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Integration of Seismic and Climate-related Constraints for WLC Benchmark Definition of Italian Residential Buildings

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Abstract. Establishing Whole Life Carbon (WLC) benchmarks by 2030 is crucial for meeting the EU's Energy Performance of Buildings Directive (EPBD) requirements. Italy currently lacks a unified methodology for WLC assessment, though the revised Minimum Environmental Criteria mandate a simplified Life Cycle Assessment (LCA) for building emissions. Due to Italy's medium-high seismic hazard and diverse climatic conditions, defining robust WLC benchmarks must account for these factors. This study addresses a major challenge: Italy's heterogeneous territory, which complicates the identification of building archetypes. An innovative framework is proposed, combining the Civil Defence Department's seismic zones with national climate classifications. This dual approach enables context-specific, nationally representative WLC benchmarks, advancing reliable and realistic assessments for residential buildings in Italy.

1. Introduction

The Energy Performance of Building Directive (EPBD) [1] requires that all Member States of the European Union (EU) establish a plan to cut the Whole-Life Carbon (WLC) emissions of buildings by 2050, which include both operational and embodied emissions.

The WLC, or life cycle Global Warming Potential (GWP) is an indicator that quantifies the GWP contributions of a building caused by Greenhouse Gas (GHG) emissions along its life cycle, including both operational and embodied emissions.

Under the updated EPBD, Member States will be required to calculate and disclose WLC data through Energy Performance Certificates (EPCs) as early as of 2028 for all new buildings with a useful floor area larger than 1000 m² [2]. To support these objectives, the definition of National WLC roadmaps is part of the requirements of the new EPBD, including targets and limit values for new buildings considering specific characteristics such as climatic zones and building typologies. In order to define targets and limit values for the WLC of buildings (with the objective



of progressively tightening these requirements over time), it is fundamental to map National building stocks to be able to identify building archetypes and characteristics affecting WLC values, therefore enabling the define National WLC benchmarks.

Benchmarking, according to the ISO 21678:2020 standard [3], is defined as: “process of collecting, analysing and relating performance data of comparable buildings or other types of construction works. The standard also recommends three types of benchmarks should be provided, namely a limit, reference, and target value, as shown in Figure 1. These values therefore represent performance levels on a performance scale, including the state-of-the-art or best practice and specific limit and target values corresponding to acceptable performance levels. Limit values can assist architects and building owners/investors to comply with minimum legal requirements, reference values assist them in positioning themselves in the market and further pushing the construction sector in reducing its life cycle environmental impacts, whilst target values should be used to guide the design and specification process.

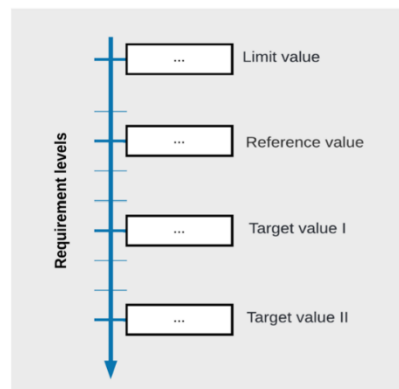


Figure 1. Graphic representation of the value collection hierarchy necessary to the process of benchmark setting. Adapted from reference [4].

Benchmark definition for building WLC target and limit setting requires thorough mapping of the available building stock, in order to define building typologies and archetypes and how their WLC values are affected by characteristics connected to building design and performance requirements. In the EU, the INDICATE LIFE project [5] has the objective of creating the methodological and data foundations essential for developing National WLC assessment frameworks across Europe. In this context, the project also wants to prepare the ground for the effective implementation of EPBD reporting requirements on WLC.

At the time of writing, in Italy there is no nationally harmonised methodology to quantify the WLC of buildings. Recently, the most significant measure undertaken to harmonise Life Cycle Assessment (LCA) of buildings is included in the Green Public Procurement (GPP) ‘Minimum Environmental Criteria’ (CAM) for Public Buildings (D.M. 23/06/2022) [6], currently under review. Among the requirements outlined in the CAM, a simplified LCA approach (i.e., targeting a reduced scope of the building’s life cycle) is included which can be applied to drive the quantification of buildings’ whole-life emissions. However, national LCA approaches need to also align with EU standards, such as the Level(s) framework, used to evaluate building’s emissions and other aspects related to sustainability. Additionally, a simplified LCA can be a first step, but the definition of an approach encompassing a full LCA scope is necessary in order to capture the building’s complexity and relative impacts. This objective requires the definition of a robust approach, with collaboration across multiple stakeholders, in particular for the determination of impacts beyond the cradle-to-gate scope.

A major issue, related to intrinsic characteristics of the Italian territory, is associated with the definition of building archetypes due to the heterogeneous subdivision of the territory from climate and seismic activity points of view, often much more granular than the subdivision into regions. Whilst the classification of the territory into climatic zones has been previously taken into account in the context of benchmark definition[7], this research project identifies a gap in this approach due to the lack of an evaluation of seismic constraints and their impacts on the WLC of buildings.

Tuscany is a region located in the North-western part of the country. It is characterised by four different climate zones and three seismic zones, as shown in Figure 2.

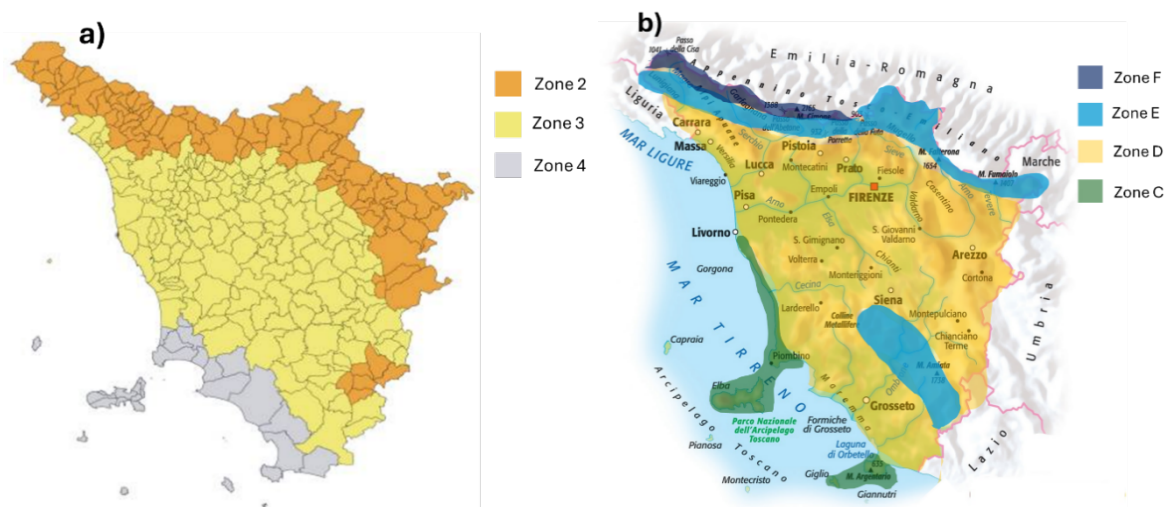


Figure 2. Climatic (a) and Seismic (b) zoning classification of the Tuscany region.

Municipalities in the region are spread across these zones as shown in Figure 3 , with most municipalities belonging to climate zones D and E and seismic zone 3. However, 6 municipalities were identified belonging to a high-constraint combination of zones (climate zone F, seismic zone 2) and 12 municipalities were instead assigned to a low-constraint combination of zones (climate zone C, seismic zone 4). The model building assessed as case study is characterised by the average-constraint case (climate zone D, seismic zone 3).

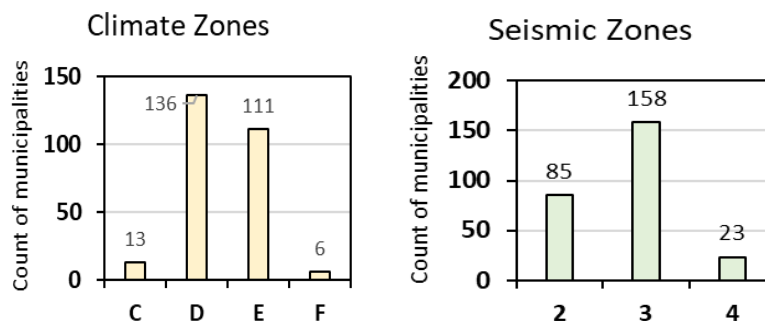


Figure 3. Number of municipalities located in each climatic and seismic zone in Tuscany.

For the purpose of defining accurate national building WLC benchmarks, it is important to consider building archetypes including design constraints due to structural resistance requirements in high-risk seismic zones. Previous studies focused on the analysis of building

archetypes in Italy taking into account emission variability due to the different climate zones; however, to the best of the authors' knowledge, seismic design requirements have not yet been added to the picture for the definition of building archetypes and, consequently, WLC benchmark values in Italy.

A recent report published in the context of the INDICATE Life project in Spain, highlighted that the environmental impacts (in terms of GWP) related to design variables of structural elements of buildings in high-risk seismic zones are substantial, compared to buildings located in low-risk seismic zones in Spain. In particular, constructions without seismic constraints can have up to 80% less impacts, compared to designs which include seismic constraints.

2. Goal and Scope

The aim of this study is to focus on the assessment of a new residential building located in Tuscany to study the variability of building elements affected by seismic design requirements and their relative environmental impact in terms of GWP. In addition to this, the analysis will also be combined with considerations on other structural design requirements connected to the building's location. The objective of the analysis is to show the effect that seismic design constraints can have on the GWP impact of a building's structure.

3. Case Study

3.1 Building characteristics

The analysis was carried out considering a model building located in Marina di Massa, Tuscany (seismic zone 3, climate zone D). The original building was erected in 1937, but the structural damage and seismic vulnerability made demolition the most suitable option, to build a new structure. The new construction (Figure 4) is a multi-user residential building, designed to accommodate both minors and adults who are temporarily or permanently without the necessary family support and may also be affected by disabilities. Therefore, the structure has been designed to be easily accessible and with specific attention to energy efficiency and sustainability, ensuring compatibility with the vulnerable residents.



Figure 4. 3D Representation of the case study building.

The building consists of only two above-ground floors (Figure 5). The ground floor will accommodate a residential facility for vulnerable individuals as part of the "Dopo di Noi" (After Us) program, while the first floor will be designated for social housing.

From a structural standpoint, the building is designed as a braced steel frame structure, engineered to ensure adequate resistance to both horizontal and vertical loads, in compliance

with current seismic regulations. The superstructure is composed of hot-dip galvanized steel members in S355J grade, organized as follows:

- Vertical columns, made of HEB260 profiles
- Horizontal floor beams, also in HEB260 profiles, arranged continuously between structural nodes and welded to the vertical elements
- Bracing members in HEB160 profiles, arranged in a triangulated configuration

All steel-to-steel connections are welded on site, in order to guarantee mechanical continuity, global frame stiffness, and deformation control. The secondary vertical stiffening system is constructed in cast-in-place reinforced concrete, providing additional resistance and bracing to the main structure. The foundations are of the shallow type with inverted beams, made of C25/30 reinforced concrete.

The intermediate floor slabs are made of lightened precast predalles panels with expanded polystyrene inserts, following a typical stratigraphy of 5 + 16 + 4 cm (panel – cast-in-place layer – topping), designed to behave as rigid diaphragms, facilitating horizontal force distribution and the proper functioning of the braced frame system.

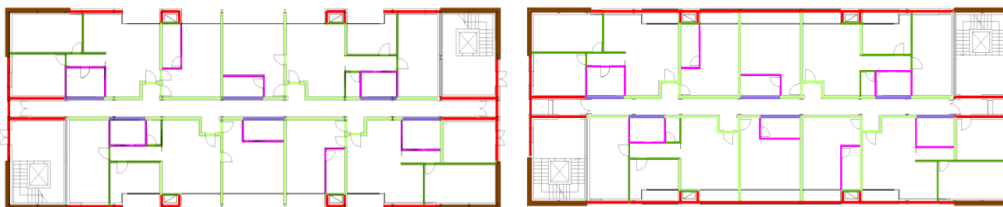


Figure 5. Building's floorplan; ground floor (left), first floor (right).

3.1.1 Scenarios

The building is located in Marina di Massa, a municipality in Tuscany on the Northern coast of the region. The location is associated with seismic zone 3.

The “Baseline” scenario defined for this study corresponds to the real building subject of the analysis, i.e., all the data on material quantities and building element types are those contained in the design and projects created for the construction of this building.

To be able to draw a comparison between seismic design requirements if the building was located in a zone with different seismic activity, a hypothetical scenario (the “Best Performance” scenario) was defined by assuming that the same building was located in seismic zone 2 (higher seismic activity risk) in a similar coastal environment.

Finally, a third hypothetical scenario was defined, named “Worst Performance” scenario, with the same building located in seismic zone 3 (like the Baseline scenario) but with smaller quantities of load bearing structural elements (lowest quantity allowed by the Norme Tecniche per le Costruzioni NTC 2018 [8]). Additionally, for this scenario it was assumed that the building was located in an internal non-coastal zone.

The only elements affected by variation between the Baseline and Best Performance scenarios were the steel load bearing columns; their quantity in the structure varies between 35202.5 kg in the Baseline scenario to 46546.7 kg in the Best Performance scenario. In both scenarios ground floor and first floor slabs and load bearing walls in the structure were made out of C35/45 XS3 S4 cement, typically used for buildings in maritime zones with mild climate.

The building in the Worst Performance scenario contains the same quantity of steel columns as the Baseline scenario, however it was assumed that the structure had no steel braces

and that ground floor and first floor slabs and load bearing walls in the structure were made out of C30/37 XC2 S4 cement, a type of cements more commonly used in colder climate zones where antifreeze treatments may be needed [9]. An overview of the characteristics of the different scenarios applied to the building's assessment is provided in Table 1.

Table 1. Overview of variations affecting the three scenarios applied to the building's model.

	Baseline	Best performance	Worst performance
	Zone 3, mild climate (coast)	Zone 2, mild climate (coast)	No braces, Zone 3, cold climate
Steel columns	Yes	Yes + 14%	Yes
Steel braces	Yes	Yes	No
Concrete type	C35/45	C35/45	C30/37

The structure of this building has a steel frame made up of columns, beams and braces (see Figure 6); this configuration guarantees a remarkable capacity of bearing loads with homogeneous strain on the foundation. The presence of the steel braces allows for a good distribution of the seismic loads, reducing unwanted twists and consequently limiting the effect of seismic acceleration on the steel structure. In the Best Performance scenario, where the building is located in seismic zone 2, thicker columns would be required to guarantee the same structural performance as the baseline scenario, whilst the rest of the structure remains unchanged.

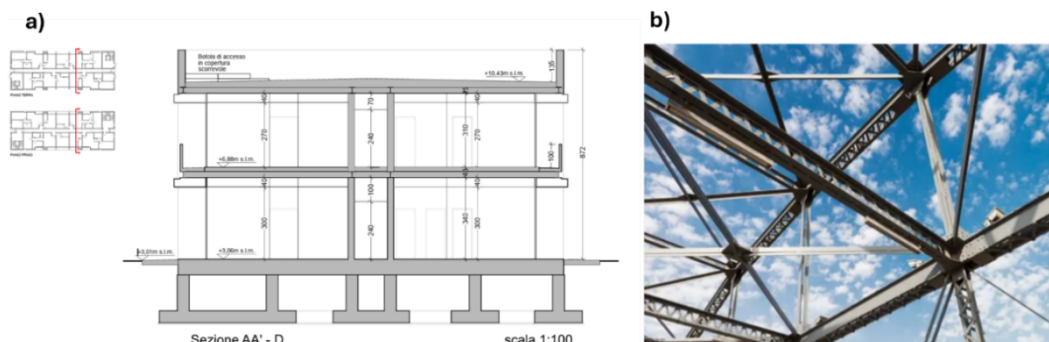


Figure 6. Section of the building showing the load bearing structure (a); a picture of a structure containing steel braces (b).

There are no changes in the building's foundations associated with the different scenarios due to the fact that in the building's original configuration (Baseline scenario) the foundations have been designed to be overbuilt and to exceed the requirements of the geotechnical characteristics of the location. In particular, the foundations are deeper and have more load-bearing capacity than what mandated in the standard requirements (NTC 2018).

An additional consideration was the selection of concrete types based on the appropriate exposure class, which—particularly in the case of freeze-thaw attack—is not easily defined. This uncertainty arises from the lack of readily available climatological data at the microclimatic scale of the site where the structure is located, as well as from design-related factors that may influence the moisture content of the concrete, and the azimuthal orientation of the various exposed surfaces of the structure.

Therefore, based on a previous study [10], the concrete types considered in the analysis are as follows:

- C30/37: Concrete resistant to freeze–thaw cycles and de-icing salts, suitable for exposure classes XC4/XF4/XD3. It is characterized by the following properties: air-entrained, maximum water/cement ratio (w/c max) = 0.45, minimum cement content (Cmin) = 360 kg/m³, and 100% natural rounded aggregates.
- C35/45: Concrete suitable for marine environments or exposure to de-icing salts, compliant with exposure classes XS2/XS3. It features a maximum water/cement ratio (w/c max) = 0.45, minimum cement content (Cmin) = 360 kg/m³, and 100% natural rounded aggregates.

3.2 Building elements and Bill of Materials

For the purpose of this study, the building elements considered were those making up the load bearing structure of the building. A detailed breakdown of these elements is shown in Table 2, including the classification of the building elements according to RICS[11], also compliant with the Level(s) framework’s indicator 1.2[12].

Table 2. Materials and quantities of building elements associated with the structure of the building.

Classification	Component name	Material	Q.ty	Unit
1.1.1.Standard foundations	Concrete layer	ready mix concrete C12/15	44.6	m ³
1.1.1.Standard foundations	Reinforcement steel bars	hot rolled reinforcement rebars	46635.24	kg
1.1.1.Standard foundations	inverted steel beams	ready mix concrete C35/45	683	m ³
1.1.3.Lowest floor construction	concrete casting for slab (Ground floor)	Ready mix concrete	140104.5	kg
1.1.3.Lowest floor construction	reinforcement steel for slab (Ground floor)	electro welded reinforced steel mesh	2220.45	kg
1.1.3.Lowest floor construction	Expanded polystyrene layer for slab (Ground floor)	Expanded polystyrene insulation	1048	kg
1.1.3.Lowest floor construction	concrete layer for slab (Ground floor)	Ready mix concrete	78600	kg
2.2.1.Floors	concrete casting for slab (First floor)	Ready mix concrete	140104.5	kg
2.2.1.Floors	reinforcement steel for slab (First floor)	electro welded reinforced steel mesh	2220.45	kg
2.2.1.Floors	Expanded polystyrene layer for slab (First floor)	Expanded polystyrene insulation	1048	kg
2.2.1.Floors	concrete layer for slab (First floor)	Ready mix concrete	78600	kg
2.3.1.Roof structure	concrete casting for slab (cover)	Ready mix concrete	140104.5	kg
2.3.1.Roof structure	reinforcement steel for slab (cover)	electro welded reinforced steel mesh	2220.45	kg
2.3.1.Roof structure	Expanded polystyrene layer for slab (cover)	Expanded polystyrene insulation	1048	kg
2.3.1.Roof structure	concrete layer for slab (cover)	Ready mix concrete	78600	kg

2.1.1.Steel frames	Reinforcement steel bars for ground floor	hot rolled reinforcement rebars	655.4	kg
2.1.3.Concrete casings to steel frames	Concrete casting for ground floor	ready mix concrete C35/45	5.8	m ³
2.1.1.Steel frames	Reinforcement steel bars for first floor	hot rolled reinforcement rebars	1.339	kg
2.1.3.Concrete casings to steel frames	Concrete casting for first floor	ready mix concrete C35/45	13	m ³
2.1.1.Steel frames	Steel columns	Structural steel beams	35202.5	kg
2.1.1.Steel frames	Steel beams	Structural steel beams	64678	kg
2.1.1.Steel frames	Steel braces	Structural steel beams	13898	kg
2.1. Frame	gypsum board	reinforced gypsum board	472	m ³
2.1. Frame	column insulation	Expanded polystyrene insulation	241.4	kg
2.7.1 Walls and Partitions	Load bearing walls	ready mix concrete C35/45	16.6	m ²
2.2.1.Floors	lightweight screed	ready mix cellular lightweight aggregate concrete with EPS	55.18	m ³
2.2.1.Floors	cementitious screed	Lightweight ready-mix concrete	551.29	m ²

4. Methods

The goal of the study is to assess the impacts associated with building elements affected by seismic and other structural design constraints as defined in section 3.1.1.

The assessment was carried out using the software OneClick LCA and following the requirements of the Level(s) framework, focusing on GWP impacts only. Level(s) is a European approach to assess and report on the sustainability performance of buildings, throughout the full life cycle of buildings. The Level(s) tool is in compliance with EN 15978[13] and EU Taxonomy.

The Level(s) life cycle carbon assessment is carried out using the CML method (EN15804+A1) and PEF data (EN15804+A2) [14].

4.1 System Boundary

The study focuses on life cycle stages as defined in EN 15978, and specifically on the production phase (stages A1, A2 and A3). This choice was made due to the relevance of these stages on the life cycle impacts of construction materials. Additionally, this study's objective is to focus on the impact of the variability of construction elements as a function of the seismic zone where the building is located, rather than wanting to assess the whole-life impacts of the building. For this reason, the impacts associated with the construction phase (A4-A5), the use stages (B1-B7) and the end-of-life stage (C1-C4) were not included in the assessment.

4.2 Data Sources

The data for the assessment was collected through the OneClick LCA software. The values used in the model come from generic datasets or EPD data; whenever possible, Italian EPDs were selected to model the materials in the building.

The GWP impacts of concrete materials (C35/45 and C30/37) were collected from a study published in the Italian database Arcadia [10], representative of concrete materials used in the construction industry in Italy.

4.3 Assumptions

In order to assess the impact of the variability connected to seismic and other structural design requirements, the building's structural elements described in section 3.2 were considered and their function within the building's structure taken into account. To be able to allocate impacts only to significantly variable elements, some assumptions were applied to the model, as detailed below.

The building's geometry is compact and symmetrical, developed on a rectangular plane. It is positioned on flat ground, free of terrain gaps and other irregularities.

For the purpose of the model, it was assumed that the terrain has mixed sand-clay composition, which remains a fixed characteristic in the model.

For the seismic analysis it was assumed that the soil belongs to category C of the NTC 2018 which corresponds to a medium-resistance soil and suitable for buildings with medium-sized foundations. The building was designed as a high load-bearing building; this decision is reflected in the type and quantity of steel beams and columns and the type of concrete used in the structure which do not vary significantly between different seismic zones. A thorough description of the variation of these elements is given in section 3.1.2.

5. Results and Discussion

The results of the assessment carried out on the building elements and materials listed in Table 2 (for the Baseline scenario) are shown in Table 3 and Figure 7. The highest GWP value is associated with the building's foundations, amounting to 58.4 % of the total GWP of the building's structure. Steel frames are associated with the second highest value (19.3 %), whilst the remaining 22.3 % is split across the other structural elements. These results are aligned with the building's characteristics, in particular with the deep foundations and the steel structure made out of columns, beams and braces.

Table 3. GWP impact results for building elements in the Baseline scenario during stages A1–A3, according to the classification of Table 2.

Building elements	GWP	
	ton CO ₂ e	%
Standard foundations	344.0	58.4
Lowest floor construction	31.3	5.3
Floors	55.5	9.4
Roof structure	31.3	5.3
Steel frames	113.8	19.3
Concrete casings to steel frames	5.2	0.9
Frame	3.2	0.5
Walls and Partitions	4.5	0.8

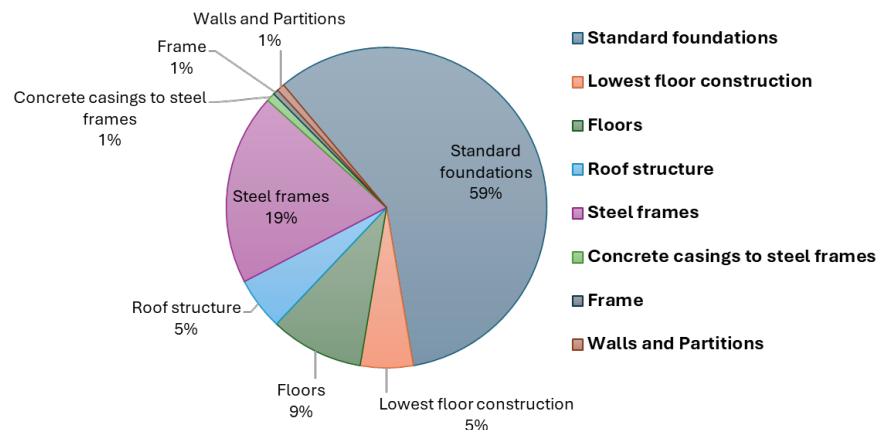


Figure 7. Relative proportion of GWP impact of each building element in the Baseline scenario, according to the classification of Table 2.

The variation of quantities and types of building elements due to the different scenarios causes a moderate variation of the GWP impacts. An overview of this variation is shown in Table 4 and Figure 8, where only affected building elements are listed, with their relative A1-A3 impacts.

From the results, it appears that the % variation between the Baseline scenario and the Best performance scenario amounts to only 13.9% more GWP across A1-A3 stages, indicating that adjustments made to the structure to make it suitable for a zone with higher seismic risk will generate approximately 10 tonnes of CO₂e emissions, associated with the additional steel needed to reinforce the structure of the building.

The comparison between the Baseline scenario and the Worst performance scenario highlights the impact difference between a structure built exceeding the mandatory requirements set in the NTC 2018 (Baseline scenario) and a structure which only meets the minimum requirements. The emissions generated by the latter amount to 15 tonnes of CO₂e less than the Baseline scenario. Additionally, the different concrete type used in this scenario contributes to an additional 1 tonne of CO₂e to this difference.

Figure 9 shows a comprehensive overview of the A1-A3 GWP impact calculated across the entire structure of the building for the three scenarios and highlights how most elements of the structure remain unchanged from the Baseline scenario, except for the steel columns, braces and load bearing walls.

Table 4. Overview of GWP impact results for building elements most affected by the scenario variations.

Building elements	A1-A3 GWP (ton CO ₂ e)		
	Baseline	Best performance (% variation from Baseline)	Worst performance (% variation from Baseline)
Ground floor slab	33.4	33.4 (0%)	33.0 (-0.6%)
First floor slab	36.0	36.0 (0%)	35.1 (-1.3%)
steel columns	34.7	45.8 (13.9%)	34.7 (0%)
steel beams	63.7	63.7 (0%)	63.7 (0%)
steel braces	13.7	13.7 (0%)	0.0 (-100%)
Walls	4.5	4.5 (0%)	3.3 (-15.4%)

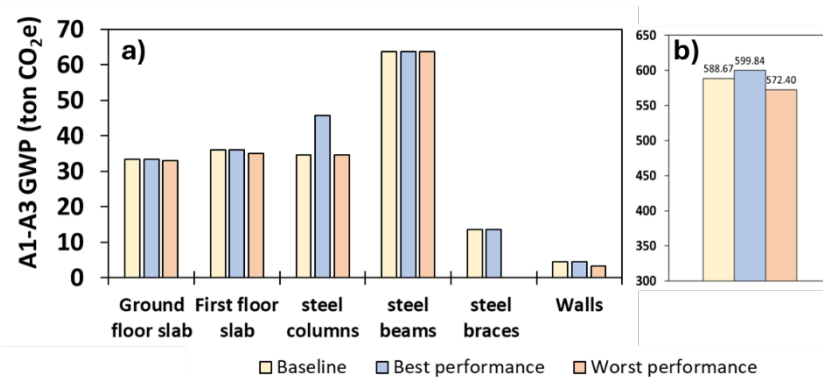


Figure 8. Overview of GWP impacts for building elements most affected by the scenario variations as per Table 3 (a); total A1-A3 GWP impacts for all structural elements assessed in the three scenarios (b).

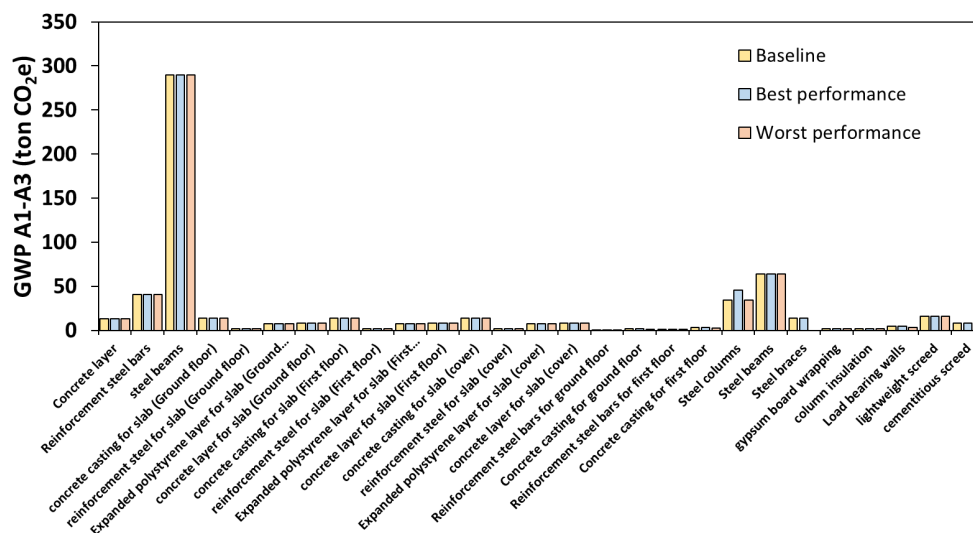


Figure 9. Overview of GWP impact in ton CO₂e of each structural element, for each defined scenario.

The superstructure of the building is developed over only two above ground floors, therefore the effect of the seismic load is limited, especially on the horizontal plane. As a consequence, the variation of the seismic zone from zone 3 to zone 2, with the amplification of the potential seismic load, does not translate into a substantial variation of the structure. It is worth noting that the effects of seismic phenomena are considerable on tall, thin and mass-heavy buildings, as the dynamic effects increase with the square of the building’s height.

6. Conclusions

The geometric characteristics of the building—namely, a compact and symmetrical two-story structure—combined with an efficient structural configuration shaped by the stringent Italian seismic design codes, led to the development of a high-performance building even when designed for a low seismic hazard zone (Zone 3). As a result, the transition to a higher seismic hazard zone (Zone 2) did not produce significant variations in the structural quantities.

A significant indication in this direction could come from increasing the number of floors in the building, as well as from adopting a different construction system, such as masonry—

typically efficient from a thermal perspective, but highly sensitive to seismic actions. Therefore, future developments of this work will focus on analysing these aspects while maintaining the same building typology.

Another aspect that the research intends to investigate in the next steps is the impact on GWP resulting from the use of higher-strength concrete mixes, especially in soils exposed to more severe environmental conditions, such as freeze–thaw cycles and marine environments. All of this aims to provide a comprehensive overview of how different national contexts can influence the calculation of GWP and the definition of limit and target values with the aim of supporting the creation of accurate WLC benchmarks in the National context.

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Conflicts of Interests

The authors have no conflicts to declare.

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