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Sustainable Retrofitting Criteria in Heritage Buildings: Case Study in Seville (Spain)

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Abstract: The construction sector has an important role to play in reducing the threat of climate change. Thus, this work proposes, analyses, and compares two constructive strategies for the intervention/rehabilitation of a protected building located in Seville (Spain). The first solution intends to follow traditional techniques and standardized criteria, while the second option takes into account environmental aspects for the constructive definition of the proposal. An environmental study of each constructive solution, using a life-cycle assessment methodology, as well as an energy behavior analysis were carried out. The results show that the "sustainable proposal" represents a significant environmental improvement, in which a reduction in CO_2 emissions and incorporated energy can be appreciated apart from an optimal energy certification. Finally, the sustainable proposal reveals a significant economic reduction in the total budget of the intervention.

Keywords: sustainable construction; eco-efficient materials; life-cycle assessment; energy simulation; economic impact

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1. Introduction

The growing development of today's societies is causing an uncontrolled increase in the level of energy demand and greenhouse gas emissions into the environment. These trends are causing climate change to accelerate significantly, causing damage to health, infrastructure, and property, which entails very high costs for society and the global economy [1].

Following the awareness of global decline in environmental terms, a succession of international agreements has been presented and signed recently in an attempt to strengthen the global response to the climate change. Among them are the Paris Agreement in 2015 [2] and the 2030 Agenda for sustainable development of the United Nations, where 17 sustainable development goals (SDG) were defined [3]. The SDG, together with the Paris Agreement, define the essential guidelines to generate routes and maps for long-term development and economic, social, environmental, and international governance cooperation.

In the European Union, the approval in 2008 of the European Energy and Climate Change Package 2013–2020 and the Roadmap towards a competitive low-carbon economy in 2050 [4] stand out. The first one defined the precise objectives for 2020 based on renewable energy, energy efficiency, and reduction in greenhouse gases (GHG) emissions, which later, after having not been achieved, were postponed until 2030 [5]. These action packages allow the European Union to evolve in the development of a climate-neutral economy and achieve the objectives set out in the Paris Agreement [6].

However, the 10th Emissions Gap Report [7], in which the United Nations Environment Program (UN-E) participated in 2019, determines that there has been no decrease in global emissions of gases. On the contrary, it has produced a significant increase of 1.5% per year in GHG emissions since 2010. Total GHG emissions reached unprecedented values in 2018, namely 55.3 GtCO_2e. That is why the G20 (forum for international economic cooperation), in 2019, promoted the definition in Europe of a methodology or tool to achieve the absence of CO_2 emissions in industrial processes [7].

In Spain, the construction sector represents 39% of the carbon dioxide (CO_2) emitted into the atmosphere while generating 30% of the solid waste and 20% of the water pollution [8]. The obligation to control and reduce the demand for energy and CO_2 emissions from this sector has triggered the adoption of new measures and legal tools that support this development guideline. This focus/support on the growth of sustainability could have a strong impact on the future of the European construction industry and also provides an opportunity for the development and commercialization of eco-efficient construction materials [9].

The growing interest in Europe in sustainable development and the efficient use of energy has generated the implementation of policies to encourage a reduction in the energy consumption of buildings [10]. In Spain, the Technical Building Code (CTE) with the Basic Energy Saving Document (DB-HE) aims to cooperate in the development of government policies on sustainability by promoting the use of tools such as LIDER–CALENER (HULC) for energy certification and quantification of CO_2 emissions and primary energy consumption, indicating the necessary corrective guidelines to be taken [11]. This type of certification only performs the energy analysis of the building during its useful life. Other tools, such as BREEAM (UK), LEED (USA), and VERDE (Spain) [12], come close to performing a complete analysis. This is why, although they are not mandatory, they are being commonly used and introduce an approach to life-cycle analysis for the evaluation and certification of entire buildings and not only for partial systems or elements.

Other of the main problems in today's society is the massive and uncontrolled production and management of construction and demolition waste (CDW) and the increase in emissions of polluting substances into the environment. The generation of CDW in one year amounts to more than one ton per inhabitant, generating 45 million tons per year in Spain [13]. The appearance in 2007–2015 of the National Integrated Waste Plan (PNIR) required the development of a CDW Management Plan to quantify and determine the wastes' nature and separate them on site. However, the latest data handled by the EU show that 75% of CDWs are managed incorrectly, causing serious environmental impacts [14]. Thus, to reduce the CDW destined for landfill and improve their quality, the management and treatment of CDW was established. Given the volume of the expected waste and its characteristics, the possibilities of use are directed towards its reuse and recycling. The recycling of CDW allows for the optimization of available resources, reducing the demand for natural resources. The decrease in raw material to collect, transform, and transport contributes to the decrease in the energy consumed during the building process [15].

The existing legislation on recycled materials is fundamentally focused on standardizing the recycling of materials in structural concrete through using recycled aggregates, wood ashes, or ceramic waste as substitutes for aggregates or cement [16]. Materials derived from concrete are also analyzed, such as concrete blocks or paving blocks. In this sense, many researchers have developed new lines of work promoting the development and creation of new materials and products through the reuse of various types of existing waste [17,18].

However, other lines of study are also being carried out whose objective is the use of ceramic or plastic waste as a substitute for cement or as an additive in the composition of mortars. Other research focuses on the introduction of recycled materials in the composition of plaster, based on the use of shredded tires, polypropylene fibers, and recycled RCD mining wool fibers as additives and the search for a lighter composite material using waste from the rehabilitation of wooden structures [19,20]. The quality and efficiency of these materials have been analyzed in different works in which they were implemented as part of the rehabilitation of traditional buildings for the purpose of carrying out an energy analysis [20–22].

In an increasingly demanding market in terms of sustainability, the choice of materials and construction solutions is complex. Professionals in the sector have different instruments to accredit and define the environmental quality of products and services, with the Environmental Product Declaration (EPD) being the most widely used option [23]. These declarations are made in accordance with the EN-14025 [24] and EN-15804 [25] standards for construction materials and products. This EPD for construction products and services is also known as eco-labels, a term defined in the EN-14020 standard [26].

In 2015, the first EPD began to be registered in the General Registry of Environmental Certifications of the Life-Cycle Assessment (LCA). This is a methodological framework of environmental management used to assess the potential services', processes', or systems' environmental impacts throughout the life cycle of the product. It ranges from the raw materials' obtention to their final disposal, including production, use, final treatment. and subsequent recycling (i.e., from cradle to grave). This work methodology has been used as a tool to study the sustainability and environmental impact during the different building materials' life cycle, such as natural cork agglomerate panels without additives [27] and gypsum plasters made with totally recycled materials [28], or the comparative analysis of different construction systems with conventional materials and recycled materials [29,30]. LCA is also contributing to the sustainability of construction solutions by identifying opportunities to progress in the environmental development of products throughout their life cycle through the selection of relevant environmental performance indicators and provision of environmental information to facilitate the design and conception of sustainable buildings [31].

Up to now, previous research has focused on the environmental analysis of various rehabilitation scenarios [32,33]. Thus, Table 1 compiles some previous experiences in which the eco-efficiency of historical/protected buildings rehabilitation has been analyzed.

Table 1. Main contributions of previous researches focused on the eco-efficiency of historical/protected building rehabilitations.

Research Paper	Type of Building	Main Gaps and Contributions
Rodríguez-Liñán et al. [21]	Protected multi-family house (Spain)	Up to 30% reduction in CO_2 emissions was achieved for a sustainable retofitting proposal compared to a traditional one.
Pérez-Gálvez et al. [22]	Protected house (Spain)	The sustainable restoration reduced CO_2 emissions by more than 50% during the useful life of the building.
Atmaca et al. [34]	Heritage building (Turkey)	Life-cycle energy consumption and related emissions of the heritage building could be decreased by up to 28.7%.
Ruggeri et al. [35]	War-wounded houses (Italy)	Energy retrofitting was used as an opportunity to protect historic buildings.
Ide et al. [36]	Historic house (Canada)	Methodology and decision framework for deep energy retrofit analyses that balances trade-offs between conservation and sustainability in heritage buildings.
Bertolin and Loli [37]	Historic buildings (focused in Italy)	Development of a decision-making tool to conduct sustainable interventions and effective zero-emission refurbishments.
Dervishi et al. [38]	Traditional building from 16–19th century (Albania)	Energy performance of traditional Mediterranean buildings. An improvement of up to 46.3% and thermal comfort of up to 7.2 °C, with a payback period of 7.9 years, was achieved.

In that sense, the main objective of this article is to propose, analyze, and compare two intervention/rehabilitation solutions in the Old Roads and Works Pavilion. The selected site is a protected building located in the San Bernardo neighborhood of Seville (Spain). In this sense, and focusing fundamentally on constructive aspects of the building envelope, two different proposals are offered. The first one intends to follow more "conventional" or "standardized" criteria, while the second option takes into account environmental aspects for the constructive definition of the proposal, mainly considering materials and solutions with a smaller sustainable footprint. A comparison is made valuing the constructive, energetic, environmental, and economic aspects of both solutions.

2. Methods

To obtain the aforementioned objective, this work was based on the following methodology:

- **Rehabilitation Project–BIM Methodology:** An architectural definition of the project of the Old Roads and Works Pavilion was reached through the use of the integrative digital design methodology known as building information modeling (BIM), specifically with Autodesk's REVIT software [39];
- **Constructive Materialization:** Two constructive solutions are proposed. In the first of the solutions, "conventional" models are followed, while in the second, sustainability criteria prevail. The use of manufacturers' catalogs and scientific articles was essential in this task;
- **Regulatory Compliance:** Once both solutions were constructively defined, compliance with current regulations was verified along with the calculation of the foundation and floor structures;
- **Environmental Analysis:** Aiming to certify the true benefit, in terms of sustainability, of the second solution, an environmental analysis of each of the developed constructive solutions was carried out. To achieve this, a "cradle to grave" LCA methodology [31] was used, using data from the literature, the manufacturers themselves, the BEDEC database [40], the price generator of CYPE [41], and mainly the Ecoinvent [42] database;
- **Energy Behavior:** Once the environmental benefits of the sustainable solution were certified, the energy performance of both proposals was analyzed. To achieve this, and using the BIM modeling previously carried out, the CYPECAD MEP software was used for the constructive definition of each constructive element, and the HULC unified tool [43] was used to obtain the energy certification. The use of these specific tools allowed for verification of the compliance with the energy requirements made by Spanish regulations [11];
- **Economic Impact:** Study of the economic impact of each constructive solution, using for this purpose the price banks obtained from the manufacturers themselves and from the CYPE price generator [41] for each constructive solution, is a novel contribution.

Although this work is focused on a case study building, a generic methodology scheme is presented in Figure 1, which can be extrapolated to any other research or model.

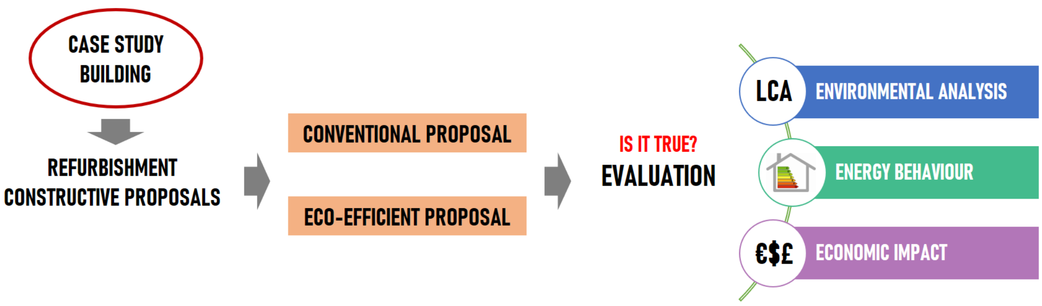

Figure 1. Methodology followed to conduct the research.

3. Case Study Building

This work proposes the rehabilitation of the building of the old "Pabellón de Vías y Obras" (19th century), located in the neighborhood of San Bernardo in Seville (Spain) (Figure 2). It is a protected building with a great urban and historical importance since it is part of one of the main railway axes of Seville. According to the Seville's urban protection plan, our case study catalogued the site as a partially protected building (grade 2), which means that façades and roof system must be conserved in case of any intervention. The implementation of the railway marked the history of the city and specifically of San Bernardo, an area crossed and limited by the railway line. In 1902, the old San Bernardo station was built, and it was the center around which all the development of the neighborhood revolved.

Figure 2. Current-state pictures of the studied building.

Although the first urban appearance dates back to 1865, it was between 1895 and 1905 when, after the enlargement of the San Bernardo area, the present building was erected, with the spatial and constructive characteristics with which it currently stands, intended at that time to house warehouses, workshops, and offices. Figure 3 shows the architectural plans of the current state of the studied building.

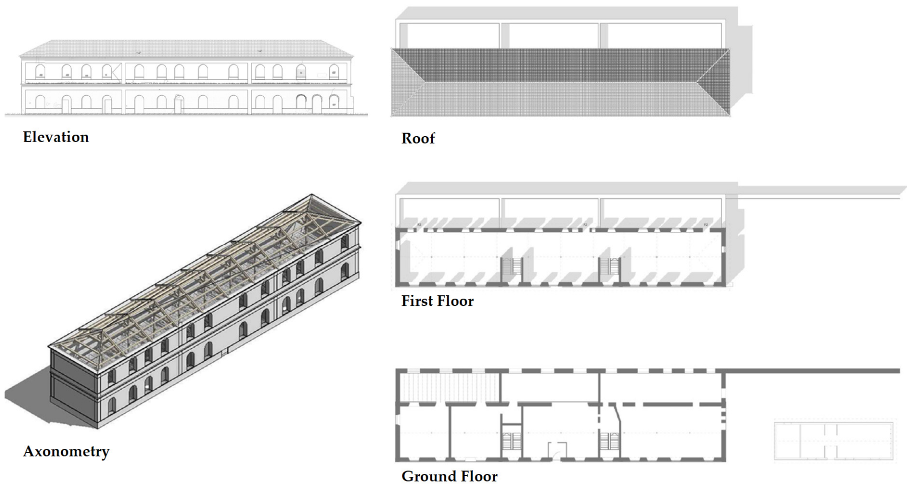

Figure 3. Architectural plans of the current state of the studied building.

3.1. Constructive Definition of the Building

The building construction followed the economy policy of the railway companies that used, in the construction of their stations and other associated buildings, the excess building materials of the railway tracks themselves, as it can be noticed in the first floor slab. On it, the use of laminated steel rails from the construction of railways as joists is evident. These joists rest on the masonry walls and on a continuous longitudinal beam that transmits the load to a central row of circular cast-iron columns. Furthermore, one of the most unique elements of the building is the wooden truss of the "Spanish knife" type that forms the roof.

Attached to the main building, there is a rear volume that is only one story high and delimited by a load-bearing brick wall 60 cm thick. This volume shares the central wall with the main building. It was initially designed as a covering element for the north area, with two arches that generated longitudinal loading and unloading access (Figure 4).

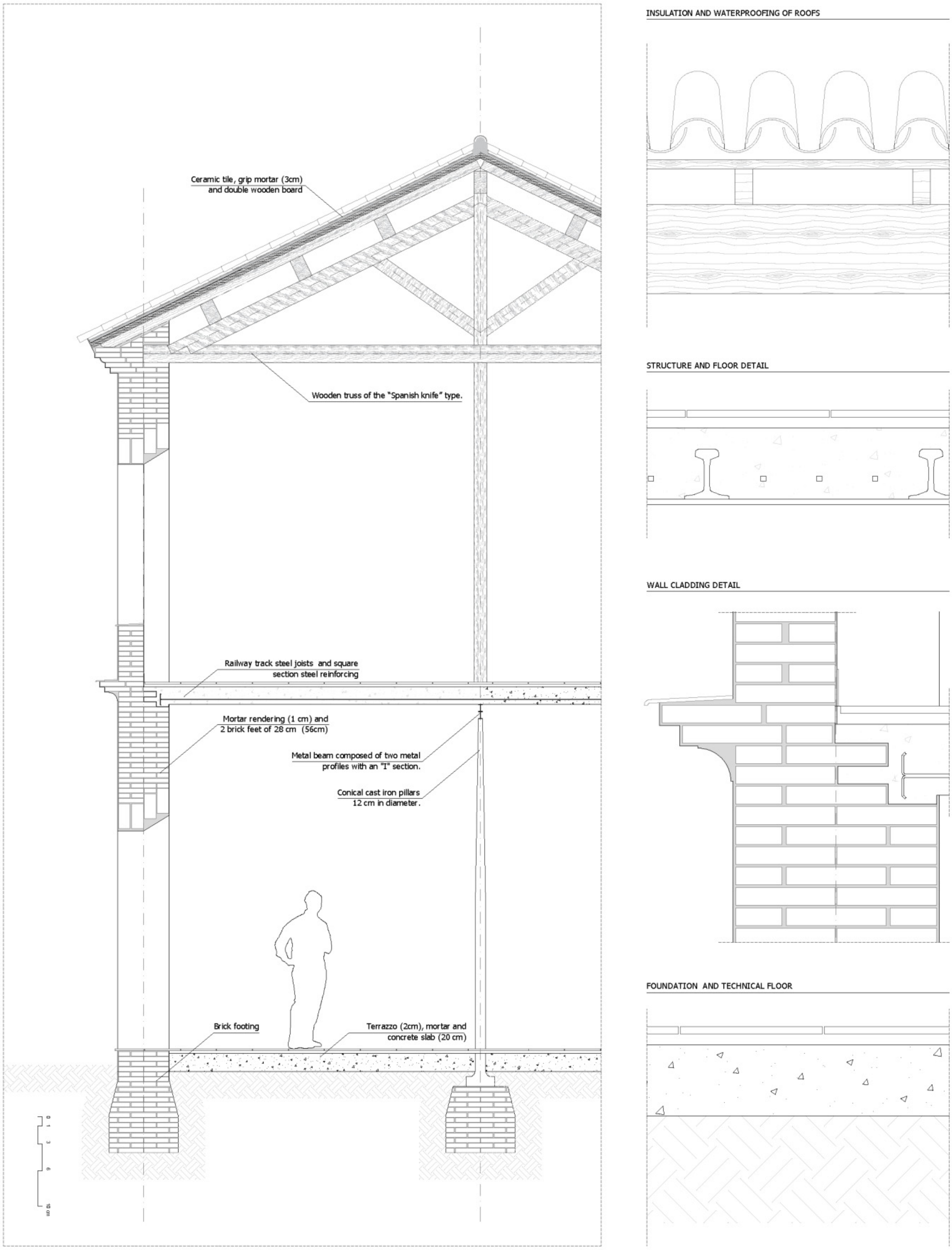

Figure 4. Constructive section of the original state of the building before the rehabilitation project.

3.2. Damages Assessment of the Current State of the Building

The building is currently without a defined use and in a continuous state of deterioration, thus being considered socially as a residue of architecture and the railway industry in the San Bernardo neighborhood. The current state of the building envelope is marked, in general, by a progressive and very prolonged deterioration over time, caused by inclement weather and the lack of adequate maintenance (Figure 5).

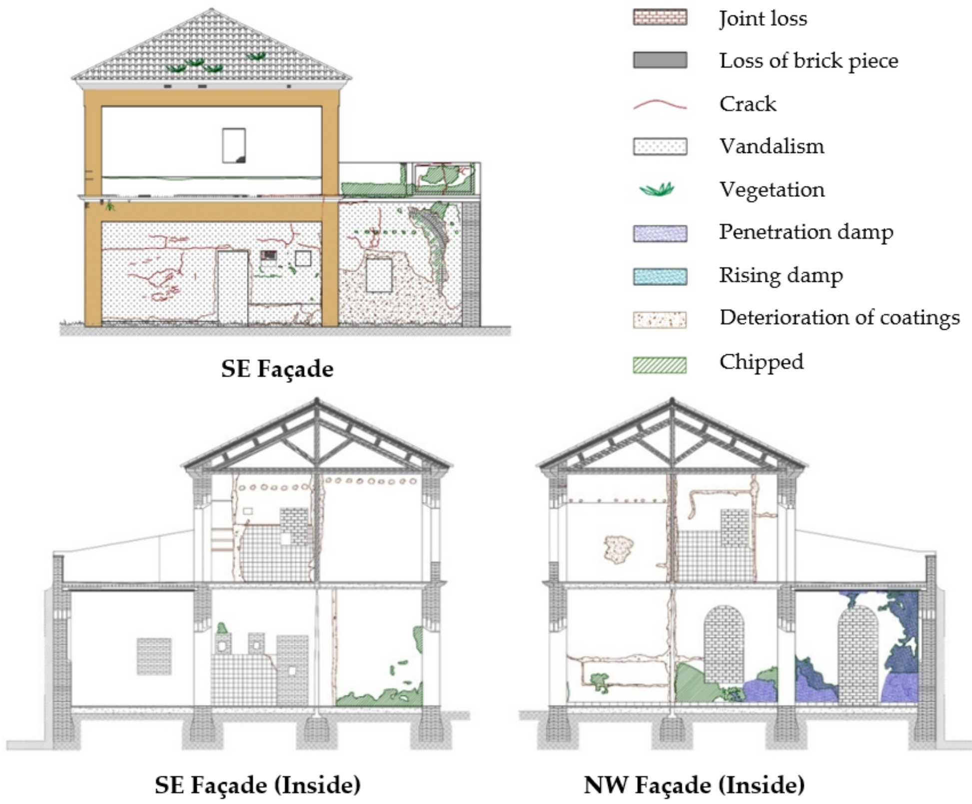

Figure 5. Current state of the building before the renovation project.

When carrying out a visual inspection of the structural elements, it can be seen that the most deteriorated structural element is the wooden truss that makes up the upper floor. These damages are caused by leaks through the cover. If the immediate perimeter of the truss–wall union is observed, loss of mortar and masonry pieces can be seen, which can lead to the disappearance of a correct support.

In addition, the need to carry out an intervention in the current slab can be observed due to a significant loss of material in almost its entire surface as well as the corrosion of the metallic elements that form it.

4. Rehabilitation Project

A simple and clean intervention is thus proposed, highlighting the singularities of the building and seeking to convert it back, with an urban perspective, into the railway axis it was before. The demolition of the annexed school and the reconstruction of the original volume as the new main access (through which the railways used to arrive) give the volume its historical and urban entity, modifying the way the building relates to its surroundings. In this way, the historical spatial character of the rear volume is recovered as an envelope that the road covered.

It must be taken into account that the current protection grade of the building limits the architectural actions that can be conducted in the design phase of the project. As the building envelope of the building cannot be modified, some aspects as openings or courtyards from its original state were respected.

The non-structural elements that fragment the building in all its spatiality were also eliminated, allowing the building to be understood and maintained as a flexible space of great length, allowing and directing the visual/physical relationships through it as well as the transversal relationship between the façade main and road.

The cleaning of the rails and joists, removing the original concrete, and partially building the slab on said rails, thus leaving these steel structural elements visible, allow one of the most important singularities of the building to be valued.

The building is organized around two main uses: the upper floor, organized by low-height volumes that allow the wooden truss to be seen and which houses the residential area and more private uses, and the lower floors that are large work spaces structured by small modules that house the group work rooms linked on rails that allow their movement and vary in their composition in plan (Figure 6).

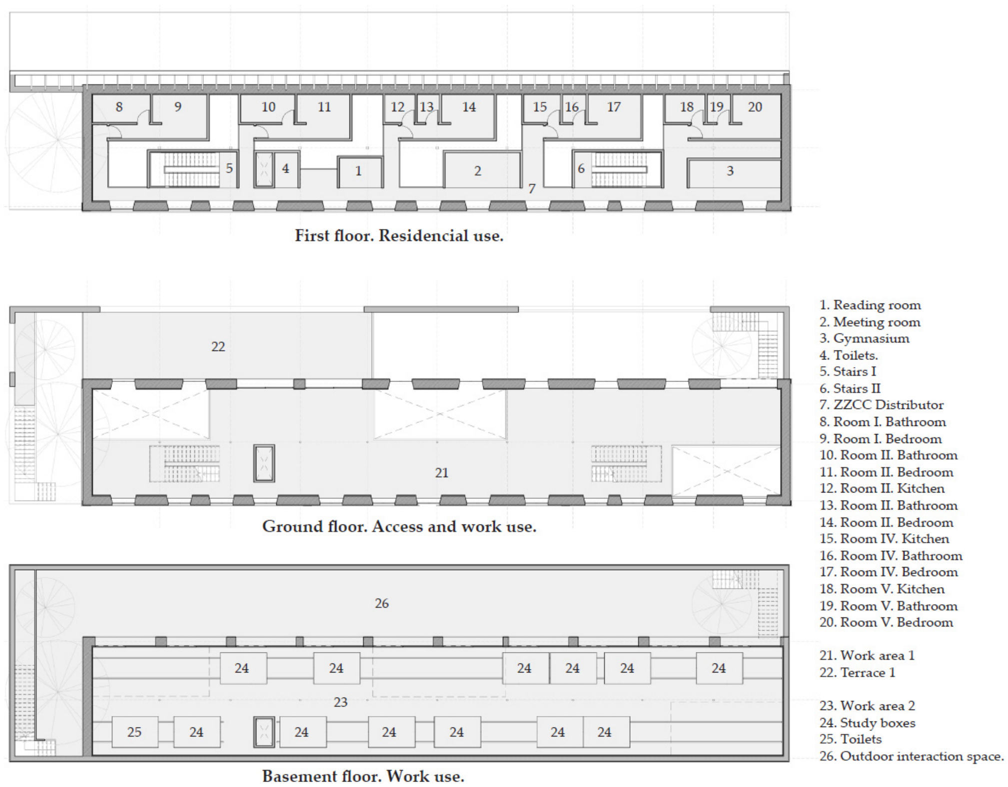

Figure 6. Floor plans of the rehabilitation project.

Regarding to the constructive definition of the building, two proposals for the rehabilitation of the building are proposed. The first one proposes the rehabilitation of the building following strict compliance with current urban regulations and using the widely used and conventional materials (model A). As an alternative, a rehabilitation is proposed according to sustainability criteria that chooses eco-efficient materials and solutions and attempts to preserve the original construction systems and unique elements of the building (model B). Other aspects such as ventilation or daylighting are not considered in this study.

4.1. Conventional Rehabilitation Proposal (Model A)

The conventional proposal (model A) is structurally defined by maintaining the "knife"-type wooden truss of the roof and the demolition of the current steel structure to build a new metal structure with a mixed slab. This solution would be adopted both in the main volume and in the annex volume (Figure 7).

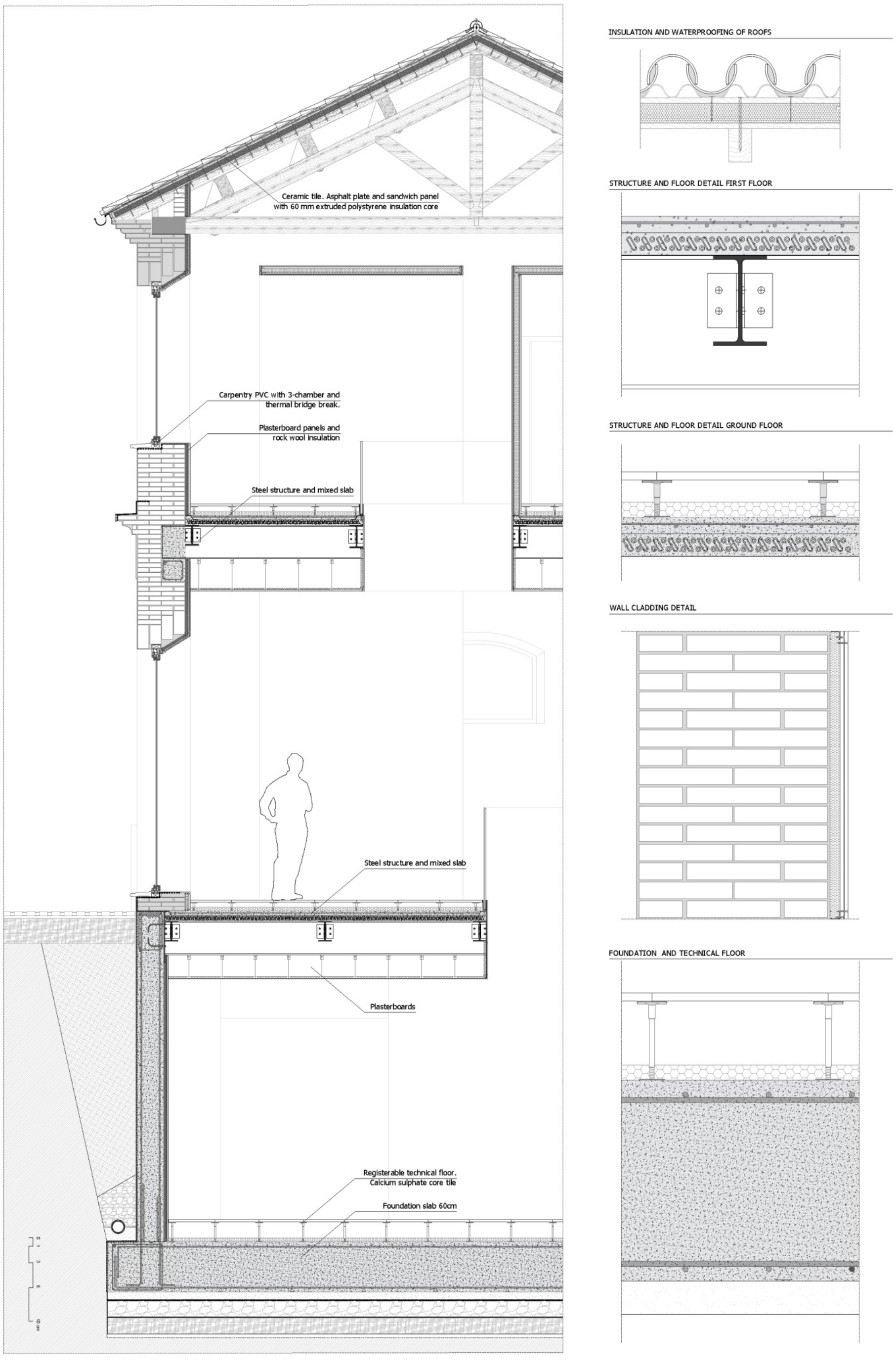

Figure 7. Conventional rehabilitation proposal constructive section (model A).

The foundation will be built on a continuous 60 cm deep slab of reinforced concrete, the vertical envelope will preserve the existing outer sheet, and a lining will be added using laminated plasterboard and insulation based on semi-rigid rock wool panels. For the roof, a waterproofing and insulation system will incorporate an asphalt plate and a sandwich panel composed mainly of a 60 mm extruded polystyrene core. The finishing materials will comprise laminated plasterboard for the false ceiling and an accessible floor based on self-supporting panels formed by a base support of calcium sulphate. Finally, the use of three-chamber PVC thermal break carpentry and standard double glazing, i.e., 4/6/8 for the openings, is proposed.

4.2. Eco-Efficient Rehabilitation Proposal (Model B)

The eco-efficient proposal (model B) is an alternative that not only aims to comply with construction regulations but also proposes to preserve the traditional construction systems of the building to minimize the production of waste in transport, aiming at a more sustainable and eco-efficient project. It is proposed to maintain the most significant construction elements, such as the old rails and other steel railway elements that form the structure of the ground floor in addition to the “knife”-type wooden truss of the roof. The expansion of the pavilion, to maintain the aesthetics and continue with the materials used in the original project of the 19th century, will be materialized by a wooden structure and slab both in the main volume and in the annex volume (Figure 8).

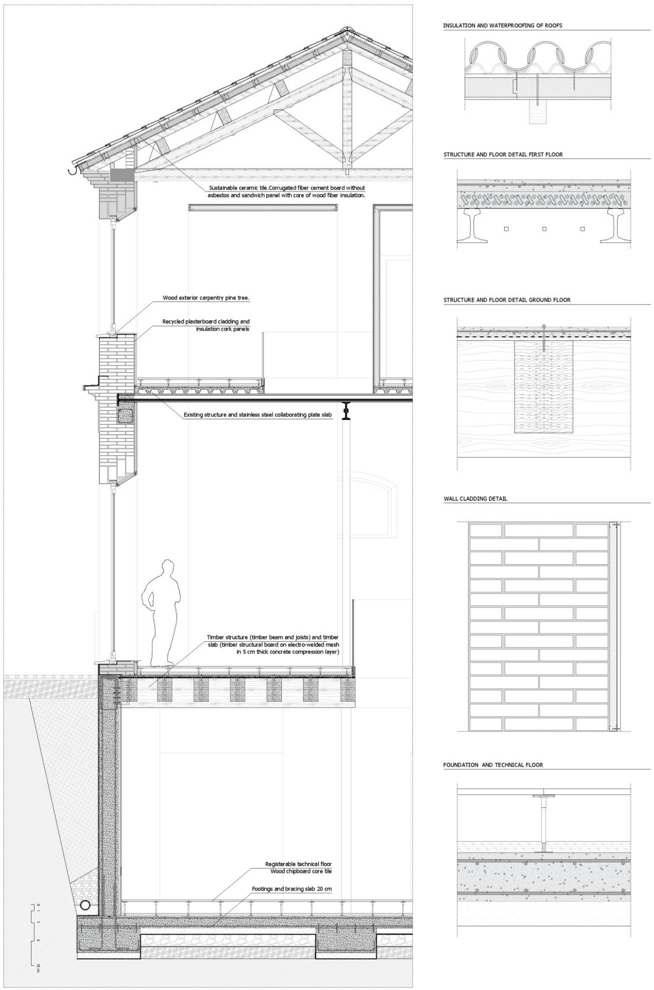

Figure 8. Eco-efficient rehabilitation proposal constructive section (model B).

In the foundations, the construction of a bracing slab is proposed as a system for tying the existing footings, and in the vertical envelope, natural cork agglomerate panels without additives and cladding using composite plaster panels will be used as a thermal and acoustic insulation system with a percentage of 20% recycled sawdust from the demolition of rehabilitation buildings. The insulation and waterproofing of the roof will be carried out using sandwich panels and ceramic tiles, which contribute to obtaining the “Verde” certificate on asbestos-free corrugated fiber cement plate, which together with the tiles also make up a double roof that guarantees the waterproofing of the roof. Another characteristic element is the use of standard wood carpentry and double glazing, i.e., 4/12/6, for the windows to the south and double glazing and low emissivity, i.e., 4/12/6, for the north windows. Finally, as cladding, an accessible technical floor of self-supporting panels formed by a compact core of high-density agglomerate particles will be used.

Finally, it should be noted that other aspects (such as natural ventilation systems, daylighting, or design criteria) could improve the eco-efficiency of the building. However, this study only focused on the constructive aspects of the envelope.

5. Energy Behavior

The analysis of the energy efficiency of models A and B was carried out using the LIDER–CALENER (HULC) computer tool [43] to assess the energy level of a building while taking $kgCO_2/m^2$ as an indicator. CO_2 emissions from the building's heating and cooling systems and hot water production are quantified. The CYPECAD MEP software was used for the construction and energy definition of each construction element and the HULC unified tool for the introduction of the facilities and for obtaining the energy certification.

For both solutions, and with the aim of not interfering with the results, the same installation systems were proposed, made up of the following:

- An energy-production system using solar panels to heat 75% of the domestic hot water required by the building. The required production system was calculated using the CHEQ4 tool;
- An independent air conditioning system, multisplit, for independent air conditioning in each of the rooms;
- A mixed system of heating and DHW formed by a condensing boiler and radiators in the private bathrooms of the rooms;
- A ducted air conditioning system for common areas that uses an autonomous heat pump unit for hot–cold production.

The energy ratings of the two proposed proposals are shown below (Table 2). In the global comparison of the qualifications obtained for both solutions, a slight decrease in the consumption of non-renewable primary energy and the carbon dioxide emissions of proposal B compared to model A can be seen.

Table 2. Energy certification.

<table>
<tr><th>MODEL A</th><th>MODEL B</th></tr>
<tr><td colspan="2">NON-RENEWABLE PRIMARY ENERGY CONSUMPTION (kWh/m^2 year)</td></tr>
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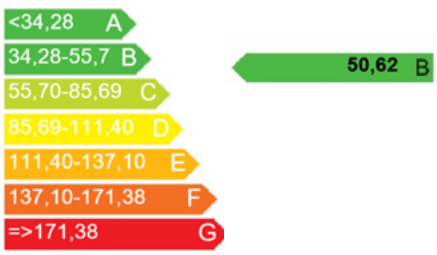
<tr><td colspan="2">CARBON DIOXIDE EMISSIONS ($kgCO_2/m^2$ year)</td></tr>
<tr><td>
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The comparison between the two strategies' energy certification results shows that a slight improvement was observed in model B, where a reduction of 2% was achieved for the non-renewable primary energy consumption, scoring a C certification for both proposals.

Moreover, in regard to the carbon dioxide emissions, a reduction of 1.3% was obtained for the eco-efficient model compared to the result achieved for the traditional solution.

In order to carry out an exhaustive analysis of the energy ratings of both proposals, a detailed comparative study of the energy demand (Table 3), the consumption of non-renewable primary energy (Table 4), and the quantification of the emissions (Table 5) are presented below.

Table 3. Heating and cooling energy demand.

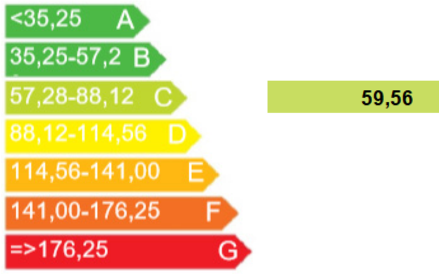
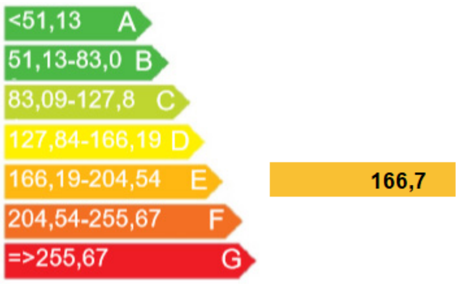
MODEL A	MODEL B
HEATING DEMAND (kWh/m^2 year)	
	
COOLING DEMAND (kWh/m^2 year)	
	

Table 4. Energy rating of the building in non-renewable primary energy consumption (PEC).

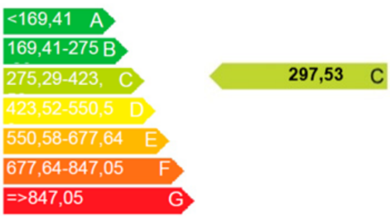
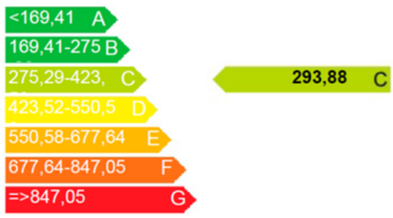
MODEL A	MODEL B
Global non-renewable primary energy consumption (kWh/m^2 year)	
GLOBAL INDICATOR	
	
PARTIAL INDICATORS	
Non-renewable primary energy heating	
35.40 kWh/m^2 year (**A**)	37.20 kWh/m^2 year (**A**)
Non-renewable primary energy cooling	
36.84 kWh/m^2 year (**A**)	38.65 kWh/m^2 year (**A**)
Non-renewable primary energy water	
2.37 kWh/m^2 year (**C**)	2.37 kWh/m^2 year (**C**)
Non-renewable primary energy lighting	
219.26 kWh/m^2 year (**E**)	219.30 kWh/m^2 year (**E**)

Table 5. Demand for emissions.

MODEL A		MODEL B	
Global non-renewable primary energy consumption (kg CO_2/m^2 year)			
GLOBAL INDICATOR			
			
PARTIAL INDICATORS			
Heating emissions			
6.37 kg CO_2/m^2 year (**A**)		6.12 kg CO_2/m^2 year (**A**)	
Cooling emissions			
6.44 kg CO_2/m^2 year (**A**)		6.24 kg CO_2/m^2 year (**A**)	
Water emissions			
0.50 kg CO_2/m^2 year (**C**)		0.50 kg CO_2/m^2 year (**C**)	
Lighting emissions			
37.15 kg CO_2/m^2 year (**E**)		37.14 kg CO_2/m^2 year (**E**)	
CO_2 emissions from electricity consumption			
17.53 kg CO_2/m^2 year	18,403.16 kgCO_2/year	17.75 kg CO_2/m^2 year	18,631.06 kgCO_2/year
CO_2 emissions from fossil fuels			
40.54 kg CO_2/m^2 year	42,555.91 kgCO_2/year	41.13 kg CO_2/m^2 year	43,176.90 kgCO_2/year

Both construction solutions defined for the envelope have thermal resistance with little variation and meet the minimum thermal-transmittance requirements defined in the Spanish CTE DB-HE for the climatic zone in which the building is located [11].

The comparative study of both interventions shows that the eco-efficient construction solution (model B) has a better energy performance than the conventional solution. In fact, there is a reduction in CO_2 emissions and in the cooling demand of the eco-efficient solution, going from an energy rating of E to D, which entails a reduction in the consumption of non-renewable raw energy.

6. Environmental Analysis

Life-cycle assessment (LCA) has been used as a methodological framework for environmental management and is currently used to analyze the potential environmental aspects and impacts of the construction solutions used in both proposals throughout the life cycle. This methodology is based on the collection and analysis of the inputs and outputs of the matter or energy system to obtain quantitative data on their potential environmental impacts and allows us to make an objective and quantitative comparison of the environmental impact of each rehabilitation proposal.

The environmental analysis is based on the use of the LCA methodology, using a simplified method that exclusively measures global warming potential (GWP) (Table 6 and Figure 9) and embodied energy (EE) (Table 6 and Figure 10) in a "cradle to grave" scenario for each solution. These indicators were taken using CML and cumulative energy demand methodologies, respectively. The data used for the study were directly taken from the manufacturer itself or from the Ecoinvent database. Then, SimaPro was used to conduct with the assessment.

Table 6. Comparative analysis of global warming potential (kg CO_2-Eq) and embodied energy (MJ).

Construction Element	Unit	Model A			Model B		
		Constructive Solution	GWP (kg CO_2-Eq)	EE (MJ)	Constructive Solution	GWP (kg CO_2-Eq)	EE (MJ)
Insulation and waterproofing of roofs	m^2	Ceramic tile. Asphalt plate and sandwich panel with 60 mm extruded polystyrene insulation core.	15,227.48	432.60	Sustainable ceramic tile. Corrugated fiber cement board without asbestos and sandwich panel with core of wood fiber insulation.	6522.55	531.82
Structure and floor slab GF	m^2	Steel laminated structure and mixed slab.	50,764.8	6798.72	Timber structure and timber slab.	5826.8	785.46
Structure and floor slab F1	m^2	Steel laminated structure and mixed slab.	50,764.8	6798.72	Existing structure and stainless-steel collaborating plate slab.	17,677.55	5853.37
Foundations	m^2	Foundation slab 60 cm.	110.83	2133.18	Footings and bracing slab 20 cm.	60.97	1234.43
Wall cladding	m^2	Plasterboard cladding and rock wool insulation.	3411.97	1102.53	Recycled plasterboard cladding and insulation cork panels.	3163.98	477.88
Raised flooring	m^2	Registerable technical floor. Calcium sulphate core tile	43.87	945.91	Registerable technical floor. Wood chipboard core tile.	35.31	347.64
Ceiling	m^2	Plasterboards.	1620.702	989.75	Not applicable.	0	0

Note: The gaps are not included in the total calculation, as it is not possible to obtain the real data of the joineries due to their shape and size, which will adapt to the current gaps.

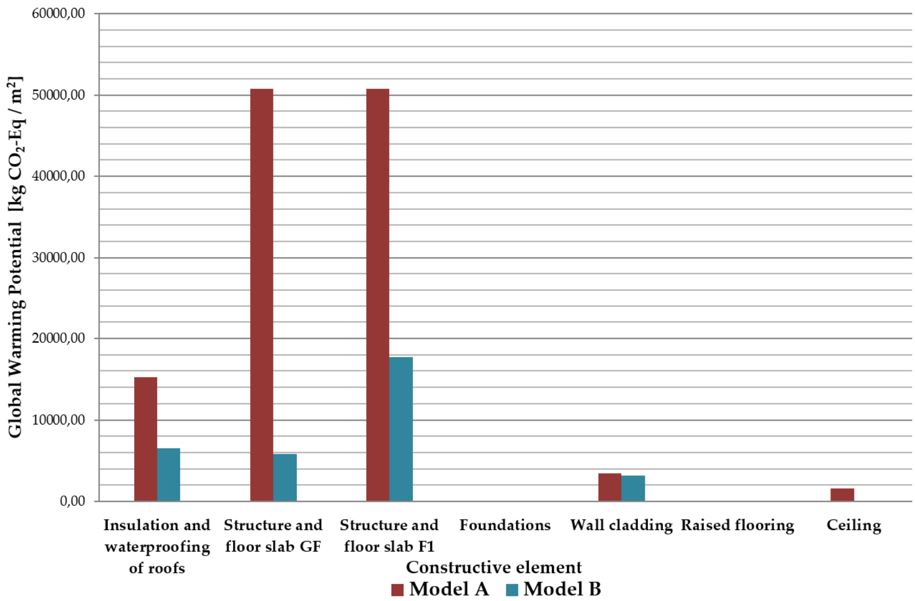


Figure 9. Comparative analysis of GWP emissions (kg CO_2-Eq).

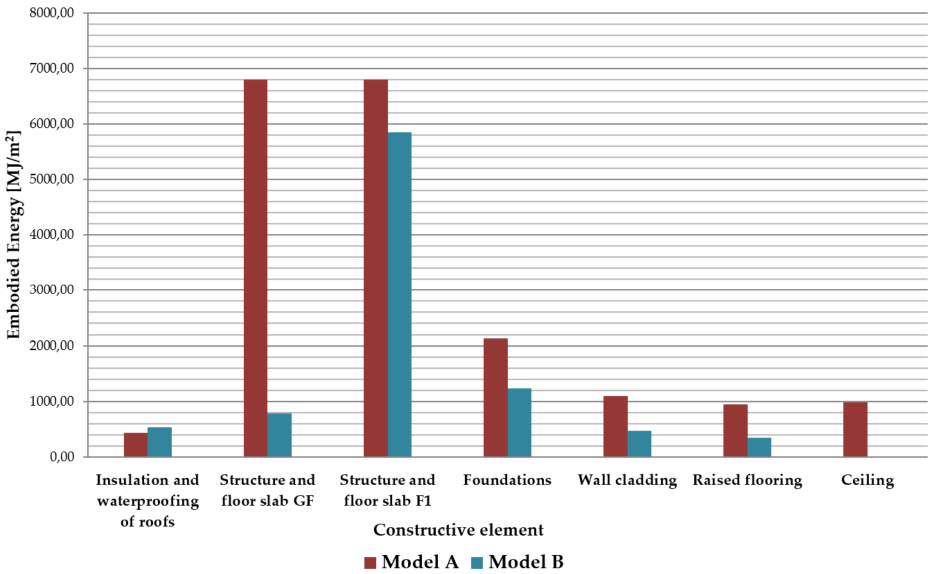


Figure 10. Comparative analysis of embodied energy (MJ).

The functional unit was defined as the square meter (m^2) of each construction solution and was defined for the roof, structure, foundation, cladding, technical floor, and glass. For the study of carpentry, the functional unit was defined by the unitary construction element.

The comparative LCA analysis of both proposals reveals a significant decrease in the environmental impact through an 86.6% reduction in CO_2 emissions and a 53% reduction in the embodied energy. This reduction is mainly marked by the constructive solution used in the structural elements (structure and floor) and the insulation and waterproofing of the roof.

The replacement of the insulation and waterproofing system of the roof, using an eco-efficient tile/panel system, contribute to obtaining the "Verde" certificate, representing a reduction of 57% in CO_2 emissions and an increase of 23% in energy demand.

The constructive solution that allows a greater reduction of CO_2 emissions and of embodied energy in the rehabilitation of the building is the substitution of the metal structure and mixed floor of the ground floor for a wooden floor structure. This intervention represents a reduction of 89% in CO_2 emissions and 88% in incorporated energy.

The main drawback of the wood-structural system proposed in the sustainable solution is its lack of stability against fire. In this way, for the dimensioning of the structure in case of fire, two solutions are proposed: the dimensioning of the square of the elements by means of the reduced section method and the protection of the elements by means of a colorless intumescent varnish. Thus, according to the environmental analysis, it can be deduced that the oversizing of the elements to maintain safety in case of fire has a lower environmental impact than the use of intumescent varnish as a protection proposal.

The rehabilitation and reuse of the rails and steel structure of the current state of the building reduces CO_2 emissions by 65% and energy demand by 14% per square meter of construction element. In addition, it allows the elimination of the false ceiling, saving 1620.70 Kg CO_2 and 989.75 MJ per square meter of false ceiling, assuming a total saving of 733,270.42 Kg CO_2 and 447,802.03 MJ for the whole building.

Although the environmental impact caused by the construction of the foundation is not so decisive in the rehabilitation, the reduction in the amount of reinforced concrete necessary for the foundation causes a 45% reduction in CO_2 emissions and a 45% reduction in incorporated energy.

The use of panels with 20% recycled wood sawdust from the demolition in the rehabilitation, taking into account the supporting structure necessary in both proposals, represents a reduction of 8% in CO_2 emissions and 15% in energy demand, and the substitution of rock wool panels for cork panels produces a 29% reduction in CO_2 emissions and a 63% reduction in energy demand [19].

A raised-access floor of self-supporting panels formed by a base support of chipboard and thermal insulation from natural cork agglomerate panels without additives, which replaces the raised-access floor composed of a base support of calcium sulphate and rock wool insulation, contributes to a reduction of 20 % in CO_2 emissions and 16% in embodied energy.

7. Economic Impact

One aspect to take into account when making a proposal for the rehabilitation of a building is the economic impact of the solution. This is why the cost of the two proposed models, models A and B, was conducted. A methodology with a hierarchical structure was used, developing simple costs (SC) for each layer of the façade solutions to be studied and complex costs (CC) for complete solutions, which are made up of several SCs. Table 7 and Figure 11 show and compare the CC of the described solutions.

Table 7. Economic impact (EUR/m^2).

Construction Element	Unit	Model A		Model B	
		Constructive Solution	Cost (EUR/m^2)	Constructive Solution	Cost (EUR/m^2)
Insulation and waterproofing of roofs	m^2	Ceramic tile. Asphalt plate and sandwich panel with 60 mm extruded polystyrene insulation core.	113.96	Sustainable ceramic tile. Corrugated fiber cement board without asbestos and sandwich panel with core of wood fiber insulation.	96.89
Structure and floor slab GF	m^2	Steel laminated structure and mixed slab.	122.58	Timber structure and timber slab.	246.53
Structure and floor slab F1	m^2	Steel laminated structure and mixed slab.	117.23	Existing structure and stainless-steel collaborating for the plate slab.	72.51
Foundations	m^2	Foundation slab 60 cm.	124.95	Footings and bracing slab 20 cm.	68.70
Wall cladding	m^2	Plasterboard cladding and rock wool insulation.	36.37	Recycled plasterboard cladding and insulation cork panels.	40.65
Raised flooring	m^2	Registerable technical floor. Calcium sulphate core tile.	142.59	Registerable technical floor. Wood chipboard core tile.	124.61
Ceiling	m^2	Plasterboards.	27.58	Not applicable.	0

The rehabilitation of the roof through the system defined in the eco-efficient construction solution (sandwich panel with a core of 80 mm thick wood fiber insulation and ceramic tiles on corrugated fiber cement plates) compared to that defined in the conventional construction solution (sandwich panel tongue-and-groove with 60 mm extruded polystyrene insulating core and Arabic curved tile under tile plate with DRS asphalt (double protective layer of resin and safety overlap)) shows an economic saving of 15%.

At a structural level, maintaining the current structure of the steel rails for the floor of the first floor represents a saving of 38% through the model B solution compared to that of model A, in which a steel structure and a mixed floor are proposed. On the other hand, the use of a structure and a wooden floor on the ground floor represents an increase in the total budget for the sustainable structural solution of 101% compared to the conventional solution. Although the surface to be rehabilitated is not too extensive, it is the constructive element whose rehabilitation raises the intervention budget the most.

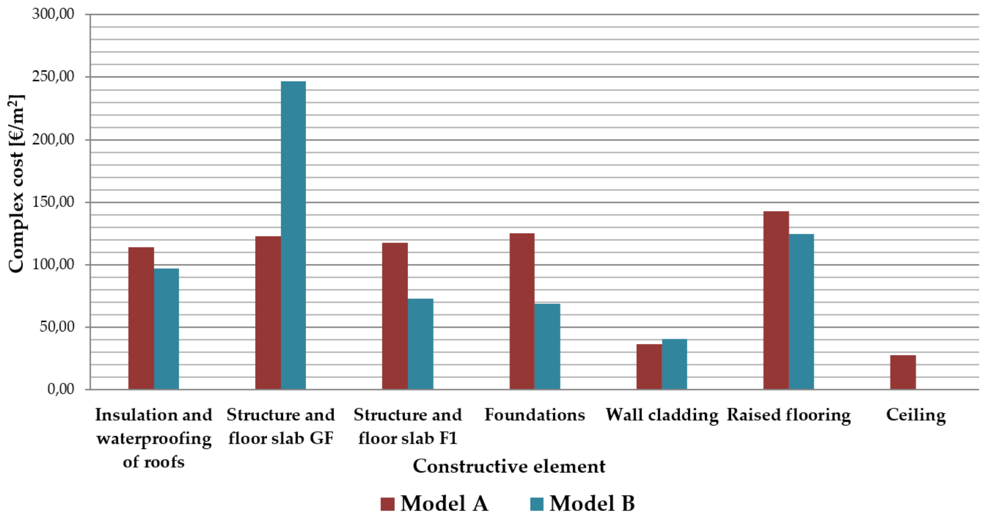


Figure 11. Economic impact (EUR/m^2).

The foundation solution of the sustainable proposal formed by footings and bracing slab compared to the execution of a continuous 60 cm depth foundation slab defined in the conventional solution supposes a considerable reduction in the volume of reinforced concrete to be used, defining an economic savings of 45%. In addition, due to its wide area of action, this is the construction element that has the highest impact on the budget for the intervention.

The rehabilitation of the vertical envelope means that the solution proposed in the eco-efficient proposal, in which a recycled plasterboard is used along with an insulation system based on natural cork, slightly increases the cost by 12% compared to the plate standard plasterboard and rock wool insulation system of the conventional model.

8. Discussion

According to the results achieved for the energy behavior of both constructive proposals, it can be seen that the two solutions reach the energy requirements made by Spanish standards [11], with both models scoring a C certification for non-renewable primary energy consumption and a B certification for carbon dioxide emissions. However, the environmental and economic analyses reveal the relevant advantages of the eco-efficient proposal (model B) compared to the conventional and standardized one (model A). Thus, Table 8 summarizes the environmental and economic benefits achieved by the implementation of an environmentally friendly intervention.

Table 8. Environmental and economic benefits achieved for the eco-efficient proposal (model B) compared to the conventional intervention (model A) results.

Construction Element	GWP Benefits		EE Benefits		Cost Benefits	
	(kg CO_2-Eq/m^2)	(%)	(MJ/m^2)	(%)	(EUR/m^2)	(%)
Insulation and waterproofing of roofs	8704.93	57	−99.22	−23	17.07	15
Structure and floor slab GF	44,938	89	6013.26	88	−123.95	−101
Structure and floor slab F1	33,087.25	65	945.35	14	44.72	38
Foundations	49.86	45	898.75	42	56.25	45
Wall cladding	247.99	7	624.65	57	−4.28	−12
Raised flooring	8.56	20	598.27	63	17.98	13
Ceiling	1620.702	100	989.75	100	27.58	100

The impact, in environmental and economic terms, for the entire building, is shown below in Table 9.

Table 9. Environmental and economic benefits achieved for the eco-efficient proposal (model B) compared to the conventional intervention (model A) results for the entire building rehabilitation.

GWP Benefits		EE Benefits		Cost Benefits	
(kg CO_2-Eq)	**(%)**	**(MJ)**	**(%)**	**(EUR)**	**(%)**
22,045,226	57.19	3,474,280	58.38	41,185	40.03

As can be seen in Tables 8 and 9, and despite the resulting cost increase in the items of the ground floor slab and wall cladding, a relevant benefit in terms of GWP (57.19%), EE (58.38 %), and economic impact (40.03%) was achieved for the model B rehabilitation proposal compared to model A.

Finally, comparing the results with those obtained by other research from the literature, in this case, the CO_2 emissions reduction was 7% higher than that achieved by Pérez-Gálvez et al. [22], who obtained the best GWP performance with the sustainable proposal. Furthermore, in terms of EE, a drop of 12% was achieved compared to the improvement scored by Dervishi et al. [38].

9. Conclusions

This paper proposes, analyses, and compares two constructive strategies for the intervention/rehabilitation of the old "Pabellón de Vías y Obras" (19th century), located in Seville (Spain). The first solution intends to follow traditional techniques and standardized criteria (model A), while the second option takes into account environmental aspects for the constructive definition of the proposal (model B). For both proposals, a constructive, environmental, energy, and economic analysis of the solution was carried out, obtaining the following conclusions:

- Both intervention proposals meet the compliance requirements marked by the council and urban and heritage regulations of the city. Moreover, the technical exigencies made by the Spanish Technical Building Code, including all its documents (Structural Security (SE), Health (HS), and Energy Saving (HE), among others), were checked;
- Model A preserves the wooden-roof typology (adding an insulation sandwich panel) and demolishes the original steel structure to build a new metal one. The foundation is built on a continuous 60 cm deep concrete slab. The vertical envelope maintains the existing façade wall, with added inner MW insulation and plasterboard. Finally, original windows are replaced by new PVC ones;
- The eco-efficient proposal (model B) proposes to maintain the old rails and other steel railway elements that form the structure of the ground floor in addition to the wooden typology of the roof. Furthermore, a wooden structure and slab are projected. In the foundations, a bracing 20 cm slab and single footings are proposed. In the vertical envelope, natural cork agglomerate panels without additives and wood–gypsum covering panels are used as a thermal and acoustic insulation system. Finally, standard wood carpentries and double glazing, i.e., 4/12/6, are used;
- The use of sustainable materials and systems in the building envelope allows for a better energy certification in the sustainable proposal compared to the conventional solution. There is a considerable decrease in the cooling demand of the sustainable construction solution, reaching an energy rating of D, which results in a decrease in the consumption of non-renewable raw energy;
- When carrying out the global building study, it can be seen that the use of eco-efficient materials and solutions in the sustainable proposal (model B) contributes to a significant reduction in environmental impact through a reduction of 86.6% in CO_2 emissions and 53% in embodied primary energy;

- The constructive proposal is defined as a sustainable proposal through the use of eco-efficient materials and systems and by conserving the original systems; it supposes, in addition to the environmental and energy improvement, an economic saving of 13% in the total intervention.

As a summary, it can be concluded that model B, proposed through the use of eco-efficient materials and systems and by conserving the original systems, not only supposes the improvement of its environmental impact in terms of emissions (22,045,226 kg CO_2-Eq and 3,474,280 MJ), but it can also be an affordable (EUR 41,185 of benefits) and energy-competitive solution. Thus, this article manages to dismantle the existing false myth that the approach of an environmentally friendly proposal is always linked to an increase in the total price of the intervention. In that sense, the use of this type of eco-efficient consideration by architects, engineers, and other members of the construction industry is encouraged.

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