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Comprehensive Sustainability Assessment of Regenerative Actions on the Thermal Envelope of Obsolete Buildings under Climate Change Perspective

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Received: 12 May 2020; Accepted: 1 July 2020; Published: 8 July 2020

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Abstract: Improving the energy efficiency of existing buildings in favor of reducing consumer demand and associated emissions is one of the central strategies for achieving global GHG (greenhouse gas) emissions reduction targets. Contemplating this activity within the paradigm of long-term sustainability implies, on one hand, that project intervention strategies must be assisted by tools that integrate social, environmental, and economic indicators that must be evaluated from an LCA (life cycle assessment) perspective and, on the other hand, deviations must be considerate of the energy-saving projections that are sought to be achieved through the potential strategies to be implemented. This article develops an LCA methodology whose objective is to evaluate the comprehensive sustainability of existing passive strategies in the local industry through the quantification of environmental and economic indicators throughout different climatic scenarios, which are socially contextualized for a building existing in a Mediterranean region. Part of the results obtained showed a loss of the effectiveness of measurements with an adequate response to the current climatological reality.

Keywords: energy efficiency; sustainability; circular economy; carbon embodied; climate change

1. Introduction

The environmental and social consequences that have been indirectly generated by the political measures adopted at the global level to contain the pandemic caused by COVID-19 are significant, although they have not yet been quantified as a whole because we are immersed in it. However, if we focus on specific regions and if we look at the information available at the European Environment Agency on the data from the eighty measurement stations located throughout the Spanish territory, we can verify a reduction in the average concentration of NO_2 and PM_{10} and average $PM_{2.5}$ in the atmosphere of 40.26% since the beginning of the lockdown [1] and a reduction of 50.19% locally in the city where the present investigation was carried out. This illustrates the impact of our activity on the environment and points out the weaknesses of a traditional development model, highly inefficient and polluting from an environmental point of view, globally interdependent from an economic perspective in recession [2,3], and whose consequences aggravate the health effects that a pandemic such as the current one has had in various locations [4,5]. All this highlights a more than necessary paradigm shift and a reorientation of the economy toward a circular model, which allows, among other issues, a more than necessary increase in the resilience of our society to handle the effects of the verified climate change [6].

The adaptation of the built environment to meet the principles of a circular economy has been proven to be an effective strategy to reduce CO_2 emissions by 38% by 2050 (pp. 31–33, [6]). Particularly, in the construction industry, adopting measures such as the extension of the service life of buildings as well as the waste reduction of construction processes in buildings would allow an annual global reduction of emissions of 1.2 billion of $TnCO_2$ beyond the year 2050 [6].

In this sense, actions such as improving the energy efficiency of existing buildings and reducing the emissions associated with Heating, Ventilating and Air Conditioning (HVAC) energy consumption would lead to reductions in the total energy demand by 25% when compared to current levels [7]. Therefore, the need for improved energy efficiency strategies within the framework of a circular economy implies actions on the existing buildings oriented toward the use of low-carbon materials and the systematization and prefabrication of building systems.

Therefore, one might ask then to what extent the European Union (EU, Brussels, Belgium) policies on urban regeneration are aligned with the principles of sustainability stated. The European policies on building performance based their strategy on tackling the climate change on three main lines: promoting the production of renewable energy, reducing the consumer demand of buildings, and CO_2 emissions [8–10]. The transposition of the recent European directives into the Spanish national regulations has led to an increase in the energy-saving requirements of buildings by means of the recent update of the basic document of energy saving (DB-HE) of the Technical Building Code [11] (CTE), which introduces the limitation on total primary energy consumption as well as on the amount of non-renewable energy used in buildings. As novelty, this standard homogenized for new buildings and refurbishment the limit values for non-renewable energy consumption in order to justify a nearly zero consumption building (nZEB), which was 50 kWh/m^2 for the climate zone used in this study. Regarding this issue, the DB-HE update establishes the conditions for the thermal envelope of buildings, thus restricting the thermal transmittance limitations even more. Given these performance requirements at the regulatory level and the close relation of a limited consumption with a lower demand in buildings, it is clear that intervention on the envelope of existing buildings is paramount to achieve the global emission reduction targets set by the UE [10].

Research focused on reducing the demand for buildings has pointed out that the implementation of passive strategies in mild climates is an extraordinarily effective measure to reduce consumption, essentially due to the reduction in the large insulation thicknesses, when compared to central European climate regions and the unnecessary use of mechanical ventilation with enthalpic recuperators [12–14]. On the other hand, it has been found that excessive insulation of buildings can cause undesired effects in future climate scenarios, causing overheating inside buildings, which will be especially pronounced in climatic contexts such as the Mediterranean [15,16].

In contrast, the aforementioned environmental impact that these actions imply in research such as that carried out within the Chair of Sustainable Construction in Zürich showed optimum emission compensation through the savings generated throughout the life cycle of a high-quality refurbishment of the thermal envelope with prefabricated facade elements, which, in turn, enables energy generation through the inclusion of collectors and photovoltaic panels [17]. However, in sociocultural and climatic contexts like that proposed by this research, these actions represent an important degree of the technification of construction processes, which currently does not have enough roots in the productive fabric as well as a high cost in relation to the savings that could be obtained, essentially due to lower demand from buildings in the operational phase [18]. Whereas, as will be pointed out in this article, a certain degree of systematization and prefabrication of interventions on buildings will allow, in urban contexts integrated with similar typological and constructive solutions, an optimization of intervention costs and a necessary reduction of energy demand that will favor the promotion of integrated community energy systems [19] and/or the construction of district heating and cooling networks [20].

For all these reasons, the different strategic plans at the national and regional level are aimed toward the purpose of enhancing the value of existing Spanish cities through urban and building renovation [21–25]. In this sense, and under the premise initially stated for a sustainable development that supports these interventions, it will be desirable to integrate into decision-making, on one hand, the social, environmental, and economic aspects that allow for the definition of a holistic and perfectible system for the evaluation of the impacts associated with the construction of the renovation projects, and on the other hand, the consideration of future climatic scenarios that make it possible to determine the adequacy of said renovation project throughout its useful life, while allowing the economic impacts to be weighted and environmental impacts derived from its implementation.

At this point, it is inevitable to stop looking at the environmental and socioeconomic impacts that the construction of these renovation projects will have, especially if we pay attention to the effects of climate change, which will promote dynamic climate scenarios that will lead to the loss of the effectiveness of the renovation measures that can be adopted to improve energy efficiency that are based exclusively on the current climate reality. In this particular sense, and to quantify the economic, environmental, and social impact of the execution of renovation projects, this article sets out, develops, and applies its methodology, based on different UNE reference standards [26–35], to the evaluation of the comprehensive sustainability of different measures of renovation of the thermal envelope by adopting passive strategies on obsolete housing towers developed in the third quarter of the 20th century, evaluated concerning the expected evolution of the climate over the next sixty years.

2. Methodology

The methodology was arranged in two well-differentiated lines of work: the simulation of different building models with various climatic scenarios (building thermal simulation modeling, MS in Figure 1) and the quantification of the environmental, socioeconomic impacts through the cost of the intervention and the amount of embodied carbon of various design options (construction model of evaluation, ME in Figure 1). Figure 1 shows the workflow followed in the research. Once the results of each of these lines of work (results, RR Figure 1) were obtained, it prioritized the constructive solutions that minimize the economic and environmental impacts (decision making, DM on Figure 1) and the results were integrated into a new simulation model (MS4). Finally, the results of MS4 and that obtained for each constructive solution were integrated and related with the results for the social assessment (results of integration in a single model taking into account the three sustainability dimensions, RRIM in Figure 1).

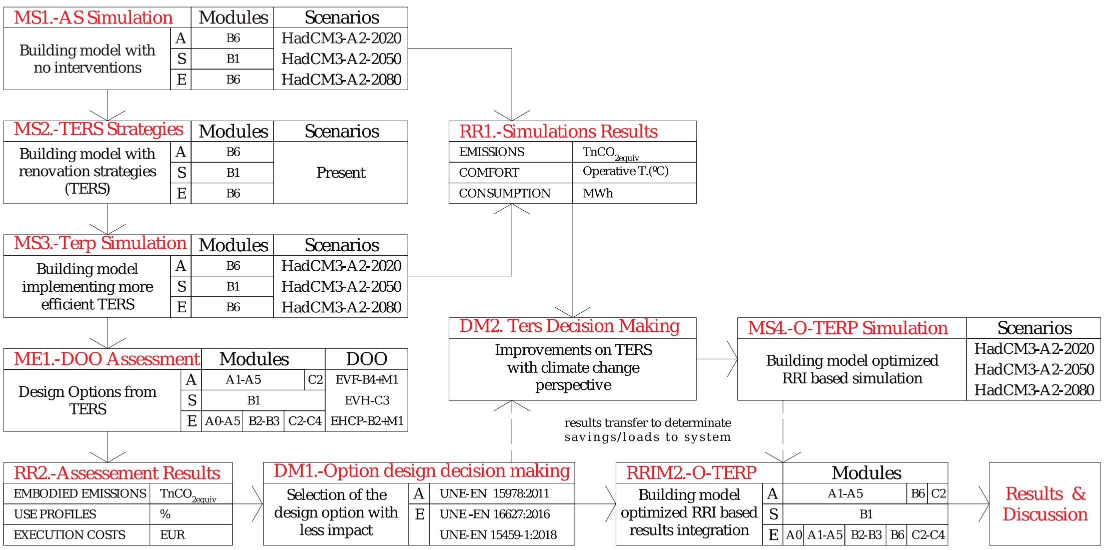


Figure 1. Methodology workflow.

In this way, through the proposed methodology, we covered different information modules throughout the useful life of the renovation strategies proposed to quantify the impact of the preconstruction and construction stages concerning the reduction of emissions that occur during the reference study period (RSP) estimated in 50 years, as will be seen later. The time scenario considered in this article for the evaluation of energy performance, year 2080, allowed us to have theorical information 20 years beyond the lifespan, that is, 104 years after the construction of the building. Thus, these data were not taken into account for this study.

The comparison of the model that is determined through the exposed premises with the model of the building without interventions will allow us to learn the adequacy of the renovation strategies proposed in the present to future climate scenarios.

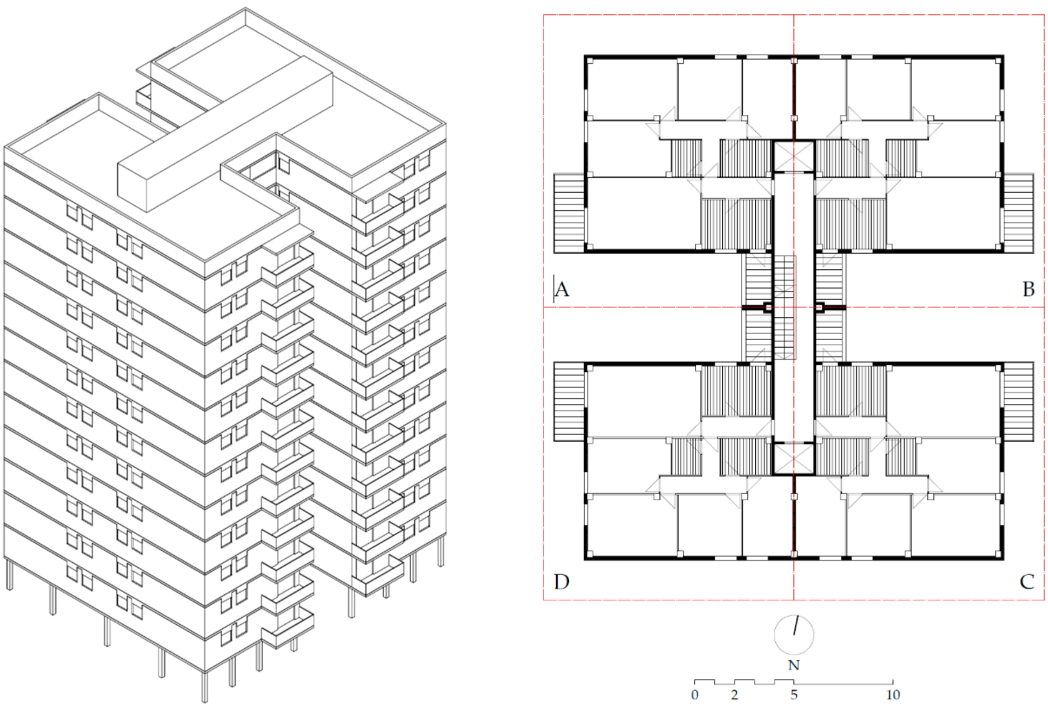
The future climate scenarios were transformed using the CCWorldWeather tool (version 1.9), according to a GCM (General Circulation Modeling) of the HadCM3 (Hadley Centre Coupled Model version 3) based on scenario A2, which projects a future about emissions in line with a productive behavior oriented to per capita economic growth [36], or what is the same, a scenario that projects the current trend of resource depletion and emissions production.

2.1. Definition of Functional Equivalent

The functional equivalent is a tower of 48 dwellings built in 1976 in the city of Malaga, being an archetypal architectural solution in the city at the time of its construction. It should be noted that between the 1960s and 1970s, there was a major rural exodus to the cities, which led to high demand for housing and the appearance of a multitude of high-density "urban organisms" [37] made up under the model of residential polygons that grew mainly on the outskirts of the city and found the residential typology par excellence in the high-rise "H" block. In the city of Malaga, according to OMAU (Urban Environment Observatory of Malaga) data, this expansion process involved the construction of a total of 142,609 homes, which represents 56% of the current dwelling stock. This important volume of new construction carried out in the third part of the 20th century added to the fact that there was a necessary optimization of the costs of these social houses and the low concern for the energy demand of buildings, in the confidence of some energy resources that they were believed to be unlimited, led to the standardization of inefficient constructive solutions from an energy point of view and that today can be considered obsolete. This productive paradigm was deeply rooted in the Malaga coast, essentially due to temperate temperatures during the winter that could be overcome by the neighbors through the occasional use of portable heating equipment, the use of HVAC systems not being widespread at the time for air conditioning spaces in hot and dry summers typical of a Csa climate, according to the Köppen–Geiger climate classification [38]. However, the INE (Statistics National Institute) database shows that currently, 44.18% of Malaga households have individual air conditioning equipment, compared to 35.5% of the national average [39]. The consideration of future climate scenarios in which an increase in temperatures is expected that will lead to a loss of comfort in homes as well as an increase in consumption by cooling, justifies the choice of climatic contexts such as the one selected for a necessary deepening of the effects of climate change on current building envelope renovation strategies from a socio-economic and environmental perspective.

In this sense, the essential premise of intervention through passive strategies on a building typology with a representative iteration within the state housing in which it is inserted will allow the optimization of resources for the energy refurbishment measures of said "urban organisms". For this, the research focused on the identification of residential sectors promoted as a whole by neighborhood cooperatives, basing their pre-selection criteria on the results obtained for the urban indicators developed in the Local Agenda XXI [40] of the city of Malaga (listed in Appendix A).

The representativeness of the selected typological solution (Figure 2) for the chosen urban organism (57%) and the set of urban organisms of the sector, in which it is inserted (72%), allow for inferences to be drawn at an urban scale from the results.



(**a**) (**b**)

Figure 2. (**a**) Perspective of the housing tower. (**b**)Type plan and zone identification.

The choice of the different renovation strategies that make up the TERP (Thermal Envelope Renovation Project) is based on the prior analysis of 16 possible passive envelope renovation strategies applicable to the reference typology (Appendix B), not all of which are widely used in the local industry (i.e., the use of PCM (phase change material)), which, despite the interest they have in improving the energy performance of buildings in warm stages [41], means that we cannot consider them. Each of the preselected strategies has been evaluated on the building as a whole for the current climate scenario (2020) in an annual simulation period through the Design-Builder tool, through which it has been possible to identify the relationship of the adoption of said strategies with sensible heating and cooling reduction, and solar gains through windows (Appendix C).

Taking into account these results for sensible heating and cooling (Appendix C), two renovation projects were developed. The first of these projects (CTE-TERP) uses the DB-HE limit transmittance values to determine the effects of climate change on an nZEB throughout its lifespan. For the second project (O-TERP), the characteristics of the thermal envelope have been calculated based on existing commercial solutions that had EPD (environmental product declarations) and sufficient information to estimate the maintenance costs. The specific values of each of the renovation projects and the calculation parameters are shown in Table 1.

Addressing the issue of the RSP and the useful life of the property, it is convenient to argue the considerations made. Palacios-Muñoz [42] points out that the lifespan is a key aspect for the results of any LCA, since the results are closely related to that period of time. However, there is no clear consensus regarding what this period is. In this sense, different authors have pointed to values ranging from 40 years to 100 years. Statistical analysis of the lifespan shows that a value of 50 years is acceptable, which is related to the aptitude of the service of a structure [43,44]. However, there is a strong connection between the reduction in the environmental impact and the prolongation of the useful life of buildings, which has been quantified by Marsh [44] and is aligned with the principles for a circular economy already mentioned.

Table 1. Parameters for the calculation of the thermal model and definition of the actual state and the renovation projects: Thermal Envelope Renovation Project based on minimum Spanish normative prescriptions (CTE-TERP) and Optimized Envelope Renovation Project (O-TERP).

Building **Year of Construction**	**Housing Tower** **1976**		
Stories	12		
Functional Program	4 bedrooms, 1 kitchen, 1 laundry room, 2 bathrooms & 1 living room		
Occupied Floor Area (m^2)	5.43380		
Occupied Floor Volume (m^3)	16.30150		
Other Electrical Gains (W/m^2)	4.40		
Occupancy (m^2/person)	0.03		
Infiltration (ac/h)	0.70		
Natural Ventilation (ac/h)	4		
Windows Opening	CTE Residential Night Ventilation		
Minimum Level of Illuminance (lux)	100		
Models	**AS**	**O-TERP**	**CTE-TERP**
Wall Construction	-1/2 foot Metric Perforated Brick	+Precast panels	-
	-Vertical unvented air chamber 4 cm	+Vertical vented air chamber 4 cm	-
	-Hollow brick partition simple 4 cm	+Metallic substructure	-
	-Plaster, low hardness 1.5 cm	+Isolation (0.0355 W/m K) 4 cm	-
Glazing Construction	-Aluminum window frame (no break)	+Addition of ventilated window (6 + 12 + 6)	-
Roof Construction	-Waterproofing sheet	+Filter slab (including isolation)	-
	-Formation of slopes & structure	+Horizontal vented air chamber 4 cm	-
Wall U-value (W/m^2K)	1.44	0.45	0.50
Glazing U-value (W/m^2K)	5.86	1.80	2.70
Roof U-value (W/m^2K)	1.25	0.44	0.44
Wall Colour	Brick	White	-
Solar Control Glazing	No	Yes	No
Roof Colour	Red	White	-

In this sense, and supporting the proposed thesis, the rehabilitation of buildings through passive standards is one of the measures that most effectively contributes to the reduction of emissions. For these reasons, we have established a reference study period (RSP) of 50 years from that of the intervention, because it is one of the commonly used values [45–47]. In this way, a lifespan of a building of 84 years is established, expecting the end of it in the year 2060. According to Rincón [48], the expected lifespan for residential buildings built between the years 1941 and 1970 (a total of 2,491,881 in Spain) is expected between the period of 2044 and 2063, so the value seems consistent with these premises.

The use of an infiltration rate of 0.70 ac/h, which is less restrictive than the regulatory recommendations of 0.63 ac/h, is justified by the fact that the windows are micro-ventilated, due to the fact that the building has a natural ventilation system that is not included in TERP.

Hereunder, each of the sources and methodological bases from which the research will be used for the evaluation of the sustainability of the renovation project that we have established as optimal from the point of view of energy efficiency will be described. In the same way, the methodology used will be contrasted with recent investigations in order to establish the differences and similarities between the items addressed.

2.2. Methodological Basis for the Selection and Calculation of Environmental Indicators for the Evaluation of Renovation Strategies According to UNE-EN 15978: 2011

The representativeness of the typology chosen at an urban level becomes an essential issue to determine the effective contribution to the global GHG emissions through the renovation of neighborhoods. Research such as that carried out by Rivero [49] highlights the importance of considering the carbon footprint of the glazing systems to be implemented for the energy refurbishment of office buildings as an essential decision-making instrument for adopting different design options. In this sense, the use of the carbon footprint indicator throughout the maintenance and cleaning of the evaluated design options is an important aspect to consider, in line with that proposed by Martínez Rocamora [50].

In this research, the consideration of the environmental impacts of the strategies to be implemented in its different stages is organized and structured around the methodological premises outlined in the UNE-EN 15978: 2011 standard. Following these premises, the different scenarios are justified, the origin of the data, their traceability are defined, and the calculation method to be used is recognized. The different aggregated data for embodied carbon will be integrated into a quantification model through shared parameters (In Building Information Modeling), in line with what was proposed by Mercader Moyano for the determination of the EE (Embodied Energy) of the existing construction solutions in social housing [51]. Subsequently, the results obtained through the said tool will be analyzed from an LCA perspective.

2.2.1. Scenarios and Quantification of the Evaluation Object for the Different Stages

The environmental information for the stage between modules A1 and A3 is defined through the environmental product declarations [52,53]. However, at present, most of the construction systems do not have such declarations, although they do have technical suitability documents (DIT), ecolabels [54], and self-declarations [55] that have allowed reference institutions to prepare bases for own data that allow us to approximately understand the environmental impacts associated with different construction systems. In this way, its use in this research aggregated data developed by the Catalan Technological Institute [56] that established its values about the surface of the constructive solution, with which the data can be integrated through the incorporation of specific information in a building information model.

On the other hand, the quantification of the use of energy in service (B6) can be determined by the calculation procedure established by regulations [26,57] regarding the energy efficiency of the buildings, global energy consumption, and the definition of energy evaluations. The calculation is made using the Design-Builder tool, while the results and their adequacy are verified through the state-recognized computer tool, HULC [58].

Finally, for the estimation of the environmental impacts associated with the treatment of waste for its reuse, recovery, and recycling as well as for the elimination of said waste in the renovation process of the buildings, none of the sources consulted could be considered valid. Therefore, it has only been possible to determine the environmental impact of transportation for CDW (construction and demolition waste) management during the implementation of the TERP. This impact has been calculated based on the weight and volume of waste generated for each design option. In this way, and depending on the maximum load of the vehicles that could be used (N1 and N2, according to directive 70/156 EEC) and the main fuel of 45% of transport trucks in the city of Malaga (gas-oil), the associated CO_2 emissions for this activity were calculated based on the type of vehicle (161.2 g CO_2/km and 218.47 g CO_2/km respectively), according to statistical tables provided by the DGT (General Direction of Traffic) about vehicle fleets [59] and the IDAE databases for vehicle emissions [60].

2.2.2. Origin of Environmental Data and Selection of Indicators

The environmental data that were consulted, except for certain isolations that have more environmental information on the ITEC (Catalan Technical Institute) platform, focused on the product and construction phase, and modules beyond these cannot be evaluated. It is for this reason, mainly, that the selected data were taken from the values calculated by the reference database [61], showing two characteristic indicators expressed per unit area of the selected system/product and defined for the modules ranging from A1 to A5, recognized by Standard EN 15804 as:

- GLOBAL WARMING POTENTIAL (GWP), expressed in $KgCO_2$ equivalent and measures the potential of global warming.
- ABIOTIC RESOURCE DEPLETION POTENTIAL FOR ELEMENTS (ADP_elements), expressed in net calorific value (MJ) and which measures the potential for depletion of abiotic resources for fossil fuels.

The justification for the selection of these environmental indicators responds, on one hand, to the existence of data associated with the surface of the intervention and, on the other hand, to the possibility that such data may be added and allow knowledge of the environmental impact of the intervention from project measurements that have been calculated using a BIM model.

The methodology that the ITEC uses to calculate the data that we used is based mainly on the determination of some percentages of recycled content and raw material that constitute each of the unit elements, which have associated values for their energy cost (MJ) and CO_2 emissions into the atmosphere; characteristics of the CDWs and their amount generated on-site, mainly aimed at site management, and, finally, the percentage of material recycled from the product, in order to obtain the emissions savings from the use of certain materials [56] (pp. 18–22). In the case of the two main characterized indicators, the results obtained for each of them started either from the consideration of the most representative values for said material through reference databases [62] or, if available, data directly provided by the manufacturer.

2.2.3. Calculation Method

For the calculation of environmental impacts in the different modules of the life cycle of the interventions, the principles established by the standard were followed [31]. Contextualizing the aforementioned indicators and modules, we obtained a matrix expression of the calculation of the environmental indicators in the different stages of the life cycle of the building's renovation strategies (Equation (1)).

Quantity of products/processes used in stage i — Environmental impact per unit of product/process — Environmental impact of stage i

$$\begin{pmatrix} a_{1,i} \\ a_{2,i} \\ a_{3,i} \\ a_{\ldots,i} \\ a_{n,i} \end{pmatrix} \bullet \begin{bmatrix} \text{database for } a_1 \text{ stage i} & \text{database for } a_2 \text{ stage i} & \text{database for } a_3 \text{ stage i} & \text{database for } a_{\ldots} \text{ stage i} & \text{database for } a_n \text{ stage i} \\ GWP_{a1,i} & GWP_{a2,i} & GWP_{a3,i} & GWP_{a\ldots,i} & GWP_{an,i} \\ ADP_{a1,i} & ADP_{a2,i} & ADP_{a3,i} & ADP_{a\ldots,i} & ADP_{an,i} \end{bmatrix} \quad \begin{pmatrix} GWP_{,i} \\ ADP_{,i} \end{pmatrix} \tag{1}$$

For i = [A1 a A3, A4, A5]

2.3. Methodological Basis for the Selection and Calculation of Social Indicators for the Evaluation of Renovation Strategies According to UNE-EN 16,309 + A1

The inner thermal characteristics of the dwellings in their use phase are decisive in order to contextualize markers of environmental and economic sustainability. Supporting this thesis, the results obtained by Sánchez-García show how, by considering the adaptive comfort of users, savings of 19% and 25% can be predicted for climatic scenarios located in the years 2050 and 2080, respectively, for buildings for housing in mild climates, based on the criteria established by standard EN 15251 [63]. Thus, the consideration of dynamic setpoint temperatures in future climate scenarios is shown to be an effective tool for reducing the consumption of cooling and heating, especially if these installations are centralized and programmable. However, the selected functional equivalent does not have centralized air conditioning systems on which operations can be considered, which motivates each user to adapt the thermal conditions of their home based on subjective criteria. For this reason, becoming aware of the consumer culture of users is also a priority, on one hand, to predict investment returns through consumption savings that are achieved through passive renovation of the building envelope, and on the other hand, identify opportunities and improvements of said renovation concerning interior redistributions and/or changes of use that could be carried out jointly and that motivates alterations of the facade.

The evaluation methodology it uses is aligned with that identified in the EN16309+A1 standard. It should be noted that the reference calculation method bases all its possible scenarios in the use stage, considering module B in three different scenarios: the current stage of the building, the projected stages (based on the premises established in the renovation project), and the execution stage (according to the course of the renovation project works).

In this research, the social aspect was understood from the perspective of the users in the use stage and according to the scenarios of the current state of the building under evaluation (AS) and the projected and ongoing state of the project of renovation on the building under evaluation (TERP). The methodology for the second of the scenarios will be described in this section and Appendix D, without having yet been able to obtain field results.

2.3.1. Identification of Indicators for Social Assessment of the Current Stage

The UNE-EN 16309+A1 standard proposes indicators and methodology for the evaluation of the information module B1 [33] (p. 50), which has been used to identify the indicators considered for the evaluation of any of the renovation project implementation scenarios (AS and TERP projected/ongoing status).

Regarding the different categories of social behavior that this first version of the standard proposes (accessibility, adaptability, health and comfort, impacts on the neighborhood, maintenance, and safety), all the proposals have been considered and taking into account or not the pertinent indicators for the social evaluation of the potential improvement strategies for the thermal envelope of the building to be proposed, as part of a building renovation project, obtaining a total of thirty-eight indicators, which will be related to the rest stages of use of the building, according to the allocation of influences determined at the normative level.

2.3.2. Influence Allocation for the Rest of the Modules

Appendix D establishes the relation of these indicators with the other stages. The consideration of module B5, related to the rehabilitation stage, becomes especially important, given that the complete renovation project will comprise a series of measures that will be carried out throughout the useful life of the building. The identification of a series of indicators that allow for an improvement of the measures to be taken in the course of the works to minimize impacts on the users of the building becomes one of the most relevant aspects, given the essential premise that the building will be in use during the execution of the works.

Once the different influences have been assigned, each one is analyzed in detail, concerning the modules already indicated.

2.4. Methodological Basis for the Selection and Calculation of Economic Indicators for the Evaluation of Renovation Strategies According to UNE-EN 16627 and UNE-EN 15459-1

From an economic perspective, determining the return on investment of a building's renovation measures is an essential indicator to determine the feasibility of the measures that are implemented. In this line of work, although focusing attention on active strategies for improving the energy efficiency of existing buildings in Portugal, it is worth mentioning the research by Tadeu [64] that related the optimal cost of the measures implemented with the return of the investment, determining that for large investment projects, the value of operating flexibility and other strategic factors such as the possibility of deferral must be added to the NPV (net present value) calculation process. On the other hand, Oregi [45] addressed the evaluation of economic and environmental aspects (Embodied Energy) of renovation strategies of the envelope of buildings in Spain through the perspective of the LCA, concluding that the maintenance stages had greater importance in the evaluation as a whole, especially from an economic perspective, something that can also be seen in this research.

To satisfy the specific conditions established by regulations for the calculation of the LCA, the scenarios that were selected will be developed in this subsection and their indicators, the origin of the data, and the calculation method that we will use will be reflected.

Despite the socio-economic impacts derived from the current crisis generated by COVID-19, we are not yet able to precisely know the calculation parameters with traditional investment analysis criteria and they essentially depend on macroeconomic scenarios that are deduced from the current situation [65]. In this way, the results presented in this article regarding the different economic indicators calculated respond to a global reality before the current crisis, without having been able to incorporate updated data for the discount rate and/or price developments. However, the methodology developed allows, once these parameters are known, for the calculation and comparison of the socioeconomic and environmental impacts in countries with mild climates.

2.4.1. Scenarios, Calculation of Income, and Costs of the Evaluation Object and Origin of the Data for the Different Stages

A precise knowledge of the costs (license, technical fees, industrial benefit, and indirect costs) and incentives (subsidies) associated with the actions to be carried out must be known. For the determination of the second of these issues, the data are contextualized at the building level through a complementary survey to the residents, thus determining the IPREM (Multiple Effect Public Income Indicator) of the families to understand the access to the subsidy that they would have.

On the other hand, the costs associated with the construction stages from modules A1 to A5 have to be determined. The main source for obtaining this data will be the regional existing databases. As the results of the application of said costs to the measurements in the BIM model are analyzed later, the non-annual costs and revenues obtained in the pre-construction stage have also been included.

In the use stage, modules B2, B3, and B4 are studied. In this way, the objective is to quantify the costs and income in the execution stage of the Renovation Project analyzed. The actual costs of maintenance, repair, and replacement are extremely complex to foresee, since it is difficult to determine the number of repairs that the elements will require, the accidents or meteorological catastrophes that may occur, etc. That is why, for the evaluation of these scenarios, we will use the 10-year maintenance module developed by the CYPE tool given its accessibility, and on which we base its calculations on the direct information contained in the technical suitability documents of the systems, constructive employees, and other information provided by the manufacturers. In this way, we can determine the estimated 10-year maintenance cost of each of the proposed renovation operations as well as the cost of all of them.

On the other hand, and concerning this stage of use, we will have to determine the evaluation of the costs derived from the use of energy from buildings (B6) to quantify the savings in the energy bill. For the determination of said economic costs, we will use the Regulated Energy Prices Report drafted annually by the Institute for Diversification and Economic Savings, dependent on the Ministry for the ecological transition based on the calculation methodology expressed in Royal Legislative Decree 216/2014 [66]. By using this data source and the aforementioned methodology, we have a source of information whose implementation is booming and which, at present, applies to households that have a smart meter, which is why this method of determination of costs is adequate, given that such reading devices have already been installed in the reference building. The hypothesis of calculating these costs starts from the premise of having low-voltage access tolls that do not set time discrimination, which establishes that we are at a 2.0 A rate type. Notwithstanding the foregoing, these costs fluctuate daily and their calculation is also legislated through RD 216/2014, but different entities express such data through their pages [67,68], given the complexity of the calculation, which is subject to multiple economic variables. In this way, and considering the different tools that are put at the level of users to determine the costs associated with energy consumption [68], the different values that allow us to determine the evolution of PVPC (Voluntary Price for the Small Consumer) over the last few years are determined for five years for the selected rate type. At the date of the consultation, a voluntary reference price is determined for the small reference consumer, which stands at €0.113466/KWh. Said energy cost has been compared with the actual consumption values, verifying a margin of error of 4.13%, for which reason these data are understood as adequate to estimate the return on investment through savings on the invoice energy after the implementation of the renovation project.

Furthermore, and to obtain future income/costs that allow the data to be taken at present, it is convenient to determine the increase by which the evolution in electricity prices is calculated. In this sense, the Iberian Energy Market Operator, in its last report (p. 56, [69]), contributed a weighted price increase for marketers (except for reference marketers) and direct consumers, which stood at 2%. Said increase concurs with the default values for the same concept established in the UNE 15459-1: 2018 standard, which details the procedure for the economic evaluation of energy systems in buildings, following the directive on energy efficiency in buildings (EPBD), and is therefore understood to be suitable as a reference value.

Finally, the consideration of scenarios at the end of life stage will include the dismantling of the implemented assembled systems (C1) as well as the transport of the generated waste to the locations for processing and/or storage (C2). Similarly, the costs derived from the treatment of construction waste, subject to a series of municipal taxes (C3 and C4), should be considered. Without affecting that above, not all the materials that make up the different potentially implementable construction systems carry economic loads since their sale for reuse and/or recycling produces benefits beyond the end of life of the object of evaluation, so we would have to reflect them in module D. However, and taking into account the building where the methodology is developed, it does not seem a priori that the consideration of this stage is useful for economic evaluation. This is due to the fact that the owners of each of the houses will not bear, in principle, the expenses derived from the dismantling of the building, having to be the natural or legal person who owns the land and/or the building in charge of dealing with these costs.

2.4.2. Indicators Selection and Calculation Method

The indicators were developed on the reference standard [34] (pp. 45–50,) and the UNE EN 15459-1: 2018 standard. The calculations of the aggregate costs of the operations to be considered and/or economic benefits that can be calculated throughout the lifespan of building after the interventions constitute the basis for determining what is financially known as the cash flow of the investment to be made (CF).

One of the main indicators recognized by the UNE-EN 16,627 standard is the NPV (Equation (2)). By obtaining this indicator, we can determine the current value of the evaluated project throughout the evaluation period to be able to compare it with other alternative projects. As recognized in the standard, to evaluate different projects we will have to consider a real discount rate of 3%, which in turn is taken from Commission Delegated Regulation No. 244/2012 of the Commission of 16 January 2012 for the calculation of optimal cost measures, expanding Directive 2010/31/EU of the European Parliament and the Council [34] (p. 48).

$$NPV = -CO_{INIT} + \sum_{t=1}^{n} \frac{CF_t}{(1 + RAT_{disc})^t} \tag{2}$$

where:

- CO_{INIT} the initial investment to cover the costs of the works, including incentives and aid;
- CF_t the income and costs during the study period associated with the renovation project;
- t number of periods considered;
- RAT_{disc} discount rate.

The determination of costs and income throughout the RSP starts from the essential premise of comparing the costs of the reference building, that is, the building in its current state and under the premises of maintenance following the thermal envelope systems integrating it, with the costs associated with maintaining the envelope renovation strategies and the income derived from energy savings. The level of aggregation of costs and income is a function of the level of detail available, the sources of which were specified at the beginning of this subsection.

To clarify how one of the most important elements defined in Equation (2) such as the initial cost will be calculated, the concepts included in said initial investment are established in Equation (3).

$$CO_{INIT} = C_{pem} + C_{ht} + C_{tm} - S \tag{3}$$

where:

- C_{pem} material execution budget costs (without VAT);
- C_{ht} technical fee costs (without VAT);
- C_{tm} municipal fee costs;
- S subsidy granted by the administration to cover part of the construction costs.

Parallel to obtaining the NPV, we must be able to determine the Equivalent Annual Annuity (EAA) obtained with the different combinations of strategies at the envelope level that are intended to be evaluated. For the determination of the EAA, which allows knowing the equivalent income that would be produced throughout the reference study period, we use the expression collected in Equation (4).

$$EAA = NPV \times \left[\frac{RAT_{disc}}{1 - (1 + RAT_{disc})^{-t}} \right] \tag{4}$$

where:

- NPV net present value;
- t number of periods considered;
- RAT_{disc} discount rate.

On the other hand, to determine complementary indicators to the aforementioned standard such as the period of return on investment and the overall cost of the intervention, the provisions of standard UNE-EN 15459-1: 2018 will be considered for the calculation of said indicators.

For the determination of the general cost (Equation 5), the different costs associated with the implementation of the construction solutions must be considered as well as the residual value of those systems implemented. Within the annual costs will be taken into account the costs of energy and the maintenance of the elements of the envelope on which it would intervene. Updated prices of the components and/or services will be established for each of the costs listed as well as the costs for the emission rights according to the data collected by the online platform Carbon Pricing Dashboard [70] for the year 2019, which establishes a cost of $16.56 per ton of CO_2 emitted. Likewise, the costs involved in the removal and dismantling of the different construction systems that make up the envelope will be considered at the end of the expected useful life of the building.

$$GC = CO_{INIT} + \sum_{i} \left[\sum_{i=1}^{TC} \begin{matrix} (CO_{a(i)}(j) * \left(1 + RAT_{xx(i)}\right) \\ +CO_{CO2(i)}(j)) * \mathrm{D}_{\_f(i)} + CO_{fdisp(TLS)}(j) - VAL_{fin(t_{TC})}(j) \end{matrix} \right] [€] \tag{5}$$

where:

- CO_{INIT} initial investment cost;
- $CO_{a(i)}(j)$ annual cost for year i of component or service j
- $\left(1 + RAT_{xx(i)}\right)$ evolution of prices for year i of the component or service;

- $CO_{CO2(i)}(j)$ cost of CO_2 emissions for measure j during year i;
- $D_{-f(i)}$ discount factor of year i;
- $CO_{fdisp(TLS)(j)}$ final disposal cost for decommissioning;
- $VAL_{fin(t_{TC})}(j)$ residual value of the assembled system j for the year TC;
- TC calculation period.

For the state of the renewed project, the forecast that all the systems implemented in the building has an expected useful life equal to the calculation period makes the said residual value zero. However, the consideration of said final residual value (Equation 6) is interesting to foresee the overall costs of a building without an intervention on it, since a maintenance and renovation plan of the different systems will have to be carried out. These are aimed at improving energy efficiency, which will produce a residual value since the useful life of the systems implemented will be under the building's maintenance plan and in some cases, the useful life of these systems will exceed the reference study period.

$$VAL_{fin}(j) = V_{(0)}(j) * \left(1 + RAT_{pr}\right)^{n*LS(j)} * \left[\frac{t_{TC} - n * LS(J)}{LS(j)}\right] * D_{f_{t_{TC}}} \ [€] \tag{6}$$

where:

- $V_{(0)}(j)$ last replacement cost (on the replacement date);
- n number of substitutions during the calculation period;
- RAT_{pr} evolution of product prices;
- $LS\ (j)$ expected life of the assembled system j;
- $\left[\frac{t_{TC} - n*LS(J)}{LS(j)}\right]$ linear amortization of the last replacement cost;
- $D_{f_{t_{TC}}}$ value of the discount rate at the end of the calculation period.

Another of the complementary indicators already referenced and that is especially interesting for decision-making is the period of return on investment. Through this indicator, it will be possible to clearly establish the number of years necessary for the initial investment made to be compensated by reducing the costs associated with energy consumption (Equation 7). Regarding the case at hand, since the initial reference cost for the building in its current state would be 0, since no cost associated with the non-adoption of any measure is expected, it implies that the following expression is the same as the value nominal current, or what is the same, and investment returns will occur when the nominal present value is equal to zero.

$$\sum_{t=1}^{TPB} CF_t * \left(\frac{1}{1 + RAT_{disc}}\right)^t - CO_{INIT} + CO_{INIT\ ref} = 0 \tag{7}$$

where:

- TPB is the last year of the payback period (when the formula equals zero);
- t number of years from the starting year.
- RAT_{disc} the discount factor;
- CO_{INIT} initial investment costs;
- $CO_{INIT\ ref}$ initial investment costs for the reference case (0 for the option of not renovate the envelope);
- CF_t difference in annual costs (difference in cash flow) between the renewed building and the building without any action on it.

3. Results

Once both the methodology that will allow us to obtain the different indicators for each of the evaluations and their contextualization through the surveys that have been carried out have been determined, we can analyze the results that have been obtained.

3.1. Simulation Results for the Different Climate Change Scenarios

The simulation of the thermal models of the building in its current state (MS1) after the implementation of a TERP according to Ulim (Thermal transmittance) values determined through the CTE for an nZEB based on the most efficient renovation strategies according to MS2 (MS3) and after the application of an O-TERP (MS4) in the different climatic scenarios that have been indicated, highlights the specific weight, in terms of consumption and emissions, of the cooling equipment. In this sense, we observed an evolution of heating consumption that decreases over the different years, compared to an increase in the consumption of cooling; which motivates that, despite the adoption of TERS, as of the year 2050, the consumption in the hot months and the cold months will be offset, reaching the consumption of cooling above 70% of the total (Table 2). This inevitably leads to a loss in the effectiveness of the measures, since the percentages of reduction in consumption (compared to the AS) dropped from 47% for the current situation to 34% by 2080. Therefore, energy savings as well as the emissions will vary throughout the reference study, which will be taken into account from the perspective of the LCA of the TERP.

Table 2. Homogenized by surface consumption and operative temperature simulation during different years for climate projections based on HadCM3-A2.

			HadCM3-A2-2020	**HadCM3-A2-2050**	**HadCM3-A2-2080**
AS	Heating	kWh/m^2	19.74	12.22	6.39
		MWh	107.26	66.40	34.74
		%	66.09	41.72	18.82
	Cooling	kWh/m^2	10.13	17.07	27.58
		MWh	55.04	92.76	149.85
		%	97.44	35.79	11.59
	Total	kWh/m^2	29.87	29.29	33.97
	Total Consumption	kWh/m^2	58.78	58.20	62.88
	Max. Operative TEMP	°C	28.02	28.74	31.40
	Min. Operative TEMP	°C	18.27	18.43	18.69
	Mean Operative TEMP	°C	22.67	23.60	24.95
	Total emissions	$TnCO_{2equiv}$	193.54	191.64	207.05
CTE-TERP	Heating	kWh/m^2	9.78	5.46	2.25
		MWh	53.14	29.65	12.22
		%	56.17	29.82	9.73
	Cooling	kWh/m^2	7.63	12.84	20.86
		MWh	41.46	69.78	113.36
		%	64.08	21.25	5.39
	Total	kWh/m^2	17.41	18.30	23.11
	Total Consumption	kWh/m^2	46.32	47.21	52.02
	Reduction	%	41.71	37.53	31.97
	Max. Operative TEMP	°C	27.50	29.95	32.04
	Min. Operative TEMP	°C	18.88	19.08	19.38
	Mean Operative TEMP	°C	22.99	23.93	25.25
	Total emissions	$TnCO_{2equiv}$	152.52	155.45	171.29

Table 2. *Cont.*

			HadCM3-A2-2020	HadCM3-A2-2050	HadCM3-A2-2080
O-TERP	Heating	kWh/m^2	8.05	4.27	1.53
		MWh	43.73	23.18	8.31
		%	50.81	24.78	6.82
	Cooling	kWh/m^2	7.79	12.95	20.88
		MWh	42.33	70.36	113.46
		%	51.66	16.47	3.66
	Total	kWh/m^2	15.84	17.22	22.41
	Total Consumption	kWh/m^2	44.78	46.12	51.32
	Reduction	%	46.97	41.22	34.03
	Max. Operative TEMP	°C	27.64	29.29	32.45
	Min. Operative TEMP		19.02	19.22	19.56
	Mean Operative TEMP		23.20	24.14	25.49
	Total emissions	$TnCO_{2equiv}$	147.35	151.88	168.98

The results show, in line with the results obtained by Rodrigues for the same climate context [15], that the internal gains are not easily dissipated through the envelopes with the lowest transmittance values, which means that for climate scenario 2080, increases in total energy consumption of 41.50% for the TERP, compared to 13.14% for the AS, concerning the consumption present for each of the simulated models. However, and for the same simulation period, if we compared the total consumption of the TERP for the not renewed building, we observed reductions of 25%, evidencing, however, a loss in the effectiveness of the strategies caused essentially by overheating of inner spaces were more pronounced in the warm periods of the renewed building, which implies a reduction in the efficiency of the renovation strategies of 13% compared to the not renewed building. The cooling demand for the TERP increases for the years 2050 and 2080 by 66.22% and 168.03%, respectively, for the values obtained for the present (Figure 3b).

In order to illustrate the loss of efficiency, it is convenient to compare the values obtained for the total consumption of the building in the present and at the end of the RSP, with the limitation established in the recent update of the DB-HE for the justification of an nZEB, which for winter climatic zone A is limited to 50 kWh/m^2.year. By means of a quadratic segmental interpolation of the values obtained for the three years in which the simulation was conducted, it has been possible to determine the evolution of consumption and emissions throughout the useful life of the renewed building (Figure 3a). In this way, we obtained that for the CTE-TERP, thanks to which by 2020, a total consumption of 46.32 kWh/m^2.year is achieved, at the end of its useful life (2070), the total consumption will be 49.98kWh/m^2.year, exceeding in 2071 the value limit of total consumption established at 0.16 kWh/m^2.year. Consideration of a renovation strategy in accordance with the calculated envelope characteristics values (O-TERP) allow for the total consumption of the building to remain four years beyond the RSP below the limit value. However, it should be noted that the recent update of the CTE introduces for the first time the concept of nZEB, and these values may be altered in subsequent updates that would motivate the increased demands on buildings in this regard. As verified under the initial hypotheses, the results show that a rehabilitation of the building aimed at transforming it into an nZEB will have a period of serviceability that will not exceed 50 years (TERP) and 54 years for options of optimized design and that present in the current industry (O-TERP).

On the other hand, and in relation to comfort, the operating temperature has been calculated for the different models and scenarios, confirming that the smallest increase in average temperature responds to the implementation of the renovation project in accordance with the values established by regulations (CTE-TERP), followed by the non-rehabilitated building (Actual State, AS) and the optimized renovation project (O-TERP). It is confirmed, therefore, that an envelope with a lower thermal transmittance causes overheating in future scenarios, which is detrimental to the comfort of the spaces, which, in any of the renovation hypotheses considered, increased the average temperature interior with respect to the projections for its current state in the year 2080 (24.90 °C) between 1.20% (CTE-TERP) and 2.16% (O-TERP).

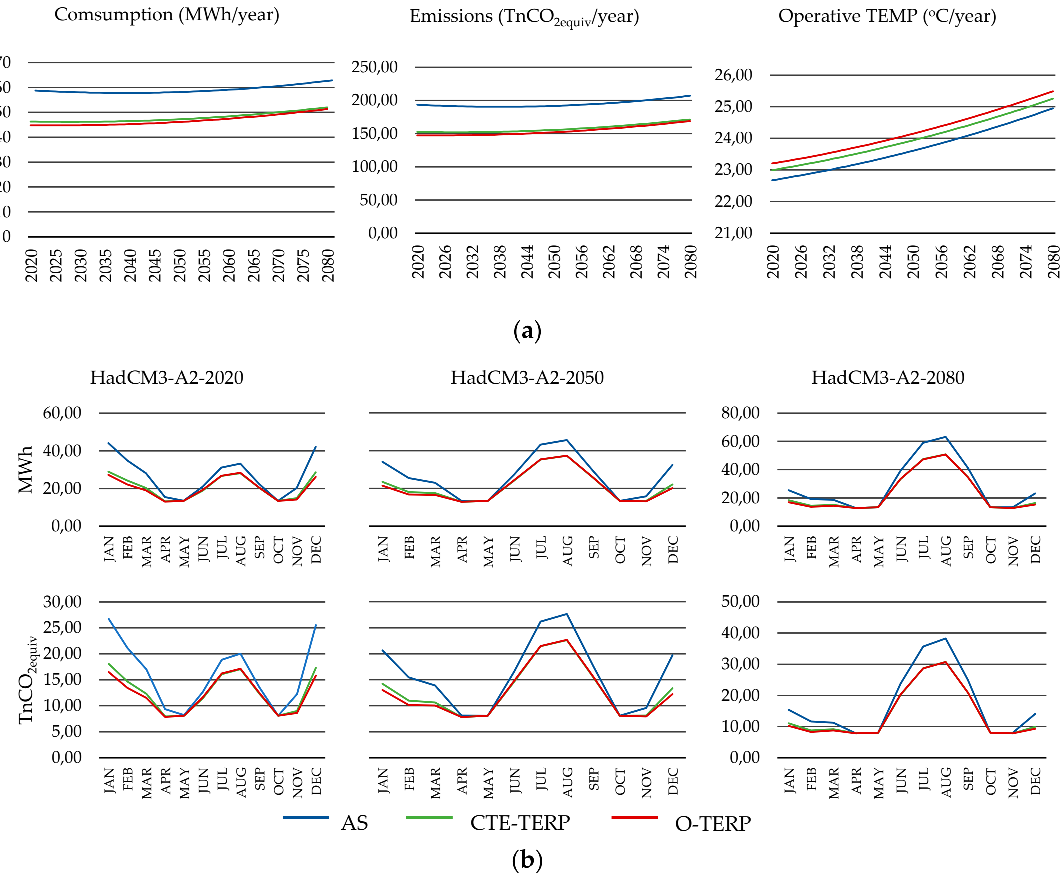


Figure 3. (**a**) Year-on-year evolution of total consumption, emissions, and operative temperature. (**b**) Monthly evolution of consumption and emissions in calculated years.

3.2. Assessment of the Environmental Sustainability of Thermal Envelope Renovation Projects and Communication of Results

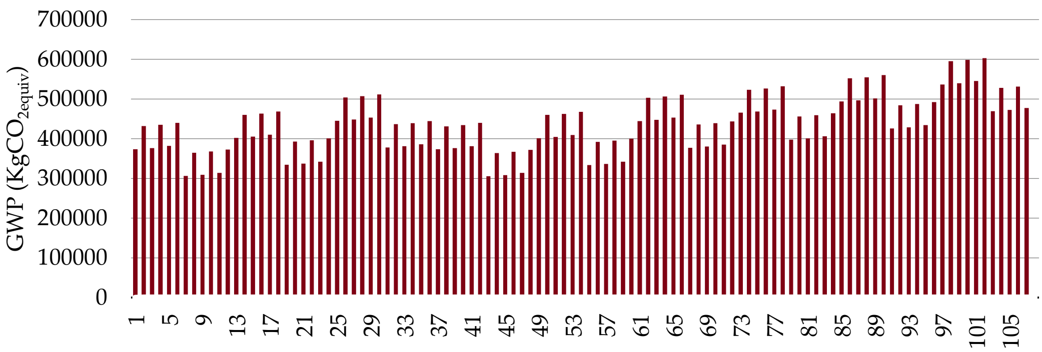
Table 3 shows, as a summary, the results obtained to estimate the emissions associated with the implementation of each of the different OODs. As noted, improvement strategies on the facade hollows are those with the greatest impact concerning the surface of the implemented construction system, the impact of solutions based on the use of aluminum profiles being notable, the implementation of which involves between 30% and 61% of the total emissions associated with the sets of combinations of strategies analyzed that we will see later. This, added to a greater benefit in terms of reducing consumption of the strategies at the level of blind walls, suggests that refurbishment of these elements entails a lower impact for the building under the study environment. Likewise, we can see that the emissions associated with the transport of waste averaged per square meter of the strategy implemented were very similar for all interventions carried out at the blind cloth level. However, for facade hollows and roof interventions, the said emissions increased, since the intervention areas were smaller and, therefore, the emissions increased. This would suggest that these types of strategies are more interesting when carried out jointly, either at the level of the building being operated on or on a set of similar buildings.

Table 3. Environmental assessment of module A of the Thermal Envelope Renovation Project (TERP) per unit area of different Options Design (OOD) constructive systems.

Module				**A**		
				Product and Construction Stage		CDW
Indicator				ADP	GWP	GWP
Units				MJ/m^2	KgCO$_{2equiv}$/m^2	KgCO$_{2equiv}$/m^2
EVF	B4	OP.1	HPL high pressure decorative laminated panel.	367.41	21.33	0.53
		OP.2	Single-sided polymer concrete pieces.	320.64	21.04	0.53
		OP.3	Large format ceramic pieces	754.07	44.11	0.72
EHCP	M1	OP.1	Mineral wool (MW)	143.20	4.26	0.53
		OP.2	Expanded polystyrene (EPS)	76.72	11.32	0.53
		OP.3	Extruded polystyrene (XPS)	150.44	22.20	0.53
	B2	OP.1	Lightweight and filtering precast concrete tile	220.94	218.53	3.84
		OP.2	Terrazzo flooring system on plots	332.22	32.18	3.84
EVH	C3	OP.1	Windows and balcony doors in non-laminated PVC	6747.02	730.35	3.48
		OP.2	Windows and balcony doors in alum. with thermal break	8409.56	990.47	3.48

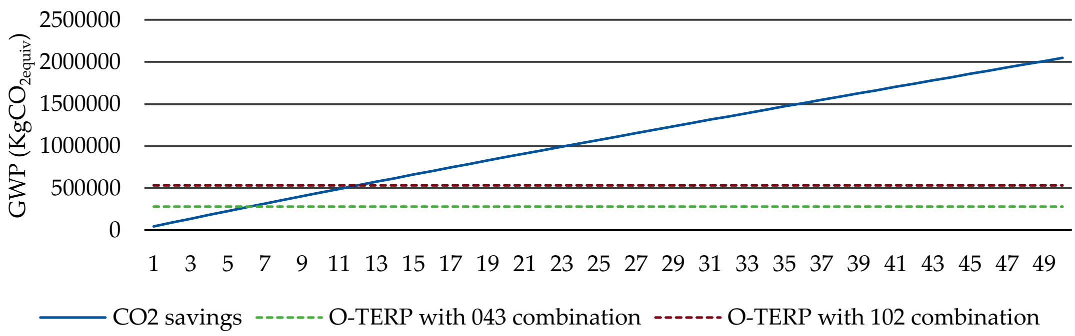
On the other hand, the 108 possible combinations between the different envelope renovation strategies were analyzed (Figure 4a), identifying the greatest/least environmental impact of each of them. The results of this analysis show that, even in the least impact combination (043 ODC), the emissions associated with the evaluation of modules A1–A5 and C2 were 278,362.78 KgCo$_{2equiv}$. If we compare this result with the evolution of the CO_2 emissions savings achieved through the intervention proposed throughout the RSP for the O-TERP renovation project, which allows greater emissions savings throughout its life useful (2,056,619.17 KgCo$_{2equiv}$), we can see that the embodied emissions into the project of execution will be offset within a period of six years, after which period we could be talking about real savings in GHG emissions (Figure 4b). The determination of CO_2 payback-time contemplates the loss of efficiency of the TERP caused by the increase in the demand for refrigeration throughout the RSP, which is a differentiating factor compared to previous investigations [71].

From all the information analyzed, it can be concluded that the emissions associated with the construction processes of the evaluated OODs represent between 14% and 26% of the total emissions saved throughout the RSP. It should be noted that for the calculations, the emissions associated with modules C3 and C4 have been omitted due to a lack of confidence in the analyzed data, therefore, the exposed environmental impacts are significantly less than the real ones.



(a)

Figure 4. *Cont.*



(**b**)

Figure 4. (**a**) Results for Global Warming Potential (GWP) indicator of 108 combinations of strategies applied on building. (**b**) Results for GWP indicator of 043OD (lowest-carbon design option) and 102OD (highest-carbon design option) in relation to the assessment of emission reductions during RSP with O-TERP considering climate change alterations on consumption.

3.3. Assessment of the Social Sustainability of Thermal Envelope Renovation Projects and Communication of Results

The surveys were carried out between March and June 2019 in two different phases. The total number of people surveyed was 34, which represents 71% of a building and 14% concerning the total number of urban cells in the different groups of the housing estate studied. These participation rates allowed us to consider the results with a margin of error of 10.18% and a confidence level of 80%, if they are contextualized at the neighborhood level, but with a margin of error of 5.99% if the data are contextualized at the building level, under the premise of the same level of confidence. However, we considered the sample representative enough to be able to conclude the results obtained, given the uniformity of the responses (Tables 4 and 5).

It was verified that the total of the people surveyed were homeowners. Likewise, the average age of the people surveyed was mostly above 65 years, which establishes an old population profile in the buildings. The relation of these two circumstances is a determining aspect to frame the results of the evaluations of the other two dimensions of sustainability since the analysis of issues such as the periods of return on investments to be made or the manifest interest on the part of users in adopting measures with less environmental impact are decisive in determining the degree of acceptance of which measures.

Furthermore, and concerning the physical characteristics of dwellings, a certain balance is recognized between their orientations, with a greater number of homes with rooms facing south (southeast). In the same way, it was verified that 76% of the houses from which data were obtained ed to flats located between floors 2 and 11, thus limiting them horizontally with thermally conditioned spaces, which is consistent with the model of the building that had been developed and from which results have already been obtained.

Next, the results of the surveys will be analyzed for each of the categories of social behavior. Additionally, we wanted to determine through the survey which aspects were related to the environmental and economic dimensions, so that they can be incorporated as two complementary categories of social behavior (Table 6).

Table 4. Survey results in the building for selected indicators in relation with the culture of use of neighbors and issues related to the potential TERP to be implemented in the building.

Starting Data									
Orientation (Living-dIning Room)		24%	North	32%	South	21%	East	24%	West
Flat				12%	01	76%	02–11	12%	12
Owner or Lessee									100%
Age Profile of Home Users (Years)				12%	20–45	41%	41–65	47%	>65
Adaptability									
2/1.1	How many people do you live in the house?								2.4
	Evaluate from 0 to 5. five being the highest score. how satisfied you are with the characteristics of each of the rooms in the house.							Hall	3.9
								Kitchen	4.3
								Laundry	4.2
								Dining room	4.4
								Toilet	3.9
								Bedrooms	4.3
								Bathroom	4.1
								Terrace	4.2
								Mean	4.2
2/1.2	Does the house fit your current needs?					100%	Y	0%	N
	Does the house adapt to the changes that occur in your life?					94.1%	Y	5.9%	N
	Have you thought about changing your home?					11.8%	Y	88%	N
	Have you thought about modifying the house where do you live?					41%	Y	59%	N
2/1.3	Does the house accommodate? to new technology?					97%	Y	3%	N
2/1.4	Have you thought of a different use for this dwelling compatible with the residence?					0%	Y	100%	N
Health and comfort									
3/1.1	Do you get cold inside the house in winter?					24%	Y	77%	N
	What measures are taken to avoid it?			58%		8.3%		33%	
				Heater		HVAC		Cloth.	
	Do you pass heat inside the house. in summer?					55.9%	Y	44.1%	N
	What measures are taken to avoid it?			40.0%		55.0%		5.0%	
				HVAC		Fan		Cloth.	
3/1.2	Do you feel excessive humidity in your home?					8.8%	Y	91.2%	N
3/1.3	Do you ventilate the house daily?					97.1%	Y	2.9%	N
3/1.4	Do you feel comfortable in the activities you do inside?					97.1%	Y	2.9%	N
3/1.5	Do you consider it annoying to change your clothing?					5.9%	Y	94.1%	N
3/2.2-3/4.2	Can you control the air conditions in the rooms?					88.2%	Y	11.8%	N
	If yes. what system do you use?				100%	Manually		0%	Auto
3/2.3	Do you have any syst. to know the internal air conditions?					14.7%	Y	85.3%	N
3/5.5	Do you consider adequate the acoustic insulation?					52.9%	Y	47.1%	N
3/5.6	Does the house have enough natural light?					100%	Y	0%	N
3/7.2	Does the house have awnings? Do you use them?	5.9%	Y	35.3%	Y	8.8%	Y	50.0%	N
		never		daily		by season			
3/8.2	Do you consider that the interior height of your home is adequate?					97.1%	Y	2.9%	N
3/8.6	Do you have a terrace with a sufficient surface for the use you make of it?					94.1%	Y	5.9%	N
3/11.1	Do you consider that there is a lot of external contamination and that affects the cleaning needs of the home?					58.8%	Y	41.2%	N

Table 5. Economic and environmental information obtained through the survey.

Economic Information	Is the average household income below the following figures?	47.1%	17.6%	8.8%	26.5%
		800 €/month	1.300 €/month	1.600 €/month	N
	What is the average monthly cost of your energy bill?	55.58 €			
Environ-Mental Information	Did you know that transforming thermal envelope can save up to 20% in energy?	57.1%	42.9%		
		Y	N		
	Do you know what GHG are and what is their impact in terms of accelerating climate change?	42.9%	57.1%		
		Y	N		
	Do you consider yourself a person concerned about environment?	92.9%	7.1%		
		Y	N		
	Who do you think should take an active part to minimize the impacts of climate change?	85.7%	7.1%	7.1%	
		Society	Politicians	Enterprises	
	Would you be willing to put your own money to implement in your building measures to reduce emissions from energy consumption?	100%			
		Y			

Table 6. Survey results in the building for the selected indicators in relation to the culture of use of neighbors and issues related to the potential TERP to be implemented in the building (continuation).

3/11.2	Perceiving bad odours in your home derived from the building's facilities? What facilities specifically?			26.5% sanitation	Y	2.9% shunt vent.	Y	8.8% both	Y	61.8%	N
3/11.3	Do you have air conditioning in the house?							82.4%	Y	17.6%	N
	If yes, do you use it very often?			0%	Always	18%	summer days		82%	hot days	
3/12.1	Do you consider that there is excessive light pollution in your environment? Is it difficult to darken the house at night?					11.8% difficult darkening	Y	8.8% no difficult darkening	Y	79.4%	N
3/12.2 y 3/12.3	Do the surrounding buildings shade the home? Would you claim that you don't have enough direct light?					2.9% more light	Y	11.8% no more light	Y	85.3%	N
3/14.1	Would you say that proper house maintenance is carried out? How often are repairs made?	2.9% monthly	Y	55.9% annually	Y	5.9% monthly	N	35.3% annually	N		
	Security										
4/15.1	In your experience, would you say your house adequately resist the torrential rains of recent years? Do you notice any damage / humidity / leaks?					5.9% failures in facade	Y	8.8% 2.9% failures in hollows	Y Y	0.0% 82.4% no failures	N Y
4/15.2	Have you had problems with rainwater leaks?							2.9%	Y	97.1%	N
4/18.3	Have you had a problem with humidity / condensation / leaks on the facade?			5.9% humidity	Y	0.0% condensations	Y	0.0% leaks	Y	94%	N
4/19.1	What solar control measures do you use most frequently?					71% blinds		15% curtains		15% awnings	
4/19.2	Have you exchanged windows for better features in the last 10 years?							53%	Y	47%	N
4/19.6	Do you consider the orientation of the house good? Do you save energy for it?					68%	Y	2.9%	Y, no savings	29%	N

3.3.1. Results for Survey in Relation to the Category of Social Behavior "Adaptability"

As a question before evaluating the adaptability of the dwellings, the survey aimed to determine both the number of people living in the dwellings and the level of satisfaction with the different dependencies. In this way, it was possible to quantify that the majority, with 42.2%, resided in homes consisting of two people with average ages between the ages of 20 and 65. The profile of dwellings inhabited by three people comprised 23.5% of the respondents, mainly aged between 45 and 65 years. Households made up of a single person represented 17.6%, being entirely people over the age of 65.

On the other hand, and concerning the satisfaction level of users with their home, we observed that it was quite high, which is why they would hardly require far-reaching functional transformations. By room, the worst-rated were the toilets and the lobby.

On the other hand, the homes of the people surveyed were mainly adapted to their current needs as well as to the changes that took place in their lives and technological changes. On the other hand, 88.2% of those surveyed had not thought about changing their homes. However, the proportion between those who wanted to modify their home and those who were not more balanced, being 58.8% of the neighbors who did not want to modify their home and 41.2% who would be willing to carry out interior modifications and/or redistributions. Regarding the approach of new uses of dwellings, the residents responded in their entirety that they had not thought about making the use of housing compatible with any other.

3.3.2. Results for Survey in Relation to the Category of Social Behavior "Health and Comfort"

Understanding the uses and customs of the users to air-condition their residence in both the hot and cold months is important, since, to a large extent, the renovation strategies of the buildings will have to respond to these user profiles. In this sense, it should be noted that, in general, the neighbors do not recognize being cold in the winter months. However, the number of residents surveyed mostly admit overheating inside the home in the warm months (55.9%), which will be an effect that will increase over the following years as a consequence of climate change.

By season, the most widely used indoor climate conditioning equipment was, in winter, individual heating equipment connected to the electricity grid at 58.3% and individual air conditioning equipment at 8.3%; in summer, portable ventilation and cooling equipment connected to the mains power at 55% and individual air conditioning equipment at 40%. In general, it is observed that a significant number of those surveyed tend to only and exclusively modify their clothing in the interior of the dwellings to improve their comfort conditions therein, with a greater number of neighbors increasing the degree of clothing in the cold months (33.3%), compared to those who reduced this clothing insulation in the warmer months (5%). There is a high percentage of residents (41%), who did not feel thermal discomfort inside their home in any of the two climate classifications.

If we look at the profiles of the use of cooling and heating systems, we see that there is greater use of individual equipment connected to mains power. Similarly, and as the use of air conditioning equipment is more widespread in hot periods, it was observed that only 13% of people, who recognized thermal discomfort in their home throughout the year, used this device to acclimatize their homes in both regimes. With all of this, it was established that part of the energy consumption of 56% of users was used to thermally acclimatize the home, while the other residents did not use electrical energy to acclimatize their home. This is a relevant fact, especially if we consider that renovation actions aim to reduce said consumption, which would not exist, according to the groundwork carried out, in just under half of the building. This, as will be seen in the discussion of the results, will have repercussions regarding the expected return on investment, since these periods extend over time, given the representativeness of the consumption associated with interior thermal conditioning.

3.3.3. Results for Survey in Relation to the Category of Social Behavior "Security"

In general, there are no notable problems to be addressed from the perspective of the category of indicators evaluated. Likewise, there is a general perception that homes have an adequate orientation (70.5%), with homes facing north and/or west being the most penalized in this regard, whose users (29.4%) acknowledge that their home did not have a good orientation.

On the other hand, it should be noted that around 53% of the residents had changed their windows in the last 10 years, so considering a strategy that pursues the replacement of such an element would entail at least an expense that is hardly justifiable for these residents since they have so far invested in improving the internal conditions of their home.

3.3.4. Results for Survey Regarding Environmental and Economic Dimensions

To relate the environmental and economic dimensions to the profiles of the different users, we wanted to incorporate into the survey a series of questions (not included in the reference methodology) that are considered particularly relevant to know the degree of the commitment of the environmental protection of users as well as evaluate the energy consumption profile and income level of families (Table 4).

From an economic perspective, it was confirmed that most of the families (73.5%) had a family income of less than €1600 per month, which makes it possible to increase the amount allocated through subsidies for building refurbishment. With these premises, the amount to which the building understudy would have access will be established for economic calculations. Another issue to consider has to do with the average expenditure per family on energy, which will also allow us to establish returns on economic investment through savings on bills. This average cost is estimated at €55.58.

From an environmental point of view, the survey provides information about the degree of the commitment of users to fight against climate change and their knowledge of specific issues regarding energy efficiency and environmental commitment.

It was observed that practically all the people surveyed expressed a concern for the environment (92.9%) while assuming that it is a problem that will have to be tackled on a general level by all of society. On the other hand, and concerning aspects that focus more on the knowledge of the people surveyed regarding the issues raised, it was noted that in a significant percentage (78.60%), there was a specific weight of the residential sector in the set of GHG emissions to the atmosphere. In contrast, a greater knowledge was perceived regarding the reduction in energy consumption that is achieved through measures such as changing windows. All the people surveyed stated that they would be willing to contribute financially to the transformation of their building in order to reduce the emissions that derive from its consumption.

The results obtained from the environmental perspective are in turn aligned with those obtained by the Royal Elcano Institute for its July 2019 report on the perception of Spanish citizens regarding climate change [72]. This report stressed that the majority of the Spanish population (97%) perceived climate change with great concern, being the greatest threat facing our society today. Although concerning the increase in the circulation tax to allocate these funds to mitigate climate change, it is appreciated that the majority (56%) of respondents were willing to economically face expenses in favor of global improvement in environmental terms.

3.4. Assessment of the Economic Sustainability of Thermal Envelope Renovation Projects and Communication of Results

Table 7 follows the same scheme as that already analyzed from an environmental perspective, but unlike it, this time the economic impacts associated with CDW management will be analyzed including in addition to transportation to landfill, the waste fee. In line with the results for the environmental evaluation, we observed that the systems with the highest economic cost concerning the surface were those that sought to improve the hollows. In contrast, the renovation of the roof through a lightweight and filtering precast concrete tile system was the most economical option of renovation of the envelope, followed with a significant difference by the ventilated facade system using ceramic pieces.

Table 7. Economic assessment of modules A and B of TERP per unit area of different design options (OOD) constructive systems.

Module				A		B
				Product & construc-tion	CDW	Maintenan-ce
Indicator				Non annual cost	Non annual cost	Annual cost
Units				€/m^2	€/m^2	€/m^2
EVF	B4	OP.1	HPL high pressure decorative laminated panel.	128.11	19.20	1.00
		OP.2	Single-sided polymer concrete pieces.	133.59	114.36	0.88
		OP.3	Large format ceramic pieces	111.18	183.95	2.56
EHCP	M1	OP.1	Mineral wool (MW)	11.28	15.90	0.02
		OP.2	Expanded polystyrene (EPS)	8.82	11.03	0.02
		OP.3	Extruded polystyrene (XPS)	8.30	15.33	0.02
	B2	OP.1	Lightweight and filtering precast concrete tile	46.11	39.96	3.04
		OP.2	Terrazzo flooring system on plots	133.59	122.12	0.40
EVH	C3	OP.1	Windows and balcony doors in non-laminated PVC	484.06	0.01	0.05
		OP.2	Windows and balcony doors in alum. with thermal break	578.92	0.01	0.06

In addition, the results were evaluated on the selected typology, given that its morphological characteristics will implement the different construction systems combined have an economic impact that will have to be evaluated and compared. To do this, the data were contextualized with the surface of the different envelopes.

At the same time, and for all combinations of strategies studied, the economic returns were equate, in the form of reducing energy costs derived from a lower consumption of the homes, consigning them based on the O-TERP renovation project, whose energy savings were modified throughout the RSP as a consequence of the effects of climate change. This entails for each of the combinations of OOD reductions in expenditure for the AS (CF) throughout the entire useful life of the variable building and essentially conditioned by the annual maintenance costs of each of the strategies, the evolution of energy prices (2%), and the loss of efficiency of the renovation strategies analyzed in Section 3.1.

As can be seen in Figure 5a, there is a remarkable relationship between the maintenance costs and the initial investment cost of the renovation strategies analyzed, verifying that options with a lower initial investment cost (from 073 ODC) have higher annual maintenance costs. This will be of great importance if the solutions are studied from the perspective of the life cycle analysis, since combinations of strategies with a high cost, despite the fact that they could have low maintenance costs, will lead to longer periods of return on investment than those options with lower initial implementation costs. This leads us to the conclusion that the most suitable options from the economic point of view will have to be those with a lower initial investment cost and a lower annual maintenance cost. If we analyze the set of combinations under this criterion, we see that 029 ODC is the most appropriate, with an initial investment cost of €556,184.51 (not including subsidies) and annual maintenance costs of €5439.64/year. Therefore, it will be said combination 029 that will be analyzed from a life cycle analysis perspective, in order to calculate the different economic indicators that will allow us to obtain the implications of adopting this measure in-depth.

On the other hand, and with the purpose of establishing the difference between the global cost of the conservation of the construction systems of the building without restoration and the global cost of the improvement systems to be implemented, a series of costs associated with the plan of maintenance would have to be followed to ensure the correct behavior of the different existing construction systems. For this calculation, the residual value for amortization of the replacement cost of the systems that are maintained is also determined by the number of replacements that occur and their useful life. Likewise, the cost of GHG emissions from the non-rehabilitated building is calculated according to the platform

Carbon Pricing Dashboard [62] for the year 2019, which established a cost of €14.84 per ton of CO_2 emitted with an inter-annual evolution of said rates of 1.40%. Finally, for the determination of the global cost in line with the provisions of the UNE-EN 15459-1: 2018 standard, the disposal costs for the dismantling of the existing construction systems were also determined. With all of the above, it can be obtained that the overall cost of not adopting measures for the building that only pursues the mere maintenance of existing systems is €1,077,175.87.

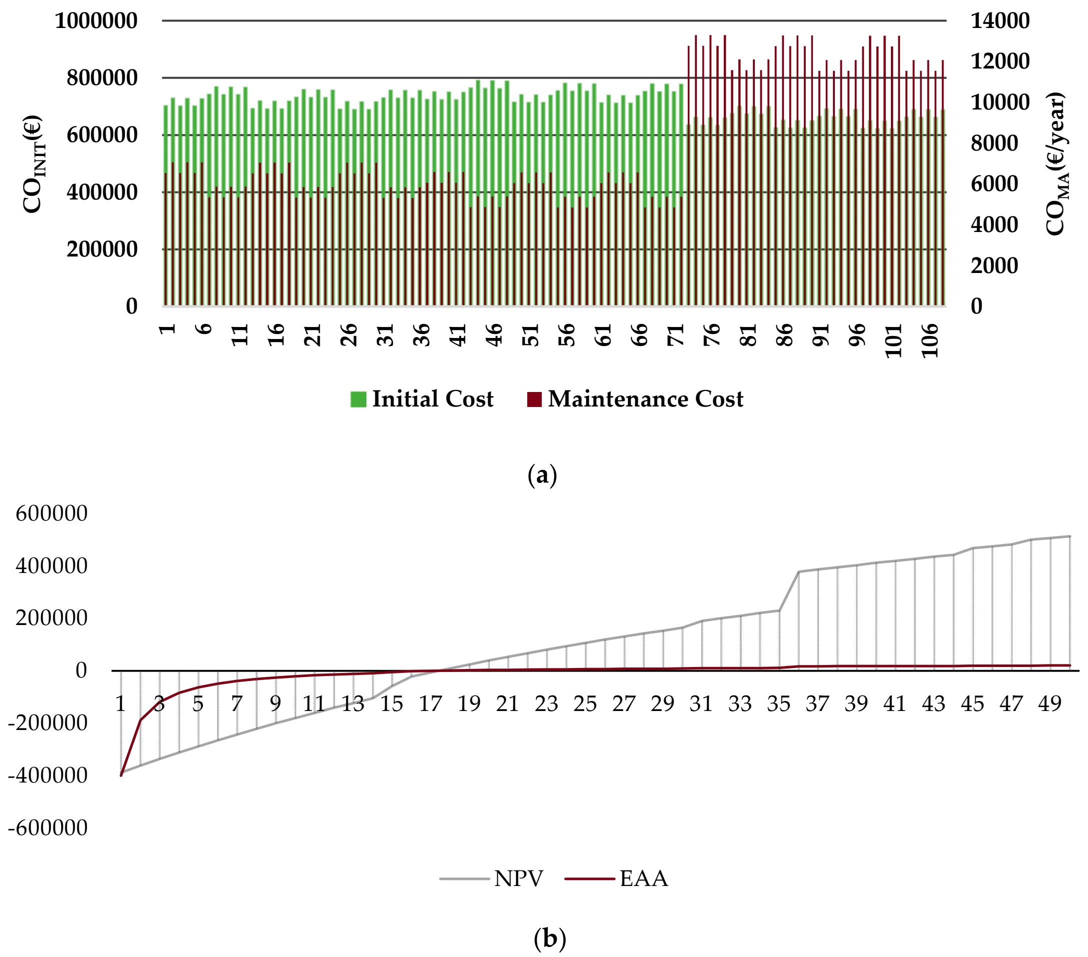


Figure 5. (**a**) Results for the indicators Initial Cost (CO_{INIT}) and annual Maintenance Cost (CO_{MA}) of the 108 combinations of Thermal Envelope Renovation Strategies (TERS) applied. (**b**) Net Present Value (NPV) and Equivalent Annual Annuity (EAA) evolution through Reference Study Period (RSP) for the 029 OD.

To calculate the initial cost, it will consider the costs and income throughout the useful life of the 029 OD. For the determination of said cost, the Execution Material Project (PEM) is increased, when considering concepts such as urban rates, general expenses (13%), industrial profit (6%), and technical fees (6%).

Once this real cost is obtained, we will then be able to determine the different economic indicators, which we have analyzed in the previous section, for the option that is the most economically optimal one. These economic indicators are the Global Cost, GC (Equation (5)); net present value, NPV (Equation (2)), and equivalent annual value, EAA (Equation (4)).

The evaluation results showed that the said combination had the lowest overall cost, being the same as €1,256,112.00, which is 16.61% higher than the CG of not intervening on the building. At the same time, we obtained a NPV for the RSP of €513,044.82, which will entail returns on investment from year 17 (Figure 5b).

Regardless of all of the above, we observed that the returns on economic investment and emission offsetting are closely conditioned on the consumer culture of users, who mostly acknowledge not making use of the energy for its thermal conditioning. For this reason, the social context is shown as a key factor when evaluating the environmental and economic impacts throughout the LCA, and the relationship between these impacts having to be contextualized to guide decision-making toward a reasonable balance that allows for benefits in the short- and long-term.

4. Discussion

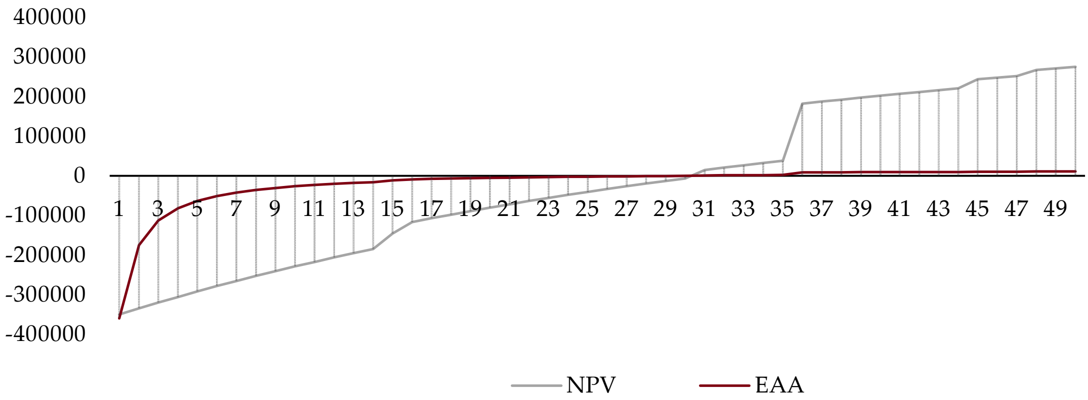
The discussion of the results obtained will focus on the contrast between the quantitative data at the economic–environmental level calculated and the qualitative results that have been determined from the surveys carried out through the results of the RRIM.

As we have seen, the emissions associated with the improvement strategies studied entail an environmental impact due to the embodied carbon in the materials used, which allows us to state the compensation period for the embodied emissions that would be achieved through the emission savings in 6.77 years for the most environmentally sustainable combination (043 ODC, Option Design Combination) and 12.93 years for the combination with the highest environmental impact (102 ODC). From a socio-environmental perspective, and if we contextualize the results based on the current culture of the residents about the use of energy for the thermal conditioning of their homes, we can observe that said emission compensation terms for the aforementioned options are extended to 12.13 and 23.18 years, increasing the emissions offset period by an average of 79.22%. These data, extrapolated to the set of buildings with similar characteristics that form the neighborhood, allowed us to determine that the emission offset period for the execution project for the renovation of the building envelope is 59.65 years for the 043 ODC and 113.95 years for 102 ODC, this second one being the one with the greatest environmental impact. The total expected savings for the set of residential units with identical characteristics at the end of the RSP is 5640.30 $TnCo_{2equiv}$ after the implementation of the O-TERP; the most environmentally efficient ODC involves emissions at the urban level of 1368.62 $TnCo_{2equiv}$ and the least efficient of 2614.37 $TnCo_{2equiv}$. Thus, we can affirm that, at the urban level, around 24.26% and 46.35% of the expected savings in emissions for the RSP as a result of the implementation of the analyzed TERS (thermal envelope renovation strategies) only compensate the emissions incorporated in the current and most widespread industrial design options.

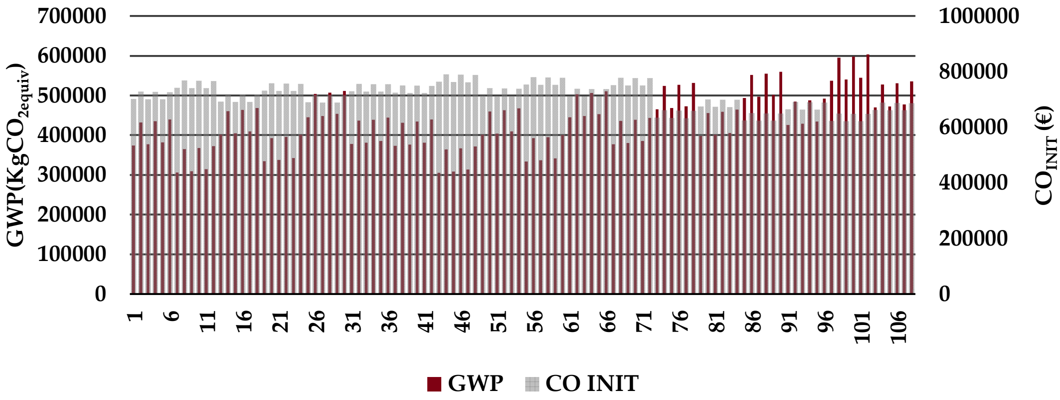
On the other hand, from a socio-economic perspective, it was possible to verify that the surveyed users had a good disposition to participate economically in the transformation of their buildings to improve their sustainability; nevertheless, there is a high degree of user satisfaction with their dwellings that does not justify functional interventions. Likewise, the significant deviation of the results obtained for the evaluation of the economic sustainability of the implementation of the different ODs associated with the O-TERP throughout the life cycle of the building was verified, as they are related to the results of the surveys. The consideration of aspects such as the percentage of neighbors who had replaced the windows with those with better characteristics and the low number of users who claimed to consume energy to acclimatize their home throughout the year, makes the consideration of investment returns that had been determined for the combination of strategies 029 (the most efficient from an economic point of view), extend to 30 years (Figure 6a).

In addition, and to draw partial conclusions regarding the economic and environmental issues, we were able to verify that the combination with the lowest economic cost, 029 ODC, had an environmental impact, measured through the GWP indicator, of 317,442.70 $KgCO_{2equiv}$, the sixty-fifth combination was more environmentally sustainable, which is far from a positive aspect from the environmental point of view, also entails a period of emission compensation through the expected savings over the useful life of 13.84 years at the building level, considering the social aspects previously seen. On the other hand, the economic indicators of the design option with the least environmental impact (043 ODC), contextualized at the social level, showed an overall cost of €1,157,633.05 and a return on investment period of 31 years, which increased the values obtained for the 029 ODC by

2.30% and 3.33%, respectively. This shows that, at present, the measures with the least environmental impact are not optimal from the economic point of view, verifying that the combination of the least environmental impact occupied position 92 of the most economically profitable of all those entired studied (Figure 6b).



(**a**)



(**b**)

Figure 6. (**a**) Net Present Value (NPV) and Equivalent Annual Annuity (EAA) evolution throughout the RSP for the 029 ODC considering social issues. (**b**) Comparison of the initial cost and emissions associated with each design option combination.

Finally, it should be pointed out that the methodology developed does not have a reference framework that allows us to understand the adequacy of the renovation project concerning the economic and environmental aspects that have been socially contextualized. However, and taking into account the context in which the research has been carried out, the important specific weight of the environmental impact in the construction phase of the analyzed TERS indicates that the current construction means, techniques, and materials do not allow us to tackle a renovation of the existing environmentally sustainable state housing, essentially due to the long compensation period for GHG emissions through the reduction in consumption that the evaluated design options have. Considering this issue in decision-making will imply that renovation strategies that allow for both a shorter period of return on investment and a shorter period of emissions compensation must be prioritized.

5. Conclusions

The two main conclusions of this article after the development, application, and discussion of the results of the proposed methodology, whose main objective is to evaluate the comprehensive sustainability of existing passive strategies in the local industry:

- The loss of the effectiveness of the renovation strategies adopted for a climatic situation such as the current one throughout the reference study period.
- The deviations from expected economic investment returns and CO_2 payback time when considering the social dimension and its importance from an urban perspective.
- The necessity of a local framework to determine the adequacy of the economic and environmental impact of the renovation project.

Through the evaluation of the integral sustainability proposed in this article, it was possible to verify a loss of efficiency of 13% of the measures adopted in the present for the renovation of the thermal envelope, a direct consequence of the effects of climate change that were estimated through HadCM3-A2. This led to an increase in the demand for cooling in future scenarios, which shows, on one hand, the interest in renovating the envelope of existing buildings in Mediterranean climates based on these premises and attending to the significant demand for cooling in our buildings for years to come. In this regard, it is worth underlining the importance of more easily dissipating internal loads through the enclosure. In a context such as the one given, this highlights, on one hand, the importance of the materials used for the renovation and its ability to modify its transmissivity in warm periods [41] and, on the other hand, the need to advance in the definition of decentralized energy models based on the use of renewable sources to meet the future demands of residential estates [19,20] that, as we have seen, will increase.

In the same way, the importance of considering qualitative models for the evaluation of comprehensive sustainability is revealed, since the economic returns of the investment to be made to regenerate the buildings such as the offset period of the emissions generated by the actions of renovation (TPB CO_2) are conditioned to the energy consumption profiles of the users of the dwellings. For the different design options studied, it has been possible to determine that the consideration of these consumption profiles makes the emission compensation periods at the building level, and therefore of the "urban organism" they constitute, increase by around 80%, the average standing at 17.65 years. Along this line, it was verified that the consideration of said consumption profiles on different economic indicators motivates an increase in the general cost of the most profitable design option, which is around 2.30%, and an increase in the return period of the 3.33% investment compared to the developed quantitative model. Appendix E defines the different combinations of options to which we have referred (043 ODC, 029 ODC) and the calculated indicators as well as the design option with the least environmental and economic impact (001ODC), which is also graphically characterized.

With all this, the importance of considering the three dimensions of sustainability for the evaluation of the LCA of the building is revealed, since only through tools based on holistic methodologies such as the proposed one, is it possible to estimate results that allow for measures to be adopted in the present to suit both current and future needs. The results obtained for the object of the study show the need for different tools to be articulated that enable a systemic renovation of the existing real estate park that is environmentally and economically sustainable. In this sense, the need for specific plans that establish reference frameworks at the local level in order to limit the embodied energy in the interventions on buildings as well as to limit the periods of return of desirable investment. Only in this way will it be possible to provide the stakeholders in the building refurbishment process with tools that allow the interests of reducing emissions at the global level to be articulated with the actions carried out on the buildings.

As long as these renovation processes are not approached from this perspective, we can talk about improving comfort, the observed reduction in consumption, and even the urban image of our cities, but there are inconsistencies in the traceability of how this contributes to an improvement in terms of a comprehensive sustainability.

Author Contributions: Formal analysis, P.M.-M.; Investigation, M.R.-M. and P.M.-M.; Methodology, M.R.-M. and P.M.-M.; Project administration, P.M.-M. Resources, P.M.-M. and M.R.-M.; Software, M.R.-M.; Supervision, P.M.-M.; Validation, P.M.-M.; Visualization, M.R.-M.; Writing—original draft, M.R.-M.; Writing—review & editing, M.R.-M. and P.M.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This paper and the costs for its publication in open access were funded by the CircularBIM project (code 2019-1-ES01-KA203-065962), an ERASMUS+ project co-funded by the European Union and within the framework of an initiative of 2019 KA203, Strategic Partnerships in the Field Of Higher Education), with the support of the "Servicio Español Para la Internacionalización de la Educación" (SEPIE, Spain). This research was funded by the ERASMUS+ Program and the research projects art. 68/83 LOU ref.2827/0632 "Diagnosis of Energy Poverty in Buildings and Eco-Efficient Repair Proposal" and ref. 2688/0632 "NZEB: Technical Project, Coordination and Technical Advice in the Direction of the Works of the Pilot Project" Nearly Zero-Energy-Building "of Single Family House in the Smithy, Fuente Palmera (Córdoba). The results of this work are part of the main author's doctoral thesis, which developed the knowledge acquired during the research stay at the National University of La Plata, Buenos Aires, Argentina, from the co-author of the article and as results of the same, hence the application to temperate climates, which include Spain and Argentina.

Conflicts of Interest: The authors declare no conflict of interest

Abbreviations

AS	Actual State
BEDEC	Structured data bank of cons- truction elements developed by ITEC (Spanish acronym, SA)
CDW	Construction and Demolition Waste
CF	Cash Flow
CTE	Technical Building Code (SA)
DGT	General Direction of Traffic (SA)
DIT	Technical suitability document (SA)
DM	Decision Making based on minimize environmental and economic impacts
EAA	Equivalent Annual Annuity
EE	Embodied Energy
EHCP	Horizontal Envelope Flat Roof (SA)
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declarations
EU	European Union
EVF	Vertical Envelope Facade (SA)
EVH	Vertical Envelope Hollow (SA)
GCM	General Circulation Modelling
GHG	Greenhouse Gases
HadCM3	Hadley Centre Coupled Model version 3
INA	Indicator Not Assessed
INE	Statistics National Institute (SA)
IPCC	Intergovernmental Panel on Climate Change
IPREM	Multiple Effect Public Income Indicator (SA)
RRIM	Results Integration in a single Model after the decision making taken
ITEC	Catalan Technical Institute (SA)
LCA	Life Cycle Assessment
ME	Construction Model of Evaluation
MS	Building Thermal Model Simulation
NO_2	Nitrogen dioxide
NPV	Net Present Value
nZEB	Nearly Zero Energy Buildings
NR	Not Relevant
OMAU	Urban Environment Observatory of Malaga (SA)
OD	Option Design
ODC	Option Design Combination
O-TERP	Optimized Thermal Envelope Project
PCM	Phase Change Material
PM2.5	Particulate Matter, combustion particles, organic compounds, metals, etc.(<2.5 μm)
PM10	Dust, pollen, etc.(<10 μm)
PVPC	Voluntary Price for the Small consumer (SA)
REE	Spanish Electrical Network (SA)
RR	Results of model evaluation
RRI	Results Integration
RSP	Reference Study Period
TAR	Third Assessment Report of the IPCC
TEMP	Temperature
TERP	Thermal Envelope Renovation Project
TERS	Thermal Envelope Renovation Strategies
TPB	Payback-time
Ulim	Thermal transmittance

Appendix A

Table A1. Urban indicators for the housing polygon preselected.

Urban Area not Protected and Susceptible to Intervention on the Envelope of Buildings				151. Polygon Carretera de Cártama
	Local Agenda XXI	**Desirable Trend**	**2050 Target**	
Urbanization and Territorial Occupation	population density (inhabitants per hectare)	∧	>120	200/400
	houses built (numbers of dwellings)	=	-	1540
	housing density (housing per hectare)	∧	>45	90.6
	housing typology	∧	>95%	isolated multi-family
	net compact-ness (built area/urban area)	∧	>0.80	3.00/4.00
Complexity and Diversity of Uses	urban complexity (mean dimension-less index)	∧	>5	2.7/2.9
	built roof (residential area/total built area)	∨	75%	85/90

Appendix B

Table A2. Possible thermal envelope renovation strategies to apply on the functional equivalent.

Part of the Envelope	Constructive System			[C] [1]	[M] [2]	[B] [3]
[EH] Horizontal Thermal Envelope	[C] Roof	[P] Flat	Transformation into an extensive/intensive green roof	-	-	EHCP-B1
			Transformation in vented roof	-	-	EHCP-B2
			Incorporation of external thermal insulation	-	EHCP-M1	-
	[T] Ceiling		Incorporation of internal thermal insulation	-	EHT-M1	-
[EV] Vertical Thermal Envelope	[F] Facade		Transformation into ventilated facade	-	-	EVF-B3
			Transformation by repair and painting with thermal insulating paint			EVF-B6
			Transformation using PCM materials	-	-	EVF-B7
			Incorporation of external thermal insulation	-	EVF-M1	-
			Incorporation of thermal insulation inside the envelope	-	EVF-M2	-
			Incorporation of internal thermal insulation	-	EVF-M3	-
	[PT] Thermal Bridge		Incorporation of external thermal insulation	-	EVPT-M1	-
			Incorporation of internal thermal insulation (only in pillars)	-	EVPT-M2	-
	[H] Doors and windows		Adding a shadow element outside	-	-	EVH-B1
			Adding a shadow element inside	-	-	EVH-B2
			Adding a vegetation elements outside	-	-	EVH-B3
			Replacement of external carpentry	EVH-C1	-	-
			Replacement of glazing in hollows by low emissivity	EVH-C2	-	-
			Adding a new external carpentry	EVH-C3	-	-

[1] Change/Combination by/with new constructive system; [2] Improvement of insulation; [3] Bioclimatic transformation.

Appendix C

Table A3. Percentage of reduction of solar gains, sensible heating, and sensible cooling with pre-selected thermal envelope renovation strategies (TERS) per stories with respect to the actual state (AS). −.

Renovation Strategy	Story	Zones	Solar Gains (%)	Sensible Heating (%)	Sensible Cooling (%)
EHCP-B2	12	A	-	−4.86	−15.25
		B	-	−3.47	−20.59
		C	-	−4.14	−20.24
		D	-	−5.39	−17.59
EHCP-M1	12	A	-	−22.59	−18.64
		B	-	−19.49	−21.28
		C	-	−21.33	−20.87
		D	-	−24.10	−17.71
EVF-B4	1	A	-	−10.70	−7.12
		B	-	−10.17	−6.42
		C	-	−8.87	−8.18
		D	-	−9.11	−8.45
	2-11	A	-	−11.17	−6.55
		B	-	−10.57	−5.60
		C	-	−9.77	−7.30
		D	-	−10.13	−7.75
	12	A	-	−5.91	−5.61
		B	-	−5.58	−4.87
		C	-	−5.28	−5.22
		D	-	−5.48	−5.96

Table A3. *Cont.*

Renovation Strategy	Story	Zones	Solar Gains (%)	Sensible Heating (%)	Sensible Cooling (%)
EVF-M1	1	A	-	−52.34	−5.23
		B	-	−49.27	−3.53
		C	-	−51.06	−8.10
		D	-	−52.90	−9.13
	2-11	A	-	−52.14	−3.13
		B	-	−48.92	−0.73
		C	-	−51.18	−5.12
		D	-	−53.29	−6.72
	12	A	-	−28.76	−2.98
		B	-	−27.24	−0.96
		C	-	−27.14	−1.80
		D	-	−28.13	−9.82
EVH-C3	1	A	−52.69	−10.48	−18.88
		B	−52.91	−12.93	−18.40
		C	−53.33	−11.90	−17.45
		D	−52.93	−9.58	−19.15
	2-11	A	−52.77	−11.28	−19.64
		B	−52.94	−13.82	−19.17
		C	−53.33	−12.83	−18.25
		D	−52.93	−10.25	−19.80
	12	A	−53.03	−4.78	−14.77
		B	−53.38	−6.78	−12.65
		C	−53.39	−6.10	−12.61
		D	−53.06	−4.05	−15.32

Appendix D

Table A4. Assignment of influences of the social assessment indicators selected for the different remaining information modules.

Aspect/Indicator		Indicator	Specific Provision, Measure or Activity	B2	B3	B4	B5	B6
Aspect According to Section								
1	Accessi-bility	7.2.2.1 Approach to the building 7.2.2.2 Access and movements in the building						
2.9	7.2.2	Layout, dimensions and ease of operation of elevators	Elevator replacement	X	X	X	X	X
2	Adapta-bility	7.3 Adaptability						
1.1	7.3	building's ability to accommodate indi-vidual user requirements	Enable new redistributions	INA	INA	INA	X	INA
1.2	7.3	building's ability to accommodate changes in user requirements		INA	INA	INA	X	INA
1.3	7.3	building's ability to accommodate technical changes	Update obsolete installations	INA	X	X	X	X
1.4	7.3	building's ability to accommodate change of use	Inventory compatible activities	INA	INA	INA	X	X
3	Health & Comfort	7.4.2.1 Aspects of thermal characteristics related to the structure of the building 7.4.2 Thermal characteristics						
1.1	7.4.2.1	operating temperature (°C or K) (radiant surface temperature, air temperature and distribution)	Adopt transformation measures for the building envelope	INA	INA	INA	X	X
1.2	7.4.2.1	humidity (% or g/kg)		INA	INA	INA	X	X
1.3	7.4.2.1	air speed (m/s) and distribution	Renovate the building's natural ventilation system	X	X	X	X	X
1.4	7.4.2.1	type of activities in space	-	INA	INA	INA	INA	X
1.5	7.4.2.1	type of users (Clothing insulation)	-	INA	INA	INA	INA	X
		7.4.2.2 Aspects of thermal characteristics related to the user and the control system						
2.2	7.4.2.2	the operating temperature in individual spaces can be controlled [Yes / No].	Manual control measures: use of awnings, blinds and carpentry	X	X	X	X	INA
2.5	7.4.2.2	humidity in individual spaces can be controlled [Yes / No].		INA	INA	INA	X	INA
2.7	7.4.2.2	speed and air distribution in individual spaces can be controlled [Yes / No].		X	X	X	X	INA
		7.4.3 Indoor air quality characteristics 7.4.3.2 Indoor air quality aspects related to the user and the control system						
4.2	7.4.3.2	Is there control of the ventilation of the users by means of automatic and / or manual control? [Yes / No].	Manual control measures	INA	INA	X	X	X
		7.4.4 Acoustic characteristics						
5.5	7.4.4	acoustic insulation of existing buildings	Conduct test and take corrective action	NR	INA	INA	X	INA
		7.4.5 Visual comfort characteristics 7.4.5.1 Aspects of the visual comfort characteristic related to the structure of the building						
6.2	7.4.5.1	Contribution of natural light	Lighting study in order to withstand potential changes in use	INA	INA	INA	X	X

Table A5. Assignment of influences of the social assessment indicators selected for the different remaining information modules (continuation).

Aspect/Indicator	Aspect According to Section	Indicator	Specific Provision, Measure or Activity	B2	B3	B4	B5	B6
6.3	7.4.5.1	Is there a visual connection to the outside world [Yes / No]? (1) What is the height of the windowsill ? (2) Is there a view of the different layers: sky, city / landscape and /or terrain?	Transform hollows and enhance visual connection with the outside	INA	INA	INA	X	INA
		7.4.5.2 Aspects of visual comfort related to the user and the control system						
7.2	7.4.5.2	Can the user control the amount of natural lighting in individual spaces? - [Yes / No].	Manual control measures	INA	INA	INA	X	INA
		7.4.6 Spatial characteristics						
8.2	7.4.6	height from floor to ceiling (m)	Height reduction in distributors and bathrooms for implementation of centralized climate system in housing	INA	INA	INA	X	INA
8.6	7.4.6	outdoor space (type, for example balconies, terrace or garden and area (m2)	Possibility of increasing depth of existing terraces or generating new ones	INA	INA	INA	X	INA
		7.5 Impacts on the neighbourhood						
11.3	7.5.3	water (for example droplets from air conditioning, gutter and downspouts)	Redirect a water evacuation net	NR	INA	INA	X	INA
		7.5.4 Glare / Over Shading						
12.1	7.5.4	night glare: (1) protection and illuminance (lux) of the evaluation object at night and whether it is continuous or intermittent; (2) the presence of light (for example flashing, intermittent, red) that causes irritation, loss of concentration, etc.	Reduce levels of light pollution in the environment. There are problems with natural ventilation on summer nights	INA	INA	INA	INA	INA
12.2	7.5.4	daytime glare: (1) glare emitted from the surface of a building, for example caused by high reflectivity exterior materials.	Ensure that interventions at the envelope level do not affect this indicator	INA	INA	INA	INA	INA
12.3	7.5.4	overshadowing: (1) overshadowing with detrimental effects on the neighbourhood (area and hours of overshadowing on neighbors).	Avoid overshadowing with terrace operations	INA	INA	INA	INA	INA
		7.6 Maintenance and maintainability						
14.1	7.6	frequency and duration of routine maintenance (including cleaning), repairs, replacements and / or rehabilitation	Prepare a Book of the regenerated building	X	X	X	X	INA
14.2	7.6	impacts on the health and comfort of users during maintenance tasks	Health and safety study	X	X	X	X	INA
14.3	7.6	user safety during maintenance tasks		X	X	X	X	INA

Table A6. Assignment of influences of the social assessment indicators selected for the different remaining information modules (continuation).

Aspect/Indicator	Aspect According to Section	Indicator	Specific Provision, Measure or Activity	B2	B3	B4	B5	B6
14.4	7.6	ability to use the building while carrying out maintenance tasks, i.e. as a ratio of the expected duration of maintenance and cleaning causing disruption on days of normal use.	Carry out a Health and Safety Study for the course of building renovation works	X	X	X	X	INA
4	Security	7.7.2 Resistance to the consequences of climate change						
			7.7.2.2 Rain resistance					
15.1	7.7.2.2	resistance to rains and torrential rains	Control by means of specific tests	INA	INA	INA	X	INA
15.2	7.7.2.2	water evacuation capacity	Provide a separate network for the reuse of rainwater	INA	INA	INA	X	INA
			7.7.2.3 Wind resistance					
16.1	7.7.2.3	increased structural strength		INA	INA	INA	INA	INA
16.2	7.7.2.3	measures to prevent detachment of the facade or its elements	Rehearse structure	INA	INA	INA	X	INA
16.3	7.7.2.3	measures to improve the air permeability of building enclosures against wind		INA	INA	INA	X	INA
			7.7.2.5 Flood resistance					
18.3	7.7.2.5	water integrity of building enclosures and basements		INA	INA	INA	X	INA
			7.7.2.6 Resistance to solar radiation					
19.1	7.7.2.6	solar control measures such as shading (for example blinds, cornices, eaves, screens) and / or types of window glass	Require compliance with installed products and based the measures on a prior solar study	INA	INA	INA	X	INA
19.2	7.7.2.6	ultraviolet filters	Require standard compliance in relation to the light and solar characteristics of the glazing	NR	INA	INA	X	INA
19.5	7.7.2.6	air conditioning, ventilation systems	-	X	X	X	X	X
19.6	7.7.2.6	thermal inertia	Study the incorporation of blind panels of the envelope that could function as waterspouts	INA	INA	INA	X	X

Appendix E

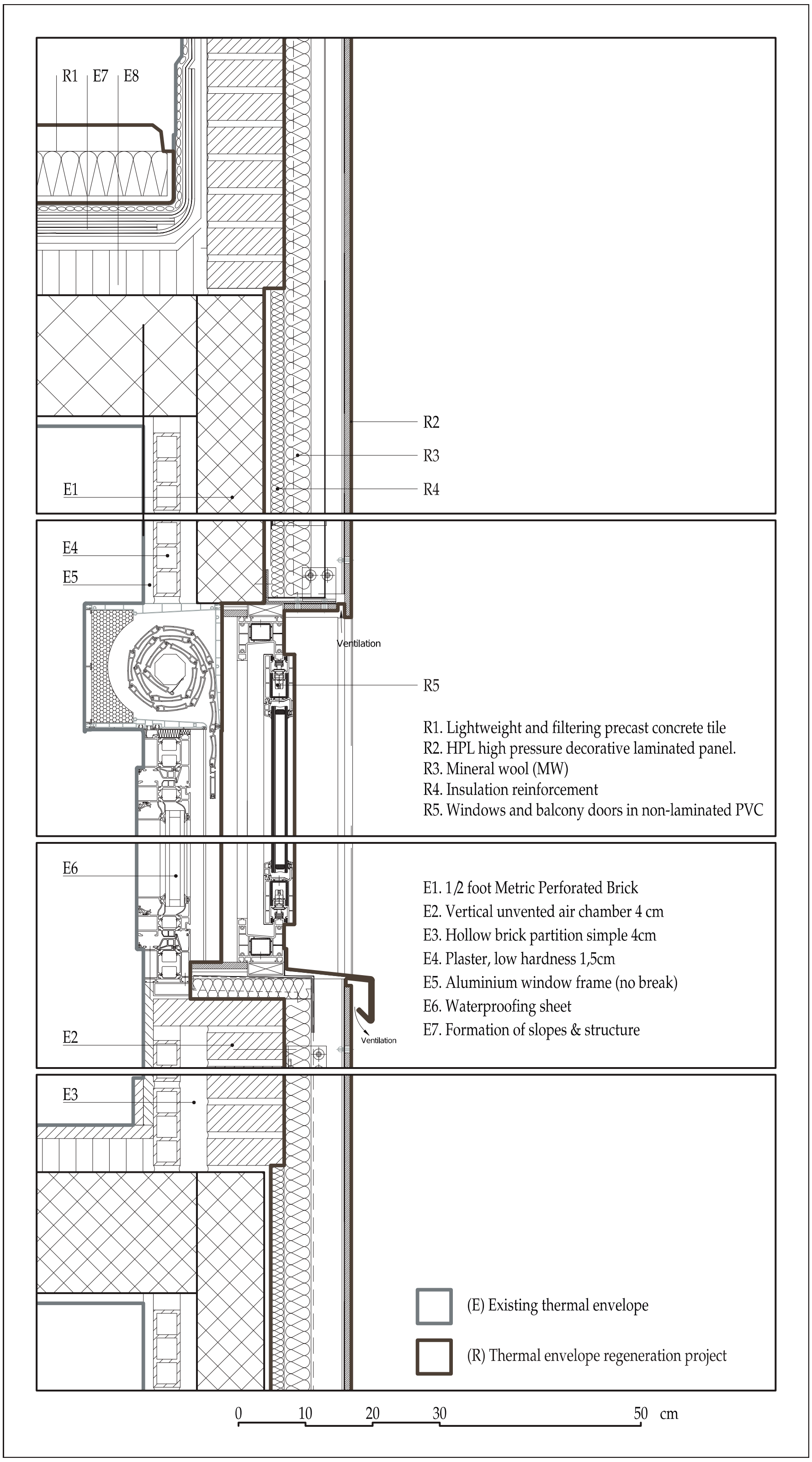


Figure A1. Graphic definition of the most efficient solution existing in the current industry from the economic and environmental point of view.

Table A7. Results for the analyzed indicators of the different most efficient design options.

001 ODC	EVF	B4+M1	OP1	HPL high pressure decorative laminated panel.
			OP1	Mineral wool (MW)
	EHCP	B2+M1	OP1	Lightweight and filtering precast concrete tile
			OP1	Mineral wool (MW)
	EVH	C3	OP1	Windows and balcony doors in non-laminated PVC
Economic indicators	CO_{INIT}	€		396.19349
	CO_{MA}	€/year		4.89040
	NPV	€		266.22195
	EAA	€		10.34685
	CG	€		1139.97137
	TPB	years		30
Environmental indicators	GWP	$KgCO_{2equiv}$		317.44270
	TPB CO_2	years		11.14
029 ODC	EVF	B4+M1	OP1	HPL high pressure decorative laminated panel.
			OP3	Extruded polystyrene (XPS)
	EHCP	B2+M1	OP1	Lightweight and filtering precast concrete tile
			OP3	Extruded polystyrene (XPS)
	EVH	C3	OP1	Windows and balcony doors in non-laminated PVC
Economic indicators	CO_{INIT}	€		388.10241
	CO_{MA}	€/year		4.87218
	NPV	€		274.94000
	EAA	€		10.68568
	CG	€		1131.57801
	TPB	years		30
Environmental indicators	GWP	$KgCO_{2equiv}$		255.54451
	TPB CO_2	years		13.84
043 ODC	EVF	B4+M1	OP2	Single-sided polymer concrete pieces.
			OP1	Mineral wool (MW)
	EHCP	B2+M1	OP2	Terrazzo flooring system on plots
			OP1	Mineral wool (MW)
	EVH	C3	OP1	Windows and balcony doors in non-laminated PVC
Economic indicators	CO_{INIT}	€		438.19132
	CO_{MA}	€/year		3.42327
	NPV	€		274.70023
	EAA	€		10.67636
	CG	€		1157.63305
	TPB	years		31
Environmental indicators	GWP	$KgCO_{2equiv}$		192.19218
	TPB CO_2	years		8.38

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