Bottle kilns at the Pujol i Bausis factory "La Rajoleta" in Barcelona (today Ceramics Museum) built in 1915. Photo by the author

Methodology for LCA Assessment of Heritage Buildings and their retrofitting works

Belén Onecha *[1], Patricio Suárez [2]

[1]Barcelona School of Architecture. Universitat Politècnica de Catalunya, Spain.
[2]Universitat Politècnica de Catalunya, Spain.
**Email: belen.onecha@upc.edu*

Abstract: In the current context of necessary reduction of environmental impact, retrofitting historical buildings is essential, but it must be specified the total carbon footprint, considering the original construction and the current restoration.

This research has a double objective: firstly, to develop a methodology to establish the carbon footprint of three historic Catalan Modernist buildings at the time of their construction; and secondly, to determine the carbon footprint of the restoration works of one of them.

An exhaustive analysis is carried on about the materials used, their extraction, transportation and manufacturing methods at the time. Following the methodological structure of contemporary EPDs and LCA, both aligned with the UNE-EN 15804 standard. This ensures methodological consistency between historical and modern datasets and provides a robust basis for comparison.

Then, the embodied carbon of these buildings is compared with that of modern buildings construction, in order to establish which is higher. Finally, the carbon footprint of retrofitting one of them is also calculated.

The importance of this research lies in the methodology for the quantification of the total environmental impact of historic buildings, from their original construction to their restoration. The limitation of the study lies in the fact that only one of the three case studies has been retrofitted so far.

Keywords: Heritage; environmental impact; carbon footprint; Catalan Modernism; Gaudí.

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1. Introduction

1.1. Sustainability and Architectural Heritage

The overall energy consumption of building construction is considered to account for 35%, while CO2 emissions account for 40% (Atmaca et al., 2021). In order to meet sustainability targets (EU Directive 2023/1791), historic buildings have a key role to play (Walsh-Korb, 2022), especially as they constitute approximately 30% of the building stock in Europe (Buda et al., 2021).

It is common to consider historic buildings as a source of excessive energy consumption, usually from fossil sources, and thus also of pollution (Cinieri & Zamperini, 2013). However, the reuse of these buildings is much more sustainable than demolition and new construction (Sigmund, 2016). Moreover, historic buildings are quite capable of adapting to energy efficiency regulations (Caro et al., 2021). But the energy aspect is not the only one responsible for sustainability problems; the consumption of material resources, the waste generated and the pollution associated with all these factors must also be considered (Cinieri & Zamperini, 2013).

Within the group of historic buildings, heritage ones represent the culture of societies, the past-present connection, and the optimisation of local resources (Billore, 2021). However, cultural heritage has not received specific attention in the documents relating to the goals of the 2030 Agenda (Lerario, 2022). In this sense, the two key benefits of the restoration and reuse of historic buildings are heritage conservation itself and the reduction of greenhouse gases from the production of new materials (Baker et al., 2021), since they are buildings whose embedded energy has already been spent in the past (Cinieri & Zamperini, 2013). There are still many challenges to be solved in relation to their sustainability, Panakaduwa et al. (2024) identified the following: "High cost, difficulties in finding materials, unknown building conditions, lack of expertise, complexity of the retrofit, difficulty in obtaining planning approvals, stakeholder management, and unintended consequences are the other challenges." Intensive building decarbonisation programmes are currently underway worldwide, and it remains to be seen what consequences this will have for historic buildings (Fouseki et al., 2020). But sometimes, interventions to improve the energy performance of these buildings may weaken the potential of traditional climate adaptation solutions, such as thermal inertia or night ventilation. In fact, super-insulated envelopes can lead to overheating in temperate climates (Hao et al., 2020).

It is necessary to establish a solid basis for intervention, incorporating innovative solutions in terms of sustainability of materials and energy, incorporating bioclimatic ancestral knowledge (Velosa et al., 2024).

1.2. Environmental impact assessment and architectural heritage

Environmental impact assessment is highly developed for new construction, but hardly at all for the maintenance and restoration of cultural heritage, making sustainable heritage restoration one of the major challenges for public and private entities (Settembre et al., 2018; Mamo Fufa et al., 2021). UNESCO and the Advisory Bodies to the World Heritage Committee, ICCROM, ICOMOS and IUCN developed in 2022 the Guidance and toolkit for impact assessments in a World Heritage Context (UNESCO et al. 2022), which provides a framework for conducting impact assessments for cultural and natural heritage sites. One of the two types of impact assessment considered is the Environmental and social one, that suggest a procedure to think about and avoid some kind of environmental impact, but not specifically the restoration processes.

The building sector actors will not take actions on reducing the environmental impact of heritage buildings until the legal obligation exists (Mahamd et al., 2024). But despite the fact that these buildings are not 100% compliant with legislation in terms of energy efficiency, they have many sustainable features: the construction energy is amortised, they save material resources as they do not even need a new plot of land, and present multiple climate adaptation strategies (Cinieri & Zamperini, 2013) (Mamo Fufa et al., 2021).

The analysis of the environmental impact of buildings is based on two main concepts: the operational impact (OI) consumed during the use phase, and the embedded impact (EI), corresponding to the energy required for the construction of the building (Atmaca et al., 2021). The Climate Change Panel for the building sector for the reduction of CO_2 emissions proposes to reduce both operational and embedded impacts.

1.3. Operational environmental impact on architectural heritage

Corresponds to the CO_2 emissions generated by energy consumption during the use of the building.

Usual measures to reduce greenhouse gas emissions are limited to improving energy efficiency, incorporating insulation and upgrading air-conditioning and lighting systems. This is not only limited to the use phase of the building, but also clashes with the preservation of the building's authenticity, its energy performance based on traditional passive systems, with adaptive solutions compatible with the characteristics of the materials used (Sesana et al., 2019).

Caro et al. (2021) studied a case of heritage buildings where thermal comfort and indoor air quality were improved, reducing fossil energy consumption and correspondingly CO2 emissions by 51%. Even so, the building cannot be considered NZEB, it requires supporting technologies such as photovoltaic panels. However it is not always possible due to space restrictions, or heritage, archaeological or landscape protection laws, also, these active renewable systems increase the embedded carbon of the building (Opher et al., 2021). In 2023, ICOMOS published the "Guidelines for the installation of renewable energy-related infrastructures and equipment and their potential impact on cultural heritage", in order to provide practical advice on how to align the protection of World heritage properties with renewable energy development, through some case-studies not yet published openly.

Adaptive reuse is also a form of sustainable urban regeneration, as it extends the life of the building and avoids waste generation (Yung & Chan, 2012). Experts underline the need to preserve heritage through adaptive reuse, which corresponds to social, economic and environmental needs, while ensuring heritage continuity, in addition to increasing community resilience against climate change (Fatoric & Egberts, 2020).

For heritage buildings that are not under continuous use, Onecha et al.(2025) demonstrated through a dynamic simulation that it is possible to refurbish them while avoiding air conditioning facilities, avoiding the embedded carbon of them and CO2 emissions derived from energy consumption, through taking into account the inertia, improving passive systems, and adapting uses to favourable climate zones according to the time of day and season.

In order to help make informed decisions based on criteria that are as objective as possible, there is a figure which can be of great interest in these cases: The Heritage Impact Assessment, which must be prepared by professionals with high specialisation and in-depth knowledge of the regulation in the local heritage or cultural sphere, the site affected by the infrastructure and the proposed project (Alonso Campanero 2022).

1.4. The embedded environmental impact on architectural heritage

It refers to the CO_2 emissions related to the extraction, transformation, transport and commissioning of the materials that make up the building (Huang et al., 2025).

Opher et al. (2021) reviewed 239 LCA studies, extracting that embedded carbon is 64% for the production process of materials and construction; 22% derived from maintenance during the use phase; and 14% for the end-of-life phase. And yet, most LCA of building retrofit projects only consider operational energy and not the embedded impact (Cinieri & Zamperini, 2013).

The assessment of embedded carbon (EC) for historic structures is often neglected due to the difficulty of calculating it (Huang et al., 2025). Furthermore, when historic buildings do not have enough heritage values, it is common to demolish them rather than to preserve them, without considering the savings in carbon emissions that this would entail. But there are no methods to assess the retrofitting process itself (Loli & Bertolin, 2018). It is crucial to calculate the embedded and operational impact of both demolition and retrofitting operations to make the most sustainable decision (Baker et al., 2021), which must also consider the balance between environmental impact and technical and economic performance, as well as the preservation of social, cultural and historical significance (Huang et al., 2025). In addition to the environmental benefits derived from the conservation of building materials (embedded carbon), conservation projects help to retain a sense of community and roots in society (Fatoric & Egberts, 2020), although economically, the cost may be higher than constructing a new building, which also tends to have fewer restrictions and can offer a higher level of utility (Guo et al., 2019)

However, there are still many ambiguities in the consideration of heritage values and the embedded energy of historic materials, as well as the potential of traditional passive measures, when adapting heritage buildings to mitigate climate change (Sesana et al., 2019).

This paper research aims to overcome several of the issues raised in these lines that highlight the current context in the field of embedded impact in heritage buildings by: 1) Designing a calculation method to establish the carbon footprint emissions of the original construction for Catalan Modernist buildings, which is the main novel contribution of this study; 2) Comparing these emissions with those of current construction, based on data provided by internationally recognised databases; 3) Determining the emissions of retrofitting operations for one of the three case-studies analysed, in order to

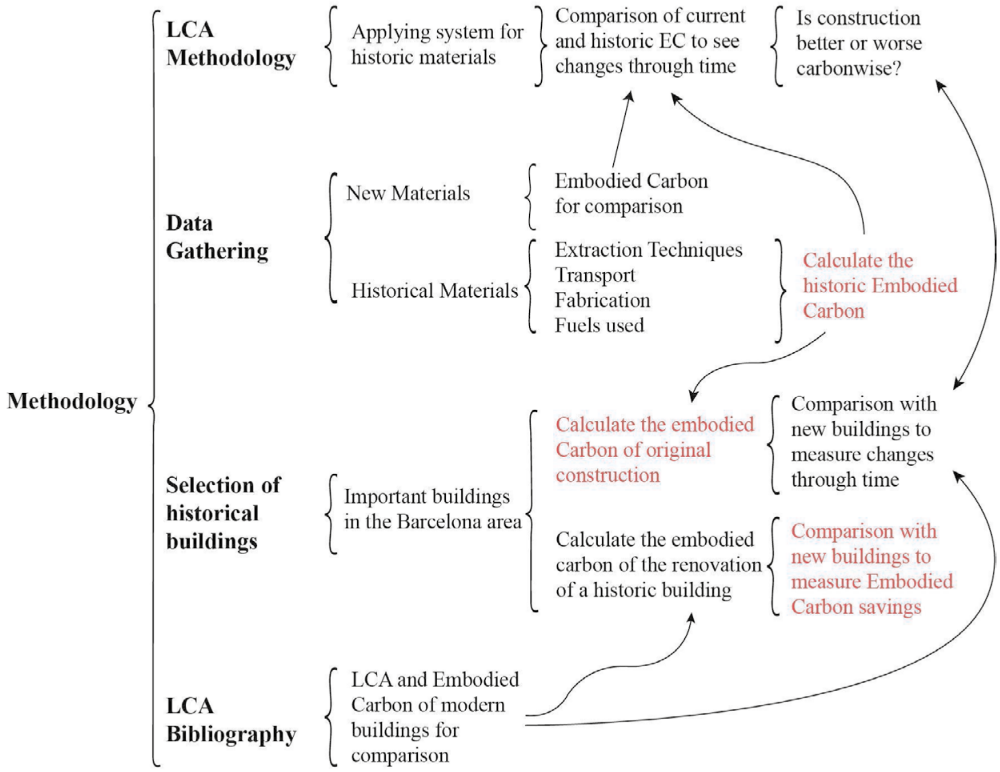


Figure 1 | Conceptual mapping of the methodology.

consider it as a reference, even though we know that the magnitude of the environmental impact will depend on the state of conservation of the building in its initial state.

2. Materials and methods

The methodology was structured in three phases: 1) the analysis of construction materials used during the late 19th and early 20th centuries, along with research into their production processes to obtain quantifiable data on energy consumption and carbon emissions; 2) the selection, analysis and calculations of heritage buildings for a life cycle assessment (LCA); and 3) the compilation of modern sources for comparison with historical results and for the calculation of the embodied carbon associated with the retrofitting works of one of these selected buildings.

2.1. Historical materials

In the first phase, historical data were collected on construction materials used in Barcelona -and in the houses studied in particular- during Spain's Second Industrial Revolution (1870–1914) (Geddes, 1915). The effort focused on gathering detailed information on raw material extraction, manufacturing and transformation processes, energy consumption, fuel types, transportation, and related factors. All information was sourced from Spanish archives and publications, drawing on both primary and secondary data sources, as summarized in Table 1. (Arup, 2023, Baila Lletí, 2012, Berg, 2021, Betevé, 2015, Bing et al., 2023, Boglo Etcheverri, 2016, Busquets Relats, 2021, Calder, 2021, Carreras, 1989, Cavert, 2017, Comas, 2011, De Decker, 2009, Hill, 2016, Houpt, 2002, La Spina, 2016, Marcos Vallaure, 1991, Marcos y Bausá, 1879, Miguel, 2012, Moore, 2011, Quorum Corp, 2005, Smil, 2017). Efforts were made to obtain data from multiple sources; however, due to the scarcity of available information, primary sources such as factory archives, and site museums were of great importance, research studies and local archives were the other main source, although a great amount of research in this field is required. Broader data —such as types of fuel, labour input, and industrial output— was mainly drawn from 'Energy and Civilization' by Vaclav Smil (Smil, 2017) and other academic works, although not all figures were specific to Spain. Nonetheless, these values are considered relatively stable across time and geographic location. Distances were estimated based on the known locations of factories and extraction sites from the era within the greater Barcelona area, shown in

Table 1 | Own making. This table contains the materials analysed, their place of origin, their place and method of transformation (factory, workshop, etc.), including fuel type, temperature and time needed, material input and output and the most common method of transportation. This was the main data sought.

Material	Origin		Analyzed Factory/Site	Transformation Process	Fuel Type	Temp.	Time	Material input	Material output	Transport
Stone, sands	Barcelona	Montjuïc and Collserola quarries	-	No transformation	-	-	-	-	-	Animal
Plaster	Barcelona, Catalonia	Vinaròs quarries	Plaster kilns in La Almolda	Furnace firing	Brushwood	1000°	48h	1.5 t of fuel + 30 t plaster	15 t	Animal
Lime	Zaragoza, Aragón	Zaragoza quarries	Lime kilns in Vinaròs	Furnace firing	Brushwood	1000°	48h	1 t of fuel + 10 t lime	7 t	Animal
Brick	Barcelona, Catalonia	Barcelona (Les Corts, Nou Barris) and Esplugues	Bòbila Framis i Pellicer and Bòbila de Calafell	Firing in Arab or industrial kilns	Coal	1000°	24h	1 t of fuel + 15 t of clay	15 t	Animal
Cement	Barcelona, Catalonia	Serra del Catllaràs mines	Asland Cement Factory	Horizontal rotary kiln	Coal	1200°	96h	12 t of fuel 45 t of clinker	20 t	Railway
Tiles	Barcelona, Catalonia	Barcelona (Les Corts, Nou Barris) and Esplugues	Bòbila Framis i Pellicer and Bòbila de Calafell	Firing in Arab kilns	Firewood	1000°	24h	1 t of fuel + 11 t of clay	10 t	Animal
Glazed ceramics	Barcelona, Catalonia	Esplugues clay	Pujol i Bausis 'La Rajoleta' Factory	Firing in under-ground kiln	Firewood	1200°	96h	4.5 t fuel	20–25,000 pieces	Animal
Wood	Catalonia	Vallès, Montseny, and Pyrenees forests	-	-	-	-	-	-	River, rail or animal	
Glass	Gijón, Cantabria	Manually extracted sand	Cifuentes, Pola y Compañía Glass Factory	Siemens-type furnace firing	Coal	1100°	72h	1.05 t of fuel + 1 t of sand and other materials	1 t	Railway
Steel	Vizcaya, Basque Country	Basque Country mines	Altos Hornos de Vizcaya	Industrial and artisanal furnace firing	Coal	1200°	96h	2.5–4 t of fuel + 2 t of iron ore	1 t	Railway

Figure 2. TheCO_2 of production/manufacture stage was calculated based on the fuel used and its emissions (Smil, 2017), also shown in Table 1.

Table 1 lists the materials analysed, which are the ones present in the selected buildings (and in buildings in general in that period, along with their origin -for extraction and production-, fuel type, transformation process and the factory analysed. Once collected, the data was structured following a modern Whole Life Cycle Assessment (WLCA) framework and allocated to the relevant modules for computation. It is important to note, that some materials, such as paint, copper, rubber, etc, were not analysed as the information was too scarce, or its use was very limited -if at all- in the chosen projects.

2.1.1. CO_2 calculation of historical materials

Once the information for each material is complete, and the LCA methodology to be followed is established, it needs to be separated to fit the right stage. First, general units used in one or more stages are shown.

First, emissions generated by people and draft animals. Carbon dioxide generated only when performing a task is considered; that is, the extra carbon dioxide produced by the body simply by being alive. We produce 0.70 $kgCO_2$/day at rest (LeMone, 2020). This increases by 30% when performing manual labour (Smil, 2017). For the value of a person carrying a load, LeMone tells us that walking produces 0.021 $kgCO_2$/km, and Smil writes

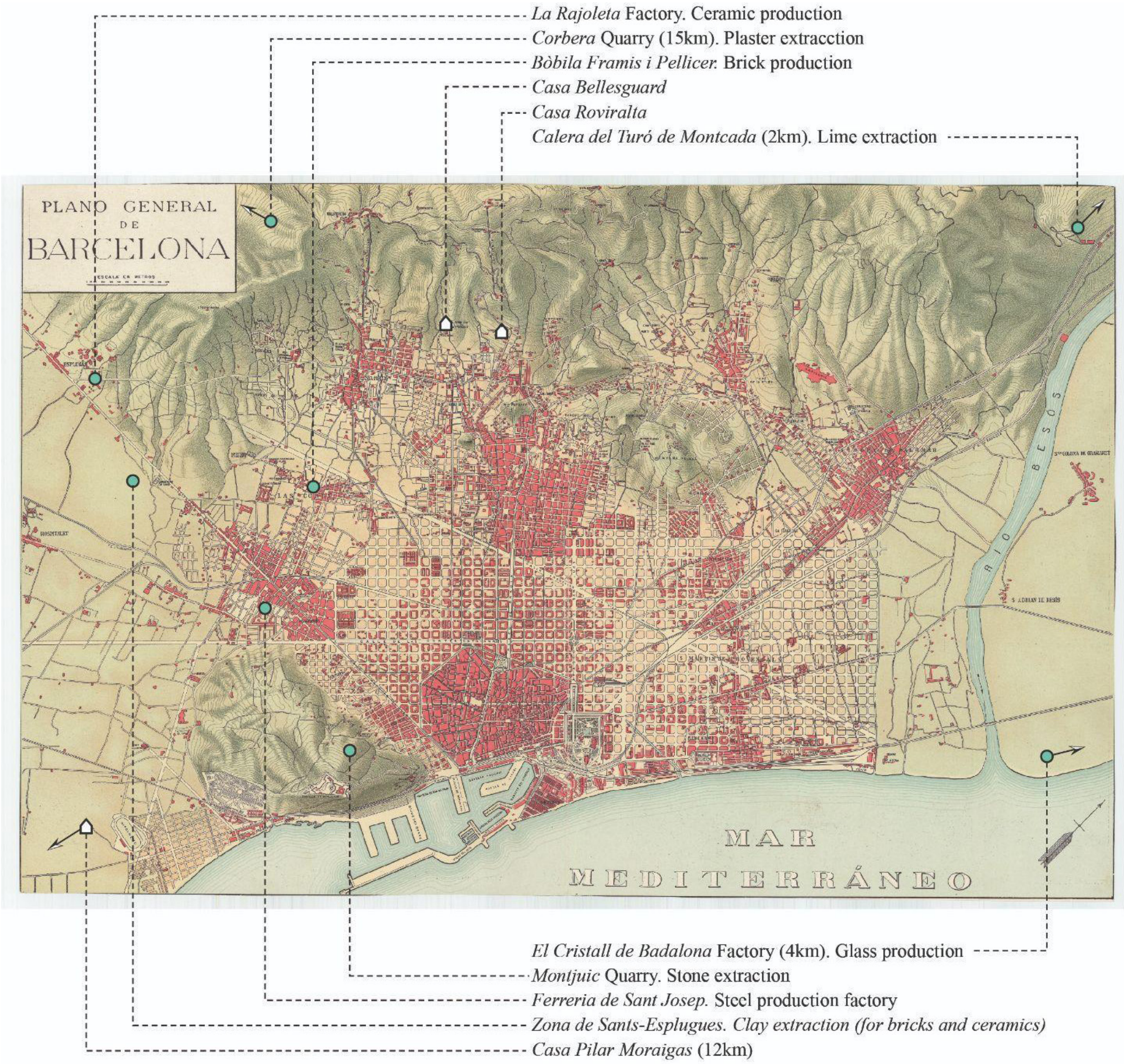


Figure 2 | Map 0 SEQ Map * ARABIC 1: Location of the projects in white and location of factories/quarries in the area.

that carrying a 40 kg load requires three times the effort (Smil, 2017). For the animal value, a 1.4t cart was used as it was the standard in England in 1900 (Smil, 2017).

Rail transport required more complex research, as coal use varies greatly depending on the locomotive model, year of construction, and haulage. For this study, data from the Sharp, Slaughter, and Caldas locomotives, used on the Barcelona railway (Comas, 2011), were used and averaged. Since the data varies significantly and complete information rarely available, volumes of 250 ton per train at 50 km/h were calculated (Comas, 2011) for a 100 km route, requiring 22,00, 23,20, and 44,00 kg of coal per km travelled, respectively, resulting in an average of 33.32 kg CO_2/t/100 km. This is compared to 2.7 kg CO_2/t/100 km today (Arup, 2023).

The primary fuel of the era was coal, accounting for 89% of Spain's energy production in 1900 (Carreras, 1989). It enabled the production of most manufactured goods of the time. In Catalonia, mines were located mainly in Cercs, north of Berga, from where coal was transported by rail to the city and existing factories. A value of 2800 kgCO_2/t (Slatick & Hong, 1994) was assigned. It is important to note that no distinction was made between coal and coke.

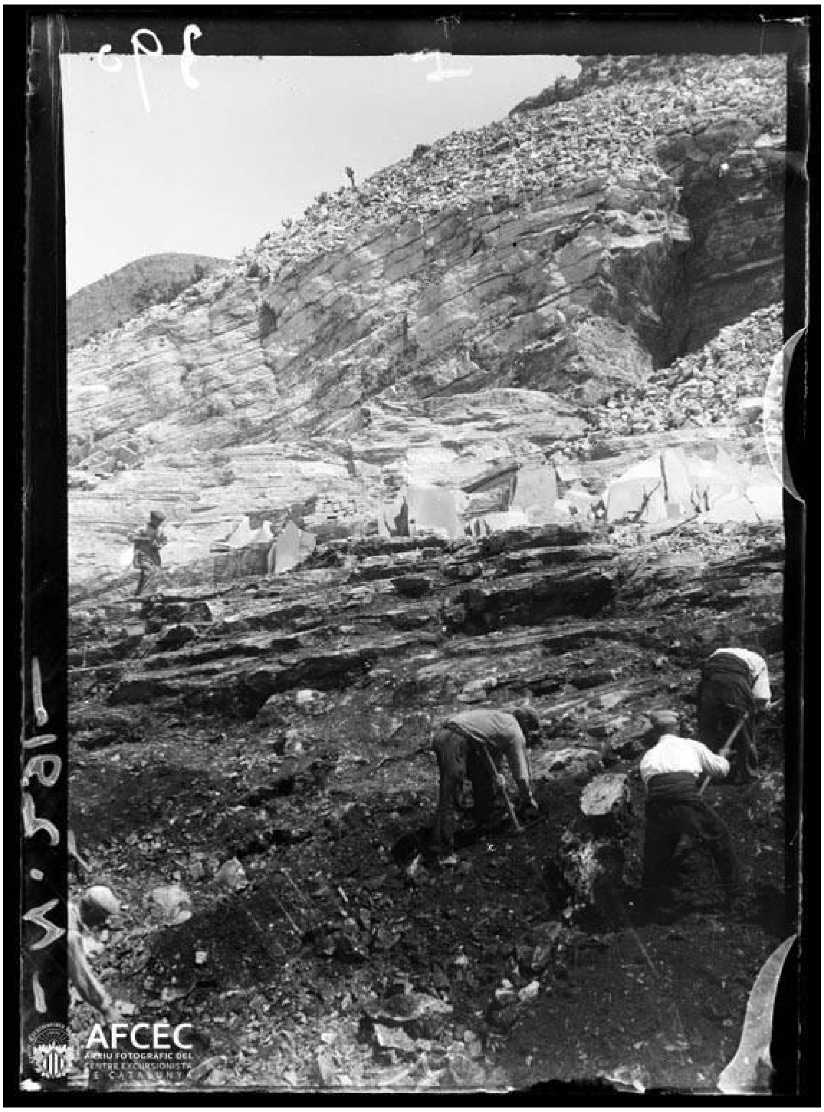


Figure 2 | *Miners a la pedrera de Meià* (ca. 1900), Lluís Marià Vidal. Arxiu Fotogràfic Centre Excursionista de Catalunya (MDXC). CC BY-NC-ND 3.0.

Once the basic units have been defined, it is necessary to divide the information in the corresponding column (A1 – A5) and multiply it by the appropriate unit. A1) Extraction, it must be known the volume extracted over a period of time. A2) A distance and transport must be defined. 3) Input of material, fuel (quantity and type) and output of material must be known. 4), same as in (2) and 5) It is necessary to know the material placement time.

Once all the information is available, it can be used to make a modern EPD and LCA.

Table 2 | Basic work/transport/fuel units measured.

Work/transp./fuel unit measured	Embodied Carbon	Unit
Person carriyng 40 kg	0.063	$KgCO_2$/km
Person doing manual labour	0.263	$KgCO_2$/day
Draft animals with a 1.40t load	0.2	$KgCO_2$/km
Rail	33.32	$KgCO_2$/100km
Brushwood	1700.00	$KgCO_2$/t
Wood	1830.00	$KgCO_2$/t
Coal	2800.00	$KgCO_2$/t
Diesel	3150.00	$KgCO_2$/t

Table 3 | Shows the three analyzed projects with information about them, note that all 3 belong to the Catalan modernism movement and are located within Barcelona.

House	Architect	Construction	m²	Main materials	Plan Tipology
Torre Bellesguard	Antoni Gaudí	1902 - 1909	952.77	Stone for main walls and brick for inside walls, structure and vaults. Finished with white plaster and glazed ceramics	Square, with the staircase and tower as an attached square. Divided in 5 levels.
Casa Roviralta	Joan Rubió y Bellver	1903 - 1913	1,481.28	Built on top of an existing building. Brickwalls, interiors with glazed ceramics and tiles, wood and marble, finished with white stucco	L' shaped, from the original rectangle, a series of rooms were attached during restoration, divided in 3 levels
Casa Pilar Moragues	Josep Puig i Cadafalch	1914 - 1917	285.50	Walls made of brick with white stucco and mortar. Roof made of wooden beams and ceramic tiles, hydraulic tile flooring	Rectangular shape divided in three levels, public, private and attic

2.1.2. LCA calculation of historical materials

To evaluate the embodied carbon of historical construction materials, the methodological structure of contemporary Environmental Product Declarations (EPDs) and LCA was adapted and applied to the period studied. Following the EN 15804 modular framework, the historical dataset was organised to match the information requirements of modules A1–A5. Data on raw material extraction, energy sources, manufacturing processes and transportation modes is explained above in 2.1 Historical materials and in Table 1 and is mapped onto the adequate stages. This approach allowed the reconstruction of the life-cycle profile of historical materials by substituting modern industrial parameters with documented nineteenth- and early twentieth-century production conditions. As a result, the historical LCA maintains methodological equivalence with current EPD-based assessments, enabling a consistent and transparent comparison between past and contemporary construction materials. Thus, a high level of confidence is placed in the method and the results, which will improve as more research and documentation exists on the subject, helping to provide more references, averages and better results.

2.2. Case Studies: A Comparative Analysis of Embodied Carbon

The three buildings chosen for the study date from the turn of the 20th century, this moment in history was chosen because, as the industrial revolution progressed, industrialized materials became cheaper and more available (Calder, 2021), becoming popular in residential buildings, not just as construction solutions, but also as signs of status and wealth. It is important to note, that although residential historical buildings will be analysed, the sample is not universal, as more traditional ways of building, still wildly popular, were not as energy intensive.

All three are single-family homes designed in the context of Catalan Modernism, a cultural and artistic movement that flourished in Barcelona as a response to industrialization and social change. This period was marked by an explosion of creativity, blending traditional craftsmanship with industrial innovations, and reflecting a strong connection to Catalan identity and nature. (Lahuerta 2021).

2.2.1. Torre Bellesguard by Antoni Gaudí

Given its architectural and historical relevance, *Torre Bellesguard* was selected as the foundational case. Gaudí, a central figure in Catalan architecture, uniquely integrated industrial advancements with traditional construction techniques. Commissioned in 1900 by Maria Sagués i Molins, the project integrates religious symbolism with Catalan nationalist ideals, exemplifying the dual themes of faith and homeland. Construction began in 1902, with the main structure completed the same year. Gaudí handed over the execution to Domènec Sugrañes in 1909 due to financial constraints and refocused his efforts on the Sagrada Familia.

Architecturally, the house resembles a neo-Gothic castle. Its façade consists entirely of natural stone blocks approximately 50 cm thick, serving as load-bearing walls. Internally, brick masonry was used throughout for walls,

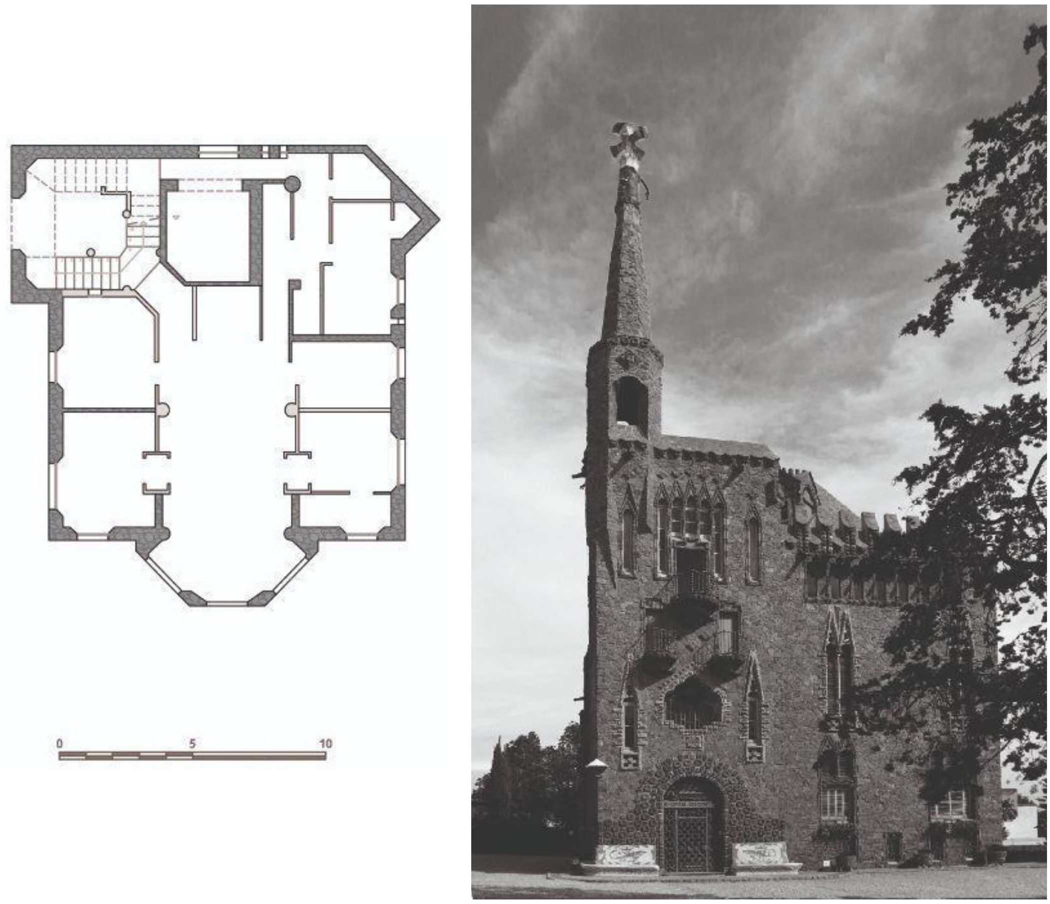


Figure 3 | *Torre Bellesguard.* The first case study house. Photo: Taken by the author. Plans: Own making by the author from original drawings.

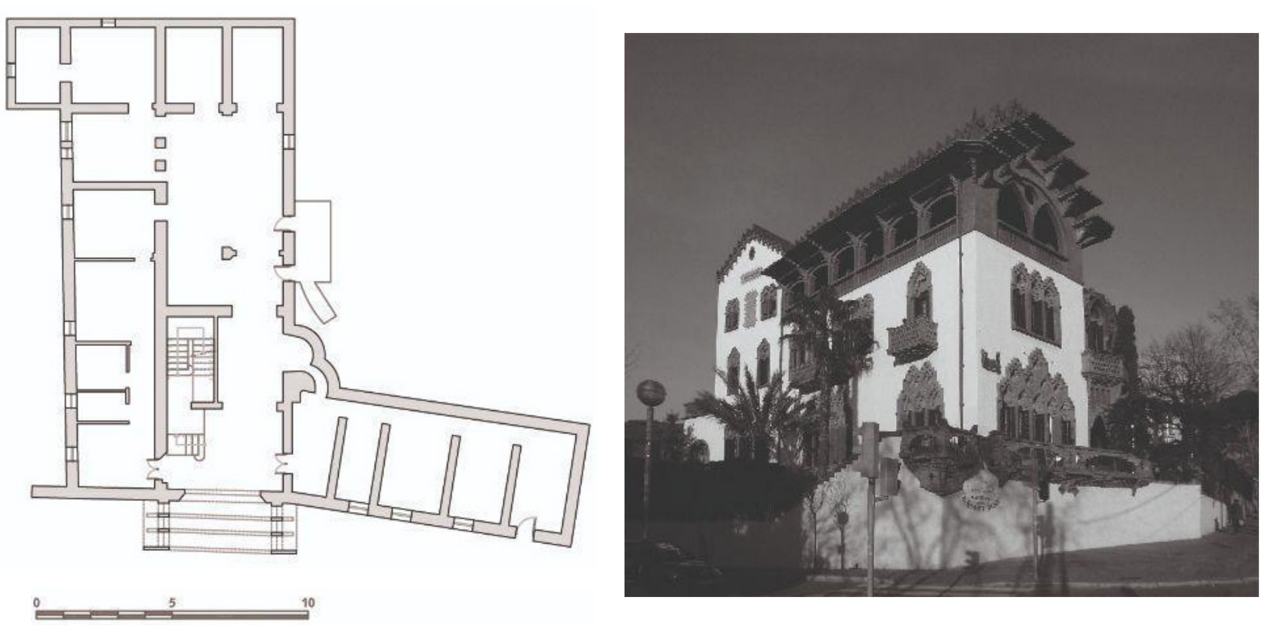


Figure 4 | *Casa Roviralta.* The second case study house. Photo: Taken by the author. Plans: Own making by the author from original drawings.

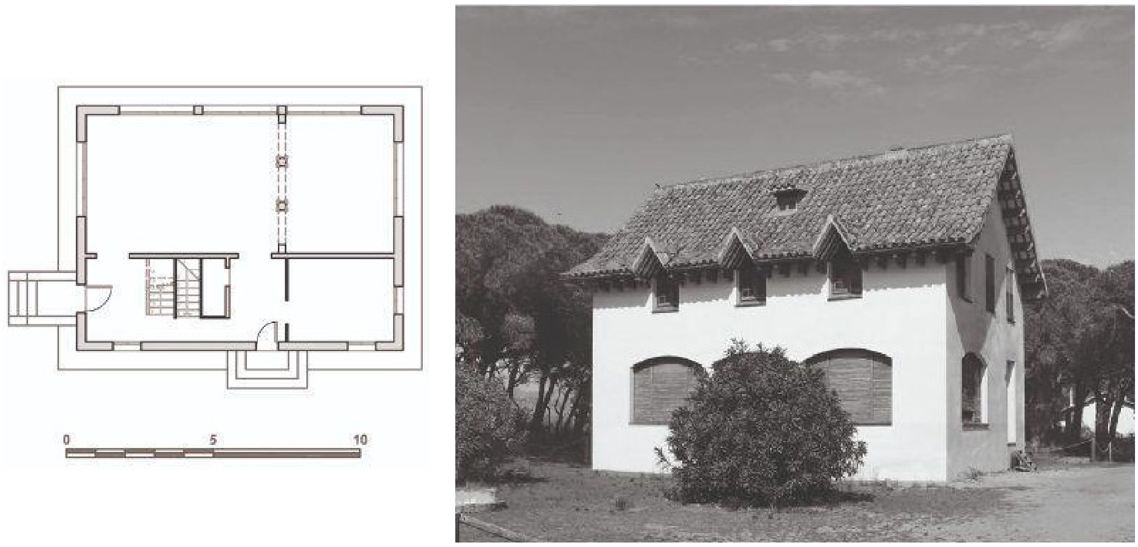


Figure 5 | *Casa Pilar Moragas.* The third case study house. Photo: Taken by the author. Plans: Own making by the author.

floors, and vaulted ceilings (Trouerbach & Molema, 1989), with additional use of iron ties, pine wood for window frames, and glass. Except for the "*maó*" room—composed entirely of exposed structural brickwork—the interiors are finished in plaster and ceramic. These materials were typical of the period (Trouerbach & Molema, 1989).

2.2.2. Casa Roviralta by Joan Rubió i Bellver

Also known as *El Frare Blanc*, this house was designed by Gaudí's disciple Joan Rubió i Bellver and built on the remains of a 17th-century farmhouse. The project was part of the *Tibidabo* development plan initiated in 1899 and aimed at an upper-middle class seeking suburban, garden-city-style residences (Lahuerta, 2021).

Construction began in 1903 and concluded in 1913. The design blends white stucco and exposed brick on the exterior with decorative interiors featuring stained glass, glazed ceramics and tiles, polychrome wood, carved stone, and marble. It spans four levels, with the ground and upper floors for family use and the top floor for service quarters (Corrijos, 2009).

Casa Roviralta serves as a significant case for the study due to its high use of energy-intensive materials such as brick and ceramics, resulting in a relatively high embodied carbon per square meter. The study differentiates between original materials (38%) and additions by Rubió i Bellver (62%), allowing for a detailed environmental assessment. This residence exemplifies bourgeois Modernisme and serves as a valuable model for historic embodied carbon analysis.

2.2.3. Casa Pilar Moragas by Puig i Cadafalch

This smaller, later project—completed in 1917— is located in the then-rural beaches of *Viladecans*. Commissioned by Pilar Moragas and designed by Josep Puig i Cadafalch, reflects the style of a Catalan aristocratic country house, with modest exterior aesthetics and modernist interior elements. Notably, the original design included a lookout tower, later removed at the request of *El Prat* Airport (Cols, 2014).

The house features a ground floor, upper floor, attic, and semi-basement. Its walls are entirely masonry with a white stucco exterior and mortar base. The roof comprises wooden beams and ceramic tiles, while the interiors are highlighted by hydraulic tile flooring. The rehabilitation of this project will later serve as the case for modern comparison.

2.3. Modern sources for comparison

Modern embodied carbon data employed in this study were obtained from three established life-cycle inventory and EPD databases: DAPcons (Spain), Ökobaudat (Germany), and the ICE Database (UK). These programmes compile verified environmental product information and life-cycle impact data in accordance with internationally recognised standards. DAPcons and Ökobaudat operate under the framework of EN 15804 for construction product environmental declarations, while all three sources are compatible with the methodological principles of ISO 14040 and ISO 14044 and aligned with European (UNE-EN) and international LCA requirements. Secondary sources (Bing et al., 2023,

Figure 6 | Taken by the author. *Process of retrofitting the roof at* Casa Pilar Moragas.

Fernández Martínez & Pérez García, 2020, Jones, 2014, LeMone, 2020, Pacheco Torres et al., 2014, Smil, 2017) for specific materials were also used, this with the objective of making an average. This approach enables the comparison of the same material across different timeframes, as well as the assessment of buildings as a whole. Providing insight into how embodied carbon in buildings has evolved over time. A further objective was to evaluate the carbon implications of restoration works in heritage buildings. Retrofitting generally entails a significant reduction in greenhouse gas emissions compared with demolition and new construction: (a) between 42% and 75% lower emissions, and (b) between 57% and 77% lower embodied energy in materials and construction processes (Gummà, 2024). Such comparisons allow for a more accurate understanding of how restoration interventions influence total emissions. Nevertheless, in the context of heritage buildings, benchmarking against new construction is not feasible. For this reason, the present study adopts an alternative approach: the building is compared against itself.

When considering the retrofitting works for heritage-protected buildings, it should be noted that their facades and roofs are specifically protected elements, which means that works are usually limited to:

- Window replacement
- Roof repair and insulation
- Elimination of moisture and biological agents
- Replacement of damaged or lost structural and finish elements

Table 4 | Shows the materials analyzed, its historical and modern embodied carbon and the change through time.

	Embodied Carbon			
Material	Total Historic	Current Average	Unit	Change over time
Stone	1,53	5,72	$kgCO_2/T$	**214%**
Sand/Gravel	1,57	7,3	$kgCO_2/T$	**318%**
Plaster	247,97	193,4	$kgCO_2/T$	21%
Lime	174,38	564	$kgCO_2/T$	**320%**
Brick	271,94	170,8	$kgCO_2/T$	24%
Cement	1798,46	406,58	$kgCO_2/T$	76%
Tiles	331,02	279,33	$kgCO_2/T$	**35%**
Glazed Ceramics	593,29	1017,85	$kgCO_2/T$	**31%**
Wood	300	361,18	$kgCO_2/T$	14%
Glass	3022,74	1212	$kgCO_2/T$	70%
Steel	6893,91	1876,4	$kgCO_2/T$	75%

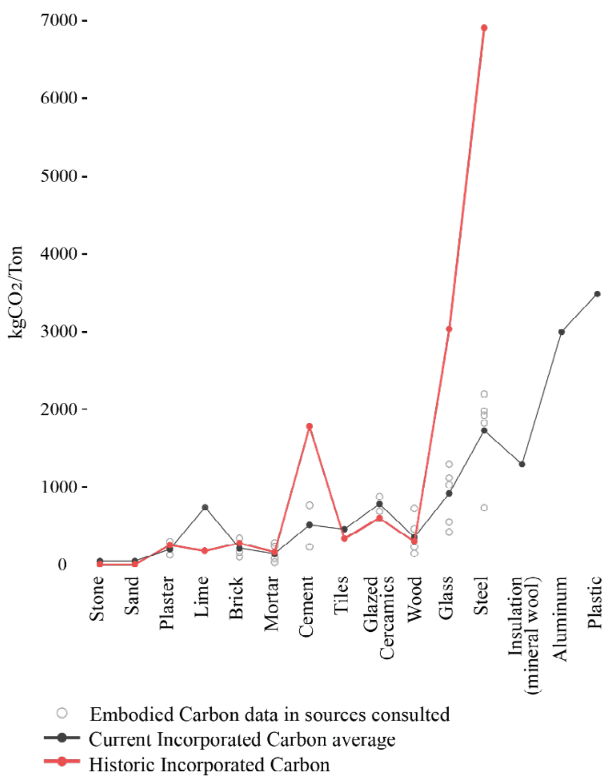


Chart 01 | Embodied Carbon, historic and modern sources comparison.

These works can be considered as the minimal restoration works.

As mentioned, Casa Pilar Moragas was selected for this case study. The intervention sought to preserve the building while addressing structural degradation and improving thermal performance. Key actions included the replacement of windows with pinewood double-glazed units, repair of roof leaks and capillary moisture, selective roof reconstruction while salvaging existing tiles and beams, and the renewal of damaged surfaces.

The roof process involved:

- Removing and sorting tiles and flooring for reuse
- Sanitizing the timber structure, replacing damaged elements
- Waterproofing with liquid rubber
- Installing 40 mm extruded polystyrene insulation
- Replacing the roof tiles

The building was in a state of significant disrepair, and yet it was still possible that 50% of the tiles and 80% of the wooden structure were reused (Dotor-Onecha 2009). The rest was replaced with new materials. The roof area was approximately 130 m^2.

3. Results

This section illustrates the results obtained in the series of investigations described above (2.1 and 2.3). In this table (Table 4), we can see the results of the historical embodied carbon research shown in the second column, as noted above, data sources include museums and factory archives and secondary literature on the matter: (Arup, 2023; Baila Lletí, 2012; Berg, 2021; Betevé, 2015; Bing et al., 2023; Bogllo Etcheverri, 2016; Busquets Relats, 2021; Calder, 2021; Carreras, 1989; Cavert, 2017; Comas, 2011; De Decker, 2009; Hill, 2016; Houpt, 2002; La Spina, 2016, LeMone, 2020; Marcos Vallaure, 1991; Marcos y Bausá, 1879; Miguel, 2012; Moore, 2011; Quorum Corp, 2005; Smil, 2017). In the third column, the current average embodied carbon is shown, with data from: (DAPcons; Ökobaudat; ICE Database; Arup, 2023; Bing et al., 2023; Fernández Martínez & Pérez García, 2020; Jones, 2014; Lee, 2012); and in the fourth, the percentage that has increased or decreased over time (red for increase and green for decrease).

3.1. Historical embodied carbon

Chart 01 illustrates the results of Historical materials presented in Table 1 and Modern sources, that is, calculate the embodied carbon of historical materials and compare them to their modern counterparts. The result of each material is in orange and its current equivalent in black. This comparison reveals three key trends: 1) natural materials exhibit low and relatively stable carbon values over time; 2) semi-industrial or non-industrial materials involving combustion processes show slight variations; and 3) fully industrialized materials such as cement, metal, and glass demonstrate a significant decrease in their current embodied carbon values, suggesting improved production efficiency. For comparison, other modern materials commonly used in construction were also included.

Using these values, the total carbon footprint for the construction of the three selected heritage buildings was calculated.

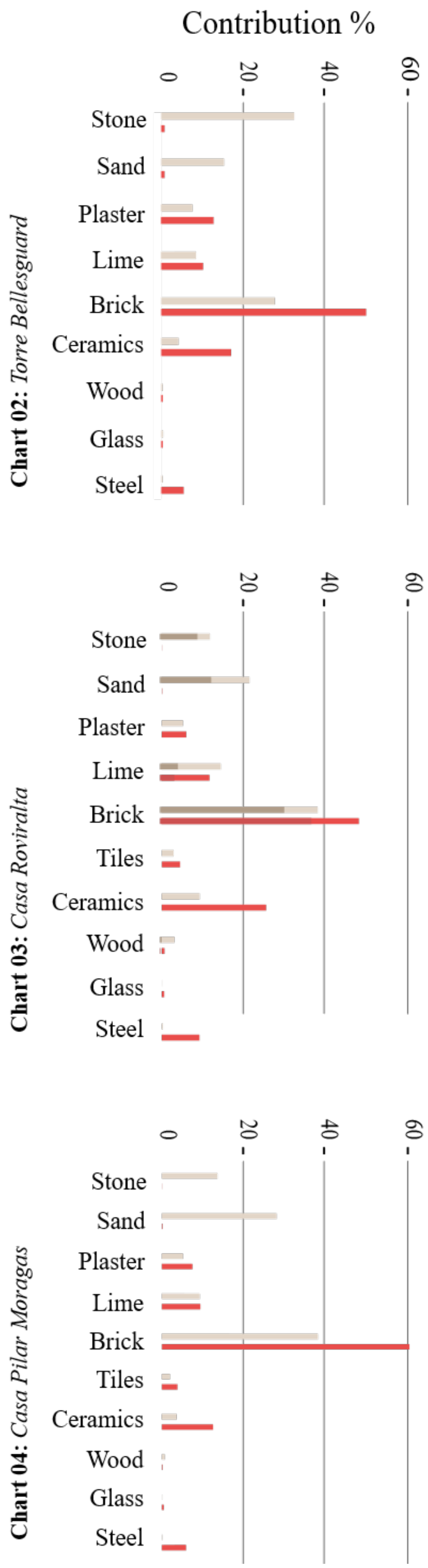
3.2. Embodied carbon in case studies

Material usage across the three projects was relatively similar, with the greatest variation observed in the use of industrial materials, which were not yet widely distributed in residential construction. When unknown, materials were assumed to be of local or national origin. The results of each case are illustrated in Charts 02, 03 and 04, where beige represents the percentage of the material used in relation to the total amount of materials used in the construction, and orange, its percentage of embodied carbon.

The average embodied carbon across the three case studies was calculated at 467.87 $kgCO_2/m^2$, slightly higher than the modern average of 432.66 $kgCO_2/m^2$ (as shown in Chart 05). However, these modern figures cover a wide range of building typologies (as shown in Chart 07) and should not be viewed as definitive. Continued research and comparable case studies will enable more precise benchmarking.

These findings suggest that while production processes—particularly for concrete and steel—have become more efficient, the average carbon footprint remains stable due to the introduction of numerous modern materials such as plastics, aluminium, alloys, synthetic insulators, etc. Thus, maintaining a similar footprint while improving building performance represents notable progress. For instance, a separate study (González & García, 2006) demonstrated that sustainable construction practices in Spain reduced embodied carbon by 30%.

Concrete and steel remain the most used materials, consuming four times less energy today than a century ago (Smil 2017), followed by glass at 3.4 times less. While these improvements are significant, further innovation and alternative materials are necessary. Chart 05 compares the material volume used in the study cases in beige and its embodied carbon percentage in orange, highlighting the difference between one value and the other in non-industrialized and industrialized materials (although inverted) and the more stable relationship in semi-industrialized or low-energy consumption materials. In green, it shows the material lifespan, with 100% equivalent to 1,000 years. This highlights the durability of



Charts 02, 03, 04 | Embodied carbon in each study case. Own Making, based on data and sources listed in Table 1

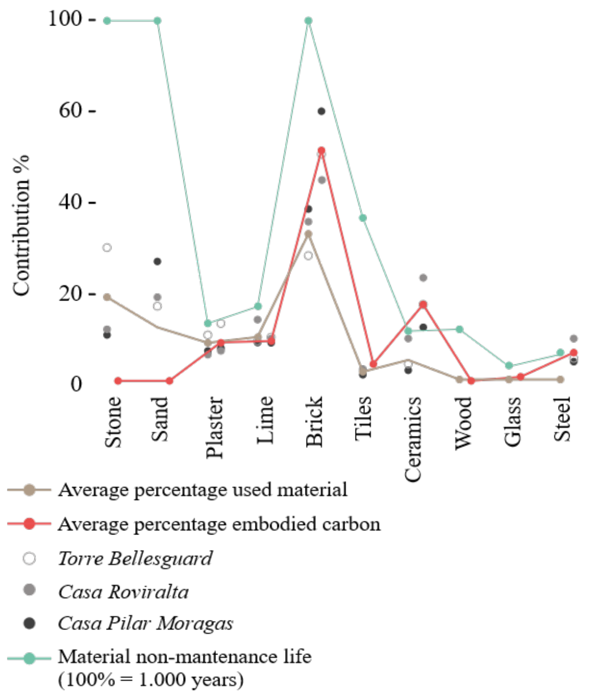


Chart 05 | (Above), Average embodied carbon. Own Making, based on data and sources listed in Table 1 and Charts 02, 03 and 04.

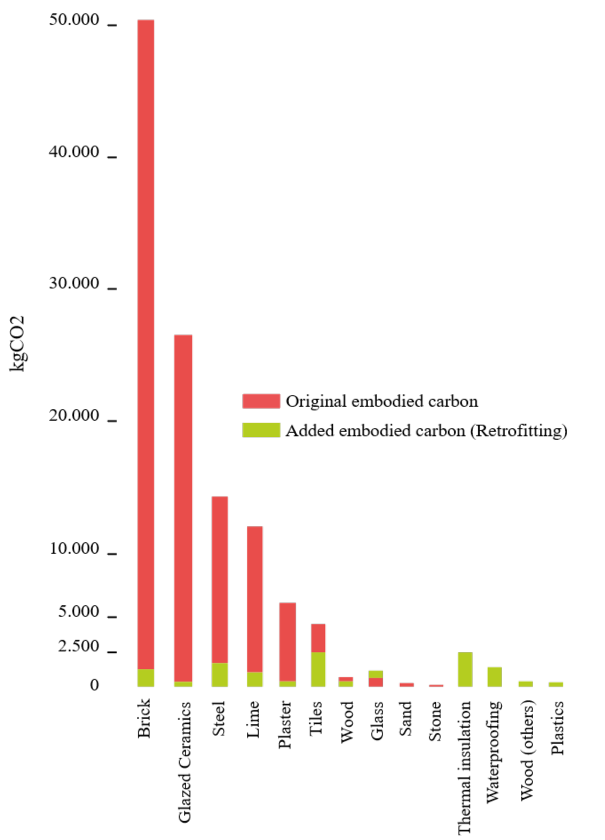


Chart 06 | (Below), *Casa Pilar Moragas* original and added embodied carbon.

traditional materials such as brick, and the relative impermanence of others, which require ongoing maintenance and eventual replacement.

3.3. Intervention Analysis: A Minimal Restoration Scenario

The embodied carbon values of original and modern materials are detailed in Chart 06 as follows: in orange the original incorporated carbon and in green the added one, including new materials. This highlights the amount of carbon saved. This targeted intervention increased the building's carbon footprint by just 9.12% compared to its original value. In other words, full habitability was restored with less than 10% of the original emissions. When compared to the average emissions of new construction (444 $kgCO_2/m^2$), the restoration generated only 7.92% of those emissions, exceeding the 40% savings target set by the World Green Building Council. As mentioned above, 6 modern cases were taken for comparison, this is shown in Chart 07, where the average embodied carbon of the three study cases is compared to the six modern cases. The results indicate that the embodied carbon is stable through time, except in case 4, since they were homes specifically designed to use low-energy intensive materials (González & García, 2006). This is important because it underlines the need to continue searching for low-impact solutions in construction, but also shows that we have managed to improve the comfort features of buildings while maintaining the same carbon footprint.

4. Conclusion and Discussion

In the introduction of this article, it has become clear that retrofitting is better than constructing a new building in life cycle terms, but also the need to provide reliable historical and constructive data and criteria guidance for intervention, resulting in a better understanding of the energy and carbon impact of any retrofitting process (Huang et al., 2025). In sum, a method for LCA assessment prior to refurbishment to understand the environmental impact of proposed solutions (Sesana et al., 2019), as well as a policy and certification schemes to measure life-cycle impacts and to propose low-impact refurbishment strategies that are sensitive to heritage buildings (Wise et al., 2019).

If buildings professionals need help to achieve sustainability objectives, architectural heritage professionals even more so, as they have to be able to detect heritage values and propose sustainable actions, this is a

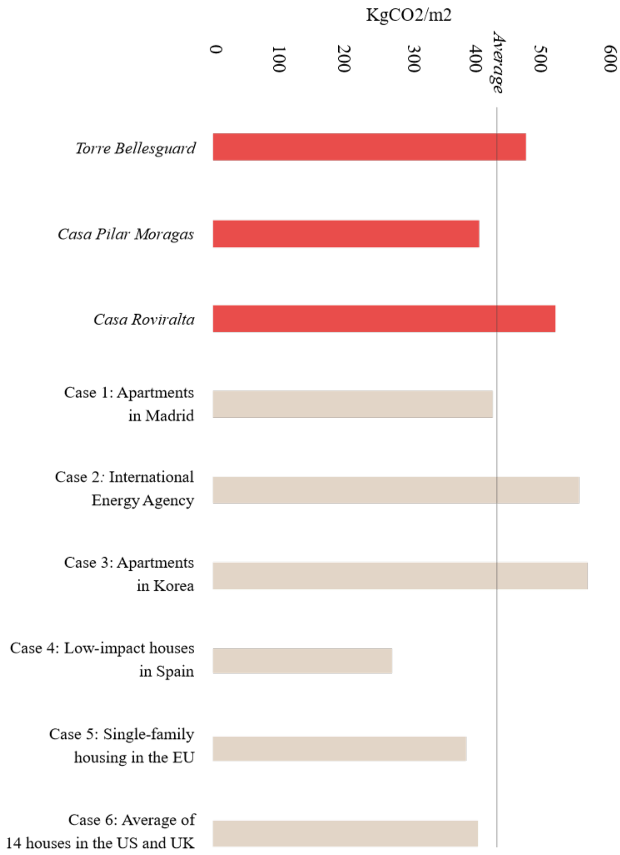


Chart 07 | Own Making, comparison of Embodied Carbon in different projects, in red are the three case studies and in beige are modern projects of different typologies. based on data from: Case 1: Fernández Martínez 2020, Case 2: Yokoo & Yokohama, 2016, Case 3: Lee, 2012, Case 4: González & García 2006, Case 5: Pacheco-Torres et.al, 2014, Case 6: Jones 2014.

further degree of difficulty (Muldoon et al., 2024), as the historical value of a building cannot be compromised, as it is a non-renewable resource.

This paper offers a response to the above considerations by developing a detailed method of analysis of the embodied carbon of historic buildings, that allows the comparison with modern buildings, revealing interesting results. Because of the differences in technologies and construction methods between the two eras, the findings suggest that the energy expenditure associated with building construction has decreased over the past century and a half. Improved technology, better use and higher prices of fuels, manufacturing efficiency and concern for sustainability, have meant that energy expenditure today is lower than in the years before and after 1900. While traditional manufacturing methods and materials were still used, the introduction of industrialised materials and processes such as cement, iron, steel, ceramics and glass, with their high energy demands, increased the overall footprint. It should be noted that these materials were not a discovery of the Industrial Revolution, and that their manufacture before it was even more demanding of energy and resources, however, it was at this time that their use became widespread as they became cheaper and more massive. Therefore, they appeared in greater quantities in this period than in previous ones. In short, building at the dawn of the 20th century is not as sustainable as is commonly claimed. Embedded carbon is inferior for contemporary construction; if we currently pollute more, it is because of the volume of materials and energy we consume per person, as it is estimated that we use four times more energy per capita (Smil, 2017).

There are three types of results for the materials analysed when we compare their embodied carbon and the volume that each value represents in the total construction, as we have already seen in chart 05:

1. Stone, sand and wood. As they do not undergo industrial transformation processes, their footprint is minimal, and as they are widely used in this type of construction, the volume/ incorporated carbon ratio is very high.

2. Gypsum, lime, mortar, bricks and tiles. These materials already have a transformation process that includes the burning of fuel, so their volume/ incorporated carbon ratio tends to be more stable, with similar percentages, from 1:1 for lime to 2:1 for tiles and bricks.

3. Ceramics, glass and metals. In the production of these materials, there was a high level of combustion, train transport and other energy-intensive activities, so their ratio is the inverse of that of the first materials. Ceramics have a 4 times higher percentage of embodied carbon than volume, the ratio increases to 15:1 with glass and 30:1 with steel.

Of these materials, stone and brick are the most resistant to the passage of time, which potentially reduces their footprint, as they can be preserved in an intervention. The other materials, to a greater or lesser extent, in more or less years, will have to be replaced. When we talk about the retrofitting of architectural heritage, in addition to the 3 classic components of sustainability: social, economic and environmental, it is also essential to consider 2 more factors: Culture and Time, this last meaning durability (Moioli, 2015).

The methodology used here can be replicated, looking for similar data to those obtained in this study and applying it in the same way to any other historic buildings. It shows the importance of calculating the embodied carbon of historic buildings as a tool to understand their total environmental impact and to provide additional information for the design of sustainable restoration. It is estimated that restoration results in energy savings of 60% (Royal Institution of Chartered Surveyors, 2023). By calculating the total embodied carbon of restorations, which includes both the original materials and those used during the restoration process, a complete picture of the environmental impact of the intervention is obtained. This allows informed decisions to be made during the design and implementation of the restoration, prioritising materials and construction practices that minimise the carbon footprint and promote long-term sustainability.

The study case whose retrofitting has been analysed in this paper implied a great quantity of work, but only 7.92% carbon emissions, when compared to the average emissions of new construction. There are many heritage buildings that require less restoration work, as the base materials are strong and of good quality, and the use remains unchanged, so we can hypothesize that the retrofitting works are reduced to the addition of insulation and replacement of windows. In these cases, the environmental impact is further reduced and, if the materials used are sustainable (ecological insulations, wood windows) it would be reduced to minimum, obtaining Near Zero Environmental Impact Buildings, NZEIB.

In this way, the values approach cannot only consider the cultural, architectural, etc. aspect of historic buildings, but also its environmental footprint over time, expanding the knowledge of the ecological value of the building. As Onecha et al. (2021) established "...to consider the paradigm of sustainability to be integrated as another historic layer in protected buildings that express the values, technologies and materials of contemporary societies, with similar relevance to that posed by past values, technologies and materials…in the future, those values will also be history".

If we want to curb the environmental impact of construction, and meet the goals of the Global Agenda, we must recognise heritage and historical buildings retrofitting as one of the most efficient ways to do so, since, as has been said, a minimal intervention only represents an increase of the original embodied carbon of about 5%, saving up to 90% of materials. According to the results and shown in Chart 06**.**

The calculation of the embedded impact should be included in the regulations, as well as the demonstration of the reduction of the total environmental impact over the life of the building (Baker et al., 2021).

To further minimise the environmental impact of retrofitting, the focus could be changed and as Cuchí said (2021): "... We learned then that perhaps heritage buildings are no less subject to energy retrofitting for their infill with discretionary activities, but should be seen as opportunities to accommodate uses that can be coupled to them by taking advantage of the environmental benefits they offer…".

Future lines of research arising from this manuscript are the development of standardized LCA databases for historical materials and processes, the quantification of restoration processes with the highest carbon footprint, or digitization in rehabilitation.

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