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Sustainability Perspective to Support Decision Making in Structural Retrofitting of Buildings: A Case Study

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Abstract: The reuse of existing materials in buildings can give a contribution to sustainable practices such as a balance in embodied energy, water, and emission reduction. However, it is not always possible to maintain the existing structural materials because some different technical variables could hamper their usability, namely seismic reinforcement needs, fire safety protection, conservation state, and new legal requirements. The paper follows a case study approach for assessing the technical and environmental performances of structural options for old building retrofitting works. All structural options were analyzed through the results of several categories of environmental impact. Some parameters of a retrofitting management system were also used to frame in a comprehensive way the technical constraints pertaining to building retrofitting works. The structural option choice was taken by the owner with the contribution of the design team and the construction manager of the construction project as well as the results of interviews with other construction professionals, considering the variables related to technical suitability and environmental impact. The results of the study show that the steel structure is the solution that best addresses the technical constraints of the building retrofit works and minimizes environmental impact. The results of the study also suggest that the consideration of other variables other than the technical ones can contribute to the effective functioning of the renovation subsegment of the building market. Some suggestions for further studies to enhance the results of this work are put forward.

Keywords: structural materials; retrofit works; sustainability; management; building; design

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1. Introduction

The European Commission has proposed ambitious targets for the next 10 years to reduce greenhouse-gas emissions to at least 55% below 1990 levels by 2030, according to the EU 2030 Climate Target Plan [1]. All these targets are in accordance with the Paris Agreement objectives to keep the global temperature increase below 2 °C and pursue efforts to keep it to 1.5 °C [2]. The retrofitting works of old buildings and of more recent ones can be nowadays considered a usual practice in European countries, including Portugal more recently. Indeed, in most developed countries, there is a significant shift from new construction to adaptation and reuse of existing structures [3]. However, in old buildings, a set of precautionary measures should be considered in light of the innumerable specificities of each project. Some retrofit works are more intrusive, especially when they involve the demolition of materials and structural elements that can be reused [4]. Often, the choice for demolishing is based on the uncertainties of structural resistance for seismic actions and other load actions [5].

The reuse of existing materials in a good conservation condition can reduce the extraction of natural resources as well as atmospheric emissions and embodied energy and water, which, in turn, contributes to reducing global warming, ozone depletion, acidification, eutrophication, among others [6]. The retrofitting practices contribute to a great extent to promote sustainability and to preserve the authenticity and uniqueness of the building's originality [7]. There are solutions that, even if they are not original, can bring benefits in the context of sustainability and increase structural resistance [8]. These solutions can also guarantee a more effective response to the specific problems and constraints of each work, related to planning, deadlines, cost overruns, changes, non-contractual works, among others [9]. Building envelope durability in building renovation, for example, is considered "a technical performance indicator which are added to the environmental performance indicators in a sustainability assessment" [10]. However, to the best of our knowledge, these studies have not addressed the technical compatibility of different structural solutions with existing materials, and other constraints that are prevalent in building retrofitting works, such as site works space, adjoining building consolidation, waterproofing needs, specialized subcontractors, and many others. These requirements are frequently neglected or are not taken into account in the design phase of the building retrofitting process [11]. Thus, some of these aspects need a fresh look from the part of the research community.

This paper describes the application of some parameters of a toolkit for old building retrofitting works, henceforth "retrofitting management system" developed in an earlier work [9]. This toolkit is an aid in the management of the project, seeking to preserve the authenticity of buildings, as well as contributing to the decision-making of the stakeholders involved in retrofit works practices. The main objective of this study is to present an analysis of possible structural options to be applied in real building retrofitting works according to their own constraints and possible solutions based on the scope of the retrofitting management system. These structural options have also been analyzed on the basis of environmental impact categories, namely Global Warming Potential (GWP); Destruction of Atmospheric Ozone (ODP); Acidification Potential (AP); Photochemical Ozone Creation, Smog (POCP); Eutrophication Potential (EP); Fossil Fuel Depletion Potential (FFDP) [12].

The remainder of the paper is organized as follows: Section 2 provides a brief review on the link between sustainability benefits and the reuse of existing materials and components of buildings; the methodology is presented in Section 3; Section 4 presents the results of the application of the retrofitting management system; concluding remarks are drawn in the last section.

2. Sustainability Context in Building Retrofitting

Building retrofit is directly connected to sustainable practices not only in the context of existing material reuse but also in natural-resource extraction and emissions reduction, embodied water and energy contents, and even land reuse [6]. Existing buildings, even old ones, in good conservation status can be adapted by the improving of their comfort and performance conditions. Whenever possible the existing elements must conform to new functional exigencies, and preserve their original identity [13]. Some building environmental sustainability assessment methods have been put forward considering the environmental, social, and economic dimensions according to the Life Cycle Assessment (LCA) methodology [14].

According to the EN 15978:2011 standard, there are different environmental indicators considered in a building's environmental assessment performance [15]. Some of these indicators' values are described in the EPD (Environment Product Declaration) of each product published. All materials/construction products reused from other deconstructed or retrofitted buildings do not cause environmental impacts related to new material acquisition, besides the delaying of their demolition/treatment guiding [14]. In the oldest buildings, these reused materials/construction products could be stone, steel profiles, wood, ceramic elements, and others. In most recent buildings, the reused materials could be, in addition to the materials described above, insulation materials, windows, doors, glass, bricks, concrete. On the other hand, construction materials/construction element wastes include plastics, steel elements, concrete, electric cables, and many others. Although the sustainability of the built environment has been extensively researched, some caveats/refinement in this research arena could be stated as follows [16]:

- The use of building environmental sustainability assessment methods are not mandatory in national law;
- A complete LCA building quantification is difficult and almost impossible, but some simplified methodology could be an auxiliary for stakeholder's decisions;
- Orientations and methodology for the use of new structural technologies in existing buildings with a focus on sustainable benefits;
- Building retrofitting levels and consequent technical guidelines are required;
- Regarding Portugal, recent legislation introduced changes in technical regulations of building retrofitting, with exceptional regimes for certain types of existing buildings. However, there is no explicit requirement in the regulation concerning sustainability.

This paper intends to present a connection between technical structural solutions in the design phase and their appropriateness to overcome the technical constraints of retrofitting works. And the environmental impacts of these technical structural solutions could provide a different overview of the environmental perspective which is often forgotten. However, this research presented the calculations of some different categories of environmental impacts, such as Global Warming Potential (GWP); Destruction of Atmospheric Ozone (ODP); Acidification Potential (AP); Photochemical Ozone Creation, Smog (POCP); Eutrophication Potential (EP); Fossil Fuel Depletion Potential (FFDP). Thus, these results can be seen as a useful tool that informs on the solution that brings the most potential benefits for the sustainability context.

3. Research Methodology

The research methodology used in the paper is described in a schematic way in Figure 1.

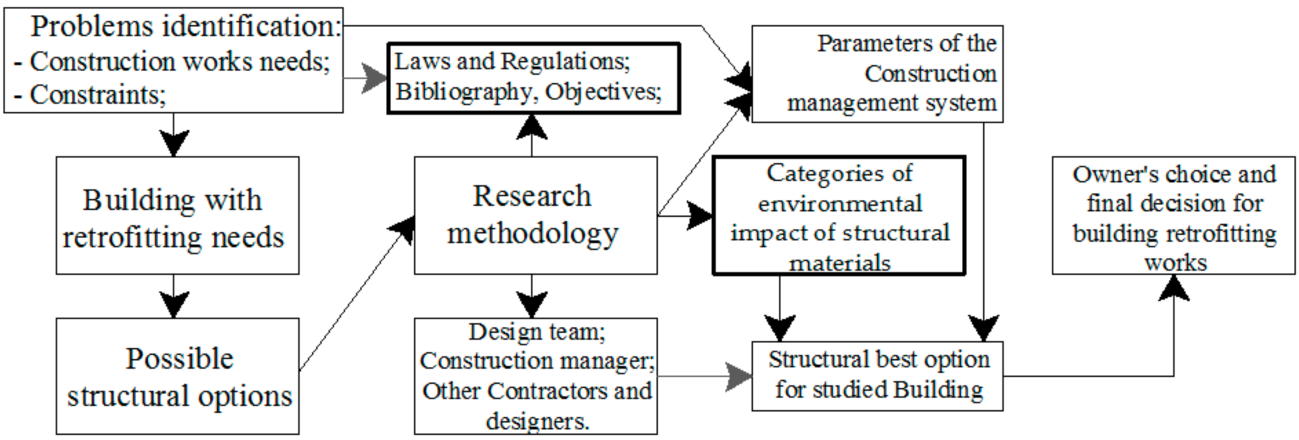


Figure 1. Schematic research methodology.

This research assessed the technical and environmental performance of structural options for building retrofitting projects with reference to a single case study [17,18]. It analyzed the application of some parameters of a retrofitting management system in a real project concerning building retrofitting works. This analysis, which had the input of the design team and a construction manager, also considered the specificities and constraints of the works to be retrofitted, such as an increase in seismic resistance, fire safety protection, and sustainable solutions to upgrade energy performance and improve energy efficiency. A set of feasible proposals/options for structural solutions were considered and compared between each other in the light of the results of the quantification of environmental impact categories [19], as well as other aspects under analysis. The structural options studied involved a wooden structure (similar to the original structure), a concrete reinforced structure (conventional use in new buildings in Portugal), and a steel structure with metallic elements (a modern structure more compatible with the existing materials and components). Then, the quantity of materials of each structural solution option was calculated, followed by the quantification of each category of environmental impact [19].

To undertake this quantitative analysis, a survey was conducted on construction professionals with knowledge on the environmental aspects of building retrofitting to elicit their opinions on the allocation of criteria weights to be used in the environmental analysis, which took into account the parameters of the retrofitting management system and the categories of environmental impact. This survey consisted of interviews with the design team leader and the construction manager of the construction enterprise. This was extended to representatives of seven design consulting firms and eleven construction firms, which were in the subscription list of "List of Qualified Companies (R.U.-I.S.)—Intelligent and Sustainable Urban Retrofitting" managed by the Portuguese association AICCOPN (Association of Civil Construction and Public Works Companies). For each parameter of the management system and category, the environmental impact was defined as a classification ranging from 1 "worst technical solution" to 3 "best technical solution" for all structural options analyzed.

Finally, the choice of the structural solution was taken by the owner through the means of a quantitative analysis of all preponderant factors, namely technical constraints, solutions that best fitted the guidelines of the retrofitting management system, the categories of environmental impact, and, implicitly, the advantages and disadvantages of each structural option for the structural design development. The next subsections present the contents of the retrofitting management system, the characteristics of the building, and the technical constraints of the retrofitting works.

3.1. Retrofitting Management System

The case study used the toolkit "Retrofitting management system" to support retrofitting of old buildings. This management system is structured in four main areas. These 4 areas consist of 15 indicators and 50 thematic parameters encompassing strategies, solutions for constraints, best practices used in building retrofitting, and legal requirements [9]. Each parameter is classified into 5 possible options, from less sustainable (level 1) to most sustainable (level 5). Table 1 does not show the areas "A1—Surroundings and location" (parameters P1 to P11) and "A4—Costs" (Parameters P47 to P50) as they are not used in this research.

Table 1. Retrofitting management system thematic areas, indicators, and parameters used in the research.

Area	Indicators	Parameters Description
A2. Project design	I5. Characterization of building conditions	P12. Request for technical studies P13. Characterization diagnoses of building conservation status P14. Project Design specificities
	I6. Architectonic organization and salubrity	P15. Conceptual architecture configuration and adaptability P16. Ratio useful floor area/gross lettable area (GLA) P17. Acoustic insulation and indoor air quality
	I7. Infrastructures, foundations, and structural elements conditions	P18. Building technical networks P19. Peripheral retaining structures P20. Foundations P21. Structural elements
	I8. Materials	P22. Materials reuse P23. New materials P24. Fire safety
	I9. Sustainability promotion	P25. Water recovery and reuse P26. Solar collectors for hot water production P27. Electrical energy production P28. Energetic efficiency in thermal comfort P29. Other solutions for energetic efficiency P30. Bioclimatic solutions P31. Other sustainable solutions

Table 1. *Cont.*

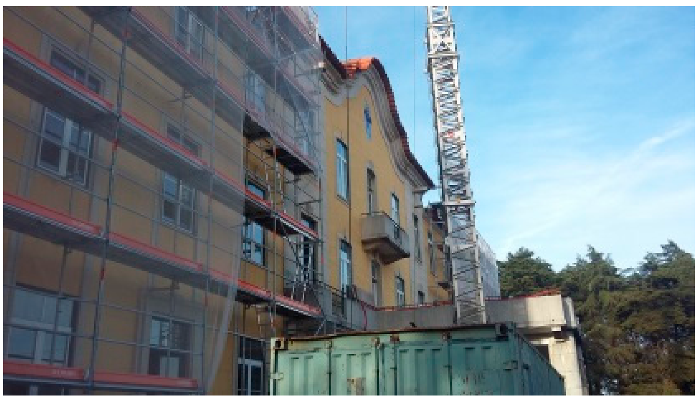
Area	Indicators	Parameters Description
A3. Construction works and site works	I10. Initial works constraints	P32. Site works and surrounding space P33. Adjoining building conservation state P34. Stabilization and consolidation of building works and adjoining buildings P35. Adjoining building waterproofing
	I11. Industrialization/execution of works	P36. Workforce P37. Specialized workforce and company's technical capacities P38. Specialized subcontracts P39. Technical requirements monitoring
	I12. Risk and constraints potential	P40. Propensity to project design changes P41. Propensity to the occurrence of unexpected works P42. Propensity to time overruns P43. Propensity to other work constraints
	I13. Other features resulting from works	P44. Archaeological works prospection P45. Construction and demolition waste management

3.2. Case Study Building

This study deals with a building retrofit project which was built in the early 1940s and is located in Bragança (Portugal). This building belongs to a private entity and it is recognized by its localization, history, and interest in the city. The building had originally 3 floors with 572 m^2 each and a floor below level 0 with 150 m^2, totaling 1766 m^2. The original materials are schist stone and granite stone in the external walls, wood in the floors structure, and also wood with plaster internal walls. The building presented good conservation status in the external walls (Figure 2a) but several damages in floors structures (Figure 2b) and problems in the roof caused by rain permeability (Figure 2c). The building had no thermal or acoustic insulation, and some technical failures occurred in hydraulic networks and seismic-resistance construction solutions. Fire safety protection was also compromised, especially in electrical networks.

The owner decided to maintain external walls and demolish original floors, roof, internal walls, and all networks installations. The new project design involved a new structural frame and roof, internal walls adapted to the needs for wheelchair mobility, new network installations, thermal and acoustic insulation, and fire safety protection, all according to technical regulatory requirements. The building retrofit project had some additional floor areas namely.

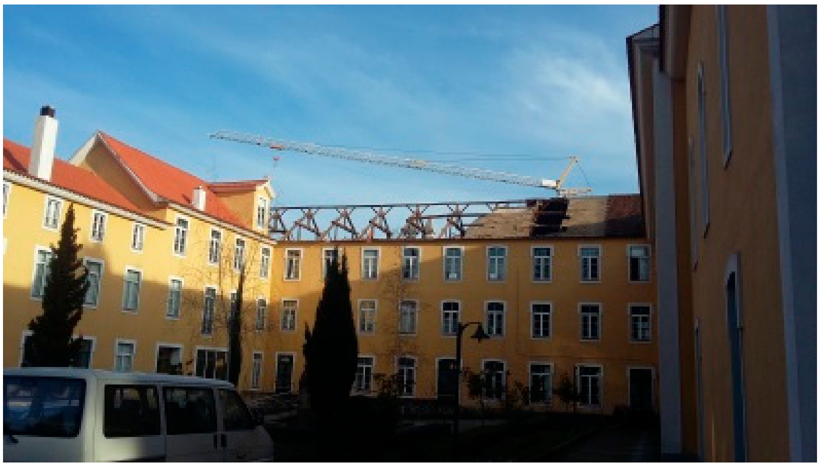
- Floors with 595 m^2 (new stair construction in posterior façade), use of the attic (450 m^2);
- The floor area below level 0 has increased to 360 m^2 (removal of soil and rocks).



(**a**)

Figure 2. *Cont.*

(**b**)



(**c**)

Figure 2. (**a**) Principal façade (exterior walls); (**b**) floor degradation; (**c**) posterior façade and roof structure.

The total area of retrofitting works had a total of 2595 m^2 (an increase of 829 m^2 compared to the original one). Owing to financial constraints, the owner decided to retrofit the building in 2 phases [20]: first phase (demolishing, structural floors, and roof finishing); second phase (hydraulic, electrical, communication heating and cooling networks, thermal and acoustic insulation works, and all finishing works).

The stated aims of the building retrofitting works involved the preservation of the original façade, reorganization of the interior spaces, and the selection of adequate and compatible solutions to promote comfort and performance levels. The design was developed by a design team with the contribution of a construction manager, who was hired for the management of the project design phase. The design team has experience in similar retrofitting works and is knowledgeable of the environmental aspects pertaining to building project design. The construction manager is a civil engineer, had some knowledge of environmental assessment methods, and is a senior professional of a construction company with experience in building retrofit works. The priority was to retrofit the frame structure and the roof to protect the building from rainwater flowing through external walls. Table 2 describes the technical constraints of the structural retrofitting works.

Table 2. Technical constraints about building retrofit structure (existing and design project).

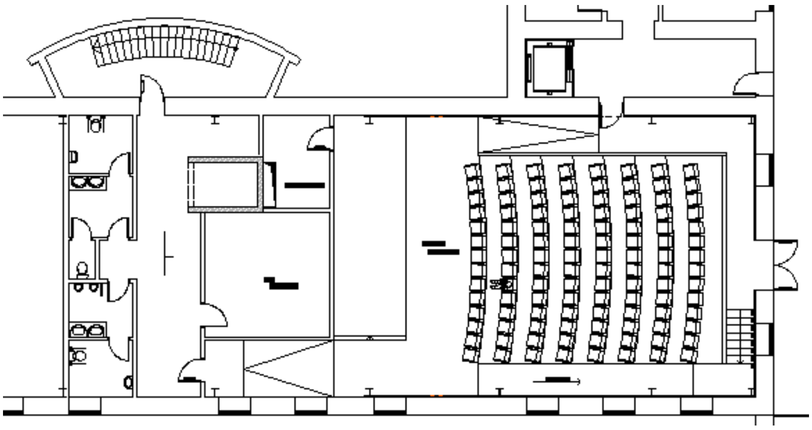
Code and Group	Description
(X) Existing and design project aspects	- (X1) Wood structure in ruins with demolition cleaning needs (Figure 2c); - (X2) The building has 5 floors, but one is the attic and the other is the floor below level 0. The floor below level 0 is 2.46 m high and it is necessary to extract rocks and reinforce all external walls below level 0 (Figure 3a). The slabs are less than 25 cm thick (Figure 3b); - (X3) The building has two parts partially leaning against an adjoining building which needs special waterproofing in different parts of its roof (Figure 3c); - (X4) Internal stairs steps are too high and are not in compliance with fire safety regulations; - (X5) The connection between schist stone and granite stone needs reinforcement; - (X6) Principal façade has some sculpture elements (pinnacles and an exterior staircase); - (X7) Elevator with space provisions for persons with mobility impairment (Figure 3d); - (X8) Structural reinforcement needs to be reversible and compatible with existing ones; - (X9) New spaces (auditorium (Figure 3d), library, teaching rooms) require complex structure; - (X10) Compliance with fire safety regulations, access for wheelchair mobility (Figure 3d).
(Y) Economical, financial, and sustainability	- (Y1) Priority to protect external walls from rain waters as soon as possible; - (Y2) Financial resource constraints (limited budget); - (Y3) Some materials have environmental concerns;
(Z) Site works and retrofitting works	- (Z1) Site works with limited access, inclined entrance, and garden to preserve (Figure 2c); - (Z2) Scaffolds needed around all building, obstructing all principal façade (Figure 2a); - (Z3) Building windows preservation;

(**a**)

Figure 3. *Cont.*

(**b**)

(**c**)



(**d**)

Figure 3. (**a**) Exterior wall reinforcement; (**b**) reduced slabs thickness; (**c**) waterproofing needs in different buildings roofs; (**d**) drawing floor with auditory, elevator (underground level floor).

4. Retrofitting Management System Application and Results Discussion

To address the constraints (Section 3.2—Table 2) related to the structural and roof works, some recommendations [21] and parameters (Section 3.1—Table 1) of retrofitting management systems were applied. Some of those parameters were aggregate because either their sphere of actions were connected or belonged to a similar group of information, such as P14-17-19-20-21, P26-to-21, P36-37, P41-42, and P13-40-45 (Table 3).

Table 3. Retrofitting management system thematic parameters application.

Parameters	Constraints	Recommended Solutions/Best Practices
P12	X3, X5	The real position and characterization of the stone masonry can only be modeled through the means of approximate methods.
P14, P17, P19, P20, P21	X8, X9, X10	The project design must address a structural reinforcement that is compatible with the existing one and comply with actual regulations, including thermal and acoustic comfort.
P15	X2, X4, X6, X7, X9, X10	A new stair block and also a lift for 12 people capacity were created. Regulations compliance were required in all architecture and technical project design. The auditorium was on the floor below level 0 with a distance between pillars of 10.90 m. The solution required a thicker frame structure, without pillars inside rooms and circulatory zones and in the auditorium. The library, meeting room, teaching room, and rooms need to comply with new regulations on space and mobility performance with adapted structure.
P22	Y1, Y3, Z3	Reutilization of existing materials (stones, exterior walls, woods, windows).
P23	X8, X11, Y3	Prefabricated solutions promote the reversibility principle.
P24	X10	New structure and materials must comply with fire safety regulations.
P25	X12	Compatible materials with existing ones and that enhance comfort levels benefits.
P26 to P31	X12, Y2, Y3	Some of these ideas will be dealt with in the project's second phase (not analyzed in the paper).
P32	Z1, Z3	The access to the site works is limited with traffic signals. For ready-mixed concrete supply, a traffic controller ensures the smooth entry/exit to/from the workplace.
P33	X3	The adjoining building is in a good conservation state without need of any work.
P34	X1, X8, Y1	The adjoining building does not need any reinforcement or consolidation works. Reinforcement needs in all frame structures connected to the external walls are presented in the project design.
P35	X3	Construction of the lateral roof wall was lacking in the adjoining building.
P36, P37	Y1, Y2	Structure with prefabricated elements, manufactured by a specialized enterprise with a quality control system, promoting fast work in assembly, without skilled workforce needs.
P38	X4, X6, X7	The new staircase construction and the façade conservation works do not require a specialized company. The elevator assembly needs a specialized company.
P39	X8	The project design is very detailed without the need for permanent technical monitoring. It also allows the clarification of specific questions not frequent in design.
P41, P42	Y2	The project design has a detailed survey of all constraints as well as their resolution measures and guidelines for real planning, reducing the exposure to occupational hazards.
P43	X6	The pinnacles need reinforcement during roof works execution.
P13, P40, P45	X1, X2	The building retrofitting works reutilize the existing materials of the façade, using some wood elements and some deconstruction/demolition wastes were reused. The solution for a prefabricated structure contributes to minimizing construction waste.

4.1. Structural Technology Options and Sustainability Analysis

The project design of the building retrofitting considered the constraints described in point 2.2, as well as the solutions and recommendations used in the management system parameters presented in Table 3. The study devised three different structural options for the building [22]:

- Option O1—Foundation and exterior walls below level 0 in a concrete structure. Wood flooring on wooden structure (similar to the existing one) with metallic elements;
- Option O2—T beam and block system slab in the roof. Pillars, beams, foundations, and slabs (floors) are in concrete (similar to new construction).
- Option O3—Foundation and exterior walls below level 0 in concrete, beams, and pillars in steel structure and metal deck for floors slabs.

These different options were analyzed according to the advantages and disadvantages of each possible option. All different solutions were studied in the design phase and the results of the environmental impact categories were quantified into benefits to sustainability (Tables 4 and 5). For this proposal, the building sustainable assessment method SBTool was used and, particularly, its methodology for calculating the parameter P1 “Construction materials’ embodied environmental impact”. This parameter encompasses the following environmental impact categories [16,19]:

- GWP (Global Warming Potential—KgCO_2);
- ODP (Ozone Depletion Potential—KgCFC-11);
- AP (Acidification Potential—KgSO_2);
- POCP (Photochemical Ozone Creation Potential—KgC_2H_4);
- EP (Eutrophication Potential—KgPO_4);
- FFDP (Fossil Fuel Depletion Potential—MJ equiv.).

The unitary values for GWP, ODP, AP, POCP, EP, FFDP indicators are in an LCA Database for specific calculation types. This covers a wide range of solutions concerning building elements and construction materials. Table 4 shows the unitary values of those categories of environmental impact.

Table 5 presents the quantification of the environmental impacts of the constructive solution parts of each structural option studied which results from the values presented in Table 4 multiplied by the quantities (in square meter, or kilogram) of each constituent part [19]. Table 5 also shows the total results of the environmental impacts of all structural options. These calculations considered the quantity of different materials and components applied in all different solutions analyzed. The calculations did not consider the quantity of materials and construction components used for the same works in all structural options, such as the elevator structure, reinforced exterior walls in concrete by the internal side, among others.

Table 4. Unitary values of the categories of environmental impact according to constructive solution types.

Option	Constructive Solution Types	Unitary Values of the Categories of Environmental Impact					
		GWPO2	ODP	AP	POCP	EP	FFDP
O1	Weak fill concrete (kg)	1.10×10^{-1}	3.55×10^{-9}	1.79×10^{-4}	6.49×10^{-6}	2.84×10^{-5}	5.56×10^{-1}
	Foundations concrete (kg)	1.48×10^{-1}	3.55×10^{-9}	5.56×10^{-4}	5.28×10^{-5}	5.76×10^{-5}	0.124×10^{1}
	Metallic structure (kg)	5.71×10^{-1}	5.40×10^{-8}	3.04×10^{-3}	1.85×10^{-4}	4.86×10^{-4}	0.866×10^{1}
	Wooden structure (floors) (m^2)	0.868×10^{1}	1.37×10^{-6}	6.06×10^{-2}	3.53×10^{-3}	1.96×10^{-2}	2.02×10^{2}
	Roof wooden structure (m^2)	-1.51×10^{1}	2.05×10^{-6}	7.17×10^{-2}	6.01×10^{-3}	8.71×10^{-3}	2.76×10^{2}
O2	Weak fill concrete (kg)	1.10×10^{-1}	3.55×10^{-9}	1.79×10^{-4}	6.49×10^{-6}	2.84×10^{-5}	5.56×10^{-1}
	Concrete structure (kg)	1.48×10^{-1}	3.55×10^{-9}	5.56×10^{-4}	5.28×10^{-5}	5.76×10^{-5}	0.124×10^{1}
	Reinforced concrete slabs (m^2)	1.09×10^{2}	8.71×10^{-6}	3.32×10^{-1}	1.9×10^{-2}	6.44×10^{-2}	1.14×10^{3}
	T beam and block slab (m^2)	1.76×10^{1}	1.46×10^{-6}	5.32×10^{-2}	3.14×10^{-3}	9.80×10^{-3}	1.94×10^{2}
O3	Weak fill concrete (kg)	1.10×10^{-1}	3.55×10^{-9}	1.79×10^{-4}	6.49×10^{-6}	2.84×10^{-5}	5.56×10^{-1}
	Foundations concrete (kg)	1.48×10^{-1}	3.55×10^{-9}	5.56×10^{-4}	5.28×10^{-5}	5.76×10^{-5}	0.124×10^{1}
	Metallic structure (kg)	5.71×10^{-1}	5.40×10^{-8}	3.04×10^{-3}	1.85×10^{-4}	4.86×10^{-4}	0.866×10^{1}
	Steel decking slab (m^2)	1.02×10^{1}	6.29×10^{-7}	3.35×10^{-2}	3.63×10^{-3}	6.68×10^{-3}	1.32×10^{2}
	T beam and block slab (m^2)	1.76×10^{1}	1.46×10^{-6}	5.32×10^{-2}	3.14×10^{-3}	9.80×10^{-3}	1.94×10^{2}

Table 5. Quantification of the categories of environmental impact (total results by option).

Option	Constructive Solution Types	Quantification of the Categories of Environmental Impact (Total)					
		GWP	ODP	AP	POCP	EP	FFDP
O1	Weak fill concrete (16,560 kg)	1.82×10^3	5.88×10^{-5}	0.296×10^1	1.07×10^{-1}	4.70×10^{-1}	9.21×10^3
	Foundations concrete (302,500 kg)	4.48×10^4	1.07×10^{-3}	1.68×10^2	1.60×10^1	1.74×10^1	3.75×10^5
	Metallic structure (45,435 kg)	2.59×10^4	2.45×10^{-3}	1.38×10^2	0.841×10^1	2.21×10^1	3.93×10^5
	Wooden structure (floors) (2175 m^2)	1.89×10^4	2.98×10^{-3}	1.32×10^2	0.767×10^1	4.26×10^1	4.39×10^5
	Roof wooden structure (642 m^2)	-9.69×10^3	1.32×10^{-3}	4.60×10^1	0.386×10^1	0.559×10^1	1.77×10^5
	Total results for Option O1	8.17×10^4	7.88×10^{-3}	4.87×10^2	3.60×10^1	8.82×10^1	1.39×10^6
O2	Weak fill concrete (33,060 kg)	3.64×10^3	1.17×10^{-4}	0.592×10^1	2.15×10^{-1}	9.39×10^1	1.84×10^4
	Concrete structure (1,095,250 kg)	1.62×10^5	3.89×10^{-3}	6.09×10^2	5.78×10^1	6.31×10^1	1.36×10^6
	Reinforced concrete slabs (2173 m^2)	2.37×10^5	1.89×10^{-2}	7.21×10^2	4.13×10^1	1.40×10^2	2.48×10^6
	T beam and block slab (642 m^2)	1.13×10^4	9.35×10^{-4}	3.42×10^1	0.202×10^1	0.629×10^1	1.24×10^5
	Total results for Option O2	4.14×10^5	2.39×10^{-2}	1.37×10^3	1.01×10^2	2.10×10^2	3.98×10^6
O3	Weak fill concrete (19,920 kg)	2.19×10^3	7.07×10^{-5}	0.357×10^1	1.29×10^{-1}	5.66×10^{-1}	1.11×10^4
	Foundations concrete (362,500 kg)	5.37×10^4	1.29×10^{-3}	2.02×10^2	1.91×10^1	2.09×10^1	4.50×10^5
	Metallic structure (77,515 kg)	4.43×10^4	4.19×10^{-3}	2.36×10^2	1.43×10^1	3.77×10^1	6.71×10^5
	Steel decking slab (2173 m^2)	2.21×10^4	1.37×10^{-3}	7.27×10^1	0.788×10^1	1.45×10^1	2.87×10^5
	T beam and block slab (642 m^2)	1.13×10^4	9.35×10^{-4}	3.42×10^1	0.202×10^1	0.629×10^1	1.24×10^5
	Total results for Option O3	1.33×10^5	7.84×10^{-3}	5.48×10^2	4.35×10^1	7.99×10^1	1.54×10^6

An analysis of Table 5 indicates option O2 (concrete) as the solution with the highest impact in all parameters. In contrast, option O1 (wooden) is the solution with fewer environmental impacts in all analyzed environmental categories, except in parameters EP (steel is smaller) and DP (same result for wood and steel). However, in parameters AP, POCP, and FFDP the differences between wood and steel are minimal. Considering all categories of environmental impacts analyzed, the concrete frame structure is the worst solution but there are no significant differences between steel and wood solutions.

4.2. Structural Option Choice

The choice of the structural option involved a specific study about each structural option's potential contribution to GWP, ODP, AP, POCP, EP, and FFDP.

As stated before, the quantitative analysis considered the categories of environmental impact results (Table 5), the retrofitting management system guidelines (Table 1), and its proposals for solving the technical constraints of the building retrofitting works (Tables 2 and 3). The criteria weights for the aggregated parameters "Retrofitting management system" and "Environmental impact categories" were, respectively, 60% and 40%. These values were the average results of the responses of all interviewees that participated in the survey. Within each of the aggregated parameters, the same weight was assigned to each item. In this context, each item of the aggregate parameters was classified as "1" for the worst solution, "3" for the best solution, and "2" for the intermediate solution. The assignment of this classification in each structural option was jointly made by the design team leader and the construction manager of the construction project (Table 6). Subsequently, the average score of each structural option was calculated through the following (Formula (1)),

$$S\theta = \sum_{*=1}^{17} (P * \_O\theta) \times 0.03529 + \sum_{*=1}^{6} (EC * \_O\theta) \times 0.06667 \quad (1)$$

Notes: *P** (retrofitting management system parameters)—P12, P14/17, P15, P22, P23, P24, P25, P32, P33, P34, P35, P36/37, P38, P39, P41/42, P43, P13/40/45. *EC** (categories of environment impact)—GWP, ODP, AP, POCP, EP, FFDP. *Oθ* (structure option)—O1, O2, O3.

Table 6. Classification of each structural solution according to its technical suitability and environmental impact results.

Option ($O\theta$)	Retrofitting Management System Parameters (60%)—*P**																	Categories of Environment. Impact (40%)—*EC**						$S\theta$-Score Result
	P12	P14,17(. . .)21	P15	P22	P23	P24	P25	P32	P33	P34	P35	P36/37	P38	P39	P41/42	P43	P13,40, 45	GWP	ODP	AP	POCP	EP	FFDP	
O1	3	3	2	2	2	1	2	2	2	1	3	2	1	2	2	2	2	3	3	3	3	2	3	2.33
O2	1	1	1	1	1	3	1	1	1	3	1	1	3	1	1	3	1	1	1	1	1	1	1	1.88
O3	2	2	3	3	3	2	3	3	3	2	2	3	2	3	3	1	3	2	2	2	2	3	2	2.38

Table 6 presents the different structural options' relative scores in each item of the aggregated parameters (retrofitting management system and environmental impact categories). Table 6 also indicates that O3 (steel structure) has the best average results, followed by O1 (wood structure) and lastly by O2 (concrete structure). This analysis supported the owner's choice [20,23] for the steel frame structure (O3) to be used in the building retrofitting works. In addition, some qualitative aspects have also informed that decision, namely

- Good results in the categories of environmental impact despite the wood option having better ones;
- The previous negative experience with wooden structures and maintenance needs;
- Architectonic layers between floors (minimize the difficulty in pillars alignment—foundation to roof);
- Lighter frame structure (beams and pillars) for the auditorium;
- Cost-benefit contribution, compliance with the required regulations;

Specifically, the steel structure (O3) is also the solution that provides the best fit to the parameters used in the retrofitting management system, namely

- Reversibility and compatibility with existing materials and elements (P13, P14, P23, P43);
- Reduce structural reinforcement in walls and foundations (P19, P20, P21);
- Regulation compliance (P15, P17, P24, P38);
- Reuse of existing elements (P22, P25);
- Reduced space for site works space availability (P32);
- Less intrusive solutions for the adjoining buildings (P33, P34, and P35);
- Improved quality control (P36, P37, P39);
- Reduction of occupational hazards (P41, P42);
- Reduction of construction and demolition waste due to the use of prefabricated pieces (P40, P45);
- Sustainability concerns for the operation phase of the building (P26 to P31).

Obviously, the steel structure is not the best option in all factors or parameters but it is the option that better tackles the building works' constraints and fulfills the owner's requirements. In short, option O3 encompasses a steel structure with easy and quick assembly, being light, reversible, and has some potential for reutilization in the future. The structural slabs option resolves the floor's thickness limitation with durable characteristics and requires less maintenance work than other structural options. Lastly, the steel structure and its assembly works have a beneficial contribution to safety risk reduction.

5. Conclusions

This paper has presented an analysis of some structural design options that can bring sustainability benefits and solve technical problems in the retrofitting works of an old building. The existing constraints were exhaustively described and analyzed in the project design phase, which took into account the guidelines of a retrofitting management system developed in an earlier work. A set of three possible structural options were considered to solve the structural requirements and constraints of the building work, namely wood, concrete, and steel frame structures.

Subsequently, the structural options were weighted considering a simple quantitative approach that converged information [24,25] about existing constraints, retrofitting management system guidelines, and the technical advantages and disadvantages for each option. For each structural solution, the quantification of some categories of environmental impact was developed. The results show that the wooden structure solution (O1) had the best results in the quantification of environmental impact categories and the concrete-framed structure solution (O2) was the worst performer in this quantitative analysis. However, the steel structure (O3) also had good results in the quantification of environmental impact categories, which were very close to O1. This option was the solution that presented the most advantages in relation to the technical requirements of the building, as described in the guidelines of the retrofitting management system. It allows reversibility and quick assembly and responds to the constraints and compatibility with existing materials and components.

In addition, the steel structure allows greater durability and does not require large maintenance until the start of building infrastructures and finishing works and also during the utilization phase. This study can be perceived as a useful tool for helping designers strive for more sustainable building retrofitting. It emphasized the following aspects that need to be considered in the building retrofitting process: the importance of the participation of a skilled construction manager in the design phase of the project development [25]; the consideration of other variables other than technical aspects (stakeholders experience and expertise; time planning needs; unforeseen aspects to account for; social impact; site works surroundings impact; aesthetic and location restrictions and their impact on construction costs); simplicity of calculations of different environmental categories for each structural option; the interaction of the technical analysis with sustainability proposals.

However, the study had some limitations that could be addressed in future research. They are as follows: the data used for the quantitative analysis derived from interviews conducted on a limited number of representatives of construction firms and design consulting firms. The sample could be widened to a large number of construction professionals with experience in environmental assessment methods (LEED, BREEAM; SBTool) as wells as to include other key stakeholders in the building retrofitting market segment; the study only considered the environmental aspects of sustainability. The social and economic dimensions of sustainability were not considered. This aspect could be addressed in future works; the framework developed here focused on the Portuguese context. The scope of the study could also be widened to investigate its relevance to the international context.

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Abbreviations

GWP	Global Warming Potential
ODP	Destruction of Atmospheric Ozone
AP	Acidification Potential
POCP	Photochemical Ozone Creation Potential
EP	Eutrophication Potential
FFDP	Fossil Fuel Depletion Potential
LCA	Life Cycle Assessment
EPD	Environment Product Declaration
R.U.-I.S.	Intelligent and Sustainable Urban Retrofitting
AICCOPN	Association of Civil Construction and Public Works Companies
LEED	Leadership in Energy and Environmental Design
BREAM	Building Research Establishment Environmental Assessment Methodology
SBTool	Sustainable Building Assessment Tool

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