

Article

Long-Term Comparative Life Cycle Assessment, Cost, and Comfort Analysis of Heavyweight vs. Lightweight Construction Systems in a Mediterranean Climate

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Abstract: Massive construction systems have always characterized traditional architecture and are currently the most prevalent, straightforward, and cost-effective in many Mediterranean countries. However, in recent years, the construction industry has gradually shifted towards using lightweight, dry construction techniques. This study aims to assess the effects on energy consumption, comfort levels, and environmental sustainability resulting from the adoption of five high-performance construction systems in a multi-family residential building: (i) reinforced concrete structure with low-transmittance thermal block infill; (ii) reinforced concrete structure with light-clay bricks and outer thermal insulation; (iii) steel frame; (iv) cross-laminated timber (CLT); (v) timber-steel hybrid structure. To achieve this goal, a multidisciplinary approach was employed, including the analysis of thermal parameters, the evaluation of indoor comfort through the adaptive model and Fanger's PMV, and the quantification of environmental and economic impacts through life cycle assessment and life cycle cost applied in a long-term analysis (ranging from 30 to 100 years). The results highlight that heavyweight construction systems are the most effective in terms of comfort, cost, and long-term environmental impact (100 years), while lightweight construction systems generally have higher construction costs, provide lower short-term environmental impacts (30 years), and offer intermediate comfort depending on the thermal mass.

Keywords: construction systems; building envelope; life cycle assessment; life cycle cost; thermal comfort; thermal mass; zero energy building; building lifespan; building service life; Mediterranean climate



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1. Introduction

Heavyweight constructions that use reinforced concrete frames and hollow bricks for infill walls are widespread in many countries around the world. The extensive use of this type of structure depends on numerous factors, including the reduced construction cost compared to other techniques; the ease of sourcing construction materials (reinforcing bars, gravel or crushed rock, sand, water, and cement); the simplicity of execution; the durability of the material even in challenging weather conditions; and the flexibility to construct various typologies of structures, including infrastructure and buildings [1]. In addition, heavyweight construction systems are mainly used in hot climates, such as the Mediterranean, to ensure good thermal comfort due to the high thermal inertia, which is related to the greater mass of the materials compared to those used in other construction techniques, such as steel and wood [2].

Thermal mass slows the speed at which internal temperatures rise due to external solar radiation or internal heat sources. Similarly, it slows the speed at which internal temperatures fall when heating effects are removed [3]. In the summer period, thermal

inertia reduces high temperatures [4,5] and cooling energy consumption [6]. In the winter, thermal mass may be helpful in reducing the peak energy demand for heating [7,8]. Consequently, thermal mass plays a crucial role in ensuring a good indoor environment in a passive way [9]. Other factors that can significantly improve summer thermal comfort in buildings include insulation levels, blinds, light-colored external walls, and the adoption of appropriate ventilation strategies [10].

These assumptions for heating and cooling in heavyweight construction systems are not valid in all contexts from an energy-saving perspective. Indeed, local climate conditions, building type, and the type/position of the insulation layer decisively influence energy consumption, making these construction techniques not always more advantageous compared to lightweight systems [11], as described below:

- (i) In cold climates, thermal mass can often be a drawback, leading to higher energy consumption for heating, as the passive solar heating function is less prevalent [12]. In England, comparable heating loads have been evaluated for lightweight (framed) and medium-weight (masonry) constructions. In heavyweight cases, the heating load is 5–8% higher, although the peak heat loads are slightly lower (10–12%) [13]. In Sweden, another study showed that in colder regions, the benefit of high thermal mass is negligible, resulting in a slight reduction in heating demand ranging from 0.5% to 2.4% when comparing a timber construction system to a concrete one [14].
- (ii) In moderate climates like the Mediterranean, heavyweight structures are well-known for regulating internal temperatures through thermal inertia and natural ventilation at night [15]. Aste et al. demonstrate that constructing buildings in Milan with walls of low thermal inertia can increase energy consumption by up to 10% for heating and 20% for cooling [16]. Evaluating the thermal comfort in Ancona, Palermo, and Cairo, Stazi et al. analyze how heavyweight construction systems ensure a slightly higher percentage of comfort hours compared to wooden construction systems, ranging from 0.8% to 3.9% [17].

While regulations on energy consumption containment are well developed and widely utilized in Italy, the effects of thermal mass on indoor comfort are only partially taken into consideration in regulations, as follows:

- (i) Regarding private buildings, the only requirement for building envelope components is a periodic thermal transmittance value (YIE) of $\leq 0.10 \text{ W/m}^2\text{K}$ for vertical elements and $\leq 0.18 \text{ W/m}^2\text{K}$ for horizontal and inclined elements. Alternatively, to comply with the periodic thermal transmittance, the regulations specify a minimum mass value of 230 kg per square meter of surface, applicable only to external walls (for horizontal elements, only periodic thermal transmittance is considered). Additional requirements pertain to the building's thermal energy demand for cooling [18]. No specific compliance checks are required for thermal comfort.
- (ii) Concerning public buildings, the regulations impose more stringent requirements than those for private buildings. Specifically, there is an additional minimum thermal comfort requirement, which must be verified by calculating the summer operative temperature or using Fanger's PMV model [19].

When analyzing the thermal comfort within a building, it is essential to specify whether a heating or cooling system is present. If the building under analysis is equipped with such a system, the indices defined by UNI EN ISO 7730:2005 [20] related to the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) can be used. However, an evaluation without considering thermal systems is necessary to assess the building envelope's ability to resist thermal exchange with the external environment. In this case, the adaptive comfort model, defined by UNI EN ISO 16798-1:2019 [21], best describes the users' perception of well-being, assessing the role of the building envelope elements.

To obtain a comprehensive comparative overview between heavyweight and lightweight construction systems, it is necessary to investigate not only aspects concerning energy consumption and thermal comfort but also those related to construction materials, partic-

ularly regarding environmental impacts and costs [22]. In recent years, the construction sector has gradually shifted towards dry construction techniques based on the principles of the circular economy [23], such as building in layers [24], designing for disassembly [25], and designing out waste [26]. These principles are more easily applied, or at least optimized, in lightweight prefabricated steel, wood, or hybrid construction techniques compared to heavier alternatives that primarily use wet connections as concrete [23].

From this perspective, the life cycle assessment (LCA) methodology can assist in the decision-making process by helping choose materials and products based on their environmental impacts [27]. However, there is a limited amount of research comparing the whole life cycle assessment of buildings characterized by different construction techniques [17,28]. Generally, lightweight construction systems emerge from these studies [29–33] as those that ensure a lower environmental impact, regardless of whether the use phase is considered in the study [31] or excluded [29,30,32,33]. This result is confirmed regardless of the type of building used as a case study and its function. Indeed, the findings from these studies highlight lightweight construction systems as the least impactful, whether in the case of a single-family detached house [31], a multi-family detached house [29,30], a mid-rise office building [32], or a 12-story mixed-use tall building [33].

However, in other studies, heavyweight construction systems emerge as technologies with lower environmental impacts than lightweight solutions [34]. These studies highlight that the use stage is a key factor in determining the final results, as it can account for a significant difference between scenarios, ranging from 20% [34] to 55% [35]. Furthermore, for an accurate long-term interpretation of the results, it is important to note that the calculation period used in many studies is often limited to an average service life of 50 [30,34] to 60 years [35]. This analysis period is suitable for evaluating the environmental impacts of a building with an average service life, such as a lightweight construction system. However, it is too short to properly assess the life cycle of a building with a heavyweight structure, which may have a service life exceeding 100 years [6].

Analyzing the topic from an economic sustainability perspective, the life cycle cost (LCC) analysis is a frequently used methodology for investigating cost-optimal solutions in the design phase of a building [35]. Even in the case of LCC analysis, limited research has been conducted to compare heavyweight and lightweight construction systems. In order to compare these technological solutions from a whole-life-cycle perspective, the building's total life-cycle cost (TLCC) must be calculated and assessed as the present value sum of the construction cost, utility cost, and maintenance cost over the service life. In general, the direct construction cost accounts for over 60% of the total cumulative cost [30].

Generally, heavyweight construction technologies are more economical than lightweight ones, regardless of the building type, maintenance operations, and interest rates applied. Based on the commercial construction cost data from the RSMeans database, GU et al. estimate that the initial costs of a mass timber 12-story mixed-use tall building project are 26% higher than those of the concrete alternative [33]. Stazi et al., on the other hand, estimate that the total cost of the timber solution is 11% higher than that of the masonry alternative for low-energy multi-family residential buildings [17]. Within lightweight construction systems, Mallo et al. evaluate the CLT structure for a performing arts center as 21.7% more economical than the steel and concrete solution [36].

In this sense, the present paper proposes a multidisciplinary approach to investigating the energy-saving, comfort, environmental, and economic aspects derived from the adoption of heavyweight or lightweight construction systems in the Mediterranean region, using a building archetype of a multi-family detached house located in Bologna, Italy, as a case study. This approach provides a multi-criteria assessment that highlights the strengths and weaknesses of various construction systems across different levels of analysis, thereby offering general guidelines for replacement interventions in urban contexts.

2. Materials and Methods

The present study aims to assess the effects on comfort levels and environmental and economic sustainability resulting from the adoption of some construction technologies diffused in the Italian Mediterranean area. In particular, five high-performance construction systems in a multi-family residential building, described in the next section, are evaluated: (i) reinforced concrete structure with low-transmittance thermal block infill; (ii) reinforced concrete structure with light-clay bricks and outer thermal insulation; (iii) steel frame; (iv) cross-laminated timber (CLT); and (v) timber-steel hybrid structure. To achieve this goal, this research employs a multidisciplinary methodological approach involving various types of analysis, with the main phases summarized in Figure 1.

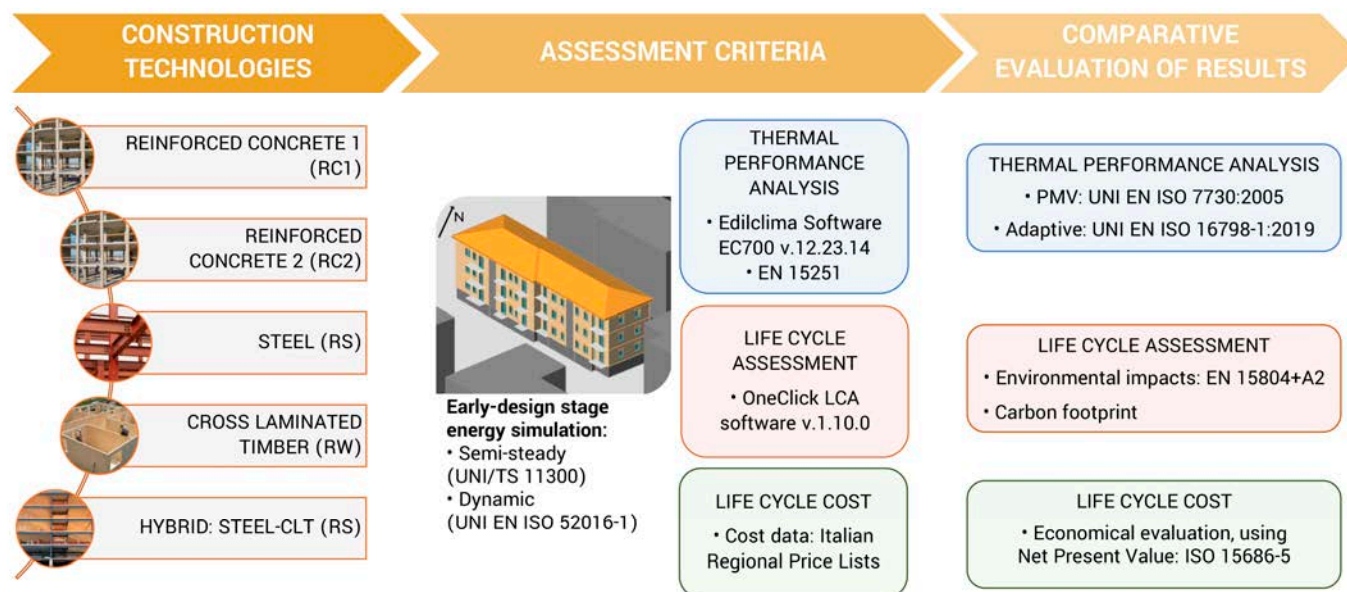


Figure 1. Methodology framework adopted in this study. On the left, the types of evaluated construction systems. In the center, the analysis criteria, along with their respective standards and software. On the right, the evaluation of the results (2024, © Authors).

In particular, the five technological solutions are designed for use in a building located in Bologna, in the warm temperate climate area (Cfa), according to the Köppen classification, which corresponds to climate zone E according to Italian regulations [37]. These regions are characterized by generally warm or very hot summers, relatively mild winters with temperatures rarely below freezing, and abundant, well-distributed precipitation. These solutions are designed to comply with current seismic and energy regulations, including achieving the zero-energy building (ZEB) standard, which means a building whose annual non-renewable primary energy consumption for heating, cooling, and domestic hot water production is zero [38].

The proposed methodology is structured into three main phases, each serving a specific purpose in the research process:

- (i) **Thermal performance analysis:** The five scenarios are modeled using the software Edilclima EC700 v12.23.14, which employs dynamic energy simulation to calculate energy consumption, hourly data necessary for assessing thermal comfort, and the quantities of materials stocked in the building.
- (ii) **Life cycle assessment:** The evaluation is conducted using the software OneClick LCA (June 2024 Release), referencing average datasets related to the Italian context. The assessment involved both the materials constituting the load-bearing structure and those of the building envelope previously calculated.
- (iii) **Life cycle cost:** The economic assessment is conducted primarily using the Italian regional price lists to estimate the construction cost. Each component of the LCC,

including construction cost, maintenance, residual cost, etc., is calculated for each year and then discounted to the base year (year 0) for the evaluation.

2.1. Construction Technologies and Application to the Case Study

To assess construction technologies comparatively, a typical building was utilized, with its geometric characteristics summarized in Figure 2 and Table 1. This case study involves a mid-rise, medium-compact, multi-family building built in 1965 in Bologna, Italy. This residential typology was prevalent during that period and is therefore considered representative of the building stock [39]. Considering the minimal construction and typological variations among buildings during those years in Bologna and Italy, assessments applied to specific case studies are particularly important for defining representative building archetypes [40]. Indeed, these archetypes are helpful in conducting comprehensive evaluations at the urban scale of energy demand and environmental impacts related to the building stock, with a view to possible replacement intervention [41]. In particular, this study aims to investigate different construction techniques that could be used in the demolition and reconstruction of the building to assess the benefits in terms of environmental impacts, thermal comfort, and costs.



Figure 2. Photograph, typical floor plan, section, and axonometric view of the model with the thermal zone considered for thermal comfort analyses highlighted in red (2024, © Authors).

Table 1. Main geometric and construction data of the case study (2024, © Authors).

Building Characteristics			
Gross volume	3980.60 m ³	No. of residential floors	3 + basement
Residential net floor area	1069.70 m ²	No. housing units	12
Gross floor area	1800.80 m ²	Potential no. of residents	50 ÷ 60
Height	12.50 m	Envelope surface	2072.50 m ²
S/V Ratio	0.53	Window surface	186.90 m ²

In evaluating construction techniques, it is proposed that the existing building be demolished and reconstructed using the same geometric and volumetric data, as shown in Table 1. In particular, this article focuses exclusively on the reconstruction process without exploring the contribution provided by demolition phases, which remain constant in all scenarios. A previous publication explored the comparison at the urban block scale between

energy retrofit techniques and demolition and reconstruction, using a case study from the same era with similar construction techniques [42].

From the perspective of energy simulation, the building is modeled in all scenarios in a simplified manner to comply with the regulatory requirements for Italian climate zone E [18,38]. The semi-stationary and dynamic energy simulation of the demolition/reconstruction scenarios is conducted using the software Edilclima EC700 v. 12.23.14 [43]. In all assumed scenarios, heating, cooling, and domestic hot water (DHW) systems are kept equal to ensure that the results are not influenced by these elements. A high-efficiency air-to-water heat pump, characterized by a COP equal to 4.10 and an EER equal to 6.08, is employed. In addition, a 30 kW peak photovoltaic system and a solar thermal system of 8 m² are required to achieve the zero energy building (ZEB) goal.

The demolition and reconstruction scenarios involve analyzing two heavyweight and three lightweight construction systems: (i) a reinforced concrete structure with low-transmittance thermal block infill (RC1); (ii) a reinforced concrete structure with light clay bricks and outer thermal insulation (RC2); (iii) a steel frame with external walls constructed using totally dry elements (RS); (iv) a cross-laminated timber structure with outer thermal insulation (RW); and (v) a timber-steel hybrid structure based on circular economy principles (RH). Tables 2–4 summarize the geometric dimensions and thermal parameters of each building element used in each scenario. Additionally, detailed sheets concerning the building components can be found in Supplementary Materials.

Table 2. Characteristics of the main building envelope elements of the heavyweight construction systems analyzed (RC1 and RC2) in this study; where: U is the thermal transmittance, Y_{ie} is the periodic thermal transmittance, and k_1 is the periodic internal areal heat capacity (2024, © Authors).

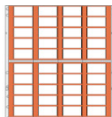
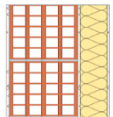
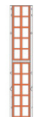
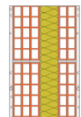
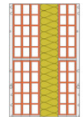
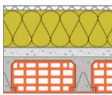
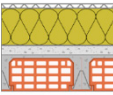
Building Components	Scenario RC1					Scenario RC2					
	Area [m²]	U [W/m²K]	Y _{ie} [W/m²K]	k ₁ [kJ/m²K]	Unit Mass [kg/m²]	Area [m²]	U [W/m²K]	Y _{ie} [W/m²K]	k ₁ [kJ/m²K]	Unit Mass [kg/m²]	
 External walls	1308.00	0.191	0.001	40.92	432.00	 External walls	1308.00	0.188	0.006	50.63	384.00
 Internal walls	1431.00	0.519	0.479	24.69	50.00	 Internal walls	1431.00	1.422	1.110	46.46	116.00
 Internal walls	539.60	0.258	0.038	47.92	251.00	 Internal walls	539.60	0.258	0.038	47.92	251.00
 Roof	478.60	0.192	0.032	58.82	336.00	 Roof	478.60	0.192	0.032	58.82	336.00
 Ground floor	420.10	0.204	0.040	43.09	376.00	 Ground floor	420.10	0.204	0.040	43.09	376.00

Table 2. Cont.

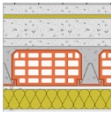
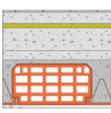
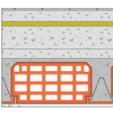
Building Components	Scenario RC1					Scenario RC2					
	Area [m²]	U [W/m² K]	Y _{ie} [W/m² K]	k ₁ [kJ/m² K]	Unit Mass [kg/m²]	Area [m²]	U [W/m² K]	Y _{ie} [W/m² K]	k ₁ [kJ/m² K]	Unit Mass [kg/m²]	
 First floor	420.10	0.199	0.003	56.08	519.00	 First floor	420.10	0.199	0.003	56.08	519.00
 Internal floors	1260.30	0.494	0.034	56.12	506.00	 Internal floors	1260.30	0.494	0.034	56.12	506.00

Table 3. Characteristics of the main building envelope elements of the lightweight construction systems analyzed (RS and RW) in this study; where: U is the thermal transmittance, Y_{IE} is the periodic thermal transmittance, and k₁ is the periodic internal areal heat capacity (2024, © Authors).

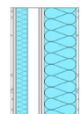
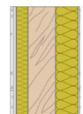
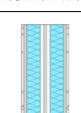
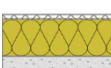
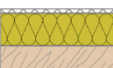
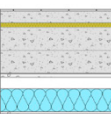
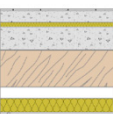
Building Components	Scenario RS					Scenario RW					
	Area [m ²]	U [W/m ² K]	Y _{ie} [W/m ² K]	k ₁ [kJ/m ² K]	Unit Mass [kg/m ²]	Area [m ²]	U [W/m ² K]	Y _{ie} [W/m ² K]	k ₁ [kJ/m ² K]	Unit Mass [kg/m ²]	
 External walls	1308.00	0.151	0.067	25.54	60.00	 External walls	1308.00	0.150	0.007	23.69	129.00
 Internal walls	1431.00	0.495	0.455	24.16	48.00	 Internal walls	1431.00	0.530	0.487	24.27	48.00
 Internal walls	539.60	0.212	0.108	25.68	65.00	 Internal walls	539.60	0.227	0.114	26.48	69.00
 Roof	478.60	0.202	0.071	108.98	311.00	 Roof	478.60	0.201	0.020	35.52	164.00
 Ground floor	420.10	0.204	0.040	43.09	376.00	 Ground floor	420.10	0.204	0.040	43.09	376.00
 First floor	420.10	0.202	0.005	56.13	421.00	 First floor	420.10	0.204	0.003	56.08	279.00

Table 3. Cont.

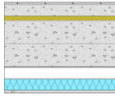
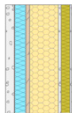
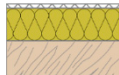
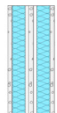
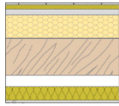
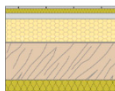
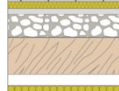
Building Components	Scenario RS					Scenario RW					
	Area [m²]	U [W/m²K]	Y _{ie} [W/m²K]	k ₁ [kJ/m²K]	Unit Mass [kg/m²]	Area [m²]	U [W/m²K]	Y _{ie} [W/m²K]	k ₁ [kJ/m²K]	Unit Mass [kg/m²]	
 Internal floors	1260.30	0.288	0.009	56.17	420.00	 Internal floors	1260.30	0.216	0.004	56.08	278.00

Table 4. Characteristics of the main building envelope elements of the RH scenario used in this study; where: U is the thermal transmittance, Y_{ie} is the periodic thermal transmittance, and k₁ is the periodic internal areal heat capacity (2024, © Authors).

Building Components	Scenario RH					Scenario RH					
	Area [m²]	U [W/m²K]	Y _{ie} [W/m²K]	k ₁ [kJ/m²K]	Unit Mass [kg/m²]	Area [m²]	U [W/m²K]	Y _{ie} [W/m²K]	k ₁ [kJ/m²K]	Unit Mass [kg/m²]	
 External walls	1308.00	0.143	0.019	51.68	116.00	 Roof	478.60	0.194	0.009	35.37	176.00
 Internal walls	1431.00	0.487	0.417	36.97	74.00	 Ground floor	420.10	0.204	0.040	43.09	376.00
 Internal walls	539.60	0.235	0.060	36.27	113.00	 First floor	420.10	0.146	0.002	24.75	172.00
 Internal floors Variant 1	1260.30	0.165	0.003	24.74	171.00	 Internal floors Variant 2	1260.30	0.214	0.003	28.90	212.00

The described construction components have been designed to reach the minimum thermal transmittance values required by Italian regulations [18] and to achieve comparable values among them. This ensures a functional unit suitable for LCA analysis, as detailed in the following chapters. The construction technologies are described as follows:

- The foundation is assumed to be the same for all replacement scenarios. It consists of inverted beams, 60 × 80 cm, with rebar assumed to be 100 kg/m³. The foundation slabs are constructed with a lean concrete slab (10 cm), plastic ventilation formwork (55 cm), reinforced concrete slab with welded mesh (6 cm), waterproofing layer, XPS insulation (8 cm), vapor barrier, concrete screed (10 cm), self-leveling mortar (2 cm), and ceramic tiles (1 cm).
- The windows are low-e double-glazed with timber frames (U = 1.3 W/m² K).
- Heavyweight building envelope elements of reinforced concrete construction systems (RC1 and RC2) are summarized in Table 2. They utilize the same reinforced concrete frame structure, consisting of a vertical structure of 32 pillars, each having a rectangular cross-section of 30 × 50 cm and two elevator cores with a thickness of 20 cm and a

height of 12.50 m. The rebar is assumed to be 160 kg/m^3 and 40 kg/m^3 , respectively. The horizontal structure comprises rectangular beams of 30×50 , with rebar evaluated at 150 kg/m^3 . The floors are constructed with a structural slab made of one-way precast lattice joists and hollow clay brick filler blocks. The roof is insulated with rock wool (16 cm) and protected by a vapor barrier, waterproofing membrane, and clay tiles. The non-structural layers for internal floors include plaster (1.5 cm), concrete screed (10 cm), insulation panels for radiant heating (2 cm), self-leveling mortar (5 cm), and ceramic tiles (1 cm), while the floor towards the cellars is insulated with rock wool panels (10 cm) covered in plasterboard (1.25 cm). In the RC1 scenario, the infill masonry is constructed with rectified building brick blocks without thermal insulation (45 cm); the internal partitions with dry elements are constructed with a double layer of plasterboard and fiber-gypsum board with rock wool insulation (5 cm). A cavity wall insulation in rock wool (8 cm) between two brick block layers (12 + 8 cm) is used for internal walls between the apartments. The difference in the RC2 scenario lies in the alternative materials used for the infill masonry in the external walls and for the internal partitions. In this case, 30 cm brick blocks and 12 cm of gray EPS for external insulation are used for the external walls, while 8 cm hollow bricks are used for the internal partitions.

- (iv) The envelope elements of lightweight construction systems with steel frames and light dry infill walls (RS) and CLT structure (RW) are described in Table 3, while circular economy principles inspire the elements of the hybrid CLT-steel construction system in Table 4. The steel structure of scenarios RS and RH was calculated as 110 tons of structural steel with 90% recycled content, consisting of a vertical structure comprising 32 HEB240 pillars; 48 main beams of the HEB180 section; secondary beams and balcony beams of HEA180; connections were evaluated as an additional weight of 10%. The CLT structure was evaluated in 382 m^3 of panels of the same thickness, measuring 12 cm for the walls and 16 cm for the floors.

Concerning the steel structure, the floors are composed of profiled steel sheeting thick 0.8 cm and a reinforced concrete slab of 5 cm; the non-structural layers of the internal floors are similar to those of the heavyweight construction systems, while the floor towards the cellars and the roof are insulated with glass wool panels (10 and 16 cm). The external walls are constructed using totally dry elements: two sub-structures, 10 and 14 cm thick, filled with glass wool insulation and closed internally with a double layer of plasterboard and fiber-gypsum board (12.5 + 12.5 mm) and externally with a cement board of 12.5 mm. The interior walls are comparable to those in scenario RC1, with the exception of the insulating material, which in this case is glass wool, while the walls dividing residential units have a double sub-structure.

The CLT scenario (RW) is the only one that employs load-bearing elements for the walls, floors, and roof structure: the vertical panels are 12 cm thick, while the horizontal panels are 16 cm thick. The non-structural layers of floors in the CLT scenario (RW) are similar to other cases. The only differences are related to the thicknesses of the rock wool on the floor towards the cellars and on the roof, which are 6 cm and 16 cm, respectively. Internal walls are similar to those in the RS scenario, but rock wool is used as insulation material in this case. The non-structural layers of external walls consist of an internal wooden sub-structure filled with rock wool panels and closed internally with a double layer of plasterboard and fiber-gypsum board (12.5 + 12.5 mm), while the external insulation measures 12 cm.

The floors of the hybrid structure (RH) consist of CLT slabs with a thickness of 16 cm, while the non-structural layers include a dry screed in cellulose flakes (10 cm), a wooden sub-structure, a double fiber-gypsum board (25 mm), dry radiant panels (2 cm), and ceramic flooring. The roof is insulated with a rock wool panel of 16 cm. The internal walls employ a totally dry solution with a wooden sub-structure, insulation in recycled textile fiber, and clay cladding. The external wall is constructed with a dry wooden frame sub-structure filled with cellulose (16 cm) and clad with a wood fiber insulation layer (4 cm). A second

version (RH2) of the internal floors has been modeled to evaluate the improvement in thermal comfort associated with the increased mass of the floors. In this latter case, the dry screed in cellulose flakes (10 cm) was replaced with an equivalent layer of expanded clay.

2.2. Thermal Performance Analysis

The energy model used for the thermal performance analysis was created using the software Edilclima EC700 v. 12.23.14 [43]. The building was modeled with the same geometry in all evaluated scenarios and was divided into thermal zones, one for each apartment. For the comfort evaluation, the thermal zone of the unit most affected by temperature variations throughout the day was used, specifically the top-floor unit with south/west exposure (Figure 1). The unit had a total floor area of approximately 75 m².

The dynamic thermal behavior of the opaque building envelope was analyzed based on UNI EN ISO 52016 [44] to understand the influence of thermal mass on internal comfort. An air infiltration rate of 0.30 air changes per hour was used to calculate heat loss due to natural ventilation [45]. The schedules regarding occupation, internal gains, and heating/cooling set points refer to UNI EN 16798-1 [21]. Specifically, an internal gain of 2.8 W/m² for occupants and 5.0 W/m² for appliances is assumed [21]. The simulation results in terms of energy demand and non-renewable primary energy demand for each scenario are presented in Table 5.

Table 5. Summary table of heating/cooling energy demand, energy consumption, and photovoltaic system production for each simulated scenario (2024, © Authors).

Building Components	Replacement Reinf. Concr. RC1	Replacement Reinf. Concr. RC2	Replacement Steel RS	Replacement CLT RW	Replacement Hybrid RH
Heat loss (transfer and ventilation) $Q_{H,ht}$ [kWh]	51,363	44,483	44,102	42,217	41,655
Heat gains $Q_{H,gn}$ [kWh]	26,129	26,178	26,587	26,476	26,471
Heating energy demand $Q_{H,nd}$ [kWh]	26,273	20,212	19,992	18,649	17,699
Heating energy demand $Q_{H,nd}$ [kWh/m ²]	25.46	19.59	19.26	17.97	17.05
Heat loss (transfer and ventilation) $Q_{C,ht}$ [kWh]	24,368	22,685	28,525	28,338	27,279
Heat gains $Q_{C,gn}$ [kWh]	31,312	33,275	37,390	38,183	37,277
Cooling energy demand $Q_{C,nd}$ [kWh]	10,773	13,216	13,690	14,416	14,121
Cooling energy demand $Q_{C,nd}$ [kWh/m ²]	10.44	12.81	13.19	13.89	13.61
Non-renewable primary energy demand for heating, cooling and DHW [kWh/m ² year]	0.00	0.00	0.00	0.00	0.00
Italian energy class	A4 (ZEB)	A4 (ZEB)	A4 (ZEB)	A4 (ZEB)	A4 (ZEB)
Lightning and equipment energy demand [18] [kWh/year]	2000 per unit				
Electricity demand [kWh/year]	24,000				
PV production [kWh/year]	28,615	28,615	28,615	28,615	28,615
Electricity from PV used by HVAC [kWh/year]	7804	8224	8486	8544	8340
Total electricity demand from the national grid [kWh/year]	3189	3613	3871	3929	3725

The assessment of thermal comfort among different construction systems was carried out using two methodologies, as follows:

- (i) Hourly dynamic assessment of summer thermal comfort is conducted by calculating the operative temperature (θ_o , t) according to the procedure described in UNI EN ISO 52016-1 [44], focusing on the summer season (20 June–21 September) in all main building spaces, without accounting for the heating or cooling system contributions. According to the adaptive model, there exists an optimal operative temperature (θ_{rif}), which represents the highest comfort level within a space:

$$\Theta_{rif} = 0.33 \cdot \Theta_{est} + 18.8 \quad (1)$$

where Θ_{est} is the average daily outdoor temperature according to UNI EN 16798-1 [21]. The regulation establishes comfort intervals that center around this optimal value, described as follows:

- Category I: High—buildings with high expectancy for sensitive occupants:
if $(0.33 \times \theta_{rif} + 18.8 - 3) \leq \theta_{o,t} \leq (0.33 \times \theta_{rif} + 18.8 + 2)$
- Category II: Normal—new buildings and renovations:
if $(0.33 \times \theta_{rif} + 18.8 - 4) \leq \theta_{o,t} \leq (0.33 \times \theta_{rif} + 18.8 + 3)$
- Category III: Acceptable—existing buildings:
if $(0.33 \times \theta_{rif} + 18.8 - 5) \leq \theta_{o,t} \leq (0.33 \times \theta_{rif} + 18.8 + 4)$
- Category IV: Low—expectancy only for short periods:
if $\theta_{o,t} \leq (0.33 \times \theta_{rif} + 18.8 - 3)$ or $\theta_{o,t} \geq (0.33 \times \theta_{rif} + 18.8 + 2)$

Points located below the lower limit of the comfort temperature represent cold discomfort situations, and similarly, those beyond the upper limit correspond to hot discomfort situations. Thermal comfort is ensured when the operative temperature falls within the Category I and II intervals for at least 85% of the hours.

- (ii) The hourly dynamic assessment of thermal comfort and indoor air quality is based on predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) according to UNI EN ISO 7730 [20]. Specifically, this methodology is applicable in the case of mechanically conditioned buildings. It utilizes six independent variables (activity level, clothing insulation, air temperature, relative humidity, air velocity, and mean radiant temperature) that influence the terms of the thermal balance. The approach integrates overall comfort with local comfort, identifying parameters to assess local conditions (such as draught rate, vertical air temperature difference, warm or cool floors, and radiant temperature asymmetry) and others for global assessment (PPD and PMV). The standard defines three comfort categories, A, B, and C, based on combinations of these parameters [20].

2.3. Life Cycle Assessment

2.3.1. Aim and Scope of This Study

The present LCA analysis aims to investigate the five high-performance construction systems proposed to determine their environmental impacts over short, medium, and long-term durations. In this sense, the assessment is conducted using three different lifespans: (i) a 30-year lifespan to ascertain the most effective construction technology for short-term duration; (ii) a 60-year lifespan to establish a mean impact value over the lifecycle, as prescribed by level(s) [46]; and a theoretical 100-year lifespan applied to both heavyweight and lightweight construction systems to evaluate the correlation between durability and environmental impacts.

2.3.2. The Functional Units

The functional unit of the present analysis is the gross floor area in square meters, including the projected area of walls and pillars in plans. This comparison is conducted based on a calculation of 1800.80 m² of gross floor area, of which 1069.70 m² is residential. In particular, the building envelope components of different scenarios are designed to have

a comparable thermal transmittance value, with a variation of $U \pm 0.01 \text{ W/m}^2\text{K}$, while the structural components are designed to withstand seismic loads.

2.3.3. Life Stage Boundary, Impact Categories, Source of Data and Assumptions

In order to assess the impacts associated with the building lifecycle, the analyses include phases related to production (A1–A3), transportation (A4), construction (A5), end-of-life (C1–C4), use phases related to materials (B4–B5), and operational energy and water phases (B6–B7), as outlined in Section 2.3.4. These evaluations are reported in terms of global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photochemical oxidant creation potential (POCP), and primary energy consumption (PE).

This study was conducted using the software OneClick LCA in accordance with the EN 15978:2011 standard [47]. The analysis was carried out employing generic materials from the OneClick LCA database that incorporates ECOINVENT processes to evaluate the materials' average environmental impact. Data specific to the Italian energy mix is used to evaluate the operational stage. The building components included in this study are listed in Table 6. The calculation of material quantities for building envelopes and internal elements derives from the geometry and stratigraphies outlined in Tables 1–3. The distribution of systems (drinking water, sewage, electrical, and heat) is assessed using average data provided by OneClick LCA per square meter of floor area [48]. Other components, such as furniture, site elements, vegetation, fences, pavings, etc., are not included in the analysis.

Table 6. System boundaries regarding building parts included in this study (2024, © Authors).

Element	Assessment	Finishes	Assessment	External	Assessment	Building Services	Assessment
Basement	Assessed	Interior surfaces	Partly Assessed	Balconies or terraces	Assessed	Heating	Partly assessed
External walls	Assessed	External surfaces	Assessed	Site	Not assessed	Cooling	Partly assessed
Internal walls	Assessed	Windows	Assessed	Vegetation	Not assessed	Ventilation	Partly assessed
Floor	Assessed	Doors	Assessed	Fences	Not assessed	Water	Partly assessed
Roof	Assessed	Furniture	Not assessed	Pavings	Not assessed	Sewage	Partly assessed
Stairs and lift	Partly Assessed			Temporary cabins or machinery	Not assessed	Electrical	Partly assessed

2.3.4. Life Cycle Inventory (LCI)

The life cycle inventory (LCI), designed to quantify input and output flows, was developed in four stages. Firstly, the bill of material quantities related to building envelope components, internal partitions, doors, and windows was calculated (these quantities are automatically calculated within the Edilclima software, similar to how it would be calculated in BIM software). Secondly, the bill of material quantities related to the materials composing the load-bearing structure was calculated (these quantities were calculated employing a structural design of the building, elaborated to comply with seismic actions according to current Italian regulations [49]). Thirdly, data concerning transport distances and on-site waste production for each material based on literature was evaluated. Lastly, the service life of each component according to the level(s) framework was assessed [46].

The production phase (A1–A3) quantifies the impacts related to the production of materials necessary for the building's construction. This stage encompasses resource extraction, transportation of raw materials to the production site, processing, and handling of resulting waste. As some research suggested, the initial quantification of materials was automated using BIM software [50]. In this study, Edilclima was employed to calculate

the quantities of each material contained within each building envelope. Subsequently, the bill of materials was imported into a spreadsheet file to implement and enrich it with additional materials that could not be evaluated automatically. In particular, structural materials were calculated directly within the spreadsheet file based on a structural design related to the building archetype. Other components, such as systems for heating, cooling, domestic hot water production, etc., were modeled directly in the OneClick LCA software using simplified modules based on average impacts per square meter of residential surface area. The environmental impacts related to the production of construction materials were estimated using the OneClick LCA database, employing processes that represent regional average data within the Italian context. When this data were unavailable, average environmental impact profiles from the European context or neighboring countries such as France or Germany were utilized. The biogenic carbon absorbed by vegetal materials during their growth has not been evaluated, considering its return to the atmosphere during the end-of-life phase. The bill of materials relating to the main building elements of each scenario is contained in Table 7.

Table 7. Bill of main material quantities for each scenario (2024, © Authors).

Scenario	Description	Unit	Quantity	Scenario	Description	Unit	Quantity
All	Concrete C 25/30	m ³	235.85	RC1, RC2, RS, RW	Ceramic tiles	t	34.32
All	Concrete C 28/35	m ³	46.46	RC1, RC2, RS, RW	Self-leveling mortar	t	85.46
All	Rebar	t	31.01	RC1, RC2, RS, RW	Radiant heating	t	2.40
All	Lean concrete slab	m ³	37.21	RC1, RC2, RS, RW	Concrete screed	t	142.83
All	Bentonite membrane	kg	2187.72	RC2	Clay bricks	t	651.96
All	Wooden formwork	m ²	160.37	RC2	Plaster mortar	t	182.29
All	Plastic formwork	kg	3360.80	RC2	Rock wool insulation	kg	17,303.92
All	XPS insulation	kg	1050.25	RC2	EPS insulation	kg	3139.20
All	Vapor barrier	kg	75.62	RC2, RS, RH	ETICS coating	m ²	1308.00
All	Waterproofing	kg	8584.45	RC2, RS, RH	Glue for insulation	kg	6540.00
All	Outdoor paint	m ²	1308	RC2	Plasterboard	kg	4505.70
All	Indoor paint	m ²	5089.8	RS	Plasterboard	kg	77,509.30
All	Wooden doors	kg	7033.92	RS	Gypsum board	kg	112,338.00
All	Window double-glazed, PVC-U frame	kg	6041.51	RS	Cement board	kg	21,255.00
All	Roof tiles	t	28.716	RS	Glass wool insulation	kg	21,306.98
RC1	Clay bricks	t	594.25	RW	Plasterboard	kg	76,106.50
RC1	Plaster mortar	t	162.55	RW	Gypsum board	kg	85,785.00
RC1	Rock wool insulation	kg	22,312.40	RS, RW, RH	Vapor barrier	kg	619.94
RC1	Plasterboard	kg	35,201.70	RW	Rock wool insulation	kg	47,124.48
RC1	Gypsum board	kg	42,930.00	RW	Steel sub-structure	t	4.80
RC1, RC2	Clay bricks	t	267.27	RH	CLT panels	t	168.90
RC1, RC2	Concrete C 28/35	m ³	355.96	RH	Structural timber	t	163.00
RC1, RC2	Rebar	t	56.885	RH	Clay board	kg	104,553.4
RC1, RC2	Wooden formwork	m ²	156.77	RH	OSB Board	kg	36,001.22
RS	Steel sub-structure	t	26.35	RH	Textile insulation	kg	3255.68
RS	Steel sheeting	t	22.67	RH	Cellulose insulation	kg	17,955.00
RS	Concrete C 28/35	m ³	215.90	RH	Wood fiber insulation	kg	19,755.00
RS, RH	Steel frame	t	110.30	RH	Rock wool insulation	kg	3360.80
RW	CLT panels	t	288.84	RH	Plasterboard	kg	18,404.06
RW	Structural timber	t	14.26	RH	Gypsum board	kg	38,875.00

Transportation to construction site phase (A4): The quantification of transports from production facilities to the construction site was modeled using the values present in the OneClick LCA database. These values are calculated assuming that the materials are transported via diesel-powered trucks with a capacity of 40 tons and a 100% fill rate (0.0383 kgCO_{2eq}/ton km). The values for each material are reported in Table 8.

Table 8. Service life and number of cycles for the main materials contained in stages B4 (replacement) and B5 (refurbishment), following the level(s) framework [46] (2024, © Authors).

Component and Description	Service Life [Years]	Number of Life Cycles in 100 Years [n]	Transport Distance [km]
Paint wall, indoor (2 coats per cycle)	10	10	470
Paint wall, outdoor (2 coats per cycle)	30	3	470
External wall thermal insulation and composite systems (including synthetic glue for insulation boards and ETICS coating)	30	3	60 (panels) 470 (ETICS/glue)
Interior wall insulation and cladding	30	3	60
External wall in lightweight construction systems (insulation, structure, and panels)	60	2	60
Internal partitioning and dry lining	60	2	60
Roof insulation panels	30	3	60
Waterproofing membrane	30	3	90
Vapor barrier membrane	30	3	90
Ceramic tiles	30	3	320
Underfloor heating system (including pipes and self-leveling mortar)	30	3	320 (system) 110 (mortar)
Wooden doors	30	3	350
Windows (including double-glazed and PVC frames)	30	3	380
Air/water heat pump (including hot water buffer tank, fan coils)	30	3	370
Electrical system (including cabling, PV, and solar thermal panels)	20	5	320
Drinking water supply and sewage water piping network	60	2	370
Heat distribution system	30	3	320

Construction stage (A5): Quantifying environmental impacts produced during a building's construction is not easy. Some studies assume this phase accounts for a small percentage of the impacts related to the production phase (A1–A3), generally between 4 and 5% [51]. In contrast, other studies proceed analytically by estimating the usage time of the machines employed [52]. In this study, the construction phase is evaluated as follows: (i) using average environmental impact profiles modeled in OneClick LCA for constructions in a Mediterranean climate; (ii) assessing the percentage of material lost during construction, according to OneClick LCA process assumptions, typically between 4 and 8%.

Repair and replacement stage (B4–B5): These phases encompass the environmental impacts of maintenance, repair, and replacement operations during a building's service life, including the associated waste flows. The maintenance and replacement phases were assessed using the service life values provided by the level(s) framework [46].

Operational energy stage (B6): This phase includes all types of energy consumption during the building's service life, such as heating, cooling, appliances, etc. This phase was calculated using (i) the energy simulation results in each scenario, (ii) the average household energy consumption for lighting and appliances [8], and (iii) the photovoltaic energy production. The results of this evaluation are reported in Table 5. An environmental profile of the Italian energy mix developed by OneClick LCA in 2024 was used to assess the impacts related to this stage. These data are based on a country-specific study on electricity mixes produced by the International Energy Agency (IEA) in 2021.

Operational water stage (B7): This stage is evaluated using two types of consumption: (i) domestic hot water consumption, calculated from the energy simulation in Edilclima; (ii) tap water consumption derived from the literature [53].

Demolition stage (C1): The environmental impacts resulting from the demolition process are calculated using a simplified module in OneClick LCA based on the estimation per square meter of surface area according to the type of construction system (reinforced concrete frame, steel frame, timber frame, and mixed frame).

End-of-life stages (C2–C4): These phases include: (i) the transportation from the construction site to disposal (C2), evaluated using specific average transportation data depending on the specific process; (ii) the waste treatment and disposal (C3–C4), estimated using the OneClick LCA database and current practices in Italy [54], assuming that metals and gypsum are considered recyclable, concrete and bricks are crushed as aggregate, wood and plastics are incinerated, and the remaining materials are landfilled.

2.4. Life Cycle Cost Analysis

The life cycle cost analysis (LCCA) is a methodology for evaluating a building's cost-effectiveness, considering costs in all life cycle phases. It includes construction, utilities, maintenance, replacements, and end-of-life and/or residual value. These elements are aggregated over a study period and discounted to the present value (PV) to be used as a decision-making parameter for design choices [55]. One of the methods for evaluating global cost (C_g) is the standard EN 15459 [56], which is based on the LCC approach. This standard is also followed by European regulations that define the following fundamental costs:

$$C_g = PV_{Constr.} + PV_{Constr.} + PV_{Util.} + PV_{MR} + PV_{EoL} + PV_{Res} \quad (2)$$

- Construction cost ($PV_{Constr.}$) represents the initial costs to build the structure, including materials, labor, and overhead during the construction process. The quantification of individual elements is based on the price list from the Emilia-Romagna region for 2023 (DGR No. 462 of 27/03/2023) [57]. These prices are corrected, applying a 22% VAT and increasing the total by 30% to cover design activities, project management, administrative expenses, surveys, inspections, etc. [55].
- Utility costs ($PV_{Util.}$) include the annual expenses for energy consumption ($PV_{Electricity}$) and water consumption (PV_{Water}). For energy consumption, the average cost per kWh in the Italian market was referenced, amounting to 0.2432 €/kWh in the third semester of 2024 [58]. Literature data were used to estimate the average consumption and annual price for tap water. Specifically, for the Italian context, an annual consumption of 200 kL/year per household is estimated, considering an average family size of 3 people, with an average annual cost of 1.127 €/kL [28].
- Maintenance and replacement costs (PV_{MR}) are the annual expenses for measures aimed at preserving and restoring the building elements. These include maintenance costs ($PV_{maintenance}$), repair costs (PV_{Repair}), and replacement costs ($PV_{Replacement}$) throughout the lifecycle. The quantification of the individual replacement work was carried out similarly to the estimation of construction costs [57], using the service life values of building components reported in Table 8. For the maintenance and repair of the photovoltaic system, a cost of 40 €/m² per year was estimated [59], while for each heat pump, an annual cost equal to 1.5% of the initial cost (1.5% C_0 €/pcs y) was estimated [60].
- End-of-life costs (PV_{EoL}) encompass the expenses for demolition, disposal, and decommissioning of a building at the end of its service life, including transportation and recycling. These costs are estimated using literature data at 131.32 €/m² GFA [6].
- Residual value (PV_{Res}) represents the remaining value of the building at the end of the evaluation period, estimated as the linear depreciation of the building construction cost over its lifespan:

$$\text{Residual Value} = \text{Initial Cost} - \left(\frac{\text{Initial Cost}}{\text{Life span}} \cdot N. \text{ years} \right) \quad (3)$$

Future costs (C_i) must be discounted to the PV of the base year to be accurately and evaluated. The discount rate (d) represents the expected return and risk on investment for the building owners. It has been assumed to be 4% [61], while the escalation rate (e) has been set at 1% for electricity, 4.5% for water, and 0.6% for maintenance/replacements [62]:

$$PV = \sum_{t=1}^N \frac{C_i \cdot (1+e)^t}{(1+d)^t} \quad (4)$$

Similar to the approach used for LCA, the evaluation is conducted using three different lifespans: 30, 60, and 100 years, to determine the cost-effectiveness of construction systems in the short, medium, and long term. This analysis does not quantify the costs associated with compensation for CO₂ emissions.

3. Results

3.1. Results of Thermal Comfort Analysis

The results of the thermal comfort analysis are presented in six scenarios, as a second version of the scenario with a hybrid structure (RH2) is also considered. This version is characterized by increased mass in the internal floors, as described in Section 2.1. Figures 3 and 4 show the hourly course of the outdoor temperature and the corresponding indoor operative temperature for each analyzed scenario over a year. The climatic data associated with Bologna predict a particularly hot summer, with 25 days when the external temperature exceeds 30 °C. The first graph (Figure 3) is modeled assuming that the heating and cooling systems are off and there are no internal heat gains from people or appliances. The second graph (Figure 4) presents the same conditions but assumes internal gains according to UNI EN 16798-1: 2.8 W/m² for occupants and 5.0 W/m² for appliances [21].

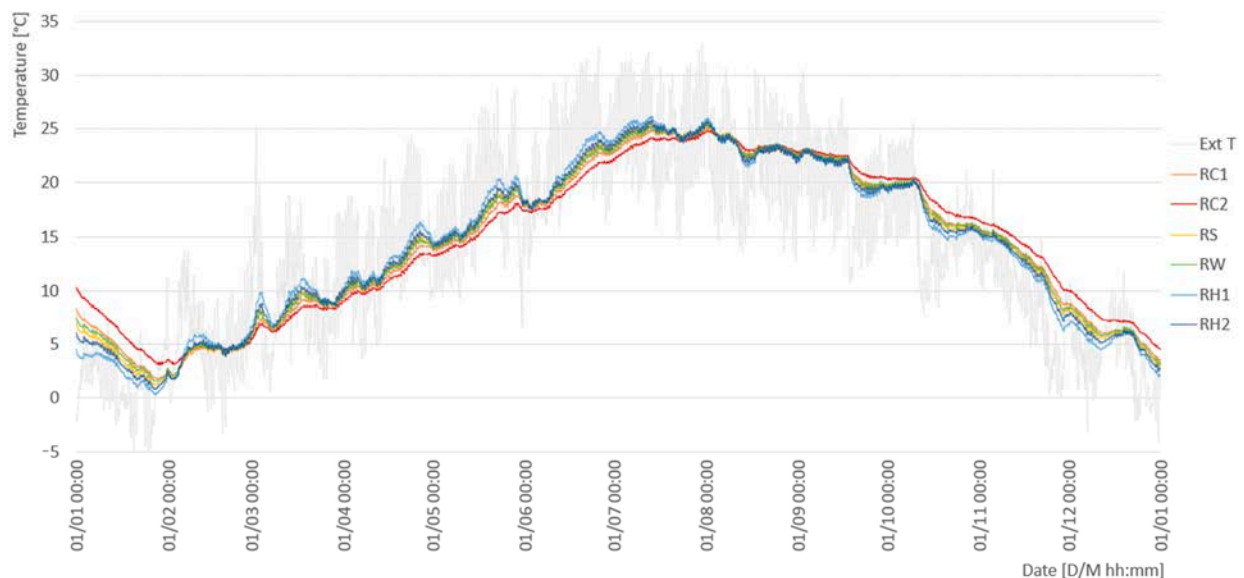


Figure 3. Simulation results in terms of hourly indoor operative temperature values throughout the year, assuming no internal gains—© 2024, Authors.

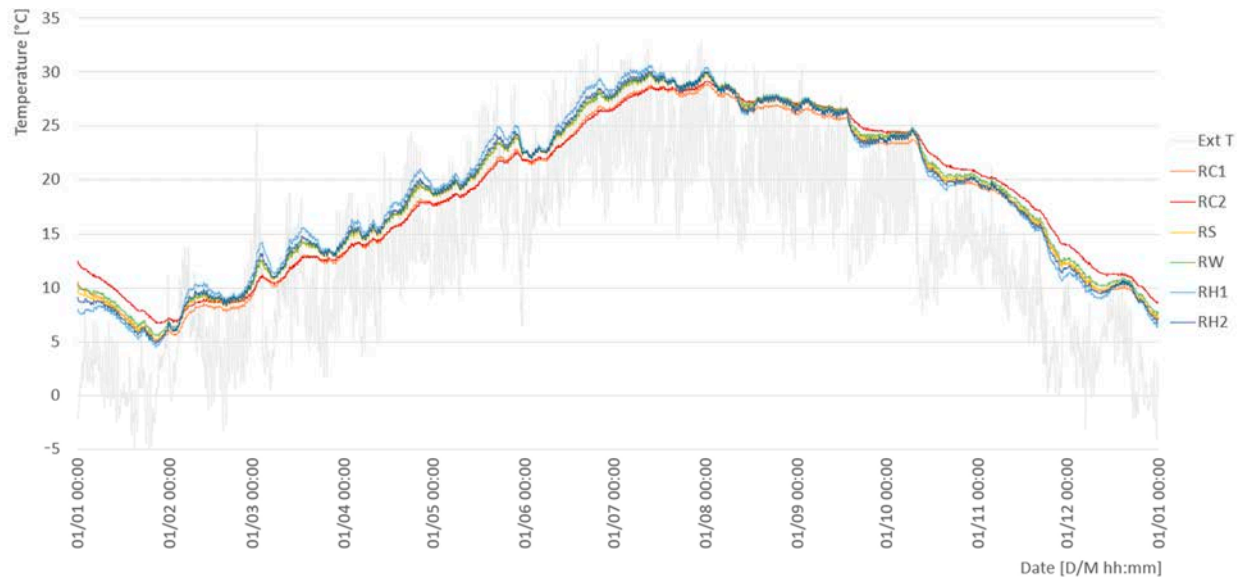


Figure 4. Simulation results in terms of hourly indoor operative temperature values throughout the year, assuming internal gains of 2.8 W/m^2 for occupants and 5.0 W/m^2 for appliances (2024, © Authors).

Considering the period corresponding to the hottest month of the year, July, the average external temperature is 24.8°C with a peak of 32.8°C and a minimum of 14.7°C . The simulation results (Table 9) show that heavyweight construction systems ensure a lower average indoor operative temperature, with a difference of approximately 1°C compared to lightweight construction systems. The most effective scenario is RC2 under the assumption of no internal heat gains, while RC1 is the best performing with internal heat gains. The worst scenario under both assumptions is RH1. This result highlights the crucial role of the thermal capacity of internal floors in managing temperature variations and internal heat gains. Indeed, by increasing the mass of the internal floors (RH2), the temperature values decrease, aligning with the results of other lightweight construction technologies.

Table 9. Thermal comfort assessment according to UNI EN 15251:2008 [63] for each scenario used in this study (2024, © Authors).

	Heating Season			Cooling Season		
	PMV [-]	PPD [%]	Category	PMV [-]	PPD [%]	Category
Replacement reinforced concrete (RC1)	−0.2754	6.5739	B	0.0929	5.1960	A
Replacement reinforced concrete (RC2)	−0.2554	6.5083	B	0.0938	5.1868	A
Replacement steel (RS)	−0.2601	6.5057	B	0.0953	5.1946	A
Replacement CLT (RW)	−0.2461	6.5553	B	0.0964	5.1910	A
Replacement hybrid (RH1)	−0.2568	6.4986	B	0.0944	5.1897	A
Replacement hybrid (RH2)	−0.2549	6.5056	B	0.0958	5.1925	A

By evaluating the graphs throughout the year (Figures 4 and 5, Table 10), it is possible to observe the contribution of thermal inertia in mitigating internal temperature variation due to external seasonal variations. Specifically, heavyweight construction systems tend to maintain a lower temperature from winter to summer and a higher temperature from summer to winter. Consequently, the use of heating and cooling systems can be slightly delayed, taking advantage of this passive capacity.

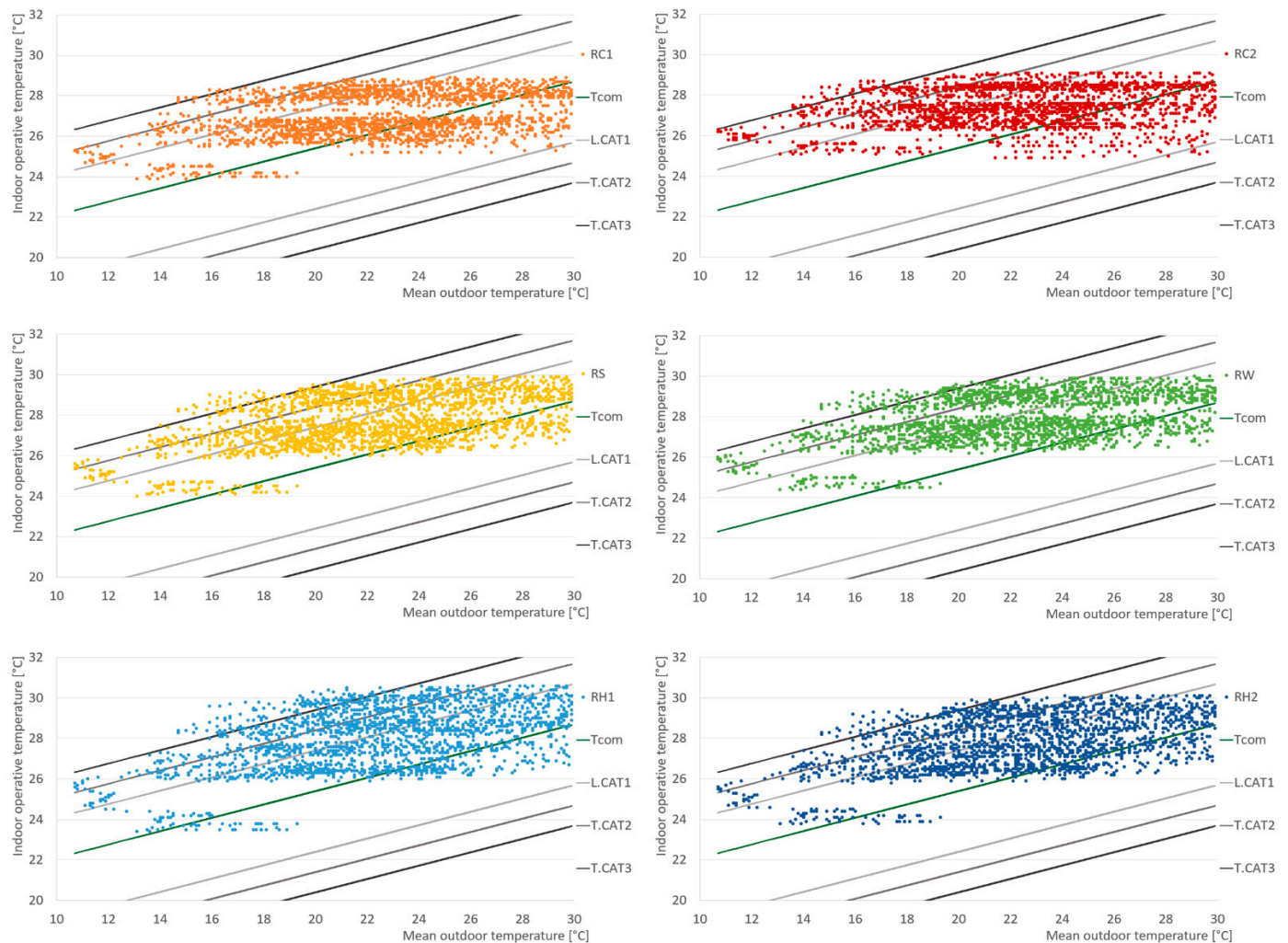


Figure 5. Simulation results in terms of hourly indoor operative temperature values, based on the adaptive model, during the summer season (20 June–21 September) (2024, © Authors).

Table 10. Hourly indoor operative temperature values during July, assuming the cooling system turned off, for each simulated scenario used in this study (2024, © Authors).

	Replacement Reinf. Concr. RC1	Replacement Reinf. Concr. RC2	Replacement Steel RS	Replacement CLT RW	Replacement Hybrid RH1	Replacement Hybrid RH2
No internal gains, average	24.2	23.8	24.6	24.5	25.0	24.7
No internal gains, max	25.0	24.7	25.6	25.4	26.2	25.8
No internal gains, min	22.8	22.1	23.1	23.0	23.7	23.4
With internal gains, average	28.0	28.1	29.0	29.1	29.5	29.2
With internal gains, max	28.8	29.1	29.9	30.0	30.6	30.1
With internal gains, min	26.7	26.5	27.6	27.6	28.2	27.8

These considerations are also confirmed when evaluating the results according to the adaptive comfort model (Figure 5 and Table 11). Heavyweight construction technologies ensure a higher number of comfort hours during the summer season (20 June–21 September), achieving 94.67% for RC1 and 87.62% for RC2 within the two highest comfort categories. Once again, the worst-performing scenario is RH1, with only 76.50% of comfort

hours. However, by increasing the mass of the intermediate floors (RH2), it is possible to achieve similar comfort value of other lightweight construction systems, 81.09% and 84.52%, respectively. The analysis results based on PMV and PPD, according to UNI EN ISO 7730, do not show significant differences in thermal comfort. This result is influenced by the type of evaluation that also considers the role played by HVAC systems.

Table 11. Evaluation of thermal comfort according to the categories specified in UNI EN 16798-1 [21], based on the adaptive model, during the summer season (20 June–21 September) (2024, © Authors).

Category [Hours (Rate)]	Replacement Reinf. Concr. RC1	Replacement Reinf. Concr. RC2	Replacement Steel RS	Replacement CLT RW	Replacement Hybrid RH1	Replacement Hybrid RH2
Category I: high—buildings with high expectancy for sensitive occupants	1674 (77.61%)	1442 (66.85%)	1329 (61.61%)	1256 (58.23%)	1154 (53.50%)	1294 (59.99%)
Category II: normal—new buildings and renovations	368 (17.06%)	448 (20.77%)	494 (22.90%)	493 (22.86%)	496 (23.00%)	494 (22.90%)
Category III: acceptable—existing buildings	106 (4.91%)	225 (10.43%)	294 (13.63%)	328 (15.21%)	378 (17.52%)	308 (14.28%)
Category IV: low—expectancy only for short periods	9 (0.42%)	42 (1.95%)	40 (1.85%)	80 (3.71%)	129 (5.98%)	61 (2.83%)
High comfort levels (Category I and II)	2042 (94.67%)	1890 (87.62%)	1823 (84.52%)	1749 (81.09%)	1650 (76.50%)	1788 (82.89%)

3.2. Results of Life Cycle Assessment

The results of the LCA analyses conducted on the five scenarios are represented in Figure 6, in terms of impact indicators reported in Section 2.3.3 (GWP, ODP, AP, EP, POCP, PE), and in Figure 7 as an increase in GWP during the analysis period, expressed in terms of $\text{kgCO}_{2\text{eq}}/\text{m}^2$ and $\text{kgCO}_{2\text{eq}}/\text{m}^2$ per year. The assessment was conducted using different analysis periods (30, 60, and 100 years) to highlight how time plays a significant role in determining the final results when comparing different construction systems. Subsequently, an assumption is made regarding the potentially shorter lifespan of buildings constructed with lightweight systems in order to also evaluate possible long-term optimizations due to the greater durability of heavy materials.

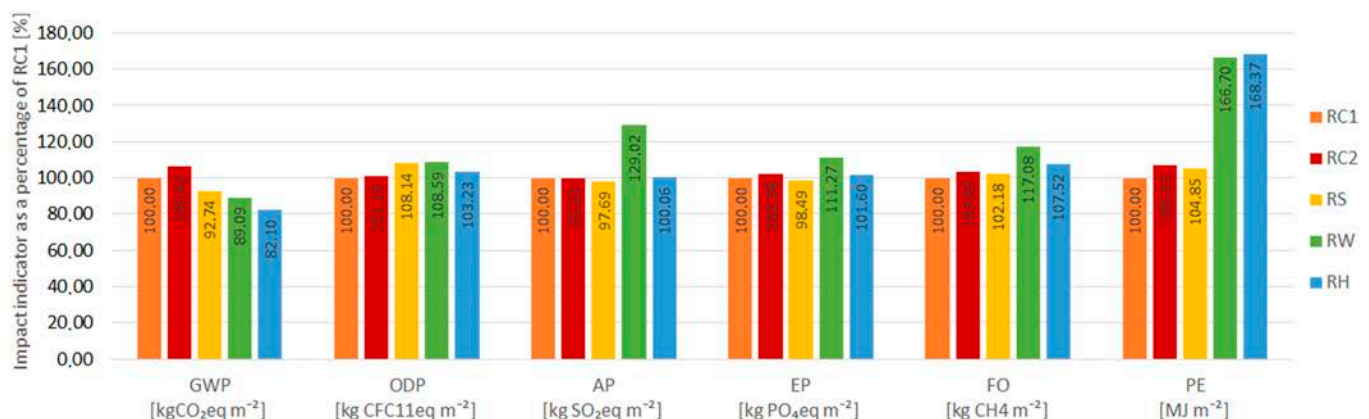


Figure 6. Cont.

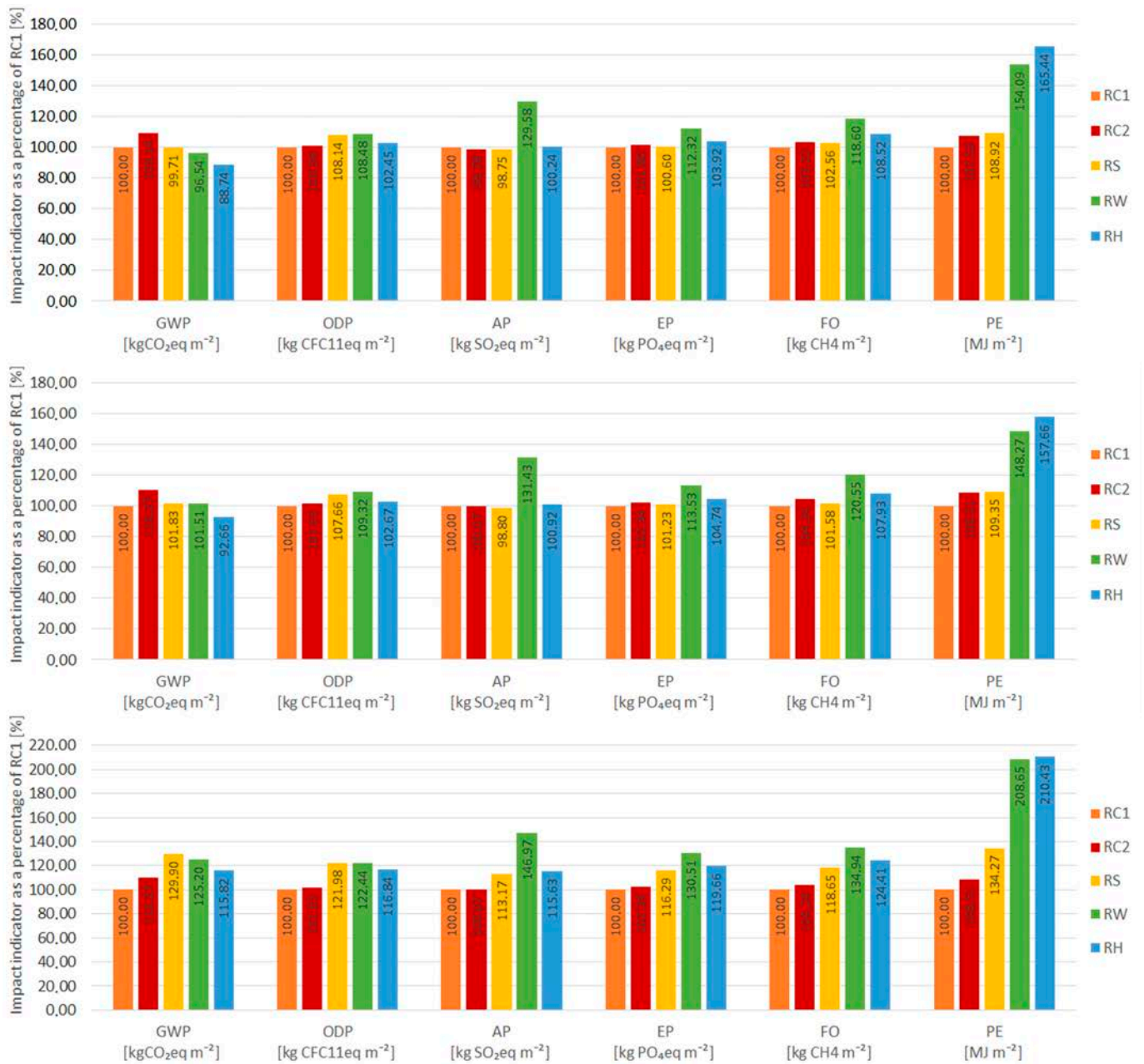


Figure 6. LCA results evaluated for different construction systems, listed from top to bottom: over a 30-year period; over a 60-year period; over a 100-year period; and over a 100-year period, assuming the replacement of light construction systems at 60 years (2024, © Authors).

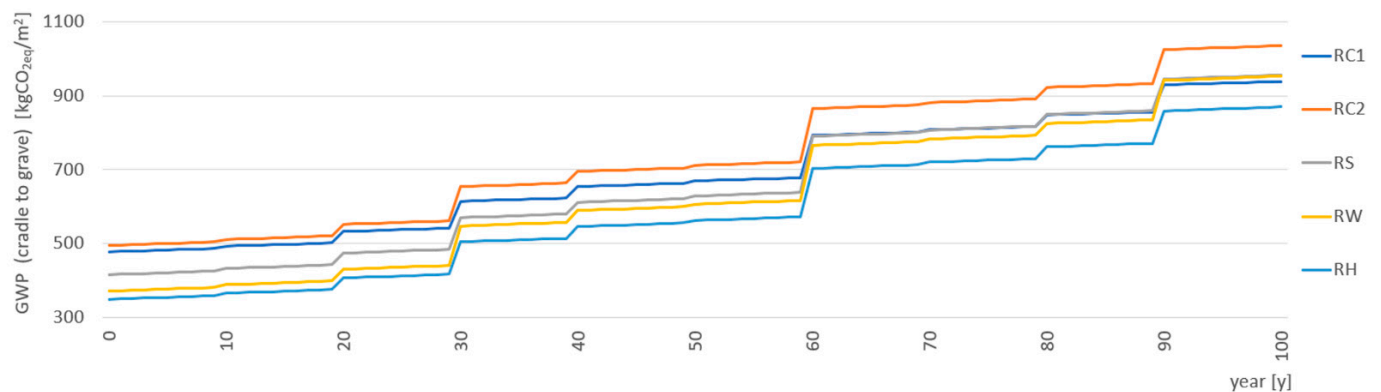


Figure 7. Cont.

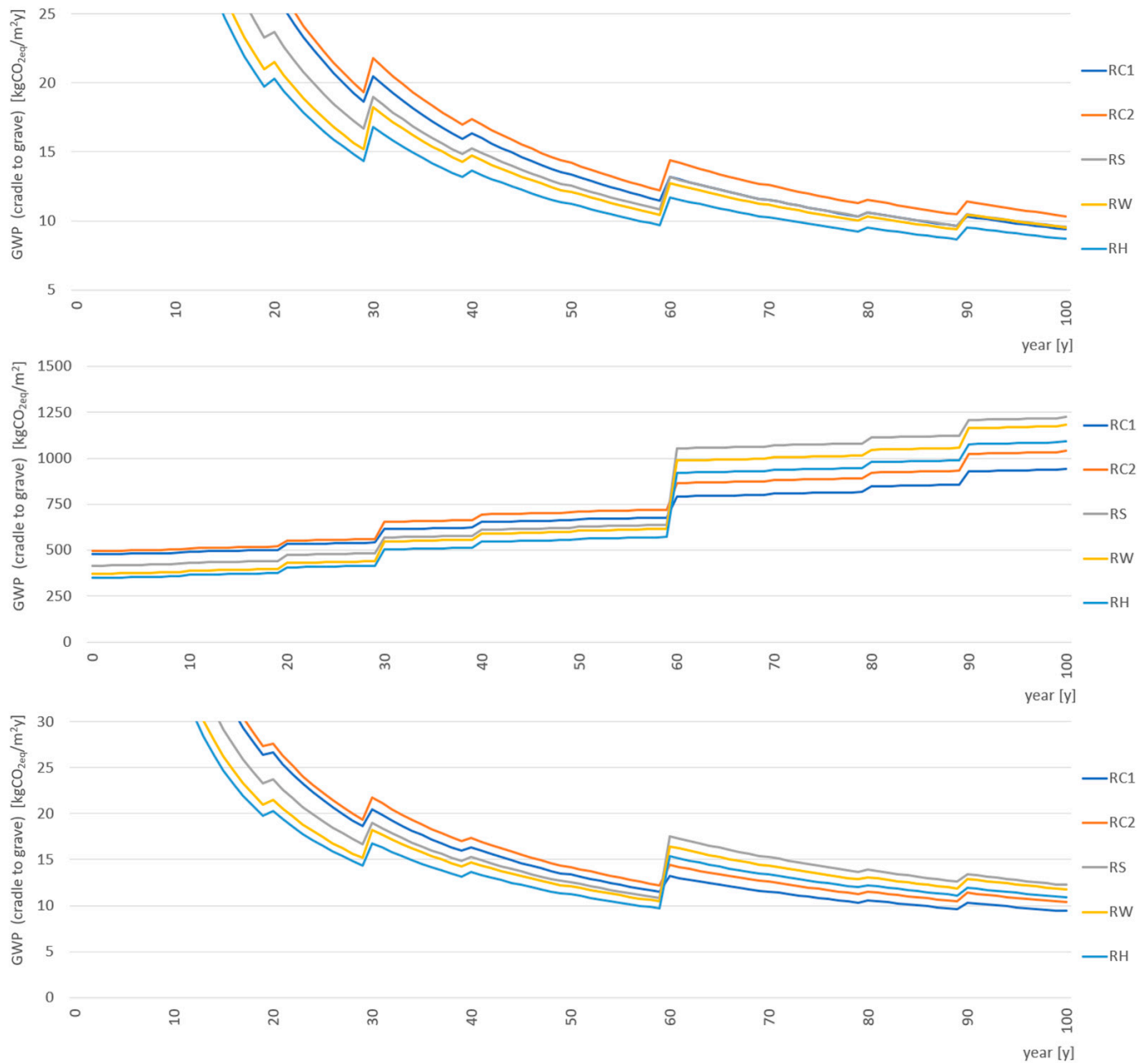


Figure 7. Carbon footprint results (evaluated in kg CO₂-eq/m² and kg CO₂-eq/m² per year) for different construction systems. At the top, over a 100-year period; at the bottom, over a 100-year period, assuming the replacement of light construction systems at 60 years (2024, © Authors).

Figure 6 presents four outcome scenarios expressed as a percentage relative to the RC1 construction system. Each of these scenarios is described below:

- (i) Short-term scenario (first graphs at the top). It considers an analysis period of 30 years, aligning with European decarbonization scenarios by 2050. From the short-term results, it emerges that lightweight construction systems offer the lowest impacts in terms of GWP, achieving up to −17.90% for the hybrid steel-wood system. However, they generally have higher impacts on the other evaluated indicators. In particular, the CLT construction system has the highest impact across all categories, particularly concerning acidification and primary energy.
- (ii) Medium-term scenario (second graphs from the top). It considers an analysis period of 60 years, in accordance with the average building lifespan predicted by the level(s) framework [46]. In this analysis timeframe, the contribution of the buildings' use

phase becomes more significant, particularly regarding maintenance and replacements, as the operational energy is very limited due to the assumption of constructing a ZEB building. The medium-term analysis results are similar to those of the short-term: lightweight construction systems have the lowest contribution in terms of GWP, although they generally have higher impacts on the other indicators.

- (iii) Long-term scenario (third graphs from the top). It assessed over 100 years of analysis without assumptions on the durability of construction systems, reflecting the minimum lifespan for constructions with high performance levels foreseen by Italian regulations [49]. In the long term, the contribution of maintenance and replacements becomes even more significant. The scenario with generally lower impacts is the heavy construction system RC1, made with highly durable building components. However, regarding the GWP, the RH scenario remains the one with the lowest impact.
- (iv) Long-term scenario (first graphs at the bottom). It assessed over 100 years of analysis, assuming that lightweight construction systems are demolished and rebuilt after 60 years. This reconstruction hypothesis based on the durability of materials leads to a significant increase in emissions for all the indicators considered in lightweight construction systems. In particular, even the second heavy construction system, RC2, proves less impactful than these technologies.

Figure 7 represents the increase in GWP in the two long-term scenarios expressed in terms of $\text{kgCO}_{2\text{eq}}/\text{m}^2$ (top) and $\text{kgCO}_{2\text{eq}}/\text{m}^2 \text{ year}$ (bottom). To facilitate the interpretation of the graphs, the values on the y-axis, representing GWP, have been limited to 1100 or 1500 $\text{kgCO}_{2\text{eq}}/\text{m}^2$ and 25 or 30 $\text{kgCO}_{2\text{eq}}/\text{m}^2 \text{ year}$, respectively. In particular, the graphs illustrating the progressive year-by-year increase in CO_2 show that, in the case of ZEB buildings, the rise in emissions is primarily associated with the phases of maintenance and replacement, while operational energy and water have less impact. Over 100 years, the use phase contributes to GWP impacts more than double those associated with the production, transport, and construction phases (A1–A5).

Consequently, between years 30 and 60 of the analysis, a significant increase in environmental impacts can be observed when the replacement of several components, such as external insulating materials, external painting, windows, internal flooring, etc., are combined. It is important to note that these operations are common to all analyzed scenarios, except those related to insulation materials, which depend on the building component, as shown in Tables 2–4.

3.3. Results of Life Cycle Cost Analysis

The life cycle cost analysis was conducted using the price list from the Emilia-Romagna region for 2023 (DGR No. 462 of 27/03/2023) [57]. This list pertains to works of standard execution difficulty at typical construction sites. Each price includes the costs of materials, labor, equipment rental, and transportation necessary to complete the work. Furthermore, the indicated prices encompass general expenses (16%) and profits for the construction company (10%). Subsequently, these prices were increased by 22% for VAT and 30% to account for design and administrative expenses [55].

The methodology described in Section 2.4 was applied to calculate the TLCC of each scenario, assessing the cost of each component (construction, operational energy, water, M&R, end-of-life, residual value) discounted to the base year (year 0). This evaluation was conducted using four different scenarios (Table 12).

- (i) Scenario 1 had the shortest calculation period, 30 years. In this case, the construction cost is predominant compared to the costs arising from the building's use phase, and the residual value is very high, considering a service life of 100 years. From this first scenario, it emerges that the first heavyweight construction system, RC1, incurs the lowest costs, followed by the second, RC2, with a difference of approximately +2.4%. The lightweight construction systems are more expensive despite the higher residual value: +7.14% (RS), +8.43% (RW), and +20.61% (RH). Among these, the hybrid construction system stands out as having significantly higher construction

- costs due to the steel structure combined with primary timber components (floors, prefabricated exterior walls, etc.).
- (ii) Scenario 2 involves a medium calculation period of 60 years, assuming a service life of 100 years for the building. With the increased use phase, the proportion allocated to maintenance and replacements takes on a greater weight in the total (approximately 30%), while the residual value of the buildings is lower. In terms of differences between the scenarios, the heavyweight construction system remains the least expensive, with the difference between the scenarios tending to increase slightly, except for the hybrid (RH), which decreases to 18.80%.
 - (iii) Scenario 3 considers a calculation period of 100 years, which coincides with the service life of buildings. In this case, the residual value of the buildings is zero, while the M&R cost exceeds 40% of the total. The difference between the scenarios tends to increase for RC2 (4.10%) and RS (7.19%), while it slightly decreases for the CLT solution (9.36%) and the hybrid (17.57%).
 - (iv) Scenario 4 includes the same 100-year evaluation period as the previous scenario, assuming that heavyweight construction systems have a service life of 100 years while lightweight construction systems have a service life of 60 years. Consequently, the residual value of buildings with concrete structures will be zero, whereas, for light construction systems, the residual value will be assessed with a linear deterioration over 40 years, which will then be discounted to year zero along with the construction cost of the new building (assuming it is rebuilt identical to the previous one). As expected, this scenario, which is characterized by unfavorable assumptions for lightweight construction systems, results in a more significant difference between techniques, with all three solutions exceeding 10%: 10.60% (RS), 12.81% (RW), and 21.41% (RH).

Table 12. Total life-cycle cost (TLCC) analysis for heavyweight and lightweight construction systems under the different scenarios (2024, © Authors).

Construction System	Cost Categories						TLCC	Difference [%]
	Construction	Energy	Water	M&R	EoL	Residual Value		
(30 years)								
Reinf. concr. RC1	4,373,274 €	15,260 €	53,219 €	390,913 €	0 €	−595,116 €	4,271,813 €	-
Reinf. concr. RC2	4,487,604 €	17,289 €	53,219 €	390,913 €	0 €	−610,674 €	4,372,613 €	2.36
Reinf. steel RCS	4,722,468 €	18,523 €	53,219 €	390,913 €	0 €	−642,634 €	4,576,752 €	7.14
Reinf. CLT RW	4,786,215 €	18,801 €	53,219 €	390,913 €	0 €	−651,309 €	4,632,102 €	8.43
Reinf. hybrid RH	5,389,612 €	17,825 €	53,219 €	390,913 €	0 €	−733,419 €	5,152,412 €	20.61
(60 years)								
Reinf. concr. RC1	4,373,274 €	21,601 €	75,336 €	1,286,553 €	32,330 €	−104,849 €	5,797,411 €	-
Reinf. concr. RC2	4,487,604 €	24,474 €	75,336 €	1,396,746 €	32,330 €	−107,590 €	6,022,064 €	3.88
Reinf. steel RCS	4,722,468 €	26,221 €	75,336 €	1,373,345 €	32,330 €	−113,221 €	6,229,644 €	7.46
Reinf. CLT RW	4,786,215 €	26,614 €	75,336 €	1,424,809 €	32,330 €	−114,749 €	6,343,719 €	9.42
Reinf. hybrid RH	5,389,612 €	25,232 €	75,336 €	1,380,892 €	32,330 €	−129,215 €	6,887,352 €	18.80
(100 years)								
Reinf. concr. RC1	4,373,274 €	24,712 €	86,185 €	1,770,866 €	8554 €	0 €	6,525,327 €	-
Reinf. concr. RC2	4 487,604 €	27,998 €	86,185 €	1,920,971 €	8554 €	0 €	6,793,046 €	4.10
Reinf. steel RCS	4 722,468 €	29,997 €	86,185 €	1,885,752 €	8554 €	0 €	6,994,691 €	7.19
Reinf. CLT RW	4 786,215 €	30,447 €	86,185 €	1,963,207 €	8554 €	0 €	7,136,342 €	9.36
Reinf. hybrid RH	5 389,612 €	28,866 €	86,185 €	1,897,111 €	8554 €	0 €	7,672,063 €	17.57

Table 12. Cont.

Cost Categories								
Construction System	Construction	Energy	Water	M&R	EoL	Residual Value	TLCC	Difference [%]
(100 years with demolition and reconstruction of lightweight systems)								
Reinf. concr. RC1	4,373,274 €	24,712 €	86,185 €	1,770,866 €	8554 €	0 €	6,525,327 €	-
Reinf. concr. RC2	4,487,604 €	27,998 €	86,185 €	1,920,971 €	8554 €	0 €	6,793,046 €	4.10
Reinf. steel RCS	4,722,468 €	29,997 €	86,185 €	1,885,752 €	437,599 €	−206,734 €	7,217,002 €	10.60
Reinf. CLT RW	4,786,215 €	30,447 €	86,185 €	1,963,207 €	443,070 €	−209,524 €	7,361,334 €	12.81
Reinf. hybrid RH	5,389,612 €	28,866 €	86,185 €	1,897,111 €	494,852 €	−235,939 €	7,922,422 €	21.41

4. Discussion

Nowadays, in a context where combating climate change is a central theme, the construction industry needs to find sustainable solutions that consider the entire life cycle of buildings. However, aspects related to thermal comfort and construction costs must also be central to ensuring that the choice of sustainable building systems is effective. Consequently, it is crucial to conduct comprehensive and multidisciplinary analyses. In this study, five scenarios are evaluated for each of these criteria (thermal comfort, environmental impacts, life cycle costs): (i) reinforced concrete structure with low-transmittance thermal block infill; (ii) reinforced concrete structure with light-clay bricks and outer thermal insulation; (iii) steel frame; (iv) cross-laminated timber (CLT); and (v) timber-steel hybrid structure.

The energy analysis results presented in this paper highlight that the energy consumption of buildings constructed with the various analyzed construction systems is quite similar. This similarity is primarily due to the performance of the building envelope, which is designed to have comparable thermal transmittance values. However, the level of indoor comfort is influenced by thermal parameters related to thermal inertia, which depend on the nature of the materials (thermal mass). Therefore, achieving good comfort levels for occupants is closely linked to the choice of the construction system. In Mediterranean temperate climates where the intermediate seasons cover a significant part of the year, thermal inertia primarily ensures indoor comfort, making massive solutions preferable. Indeed, due to the dynamic role played by thermal inertia in managing daily temperatures, thermal mass ensures higher temperatures at the end of heating periods and lower temperatures at the end of cooling periods, thereby influencing the operation periods of HVAC systems.

The results of the LCA analysis reveal that the use of materials with high durability ensures limited environmental impacts in a long-term perspective. Indeed, the RC2 scenario, which includes external insulation, exhibits greater impacts than the RC1 scenario due to more frequent replacement cycles. This factor also affects the evaluations of lightweight construction systems. Specifically, scenarios utilizing wooden construction elements are associated with higher impacts in terms of acidification and primary energy. On the other hand, from an economic perspective, the main factor influencing the final results is the initial construction cost.

In this sense, renovation cycles are significant and play a crucial role in the final results. For this reason, in this article, the stratigraphies of different scenarios have been standardized as much as possible, eliminating all non-essential differences, such as finishes, that could influence the analysis results. However, the replacement cycles of certain materials, particularly insulation materials (especially those related to the ETICS system), hold a significant role in terms of environmental impacts and costs. The durability of these materials is a debated topic, and a sensitivity analysis related to them could also represent a future perspective for this research.

This article presents a series of methodological limitations due to various factors. Firstly, the evaluation of building archetypes involves several simplifications related to

the scale of the project and its level of detail. Although architectural, structural, and energy aspects have been studied, the level of design is not equivalent to that of an actual constructed project, as the design time required would not align with the purpose of this analysis, which is to provide general considerations and guidelines applicable at the urban scale. These limitations also impact the thermal comfort analyses, the results of which are strongly influenced by the natural and built context, the types of windows and shading devices, the type of finishes, and other related factors.

- (i) From the perspective of thermal comfort analysis, this study considers the current climate context of Bologna. This presents a limitation both geographically and temporally. Indeed, variations in the climatic zone could significantly alter the results of the energy simulation, impacting both energy consumption and indoor comfort. Furthermore, environmental conditions are rapidly evolving due to climate change, especially in certain regions. Specifically, in Bologna, an increase in average annual temperatures of approximately 0.3 °C/10 years was recorded between 1961 and 2018, with similar projections expected through 2050 [64]. For this reason, using predictive tools for estimating future climate conditions, such as CCWorldWeatherGen v1.8 [65], also represents a potential future implementation of this research.
- (ii) From an LCA perspective, this study does not take into account potential pathologies or issues that could limit the useful life of the buildings. Additional factors that might impact the analysis results involve uncertainties related to variables over the long term: first, the GWP associated with the national energy mix is expected to decrease in the near future. This change will affect not only the building's operational phase but also all production processes linked to material replacement cycles. Additionally, although the analysis was structured from a long-term perspective, the methodology should be improved regarding temporal issues (e.g., dynamic LCA). The dynamic LCA approach employs characterization factors with varying time horizons to account for the atmospheric residence time of each greenhouse gas emission, which can lead to potentially significant changes in the results [66]. From this perspective, applying a discount rate could be a valid choice from a policy standpoint, although it may be seen as contradictory from an ethical perspective [67].
- (iii) From an economic analysis perspective, the construction costs were entirely based on the price list from the Emilia-Romagna region for 2023 (DGR No. 462 of 27/03/2023) [57]. Therefore, the results of this study may have limited validity both temporally, as evidenced by the significant inflation in construction material prices in recent years, and geographically, since this price list reflects the average market prices in Italy, where certain construction techniques are generally more cost-effective due to greater familiarity and prevalence.

5. Conclusions

This article presented an analysis aimed at evaluating five high-performance construction systems in a mid-rise, medium-compact multi-family building in a Mediterranean climate over the short, medium, and long term in terms of thermal comfort, environmental impacts, and life cycle costs. The evaluation was conducted by adopting two main scenarios. The first, theoretical, was employed to assess the environmental and cost implications resulting from a long-term analysis without influencing the results with assumptions regarding the durability of construction systems. For this reason, a 100-year analysis period was used without foreseeing the need to replace the buildings. The second scenario used the average lifespan of 60 years for lightweight construction systems as provided by the level(s) framework, thereby anticipating an additional replacement after this period. The main conclusions concerning both scenarios can be summarized as follows:

- The results of the thermal comfort analysis, conducted with the adaptive model (systems off), highlight that heavyweight construction systems ensure a higher percentage of comfort hours (RC1 at 94.67% and RC2 at 87.62%) compared to lightweight ones (RS at 84.52%, RW at 81.09%, and RH at 76.50%). The assessment underscores the

role of the floor's thermal mass; in fact, increasing the floor weight in the RH scenario achieves a significantly better value of 82.9% (RH2).

- Considering the active heating and cooling systems, the thermal comfort provided by the construction systems studied is comparable in terms of PMV.
- In the case of zero energy building (ZEB), the environmental impacts related to the operational energy and water stages (B6 and B7) appear less significant than those resulting from the maintenance and replacement of construction materials (B1–B5).
- Short-term results of the LCA (30 years) reveal that lightweight construction systems have a lower GWP compared to the baseline (RC1), with a range from -7.26% (RS) to -17.90% (RH). However, the impacts on other indicators are generally higher, particularly in terms of primary energy: $+4.85\%$ (RS), $+66.70\%$ (RW), and $+68.37\%$ (RH).
- Medium-term LCA results (60 years) show that the difference in GWP between heavyweight and lightweight construction systems tends to decrease: -0.29% (RS), -3.46% (RW), and -11.26% (RH), while the difference in other impact indicators generally tends to remain constant or increase due to the higher maintenance and replacement needs.
- Long-term LCA results (100 years) highlight a convergence in terms of GWP between construction systems: $+1.83\%$ (RS), $+1.51\%$ (RW), and -7.34% (RH). For other impact indicators, heavy construction systems generally present lower impacts.
- From a long-term LCA perspective, using durable materials ensures the lowest environmental impacts. Therefore, adaptability and the reusing potential are crucial for components with a limited lifespan, while the use of durable solutions and materials is essential for construction systems that remain fixed throughout the building's lifespan (such as structures, external walls, and floors).
- Considering the hypothesis on the durability of lightweight construction systems, where buildings are replaced after 60 years, the results show a clear advantage of heavy construction systems in all analyzed categories, especially for RC1, which becomes the least impactful.
- The construction cost of heavyweight construction systems is generally lower compared to lightweight ones. The most economical is RC1, followed by RC2 ($+2.61\%$), RS ($+7.98\%$), RW ($+9.44\%$), and RH ($+23.24\%$).
- In the case of zero-energy buildings, operational energy costs have a limited impact on determining the total life cycle cost, as most of the energy consumption is covered by renewable energy sources.
- In the total life cycle cost, the component of maintenance and replacement becomes progressively more significant in the long term: at 30 years, it ranges from 7.25% to 8.94% ; at 60 years, between 25.62% and 31.12% ; and at 100 years, between 35.2% and 42.81% . Consequently, selecting durable materials and technological components becomes essential from both an environmental sustainability and economic perspective.
- Although the residual value of buildings with light construction systems is higher, this difference does not compensate for the higher construction costs. Consequently, the total life cycle cost of heavyweight construction systems is lower in all evaluated periods (30, 60, and 100 years).

These results highlight how the assumptions behind the analysis strongly influence the sustainability associated with the choice between heavyweight and lightweight construction systems in a Mediterranean climate. In particular, the assumptions regarding the lifespan of buildings based on the type of construction system should be further investigated, as this factor significantly influences both the environmental and economic analysis, which in turn determine the results of the comparison in both the medium and long term.

Supplementary Materials: Additional information regarding the stratigraphies and thermal parameters of the materials of the building elements described in Section 2.1 can be downloaded at the following link: <https://www.mdpi.com/article/10.3390/su16208959/s1>.

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