buildings

Article

Double-Skin Facades for Thermal Comfort and Energy Efficiency in Mediterranean Climate Buildings: Rehabilitating Vulnerable Neighbourhoods

Álvaro López-Escamilla [1,2,*], Rafael Herrera-Limones [1,2,*] and Ángel Luis León-Rodríguez [1,3]

[1] University Institute of Architecture and Building Sciences, School of Architecture, University of Seville, Avda. Reina Mercedes 2, 41012 Seville, Spain; leonr@us.es
[2] Research Group Transhumancias HUM-965, University of Seville, 41012 Seville, Spain
[3] Research Group TEP-130, University of Seville, 41012 Seville, Spain
* Correspondence: alvlopesc@alum.us.es (Á.L.-E.); herrera@us.es (R.H.-L.)

Abstract: The ongoing global energy crisis in Europe has intensified energy poverty in vulnerable households, prompting a critical examination of passive retrofit strategies for improving the habitability of obsolete social housing in southern Europe from the 1960s. Given the Mediterranean climate's characteristics (hot summers and mild winters), these buildings possess low thermal resistance envelopes designed for heat dissipation in summer but contribute to elevated heating demands in colder months. In response to the pressing need for solutions that strike a balance between reducing energy demand and ensuring year-round comfort, this research explores diverse approaches. Drawing insights from built prototypes in Colombia and Hungary and utilizing a validated simulation model in Seville, Spain, this study investigates the feasibility of implementing a double-skin envelope on building facades and assesses the impact of thermal insulation in the air chamber. So, the research specifically aims to find an equilibrium between lowering energy demand and maintaining adequate comfort conditions, concentrating on the renovation of obsolete social housing with envelopes featuring low thermal resistance in the Mediterranean climate. Results indicate that, due to the poor thermal envelope, the influence of thermal insulation on comfort conditions and energy savings outweighs that of the double skin. Consequently, the emphasis of renovation projects for this climate should not solely concentrate on passive cooling strategies but should strive to achieve a positive balance in comfort conditions throughout the year, encompassing both warm and cold months.

Keywords: social housing; Mediterranean climate; thermal comfort; envelope; energy poverty; double-skin facade; modelling; prototype

Citation: López-Escamilla, Á.; Herrera-Limones, R.; León-Rodríguez, Á.L. Double-Skin Facades for Thermal Comfort and Energy Efficiency in Mediterranean Climate Buildings: Rehabilitating Vulnerable Neighbourhoods. *Buildings* **2024**, *14*, 326. https://doi.org/10.3390/buildings14020326

Academic Editor: Ricardo M. S. F. Almeida

Received: 10 December 2023
Revised: 7 January 2024
Accepted: 22 January 2024
Published: 24 January 2024

1. Introduction

Europe has a large number of homes that were built during the 1950s, 1960s and 1970s to house the migration from the countryside to the cities [1] and which now form obsolete neighbourhoods with a high rate of energy poverty, due to the socio-economic vulnerability of their inhabitants. Today, these homes are in need of energy renovation [2], without reducing the thermal comfort indexes [3], and for this, the improvement of the thermal envelope [4–6] is a variable to be taken into account [7,8]. These energy improvement interventions should focus on the neighbourhood scale [9] rather than localised actions on specific buildings [10,11], which goes against the criteria that many public authorities are currently following [12].

A high percentage of domestic energy consumption results from heating and cooling [13] to achieve optimum comfort conditions in the home [14]. The relationship between energy demand and comfort conditions [15] is affected by a large number of variables [16] such as the characteristics of the population [17], gender, age [18,19], household numbers, climate, etc., [20] as well as socio-economic characteristics [21] that lead to energy poverty [22] and an impact on the health of the inhabitants [23,24].

Nevertheless, there is never a simple solution to improve the comfort conditions of these houses and solve the problem of energy poverty [25]. Any possible solution should be evaluated according to the energy savings achieved [26] as well as the architectural and social [27] suitability and even local and state legislation [28].

Furthermore, when trying to resolve this question in houses built in a Mediterranean climate [29], the variables are multiplied [30]. The proposed solution should deal with the demands for both cooling and heating due to the atmospheric conditions that characterise this climate: cold winters and very warm summers [31]. This differs from what happens in other climate contexts where solutions can either focus on facing the cold or the warmth [32].

This research aims to optimise the Aura strategy via adapting it to the Mediterranean climate and a European context, after two previous experiences in the international Solar Decathlon competition [33–35].

The Aura strategy is an intervention method based on the implementation of non-destructive architectural operations and the reuse of existing potential as opposed to other possibilities tied to partial demolitions and new urban ordinances. In other words, it is the revaluation of existing conditions [36].

The Aura strategy was born out of the University of Seville's participation in the 2015 Solar Decathlon Latin America and Caribbean Competition (Proyecto AURA 1.0) [37], which continued in the 2019 edition of the Solar Decathlon Europe (Proyecto AURA 3.1) [38]. Now, in 2022, the strategy applies the knowledge gained in those previous two experiences in the renovation of obsolete social housing in the Poligono de San Pablo neighbourhood, Seville (Figure 1).

In terms of climate, in the AURA 1.0 Project, the passive conditioning solutions were adapted to a tropical climate and equatorial latitude [39]. In the case of the AURA 3.1 Project, the solutions focused on a continental climate [40]. However, in this third experience, the AURA–SAN PABLO Project, the conditioning strategies must deal with the characteristics of the Mediterranean climate.

As a theoretical concept, this strategy focuses on territorial, urban and building regeneration based on the conservation and reuse of the existing urban fabric as fundamental criteria for sustainable actions that are sensitive to the socio-cultural identity of the context in which they are carried out. It is based on the analysis of the metropolitan residential area as one territory included in another which might have different political, administrative or geographical characteristics. This leads to the necessary environmental characterisation of the site: improvement in terms of social cohesion, habitability and urban landscape.

It can be said that the Aura strategy is an urban acupuncture operation adapted to different social and urban contexts, which proposes a gradual, and at different scales, (Figure 2) reclassification of the socio-cultural identity, material and energy, with the aim of achieving an improvement in comfort conditions, the consequent repercussion on citizens' health [41] and resulting improvement in quality of life [42].

As previously outlined, the AURA 1.0 and AURA 3.1 projects were developed to participate in the Solar Decathlon competitions (Latin America 2015 and Europe 2019), which required the construction and exhibition of a 1:1 scale, single-unit dwelling on the competition site. These prototypes were visited by the general public, tested by expert judges and their interior environmental parameters (temperature, humidity, lighting, noise) were monitored.

In this case, the research on the Aura Strategy in San Pablo, Seville focuses on the urban regeneration intervention of a neighbourhood of obsolete social housing, built in the 1960s (following the guidelines employed in AURA 3.1). One of the actions will be to test one of the passive conditioning strategies developed for the AURA 1.0 project: the double skin [43].

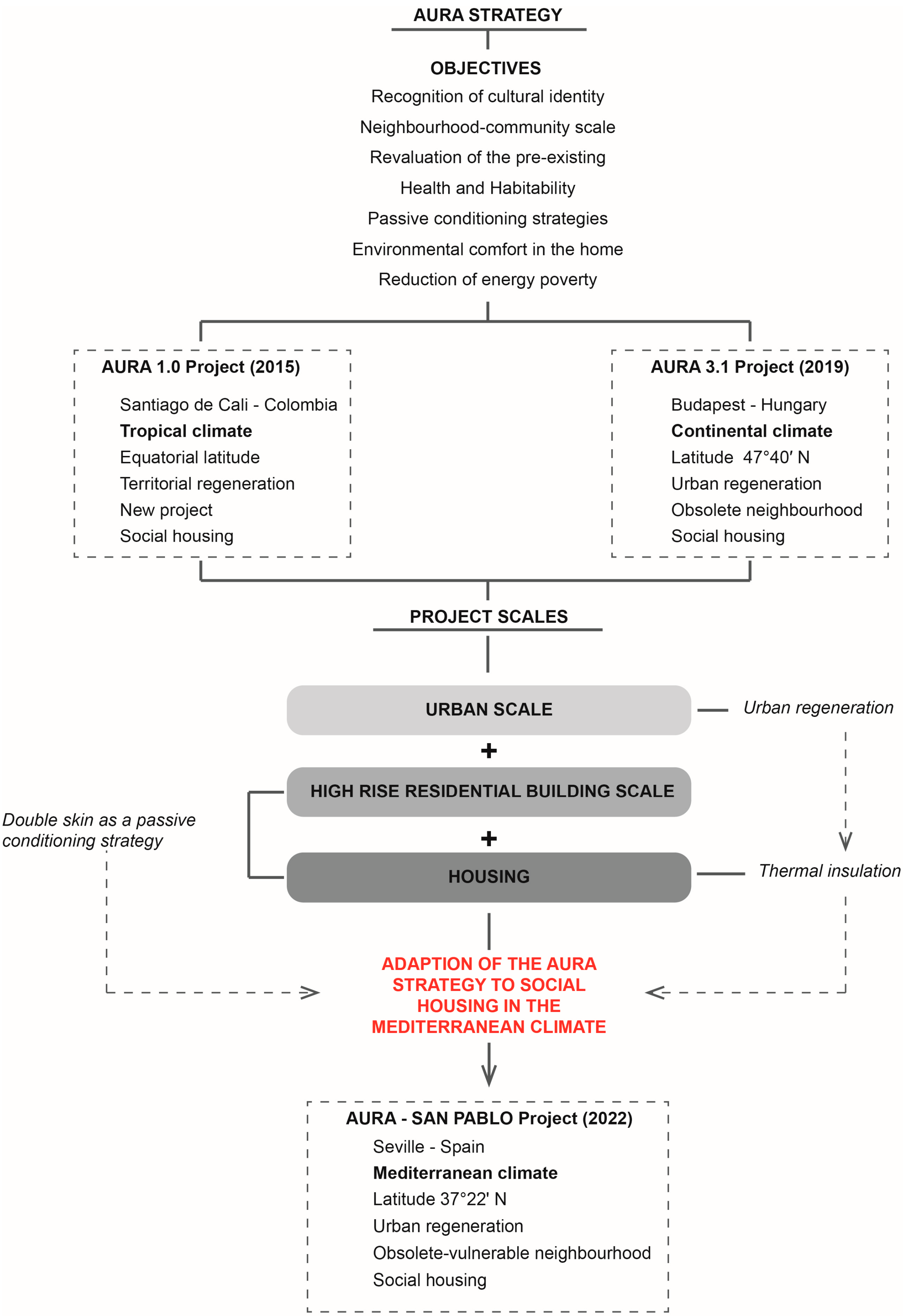

Figure 1. Development and application of the Aura Strategy.

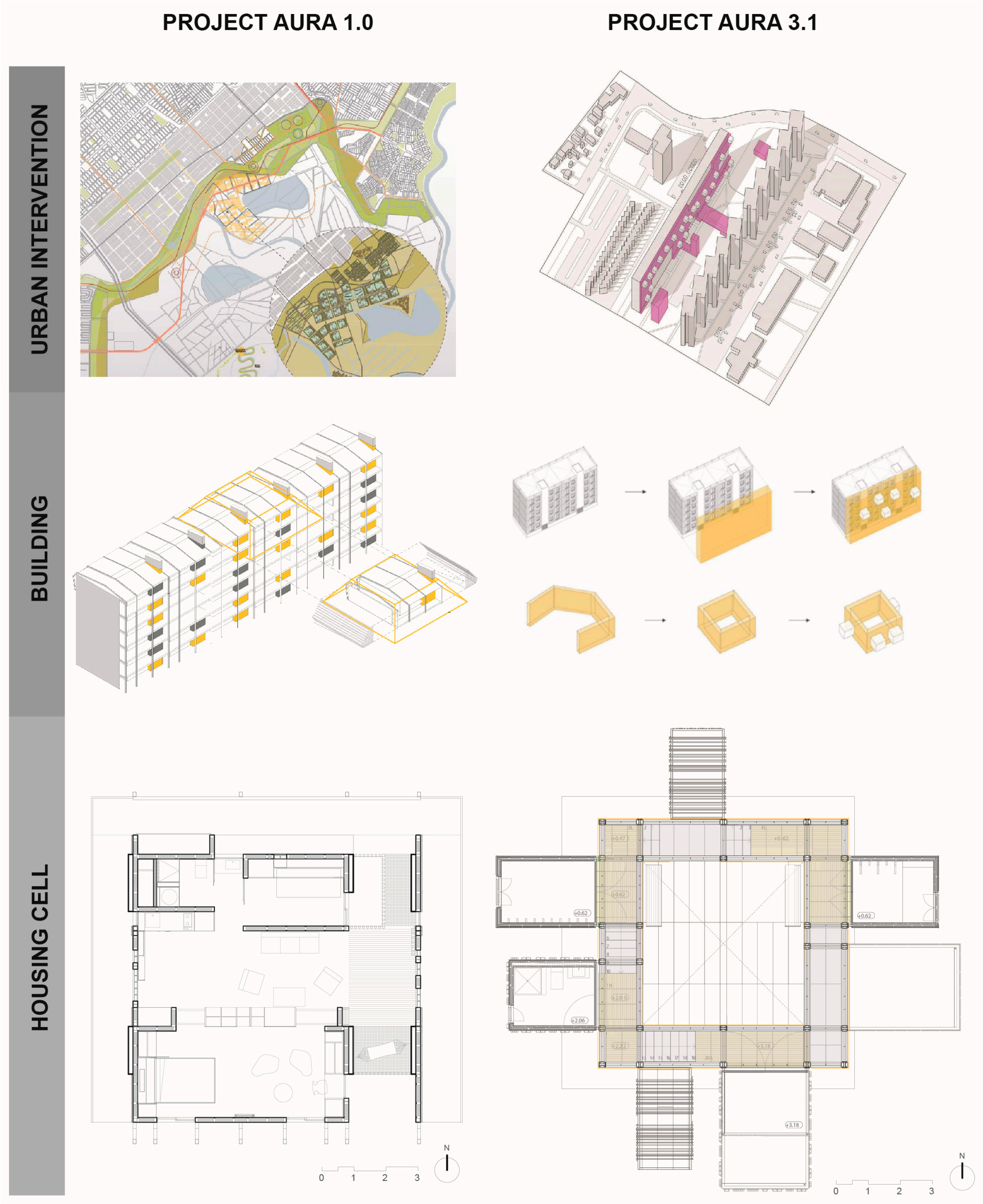

Figure 2. Framework of intervention scales in the AURA 1.0 and AURA 3.1 projects.

Although the AURA 1.0 project used thermal insulation, different passive conditioning strategies were employed in order to achieve optimal comfort conditions with minimum energy consumption. The most relevant of these actions was the installation of a double skin (Figure 3), designed for the tropical climate conditions and an equatorial latitude, such as Santiago de Cali (Colombia), which casts shade on both the facade and the roof.

Figure 3. Photograph and schematic of the AURA 1.0 prototype (Santiago de Cali, Colombia).

In the case of the AURA 3.1 project (Figure 4), there was no double skin to protect the prototype from the continual solar radiation, because, in a continental climate, reinforcing the thermal resistance of the envelope with thermal insulation was considered more relevant.

Figure 4. Photograph and schematic of the AURA 3.1 prototype (Budapest, Hungary).

Based on previous experience, the aim of this research is to find a balance between lowering energy demand and maintaining adequate comfort conditions via the evaluation of different solutions in a Mediterranean climate, focusing on the renovation of obsolete social housing with an envelope with low thermal resistance.

The knowledge acquired with the AURA strategy, understood as an architectural intervention method developed for the International Solar Decathlon competition, becomes an application directly transferable to society.

The adaptation of the double skin designed for the AURA 1.0 project to this new climate context (from tropical to Mediterranean) is analysed in order to determine whether it is necessary to implement thermal insulation so that the proposed intervention is effective over a full year. To do so, a validated energy simulation model will be used, in which different hypotheses in various orientations are analysed.

This double skin will therefore be adapted to Mediterranean climate conditions with cold winters and very warm summers, as opposed to a tropical climate where temperatures remain stable year-round. The change in latitude also influences the geometry, passing from latitude 3°27′ to 37°22′ N.

All of this is framed within the framework of Sustainable Development Goals (ODS) 7 (Affordable and Clean Energy) and 11 (Sustainable Cities and Communities).

2. Case Study: San Pablo Neighbourhood (Seville)

A home in a multi-family building in the San Pablo neighbourhood, Seville, Spain at latitude 37°22′ N was chosen for this study as its aim is to provide conclusions that can be reproduced in similar urban-social contexts:

- It is a high-rise residential estate built during the 1960s with the same construction solutions as many of the other residential areas built in southern Europe in the same period, when the mass construction of cheap housing was necessary to accommodate countryside-to-city migration [44].
- It is one of what are considered Spain's "vulnerable neighbourhoods" [45] due to its high rate of unemployment [46], low income per capita [47] and aging population [48].
- The urban fabric is high-density, with gardens and squares laid out around the geometry of the buildings themselves.
- Energy renovation in these buildings would improve the quality of life for residents, increasing the comfort of their homes, minimizing the use of active conditioning systems and reducing energy poverty situations.

Although the analysis focuses on a vulnerable neighbourhood and a serious socio-economic situation, the current extreme global energy crisis means that the conclusions obtained regarding the reduction in energy demand must be extrapolatable to other buildings with identical construction solutions and in the same climate context, regardless of their socio-economic level.

The San Pablo neighbourhood is integrated into the urban fabric, bordering the city's train station and near the historic centre. It was built in phases between 1960 and 1970, divided into five zones with different building types (Figure 5) [49].

Figure 5. General location of San Pablo.

The block of houses chosen for this study is a five-story building (ground floor + 4) with two homes per floor set parallel and perpendicular to other buildings of the same type (Figure 6).

Figure 6. Case study building.

The dwelling chosen for this analysis is on the second floor of the building. It is 44 m^2 and has windows facing both northeast and southeast (Figure 7).

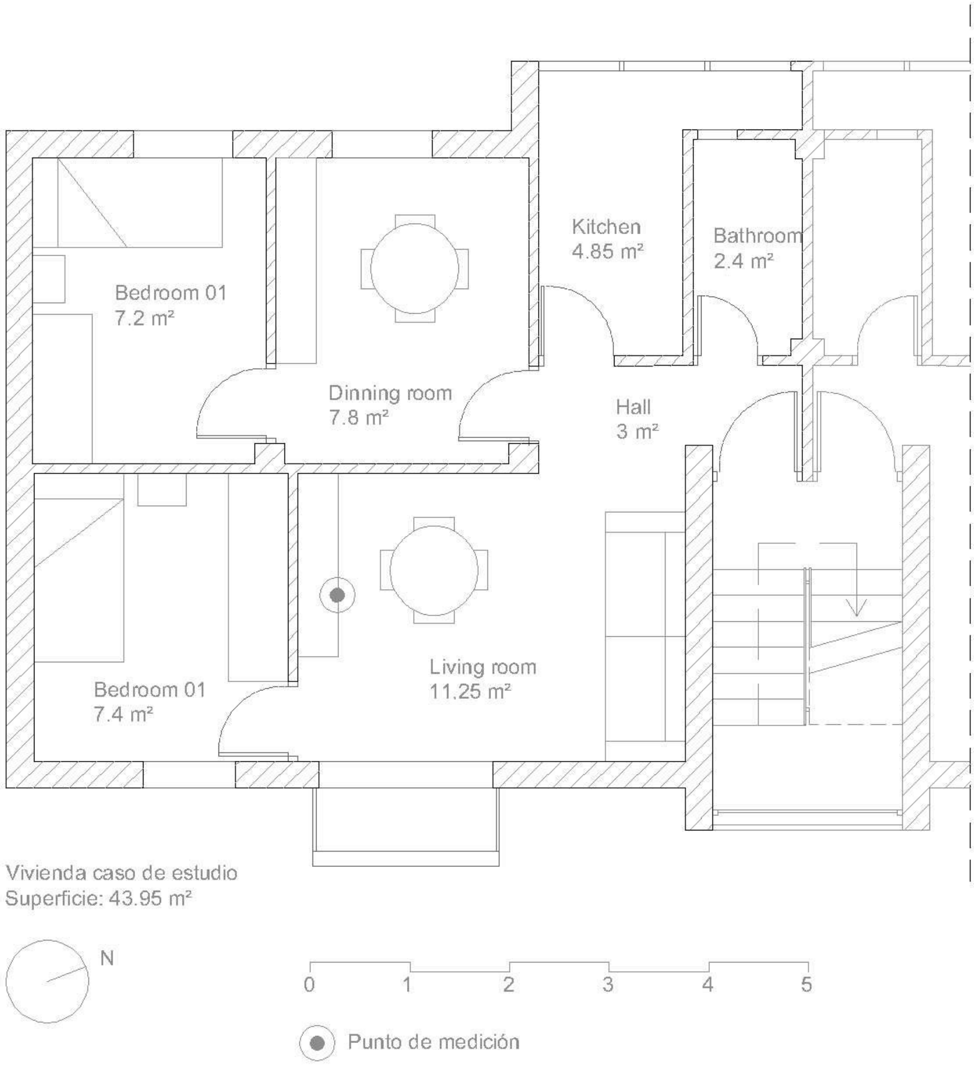

Figure 7. Floor plan.

Exterior Double Skin as a Passive Conditioning Strategy

In the hypothetical renovation of the buildings in the San Pablo neighbourhood, the double skin originally designed for the AURA 1.0 project meets two objectives: firstly, it acts as a solar protection element providing the original envelope with shade, and secondly, it improves the aesthetic aspect of the buildings, which in this case are social housing.

The residents of the Poligono de San Pablo neighbourhood have carried out numerous DIY ("Do It Yourself") renovations: small home improvements modifying some of the original aspects of the facades with no common criteria, as well as adding conditioning units, cables and networks, which degrade the formal aspect of the neighbourhood's buildings (Figure 8).

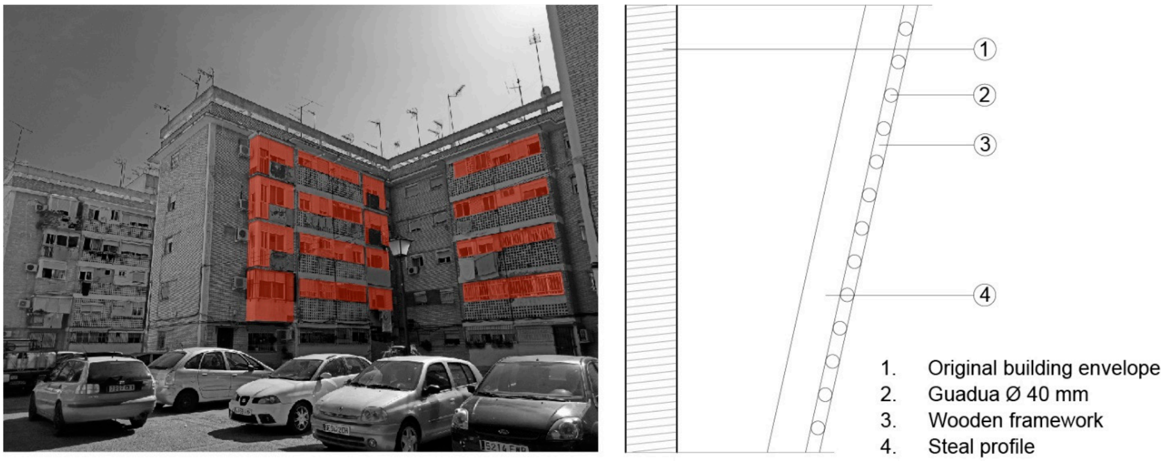

Figure 8. Some DIY renovations degrade the facades in the neighbourhood, and possible construction detail of the double skin.

Installing the AURA double skin on the complete case study building in the Poligono San Pablo, as well as other similar cases [50] if considering a complete, formal renovation of the neighbourhood, would help to improve the exterior image of the buildings. This passive conditioning strategy must be analysed and checked with the help of simulation models validated via previous monitoring of the case study building [51].

3. Materials and Methods

3.1. From the AURA 1.0 Project to the Rehabilitation of the San Pablo Neighbourhood, Seville

This paper forms part of extensive research in a series of previous publications, which begins with the origin of the Aura Strategy and the construction and analysis of the AURA 1.0 prototype [52], which was monitored, on the one hand, to analyse the conditioning strategies used based on the interior hygrothermal conditions [37], and on the other, to develop a validated simulation model and evaluate it with different hypotheses and construction, geometric and atmospheric situations.

More specifically, the double skin developed in the AURA 1.0 project was the subject of previous research [53] in which a validated simulation model of the prototype was used to establish the relevance of this skin. It was concluded that the characteristics of the tropical climate in Santiago de Cali, Colombia [54], meant that the skin had more impact on the roof than on the facade.

In the next step, the knowledge acquired from previous research carried out on the AURA 1.0 prototype would be transferred to the European-Mediterranean context (Figure 9), as an urban regeneration strategy in obsolete neighbourhoods in a Mediterranean climate. A dwelling in a five-story (ground floor + 4), 10-home, multi-family building representative of the San Pablo nieghbourhood in Seville was chosen as a case study.

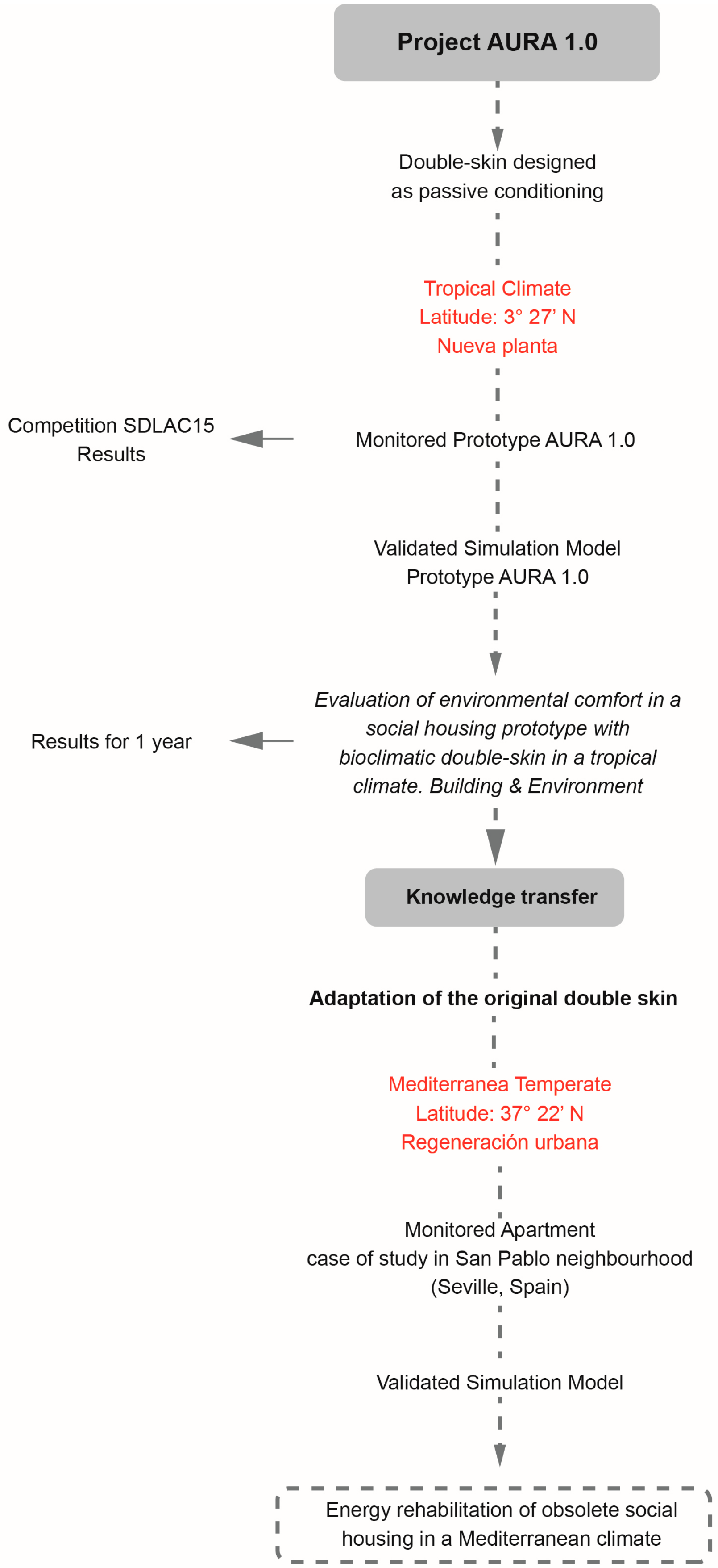

Figure 9. Method scheme.

In both the AURA 1.0 and AURA 3.1 projects, a prototype was built to compete in the Solar Decathlon competition, as set out in the event's rules. However, in this third stage, a prototype has not been built as this is a rehabilitation project for obsolete social housing. Instead, the energy simulation model on which this paper is based was built from environmental data obtained from the monitoring of the case study dwelling.

3.2. Construction of a Validated Simulation Model of the Case Study Dwelling in the Poligono San Pablo Neighbourhood, Seville, Spain

In response to the established objective, a simulation model has been developed for the case study dwelling: located on the second floor of a five-story residential block (ground floor + 4), which has 10 northeast-southeast facing homes (2 homes per floor).

This model was validated according to the temperature data obtained after monitoring the environmental conditions (temperature and relative humidity) inside the dwelling over a ten-day period between 10 and 21 December 2021.

To generate the simulation model, the SG SAVE version 2.9.2.1 tool was used. This tool uses the ENergyPlus calculation engine [55,56] developed by the United States Department of Energy's National Renewable Energy Laboratory [55,57]. SG SAVE is supported by the Sketchup 2017 modelling software, which allows highly intuitive modeling of the spaces to be simulated.

As this is a small-sized dwelling where rooms are permanently joined, a single open-plan space was generated for the simulation model.

The exterior atmospheric data used to validate the simulation model was obtained from the University of Seville's weather station, located within a 1.5 km radius of the case study in an urban area with similar characteristics. This station is used to obtain the city's environmental data on an ongoing basis.

The simulation tool was used to reproduce the dwelling's operational conditions between the 10 and 20 December, taking both the occupancy [58] and its resulting impact and interior air renewal into consideration, as well as the impact produced by lighting and installations (Figure 10).

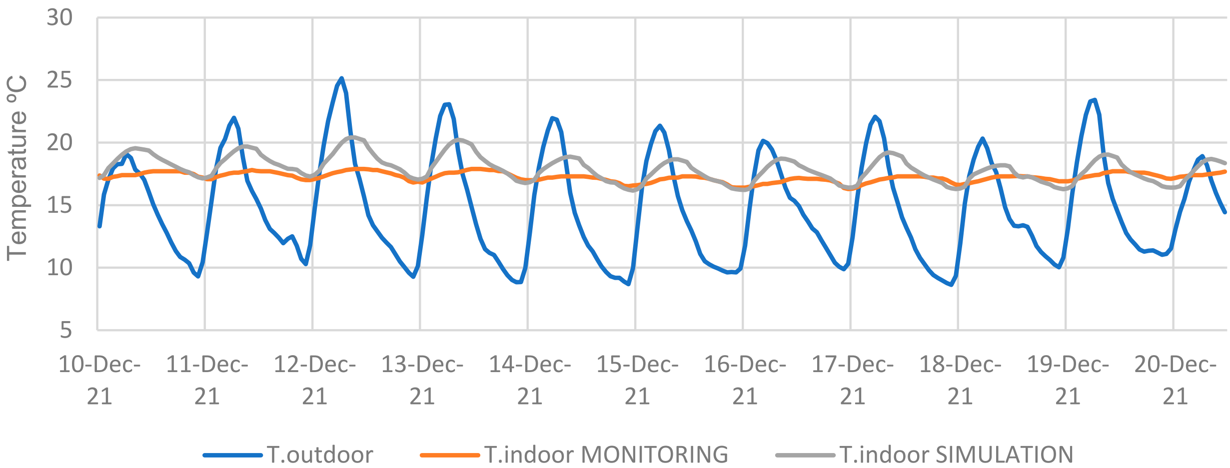

Figure 10. Temperature outdoor and temperature indoor in free evolution, in comparison to the simulation model temperature indoor.

Although the graph shows that the data obtained from the simulation model is in line with the temperature data measured in the prototype, an analytical validation was also carried out.

It is intended that the validation model complies with the ASHRAE Guideline 14:202 (ASHRAE) [59], which indicates that the calibrated model should have a normalised mean bias error (NMBE) of 5% and a coefficient of variation of the root mean square error

(CVRMSE) of 15% when monthly data is used for calibration, or requirements of ±10% and 30%, respectively, when hourly data is used, as in this case [60].

To calculate both coefficients, the expressions indicated in the aforementioned guideline, section 5.2.11.3, used the following formulas:

$$CVRMSE = 100 \times \left[\sum (y_i - \hat{y}_i)^2 / (n-p)\right]^{1/2} / \overline{y}$$

$$NMBE = \frac{\sum^{n} (y_i - \hat{y}_i)}{(n-p) \times \overline{y}} \times 100$$

The results of these calculations for the values obtained in the calibrated simulation model are:

NMBE = −3.93%

CV(RMSE) = 6.11%

As a result, and according to the aforementioned values, we can conclude that the simulation model is validated in line with this method.

3.3. Posed Hypotheses

The layout of this type of housing in the neighbourhood has two main orientations:

- Building A: northeast–southeast orientation. The monitored dwelling belongs to this building.
- Building B: southeast–northwest orientation.

Three hypotheses for actions on the original vertical thermal envelope were posed for each building (Table 1). In these, the energy demand over a one-year period was analysed.

Table 1. Hypothesis study and envelope in each hypothesis.

Element		Layer	Thickness (m)	U (W/m^{2}K)
Hypothesis n°0 Current state (Validated model)	Dwelling in block A in its current state and conditions on which the model has been validated.	Perforated brick Air chamber Single hollow brick Plaster finish	0.115 0.06 0.04 0.015	1.9
Hypothesis n°1	Same operational conditions as hypothesis n°0 but installing a double skin like the one designed for the AURA 1.0 prototype.	Double skin Perforated brick Air chamber Single hollow brick Plaster finish	- 0.115 0.06 0.04 0.015	1.623
Hypothesis n°2	Same operational conditions as hypothesis n°0 but applying a 6 cm layer of insulation injected into the chamber in the original envelope.	Perforated brick Thermal insulation Single hollow brick Plaster finish	0.115 0.06 0.04 0.015	0.446
Hypothesis n°3	Same operational conditions as hypothesis n°0 but applying a 6 cm layer of insulation injected into the chamber in the original envelope.	Double skin Perforated brick Thermal insulation Single hollow brick Plaster finish	- 0.115 0.06 0.04 0.015	0.429

The hypotheses posed respond to the peculiarity of the Mediterranean climate characteristics of Seville (Spain): very warm, dry summers and cold, damp winters. For this reason, two solutions were analysed: a cooling passive conditioning solution such as the double skin and an insulation solution injected into the air chamber in order to optimise energy demand during the coldest months of the year.

As a result, the San Pablo neighbourhood is being used as a testing ground for the most relevant conditioning strategies used in the AURA 1.0 project (double skin), corresponding to hypothesis n°1, and the AURA 3.1 project (thermal insulation), corresponding to hypothesis n°2. Furthermore, the behaviour of the combination of both these hypotheses is analysed in hypothesis n°3.

To calculate the energy demand, the following set-point temperature values were established. There are periods of the year in which, given the peculiarity of the climate in Seville, it is useful to consider the space in a state of free evolution, as during these periods heating and cooling systems are rarely used, being reserved for more extreme conditions (Table 2).

Table 2. Interior temperature values.

	Period		Temperature
HEATING	1 January	21 March	20 °C
	21 March	21 April	23 °C
	21 April	21 October	Free-running
	21 October	21 December	23 °C
	21 December	31 December	20 °C
COOLING	1 January	21 March	Free-running
	21 March	21 April	23 °C
	21 April	21 October	26 °C
	21 October	21 December	23 °C
	21 December	31 December	Free-running

3.4. Data Analysis

The data that has been obtained for analysis from each hypothesis was percentages of hours of comfort temperature and energy demand depending on the set-point temperature established in Table 3.

Table 3. Percentage of monthly hours in comfort temperature.

	BUILDING A				BUILDING B			
	Hyp. 0A	**Hyp. 1A**	**Hyp. 2A**	**Hyp. 3A**	**Hyp. 0B**	**Hyp. 1B**	**Hyp. 2B**	**Hyp. 3B**
January	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.00
February	0.00	0.00	0.00	0.00	0.60	0.00	0.00	0.00
March	26.21	17.47	31.45	22.72	32.26	21.10	40.99	25.67
April	44.58	24.86	62.36	35.97	49.03	29.58	62.08	38.06
May	91.40	77.15	95.16	90.73	88.58	75.13	94.35	84.41
June	72.36	74.17	80.69	76.39	73.89	74.72	79.03	73.61
July	52.69	59.68	60.48	75.13	55.91	63.58	74.73	81.05
August	70.03	85.75	86.42	91.26	76.48	87.10	92.88	92.34
September	71.25	75.97	76.11	74.03	70.00	77.50	79.17	76.39
October	52.42	43.95	61.42	52.15	79.17	53.63	94.09	77.82
November	0.00	0.00	0.56	0.28	3.61	0.14	5.56	1.81
December	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	40.33	38.50	46.51	43.54	44.43	40.48	52.33	46.29

The yellow color indicates the maximum values.

With regard to thermal comfort, the results of the interior temperature in free evolution were analysed according to the adaptive comfort methodology [61,62] defined by the European Standard EN 16798-1:2019 "Energy performance of buildings. Ventilation for buildings. Part.1" [63]. A comfort range was established in which we assume a percentage of dissatisfaction below 10% [64]. In other words, the dwelling's thermal behaviour was assessed before establishing a set-point temperature [65].

Once the set-point temperature had been established, energy demand for each hypothesis was analysed on a monthly basis, differentiating the demand for heating from the demand for cooling so as to obtain conclusions over a full year.

4. Results

After validating the simulation model with the measurements taken from the case study dwelling, the results are set out relating to thermal comfort and energy demand in the northeast–southeast facing building A and the northeast–southwest facing building B (Figure 11), for each of the described hypotheses.

Figure 11. Layout of the two orientations that were analysed.

4.1. Thermal Comfort

The interior temperature of the dwelling in free evolution (without heating and cooling systems) has been calculated and analysed graphically for each hypothesis and orientation studied for building A (Figure 12) and building B (Figure 13). They have also been analysed in relation to the range established for adaptive comfort.

The presented graphs reveal that, in both orientations, the dwelling consistently encounters thermal discomfort during the coldest months due to low temperatures. However, in contrast, warmer months exhibit intermittent periods of thermal comfort within the interior.

Upon conducting a monthly analysis (Table 3) for both orientations, it becomes evident that during January, February, November and December, none of the hypotheses achieve thermal comfort in free evolution. Notably, hypothesis 2 emerges as the most successful, demonstrating the highest number of hours of thermal comfort throughout the entire year. In some months, particularly in the northeast–southwest orientation (building B), this hypothesis surpasses 90% of thermal comfort hours, showcasing its effectiveness in enhancing thermal conditions. This nuanced understanding of temperature variations emphasises the significance of tailored solutions to address specific climatic challenges, ensuring improved living conditions in both colder and warmer periods.

4.2. Energy Demand

In relation to energy demand, both cooling (in blue) and heating (in red) demands in building A with northeast–southeast orientation and building B with northeast–southwest orientation were assessed (Table 4).

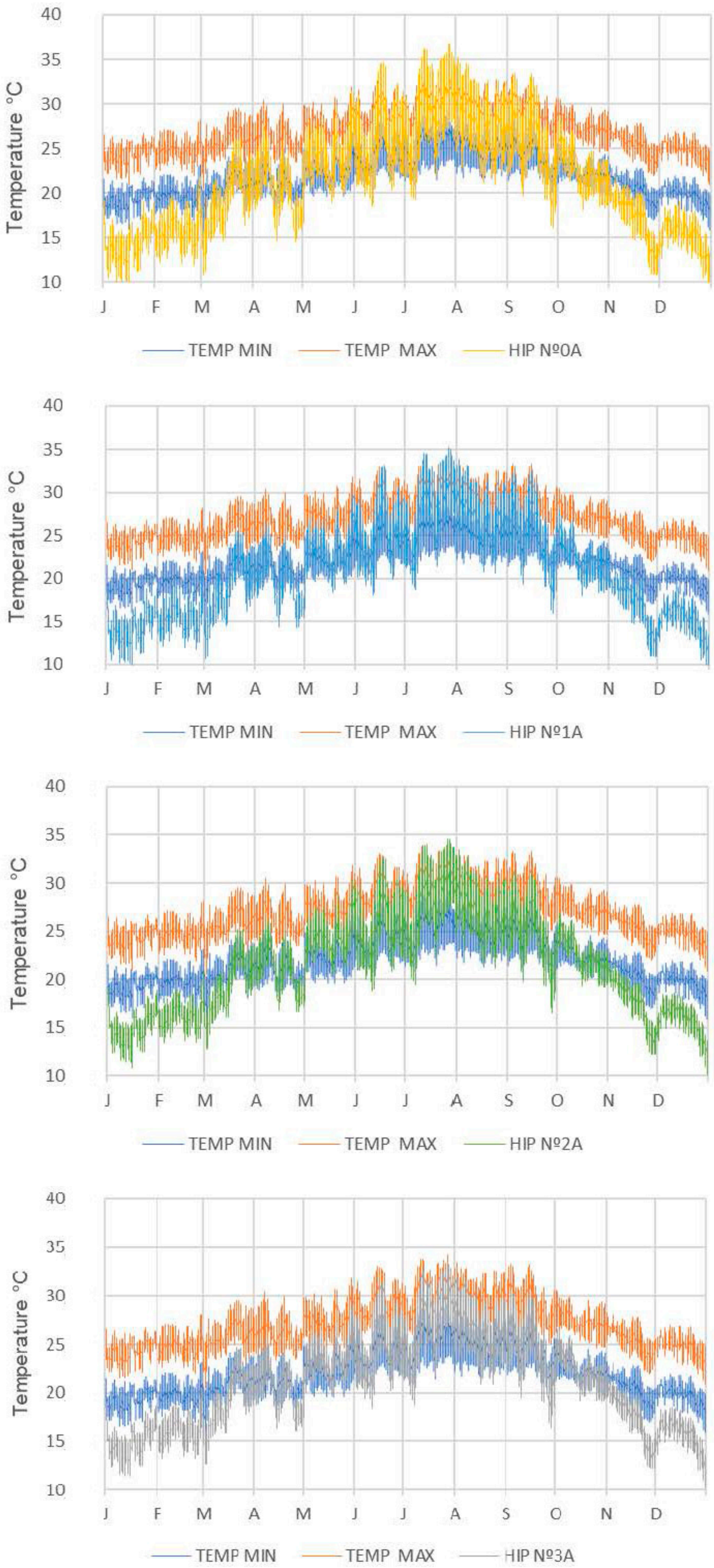

Figure 12. Thermal behaviour of the hypotheses studied in building A in relation to the minimum and maximum comfort temperatures.

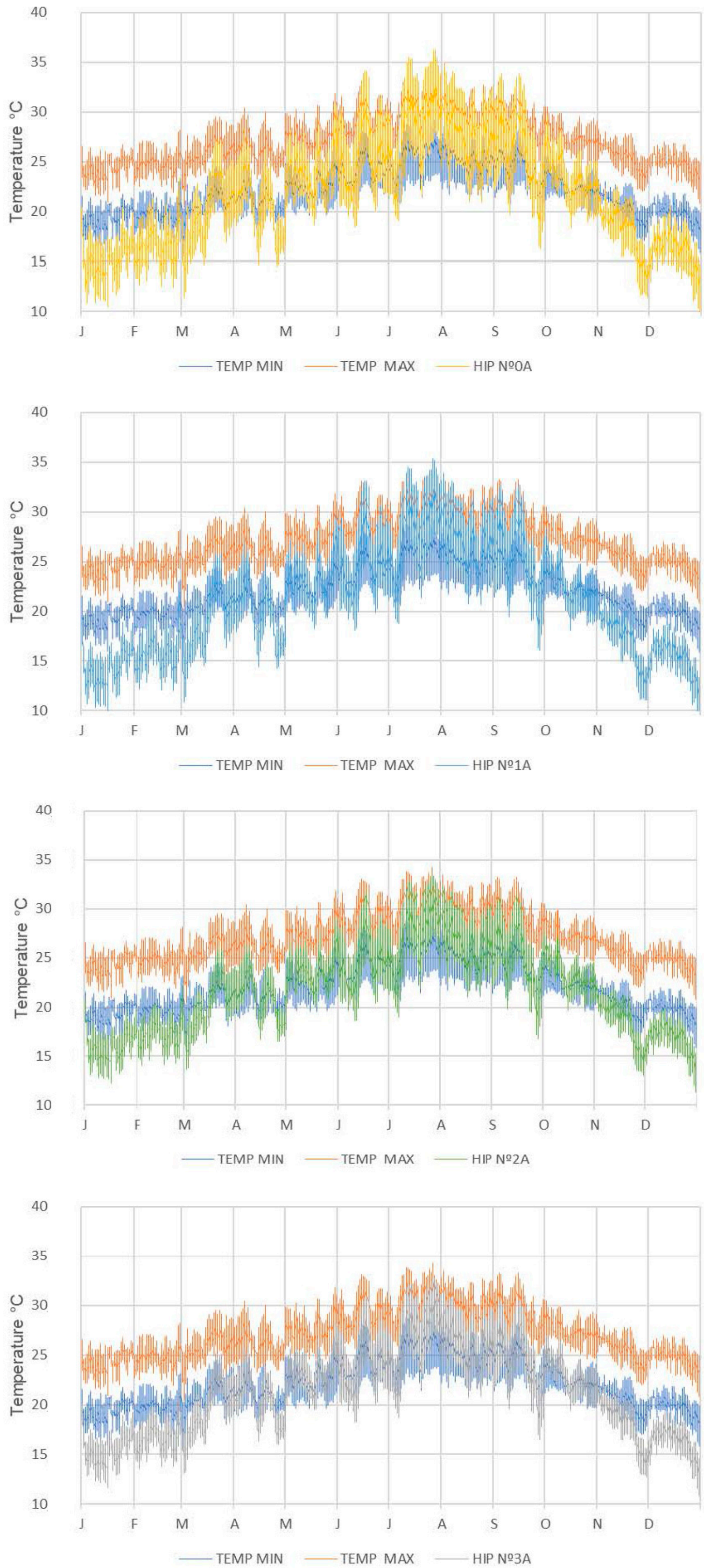

Figure 13. Thermal behaviour of the hypotheses studied in building B in relation to the minimum and maximum comfort temperatures.

Table 4. Monthly energy demand (kWh/month).

	BUILDING A				BUILDING B			
	Hyp. 0A	**Hyp. 1A**	**Hyp. 2A**	**Hyp. 3A**	**Hyp. 0B**	**Hyp. 1B**	**Hyp. 2B**	**Hyp. 3B**
JANUARY	638.91	643.62	409.91	415.37	540.98	621.05	325.81	364.74
FEBRUARY	433.43	449.06	271.75	282.54	366.31	421.49	215.53	247.08
MARCH	276.51	303.08	165.6	183.62	241.14	287.45	137.29	168.1
APRIL	170.03	199.08	98.46	119.63	165.86	193.66	98.64	119.97
MAY	211.14	124.52	168.62	102.2	175.81	121.58	116.82	79.69
JUNE	423.99	317.79	289.56	217.42	377.66	313.47	233.31	193.24
JULY	614.79	487.73	415.45	330.43	552.5	478.91	340.07	294.14
AUGUST	416.52	319.72	264.8	204.9	388.65	320.2	223.71	184.97
SEPTEMBER	263.01	209.83	149.23	121.54	286.48	222.85	158.45	126.3
OCTOBER-COOLING	85.57	69.05	60.18	49.42	120.32	78.06	89.29	63.67
OCTOBER-HEATING	74.05	76.62	48.71	50.99	57.63	69.43	33.49	41.47
NOVEMBER	653.25	659.95	428.47	435.7	571.78	636.89	354.43	389.25
DECEMBER	776.27	780.23	504.73	510.06	693.64	763.31	431.34	465.65

Analytically and graphically, with regard to cooling demand in the northeast–southeast facing building A, it is shown that hypothesis n°1 reduces the energy demand by more than 24%, yet a greater energy saving is achieved in hypothesis n°2. Using only insulation injected into the air chamber achieves a saving of 33% during the year.

In relation to heating demand, the results of hypothesis n°1 are slightly worse than those of hypothesis n°0. However, in hypothesis n°2, the energy demand for heating is reduced by over 36% (Figure 14).

It can be seen that the combination of hypothesis n°1 and hypothesis n°2, in other words hypothesis n°3, can be considered an adequate energy renovation intervention for buildings with this orientation, as it reduces cooling demand by almost 50% and annual heating demand by almost 34% (Table 5).

Table 5. Saving achieved in each hypothesis in comparison to hypothesis 0 (kWh/year).

	BUILDING A				BUILDING B			
	Hyp. 0A	**Hyp. 1A**	**Hyp. 2A**	**Hyp. 3A**	**Hyp. 0B**	**Hyp. 1B**	**Hyp. 2B**	**Hyp. 3B**
	COOLING (WARM MONTHS)							
ANNUAL DEMAND	2017.76	1529.52	1350.19	1026.74	1904.57	1536.36	1163.70	942.88
ANNUAL NET SAVING	-	488.24	667.57	991.02	-	368.21	740.87	961.69
% SAVING	-	24.20%	33.08%	49.11%	-	19.33%	38.90%	50.49%
	HEATING (COLD MONTHS)							
ANNUAL DEMAND	3022.45	3111.64	1927.63	1997.91	2637.34	2993.28	1596.53	1796.26
ANNUAL NET SAVING	-	−89.19	1094.82	1024.54	-	−355.94	1040.81	841.08
% SAVING	-	−2.95%	36.22%	33.90%	-	−13.50%	39.46%	31.89%
	TOTAL SAVING							
TOTAL DEMAND	5040.21	4641.16	3277.82	3024.65	4541.91	4529.64	2760.23	2739.14
ANNUAL NET SAVING	-	399.05	1762.39	2015.56	-	12.27	1781.68	1802.77
% SAVING	-	7.92%	34.97%	39.99%	-	−0.27%	39.23%	39.69%

Blue color, cooling demand. Red color, heating demand. Yellow, maximum percentages.

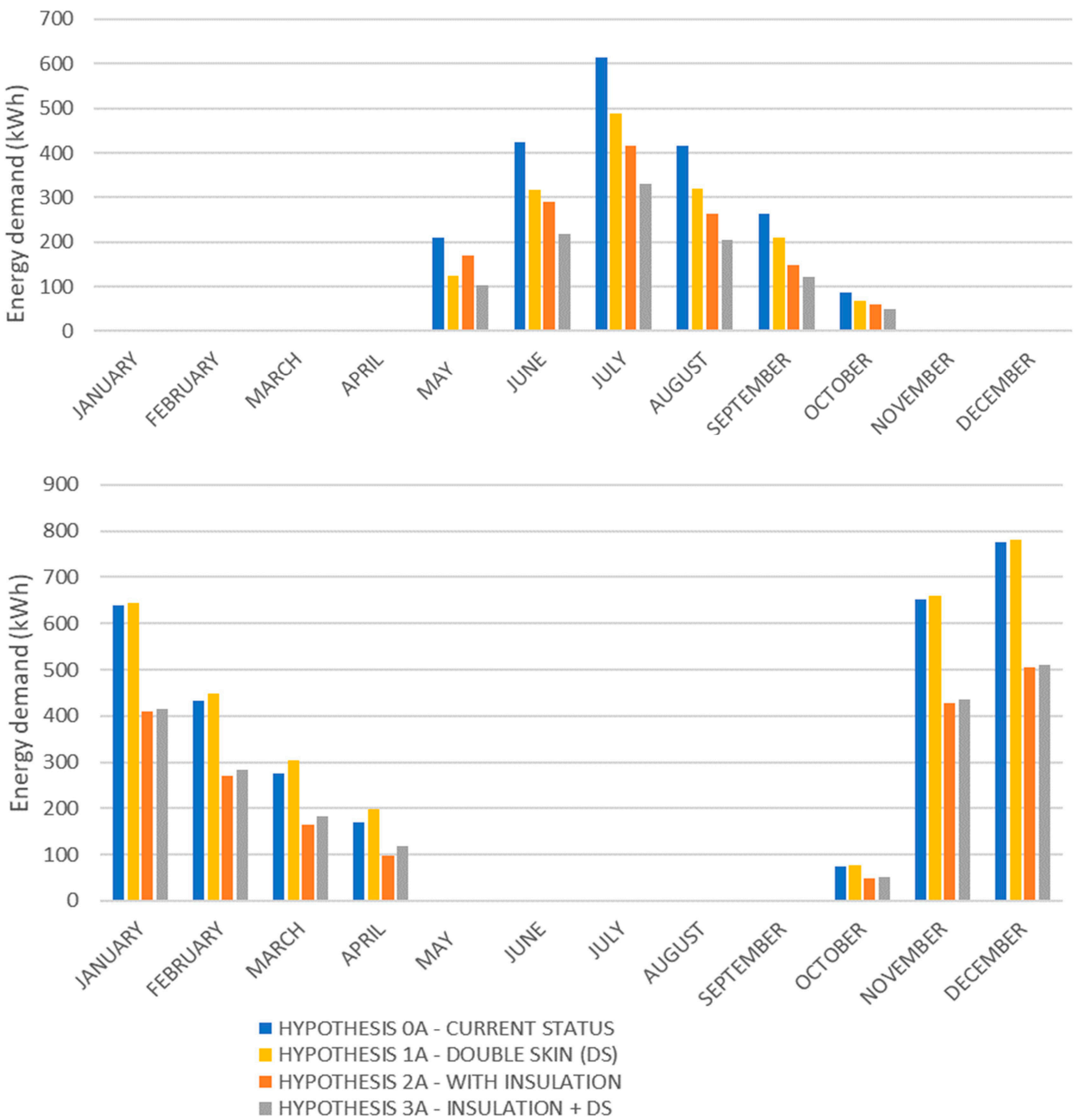

Figure 14. Monthly energy demand for cooling (kWh), (**up**), monthly energy demand for heating (kWh), (**down**).

Overall, in a one-year period, an intervention in this case study building with hypothesis n°3 would reduce current energy demand by 40%.

For the northeast–southwest facing building B, hypothesis n°1 reduces cooling demand by 19%. However, a greater energy saving is achieved in hypothesis n°2. Using only insulation injected into the air chamber achieves a reduction of almost 39% in the annual demand for cooling.

With regard to heating, hypothesis n°1 achieves worse results than hypothesis n°0. However, hypothesis n°2 reduces energy demand by 39% (Figure 15).

In contrast to what occurs with building A, in building B, the energy saving achieved using hypothesis n°2 and hypothesis n°3 is very similar over a year-long period (heating + cooling) in a hypothetical energy renovation intervention: the saving achieved would be approximately 40% in both cases (Table 5). This is due to the fact that the installation of the double skin has a notably detrimental effect during the winter months, increasing the demand for heating by almost 13%.

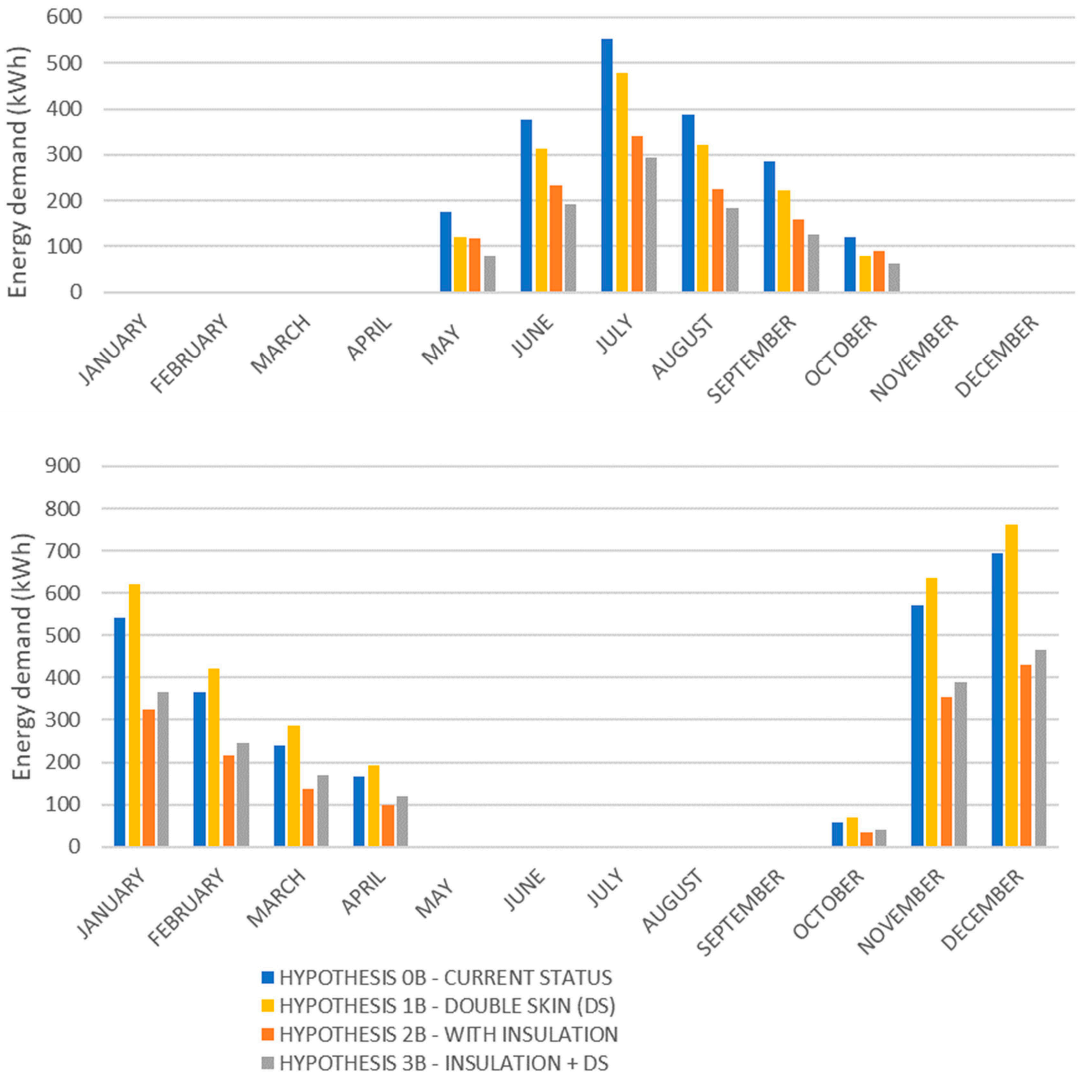

Figure 15. Monthly energy demand for cooling (kWh), (**up**), monthly energy demand for heating (kWh), (**down**).

5. Conclusions

As a result of this research, it can be confirmed that although it is necessary to anticipate passive cooling strategies for the warmer months in a Mediterranean climate, it is also essential to contemplate the energy demand for heating. It is a complex climate to deal with when designing conditioning strategies as it requires the contemplation and combination of both cooling and heating strategies because of the thermal oscillation between the colder and warmer months.

In the now obsolete working-class neighbourhoods built in the 1950s, 1960s and 1970s in the south of Europe, there is heightened thermal discomfort when temperatures are low in the coldest months of the year. This is because these homes wereconstructed, to a large extent, without any thermal insulation in the envelope, as is the case in the San Pablo neighbourhood chosen for this case study.

As these homes were built for a climate with extreme temperatures in summer, they were designed with a thermal envelope with low thermal resistance. This type of envelope may be good at dissipating heat during certain periods of the year, for example during the summer nights, but it is not effective in winter as it provokes high demands for heating to maintain minimum comfort conditions.

The thermal comfort results derived from this study highlight a critical aspect: despite the south of Europe experiencing more extreme atmospheric conditions in summer than in the colder months, the interior thermal conditions of homes are notably more unfavorable during the cold months. This discrepancy arises from the substantial heat loss of the inadequately insulated envelopes during winter. Consequently, this study underscores the imperative of tailored solutions that account for the unique challenges posed by the Mediterranean climate, emphasizing the need for comprehensive strategies that address both cooling and heating requirements to ensure year-round comfort and energy efficiency in residential spaces.

The alignment of findings with statistical data from the Instituto de Salud Carlos III, obtained using a daily mortality monitoring system focusing on temperature-related deaths [66], further emphasises the critical impact of climatic conditions on public health. In Seville, spanning the years 2015 to 2022, a concerning 767 fatalities are attributed to cold, while 549 are linked to extreme heat, underscoring the urgency of addressing temperature-related challenges.

From the perspective of thermal comfort, and anticipating a future rehabilitation of these obsolete neighbourhoods, the installation of a double skin would be detrimental in the colder months as it casts shade on the facade and windows thus impeding thermal gains from the sun. On the other hand, implementing thermal insulation in the air chamber of these dwellings (hypothesis n°2) would give the best results in terms of thermal comfort inside the homes.

If we consider energy demand, an overall assessment must be made over a full year as the installation of a double skin optimises demand in the warm months but increases it in the cold months. Furthermore, when it comes to orientation, it is worth noting that the double skin performs better when it is installed on the northeast–southeast orientation.

An individual study of each building based on its orientation should be carried out to find out if the installation of a double skin is beneficial, avoiding overall, unified actions for the whole neighbourhood.

On another front, the implementation of thermal insulation stands out as a shared solution to mitigate interior heat loss during winter, promoting effective energy savings in the Mediterranean climate. The evaluation of these strategies gains particular significance in vulnerable neighbourhoods grappling with severe energy poverty. Given the escalating global energy crisis, which is anticipated to exacerbate energy poverty, public administrations must be equipped with robust tools to address the impending challenges comprehensively.

Author Contributions: Conceptualization, Á.L.-E.; methodology, Á.L.-E., R.H.-L. and Á.L.L.-R.; software, Á.L.-E., R.H.-L. and Á.L.L.-R.; validation, Á.L.-E., R.H.-L. and Á.L.L.-R.; formal analysis, Á.L.-E., R.H.-L. and Á.L.L.-R.; investigation, Á.L.-E., R.H.-L. and Á.L.L.-R.; writing—original draft, Á.L.-E., R.H.-L. and Á.L.L.-R.; writing—review and editing, Á.L.-E., R.H.-L. and Á.L.L.-R.; supervision, Á.L.-E., R.H.-L. and Á.L.L.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This article is included in the project "Aplicación directa de la Estrategia Aura del Equipo Solar Decathlon–U.S., en rehabilitación de barriadas obsoletas andaluzas" granted by the Ministry of Development, Infrastructure and Territorial Planning of the Local Andalusian Government (Spain), with ref. US.20–11, but for its production no economic financing has been received.

Data Availability Statement: Data are contained within the article.

Acknowledgments: Research project "Direct application of the Aura Strategy by the SD-US Team for the regeneration of outdated Andalusian housing estates", as well as a methodological approach for the estate of San Pablo, Seville (as a case study for the extrapolation of results to similar environments, via the implementation of sustainable regeneration in the working-class residential area). The project was granted in the resolution of 28 July 2021 by the Ministry of Development, Infrastructure and Territorial Planning (Local Andalusian Government), within the 2020 call for grants for carrying out research projects in the areas of housing, rehabilitation and architecture.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Poza-Casado, I.; Rodríguez-del-Tío, P.; Fernández-Temprano, M.; Padilla-Marcos, M.Á.; Meiss, A. An envelope airtightness predictive model for residential buildings in Spain. *Build. Environ.* **2022**, *223*, 109435. [CrossRef]
2. Blázquez, T.; Suárez, R.; Sendra, J.J. Protocol for assessing energy performance to improve comfort conditions in social housing in a spanish southern city. *Int. J. Energy Prod. Manag.* **2017**, *2*, 140–152. [CrossRef]
3. Suárez, R.; Fernández-Agüera, J. Passive energy strategies in the retrofitting of the residential sector: A practical case study in dry hot climate. *Build. Simul.* **2015**, *8*, 593–602. [CrossRef]
4. Tabadkani, A.; Haddadi, M.; Rizi, R.A.; Tabadkani, E. A hierarchical multi-purpose roller shade controller to enhance indoor comfort and energy efficiency. *Build. Simul.* **2023**, *16*, 1239–1256. [CrossRef]
5. Tsoka, S.; Tsikaloudaki, K.; Theodosiou, T.; Dugue, A. Rethinking user based innovation: Assessing public and professional perceptions of energy efficient building facades in Greece, Italy and Spain. *Energy Res. Soc. Sci.* **2018**, *38*, 165–177. [CrossRef]
6. Alberto, A.; Ramos, N.M.M.; Almeida, R.M.S.F. Parametric study of double-skin facades performance in mild climate countries. *J. Build. Eng.* **2017**, *12*, 87–98. [CrossRef]
7. Carretero-Ayuso, M.J.; Rodríguez-Jiménez, C.E.; Bienvenido-Huertas, D.; Moyano, J.J. Interrelations between the types of damages and their original causes in the envelope of buildings. *J. Build. Eng.* **2021**, *39*, 102235. [CrossRef]
8. Sánchez, J.M.G.-C.; Meana-Fernández, A.; Ríos-Fernández, J.C.; Trashorras, A.J.G. Characterization of housing stock for energy retrofitting purposes in Spain. *Build. Simul.* **2023**, *16*, 947–962. [CrossRef]
9. Ulu, M.; Arsan, Z.D. Retrofit strategies for energy efficiency of historic urban fabric in mediterranean climate. *Atmosphere* **2020**, *11*, 742. [CrossRef]
10. Paiho, S.; Ketomäki, J.; Kannari, L.; Häkkinen, T.; Shemeikka, J. A new procedure for assessing the energy-efficient refurbishment of buildings on district scale. *Sustain. Cities Soc.* **2019**, *46*, 101454. [CrossRef]
11. An, Y.-S.; Kim, J.; Joo, H.J.; Han, G.W.; Kim, H.; Lee, W.; Kim, M.H. Retrofit of renewable energy systems in existing community for positive energy community. *Energy Rep.* **2023**, *9*, 3733–3744. [CrossRef]
12. Carnieletto, L.; Ferrando, M.; Teso, L.; Sun, K.; Zhang, W.; Causone, F.; Romagnoni, P.; Zarrella, A.; Hong, T. Italian prototype building models for urban scale building performance simulation. *Build. Environ.* **2021**, *192*, 107590. [CrossRef]
13. Ozarisoy, B.; Altan, H. Significance of occupancy patterns and habitual household adaptive behaviour on home-energy performance of post-war social-housing estate in the South-eastern Mediterranean climate: Energy policy design. *Energy* **2022**, *244*, 122904. [CrossRef]
14. Causone, F.; Tatti, A.; Pietrobon, M.; Zanghirella, F.; Pagliano, L. Yearly operational performance of a nZEB in the Mediterranean climate. *Energy Build.* **2019**, *198*, 243–260. [CrossRef]
15. Elsharkawy, H.; Zahiri, S. The significance of occupancy profiles in determining post retrofit indoor thermal comfort, overheating risk and building energy performance. *Build. Environ.* **2020**, *172*, 106676. [CrossRef]
16. Underhill, L.J.; Milando, C.W.; Levy, J.I.; Dols, W.S.; Lee, S.K.; Fabian, M.P. Simulation of indoor and outdoor air quality and health impacts following installation of energy-efficient retrofits in a multifamily housing unit. *Build. Environ.* **2020**, *170*, 106507. [CrossRef]
17. Ozarisoy, B.; Altan, H. Developing an evidence-based energy-policy framework to assess robust energy-performance evaluation and certification schemes in the South-eastern Mediterranean countries. *Energy Sustain. Dev.* **2021**, *64*, 65–102. [CrossRef]
18. Serrano, P.Y.; Gómez, D.T.; Bieńkowska, Z. Energy vulnerability and self-imposed austerity: An ethnographic approach to adaptation strategies to extreme heat among older adults in Madrid. *Energy Res. Soc. Sci.* **2023**, *103*, 103207. [CrossRef]
19. Serrano-Jiménez, A.; Lizana, J.; Molina-Huelva, M.; Barrios-Padura, Á. Indoor environmental quality in social housing with elderly occupants in Spain: Measurement results and retrofit opportunities. *J. Build. Eng.* **2020**, *30*, 101264. [CrossRef]
20. Chen, C.F.; Xu, X.; Day, J.K. Thermal comfort or money saving? Exploring intentions to conserve energy among low-income households in the United States. *Energy Res. Soc. Sci.* **2017**, *26*, 61–71. [CrossRef]
21. Domínguez-Amarillo, S.; Fernández-Agüera, J.; Peacock, A.; Acosta, I. Energy related practices in Mediterranean low-income housing. *Build. Res. Inf. Int. J. Res. Dev. Demonstr.* **2020**, *48*, 34–52. [CrossRef]
22. Clavijo-Núñez, S.; Herrera-Limones, R.; Rey-Pérez, J.; Torres-García, M. Energy poverty in Andalusia. An analysis through decentralised indicators. *Energy Policy* **2022**, *167*, 113083. [CrossRef]
23. Ortiz, J.; Casquero-Modrego, N.; Salom, J. Health and related economic effects of residential energy retrofitting in Spain. *Energy Policy* **2019**, *130*, 375–388. [CrossRef]
24. Recalde, M.; Peralta, A.; Oliveras, L.; Tirado-Herrero, S.; Borrell, C.; Palència, L.; Gotsens, M.; Artazcoz, L.; Marí-Dell'Olmo, M. Structural energy poverty vulnerability and excess winter mortality in the European Union: Exploring the association between structural determinants and health. *Energy Policy* **2019**, *133*, 110869. [CrossRef]
25. Yu, C.-R.; Liu, X.; Wang, Q.-C.; Yang, D. Solving the comfort-retrofit conundrum through post-occupancy evaluation and multi-objective optimisation. *Build. Serv. Eng. Res. Technol.* **2023**, *44*, 381–403. [CrossRef]
26. Calama-González, C.M.; Symonds, P.; León-Rodríguez, Á.L.; Suárez, R. Optimal retrofit solutions considering thermal comfort and intervention costs for the Mediterranean social housing stock. *Energy Build.* **2022**, *259*, 111915. [CrossRef]
27. Lizana, J.; Barrios-Padura, Á.; Molina-Huelva, M.; Chacartegui, R. Multi-criteria assessment for the effective decision management in residential energy retrofitting. *Energy Build.* **2016**, *129*, 284–307. [CrossRef]

28. Desogus, G.; Di Pilla, L.; Mura, S.; Pisano, G.L.; Ricciu, R. Economic efficiency of social housing thermal upgrade in Mediterranean climate. *Energy Build.* **2013**, *57*, 354–360. [CrossRef]
29. Ghoreishi, K.; Fernández-Gutiérrez, A.; Fernández-Hernández, F.; Parras, L. Retrofit planning and execution of a mediterranean villa using on-site measurements and simulations. *J. Build. Eng.* **2021**, *35*, 102083. [CrossRef]
30. Calama-González, C.M.; Suárez, R.; León-Rodríguez, Á.L. Thermal comfort prediction of the existing housing stock in southern Spain through calibrated and validated parameterized simulation models. *Energy Build.* **2022**, *254*, 111562. [CrossRef]
31. Castaño-Rosa, R.; Solís-Guzmán, J.; Marrero, M. Energy poverty goes south? Understanding the costs of energy poverty with the index of vulnerable homes in Spain. *Energy Res. Soc. Sci.* **2020**, *60*, 101325. [CrossRef]
32. Carpino, C.; Bruno, R.; Arcuri, N. Social housing refurbishment in Mediterranean climate: Cost-optimal analysis towards the n-ZEB target. *Energy Build.* **2018**, *174*, 642–656. [CrossRef]
33. Belpoliti, V. Comparative analysis of simulated and monitored energy performance of a prototype house. Lesson learnt from the project KNOW HOWse for Solar Decathlon Middle East 2018 in Dubai. *J. Build. Eng.* **2021**, *41*, 102740. [CrossRef]
34. Brambilla, A.; Salvalai, G.; Tonelli, C.; Imperadori, M. Comfort analysis applied to the international standard 'Active House': The case of RhOME, the winning prototype of Solar Decathlon 2014. *J. Build. Eng.* **2017**, *12*, 210–218. [CrossRef]
35. Cornaro, C.; Rossi, S.; Cordiner, S.; Mulone, V.; Ramazzotti, L.; Rinaldi, Z. Energy performance analysis of STILE house at the Solar Decathlon 2015: Lessons learned. *J. Build. Eng.* **2017**, *13*, 11–27. [CrossRef]
36. Domínguez-Torres, C.-A.; Domínguez-Torres, H.; Hernández-Valencia, M.; Roa-Fernández, J.; Herrera-Limones, R. A Feasible Proposal for Energy-Efficient Roof Retrofitting in Southern European Obsolete Residential Neighborhoods. *Buildings* **2023**, *14*, 88. [CrossRef]
37. Herrera-Limones, R.; León-Rodríguez, Á.; López-Escamilla, Á. Solar Decathlon Latin America and Caribbean: Comfort and the Balance between Passive and Active Design. *Sustainability* **2019**, *11*, 3498. [CrossRef]
38. Herrera-Limones, R.; Hernández-Valencia, M.; Roa-Fernández, J. Urban regeneration through retrofitting social housing: The AURA 3.1 prototype. *J. Hous. Built Environ.* **2022**, *38*, 837–859. [CrossRef]
39. Rahman, N.M.A.; Haw, L.C.; Fazlizan, A.; Hussin, A.; Imran, M.S. Thermal comfort assessment of naturally ventilated public hospital wards in the tropics. *Build. Environ.* **2022**, *207*, 108480. [CrossRef]
40. Alonso, A.; Calama-González, C.M.; Suárez, R.; León-Rodríguez, Á.L.; Hernández-Valencia, M. Improving comfort conditions as an energy upgrade tool for housing stock: Analysis of a house prototype. *Energy Sustain. Dev.* **2022**, *66*, 209–221. [CrossRef]
41. Luo, W.; Kramer, R.; de Kort, Y.; Rense, P.; van Marken Lichtenbelt, W. The effects of a novel personal comfort system on thermal comfort, physiology and perceived indoor environmental quality, and its health implications—Stimulating human thermoregulation without compromising thermal comfort. *Indoor Air* **2022**, *32*, e12951. [CrossRef] [PubMed]
42. Ahrentzen, S.; Erickson, J.; Fonseca, E. Thermal and health outcomes of energy efficiency retrofits of homes of older adults. *Indoor Air* **2016**, *26*, 582–593. [CrossRef] [PubMed]
43. López-Escamilla, Á.; Herrera-Limones, R.; León-Rodríguez, Á.L.; Torres-García, M. Environmental Comfort as a Sustainable Strategy for Housing Integration: The AURA 1.0 Prototype for Social Housing. *Appl. Sci.* **2020**, *10*, 7734. [CrossRef]
44. Vázquez, C.G.; Ramos, E.V. Intervención en barriadas residenciales obsoletas: Manual de buenas prácticas. In *Lecturas. Historia del Arte y de la Arquitectura*; Abada: Madrid, Spain, 2016.
45. Aja, A.; Alonso, R.R.; Suárez, I.R.; Giménez, J.M.G.; García, I.G.; Hernández, R.C.; Gómez, J.A.; Gutiérrez, J.C.; Mateos, F.C.; Cáceres, S.J. *Barrios Vulnerables de las Grandes Ciudades Españolas. 1991/2001/2011*; Instituto Juan de Herrera: Madrid, Spain, 2018.
46. Herna, A.; Garci, C.; Parellada, M. *Atlas de Barrios Vulnerables de España: 12 Ciudades 1991-2001-2006*; Instituto Juan de Herrera: Madrid, Spain, 2015; p. 346.
47. Aja, A.; Suárez, I.R.; Hernández, R.C.; Giménez, J.M.G.; García, I.G.; Mateos, F.C.; Heredia, M.G.; Pérez, M.B.S. *Vulnerabilidad residencial y social en las grandes ciudades españolas. 2001/2011*; Instituto Juan de Herrera: Madrid, Spain, 2018.
48. Instituto Juan de Herrera DuyOT; Ministerio de Fomento. *Síntesis Metodológica General del Catálogo de Barrios Vulnerables e Indicadores Básicos de Vulnerabilidad Urbana*; Instituto Juan de Herrera: Madrid, Spain, 2016.
49. Camarena, G.M.N.; Núñez, S.C.; Pérez, J.R.; Prieto, J.M.A.; Fernández, J.R. Memory and identity: Citizen perception in the processes of heritage enhancement and regeneration in obsolete neighborhoods—The case of Polígono de San Pablo, Seville. *Land* **2023**, *12*, 1234. [CrossRef]
50. Pomponi, F.; D'Amico, B. Holistic study of a timber double skin façade: Whole life carbon emissions and structural optimisation. *Build. Environ.* **2017**, *124*, 42–56. [CrossRef]
51. González, V.G.; Bandera, C.F. A building energy models calibration methodology based on inverse modelling approach. *Build. Simul.* **2022**, *15*, 1883–1898. [CrossRef]
52. Herrera, R.; Pineda, P.; Roa, J.; Cordero, S.; López-Escamilla, Á. Project AURA: Sustainable Social Housing. In *Sustainable Development and Renovation in Architecture, Urbanism and Engineering*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 277–287. [CrossRef]
53. López-Escamilla, Á.; Herrera-Limones, R.; León-Rodríguez, Á.L. Evaluation of environmental comfort in a social housing prototype with bioclimatic double-skin in a tropical climate. *Build. Environ.* **2022**, *218*, 109119. [CrossRef]
54. Gamero-Salinas, J.C.; Monge-Barrio, A.; Sánchez-Ostiz, A. Overheating risk assessment of different dwellings during the hottest season of a warm tropical climate. *Build. Environ.* **2020**, *171*, 106664. [CrossRef]

55. Crawley, D.B.; Pedersen, C.O.; Lawrie, L.K.; Winkelmann, F.C. EnergyPlus: Energy simulation program. *ASHRAE J.* **2000**, *42*, 49–56.
56. Crawley, D.B.; Lawrie, L.K.; Winkelmann, F.C.; Buhl, W.F.; Huang, Y.J.; Pedersen, C.O.; Strand, R.K.; Liesen, R.J.; Fisher, D.E.; Witte, M.J.; et al. EnergyPlus: Creating a new-generation building energy simulation program. *Energy Build.* **2001**, *33*, 319–331. [CrossRef]
57. Coelho, G.B.A.; Silva, H.E.; Henriques, F.M.A. Development of a three-dimensional hygrothermal model of a historic building in WUFI®Plus vs EnergyPlus. *MATEC Web Conf.* **2019**, *282*, 2079. [CrossRef]
58. Cuerda, E.; Guerra-Santin, O.; Sendra, J.J.; González, F.J.N. Comparing the impact of presence patterns on energy demand in residential buildings using measured data and simulation models. *Build. Simul.* **2019**, *12*, 985–998. [CrossRef]
59. ANSI/ASHRAE. *ASHRAE Guideline 14-2002 Measurement of Energy and Demand Savings*; ASHRAE: Peachtree Corners, GA, USA, 2002; Volume 8400, p. 170.
60. Ruiz, G.R.; Bandera, C.F. Validation of calibrated energy models: Common errors. *Energies* **2017**, *10*, 1587. [CrossRef]
61. Sánchez-García, D.; Rubio-Bellido, C.; Tristancho, M.; Marrero, M. A comparative study on energy demand through the adaptive thermal comfort approach considering climate change in office buildings of Spain. *Build. Simul.* **2020**, *13*, 51–63. [CrossRef]
62. Schweiker, M. Combining adaptive and heat balance models for thermal sensation prediction: A new approach towards a theory and data-driven adaptive thermal heat balance model. *Indoor Air* **2022**, *32*, e13018. [CrossRef]
63. Asociación Española de Normalización. *Parte 1: Parámetros del Ambiente Interior a Considerar Para el Diseño y la Evaluación de la Eficiencia Energética de Edificios Incluyendo la Calidad del Aire Interior, Condiciones Térmicas, Iluminación y Ruido. Módulo 1–6*; Asociación Española de Normalización: Madrid, Spain, 2019.
64. Zhang, S.; Lin, Z. Adaptive-rational thermal comfort model: Adaptive predicted mean vote with variable adaptive coefficient. *Indoor Air* **2020**, *30*, 1052–1062. [CrossRef]
65. Rubio-Bellido, C.; Pérez-Fargallo, A.; Pulido-Arcas, J.A.; Trebilcock, M. Application of adaptive comfort behaviors in Chilean social housing standards under the influence of climate change. *Build. Simul.* **2017**, *10*, 933–947. [CrossRef]
66. MoMo. Available online: https://momo.isciii.es/panel_momo/ (accessed on 15 January 2023).