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**Comparative analysis of the
economic and environmental
performance of a structure located
in seismic zone 3S**

Comparison between non-dissipative and dissipative design with
different mixes of ordinary and green concretes

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Abstract

In recent decades, awareness of environmental issues related to the construction industry has proven to be of great importance, particularly the impact of the use of concrete, which is the most popular material in this field thanks to its practicality, mechanical characteristics and cost. Concrete accounts for 8% of global greenhouse gas emissions. Looking at that from a different perspective, its share of pollution is four times greater than that of global aviation.

Awareness of this negative characteristic of concrete has culminated in an environmental policy tool through which public administrations integrate ecological criteria into all stages of the procurement process, known as GPP (Green Public Procurement), which promotes minimum environmental criteria (CAM). This has finally led to the marketing and use of green concrete on a large scale in public works, although its development on a private scale is still slow. These green concretes are characterised by a mixture prepared mainly from recycled aggregates and supplementary cementitious elements, making their environmental footprint much smaller. Their use substantially reduces Global Warming Potential (GWP), which indicates how much a mass of greenhouse gases (GHG) warms the atmosphere compared to the same mass of carbon dioxide. The combination of the reduction in this embodied carbon with the reduction in operational carbon emissions results in buildings' carbon footprint that are in line with the life cycle assessment standards of the Italian directives on emissions, which were created to comply with the standards of 2014/24/EU.

This gave rise to the driving idea behind this analysis of the environmental and economic impact of the engineering choices made regarding the type of concrete and the rationalisation of the volumes of the structurally resistant elements, combined with the seismic design choices made in terms of structural behaviour in relation to the satisfaction of limit state requirements. Going into detail, we opted for a comparative analysis of structures in seismic zone 3s located in Pinerolo (TO), related to the same architectural case study, that meet the technical standards for construction (DM infrastructure 17/01/2018) and relative explanatory circular (21/01/2019), although in different ways, dissipative and non-dissipative designs, with reference to the case of a structure built with non-dissipative behaviour using C25/30 non-green concrete, which involves a reference environmental impact level (GWP_ref) and a reference material cost (COST_ref). Specifically, the analysis was conducted on a total of 12 case studies, 3 different strength classes of green and non-green concrete for the two different types of seismic projects. Once the analysis is completed, the case study that optimise both global warming potential and cost is chosen.

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Contents

1	Introduction	1
1.1	Sustainability of concrete structures	2
1.1.1	Carbon Footprint of Concrete	5
1.1.2	Towards sustainable materials and design optimisation	10
2	CAM: Minimum Environmental Criteria	13
2.1	CAM 2026 as paradigm for private sector	17
2.2	Environmental Life Cycle Costing analysis	19
2.3	Environmental Product Declarations	22
3	Solutions and Developments of Sustainable Concretes	25
3.1	Composite Cements	29
3.1.1	Supplementary Cementitious Materials	29
3.2	Performance Optimization	30
3.3	Crushed concrete as recycled aggregate	31
3.4	Eco-Mechanical Analysis	32
4	Case Study	35
4.1	Comparative Analysis Framework	47
5	Comparative Analysis Assessment	57
6	Conclusion	73
	Bibliography	75
	Appendix A Architectural and Design Models	77
A.1	ND C25/30 STRUCTURAL MODEL	79
A.2	ND C28/35 STRUCTURAL MODEL	80
A.3	ND C32/40 STRUCTURAL MODEL	81
A.4	CDB C25/30 STRUCTURAL MODEL	82
A.5	CDB C28/35 STRUCTURAL MODEL	83
A.6	CDB C32/40 STRUCTURAL MODEL	84

List of Figures

1.1	Integrated sustainable solution for concrete	3
1.2	Comparison between Global cement industry's criteria air pollutants emissions and EU-27's total emissions	6
1.3	SO ₂ emissions intensity of cement industry for countries	6
1.4	Double vertical chamber heat limestone kiln (Maerz Kiln)	7
2.1	Modules and phases of the LCA study of the work	20
3.1	Supplementary cementitious materials of low carbon cement composites	27
3.2	Adimensional Diagram for Eco-Mechanic evaluation	33
4.1	Framing of the place of intervention	36
4.2	Second survey position	37
4.3	Location of the surveys performed on Google orthophotos	37
4.4	Table 3.2.III from NTC 2017	38
4.5	Final considerations of the geological report of the site	39
4.6	Basement roof slab	40
4.7	Foundation slab	41
4.8	Elevated structure	42
4.9	Roof's system	43
4.10	Elements and loads discretizations implementes in PROSAP	45
4.11	Graphical representations of the structural model.	46
4.12	Solid view FEM model	47
4.13	Top view of the fem model	47
4.14	Performance-based eco-mechanical analysis (GWP - GHG)	50
4.15	Performance-based eco-mechanical analysis (Price)	50
4.16	Prescriptive eco-mechanical analysis (Minimum Total Recycled Content)	51
4.17	Performance-based environmental-cost analysis	52
5.1	FEM model of the structure used in parametric analysis	58
5.2	Table 7.3.I from NTC 2018: limits on the behavior factor	58
5.3	Horizontal's Elastic Spectra	60
5.4	Horizontal's Design SLV Spectrum for Non Dissipative design	60

5.5	Horizontal's Design SLD and SLV spectra for CDB design	60
5.6	Structural resistant elements of the FEM model in axonometric view	61
5.7	Structural resistant R.C. elements of the FEM model in axonometric view	61
5.8	Transparent solid axonometric view of the R.C. frame	62
5.9	Solid axonometric view of the R.C. frame	62
5.10	View of the foundation's system in the solid FEM model	62
5.11	Quantities Estimates of the structural configurations	63
5.12	Values of the $ELCC_{A1-A3}$ - based cost and environmental impacts	64
5.13	$ELCC_{A1-A3}$ comparative results for ordinary concrete mixes	65
5.14	$ELCC_{A1-A3}$ comparative results for green concrete mixes	65
5.15	Percentage variation per structure typology relatively to ordinary mixes	67
5.16	Parametric Comparative EI and CI indexes with reference to ND C25/30 ordinary concrete mix case	70
5.17	Parametric Comparative adimensional diagram for Environmental- Cost assessment	70

List of Tables

1.1	Life cycle assessment indicators for conventional concrete based on literature ranges	10
4.1	Seismic design parameters	38
4.2	Seismic parameters at limit states	38
4.3	Seismic coefficients for slope stability	39
4.4	Reference sites for seismic hazard	39
4.5	Environmental and economic performance of the analysed concrete mixes (data from EPD)	49
4.6	Structural configurations analysed in the $ELCC_{A1-A3}$ -based assessment	54
5.1	Behavior factor q adopted in the analyses	59
5.2	Environmental and economic parameters adopted for reinforcing steel	63
5.3	Percentage variation of total concrete volume between ND and CDB configurations	63
5.4	Percentage variation of reinforcing steel quantities between ND and CDB configurations	64
5.5	ORDINARY CONCRETE MIXES: Percentage variation of Cost and GWP for CDB configurations with respect to the corresponding ND configuration.	66
5.6	GREEN CONCRETE MIXES: Percentage variation of Cost and GWP for CDB configurations with respect to the corresponding ND configuration.	66
5.7	ND CONFIGURATIONS: Percentage variation of cost and GWP for GREEN mixes with respect to the corresponding NON-GREEN mix .	67
5.8	CDB CONFIGURATIONS: Percentage variation of cost and GWP for GREEN mixes with respect to the corresponding NON-GREEN mix	68
5.9	Recycled content associated to the analysed structural configurations.	68
5.10	Percentage variation of total recycled content for CDB configurations with respect to the corresponding ND configuration.	69

Chapter 1

Introduction

The built environment plays a central role in the global environmental debate, as it is responsible for a significant rate of resource consumption and environmental impact throughout its life cycle. Buildings and civil structures require large quantities of raw materials, energy, and water, not only during construction phases but also throughout their operational, maintenance, and end-of-life phases; as a result, the construction sector is widely recognised as one of the most resource-demanding and polluting segments of human activity.

In recent decades, much more attention has been dedicated to reducing the operational energy demand of buildings, in particular, through improved thermal performance, energy-efficient systems, and the integration of renewable energy sources; these strategies have led to significant reductions in **Operational Carbon Emissions**. Then the focus has been shifted to another critical component of environmental impact: **Embodied Carbon**. Embodied carbon refers to the cumulative greenhouse gas emissions generated throughout the life cycle of building in terms of materials and components, from the extraction and processing of raw resources to the stages of manufacturing, transportation, construction, maintenance, and end-of-life scenarios such as demolition, and/or recycling. As operational emissions are progressively reduced through energy-efficient design strategies, embodied carbon increasingly emerges as a major contribution to the overall environmental footprint of buildings, it results understandable that construction materials play a massive role. Structural materials such as concrete, steel, and timber largely determine the embodied environmental impact of a building, due to the quantities involved and the energy-intensive processes required for their production. Among these, concrete is by far the most widely used material worldwide, owing to its durability, and cost-effectiveness. However, its extensive use also, largely, contributes to global Greenhouse Gases emissions, mainly due to cement production, the Carbon Footprint of this material has proven to be massive, seeing as the latter contributed to 8% of global emissions in 2021, with around 4 billion tons of concrete produced in that year alone. The Greenhouse Gases are atmospheric gases that trap heat, causing

global warming. The main ones include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases.

Production of concrete is more carbon intensive than the aviation industry, air travels only accounts for 2% of global emissions, the exact fourth in value than concrete in 2021.

Although most important actions and efforts, within this context, have traditionally concentrated on large-scale infrastructures and public buildings where greater resources are available, while small-scale project must often contend with tighter boundaries. Small-scale constructions and non-public structures collectively represent a significant rate of the built environment; individually, their environmental impact may appear limited; however, when considered cumulatively, their contribution becomes substantial. For this reason, addressing environmental performance at the scale of modest buildings is relevant to achieve meaningful reductions in overall environmental impact. Moreover, small-scale projects often operate under different constraints compared to large public works, such as: budget limitations, simplified design processes, and standard construction practices that frequently discourage the adoption of innovative or more refined solutions. As a consequence, environmental considerations are sometimes treated as secondary objectives rather than integral components of the design process. This gap highlights the importance of exploring strategies that can improve environmental performance without undermining economic feasibility or applicability.

In this sense, environmental sustainability within the built environment cannot be reduced to an isolated measure; instead, it requires a holistic approach that considers materials and structural efficiency by forward-thinking design choices. To recognise this complexity is a fundamental step towards identifying realistic and effective solutions, particularly in smaller projects, where opportunities for optimisation are inherently constrained.

This broader perspective sets the foundation for the present work, which focuses on the environmental impact of structural design choices and material selection. By narrowing the scope to concrete structures and exploring how material innovation and structural optimisation can jointly contribute to reduce this impact within its cost correlation.

1.1 Sustainability of concrete structures

Since we clarified that concrete has a key role in today's buildings' construction and represents a major treat in shaping its **Environmental Footprint**, even though its widespread is closely linked to a combination of practical and technical virtues as high compressive strength, durability, adaptability to complex geometries, and relatively low initial costs. These characteristics have made concrete the default structural material for a large range of applications, from small residential buildings

to major infrastructure projects.

The environmental relevance of concrete arises from the processes and resources required for its production, in particular the manufacture of cement and the extraction, processing, and transportation of aggregates. Cement production is an energy-intensive process and a major source of global CO₂ emissions. The reasons are, mainly, both the chemical process of Calcination of Limestone, the high-temperature requirements of the Clinker Production, any less, water usage for mix and cure and emissions via transportation. As a consequence, concrete structures are the final product of material production and transportation processes with high emission intensities.

Concrete constitutes the most relevant share of embodied carbon associated to buildings and civil structures. Given the large volumes typically involved, even small improvements in mix design, material efficiency and/or structural optimisation can lead to meaningful reductions in overall emissions. Here comes a new goal to achieve: sustainability-oriented interventions. The objective is to reduce embodied CO₂ emissions without compromising structural performance and the construction practices established within the building sector.

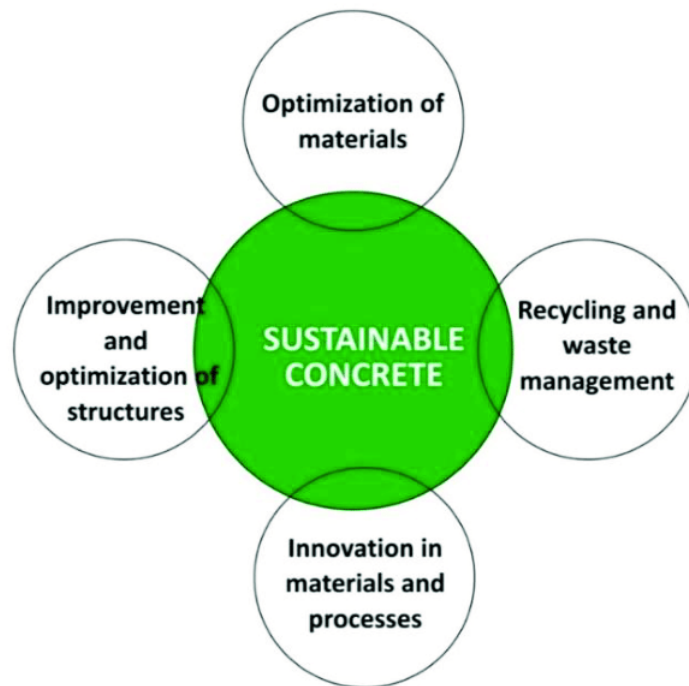


Figure 1.1: Integrated sustainable solution for concrete

These increasing concerns over the environmental impact had led both the scientific community and the European institutions to converge the need for generally

accepted criteria in the construction industry. The growing availability of life-cycle assessment (LCA) data from built environment in the past years, together with the structured researches on understanding embodied carbon, made the European Union to progressively integrate the environmental footprint of materials considerations into public procurement policies through the Directive 2004/18/EC [9] on the coordination of procedures for the award of public works contracts, public supply contracts and public service contracts; later updated and expanded by **Directive 2014/24/EU** [10] on public procurement and repealing Directive 2004/18/EC [9]; such that environmental criteria have been formally included as part of the award conditions for public contracts.

This process has culminated in the development of the so-called Green Public Procurement (GPP) framework and in the promotion of Minimum Environmental Criteria (MEC). Green Public Procurement represents a policy instrument aimed at systematically integrating environmental considerations into public purchasing decisions. Within the European Union, GPP is used as a strategic lever to reduce the environmental impacts associated with public works, goods, and services, while remaining fully consistent with the fundamental principles governing public procurement, such as transparency and competition. To support the implementation of this approach, the European Commission has developed a set of GPP criteria that define environmental requirements for specific sectors and product groups. In several Member States, these criteria have been transposed into Minimum Environmental Criteria, which establish a mandatory baseline level of environmental performance that must be met in public tendering procedures.

The introduction of GPP marks a shift from a purely economic evaluation of public procurement towards a more holistic approach that accounts for environmental externalities over the entire life cycle of products and services. Rather than focusing exclusively on the lowest initial cost, GPP promotes life-cycle thinking, encouraging contracting authorities to consider resource efficiency, emissions, durability, maintenance, and end-of-life impacts. Minimum Environmental Criteria play a crucial role in this framework by translating broader sustainability objectives into concrete and enforceable requirements. By setting minimum thresholds, MEC ensure a consistent level of environmental ambition across public tenders, reducing uncertainty for economic operators and fostering market demand for environmentally preferable solutions. In this sense, GPP and MEC not only function as regulatory tools, but also as market-shaping instruments capable of driving innovation and accelerating the transition towards more sustainable production and consumption patterns.

In the specific case of building sector, among the materials most affected by these developments, concrete stands out both for its ubiquity in construction and for the scale of its environmental impact. As one of the most widely used and emission-intensive materials in the built environment, concrete has naturally become a primary target for regulatory efforts. Subsequently, through the cement industry

and the scientific literature as well, the so called Green Concretes have been objects of development.

1.1.1 Carbon Footprint of Concrete

Let's, now, see in detail the Carbon Footprint of concrete that brings us on developing this construction material in a greener way and subject his use to European regulations promoting environmental sustainability and life cycle assessment.

Concrete Production, and in particular the manufacture of its main binding component, the Portland Cement, is considered the most environmentally burdensome stage of the construction industry. Its really high impact arises from a combination of many factors:

- the extremely high energy demand required by the process;
- an intrinsic source of CO₂ emissions derived by the chemical process of calcination;
- impacts related to aggregate extraction and transportation to the construction sites, any less depletes of resources;
- highly demanding water usage, as the process requires it to mix and cure the concrete. This means major constructions go trough excessive water supplies that could serve in other contexts.
- high air pollution, as additional polluting molecules like sulfur dioxide and nitrogen oxide are emitted.

Studies [11] about performing benchmarks on four of major criteria air pollutants were made in few past years: Sulfur Dioxide SO₂, Nitrogen Oxide NO_x, Particular Matter (PM), and NON-Methane Volatile Organic Compounds (NMVOC), emitted form production of cement in 14 countries both by onsite emissions related to process and fuel combustion in cement plants (direct emissions) and offsite emissions associated with electricity used by cement plants that is caused from electricity generation in the power sector (indirect emissions). It results in NO_x was the highest emitted criteria air pollutant from the cement industry globally, whereas the NMVOCs are the lowest emitted ones. To provide a sense of scale, the global cement industry's criteria air pollutants emissions are compared with EU-27's total emissions in 2019. The SO₂ emissions from the global cement industry in 2019 were 3% higher than the overall total SO₂ emissions of the EU-27 region. Emissions of NO_x from the global cement industry were 36% lower than the EU-27's overall NO_x emissions in 2019. The PM emissions of global cement industry were 27% lower than the overall PM emissions from EU-27 region.

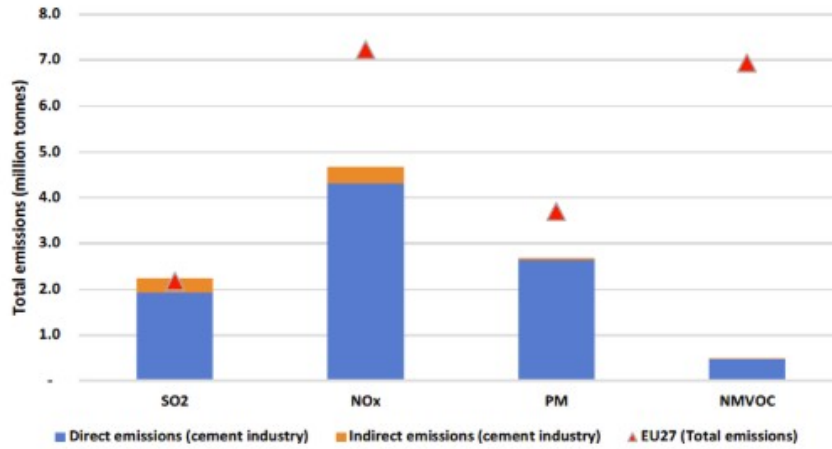


Figure 1.2: Comparison between Global cement industry’s criteria air pollutants emissions and EU-27’s total emissions

Italy results one of the most air polluting issuer between the global ones. Future reductions in criteria air pollutants will require stricter adoption of pollution control technologies in cement plants, as well as in the power sector, alongside improvements in fuel consumption efficiency and switching to lower-emission fuels.

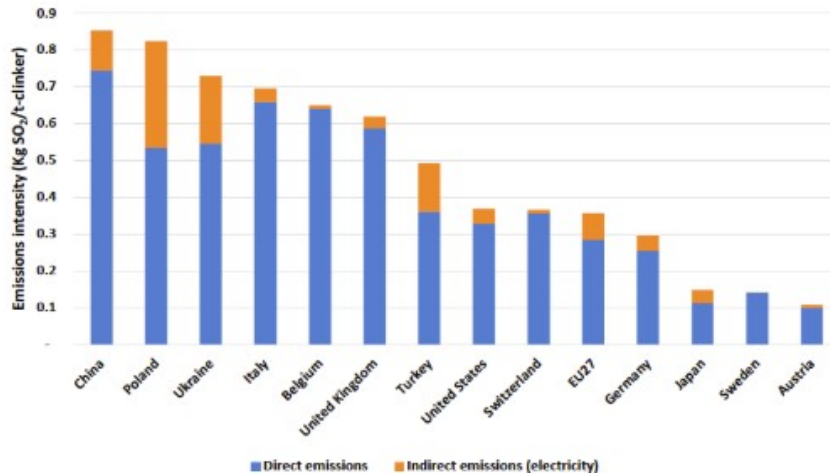
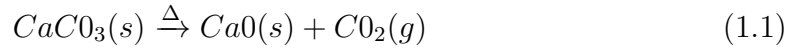


Figure 1.3: SO₂ emissions intensity of cement industry for countries

Most critical aspect is production of clinker, an intermediate material obtained in rotatory kilns where a carefully homogenised mixture of limestone (CaCO_3), clay as a source of alumino-silicate, and other minerals are heat at temperatures of around 1450°C , these are required to aggregate together the products of the chemical reaction at their sintering temperature. These high temperatures are achieved through

combustion of fossil fuels such as coal, petroleum coke (solid by-product of petroleum refining with a high carbon content), and natural gas. Current cement kilns consume between **3-6 GJ of fuel per tonne of clinker produced**, with additional electrical energy required for grinding and material handling.

Beyond the merely energy consumption, big share of CO₂ emission is intrinsic to the chemistry of the process. During calcination process, Calcium Carbonate CaCO₃ decomposes into Calcium Oxide CaO, realising CO₂ as an unavoidable by-product.



The free CO₂ released accounts for approximately 60 – 70% of direct emissions from clinker production, while the combustion of fossil fuels contributes the remaining 30 – 40%.

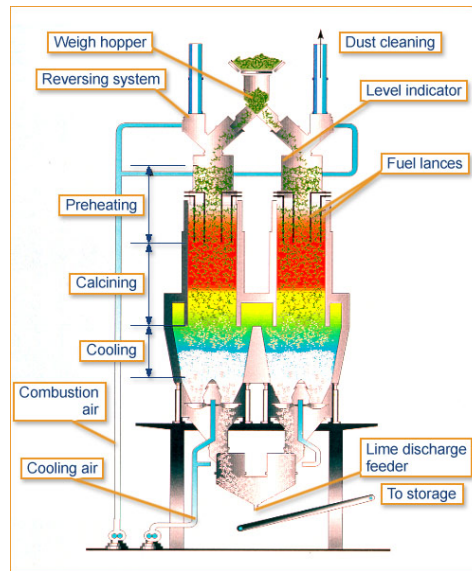


Figure 1.4: Double vertical chamber heat limestone kiln (Maerz Kiln)

Estimated from multiple life cycle assessments total Carbonic Dioxide from cement production arrives at nearly 0.65 – 0.92 tonnes of CO₂ released per tonne of cement produced under typical industry conditions.

Also, the extraction and processing of aggregates: sand, gravel, and crushed stone; contribute significantly to the life cycle impacts of concrete, particularly in terms of land use and ecosystem disruption, and particulate emissions.

According to the Joint Research Centre (JRC), aggregate production contributes approximately 0.004 – 0.01t per tonne of processed material, with additional impacts in non-climate categories, since it is source of dust, noise, vibration, and potential interference with surface and groundwater systems [6]. These effects are especially relevant in regions where quarries are located near sensitive ecological

areas or densely populated zones. Furthermore, transportation to construction sites adds an additional layer of emissions; cement and aggregates are high volume and low value materials, typically transported by trucks over distances ranging 50 km in European Contexts. Depending on the logistics configuration and vehicle load factors, the transport phase can account for 5 – 10% of the total carbon dioxide emissions per tonne of concrete [7]. In specific case studies, particularly in remote or urban delivery conditions, the transport phase has been shown to dominate the cradle-to-gate emissions profile of certain concrete mixes, underscoring the importance of local sourcing and optimized supply chains.

From a resource depletion standpoint, aggregates are among the most extracted raw materials worldwide, with global consumption estimated at over **50 billion tonnes** per year [15]. While they are not always classified as scarce resources in the conventional sense, extracting them at unsustainable rates contributes to habitat loss, hydrological changes and irreversible geomorphological transformations. Therefore, even modest reductions in aggregate use, achieved through mix design optimisation, the use of recycled aggregates, or efficient structural design, can have a disproportionately positive effect on environmental performance.

In addition to greenhouse gas emission, significant use of water resources is involved, this is required at multiple stages of the concrete life cycle particularly for mixing and curing. During mixing, water acts as a reactant in the hydration process that enables cement to harden and develop strength; during curing, large quantities of water are often applied to maintain moisture conditions that are necessary to achieve design strength and durability. The water footprint concept, as defined by ISO standards, quantifies the total volume of freshwater used directly and indirectly throughout a product’s life cycle. While there is considerable variation in the inventory data on water use in concrete production across different studies, it is recognised that concrete places significant demand on local water resources, particularly in regions subject to water scarcity. By 2050, up to 75% of the projected increase in concrete water demand is expected to occur in areas prone to water stress. This emphasises the importance of managing water resources in the cement and concrete industries, and the need to optimise mix design and manufacturing processes to reduce water consumption. [20]

From an air quality perspective, the manufacturing of cement and concrete also generates emissions of pollutants such as sulphur dioxide (SO_2) and nitrogen oxides (NO_x), which contribute to smog formation, acidification, and adverse respiratory health effects. These emissions mainly arise during high temperature combustion and raw material processing. The high temperatures of rotary kilns used in clinker production, which can exceed 1450°C , create conditions for the formation of thermal NO_x from combustion air and fuel-related NO_x from nitrogen present in fuels. The sulphur content of raw materials and fuels can oxidise to SO_2 under kiln conditions.

Emissions are influenced by the composition of feedstocks and the presence of sulphides. This can lead to measured concentrations of sulphur oxides in exhaust gases of up to $\sim 1.2 \text{ g/m}^3$ in some contexts, without abatement controls. [19]

These additional pollutants, along with particulate matter ($PM_{2.5}$ and PM_{10}), which are emitted during the handling of raw materials and kiln operations, contribute to the degradation of local and regional air quality. This necessitates the use of advanced control technologies, such as staged combustion and NO_x reduction systems, in order to comply with environmental limits and protect public health. Together, water use and air pollution pose significant environmental challenges related to concrete production, which extend beyond carbon emissions. This underscores the importance of comprehensive life cycle assessments and resource-efficient strategies in sustainable construction.

Table 1.1: Life cycle assessment indicators for conventional concrete based on literature ranges

Impact	Unit	Range	Notes
Global Warming Potential (GWP)	kg CO ₂ -eq/m ³	200–300	Cement production accounts for most of total GWP; lower values typically reflect higher SCM substitution.
Primary energy demand (non-renewable)	MJ/m ³	1400–2000	Mostly related to clinker production and kiln fuels; aggregates contribute marginally.
Primary energy demand (renewable)	MJ/m ³	50–100	Sensitive to the national electricity mix and to the use of alternative fuels.
Total primary energy use	MJ/m ³	1500–2200	Often reported in EPDs; definitions can vary slightly across PCRs.
Freshwater consumption	m ³ /m ³	0.3–0.6	Includes mixing water and upstream processes; accounting differs across datasets.
Total raw material consumption	kg/m ³	2300–2450	Aggregates are typically 75–80% by mass; binder is smaller by mass but dominant in impacts.
Cement content (typical)	kg/m ³	260–340	Strongly correlated with strength and durability requirements; main driver of embodied impacts.
Secondary materials (SCM/recycled inputs)	kg/m ³	30–100	SCMs (e.g., GGBS, fly ash) generally reduce GWP while supporting circularity targets.

Notes: Functional unit: 1 m³ of ready-mixed concrete (C25/30–C30/37). System boundaries: cradle-to-gate (A1–A3). Ranges are indicative and reflect mix design and regional variability.

Table 1.1 reports indicative ranges of cradle-to-gate (A1–A3) life cycle assessment indicators for conventional ready-mixed concrete (C25/30–C30/37) per m³. Values are presented as ranges to reflect the inherent variability associated with mix design (cement content and SCM substitution), regional production conditions, and differences among published EPDs and LCA datasets.

1.1.2 Towards sustainable materials and design optimisation

In the context of sustainable construction, concrete is a key material given its widespread use and significant environmental footprint, which is mainly due to

cement production. From a life-cycle perspective, the environmental impact embodied in concrete structures often dominates the overall balance, particularly in small-scale constructions where operational emissions are comparatively limited. Therefore, strategies aimed at reducing the environmental impact of concrete must address both material composition and the way structural demand is translated into material use.

Within this framework, concrete emerges as a material with significant environmental impact, but also as a key means of mitigating this impact when combined with material innovation and structural optimisation. Rationalising structural cross-sections and aligning mechanical performance with actual demand reduces unnecessary material use, enhancing the effectiveness of low-impact, or 'green', concretes. This is particularly relevant for small-scale constructions, where simplifications to the design and conservative assumptions can lead to high material consumption.

This innovation has two perspectives, material and structural efficiency, that form the basis for eco-friendly structural design. In this sense, structural optimisation should not be interpreted merely as a quantitative reduction in material volumes, but rather as a qualitative process that aims to distribute resistance, stiffness and ductility efficiently, **in line with performance based design principles**. This approach emphasises the active contribution of structural engineering to sustainability objectives rather than its passive reception of material-level solutions.

The way environmental performance in the construction sector is regulated is based on this conceptual and methodological background. The definition of minimum environmental requirements is the outcome of a gradual and cumulative process of knowledge consolidation. Over time, scientific research has quantified the environmental impacts associated with construction materials and structural systems, particularly through life-cycle-based assessments. In parallel, technical standards have translated these findings into harmonised methodologies, performance indicators and verification procedures, thereby enabling environmental evaluations to be both comparable and reliable.

At the same time, outcome-oriented design has demonstrated that reducing environmental impact is not limited to material substitution, but can also be achieved through informed structural design choices. Studies on structural optimisation, performance-based design and material efficiency have shown that environmental objectives can be incorporated into traditional engineering practices without compromising structural safety or functionality.

The regulatory synthesis of these converging developments is therefore represented by Minimum Environmental Criteria. Rather than introducing abstract or arbitrary constraints, they formalise solutions and performance thresholds that have already been validated from scientific, technical and design perspectives. Regulatory instruments bridge research and practice, transforming knowledge into requirements

for more sustainable construction. Consequently, understanding the evolution of sustainable material practices and design strategies is essential to properly contextualise the role of regulatory criteria as tools for reducing environmental impact through design choices.

Adopting green concretes that comply with the Minimum Environmental Criteria (Criteri Ambientali Minimi, CAM), as defined by Italian national legislation, is an opportunity within this regulatory framework to reduce embodied CO₂ emissions and improve the life-cycle environmental performance of structures. Material substitution has limited environmental benefits, more substantial reductions in environmental impact can be obtained through an integrated design approach, in which structural efficiency and cross-section optimisation are coherently pursued in both dissipative and non-dissipative structural systems.

The implementation of such an integrated approach, however, entails relevant implications. These include increased effort during the design phase, the need for more refined analytical and numerical models, longer processing times, and potentially higher design costs. In addition, questions arise regarding practical feasibility and on-site implementation, particularly when optimisation strategies lead to non-standard solutions or stricter construction tolerances.

In this context, the present work aims to investigate, from a transversal perspective, how the integration of low-impact concrete technologies, CAM criteria, and structural optimisation strategies can provide a balanced response to the sustainability demands of small-scale constructions. The objective is to assess the extent to which this synergy can effectively contribute to material reduction while balancing environmental benefits, increased design complexity, and practical implications for construction companies.

Chapter 2

CAM: Minimum Environmental Criteria

Given the considerable extent of the overview of the environmental impact of concrete and the brief mention of the possibility of using this material in a more environmental friendly way in relation to an holistic performance-based design aimed at reducing its embodied carbon, we can now move on to examine how European Green Public Procurement legislation has laid the foundations for national legislation establishing criteria for the construction sector. In this context, national frameworks such as the Italian Criteri Ambientali Minimi (CAM) have emerged as operational tools to translate European sustainability principles into measurable, enforceable requirements at the material and design level. The following chapter explores the CAM in detail, focusing on their implications for the use of concrete in small-scale construction projects. Let's clarify the evolution of the regulatory framework on sustainability and implications for structural concrete.

- We have the first European public procurement directives in 2004, particularly Directives 2004/18/EC and 2004/17/EC [9], which were mentioned above as they paved the way for the formal integration of environmental considerations into public procurement. While these directives are not specifically aimed at environmental sustainability, they introduce a significant conceptual shift, which is the replacement of the lowest price criterion with the most economically advantageous bid. This allows contracting authorities to consider qualitative factors alongside purely economic aspects. For the first time, this step opens up the possibility of considering environmental, performance and durability criteria in tender procedures. In the construction sector, and particularly in relation to structural concrete, this marks the beginning of a shift in focus beyond mere mechanical resistance to include environmental economic evaluation criteria such as the structure's durability over time, maintenance requirements, and environmental compatibility with the materials used.

- Then came the introduction of a comprehensive global framework in 2015, with the United Nations meeting that signed the 2030 Agenda for Sustainable Development [2]. The latter introduced 17 common sustainable development goals (SDGs), recognizing the strategic role of construction, which has a key role in goals 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), and 13 (Climate Action). Particular attention was paid to concrete, which is the world's most widely used building material. The 2030 Agenda involves a thorough review of its life cycle (LCA), focusing on CO₂ emissions linked to the production of its binder (cement), the consumption of natural resources, and the end-of-life management of structures. This requires not only sustainable architecture, but also targeted, pragmatic structural choices.
- Even before the adoption of Agenda 2030, the European Union had already updated its procurement regulations in line with its principles through Directives 2014/24/EU, 2014/25/EU and 2014/23/EU. These directives definitively integrated sustainability into public procurement by introducing new tools. The assessment of environmental impacts throughout the entire life cycle of the structure is established, as well as the mandatory nature of environmental criteria in contracts. Notably, they feature a methodology for conducting economic analyses that assess the total costs of a product throughout its entire life cycle, from conception to final disposal. This methodology is known as Life Cycle Costing (LCC). This methodology is used to compare similar products, define sustainable public procurement (Green Public Procurement) and reduce operating costs. Unlike Life Cycle Assessment (LCA), which assesses environmental impact, LCC focuses on the monetary quantification of these impacts and associated costs.
- These updates to European directives include Green Public Procurement or GPP, a concept that has already been introduced. It is a European policy that directs public spending towards environmentally friendly goods and services. Rather than being an autonomous regulation, it is an operational tool applied in practice through specific criteria. Consequently, it encourages the use of recycled materials and reducing climate-changing emissions, nevertheless the goal is improving the durability and maintainability of structures. The concrete sector is thus boosted by the rapid adoption of cements with lower clinker content, recycled aggregates, additives and technological solutions that extend the lifespan of structures.
- So, in 2016, the Italian Ministry of the Environment implemented the 2014 European directives by launching the 2016 Public Procurement Code. Minimum environmental criteria (MEC) became mandatory for public procurement. These criteria are established by the Action Plan for Environmental

Sustainability in Public Administration Consumption (PAN GPP), a regulatory framework that promotes Green Public Procurement (GPP) and the objectives of the 2030 agenda in Italy, and are applied to the Italian construction sector. They represent immovable constraints on structural choices and materials used, thereby reducing the environmental impact of construction. To demonstrate compliance with CAM, companies must adopt an integrated strategy that includes environmental certifications such as ISO 14001, the drafting of technical documentation to demonstrate the use of sustainable techniques and products, and the implementation of strategies for reuse, recycling, or responsible disposal. Compliance with CAMs therefore becomes not only an obligation, but also an opportunity for innovation. The market is growing, and public administrations are increasing their demand for sustainable products and services. Furthermore, sustainable strategies often lead to energy savings and greater efficiency. The binding criteria for public procurement therefore become an important feature in the private sector as well.

Now let's analyze Italian regulations in detail. The introduction of Minimum Environmental Criteria in the construction sector was first systematically organized with the CAM Construction Decree of October 11 2017, which represents the decisive transition from the enunciation of sustainability principles to their concrete technical application in public procurement. Sustainability thus becomes an integral part of the design process, no longer as an optional element but as a structural criterion for choice. In the context of reinforced concrete works, CAM 2017 marks a significant cultural shift. Structural materials are now evaluated based not only on mechanical performance and safety at limit states, but also on durability, the environmental quality of raw materials, and construction site management. Concrete is now being considered as part of a complex system whose environmental impact depends on more than just the operational phase of the structure; it also depends on cement production processes, the extraction of aggregates, and installation methods. This approach is further reinforced by the enactment of the Construction Decree (CAM) on 23 June 2022, which significantly updates and expands the previous regulatory framework. The 2022 decree is part of a European context that is strongly focused on the ecological transition and climate neutrality, with the principles of the circular economy and life cycle assessment being more explicitly integrated. In this context, durability plays a strategic and cross-cutting role; a concrete structure that is designed to have a long service life and that has correctly defined exposure classes, adequate concrete cover and strict quality control during construction is a sustainable solution in itself. Extending the structure's useful life reduces the frequency of maintenance interventions and postpones the replacement of structural elements, resulting in reduced resource consumption and associated emissions. Structural sustainability is therefore directly linked to the principles of good design that are already present in technical regulations but are now reinforced

by a binding environmental framework.

The regulatory framework outlined by the CAMs has been further consolidated with the entry into force of Legislative Decree 36/2023. This does not introduce new environmental objectives, but rather strengthens their effectiveness through a comprehensive reorganization of the procurement and design process. The new Code gives sustainability a cross-cutting role by integrating it permanently into the decision-making and operational phases of public procurement rather than treating it as a set of specific requirements.

The Environmental Criteria for Construction (CAM Edilizia) have been updated and published in the Official Gazette by ministerial decree on 24 November 2025. They will come into force on 2 February 2026, replacing and definitively repealing the 2022 edition and its 2024 amendment. The new 2026 CAM Edilizia introduces significant changes to both the technical content of the environmental criteria and their practical application within the design and public tender process.

The criteria for design services, construction management, and public building works have been completely revised to align them with the latest regulatory and technological developments, as well as the dynamics of the materials market. Consequently, the new regulatory framework definitively moves away from a purely prescriptive approach towards a systemic view of construction, in which sustainability is assessed throughout the entire life cycle and translated into design choices that can be verified from the initial stages onwards, in fact, specific criteria relating to the traceability of raw materials, minimum recycled content and the availability of recognised environmental certifications (EPD) are becoming increasingly important. For structural materials, this implies a significant change: concrete, steel and other structural materials are no longer selected solely on the basis of mechanical performance and immediate cost, but are also evaluated in terms of their environmental impact and compatibility with circular economy models. Durability is no longer just a technical requirement aimed at ensuring safety at limit states; it has become an environmental parameter in its own right, directly linked to reducing resource consumption and emissions associated with maintenance and replacement work. Structural design choices take on strategic importance, as they have a decisive impact on the overall environmental balance of the project.

A further element of discontinuity with the past is represented by the explicit integration of Environmental Product Declarations (EPDs) and Life Cycle Assessment (LCA) analyses into the design process. These tools, which were previously voluntary or supportive references, have become structural components of the design process, allowing for a quantitative assessment of the environmental impacts associated with the materials and construction solutions adopted. This approach is particularly significant for the comparative analysis of structural materials, as it makes it possible to compare design alternatives not only in terms of performance and cost, but also in terms of environmental benefits in the medium term. This

framework also includes strengthening the role of the Design Guidance Document (DIP), which acts as a tool through which the contracting authority clearly defines the environmental objectives of the project in advance, guides the project from the early stages, reducing the risk of inconsistent choices or ex post environmental assessments and promoting an integrated approach between architectural, structural and building services design. Building Information Modelling (BIM) design is now mandatory, moving from a bonus criterion to a contractual clause. This digitisation of the design process allows for greater traceability of materials, more effective control of quantities and better integration between structural modelling and environmental assessments, making both LCA analyses and economic estimates throughout the life cycle more reliable.

The significance of this update lies in the structuring of a comprehensive operating model capable of integrating environmental criteria, technical requirements and economic assessments within a verifiable design process.

2.1 CAM 2026 as paradigm for private sector

Extending CAM 2026 to all types of public construction contracts, including those relating to design, construction management, execution and maintenance activities, reinforces the public sector's role as a testing ground for innovative sustainability policies. Public construction also serves as a methodological reference for the private sector in this sense, which, although not formally bound by the CAM, can adopt its criteria for comparative analyses and technical-economic assessments.

Clearly, the paradigm is not only methodological in nature. In fact, CAM 2026 provides a set of tools, indicators and procedures that can be voluntarily adopted in private projects to improve the quality of technical choices and make different design alternatives comparable on an objective and measurable basis. This framework is useful for environmental and cost assessments in private construction, especially for comparing alternative structural solutions.

One of the most significant aspects in this perspective is the approach to structural materials. Within the framework outlined by CAM, the selection of materials is entrusted to an analysis system that considers the entire life cycle of the work. This is also fully applicable to private construction, where the adoption of similar criteria makes it possible to overcome the logic of short-term optimisation, introducing more informed assessments by integration, from CAMs, of quantitative tools such as life cycle assessment (LCA) and Environmental Product Declarations (EPDs). This allows alternative structural materials to be compared on the basis of measurable indicators, such as climate-changing gas emissions, resource consumption and embodied energy, making objective comparison possible even in the absence of regulatory requirements; these analyses can be accompanied by economic assessments throughout the life cycle, allowing the higher initial costs of some solutions to be

weighed against the environmental and management benefits that can be achieved in the long term. The comparison can also concern the emphasis placed by CAMs on the durability of structures, in the public sector, durability is explicitly recognised as an environmental factor, as it is directly related to the reduction of maintenance interventions and the minimisation of resource consumption over time. This principle is also fully applicable to private construction, where structural design geared towards the useful life of the building allows for the optimisation of environmental impact and overall management costs, thus, structural design becomes one of the main tools for pursuing sustainability, transforming requirements traditionally linked to safety into environmental and economic assessment parameters. The digitisation of the design process through BIM technology represents a further area of transfer to the private sector, in fact, the use of information models allows for the consistent integration of structural information, environmental data and material quantities, facilitating both comparative analysis and cost control; this support for design decisions makes it possible to replicate the transparency and traceability requirements of public procurement, improving the reliability of technical and economic assessments.

The voluntary adoption of CAMs allows comparative analyses to be set up based on uniform parameters, taking into account structural performance, life-cycle costs and environmental impacts simultaneously.

In this evolving context, the update of the CAM Edilizia (Minimum Environmental Criteria for Construction) takes on particular significance with regard to concrete. For the first time, the regulatory framework does not merely define general criteria for the sustainability of construction materials, but introduces specific guidelines that directly affect the composition of mixtures, the origin of raw materials and the environmental performance of structural concrete; due to volumes used and the emissions impact associated with cement production, the requirements relating to the use of recycled and recovered materials are being strengthened, particularly with regard to aggregates, encouraging the partial replacement of natural resources with materials from certified recovery processes. Compliance with the CAM additionally requires that at least 70% of the raw materials originate from sources located within a maximum radius of 150 km.

The focus is on composition and therefore on the choice of binders, favouring the use of cements with reduced clinker content and mineral additives capable of improving the environmental profile of the material without compromising its structural performance. the concept of "*green concrete*" is not understood as an abstract or merely declarative category, but as the result of a conscious design process, in which the mixture is defined according to objective environmental requirements.

The important aspect is the implicit link that CAMs establish between the composition of concrete and its durability and sustainability, it is essential to maintain mechanical performance and resistance to degradation agents, since a reduction in

the useful life of the structure would negate the environmental benefits obtained during the production phase. This results in a balanced approach, with environmental benefits of the material accompanied by careful assessment of exposure classes, required performance and operating conditions of the structure. CAM helps shift the focus from individual products to the system material, placing the concrete mix design at the centre as an element that synthesises structural requirements and environmental objectives. This approach is significant for both public construction and the private sector, where the voluntary adoption of similar criteria allows for more advanced comparative analyses between alternative structural solutions.

In light of these considerations, concrete emerges as one of the materials most affected by green evolution, as well as a privileged area for the application of the principles of sustainability introduced by the legislator. A closer look at the requirements relating to the composition of mixtures, the content of recycled materials and the environmental performance of concrete is therefore a necessary step in understanding how these criteria can be translated into design choices.

2.2 Environmental Life Cycle Costing analysis

When it comes to public works, the design phase is crucial for reducing environmental impacts in the logic of the life cycle, as it allows for early action. Designers are therefore incentivised to carry out a life cycle assessment (LCA) and a life cycle cost analysis (LCC) to justify their design choices, through bonus points. This allows projects that go beyond mere compliance with individual CAM requirements to be valued, improving the overall environmental performance of the project, as made possible by the LCA study.

In CAM Edilizia 2025, the LCA approach plays a much more important role in the sustainability report that designers are required to submit. The section dedicated to the LCA methodology to be adopted in the CAM report is much more structured, aligning perfectly with the EN 15978 and EN 15804 technical standards [3]. The assessment of the building as a whole is therefore increasingly oriented towards the life cycle. Although this does not introduce explicit LCA requirements for individual materials, it is becoming more important to be able to provide reliable environmental data on construction products. These, in fact, represent important inputs for the building LCA study. When the designer draws up a sustainability report, LCA becomes the most comprehensive and difficult to replace tool, except in justified cases decided by the Responsabile Unico del Progetto.

Life Cycle Assessment is the tool used to measure the environmental footprint throughout all stages of a product's life cycle, from the extraction of raw materials to final disposal. By quantifying the use of resources (energy, raw materials, water) and emissions into the environment (waste, emissions into the air, water, soil, etc.). This approach makes it possible to identify the most critical stages in terms of

environmental impact in the life cycle of a product or activity in order to better guide their design and management. LCA studies can be used to evaluate similar products, or different products with similar functions, in order to identify those that are most environmentally sustainable. The graph shows the environmental impact

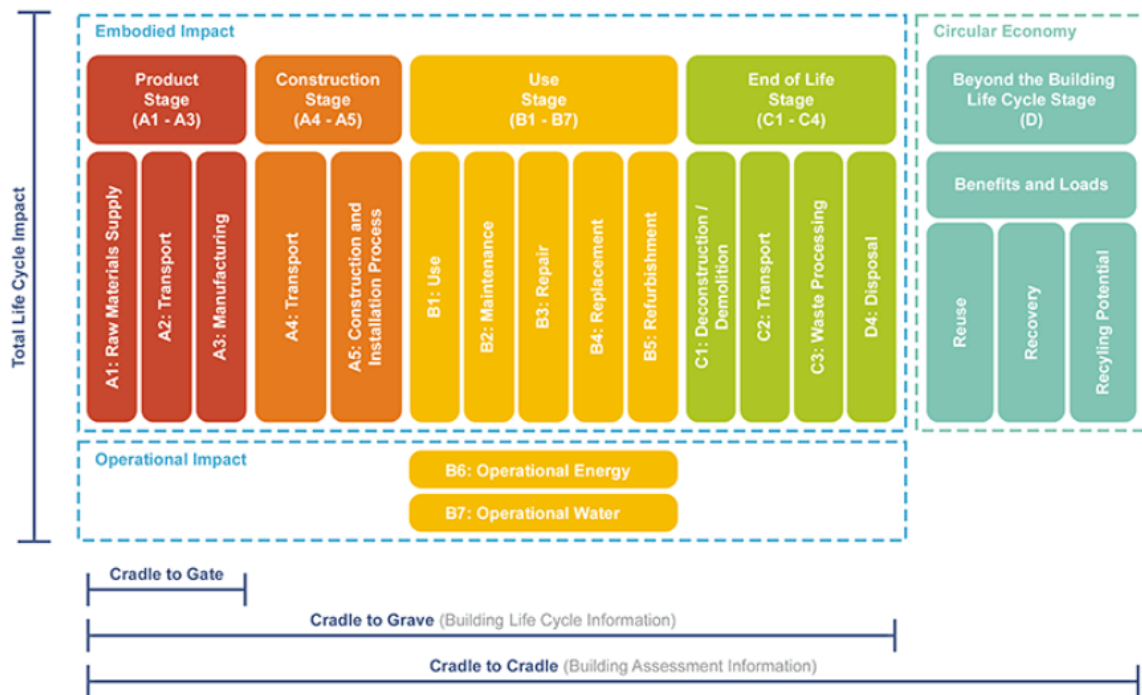


Figure 2.1: Modules and phases of the LCA study of the work

broken down by life cycle stage on the horizontal axis:

- A1 - A3 (Cradle to Gate): Production Stage (extraction, transport, manufacturing);
- A4 - A5: Construction stage (Transport and Construction);
- B1 - B7: Use Stage of building (maintainance, substitutions, energy);
- C1 - C4: End of life stage (Demolition, transport, Dsisposal);
- D: Benefits Beyond Life Cycle (Recycle, Recovery).

. The vertical axis is almost always one of the following:

- kg CO₂ eq (Global Warming Potential GWP);

- MJ of primary energy;
- multiple environmental indicators (acidification, eutrophication, etc.).

Life cycle costing (LCC) is a methodology that allows costs to be calculated throughout a product's life cycle, again using the "cradle-to-grave" approach, i.e. from the production stages to the use stages and finally to disposal. This approach makes it possible to define, on the basis of specific criteria, which solutions are most efficient not only from an environmental point of view, but also from an economic one. There is no single way to proceed with the formulation of the analysis, but four general phases have been identified in the ISO 15686-5 that contain the costs to be included in the analysis:

- procurement/acquisition of raw materials;
- operational or usage phase, including costs related to electricity, gas and water;
- maintenance and any replacements of components and spare parts for machinery;
- decommissioning or disposal of the product.

To these must be added any intangible costs, such as patents, brand and reputation; LCC analysis provides for a monetary quantification inherent in the purchase and maintenance. The analysis highlights how operating costs have a significant impact on total costs, confirming the importance of a life-cycle approach in design choices and public procurement procedures. Graphically, different types of representation can be used:

- Stacked bars for a comparison between design alternatives;
- Pie charts for the percentage weight of costs;
- Cumulative curves to show the evolution of costs over time in terms of years of useful life.

Environmental Life Cycle Costing (ELCC) is an integrated approach that simultaneously assesses economic costs and environmental impacts throughout the entire life cycle of a project, combining LCC (ISO 15686-5) and LCA (EN 15978 / ISO 14040-44) therefore considering both the costs related to the life cycle of a product and environmental aspects. However, it is not enough to simply superimpose the two models; there are specific objectives for this type of analysis. In an objective and measurable way, it is possible to compare the costs of the alternatives available throughout the life cycle of a product. Analyse direct or indirect cost factors and measure the improvements achieved by a company in relation to the reduction of

polluting emissions throughout the life cycle of a given type of projectual solution. Finally, we can estimate the environmental and economic improvements achieved by planning certain changes, including process and product innovations.

The distinctive feature of this analytical model lies precisely in its dynamic connotation, which allows for a different point of view and creates a real competitive advantage. The economic costs of the life cycle expressed in euros and the environmental impacts expressed in terms of Global Warming Potential, kilograms of carbon dioxide equivalent, are presented together in order to support multi-criteria decision-making.

Companies often tend to sacrifice environmental considerations in favour of more immediate and tangible cost savings. However, in today's complex and competitive market, it is no longer enough for a company to survive by chasing lower prices; rather, it must demonstrate its ability to pursue a sustainable management policy.

2.3 Environmental Product Declarations

The Environmental Product Declaration (EPD) is a fundamental tool within the Italian CAM for construction, as it allows for an objective and comparable quantification of the environmental performance of construction products throughout their entire life cycle. Basically, it is based on a LCA conducted in accordance with the ISO 14040 - 44 series of standards and, for construction products, in accordance with EN 15804, which defines product category rules (PCR) harmonised at European level. In the context of CAM Edilizia, they provide quantitative environmental data, such as GWP, energy and material resource consumption, and other environmental impact indicators, which are necessary for verifying the environmental requirements in public procurement procedures. The use of products with EPDs allows contracting authorities and designers to make assessments based on objective criteria throughout the entire life cycle of the project, this is particularly relevant in ELCCs comparative analysis, in which environmental data and life cycle costs are assessed jointly, in line with the principles of GPP and the circular economy.

EPDs are created using PCRs (Product Category Rules), which are the reference rules for conducting life cycle analysis for a given product category. Therefore, before developing an EPD, it is necessary to choose an appropriate PCR.

The chosen PCR must be listed in the International EPD System and valid at the time of verification. If there is no PCR for the relevant product category, one will be developed with the involvement of the main stakeholders, all through the mediation of the Programme Operator.

The resulting documents are sent to an approved third party or an accredited certification body acting as a control body. This independent body is responsible for validating and issuing product certification. The third party can then apply to the Programme Operator for the EPD to be registered and published, thereby acquiring

the right to use the logo.

There are two types of verifier involved in this process, one is Accredited certification bodies, secondly approved individual verifiers. Currently, "Accredia" is the only national accreditation body designated by the Italian government to certify the competence and impartiality of certification and verification bodies for Environmental Product Declarations. A structured set of environmental indicators is used to assess the environmental impacts associated with a product or construction project. These indicators quantitatively describe the main pressures exerted on the environment. Among these, GWP plays a central role, measuring the contribution to global warming resulting from greenhouse gas emissions generated by the activities considered. This indicator is expressed in terms of kilograms of carbon dioxide equivalent, taking carbon dioxide as the reference gas with a unit value of 1, while other climate-changing gases are assessed according to their relative global warming potential compared to it. Alongside the GWP, total greenhouse gas emissions are particularly relevant, as they include all gases released into the atmosphere during all stages, from production to use and end of life. These emissions contribute directly to the greenhouse effect. Another indicator is water consumption, particularly in industrial processes. Many manufacturing sectors, including construction, require large amounts of water for their production cycles, making it necessary to carefully monitor and assess the impact associated with the exploitation of this natural resource. Particulate matter and fine dust emissions are also important, these emissions contribute to air pollution and can have significant effects on air quality and human health, especially in urban and industrial settings. Finally, waste production is a key indicator for assessing overall environmental impact, as it refers to both the quantity and type of waste generated during the life cycle. Proper waste management and the reduction of non-recyclable fractions are key aspects in terms of CAM and the principles of the circular economy.

Within the framework of CAMs for construction, building materials play the central role, as a significant portion of the overall environmental impact of a project can be attributed to the production phase of the materials. EPDs are a key tool for verifying and demonstrating compliance with the criteria, as they make environmental data based on LCA analyses available. One of the most important requirements of the CAM for construction is, for example, the minimum content of recycled, recovered or by-product materials, expressed as a percentage and varying according to the type of construction product, such as steel and concrete. EPDs allow these percentages to be documented transparently, facilitating verification of the requirement during the design and tendering phases.

The CAM also requires that all construction products covered by harmonised standards bear the CE marking and the relevant Declaration of Performance (DoP). With the entry into force of the new Regolamento Prodotti da Costruzione (CPR),

applicable from 8 January 2026, the DoP must also include environmental information based on LCA, such as GWP and indicators related to the circularity of materials. This regulatory change further strengthens the role of EPDs, which are a reference tool for the production and communication of the required environmental data.

This helps to steer design and procurement choices towards materials with better environmental performance throughout their entire life cycle in the *private sector*, as well.

Chapter 3

Solutions and Developments of Sustainable Concretes

On the basis of the analysis on the issues relating to concrete material and the legislative context, we move on to analyse the implementation of the CAM, with particular reference to the definition of mixtures with reduced environmental impact and the comparative assessment of their technical and economic performance. In this sense, the concept of "green concrete" is not a standardized formula, but rather the result of a conscious design of the mix, in which the choices relating to the components are guided by measurable and objective environmental criteria, consistent with the performance required of the project. This approach fits naturally within the framework of the current structural technical regulations, the Norme Tecniche delle Costruzioni 2018, which define the safety, strength, and durability requirements for reinforced concrete structures. The introduction of environmental requirements for the composition of mixes cannot ignore compliance with the required mechanical performance at the ultimate and service limit states, nor the correct definition of environmental exposure classes. Any reduction in performance or the useful life of the structure would lead to increased maintenance and early replacement of structural elements, negating the environmental benefits achieved during the material's production phase. This necessitates an integrated approach to mix design that balances environmental and performance requirements, adapting the material to the specific exposure and operating conditions of the structure. Durability, already considered in the NTC as a fundamental design requirement, is reinterpreted as an environmental sustainability parameter. Indeed, it is closely related to reducing resource consumption over the entire life cycle of the structure, from construction to the reuse of the material conceived after its demolition, enabling a circular economy of resource recycling.

The CAM 2026 approach also encourages the adoption of quantitative assessment tools, such as EPDs, which allow for the comparison of different mix solutions in

terms of emissions, resource consumption, and overall performance. This is particularly relevant in the context of comparative analyses between materials or different concrete formulations, as it allows for the integration of traditional structural checks with a coherent, data-based environmental assessment. In this way, mix design also becomes a lever for objective and verifiable ELCC analysis. Concrete emerges as one of the materials most affected by the evolution introduced by CAM 2026 due to the potential for improvement offered by mix design. Exploring strategies for reducing the environmental impact of concrete represents a fundamental step in critically evaluating the potential for applying CAM both in public construction and, by methodological extension, in the private sector.

Sustainable concrete, is engineered to improve Embodied Carbon of construction without sacrificing strength and durability. They achieve this through a combination of lower carbon binders, by replacing portions of Portland cement, by incorporating recycled aggregates or crushed concrete to reduce the need for virgin resources, efficient mix design optimising the ratio of materials to reduce waste and improve performance and Carbon capture technologies may be added, infact some advanced mixes even absorb carbon dioxide during curing, locking it into the concrete permanently. They all aim at reducing the clinker content, it's arranged by increasing the amount of supplementary cementitious materials (SCM), SCMs include by-products from industrial processes, such as fly ash from coal-fired power stations, ground blast furnace slag from steel production, and silica fume from the production of silicon and its alloys. Other SCMs include natural pozzolana and limestone powder. These materials are already used in the formulation of new binders. Basically, there are an enormous family of mixtures we can achieve, all aimed at reducing clinker content or virgin aggregates, they are done by combining different materials with different weight percentages calculated on the dry mix, net of water:

- Supplementary Cementitious Materials (SCMs) added to the mix, are inorganic materials, such as fly ash, slag, silica fume and calcinated clays, used in concrete to partially replace Portland cement, they are the ingredients (natural or artificial to make the final product (Composite Cements))
- Composite Cements (*EN 197 - 1 / EN 197 - 5*) as materials that reduce clinker by acting on the binder adding *Industrial By-Products* that meet strength and durability standards. Where, Many Supplementary Cementitious Materials (SCMs) derive from industrial by-products; however, not all SCMs originate as industrial by-products. Likewise, not all industrial by-products possess characteristics that can be classified as SCMs. They coincide when an industrial by-product has cementitious and/or pozzolanic properties. They do not coincide, however, when an SCM is not derived as a by-product, and therefore naturally derived, or when a by-product does not have cementitious reactivity.
- Materials that reduce impact through the aggregate fraction, they do not

reduce the clinker directly, but they lower the overall footprint of the concrete

- Materials that act through performance optimization, Structural fibers and advanced superplasticizers

The regulatory framework does not impose univocal solutions, it defines a technical boundary within which the designer can optimize the mix while maintaining structural safety.

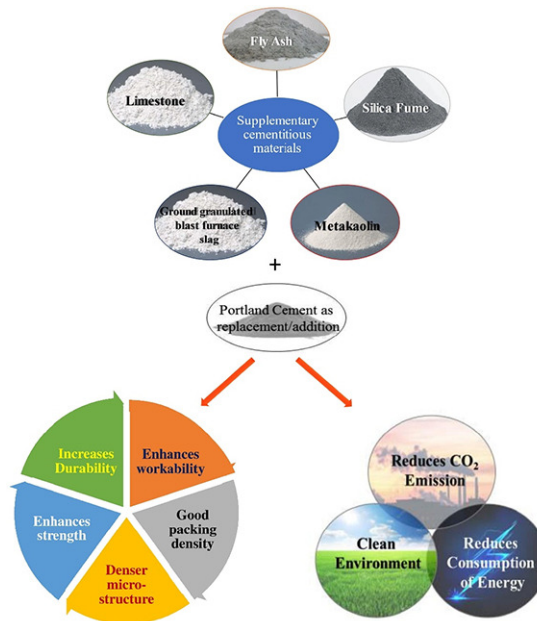


Figure 3.1: Supplementary cementitious materials of low carbon cement composites

Despite for public constructions they have been fastly introduced, since imposed by EU Directives [10], for small-scale non-public constructions, these aspects become particularly critical. Unlike large projects, where innovation can be supported by extensive testing programmes and specialised expertise, modest buildings are typically realised under tighter economic and organisational constraints, the use of green concretes in this context requires solutions that reliable, readily available, and compatible with conventional construction workflows.

This consideration highlight solely material innovation, Green Concrete technologies can significantly reduce the embodied carbon of individual structural elements, of course their effectiveness is closely linked to the quantities of material employed. Consequently, the environmental performance of concrete structures cannot be addressed exclusively through mix design, but must also consider the efficiency of the structural system as a whole.

Within the framework outlined by the updated Criteri Ambientali Minimi, which came into force in 2026 with the CAM Edilizia 2026 Decree, structural concrete is one

of the materials for which explicit quantitative requirements have been introduced regarding the minimum content of recycled, recovered, or by-product materials. For ready-mixed and site-mixed concrete, as well as for precast concrete products, the CAM 2026 standards require a minimum content of 5% by weight of recycled, recovered, or by-product materials, calculated on the dry weight of the concrete net of water. This minimum percentage requires the designer to explicitly specify the concrete's component choices and verify their consistency with structural and performance requirements. Considering ordinary structural concrete with a total dry mass of around $2,300 - 2,400 \text{ kg/m}^3$, the minimum recycled or recovered material content required by the CAM is approximately $115 - 120 \text{ kg/m}^3$. This percentage can be met through the use of certified recycled aggregates, or through a combination of recovered aggregates and industrial by-products permitted by the decree, provided that the fractions considered remain effectively incorporated into the final product. Compliance with the CAM also requires a maximum limit of raw material content equal to at least 70% coming from a maximum distance of 150 km. This highlights that this product can be produced in a very large number of different mixtures resulting from the study of the overall balance of the mixture's components. The CAM-compliant mixture can be taken as a regulatory reference scenario, to be compared with a conventional mixture without significant recycled content, the reduction in environmental impact is not hypothesized abstractly; the life cycle analysis thus allows for an objective assessment of the contribution of the recycled material share to the reduction of greenhouse gas emissions and the consumption of primary resources.

The cement industry value chain is promoted through the Concrete sustainability Council (CSC). This is an international certification scheme for concrete and its production chain, aimed at objectively and transparently assessing the socio-economic-environmental sustainability performance of companies in the sector. The scheme was launched in January 2017 as the result of a long development process that began with the Cement Sustainability Initiative of the World Business Council for Sustainable Development. Its primary objective is to promote responsible sourcing of concrete, cement, and aggregates throughout the supply chain. The CSC certification system is based on a set of criteria and scores divided into multiple categories, they include corporate management, environmental, social, and economic aspects, as well as mandatory prerequisites that must be met to obtain certification. The final score, expressed as a percentage, is derived from the sum of the credits obtained in the various criteria and can be further classified into increasing levels (Bronze, Silver, Gold, Platinum) based on the level of compliance achieved by the certified organization. In addition to encouraging improved sustainable management practices and the adoption of low-impact production processes, CSC certification is recognized by construction sustainability rating systems such as BREEAM, LEED, and DGNB, enabling the integration of concrete supply chain performance into

comprehensive assessments of sustainable buildings and infrastructure. It should be viewed as an opportunity for the sector, on a par with investments in new product research and the construction of new concrete batching plants.

3.1 Composite Cements

The use of composite cements compliant with EN 197-1 and EN 197-5 standards is growing and is widely appreciated in the industry. Portland clinker is being partially replaced by already standardized secondary constituents, without introducing performance uncertainties or regulatory compliance issues. Among these secondary constituents, limestone plays a predominantly physical role, acting as a filler and as a nucleation site for clinker hydration products. It generally allows for a clinker reduction of between 6% and 20%, although it does not directly contribute to the formation of new binders, as it lacks pozzolanic activity. Fly ash, on the other hand, exhibits marked pozzolanic reactivity and allows for a more significant clinker replacement, typically in the range of 15 - 35%. This contributes to the development of mechanical strength and the improvement of the cement paste's microstructure, although its availability is currently conditioned by the progressive decommissioning of coal-fired plants. A further and more significant reduction in clinker can be achieved through the use of blast furnace cements, in which ground granulated slag, a latent hydraulic material, can replace clinker by up to 65 - 70%, with significant benefits in terms of both reducing the carbon footprint and improving the concrete's durability. This perspective also applies to the more recent ternary cements, such as CEM II/C and CEM VI, which synergistically combine various secondary constituents to balance mechanical performance, hydration kinetics, and environmental sustainability.

3.1.1 Supplementary Cementitious Materials

In the coming decades, the formulation of new binders, partially replacing clinker, will be further increased with the greater use of limestone, the introduction of calcined clays and fine fractions originating from concrete crushing (C&DW), which will compensate for the reduced availability of fly ash and slag. Studies have demonstrated that these actions will allow the clinker/binder ratio to be reduced from the current value of 0.63 to an intermediate value of 0.58 by 2030, up to the final value of 0.52 by 2050. Unlike clinker, SCMs do not have autonomous hydraulic properties; their binding properties must be activated through the pozzolanic reaction with hydrated lime that forms during cement hydration, resulting in the formation of hydrated phases with a composition completely similar to those characterizing the silicate phases of clinker. The reaction kinetics associated with the different binder components are significantly different. Hydrated calcium silicates (C-S-H)

generated by the hydration of the clinker phases form within the first few hours after mixing with water, significantly contributing to the initial development of mechanical strength. In contrast, the reaction products deriving from supplementary cementitious materials (SCMs) develop at significantly lower rates, demonstrating a more gradual and time-delayed contribution. Furthermore, not all SCMs effectively participate in the pozzolanic reaction: limestone dust, for example, is not activated by hydrated lime and primarily performs a physical filling function, acting as a filler rather than a reactive component. Furthermore, the hydration reactions of the clinker phases themselves are never complete from a stoichiometric point of view, inevitably leaving unreacted fractions that do not contribute to the development of the mechanical performance of the material, in light of these considerations, the reduction in the clinker/binder ratio typical of low-clinker concretes (Low-Clinker Cements, LCC) may be difficult to reconcile, if not adequately designed, with the aim of maintaining mechanical strength levels comparable to those of traditional concretes characterised by a greater carbon footprint. To overcome this challenge, a new class of admixtures has been developed to compensate for the loss of mechanical properties of LCC concrete as the clinker/binder ratio decreases. Compared to traditional admixtures, which were developed primarily to control the rheological properties of fresh concrete, such as plasticizers and superplasticizers, setting and hardening times, and retarders and accelerators, this new class of admixtures is designed to control the hydration of the binder system as a whole. Since these admixtures were specifically developed to meet the sustainability and performance requirements of low-carbon LCC concretes, the name Low Carbon Concrete Admixtures (LCCAs) has been proposed for them. With these admixtures, it is possible to reduce the cement dosage in concrete or increase the fraction of SCMs in the blended cements to produce low carbon footprint LCC concrete, with performance equivalent to or superior to that of traditional Portland cement-based concrete.

3.2 Performance Optimization

Reducing environmental impact can also be achieved through the so-called "performance strategy", which consists of reducing the use of structural materials through the use of higher-performance materials. These are ultra-high-performance concretes, also known as UHPCs, characterized by the presence of silica fume: silica fume (SF) increases the density of the concrete, thanks to its fineness and extreme reactivity, making it more resistant and waterproof. UHPC is defined as a cementitious composite with compressive strength typically greater than 150MPa , very low permeability, high ductility and marked post-cracking toughness. In terms of wet mix proportions, UHPC is characterized by a very low water/cement ratio, generally ≤ 0.20 , a high content of binders, the use of homogeneous fine aggregates, highly efficient superplasticizers, and often reinforcing fibers, such as steel, to improve the

composite’s tensile strength and ductility. This microstructure optimization aims to maximize particle packing density, reduce porosity, and achieve a compact and highly integrated matrix. UHPC is being studied and used in advanced structural applications where the combination of high performance, durability and low maintenance is essential, for example in the reinforcement of infrastructure, prefabricated bridges and in aggressive environmental conditions. The unit cost of UHPC is significantly higher than that of conventional concrete and HPC, making it difficult to apply in most common situations. In literature and in practical applications, the material cost can be 3 to 10 times higher than that of ordinary concrete.

3.3 Crushed concrete as recycled aggregate

They are the most regulatory-direct tool for reducing clinker, and are partially replaced by already standardized secondary constituents. Crushed concrete resulting from selective demolition is fully eligible for recycled aggregates under the CAM Edilizia 2026 regulations, provided it meets specific quality, traceability, and regulatory compliance requirements. From a regulatory perspective, crushed concrete is not a substitute for clinker and does not directly reduce the cement content of the binder. Its environmental function is to valorize construction and demolition waste, transforming it into a resource within a circular economy model. According to the CAM regulations, crushed concrete can contribute to achieving the minimum 5% recycled content by weight. This percentage can also be achieved exclusively through recycled aggregates, provided they remain permanently incorporated into the final product and are accompanied by appropriate documentation certifying their origin and recovery process.

From a performance perspective, however, the use of recycled aggregates in concrete presents some critical issues that must be addressed in the design. The presence of mortar adhering to recycled aggregates generally leads to increased porosity and water absorption, with potentially negative effects on workability and mechanical strength if not properly compensated. Furthermore, the quality of the source material and control of the crushing process are crucial to ensuring consistent performance. For these reasons, the use of crushed concrete is now considered more suitable for partial replacement of the coarse fraction of aggregates, maintaining low percentages compatible with the required strength class. From a comparative analysis perspective, crushed concrete represents a particularly interesting case study. In an LCA comparison between a conventional mix and a CAM-compliant mix, the introduction of recycled aggregates shows clear benefits in terms of reducing natural resource consumption and waste disposal, but a more limited impact on reducing dioxide carbon emissions compared to clinker replacement. This aspect demonstrates the effectiveness of circular economy policies, rather than as the only solution for material decarbonization.

3.4 Eco-Mechanical Analysis

The assessment of environmental aspects of normal and green concretes, must be analyzed simultaneously with the mechanical performance of the design, such as strength and ductility, assessed at the serviceability and ultimate limit states. It is therefore necessary to define a so-called "eco-mechanical" assessment method that simultaneously considers these two aspects. The eco-mechanical sustainability assessment is performed using two global indices: ecological (EI = ecological index) and mechanical (MI = mechanical index).

The ecological index (EI) is estimated by considering three significant parameters, namely carbon dioxide emissions (carbon footprint), embodied energy (the total amount of energy consumed to produce a material, considering its entire life cycle before use), and the volume of water used to produce 1 cubic meter of concrete. Therefore, EI is calculated as follows:

$$EI = (\psi \cdot wc_\psi) \cdot (\delta \cdot wc_\delta) \cdot (\gamma \cdot wc_\gamma) \quad (3.1)$$

where ψ indicates the total amount of CO₂, δ the amount of embodied energy and lastly γ the volume of water. Furthermore, the ecological performance is related to the local conditions of the site where the concrete is used, three additional weighting coefficients ($wc_\psi, wc_\delta, wc_\gamma$) are introduced into the equation, which are evaluated based on the actual production/construction conditions, such as water supply, transportation and procurement of raw materials.

On the other hand, the mechanical index, it simultaneously takes into account the mechanical and structural characteristics of the concrete and the building, respectively. It is estimated using the following formula:

$$MI = mp_m \cdot mp_s \quad (3.2)$$

where mp_m is the mechanical parameter of concrete, mp_s is the mechanical parameter of the structure.

As can be understood, these are experimental evaluation indices, therefore, the acquisition of these two parameters occurs through tests that reproduce the real behavior of materials and structures, both under the serviceability limit state and ultimate limit state conditions. The values then need to be introduced into one of the two possible analysis methodologies.

First methodology is Eco-Mechanical Index (EMI). It is based on the evaluation of an eco-mechanical index, evaluated with the ratio:

$$EMI = \frac{MI}{EI} \quad (3.3)$$

from which the best conglomerate will be the one that will return a higher EMI.

The second method is, instead, diagram based, we define benchmarks relating to the ecological index and the mechanical index, which, due to regulatory requirements or specific requests in the tender specifications, must be achieved by the conglomerates used. In particular, there will be an upper limit EI_{sup} relating to the environmental impact and a lower limit MI_{INF} relating to the mechanical characteristics. Using the reference benchmarks the dimensionless diagram is made, in which four different zones are distinguished:

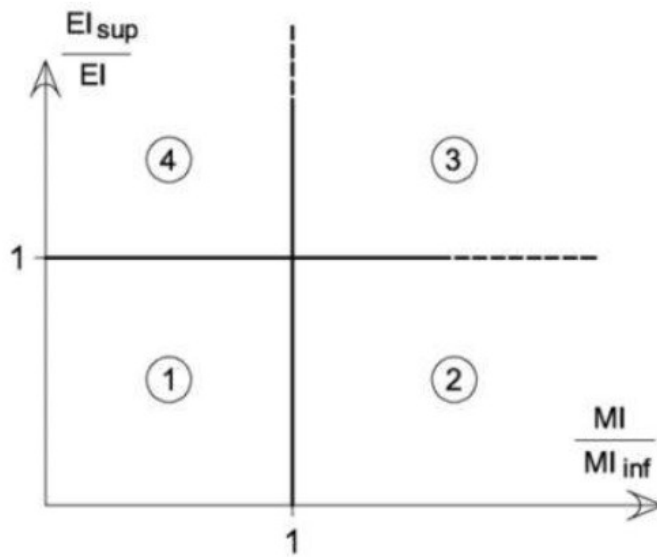


Figure 3.2: Adimensional Diagram for Eco-Mechanic evaluation

- Zone 1: Poor mechanical and environmental characteristics;
- Zone 2: Poor environmental characteristics but high mechanical ones;
- Zone 3: High eco-mechanical Conditions;
- Zone 4: High environmental characteristics and poor mechanical ones.

Consequently, those conglomerates falling within Zone 3 will be considered acceptable, as they are the only ones with both indices better than the reference ones. Among these, it is then possible to choose the most economically advantageous one, so the choice will be based on cost only once the ecological and mechanical requirements have been met.

Chapter 4

Case Study

Having completed the necessary presentation of the current state of the art regarding the environmental impact and legislation of the most widely used material in the construction sector, the concrete, it is intended to transfer the principles and methodological criteria of public procurement design, governed by European directives transposed into Italian law, to the private sector. The aim is therefore to integrate the traditional structural design of the commissioned architectural structure with a holistic economic and environmental analysis of the structural materials used, with specific reference to cost and Global Warming Potential (GWP). This will enable the identification of design solutions that, in addition to meeting the limit states required by current legislation, are optimized in terms of sustainability and environmental impact.

The building under study extends over an area of about $23m \times 20m$ and it is located in the Municipality of Pinerolo, in the Province of Torino, precisely in a hilly area between Pinerolo, San Pietro Val Lemina and Roncaglia. This rural location, detached from the inhabited center, also constituted a constraint for some structural decisions. According to the current national seismic classification, the municipal territory falls within seismic zone 3S, an area characterized by medium-low seismicity but still significant for structural design purposes. Zone 3 identifies contexts in which moderate-intensity seismic events may occur, generating significant effects on buildings, particularly for structures with a long nominal life or significant use. In the specific case of subzone 3S, regional legislation further distinguishes the territory based on geological conditions and local seismic response, introducing different levels of detail in geotechnical assessments and studies. Structural design must ensure compliance with the ultimate and serviceability limit states under seismic conditions, ensuring adequate levels of safety and damage control for frequent or moderate intensity events.

The project under study involved the demolition of a pre existing rural building, with the exception of the basement, which was restored and preserved, maintaining its intended use as a cellar. A new structure was constructed above this basement

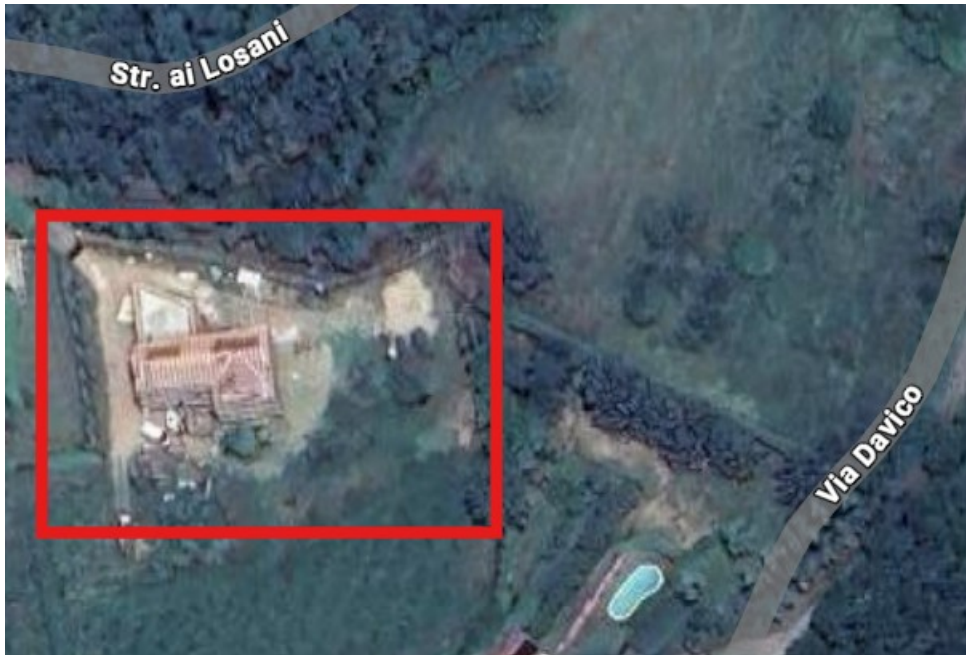


Figure 4.1: Framing of the place of intervention

level. The new building extends over two levels above ground, ground floor and first floor, constructed entirely of reinforced concrete, configuring the main volume for residential use. The roof consists of a gabled structure in laminated wood, chosen to meet both architectural and performance requirements. The project also includes a secondary building, structurally separate but functionally appurtenant to the main residence, intended for use as a garage. However, this structure was not considered in the comparative analysis of the study for practical and methodological reasons, as it is not structurally integrated. The building rests on a reinforced concrete foundation slab, designed as a single element to ensure consistent structural behavior under static and seismic loads, as well as a uniform distribution of stresses in the ground. Geological surveys revealed a lithostratigraphic situation characterized by a surface layer extending several meters in depth, consisting of predominantly silty lithium types with poor geotechnical characteristics, overlying a bedrock whose consistency increases with increasing depth. The survey campaign included three continuous cores of 5 meters deep each near the building and a MASW seismic array to determine the propagation velocity of seismic shear waves.

The seismic profile, created by laying geophones arranged along a horizontal alignment, revealed a high propagation velocity of seismic shear waves already in the first few meters of soil, demonstrating that the rocky substrate is in a sub-outcrop condition.

The assessment of the local seismic response is performed based on the INGV



Figure 4.2: Second survey position



Figure 4.3: Location of the surveys performed on Google orthophotos

grid data, considering the subsoil category (B) and the topographic category "T3" since the site is located at the top of a ridge. To take into account topographic conditions and in the absence of specific local seismic response analyses, the values of the topographic coefficient ST reported in the table below are used, based on the topographic categories defined in Table 3.2.III of the 2017 NTC and the location of the work or intervention. The calculation of the seismic parameters was carried out using the software available online on the "Geostru" web portal:

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

Figure 4.4: Table 3.2.III from NTC 2017

Table 4.1: Seismic design parameters

General settings	
Type of processing	Stability of slopes and foundations
Rigid wall	O
Site under examination	
Latitude	44.90277
Longitude	7.33988
Class of use	II
Nominal life V_N	50 years
Basic seismic parameters	
Subsoil category	B
Topographic category	T3
Reference period	50 anni
Coefficient c_u	1.00

Table 4.2: Seismic parameters at limit states

Limit state	PVR [%]	T_R [years]	a_g [g]	F_0	T_c^* [s]
SLO	81	30	0.038	2.460	0.205
SLD	63	50	0.050	2.430	0.225
SLV	10	475	0.130	2.459	0.263
SLC	5	975	0.164	2.488	0.271

Table 4.3: Seismic coefficients for slope stability

SL	S_s	C_c	S_t	K_h	K_v	A_{max}	β
SLO	1.200	1.510	1.200	0.011	0.005	0.539	0.200
SLD	1.200	1.480	1.200	0.015	0.007	0.713	0.200
SLV	1.200	1.440	1.200	0.045	0.023	1.839	0.240
SLC	1.200	1.430	1.200	0.057	0.028	2.323	0.240

Table 4.4: Reference sites for seismic hazard

Site	ID	Latitude	Longitude	Distance [m]
1	14231	44.9238	7.2767	5499.220
2	14232	44.9275	7.3470	2802.443
3	14454	44.8776	7.3520	2959.275
4	14453	44.8740	7.2818	5584.551

In summary, the site's characteristics are reported through the final considerations of the geological report prepared by the geologist registered at the Piemonte order:

Suolo di tipo 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.

La classe topografica è la T3: *settori in corrispondenza della cresta di un rilievo con pendenza media minore o uguale a 30°*

La stratigrafia "tipo" del sito di intervento può essere schematizzata come nel seguito:

Litotipo	Prof. (m da p.c.)	Peso di volume (t/m ³)	Coesione (kPa)	Angolo di resistenza al taglio (° sess.)	Adatti per fondazione
Terreni di natura eluvio - colluviale	0.0 – 1.5 / 2.0	1.8	assente	28	NO
Substrato roccioso (micasisti con grado variabile di alterazione)	> 1.5 / 2.0	2.6	175	22	ECCELLENTI

La categoria topografica è la T3 e la classe di sottosuolo è la B (con valori di Vs molto alti, al limite con la classe A).

Figure 4.5: Final considerations of the geological report of the site

The ground floor is structurally based on a reinforced concrete slab foundation of 30 cm thick, at an height of $-0.37m$ from ground floor, that extends around the

existing basement volume, connecting to the latter’s roof slab with appropriately sized curb beams. This configuration ensures structural continuity between the new construction and the preserved basement level, while also ensuring adequate transfer of vertical and horizontal forces. The slab was constructed following the conserva-



Figure 4.6: Basement roof slab

tive restoration of the basement, which included waterproofing of the exposed rock, aimed at reducing the environmental impact on the reinforced concrete and improving the structure’s durability. As part of the conservative restoration of the basement, structural consolidation work was also carried out on the existing vaults. These operations were necessary to restore and improve the load-bearing capacity of the vaulted elements, ensuring adequate levels of safety against vertical forces

and stresses resulting from the new structural configuration above, designed to preserve the original geometry while ensuring increased rigidity and resistance capacity compatible with the new load conditions. The basement slab over the cellar was designed as a composite slab of 20 cm thick made of corrugated sheet metal with additional reinforced concrete pouring. This solution allows for effective composite steel-concrete behavior and contributes to the floor's rigidity against horizontal forces, particularly seismic loads.



Figure 4.7: Foundation slab

The elevated structure consists of a reinforced concrete frame system composed of pillars and load-bearing walls, upon which a cast-in-place solid slab rests at an height of +3.10 m from ground floor. The choice of a solid slab of 20 cm thick was motivated by a combination of structural and logistical considerations. From a structural perspective, this solution ensures a substantially monolithic behavior of the building, increasing floor rigidity and promoting a more effective distribution of horizontal forces. In terms of seismic performance, the greater continuity between vertical and horizontal elements contributes to improving the overall behavior of the structure, ensuring an adequate rigid diaphragm function and a more uniform distribution of stresses between frames and walls. From a logistical and construction perspective, the location of the project was not conducive to the transportation and handling of large prefabricated elements, such as predalles-type slabs. The on-site construction of a solid slab therefore allowed for greater flexibility in execution, reducing critical issues related to access and lifting operations.

The roof with an inclination of 20° at an overall height of +7.15m from ground floor was constructed using a glulam structure consisting of inclined struts, a ridge



Figure 4.8: Elevated structure

beam, and corner elements, creating a gabled system. The wooden elements are supported by reinforced concrete connecting beams, which act as a top stringer, ensuring the connection between the pillars and the partitions emerging from the solid first-floor slab and ensuring the correct transmission of vertical and horizontal forces to the underlying structure. This solution allows for an effective interface between the wooden roof structure and the reinforced concrete structure, promoting the continuity of the load path and contributing to the overall box-like behavior of the building. The rear elevation also features a glulam truss, configured with a metal locking chain made from a solid circular steel profile. The presence of the chain absorbs the horizontal forces generated by the struts, reducing the flexural stresses on the supports and ensuring the balance of the roof's structural system. The connections between the wooden roof superstructure and the reinforced concrete connecting beams were made using bolted steel plates. This solution ensures effective load transfer between structural elements of different materials and stiffness, ensuring load continuity and adequate constraints between the roof and the underlying structure. The appropriately sized steel plates were designed to withstand vertical and horizontal loads acting on the roof, particularly seismic loads. The connection system ensures adequate resistance capacity and joint stiffness, as well as ensuring ease of installation, long-term reliability, and ease of maintenance. Above the rafters, a layered roofing package with a beading system was installed, integrated with a mineral wool insulation layer. This solution was adopted to ensure high thermal insulation performance, reducing heat loss through the envelope and

improving the thermo-hygrometric behavior of the roof. Mineral wool, in addition to offering good insulation characteristics, ensures adequate fire performance and dimensional stability over time. The choice of insulation material is consistent with the environmental criteria established by the CAM Edilizia, which promote the use of products characterized by a reduced environmental impact throughout their life cycle, the presence of recycled material content, and compliance with performance requirements in terms of durability and energy efficiency of the envelope. In this context, the adoption of CAM-compliant insulation contributes to improving the overall sustainability of the project.



Figure 4.9: Roof's system

In keeping with the design choices aimed at improving the energy performance of the building envelope, the use of Poroton-type hollow-core brick blocks was chosen for the vertical infill walls. This solution ensures adequate levels of thermal insulation thanks to the presence of internal cavities that reduce the material's equivalent conductivity, helping to reduce heat loss through the opaque vertical surfaces. The use of high-thermal-performance brick elements meets regulatory requirements regarding envelope transmittance and is part of the overall design strategy aimed at reducing the building's energy needs. All the permanent non-structural loads described above have been appropriately considered within the calculation model, as part of an overall structural analysis of the building.

Having completed the structural and architectural view of the building in this case study, we proceed with an examination of the design process adopted. In particular, we will focus on the details of specific importance in the study. The concrete used for the designed structures is class C28/35, while the reinforcing steel is type B450C, in compliance with current regulations. For the foundations, a concrete with consistency class S4 was used, with a maximum aggregate diameter of 32 mm, and a water/cement ratio of 0.60. The nominal concrete cover is 40 mm, consistent with exposure class XC2, corresponding to a humid, rarely dry environment. For the elevated structures, the same concrete strength class was maintained, while the nominal concrete cover, equal to 30 mm, and the exposure class, defined as XC1, associated with a dry or permanently dry internal environment, are differentiated. This breakdown of durability parameters was defined based on the operating environmental conditions and the regulatory requirements relating to the nominal life of the structure. For seismic design purposes, the structure was designed to have non-dissipative behavior.

The structural design was developed using numerical finite element modeling using PRO_SAP software, produced by the Italian company 2S.I., which complies with current national technical standards. The program enables structural analysis and element verification in accordance with the requirements of the Technical Construction Standards (NTC 2018) and the related Circolare Esplicativa. The structure was modeled consistently with the geometric and construction configuration of the building, using different types of finite elements: structural nodes to define the system's degrees of freedom, one-dimensional elements (beam elements) to represent beams and columns, and two-dimensional elements (shell elements) for walls and slabs. For non-structural stratigraphic packages, specific load panels were defined to which the relevant permanent and variable loads were associated. These surfaces do not constitute the primary load-bearing elements of the model, but serve to consistently transfer distributed loads to the underlying structural elements, respecting the areas of influence and constraint conditions. The non-structural elements were also subjected to verification for out-of-plane seismic actions, with particular reference

to possible expulsion mechanisms or local instability. In accordance with regulatory requirements, the anchoring and connection capacity to the main structural elements was assessed to ensure adequate levels of safety against seismic-induced accelerations and prevent detachment or overturning.

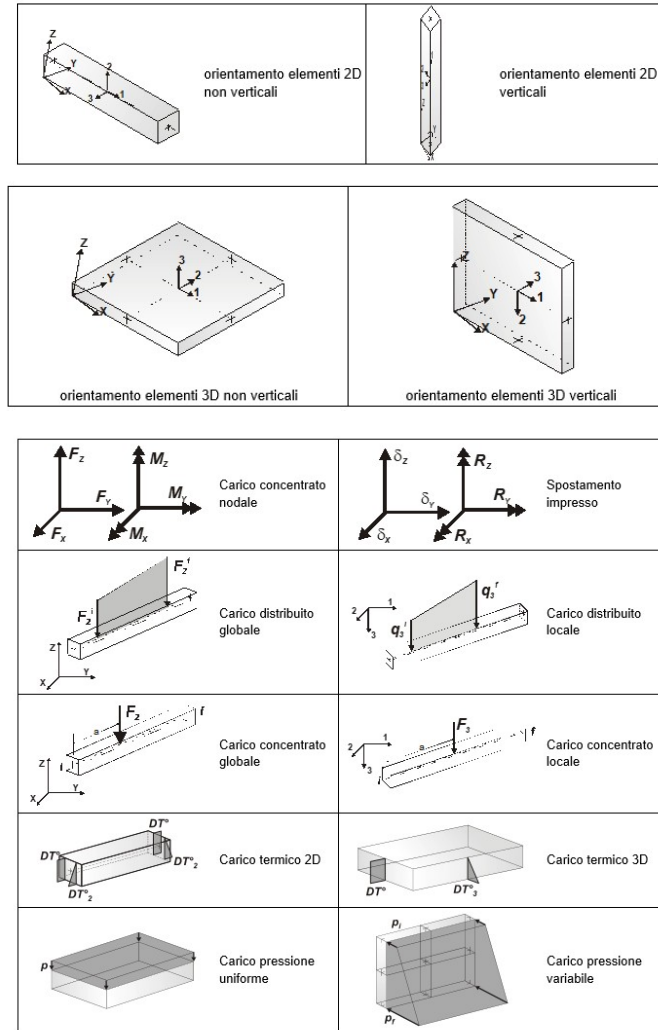
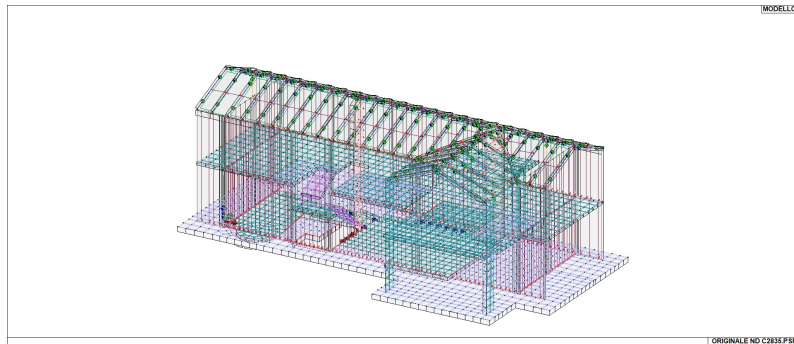


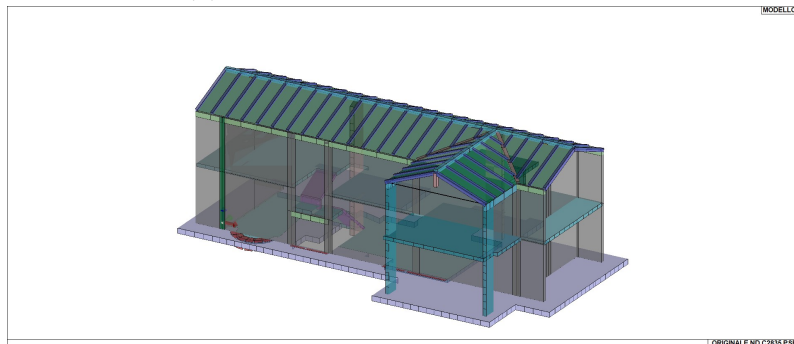
Figure 4.10: Elements and loads discretizations implementes in PROSAP

This discretization allowed to adequately reproduce the distribution of stiffness, mass, and inertia of the structural system. The load cases were defined in accordance with the actions required by current regulations, including self-weight, permanent non-structural loads, variable overloads, snow, wind, and earthquake actions. The load combinations for the Ultimate Limit States and the Serviceability Limit States were generated within the calculation environment according to the criteria prescribed by the 2018 National Technical Standards (NTC), taking into account the

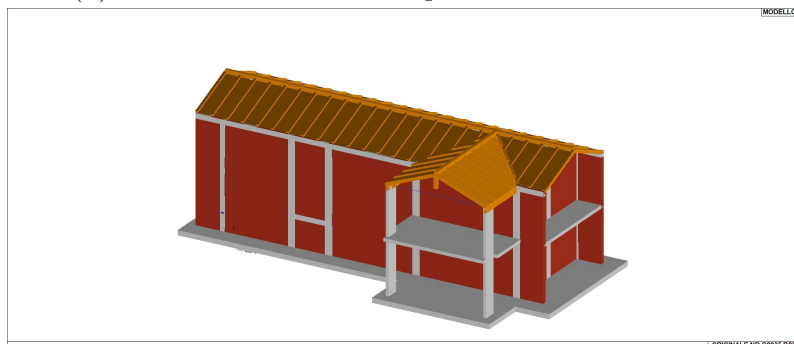
use class, the nominal life of the structure, and the seismic parameters determined for the site. Numerical analysis allows for the determination of internal stresses, displacements, and constraint reactions. Based on the obtained actions, the software proceeds with the automated verification of the reinforced concrete structural elements, comparing demand and resistance capacity according to the reference regulatory formulations.



(a) Axonometric view FEM model



(b) Axonometric view transparent solid FEM model



(c) Axonometric view solid FEM model

Figure 4.11: Graphical representations of the structural model.

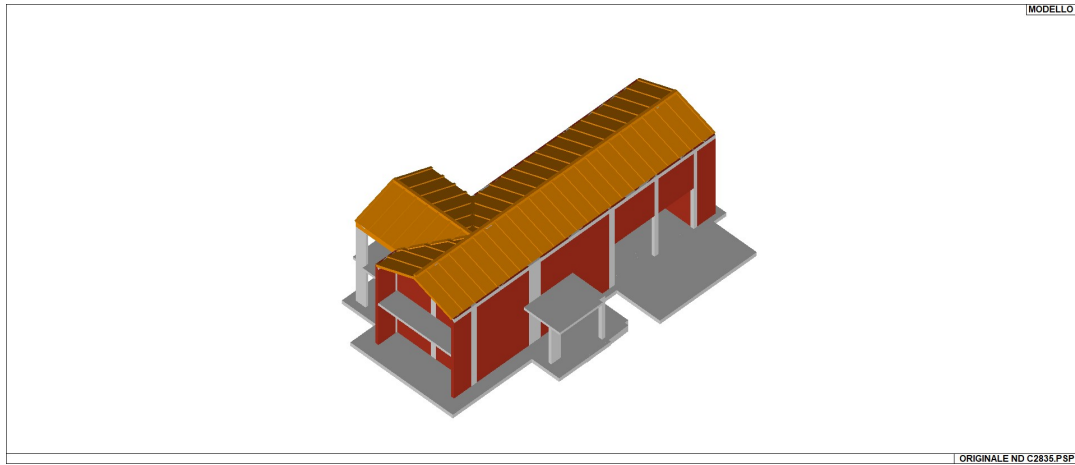


Figure 4.12: Solid view FEM model

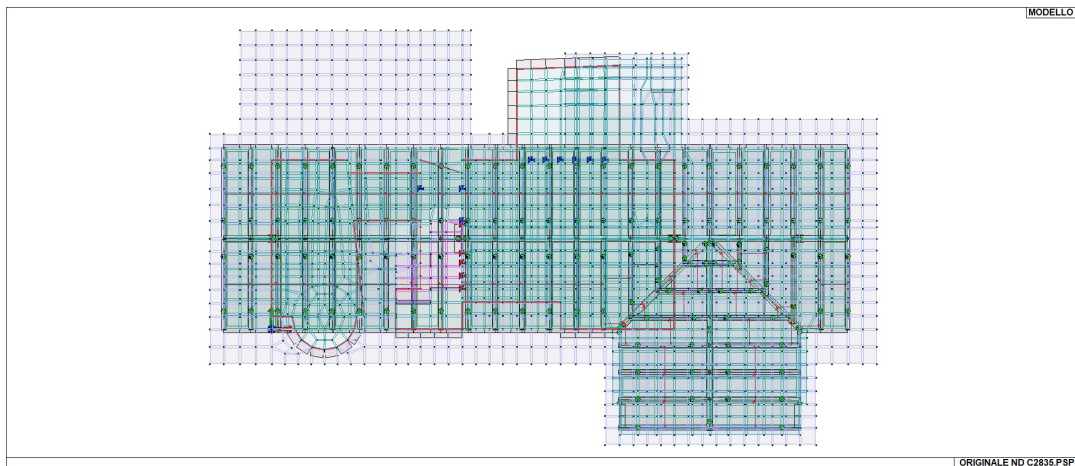


Figure 4.13: Top view of the fem model

4.1 Comparative Analysis Framework

Within the methodological framework of an Environmental Life Cycle Costing study, as commonly requested in public procurement, we now intend to define the assumptions and operational criteria for a possible analytical approach applicable to this case study. The objective is to outline a methodological procedure that, while developed for a specific project, can be extended and generalized to the context of private design. In particular, the aim is to carry out a comparative analysis between the same structure in non-dissipative construction conditions and a design for medium-class dissipative structural behavior (CDB), evaluating the use of different concretes according to resistance classes C25/30, C28/35 and C32/40, with different levels of environmental impact, therefore ordinary concretes and green concretes.

First of all, an echo-mechanical evaluation of the ordinary and non-ordinary concrete mixtures used as the object of study is presented. The concretes analyzed are produced by Heidelberg Materials and are accompanied by the relevant technical data sheets and Environmental Product Declarations (EPDs), drawn up based on Life Cycle Assessment (LCA) studies conducted by Italcementi. The EPDs were prepared in accordance with the reference standards for environmental product declarations and developed according to a "cradle-to-gate" approach. The analysis therefore considers phases A1-A3 of the life cycle, excluding phase A4. Please note:

- A1 - Extraction and processing of raw materials, processing of secondary materials;
- A2 - Transport to the manufacturer;
- A3 - Production process and treatment of generated waste;
- A4 - Transport to the construction site.

Consequently, the Global Warming Potential (GWP) values reported in the EPDs refer exclusively to the environmental impacts associated with the production of the material up to its exit from the plant, and are compliant with Type III environmental declarations, as defined by the ISO 14025:2010 standard.

These concretes are marketed under the name i.pro STRUCTURA for ordinary concretes characterized by a cubic characteristic compressive strength R_{ck} at 28 days $\leq 37MPa$, while the i.tech STRUCTURA line identifies ordinary concretes with a characteristic compressive strength $R_{ck} \geq 40MPa$; the corresponding "green" products are instead marketed under the names i.pro STRUCTURA ECO LOW CARBON and i.tech STRUCTURA ECO LOW CARBON, maintaining the same mechanical strength classes but with formulations optimized in terms of reducing GWP-GHG values. In summary, the concretes in the i.pro STRUCTURA line are suitable for the construction of reinforced concrete structures exposed to moderately aggressive environmental conditions, corresponding to exposure classes XC1 and XC2. These products meet the C25/30 and C28/35 strength classes adopted in the analysis. For simplicity of explanation, the formulations in the i.pro line will be referred to as O30, O35, G30, and G35, respectively, in the ordinary and low-carbon versions. The concretes in the i.tech STRUCTURA line, on the other hand, are intended for the construction of reinforced concrete structures exposed to more severe environmental conditions, up to exposure class XC4, and are therefore suitable for the required durability performance. For the purposes of this study, these products represent the C32/40 strength class and will be referred to as O40 and G40, respectively, in the ordinary and low-carbon versions.

Table 4.5: Environmental and economic performance of the analysed concrete mixes (data from EPD)

Mix	GWP-GHG ($kgCO_2eq/m^3$)	Total Recycled Content (%)	Cost ($€/m^3$)
O_30	260,00	1,20	155,00
G_30	221,00	6,50	170,00
O_35	293,00	1,30	162,00
G_35	236,00	7,00	178,00
O_40	326,00	1,40	170,00
G_40	251,00	7,50	187,00

To more clearly assess the performance suitability of the various mixtures analyzed, an eco-mechanical analysis can be conducted initially, correlating environmental and mechanical performance. This approach allows the mixtures to be compared against potential sustainability benchmarks required for concrete, which can be performance-based or prescriptive.

In a performance context, a concrete with a reduced environmental impact can be considered suitable for use if it has a lower GWP-GHG value than that of a standard concrete used as a reference. The two variables considered in the comparative analysis are environmental and economic in nature: the Global Warming Potential expressed in $kg CO_2eq$ per cubic meter of mixture and the unit cost per cubic meter, respectively, taking the O30 mixture as a reference, for which an environmental threshold value EI_{sup} was defined, coinciding with the GWP of concrete equal to $260 kg CO_2eq/m^3$. Two dimensionless comparison indicators were therefore introduced, obtained by normalizing the performance with respect to the reference values: the MI/MI_{inf} ratio, relating to mechanical performance, and the EI_{sup}/EI ratio, relating to environmental performance, as seen in figure 4.14. As regards economic performance, the mechanical reference remains that associated with the O30 mixture. However, the economic comparison in figure 4.15 value CI_{sup} is assumed to be equal to the unit cost of concrete of equal strength in the "green" version, corresponding to $170€/m^3$. The prescriptive approach, suggested by the CAM, establishes certain rules regarding the composition of green concrete, indeed, Italian prescription establishes that the minimum recycled material content of concrete must be no less than 5% by weight. Therefore, in the eco-mechanical analyses of figure 4.16, $EI_{inf} = 5\%$ is considered, while the lower limits of mechanical performance are relative to the reference mechanical strength class.

It should be noted that the assessments reported above constitute an introductory comparison between the different mixtures analyzed, based exclusively on the environmental and economic data derived from the "cradle-to-gate" LCA studies

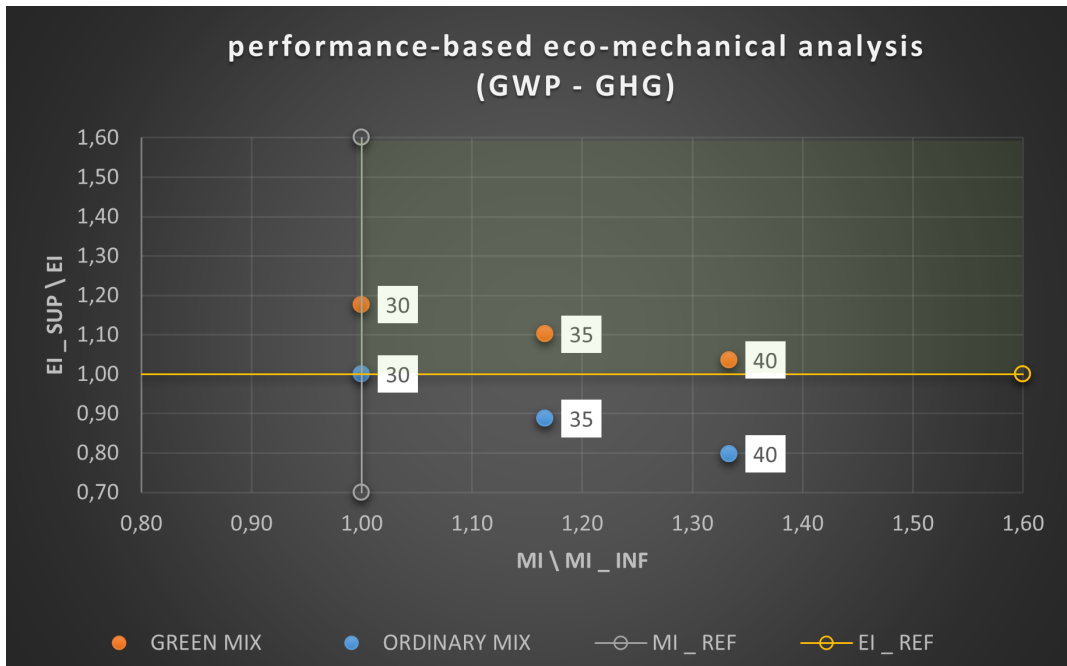


Figure 4.14: Performance-based eco-mechanical analysis (GWP - GHG)

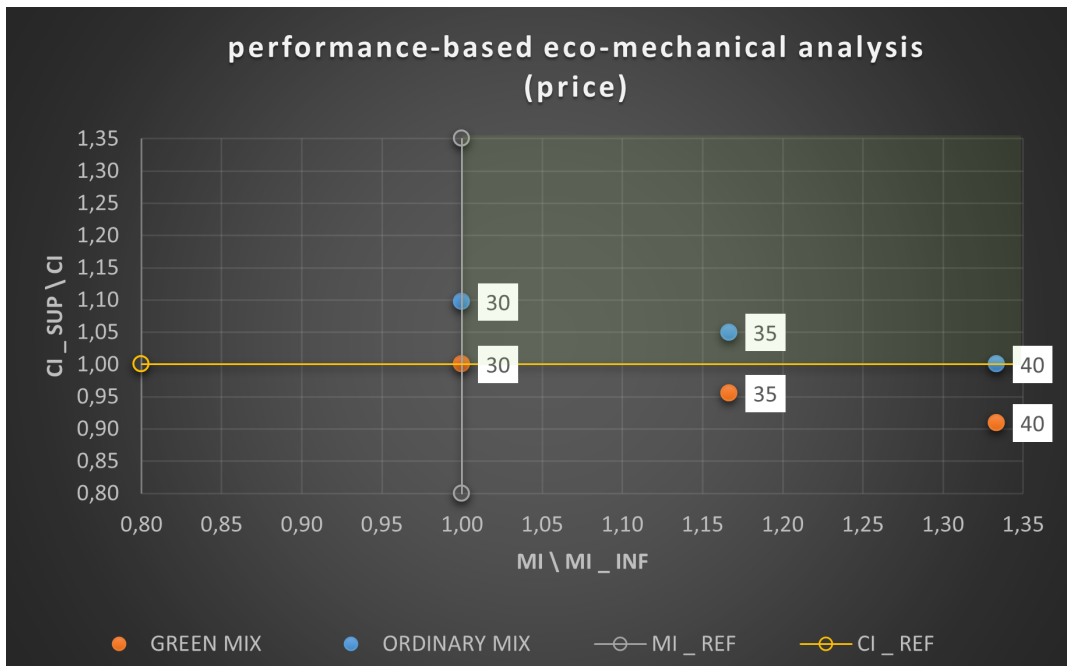


Figure 4.15: Performance-based eco-mechanical analysis (Price)

reported in the respective Environmental Product Declarations (EPDs). This comparison does not, at this stage, take into account the implications arising from the

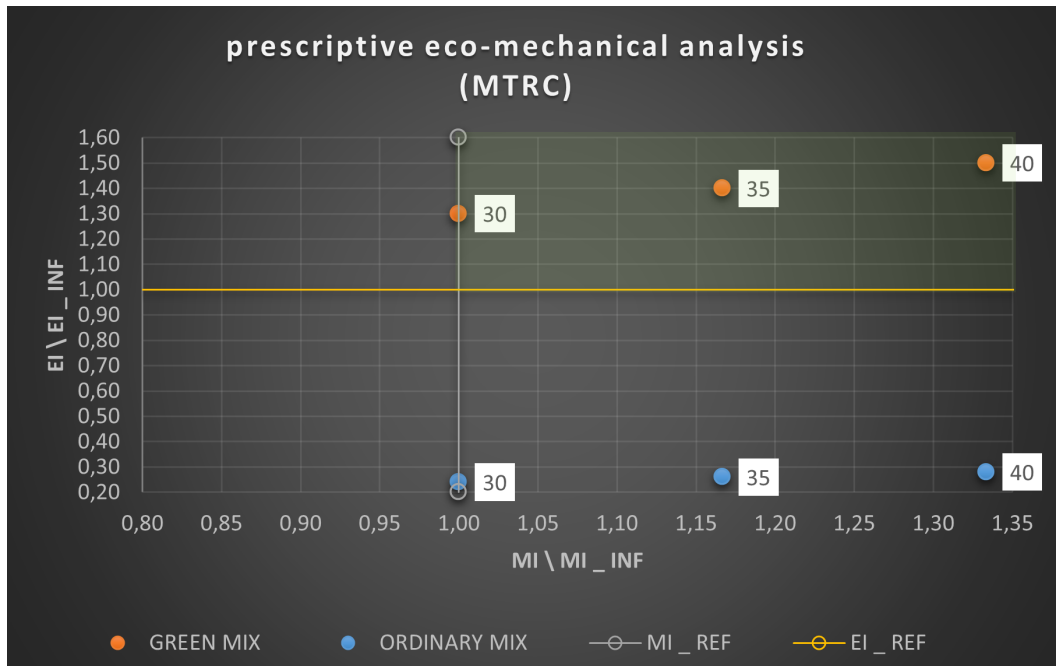


Figure 4.16: Prescriptive eco-mechanical analysis (Minimum Total Recycled Content)

actual implementation of the mechanical, environmental, and economic characteristics within the structural design, in other words, the proposed analysis represents a preliminary parametric comparison, which ignores the influence of the different strength classes on the overall behavior of the structure and on the quantities of material actually used in the design.

From the environmental analysis based on GWP-GHG in figure 4.14 it emerges that all the "green" mixtures satisfy the performance benchmark defined by the O30 reference mixture and the comparison between mixtures of the same resistance class highlights a reduction in emissions equal to approximately:

- 18% between O30 and G30,
- 24% between O35 and G35,
- 30% between O40 and G40.

Instead, assuming O30 as an absolute reference, the G35 and G40 mixtures show a reduction of 10% and 3,6% respectively, still confirming an environmental improvement compared to ordinary concrete of a lower class.

From an economic standpoint from figure 4.15, considering the price of the G30 mix as a reference, G35 and G40 concretes show an increase of 4.5% and % respectively, while O35 has a 5% lower unit cost. A direct comparison between ordinary

and green versions of the same class (O30-G30, O35-G35, O40-G40) highlights an average price difference of close to 10%. It is also interesting to note that the unit price of the G30 mix is equivalent to that of the O40 mix, highlighting a possible economic overlap between higher strength classes and lower environmental profiles.

Regarding the total content of recycled aggregates, the comparison with the minimum 5% requirement set by the CAM highlights the greatest percentage deviation between the mixtures analyzed, contributing more significantly to the satisfaction of the minimum environmental criteria.

In all three graphs, the third quadrant, the one in the upper right, identifies the area in which performance compared to the reference benchmarks is simultaneously maximized, and therefore, within the parametric analysis adopted, the most favorable solutions. With regard to environmental performance, ordinary concretes represent, in relative terms, the least performing options compared to their respective benchmarks, while green formulations show a systematic improvement; conversely, from an economic perspective, ordinary mixtures are generally more competitive than their corresponding low environmental impact counterparts. Regarding total recycled material content, green mixtures not only meet the minimum 5% requirement set by the CAM, but significantly exceed it, demonstrating greater consistency with the prescriptive environmental criteria.

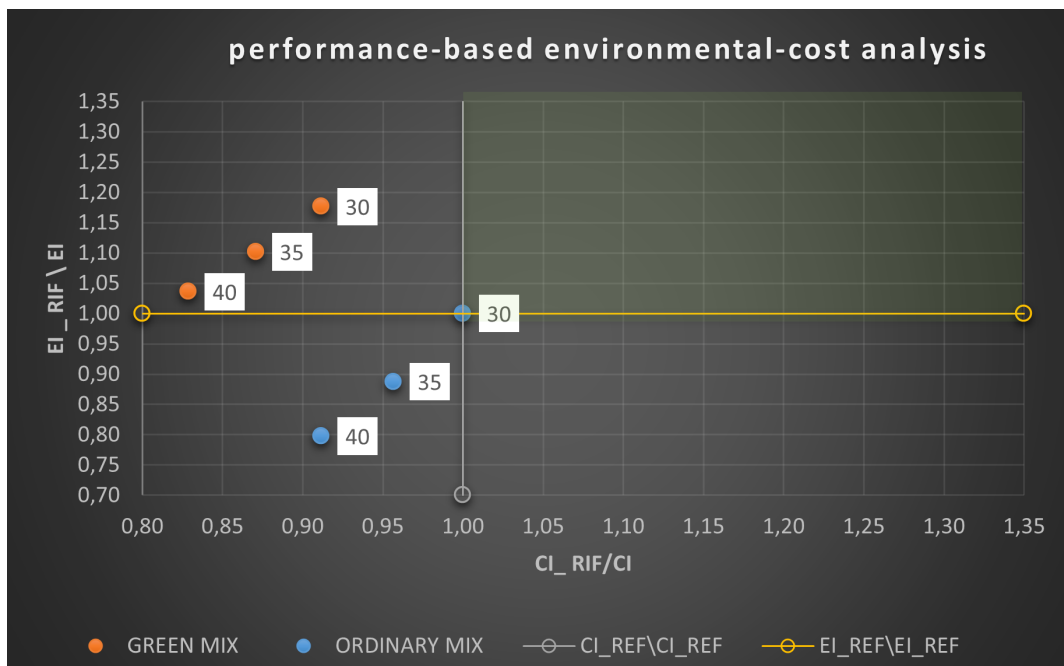


Figure 4.17: Performance-based environmental-cost analysis

It is interesting to note, however, how the picture changes significantly when environmental and economic performance is assessed per unit of volume using the

O30 mixture as a reference, which, due to its widespread application, can be considered representative of the most commonly adopted solution; in this scenario, green mixes only show an environmental improvement compared to the reference, while the higher strength classes in the ordinary version are less cost and environmental effective, as the performance don't meet the reference benchmarks.

All the considerations above are based exclusively on a comparison per unit volume of material and do not imply, at this stage, the integration of mixes into the structural sizing; it is precisely the latter that is the true deciding factor in the choice of material.

In this study, the structure will be analyzed based on the three different concrete strength classes previously defined, a structural analysis will be conducted for each configuration, in accordance with the 2018 Norme Tecniche per le Costruzioni (NTC), assuming elastic behavior for the first structural type and ductility class B for the second. For the ductility class B solution, specific checks for dissipative behavior are requested, such as checking the local ductility of the elements, checking the global ductility of the structural system, and applying resistance hierarchy criteria. These aspects, which are not required for the elastic solution, determine a substantial difference in the sized elements. Following the structural checks, for each combination of concrete strength class and structural type, an estimated bill of quantities will be prepared relating to the structural materials used, with particular reference to the volumes of concrete and the quantities of reinforcing steel. These quantities will then be integrated with the economic and environmental data (GWP-GHG) derived from the EPDs to obtain an Environmental-Costing assessment of the building, limited to the previously mentioned resistant structural elements.

Overall, the analysis will produce six distinct bills of quantities, corresponding to the combinations of resistance classes and structural types. For each estimated bill, two ELCC-based assessments will be developed, one for the standard version and one for the green version, for a total of twelve final results subject to comparison and critical analysis. The LCAs performed in this study is limited to the cradle-to-gate modules (A1-A3) as defined by UNI EN 15804:2012+A2:2019. The environmental impacts are derived directly from the EPDs of the analyzed concrete and steel. The assessment does not include transport to site (A4), construction processes (A5), use phase (B), end-of-life stages (C) nor benefits beyond the end of life (D); as a consequence, the analysis cannot be formally considered a complete ELCC assessment.

We can therefore speak of a **parametric and comparative ELCC-based assessment of Embodied Environmental and Cost of the functional unit of the resistant structure** designed according to NTC 2018. The evaluation can be defined as *parametric*, since each structural configuration depends on two main parameters: the characteristic compressive strength of concrete R_{ck} and the seismic behavior factor q . These parameters represent respectively a mechanical index and

a structural index governing the structural design process. The analysis is also *comparative*, as each configuration is evaluated in terms of environmental impact and economic cost associated with the structural materials. More rigorously, the relationship between design parameters and performance indicators can be expressed through the following functional flow:

$$Q = f(R_{ck}, q) \quad (4.1)$$

$$(GWP, COST) = g(Q, EPD, C_m) \quad (4.2)$$

where C_m represents the market unit cost. The total environmental impact for each configuration is determined as:

$$GWP_{tot} = \sum_i (Q_i \cdot GWP_{i,A1-A3}) \quad (4.3)$$

where Q_i is quantity of the i -th structural material, m^3 of concrete and kg of steel, $GWP_{i,A1-A3}$ is unit environmental impact derived from the EPD, $kgCO_2eq$ per unit of material. While, the total structural material cost is obtained as follows:

$$COST_{tot} = \sum_i (Q_i \cdot C_i) \quad (4.4)$$

where C_i is the unit market cost of the i -th material.

ANALYSIS	CLASS OF CONCRETE	TYPE OF STRUCTURE	TYPE OF CONCRETE
ND O_C25/30	25/30	ND	O
ND O_C28/35	28/35		
ND O_C32/40	32/40		
CDB O_C25/30	25/30	CDB	
CDB O_C28/35	28/35		
CDB O_C32/40	32/40		
ND G_C25/30	25/30	ND	G
ND G_C28/35	28/35		
ND G_C32/40	32/40		
CDB G_C25/30	25/30	CDB	
CDB G_C28/35	28/35		
CDB G_C32/40	32/40		

Table 4.6: Structural configurations analysed in the $ELCC_{A1-A3}$ -based assessment

Where O is ordinary concrete, G is the corresponding green one, ND is the non dissipative typology of design construction, CDB is medium ductility one and the class of concrete is the resistance in compliance with Italian Regulations.

Reference standards implemented in ProSap

1. D.M. Infrastrutture, Interno e Protezione Civile 17 gennaio 2018 e s.m.i., “Norme tecniche per le costruzioni”.
2. Circolare 21 gennaio 2019, n. 7 C.S.LL.PP., “Istruzioni per l’applicazione dell’aggiornamento delle Norme Tecniche delle Costruzioni di cui al D.M. 17 gennaio 2018”.
3. D.M. Infrastrutture e Trasporti 14 settembre 2005, “Norme tecniche per le costruzioni”.
4. D.M. LL.PP. 9 gennaio 1996, “Norme tecniche per il calcolo, l’esecuzione ed il collaudo delle strutture in cemento armato, normale e precompresso e per le strutture metalliche”.
5. D.M. LL.PP. 16 gennaio 1996, “Norme tecniche relative ai criteri generali per la verifica di sicurezza delle costruzioni e dei carichi e sovraccarichi”.
6. D.M. LL.PP. 16 gennaio 1996, “Norme tecniche per le costruzioni in zone sismiche”.
7. Circolare 4 luglio 1996, n. 156AA.GG./STC, Istruzioni per l’applicazione del D.M. 16 gennaio 1996.
8. Circolare 10 aprile 1997, n. 65AA.GG., Istruzioni per l’applicazione del D.M. 16 gennaio 1996 relativo alle costruzioni in zone sismiche.
9. D.M. LL.PP. 20 novembre 1987, “Norme tecniche per la progettazione, esecuzione e collaudo degli edifici in muratura e per il loro consolidamento”.
10. Circolare 4 gennaio 1989 n. 30787, Istruzioni relative al D.M. 20 novembre 1987.
11. D.M. LL.PP. 11 marzo 1988, “Norme tecniche riguardanti le indagini sui terreni e sulle rocce, la stabilità dei pendii naturali e delle scarpate e le opere di fondazione”.
12. D.M. LL.PP. 3 dicembre 1987, “Norme tecniche per la progettazione, esecuzione e collaudo delle costruzioni prefabbricate”.
13. UNI 9502:2001, Procedimento analitico per la valutazione della resistenza al fuoco degli elementi in calcestruzzo armato.
14. Ordinanza P.C.M. n. 3274 del 20 marzo 2003 e s.m.i., “Criteri generali per la classificazione sismica del territorio nazionale”.

15. UNI EN 1990:2006, Eurocodice 0 - Criteri generali di progettazione strutturale.
16. UNI EN 1991-1-1:2004, Eurocodice 1 - Azioni sulle strutture - Parte 1-1.
17. UNI EN 1991-1-3:2004, Eurocodice 1 - Azioni sulle strutture - Carichi da neve.
18. UNI EN 1991-1-4:2005, Eurocodice 1 - Azioni sulle strutture - Azioni del vento.
19. UNI EN 1991-1-5:2004, Eurocodice 1 - Azioni termiche.
20. UNI EN 1992-1-1:2005, Eurocodice 2 - Progettazione delle strutture in calcestruzzo.
21. UNI EN 1992-1-2:2005, Eurocodice 2 - Progettazione contro l'incendio.
22. UNI EN 1993-1-1:2005, Eurocodice 3 - Progettazione delle strutture in acciaio.
23. UNI EN 1993-1-8:2005, Eurocodice 3 - Progettazione dei collegamenti.
24. UNI EN 1994-1-1:2005, Eurocodice 4 - Strutture composte acciaio-calcestruzzo.
25. UNI EN 1995-1-1:2005, Eurocodice 5 - Progettazione delle strutture in legno.
26. UNI EN 1996-1-1:2006, Eurocodice 6 - Strutture in muratura.
27. UNI EN 1997-1:2005, Eurocodice 7 - Progettazione geotecnica.
28. UNI EN 1998-1:2005, Eurocodice 8 - Progettazione per la resistenza sismica.
29. UNI EN 1998-3:2005, Eurocodice 8 - Valutazione e adeguamento edifici.
30. UNI EN 1998-5:2005, Eurocodice 8 - Fondazioni e aspetti geotecnici.
31. CNR DT-200/2013, Istruzioni per interventi di consolidamento mediante FRP.
32. CNR DT-215/2018, Istruzioni per interventi di consolidamento mediante FRCM.

Chapter 5

Comparative Analysis Assessment

All the structural configurations were designed with the objective of optimizing the resistant sections in relation to the increasing mechanical strength of the concrete and the different seismic behaviour of the structural system.

As mentioned, the designs were developed using the PRO_SAP finite element software. Thanks to its integrated verification and sizing modules, it allows the design of reinforced concrete cross-sections based on the geometry of the elements, the concrete cover, the reinforcement areas, and any additional reinforcement needed to compensate for the deficiencies identified by the checks. The same modules also allow for the quantification of the structural elements and the preparation of a bill of quantities estimates for the materials used. This estimate of quantities is generally consistent and comparable with those prepared in professional practice, although the latter benefits from a greater level of details, especially with regard to construction aspects.

It should be emphasized that the estimated quantities computed by the software must be interpreted critically, as they always require verification and refinement by the designer. These drawings, although susceptible to improvement, are nonetheless the result of a comprehensive design process, which includes structural modeling, the definition of resistant geometries, the evaluation of permanent and variable loads and acting actions, such as wind, snow, and earthquakes, as well as the consideration of non-structural elements, such as infill walls and the roofing package, up to the sizing and design of supplementary reinforcement. In the context of this study, however, an extremely in-depth analysis of all the construction details for each configuration would not have been consistent with the research objective. The primary objective is to develop a parametric comparison between different structural configurations, maintaining a consistent level of modeling and detail across the various cases analyzed. From this perspective, the estimated quantities generated by the software provide a sufficiently reliable basis for evaluating and comparing the quantities of structural materials used in the 6 design configurations considered in the study that, though in different ways, comply with the standard NTC in all the

aspects. Figure 5.1 shows one of the finite element models used in the study, it is

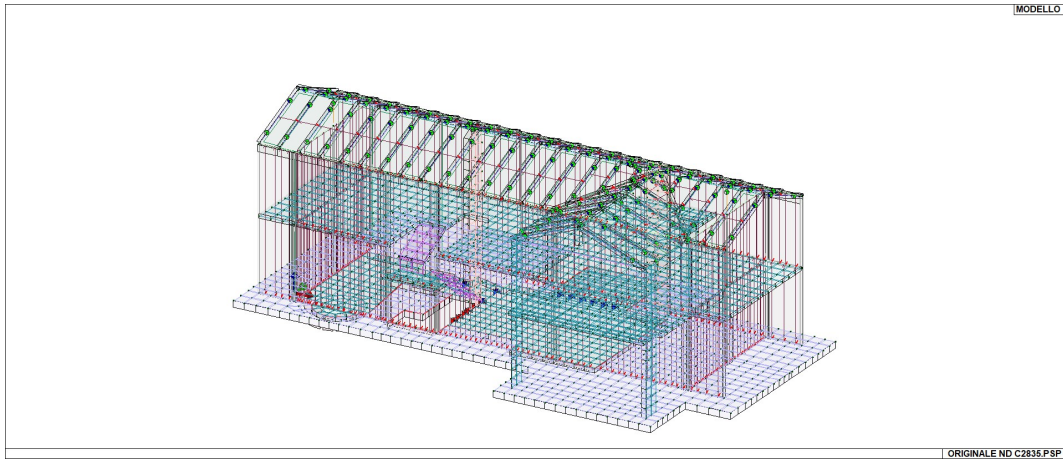


Figure 5.1: FEM model of the structure used in parametric analysis

representative of all the configurations analyzed, as the architectural geometry of the structure remains unchanged across the entire set of cases considered.

The variations introduced in the different models concern exclusively the characteristics of the resistant cross-sections, which are progressively updated based on the analyzed design parameters, specifically the characteristic strength of the concrete and the seismic behavior factor q , as well as the **Elastic and Design Spectra** used. In this way, it was possible to maintain the architectural and distributional layout of the structure constant, isolating the effect of the structural design choices on the quantities of materials used and the resulting environmental and economic performance. Seismic design is conducted following the constraints of the regulations on behavior factors q for structural typology and limit states: In addition to

STATI LIMITE		Lineare (Dinamica e Statica)		Non Lineare	
		Dissipativo	Non Dissipativo	Dinamica	Statica
SLE	SLO	$q = 1,0$ § 3.2.3.4	$q = 1,0$ § 3.2.3.4		
	SLD	$q \leq 1,5$ § 3.2.3.5	$q \leq 1,5$ § 3.2.3.5	§ 7.3.4.1	§ 7.3.4.2
SLU	SLV	$q \geq 1,5$ § 3.2.3.5	$q \leq 1,5$ § 3.2.3.5		
	SLC	---	---		

Figure 5.2: Table 7.3.I from NTC 2018: limits on the behavior factor

the limits on the behavior factor q reported in the Table 5.2, the Instructions to the

NTC 2018 (C.7.3.1) clarify that, if the application of high values of q to the SLV leads to ordinates of the design spectrum lower than those at the SLD, it is possible to reduce the behavior factor adopted at the SLV by introducing a corrected value defined as:

$$q' = q_{\text{ND}} \frac{S_{e,SLV}(T_1)}{S_{e,SLD}(T_1)} \quad (5.1)$$

where T_1 is the period of the first translational mode in the considered direction, while $S_{e,SLV}(T_1)$ and $S_{e,SLD}(T_1)$ are the ordinates of the elastic spectrum at the two limit states. The reinforced concrete structure was classified as a mixed frame-wall system equivalent to a frame. The values of q were therefore determined based on the reference q_0 values reported in Table 7.3.II of Chapter 7 of the NTC 2018, subsequently evaluated based on the regularity characteristics of the structure. Both constraints were satisfied. Furthermore, in the **linear dynamic analyses** for the non dissipative structural typology, a more conservative behavior factor q was deliberately adopted in the SLD compared to the maximum values allowed by the code, in order to maintain the structural response essentially in the elastic range at the damage limit state. For the dissipative configuration designed in ductility class B, a conservative behavior factor q was selected at the SLV, with the aim of containing inelastic demand and limiting excessive plasticization of the structure. These

Table 5.1: Behavior factor q adopted in the analyses

Structural behaviour	Limit state	q
ND	SLD	1.0
	SLV	1.5
CDB	SLD	1.5
	SLV	2.604

choices are consistent with a conscious and critical design approach, aimed at ensuring a balance between structural safety, performance and rationalization of design solutions. From a structure's end-of-life perspective, a more conservative seismic design can facilitate overcoming seismic events with lower levels of damage, helping to limit structural degradation throughout the structure's useful life. Maintaining greater material integrity can reduce the need for repairs and promote the recovery and recycling of materials in the final phase of the life cycle (LCA's phase D).

Here are now reported the horizontal's elastic and design spectra, from which the linear dynamic analysis are conducted, respectively for the Non Dissipative case and the low ductility case (CDB), for which the limit states' seismic parameters have already been reported in the table 4.2:

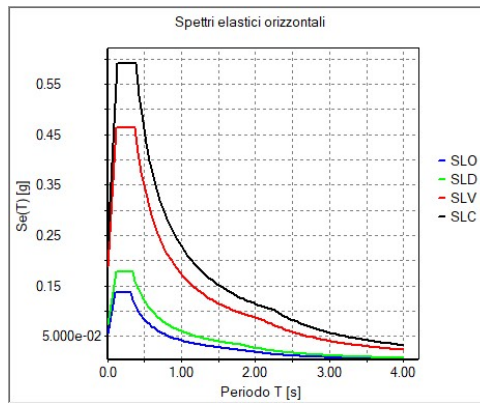


Figure 5.3: Horizontal's Elastic Spectra

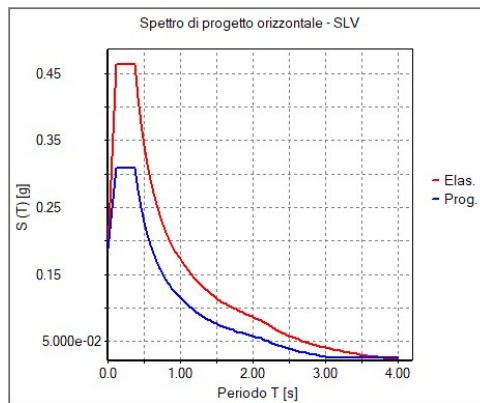


Figure 5.4: Horizontal's Design SLV Spectrum for Non Dissipative design

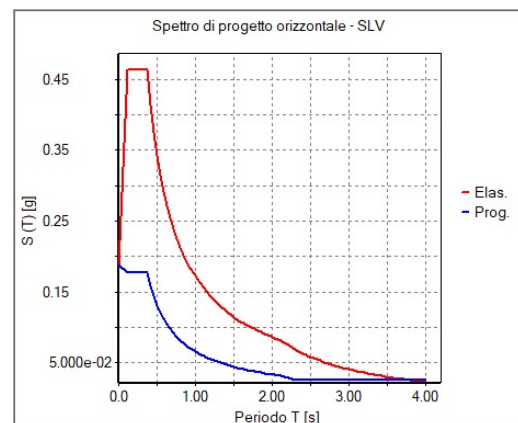
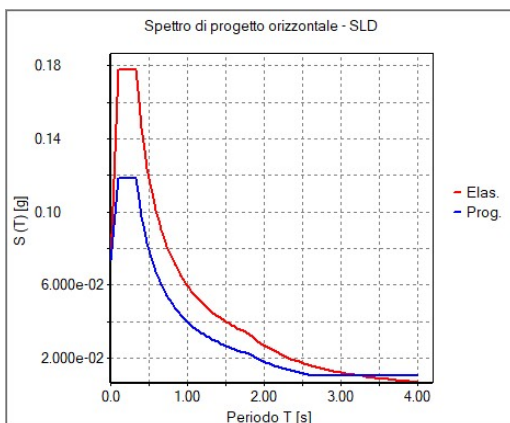


Figure 5.5: Horizontal's Design SLD and SLV spectra for CDB design

For clarity, the following images show the configuration of the structural skeleton, excluding secondary elements. The focus is on the configuration of the system of reinforced concrete resisting elements, the subject of the comparative analysis.

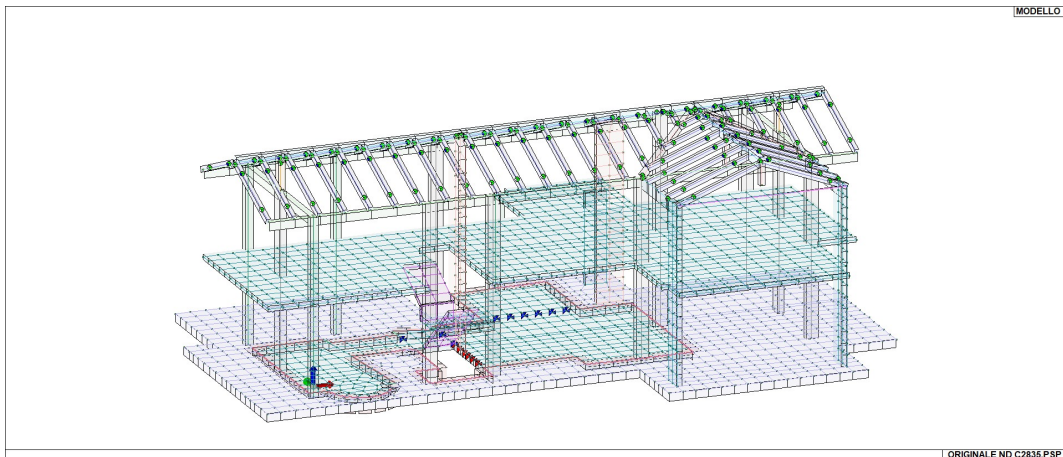


Figure 5.6: Structural resistant elements of the FEM model in axonometric view

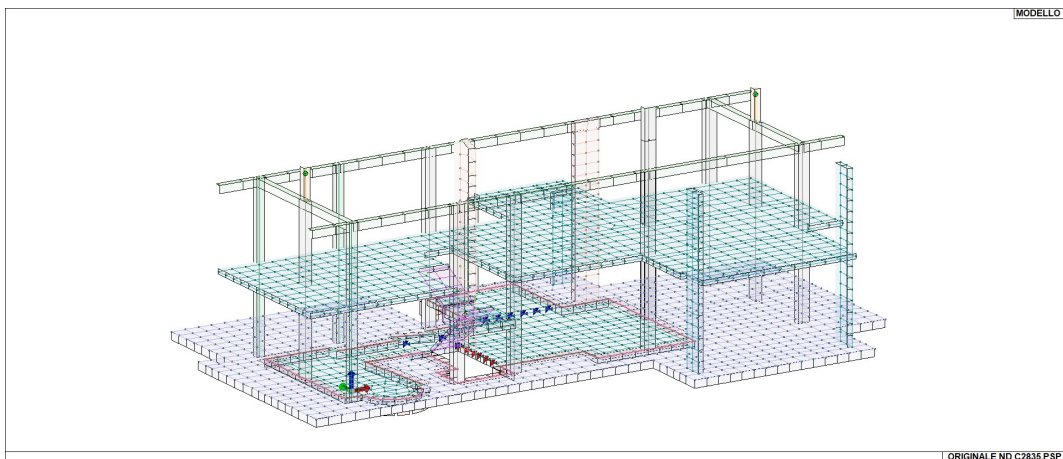


Figure 5.7: Structural resistant R.C. elements of the FEM model in axonometric view

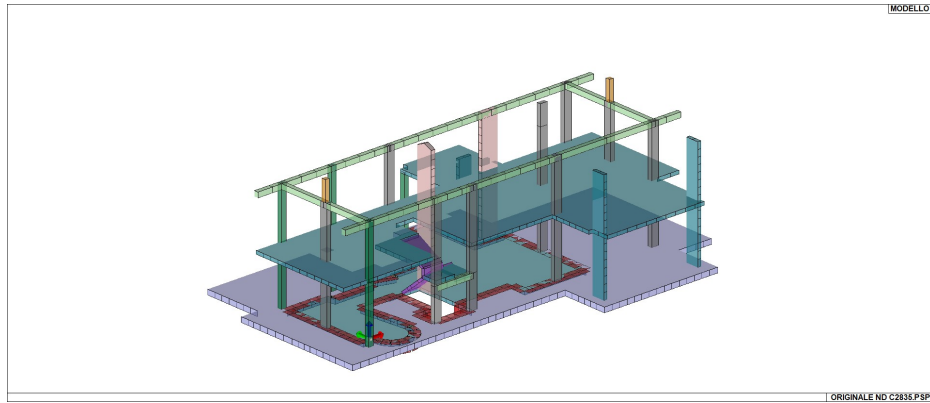


Figure 5.8: Transparent solid axonometric view of the R.C. frame

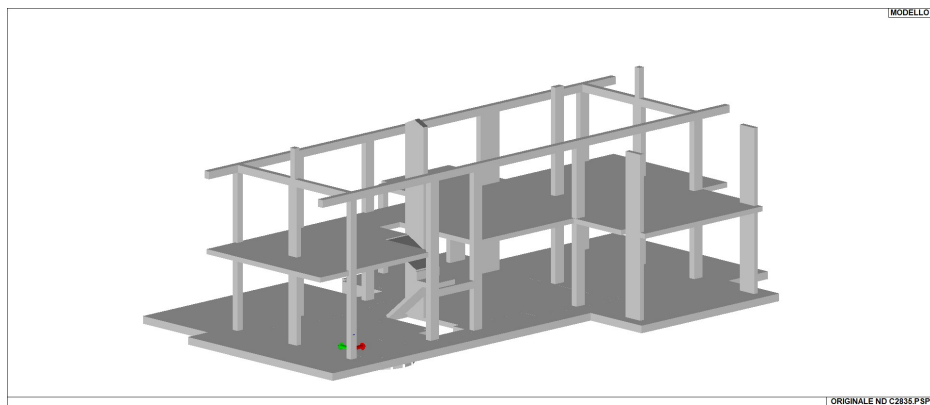


Figure 5.9: Solid axonometric view of the R.C. frame

The connecting foundation beams, configured as foundation curbs and connecting the foundation slab to the solid basement roof, ensure the structural continuity of the system. A stairwell also connects the ground floor to the basement.

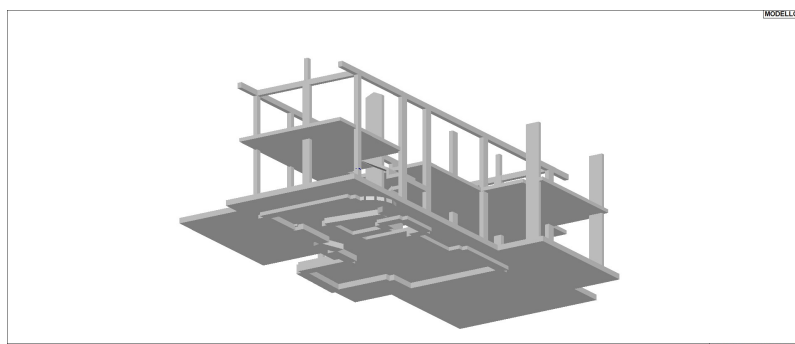


Figure 5.10: View of the foundation's system in the solid FEM model

Furthermore, in line with what was presented for concrete, the unit price and the GWP value associated with the reinforcing steel are reported.

Table 5.2: Environmental and economic parameters adopted for reinforcing steel

Material	GWP-GHG <i>kgCO₂eq/kg</i>	Cost euro/kg
Steel	0,50	2,11

Applying the relationship 4.1 the results of the quantity estimates relating to the concrete, divided by category of structural element, and the total reinforcing steel used are reported below.

QUANTITY SURVEYS			ND C25/30	D C25/30	ND C28/35	D C28/35	ND C32/40	D C32/40
CONCRETE	Foundation Beams	Volumes [mc]	17,41	17,57	17,41	17,58	17,41	17,54
	Elevation Beams	Volumes [mc]	4,35	10,16	4,35	10,45	4,35	9,14
	Columns	Volumes [mc]	8,61	14,21	8,61	12,81	7,19	15,78
	Foundation Slab	Volumes [mc]	50,95	50,95	50,95	50,95	50,95	50,95
	Slabs	Volumes [mc]	74,17	65,67	49,27	57,75	49,27	57,75
	Load Bearing Walls	Volumes [mc]	8,31	8,27	6,25	6,81	6,25	6,94
	TOTAL	Volumes [mc]	163,80	166,82	136,85	156,35	135,44	158,11
STEEL	REBARS	Weight [kN]	273,26	230,02	223,20	188,54	228,62	200,19
		Weight [kg]	27.863,91	23.455,24	22.759,70	19.225,63	23.312,08	20.413,78
		Steel/Concrete [kg/mc]	170,11	140,60	166,31	122,97	172,13	129,11

Figure 5.11: Quantities Estimates of the structural configurations

The transition to CDB generally involves an increase in concrete volumes, due to the increase in resistant cross-sections necessary to satisfy the ductility and resistance hierarchy requirements.

Table 5.3: Percentage variation of total concrete volume between ND and CDB configurations

$\Delta[\%] = \frac{X_{CDB} - X_{ND}}{X_{ND}} \times 100 \quad (X = \text{Concrete [m}^3\text{)})$			
Concrete class	ND [m ³]	CDB [m ³]	Δ [%]
C25/30	163,80	166,82	+1,8
C28/35	136,85	156,35	+14,3
C32/40	135,44	158,11	+16,7

While in terms of steel, the CDB configuration shows a reduction between 12% and 16%.

Table 5.4: Percentage variation of reinforcing steel quantities between ND and CDB configurations

$$\Delta[\%] = \frac{X_{CDB} - X_{ND}}{X_{ND}} \times 100 \quad (X = \text{Steel [kg]})$$

Concrete class	ND [kg]	CDB [kg]	Δ [%]
C25/30	27.863,91	23.455,24	-15,8
C28/35	22.759,70	19.225,63	-15,5
C32/40	23.312,08	20.413,78	-12,4

The ND-CDB comparison highlights a trade off between the amount of concrete and steel, the adoption of a higher behavior factor q in the CDB configuration reduces the design seismic demand at the SLV, with a possible decrease in the overall longitudinal reinforcement. At the same time, the ductility and resistance hierarchy requirements may lead to an increase in the cross-section dimensions and a different distribution of the reinforcement, determining an increase in the concrete volumes and a consequent variation in the steel - concrete ratio.

Once Quantities Q_i are defined, the logical relation 4.2 relies on the mathematical computations of 4.3 and 4.4. The values of the results of the $ELCC_{A1-A3}$ -based parametric comparative analysis are then defined:

	GWP-COST	ND C25/30	CDB C25/30	ND C28/35	CDB C28/35	ND C32/40	CDB C32/40
NON-GREEN	CLS Volumes [mc]	163,80	166,82	136,85	156,35	135,44	158,11
	CLS COST [€]	25.388,54 €	25.857,57 €	22.169,70 €	25.328,70 €	23.023,95 €	26.878,53 €
	Steel Weight [kg]	27.863,91	23.455,24	22.759,70	19.225,63	23.312,08	20.413,78
	Steel COST [€]	58.792,86 €	49.490,56 €	48.022,98 €	40.566,07 €	49.188,48 €	43.073,08 €
	CLS GWP [kg CO2]	42.587,22	43.373,98	40.097,05	45.810,55	44.151,81	51.550,05
	Steel GWP [kg CO2]	13.931,96	11.727,62	11.379,85	9.612,81	11.656,04	10.206,89
	COST [EURO]	84.181,39 €	75.348,12 €	70.192,68 €	65.894,77 €	72.212,43 €	69.951,61 €
	GWP [kg CO2]	56.519,18	55.101,60	51.476,90	55.423,36	55.807,85	61.756,95
GREEN	CLS Volumes [mc]	163,80	166,82	136,85	156,35	135,44	158,11
	CLS COST [€]	27.845,49 €	28.359,91 €	24.359,30 €	27.829,05 €	25.326,35 €	29.566,38 €
	Steel Weight [kg]	27.845,49	28.359,91	24.359,30	27.829,05	25.326,35	29.566,38
	Steel COST [€]	58.792,86 €	49.490,56 €	48.022,98 €	40.566,07 €	49.188,48 €	43.073,08 €
	CLS GWP [kg CO2]	36.199,14	36.867,88	32.296,60	36.896,95	33.994,19	39.685,36
	Steel GWP [kg CO2]	13.931,96	11.727,62	11.379,85	9.612,81	11.656,04	10.206,89
	COST [EURO]	86.638,35 €	77.850,47 €	72.382,28 €	68.390,40 €	74.514,82 €	72.639,46 €
	GWP [kg CO2]	50.131,09	48.595,50	43.676,45	46.508,64	45.650,22	49.892,25

Figure 5.12: Values of the $ELCC_{A1-A3}$ - based cost and environmental impacts

For the sake of brevity and clarity, the results are presented using a graphical scheme similar to that frequently used in economic-environmental analyses of public procurement. Specifically, the results are illustrated using a combined column-line

graph, where the columns represent the cost values of the analyzed structural materials, while the line represents the corresponding environmental indicators. The two indicators are plotted on separate vertical axes to allow for simultaneous reading.

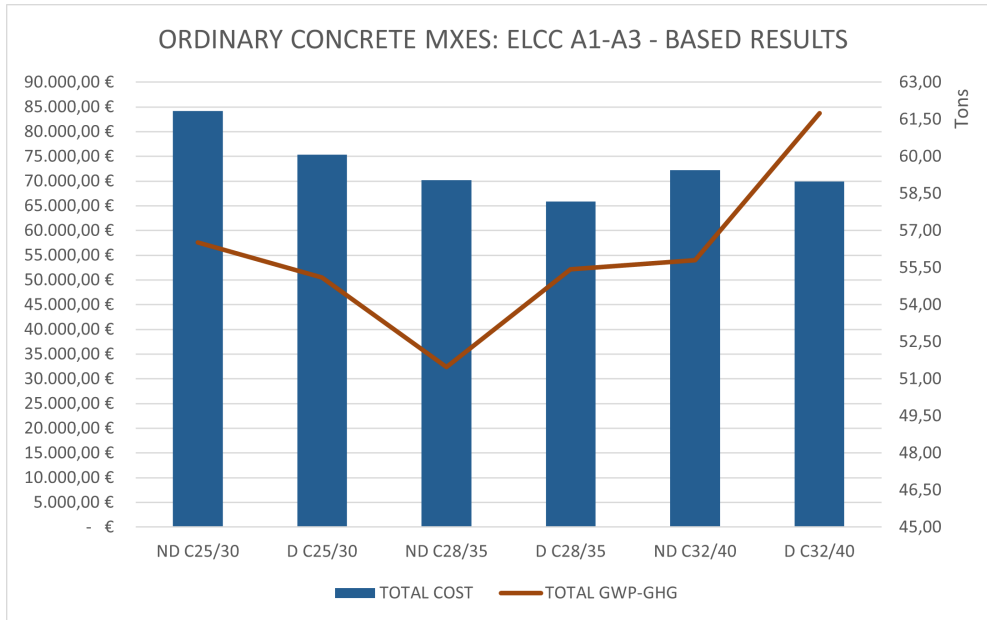


Figure 5.13: $ELCC_{A1-A3}$ comparative results for ordinary concrete mixes

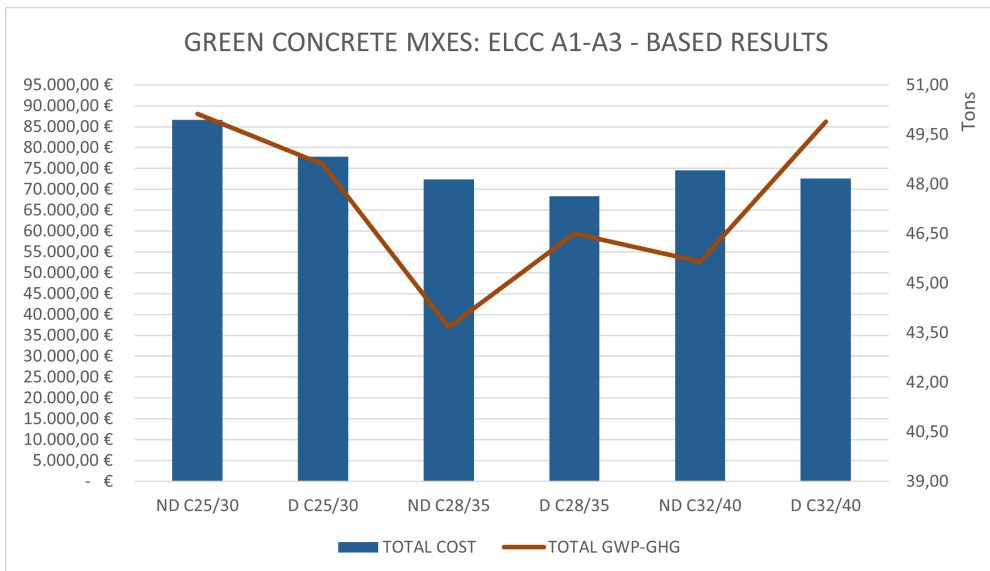


Figure 5.14: $ELCC_{A1-A3}$ comparative results for green concrete mixes

The comparison of the results highlights some significant trends in relation both

to the type of structural behaviour under seismic actions, therefore non-dissipative and dissipative in the medium ductility class, and to the type of concrete mix used, ordinary type and green type. First, considering ordinary mixes, the transition from the non-dissipative configuration to the ductility class B configuration results in a systematic reduction in the overall cost of the structure. Specifically, a cost reduction of approximately range of 3%, 10% is observed, with the most significant reduction associated with the C25/30 strength class. From an environmental perspective, expressed through the GWP indicator, the behavior is different: while for the C25/30 class a slight reduction in environmental impact of -2.5% is recorded, for the higher strength classes an increase in GWP of $+7.7\%$, $+10.7\%$ is observed, respectively. This trend is due to the increased volume of concrete used in dissipative configurations, necessary to meet the ductility and strength hierarchy requirements, in relation to the significant unit increase of the embodied carbon in the higher strength mixes.

Table 5.5: ORDINARY CONCRETE MIXES: Percentage variation of Cost and GWP for CDB configurations with respect to the corresponding ND configuration.

$$\Delta[\%] = \frac{X_{CDB} - X_{ND}}{X_{ND}} \times 100 \quad (X = \text{Cost, GWP})$$

Concrete class	Δ Cost [%]	Δ GWP [%]
C25/30	-10.5	-2.5
C28/35	-6.1	+7.7
C32/40	-3.1	+10.7

A similar pattern emerges when analyzing configurations made with green concrete: the transition from ND to CDB results in a reduction in structural costs, with variations ranging from approximately -2.5% , -10% depending on the strength class. Regarding environmental impact, the C25/30 class shows a reduction in GWP of approximately -3.1% , while for the higher classes, increases of approximately $+6.5\%$, $+9.3\%$ are recorded, respectively.

Table 5.6: GREEN CONCRETE MIXES: Percentage variation of Cost and GWP for CDB configurations with respect to the corresponding ND configuration.

$$\Delta[\%] = \frac{X_{CDB} - X_{ND}}{X_{ND}} \times 100 \quad (X = \text{Cost, GWP})$$

Concrete class	Δ Cost [%]	Δ GWP [%]
C25/30	-10.1	-3.1
C28/35	-7.4	+6.5
C32/40	-2.5	+9.3

Finally, directly comparing green and non-green mixes for the same structural configuration and strength class, a consistent and stable trend emerges.

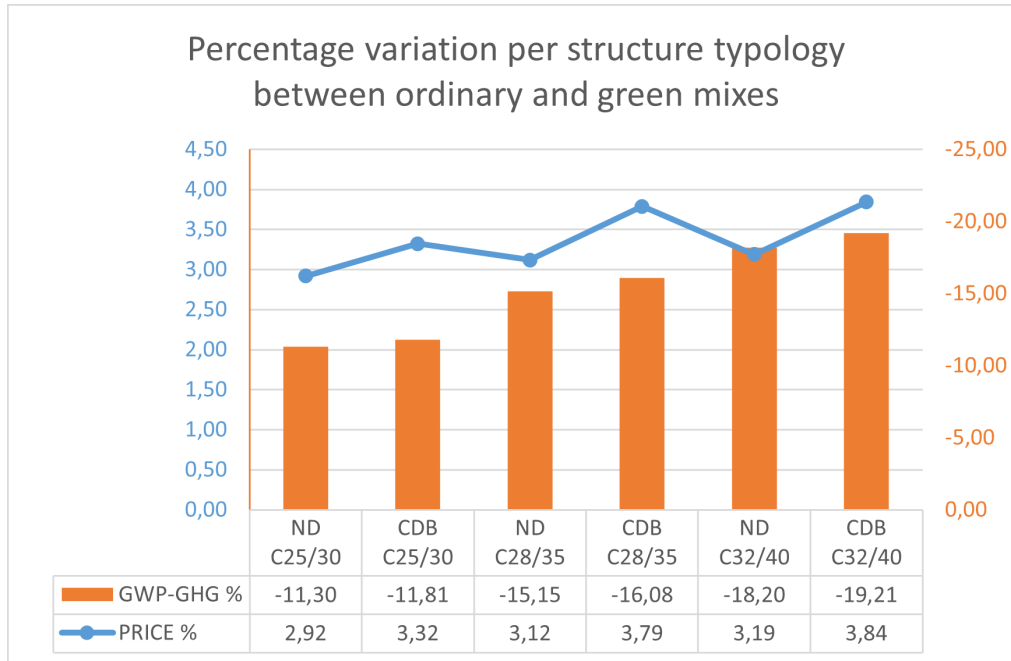


Figure 5.15: Percentage variation per structure typology relatively to ordinary mixes

For ND configurations, the use of green concretes leads to a limited increase in overall cost, in the order of approximately +3%, at the same time to a significant reduction in embodied $kgCO_2eq$, between approximately -11%, -18%.

Table 5.7: ND CONFIGURATIONS: Percentage variation of cost and GWP for GREEN mixes with respect to the corresponding NON-GREEN mix

$$\Delta[\%] = \frac{X_G - X_O}{X_O} \times 100 \quad (X = \text{Cost, GWP})$$

Concrete class	Δ Cost [%]	Δ GWP [%]
C25/30	+2.9	-11.3
C28/35	+3.1	-15.2
C32/40	+3.2	-18.2

The behavior is similar in the cases of medium ductility, with same magnitude of cost increases and embodied carbon reductions in the order of -12% , -19% . It follows that sustainable oriented mixes allow for a significant reduction in the embodied climate impact (A1-A3), with a relatively much limited additional economic cost.

Table 5.8: CDB CONFIGURATIONS: Percentage variation of cost and GWP for GREEN mixes with respect to the corresponding NON-GREEN mix

$$\Delta[\%] = \frac{X_G - X_O}{X_O} \times 100 \quad (X = \text{Cost, GWP})$$

Concrete class	Δ Cost [%]	Δ GWP [%]
C25/30	+3.3	-11.8
C28/35	+3.8	-16.1
C32/40	+3.8	-19.2

As regards the total content of recycled material involved in the different configurations, we have:

Table 5.9: Recycled content associated to the analysed structural configurations.

Mix type	Total Recycled Content [m^3]					
	ND C25/30	CDB C25/30	ND C28/35	CDB C28/35	ND C32/40	CDB C32/40
Ordinary	177.91	203.26	196.56	200.19	189.61	221.35
Green	957.95	1094.40	1064.68	1084.35	1015.76	1185.82

As discussed above, the requirement for the minimum recycled content set by the Minimum Environmental Criteria (CAM) represents the discriminating parameter in the evaluation of different concrete mixes, since compliance is determined precisely by the variation in percentage points of recycled content, as illustrated in Figure 4.16. In this context, the analysis of the total recycled content at the structural scale assumes particular relevance. Total recycled material content shows a perfectly consistent trend between ordinary and green mixtures, since the percentage difference between ND and CDB configurations depends mainly on the variation in the overall quantities of material used in the structure. As we can see in Tab 5.10, for classes C25/30 and C32/40 the transition from ND to CDB entails a significant increase in the total recycled material content, equal to an average value of $+15\%$, while for class C28/35 the increase is more limited, less of one order of magnitude. This trend directly reflects that the dissipative configuration requires a greater use

Table 5.10: Percentage variation of total recycled content for CDB configurations with respect to the corresponding ND configuration.

$$\Delta[\%] = \frac{X_{CDB} - X_{ND}}{X_{ND}} \times 100$$

Concrete class	$\Delta[\%]$ Recycled Content
C25/30	+14.2
C28/35	+1.8
C32/40	+16.7

of material to comply with capacity design, the total amount of recycled content associated with the structure also increases proportionally. Consequently, in this case, the comparison between structural typologies is more meaningful than the comparison between mix types, as it allows us to highlight the effect of the design solution on the overall content of recycled material incorporated into the work.

The results presented allowed us to understand that the parameters vary in a systematic way. Therefore, the comparative parametric **Assessment** of the economic and environmental performance of the structure can be constructed in a more simplified and rigorous manner, allowing for greater clarity in the exposition of intent. The assessment is comparable to that of the Eco-Mechanical predictive analysis on concrete which takes place upstream, as it can be presented in Figures 4.14 and 4.15. In a certain sense, the method that will be presented is a fusion between the two intents, simultaneously presenting the environmental and economic performance of equal structures that satisfy the standards by parameterizing the behavior under seismic actions and the mechanical and environmental characteristics of the concrete material.

A reference structural configuration is assumed, to which the total Cost and Embodied Carbon content (A1-A3) values of the structure are associated, respectively indicated as $COST_{ref}$ and GWP_{ref} . In this study, this reference configuration was assumed to be equal to the **ND C25/30 with non-green concrete case**, as it represents the conventional use solution; the latter is associated with a reference EC parameter:

$$EC = \frac{GWP_{ref}}{COST_{ref}} = \frac{56.519,2 \text{ kgCO}_2eq}{84.181,4 \text{ €}} \simeq 0,67 \frac{\text{kgCO}_2eq}{\text{€}} \quad (5.2)$$

Starting from this reference two dimensionless indicators are defined for each analyzed configuration:

$$\begin{aligned} EI &= \frac{GWP_{ref}}{GWP_i} && \text{Environmental Index} \\ CI &= \frac{COST_{ref}}{COST_i} && \text{Cost Index} \end{aligned} \quad (5.3)$$

where GWP_i and $COST_i$ are, respectively, Environmental impact and total Cost of the i -th configuration. Where coefficient values greater than 1 indicate improved performance and values less than 1 identify configurations that perform less well than the reference case. The indices are computed and brought into a tabular form, then represented in a parametric diagram with abscissas CI and ordinates EI ; intuitively, the reference case assumes a pair of unit coordinates (1 ; 1), dividing the graph into four quadrants. The third quadrant, top right, represents the configurations that maximize both cost and ecological footprint. By changing the base

PARAMETRIC COMPARATIVE ENVIRONMENTAL-COST PERFORMANCE ANALYSIS	ND C25/30	CDB C25/30	ND C28/35	CDB C28/35	ND C32/40	CDB C32/40
	$EI = GWP_{ref}/GWP_i$	1,000 1,127	1,026 1,163	1,098 1,294	1,020 1,215	1,013 1,238
$CI = COST_{ref}/COST_i$	1,000 0,972	1,117 1,081	1,199 1,163	1,278 1,231	1,166 1,130	1,203 1,159

Figure 5.16: Parametric Comparative EI and CI indexes with reference to ND C25/30 ordinary concrete mix case

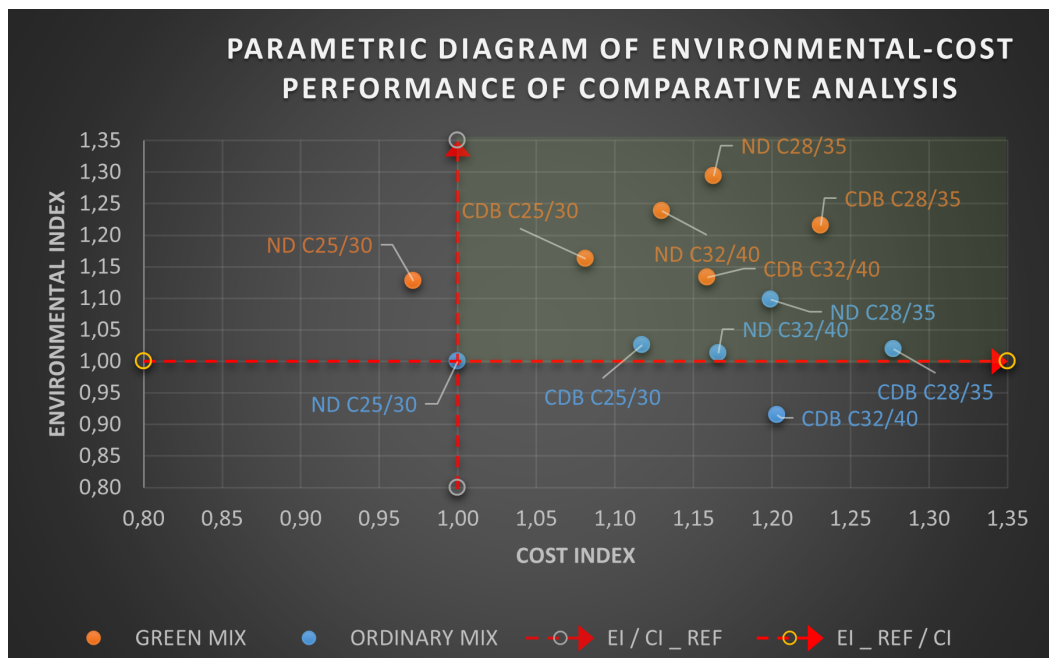


Figure 5.17: Parametric Comparative adimensional diagram for Environmental-Cost assessment

case, the numerical values of the indices vary and, consequently, also the coordinates of the configurations in the parametric diagram, and the entire reference system of the graph is recalculated with respect to the new case taken as the base. But it is important to note that the analysis method does not depend substantially on the configuration taken as a reference, since the indices are defined as normalized ratios with respect to the reference case, the comparative relationships between the configurations remain unchanged. The relative distances between the points, and therefore the percentage differences, and the hierarchy of the performance do not change, but are simply reinterpreted with respect to a different reference. Consequently, the configuration chosen as the baseline modifies the point with respect to which the normalization is performed, without altering the comparative structure of the assessment.

In this sense, the method takes on a systematic character and is independent of the specific reference adopted, since it allows for a coherent comparison of the relative performances of the different configurations.

Therefore, with reference to Figure 5.17, it is clear at a glance that the preferred configuration from an environmental standpoint is that of the non dissipative structure designed with class C28/35 green concrete because it is the result of a design balance between the geometry of the resistant sections and the ecological footprint. In terms of structural raw resource costs, the preferred configuration is the structure designed in medium class dissipative terms with ordinary concrete, also in class C28/35. This latter configuration relatively maximizes the economic savings by approximately 15%, while the ecological savings are set aside by a relative percentage of almost -30%; in fact, it is on par with the reference configuration of unit coordinates.

Meanwhile, looking at the general situation in relation to the case study configuration (no - green ND C28/35), there is the green solution CDB C28/35 which improves both environmental (20%) and economic (5%) performance, making it the third quadrant solution.

In absolute terms, the use of green concrete in the structural configuration analyzed results in a reduction in embodied carbon equal to approximately 8 tons of carbon dioxide equivalent, compared to a cost increase of a few thousand euros. While this reduction may appear relatively small when viewed within the overall picture of global emissions, it becomes more significant when compared to other reference quantities.

For example, a reduction of this magnitude is comparable to the environmental footprint generated by approximately two years of use of a car, or the energy life cycle associated with approximately 19 barrels of oil, or even over 400,000 km traveled by a person by train.

If interpreted in the context of the building's life cycle, this reduction is comparable to approximately 3 to 4 years of emissions associated with the building's energy

needs for heating, highlighting how even interventions limited to the choice of structural materials can contribute significantly to reducing the overall environmental impact.

Chapter 6

Conclusion

The results show that the economic and environmental performance of a structure depends strongly on the overall design configuration, which directly determines the total quantities of materials employed. From this perspective, a structural solution may appear relatively sustainable even when ordinary materials are used, provided that the adopted configuration allows a significant reduction in the overall material quantities. Conversely, the use of materials with lower environmental impact does not automatically guarantee the best economic or environmental performance if the structural configuration leads to higher material consumption. These observations highlight the importance of adopting a holistic design approach, in which different structural configurations are evaluated simultaneously in terms of economic and environmental performance, rather than relying solely on a preliminary selection of materials based on their unit impacts.

Nevertheless, the results also show that the green concrete solutions analysed consistently provide a significant higher relative reduction in environmental impact compared with their ordinary counterparts, even when the structural configuration varies, bringing them in the higher zones of the quadrant of the diagram. This confirms that the adoption of low carbon mixtures can effectively contribute to reducing the embodied emissions of structural systems, provided that the design process correctly balances structural performances, and material quantities with respect to environmental indexes.

When the analysis is extended to the scale of the entire life cycle of the structure, the distinction between green and non green materials becomes even more relevant. Differences in the unit environmental performance of materials translate into significantly different absolute quantities of embodied emissions and recycled content within the structure. In particular, mixtures characterized by lower embodied carbon and higher recycled content result in substantially larger amounts of recovered material employed at the start of the structure's life cycle. This aspect is particularly relevant in the context of circular economy strategies in the construction sector, where the ability to recover and reuse materials from demolition or end-of-life phases

represents a key mechanism for reducing the demand for virgin resources and limiting the environmental impacts associated with the production of new construction materials.

In this perspective, the sustainability of concrete should be understood primarily as a design driven issue, and only secondarily as a material issue. The key challenge lies in the ability to coherently integrate mechanical performances, durability and environmental impacts across the entire life cycle of the structure. Consequently, the sustainability of concrete cannot be reduced to a simple distinction between "green" and "non - green" materials, but must instead be evaluated within a holistic design framework capable of integrating material selection, structural configuration, durability requirements and end life's management strategies.

Within this framework, the integration of the directives introduced by the Minimum Environmental Criteria (CAM), particularly those related to life cycle assessment methodologies and the evaluation of material related costs and impacts, could represent a significant opportunity for innovation in the private construction sector. Although these approaches are currently mandatory mainly in public procurement, their broader adoption in private projects could support more informed decision making during the design process. The application of such methodologies would encourage designers to evaluate structural solutions not only in terms of initial performance, but also with respect to their life cycle economic and environmental implications, promoting design practices more closely aligned with the principles of circular economy and resource efficiency. In the long term, extending these practices to the private sector could contribute to a meaningful reduction of greenhouse gas emissions associated with the built environment, while supporting the transition toward one more sustainable model.

Finally, further research should focus on the long term mechanical performance and durability of structural systems realized with green concretes containing high percentages of recycled materials, in order to support their wider and more reliable application in structural engineering practice.

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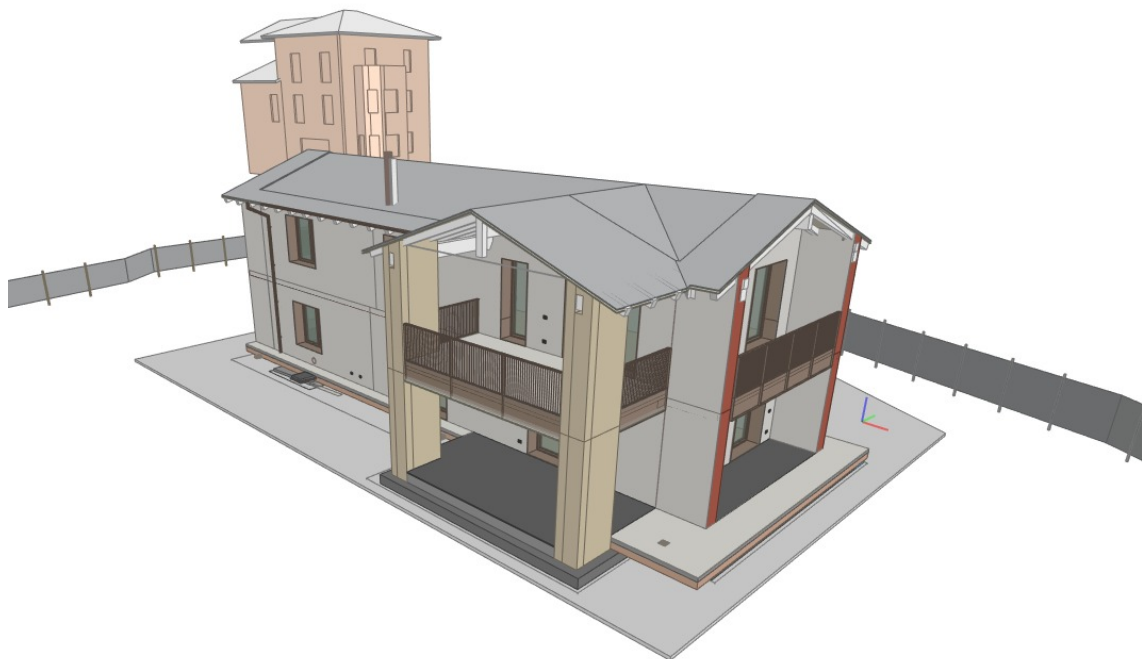
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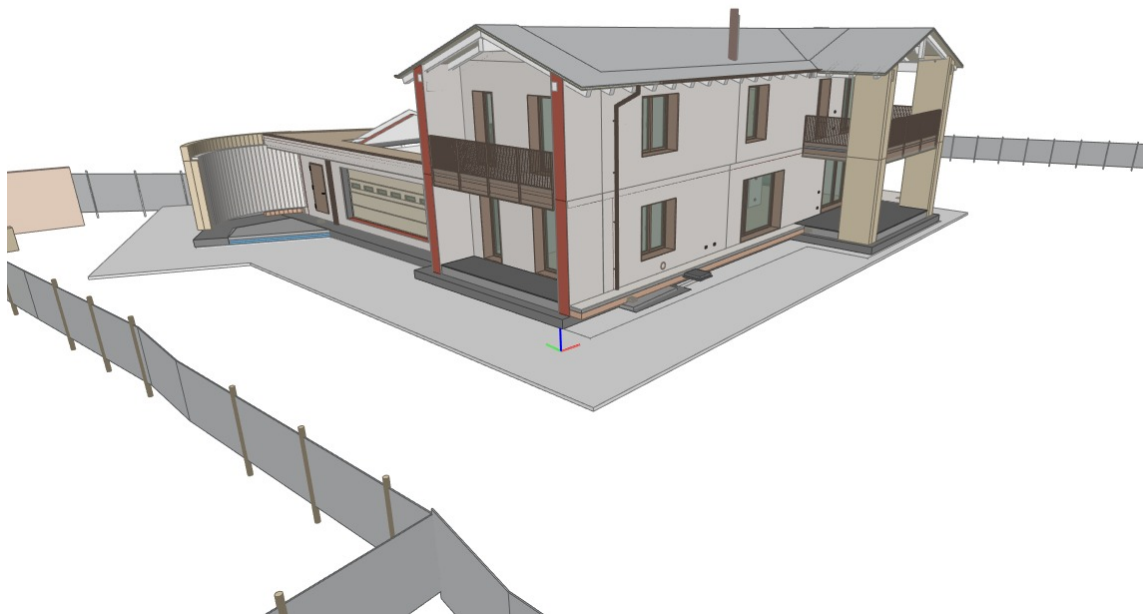
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Appendix A

Architectural and Design Models

Below is the architectural representation of the structure extracted from the BIM:





Below, the structural case study models are now reported, with the related quantitative estimates of the construction materials, both extrapolated from the PROSAP structural designs.

A.1 ND C25/30 STRUCTURAL MODEL

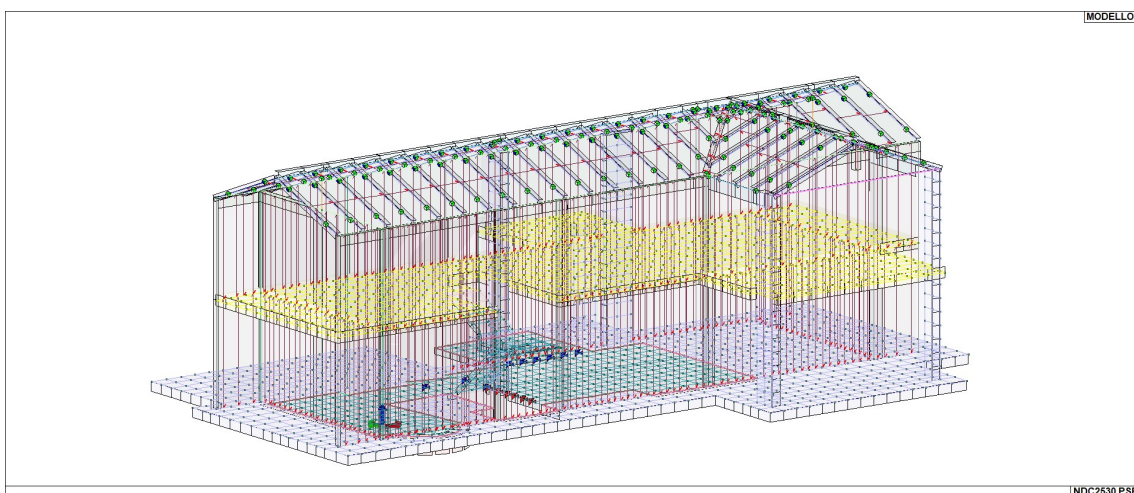


Tabella per il calcolo del costo indicativo delle opere

Cubature	mc	incidenze(*) daN/mc	Euro/mc	totale
Piinti	0.0	0.0	130.0	0.0
Travi rovesce	17.41	69.759	130.0	2263.31
Travi elevazione	4.353	183.588	180.0	783.54
Pilastr	8.605	181.935	180.0	1548.99
Platee	50.954	74.522	130.0	6623.976
Piastre	74.17	243.669	150.0	11125.453
Pareti	8.305	225.932	150.0	1245.69
Peli	0.0			

(*) incidenze ottenute da armature di progetto e pertanto solo indicative. I valori esatti si possono ottenere generando gli esecutivi con PRO_CAD.

Carpenterie	mq	Euro/mq	totale
Piinti	0.0	22.0	0.0
Travi rovesce	58.595	20.0	1171.891
Travi elevazione	49.334	35.0	1726.69
Pilastr	111.444	35.0	3900.54
Piastre	247.774	20.0	4955.477
Pareti	55.796	30.0	1673.88
Area solai e balconi	0.0	[esclusi dal computo]	

Acciaio	kN	Euro/kN	totale
Armature lente	273.256	100.0	27325.624
Pilastr	0.0	300.0	0.0
Travi	0.0	0.0	0.0
Aste	0.154	0.0	0.0

Elementi in legno	mc	Euro/mc	totale
Pilastr	8.0000e-02	0.0	0.0
Travi e aste	9.167	0.0	0.0
Pareti XLAM	0.0	0.0	0.0
Piastre XLAM	0.0	0.0	0.0
Solai XLAM	0.0	0.0	0.0

Costo indicativo opera

64.345 euro x mille

Esporta dati

Aggiorna Esci

A.2 ND C28/35 STRUCTURAL MODEL

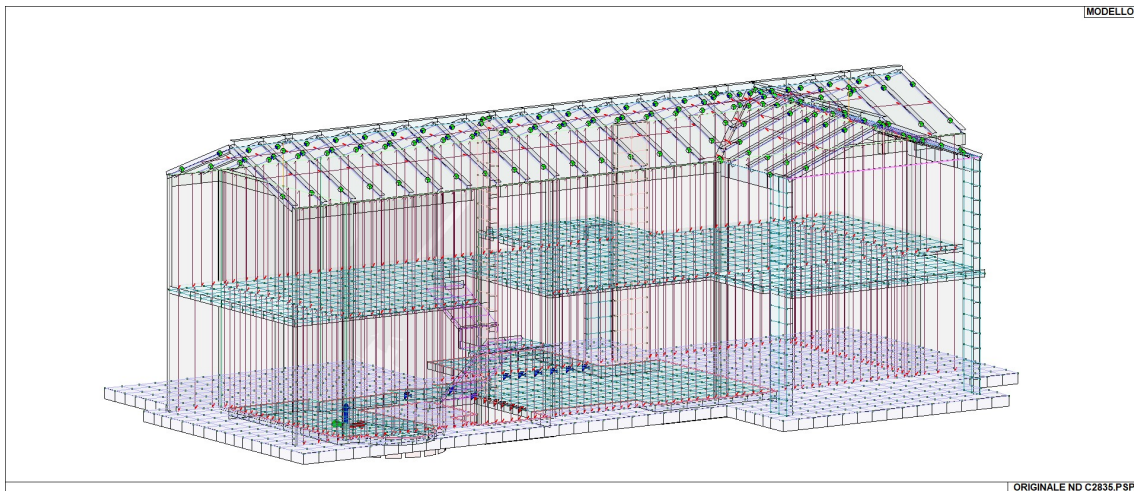


Tabella per il calcolo del costo indicativo delle opere

Cubature	mc	incidenze(*) daN/mc	Euro/mc	totale
Plinti	0.0	0.0	130.0	0.0
Travi rovesce	17.41	69.182	130.0	2263.31
Travi elevazione	4.353	185.255	180.0	783.54
Pilastri	8.605	181.386	180.0	1548.99
Platee	50.954	81.962	130.0	6623.976
Piastre	49.274	261.326	150.0	7391.057
Pareti	6.254	271.104	150.0	938.055
Pali	0.0			

(*) incidenze ottenute da armature di progetto e pertanto solo indicative. I valori esatti si possono ottenere generando gli esecutivi con PRO_CAD.

Carpenterie	mq	Euro/mq	totale
Plinti	0.0	22.0	0.0
Travi rovesce	58.595	20.0	1171.891
Travi elevazione	49.334	35.0	1726.69
Pilastri	111.444	35.0	3900.54
Piastre	247.774	20.0	4955.477
Pareti	55.796	30.0	1673.88
Area solai e balconi	0.0		[esclusi del computo]

Acciaio	kN	Euro/kN	totale
Armature lente	223.2	100.0	22319.985
Pilastri	0.0	300.0	0.0
Travi	0.0	0.0	0.0
Aste	0.154	0.0	0.0

Elementi in legno	mc	Euro/mc	totale
Pilastri	8.0000e-02	0.0	0.0
Travi e aste	9.167	0.0	0.0
Pareti XLAM	0.0	0.0	0.0
Piastre XLAM	0.0	0.0	0.0
Solai XLAM	0.0	0.0	0.0

Costo indicativo opera

55.297 euro x mille

Esporta dati

Aggiorna

Esci

A.3 ND C32/40 STRUCTURAL MODEL

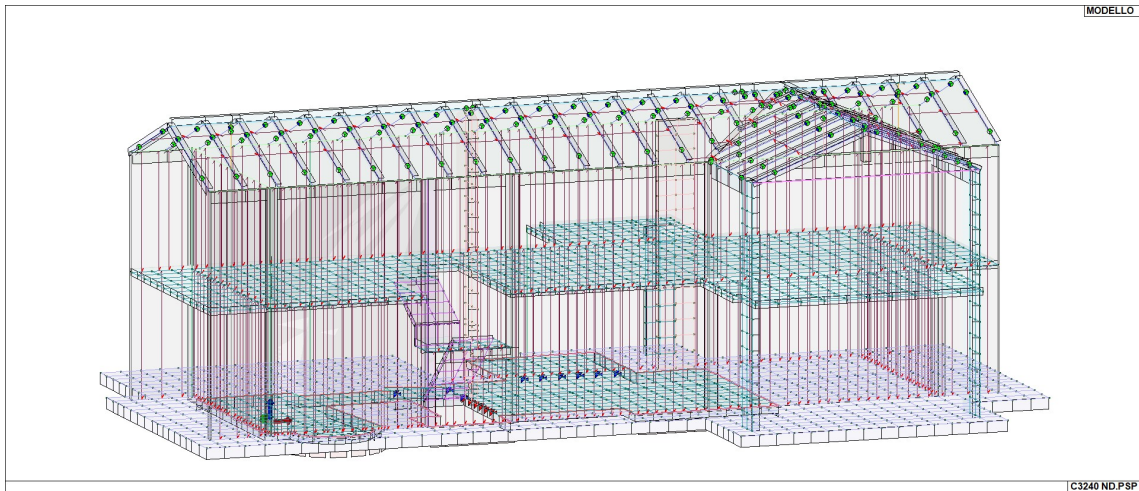


Tabella per il calcolo del costo indicativo delle opere

Cubature	mc	incidenze(*) daN/mc	Euro/mc	totale
Plinti	0.0	0.0	130.0	0.0
Travi rovesce	17.41	69.345	130.0	2263.3
Travi elevazione	4.353	185.93	180.0	783.54
Pilastrini	7.19	213.36	180.0	1294.2
Platee	50.954	81.02	130.0	6624.02
Piastre	49.274	277.974	150.0	7391.1
Pareti	6.254	237.585	150.0	938.1
Pali	0.0			

(*) incidenze ottenute da armature di progetto e pertanto solo indicative. I valori esatti si possono ottenere generando gli esecutivi con PRO_CAD.

Carpenterie	mq	Euro/mq	totale
Plinti	0.0	22.0	0.0
Travi rovesce	58.595	20.0	1171.9
Travi elevazione	49.334	35.0	1726.69
Pilastrini	100.12	35.0	3504.2
Piastre	247.774	20.0	4955.48
Pareti	55.796	30.0	1673.88
Area solai e balconi	0.0	[esclusi dal computo]	

Acciaio	kN	Euro/kN	totale
Armature lente	228.617	100.0	22861.749
Pilastrini	0.0	300.0	0.0
Travi	0.0	0.0	0.0
Aste	0.154	0.0	0.0

Elementi in legno	mc	Euro/mc	totale
Pilastrini	8.0000e-02	0.0	0.0
Travi e aste	9.167	0.0	0.0
Pareti XLAM	0.0	0.0	0.0
Piastre XLAM	0.0	0.0	0.0
Solai XLAM	0.0	0.0	0.0

Costo indicativo opera
 euro x mille

A.4 CDB C25/30 STRUCTURAL MODEL

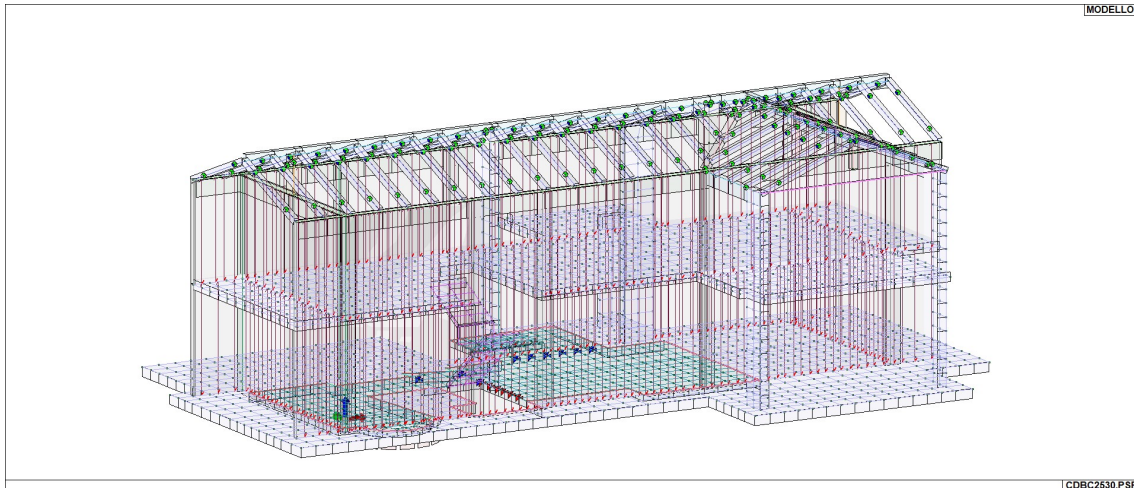


Tabella per il calcolo del costo indicativo delle opere

Cubature	mc	incidenze(*) daN/mc	Euro/mc	totale
Plinti	0.0	0.0	130.0	0.0
Trevi rovesce	17.57	69.173	130.0	2284.1
Trevi elevazione	10.157	267.223	180.0	1828.26
Pilastri	14.205	164.256	180.0	2556.9
Platee	50.954	72.133	130.0	6624.02
Piastre	65.665	181.231	150.0	9849.75
Pareti	8.272	140.63	150.0	1240.8
Pali	0.0			

(*) incidenze ottenute da armature di progetto e pertanto solo indicative. I valori esatti si possono ottenere generando gli esecutivi con PRO_CAD.

Carpenterie	mq	Euro/mq	totale
Plinti	0.0	22.0	0.0
Trevi rovesce	59.236	20.0	1184.72
Trevi elevazione	78.354	35.0	2742.39
Pilastri	141.828	35.0	4963.98
Piastre	247.774	20.0	4955.48
Pareti	55.796	30.0	1673.88
Area solai e balconi	0.0		[esclusi dal computo]

Acciaio	kN	Euro/kN	totale
Armature lente	230.021	100.0	23002.1
Pilastri	0.0	300.0	0.0
Trevi	0.0	0.0	0.0
Aste	0.154	0.0	0.0

Elementi in legno	mc	Euro/mc	totale
Pilastri	8.0000e-02	0.0	0.0
Trevi e aste	9.167	0.0	0.0
Pareti XLAM	0.0	0.0	0.0
Piastre XLAM	0.0	0.0	0.0
Solai XLAM	1.675	0.0	0.0

Costo indicativo opera

62.906 euro x mille

Esporta dati

Aggiorna Esci

A.5 CDB C28/35 STRUCTURAL MODEL

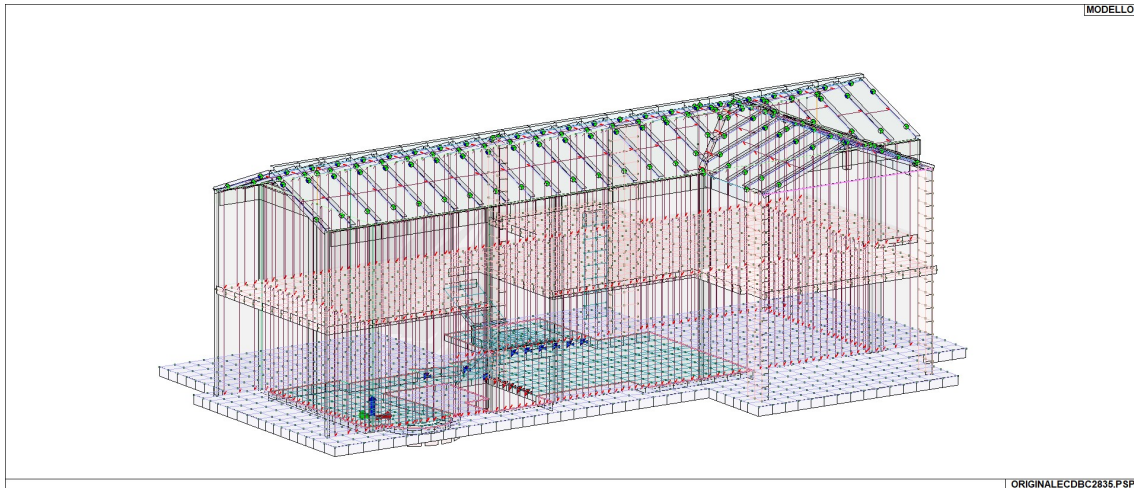


Tabella per il calcolo del costo indicativo delle opere

Cubature	mc	incidenze(*) daN/mc	Euro/mc	totale
Plinti	0.0	0.0	130.0	0.0
Travi rovesce	17.578	69.128	130.0	2285.14
Travi elevazione	10.447	172.437	180.0	1880.46
Pilastri	12.813	183.743	180.0	2306.34
Platee	50.954	69.111	130.0	6624.02
Piastre	57.75	155.645	150.0	8662.5
Pareti	6.808	142.975	150.0	1021.2
Pali	0.0			

(*) incidenze ottenute da armature di progetto e pertanto solo indicative. I valori esatti si possono ottenere generando gli esecutivi con PRO_CAD.

Carpenterie	mq	Euro/mq	totale
Plinti	0.0	22.0	0.0
Travi rovesce	59.075	20.0	1181.5
Travi elevazione	75.452	35.0	2640.82
Pilastri	133.548	35.0	4674.18
Piastre	247.774	20.0	4955.48
Pareti	55.796	30.0	1673.88
Area solee e balconi	0.0	[esclusi dal computo]	

Acciaio	kN	Euro/kN	totale
Armature lente	188.542	100.0	18854.235
Pilastri	0.0	300.0	0.0
Travi	0.0	0.0	0.0
Aste	0.154	0.0	0.0

Elementi in legno	mc	Euro/mc	totale
Pilastri	8.0000e-02	0.0	0.0
Travi e aste	9.167	0.0	0.0
Pareti XLAM	0.0	0.0	0.0
Piastre XLAM	0.0	0.0	0.0
Solai XLAM	0.0	0.0	0.0

Costo indicativo opera: 56.76 euro x mille

Esporta dati

Aggiorna Esci

A.6 CDB C32/40 STRUCTURAL MODEL

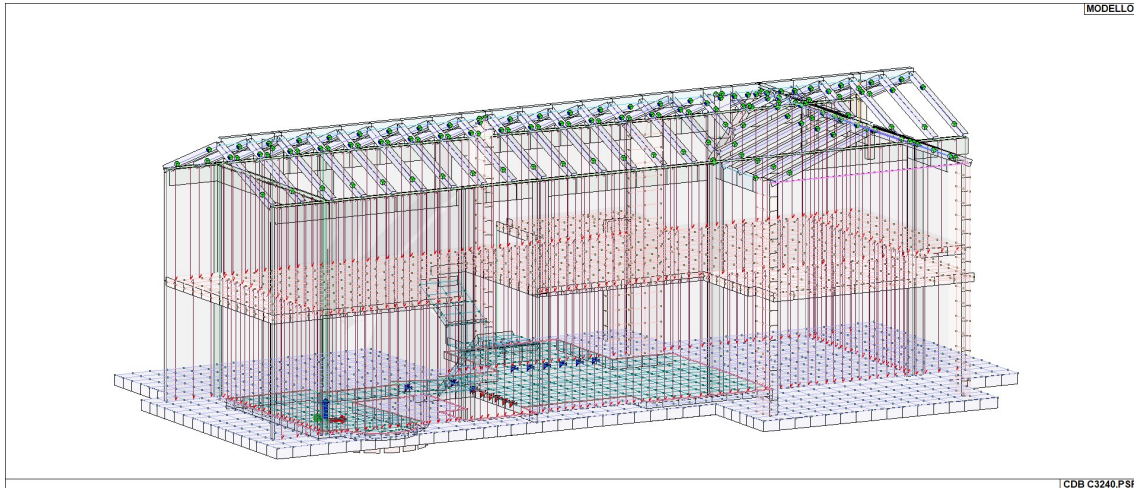


Tabella per il calcolo del costo indicativo delle opere

Cubature	mc	incidenze(*) daN/mc	Euro/mc	totale
Plinti	0.0	0.0	130.0	0.0
Travi rovesce	17.542	53.075	130.0	2280.46
Travi elevazione	9.141	202.465	180.0	1645.38
Pilastrini	15.78	186.253	180.0	2840.4
Plattee	50.954	66.412	130.0	6624.02
Piastre	57.75	176.053	150.0	8662.5
Pereti	6.942	107.681	150.0	1041.3
Pali	0.0			

(*) incidenze ottenute da armature di progetto e pertanto solo indicative. I valori esatti si possono ottenere generando gli esecutivi con PRO_CAD.

Carpenterie	mq	Euro/mq	totale
Plinti	0.0	22.0	0.0
Travi rovesce	59.075	20.0	1181.5
Travi elevazione	72.55	35.0	2539.25
Pilastrini	148.176	35.0	5186.16
Piastre	247.774	20.0	4955.48
Pareti	55.796	30.0	1673.88
Area solai e balconi	0.0		[esclusi dal computo]

Acciaio	kN	Euro/kN	totale
Armature lente	200.194	100.0	20019.386
Pilastrini	0.0	300.0	0.0
Travi	0.0	0.0	0.0
Aste	0.154	0.0	0.0

Elementi in legno	mc	Euro/mc	totale
Pilastrini	8.0000e-02	0.0	0.0
Travi e aste	9.167	0.0	0.0
Pareti XLAM	0.0	0.0	0.0
Piastre XLAM	0.0	0.0	0.0
Solai XLAM	1.675	0.0	0.0

Costo indicativo opera

58.65 euro x mille

Esporta dati

Aggiorna Esci