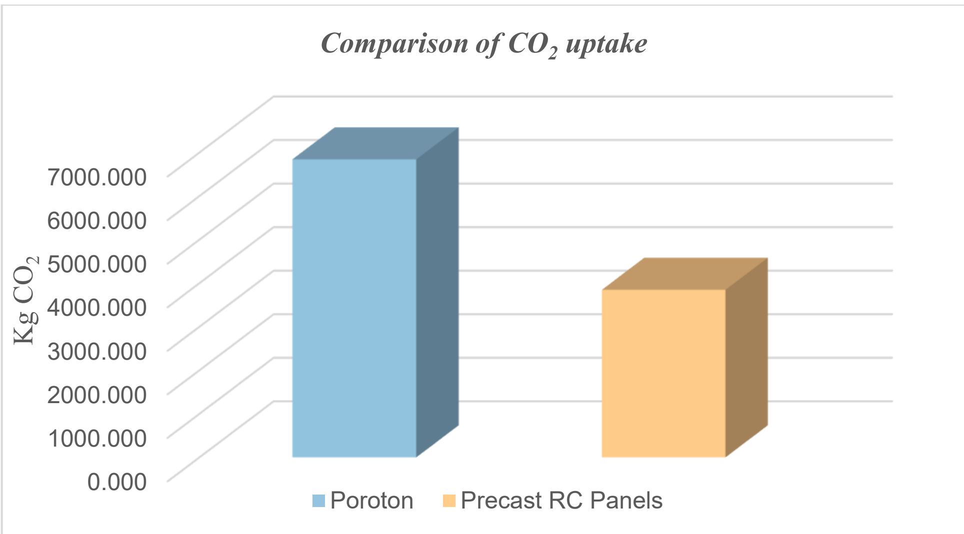


Figure 10.7 - Comparison of CO_2 uptake between Poroton and Precast RC Panels

From the graph, we can see how the amount of CO_2 uptake does not have a significant contribution in order to decrease CO_2 equivalent emissions if we consider the entire construction.

However, if we pay attention only on concrete and cement-based materials, we obtain the following results:

Building Type	CO_2 - Eq Emissions [Kg CO_2]
Poroton	13856.7
Precast RC Panels	9202.2

Table 10.6 – CO_2 emissions of only concrete and cement-based materials

In this case, it becomes necessary to consider the carbonation since it allows to reduce CO_2 equivalent emissions.

10.4 Costs comparison between Poroton, XLAM and Precast Concrete Panels

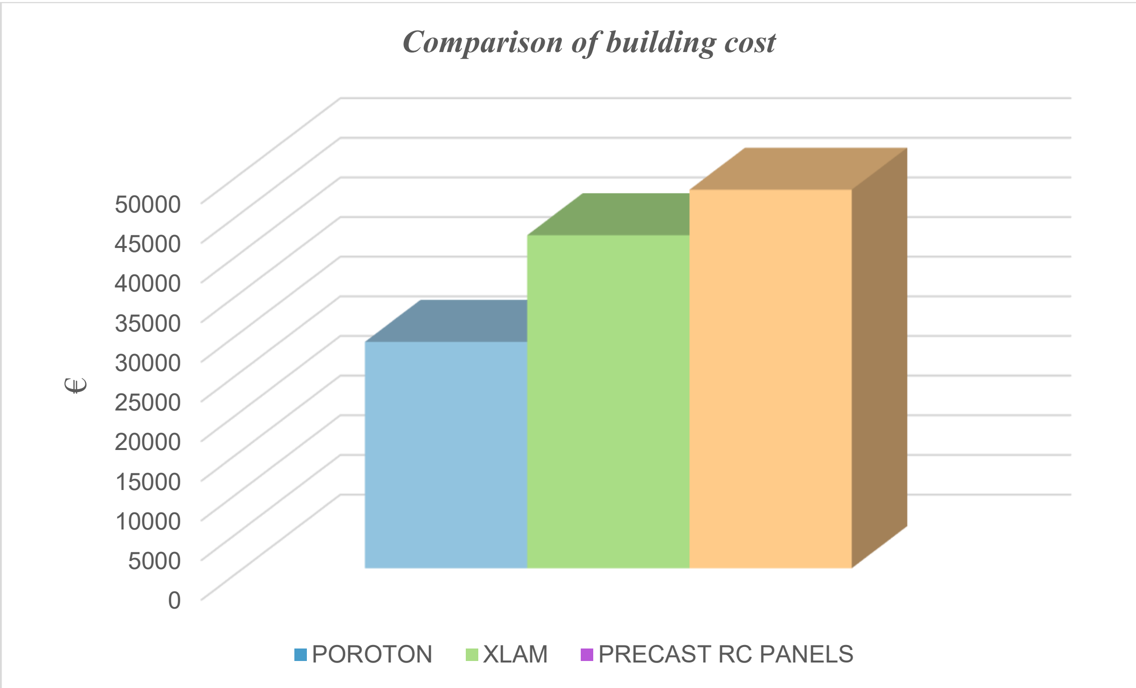


Figure 10.8 - Comparison of building cost

From the Figure we can see how the building in precast concrete panels is the most expensive. This probably depends on the greater complexity of processing which requires a more quality control. However, it is important to underline how the costs include only the cost of materials: we did not consider both labour's cost, VAT and the fee of the professional

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