Improving habitability in social housing through passive cooling: a case study in Mengíbar (Jaén, Spain)

Abstract

This paper presents the deep renovation of a social housing district in Mengíbar (Jaén, Spain). Among the aims of the renovation of this district is the promotion of passive improvement strategies adapted to the reality of the inhabitants: a population with limited resources that often finds itself in a situation of energy vulnerability. The actual energy situation is characterised by a severe climate, in particular regarding cooling needs. The district is located in a predominantly hot climate where the buildings suffer from severe overheating. This poor habitability is due to the high thermal discomfort associated with the observed energy poverty. Therefore, the first mitigation action is the proposal of optimal renovation measures for the energy renovation of the district. However, this actuation is not enough to solve the problem. A ventilated roof is proposed and implemented as a passive cooling technique that allows environmental heat sinks such as night ventilation and evaporative cooling. This solution is implemented on roofs measuring more than 2500 m^2 to demonstrate its level of technological readiness in a relevant environment. Together with the proposed ventilated roof, the renovation studied produces a significant decrease in thermal discomfort of up to 80% and 70% in cooling needs.

Keywords: energy poverty, social housing, deep renovation, double-skin roof, natural heat sinks

1 Introduction

1.1 Context

The building sector must comply with current European Union directives aimed at mitigating the effects of climate change. Buildings are responsible for 40% of the energy consumption of the EU and 36% of greenhouse gas emissions ("Tracking Buildings 2021 – Analysis - IEA," n.d.). Consequently, improving the energy efficiency of buildings will be crucial if the climate and energy objectives set by the European Union are to be reached (European Comission, 2014). Furthermore, the low energy efficiency of apartments in areas suffering from energy poverty can lead to continued discomfort, resulting in serious health problems for their occupants (Z. Zhang, Shu, Yi, & Wang, 2021). In Spain, between three and a half million people are affected by energy poverty, meaning they live in thermal discomfort conditions in summer, winter, or both (DCLG, 2012). This situation is even worse in social housing districts in the south of Spain, which is exacerbated by the gradual increase in overheating in the cooler months (Rodrigues & Fernandes, 2020). In this line, this study aims to design and evaluate a passive cooling solution that mitigates overheating, thus improving citizens' quality of life and adapting to the reality of social housing tenants (low income).

1.2 Social housing renovation

Among the aims of housing renovation, districts are the promotion of passive improvement strategies adapted to the reality of occupants, a population with limited resources often affected by energy vulnerability (Serrano-Jiménez, Lizana, Molina-Huelva, & Barrios-Padura, 2020). The literature review shows different case studies on the rehabilitation of social housing.

Here are some prominent examples. Curado. et al. (Curado & de Freitas, 2019) evaluated the thermal comfort of a rehabilitated social housing district. The authors studied the improvement of envelopes focused on roofs and windows. Subsequently, they evaluated the importance of façade thermal insulation in reducing thermal discomfort by applying a validated simulation model. The results show the importance of integrating the façade insulation in different climatic zones to achieve thermal comfort during the heating period. Casquero-Modrego et al. (Casquero-Modrego & Goñi-Modrego, 2019) described the real case of an energy rehabilitation of a residential block located in Barcelona. The authors carried out the renovation of the main facades and the roof of the building with the financial support of the public institution. However, the data measured after the renovation show that a greater depth of reform is necessary to improve the thermal comfort of the building during winter. Carpino et al. (Cristina Carpino et al., 2018) analysed traditional social housing in the Italian territory. The renovation project contemplates the insulation of the façades and the replacement of the windows. Furthermore, the authors proposed improving the HVAC because the proposal before was not enough to achieve acceptable thermal comfort conditions. The authors of this study conclude on the need to address economic incentives for the achievement of NZEB buildings through the exploitation of heat pumps and renewable sources. Finally, Luxán et al. (Luxán, n.d.) defined the most appropriate methodology and best practices to improve historic social dwellings. The authors validated their proposal into a residential block with 18 dwellings in Zaragoza (Spain), where authors proposed the insulation of wall, roof and floor, and replaced windows to reduce heating needs. Also, authors incorporated solar protection systems on the south façade for the reduction of solar gains in summer.

Typically, energy efficiency in retrofitting includes adding insulation, replacing existing windows with more efficient ones, reducing or eliminating thermal bridges, and increasing the airtightness of the envelope (Serrano-Lanzarote, Ortega-Madrigal, García-Prieto-Ruiz, Soto-Francés, & Soto-Francés, 2016). These conventional strategies lead to significant reductions in building heating needs (Eskander, Sandoval-Reyes, Silva, Vieira, & Sousa, 2017). However, these cooling solutions are insufficient in areas with a predominantly summer climate, such as southern Spain. In this regard, there is growing interest in using passive cooling techniques in buildings based on solar and heat control, heatwave damping, and heat dissipation (Santamouris, Pavlou, Synnefa, Niachou, & Kolokotsa, 2007). Research conducted in recent years has resulted in important improvements in solar protection features. The main progress in solar control comes from developing switchable glazing technology, particularly electrochromic glass (Ghoshal & Neogi, 2014). However, despite its potential for improving living conditions, this kind of solar protection is not commonly found in social housing districts due to its high cost and the fact that the participation of the occupants is necessary for them to function correctly (Carpino, Bruno, & Arcuri, 2020). Solar and thermal protection of non-transparent components can be achieved by using reflective coatings on the roofs of buildings (cool roofs). Santamouris et al. (Santamouris et al., 2007) evaluated the possible benefits of applying a white coating to the roofs of low-income housing, reporting that the expected decrease in the annual cooling demand may range between 5 and 70 kWh / (m^2 year) depending on the climate. Along these lines, A. Synnefa et al. (Synnefa, Santamouris, & Akbari, 2007) suggest that increasing the solar reflectance of the roof by 0.65 by applying a cool coating reduces the cooling demands by 8-48 kWh / m2 and the maximum temperature by 1.2-3.7ºC, depending on the climate conditions. However, the authors show that applying this cool coating may result in a heating penalty of up to 17 kWh/m^2

year. Along these lines, Domínguez-Delgado et al. (Dominguez-Delgado, Domínguez-Torres, & Domínguez-Torres, 2020) also report the need to perform an in-depth assessment of the ageing effect on the energy performance of cool roofs, in addition to the implications for the economic assessment and energy life cycle of this kind of roofs when they are used in the renovation of the social housing stock under consideration. Night ventilation is an efficient and low-cost passive cooling technique that involves using the thermal mass of the building to store cool night air. Santamouris et al. (Santamouris, Sfakianaki, & Pavlou, 2010) suggest that this technique may lead to a decrease in cooling demands of nearly 40 kWh / (m^2 year) in residential buildings, with a mean contribution of 12 kWh / (m^2 year). However, high levels of pollution and outside noise can be severe problems associated with these natural systems. Furthermore, it has several practical limitations, such as the thermal mass required (inertia) and its correct activation (Bienvenido-Huertas, Sánchez-García, Rubio-Bellido, & Pulido-Arcas, 2021). Finally, the authors highlight that the technique depends on the climate, with low outdoor temperatures required during the night. Consequently, night ventilation is insufficient as a standalone strategy to significantly reduce indoor temperatures in regions with extreme cooling demands, implying the need to combine different passive mitigation strategies and/or the inclusion and development of innovative components and technologies in the building envelope.

1.3 Ventilated roof

In the context of energy rehabilitation of existing buildings in urban areas, the façade of the building is more important than the roof due to the increased height of the buildings relative to the horizontal area (Redweik, Catita, & Brito, 2013). However, the façade presents obstacles that make it challenging to create cavities or circuits into which a heat transfer fluid can be integrated (Ibañez-Puy, Martín-Gómez, Bermejo-Busto, Sacristán,

& Ibañez-Puy, 2018). Furthermore, it is worth high lighting that, in summer, solar radiation is absorbed by the building envelope, particularly the roof (Barrios, Huelsz, Rechtman, & Rojas, 2011). The roof is a critical element for cooling needs due to its surface area, exposure to solar radiation, and the absence of solar protection elements. Consequently, the accumulation of heat on the roofs of buildings requires solutions. Along these lines, as mentioned above, cool roofs to control solar radiation and heat can achieve significant reductions in cooling needs by neutralising solar heat gains, but incorporating them may lead to a heating penalty. This problem is most noticeable in zones with high cooling needs, such as the south of Spain, where solutions are required to improve the cooling of the building. Double skin systems are a kind of passive cooling technology that saves energy and can be adapted to different climates (Ascione, Bianco, Iovane, Mastellone, & Mauro, 2021). These bioclimatic strategies involve designing the building envelope to form two continuous, ventilated layers (Tao et al., 2021). These elements have been widely developed and used for passive heating purposes. However, these elements' study and development for passive cooling are currently limited (Bhamare, Rathod, & Banerjee, 2019). Double skin solutions incorporate natural cooling techniques, such as night ventilation and evaporative cooling. Many studies in the literature report the integration of night ventilation through these elements in the envelope (Ran & Tang, 2018). However, evaporative cooling has become increasingly popular in the last decade due to its simplicity, reduced costs, and low use of natural resources (Bhamare et al., 2019). Its high cooling efficiency makes it an appealing alternative in hot, dry climates. Moreover, if this system is combined with night ventilation (Evangelisti, Guattari, & Asdrubali, 2019), it can achieve a considerable cooling potential. In a previous study, the authors of the present paper propose a double skin façade system that incorporates environmental heat sinks as thermal inertia activation elements (Guerrero Delgado, Sánchez Ramos, Cabeza, & Álvarez Domínguez, 2020). The results obtained from evaluating the solution's integration into an experimental prototype show that incorporating night ventilation as a heat sink is attractive. However, the evaporative system provides a solution that maximises the impact on energy efficiency. Consequently, it is necessary to redesign ventilated roof solutions to integrate natural heat sinks and achieve optimal results, making them viable according to the directives defining rehabilitation projects (Lissen et al., 2021). Finally, a literature review shows a limited number of roof designs as passive cooling solutions. In addition, there is a lack of buildings that incorporate ventilated roofs and, consequently, assessments of the impact of this technology on energy needs.

1.4 Aims

This paper aims to improve the habitability of a social housing district by performing a comprehensive renovation bolstered by passive cooling techniques. The district is located in Mengibar (Jaén, Spain), a region characterised by a severe climate and high heating and cooling needs. Passive techniques are proposed based mainly on improving envelope behaviour to mitigate energy poverty and thermal discomfort in the district. Furthermore, given the predominantly hot climate and severe overheating, it is proposed to incorporate a ventilated roof that allows integrating environmental heat sinks such as night ventilation and evaporative cooling. This solution must comply with defined energy goals and be affordable for the occupants of the apartments, which are characterised by a lack of financial resources.

The main contributions of the work carried out are the following:

- Real monitoring and evaluation of existing thermal discomfort in a social housing district located in southern Spain.

- The conventional renovation plan for the district has been defined by the implementation of the life cost analysis. For that, different passive measures have been studied to reduce heating and cooling needs. The 540 combinations of improvement measures consider different improvements for the insulation of the envelope, replacement of windows, improvement of thermal bridges, solar control elements, and the integration of night ventilation. However, the selected conventional renovation plan is not enough to achieve thermal comfort in this social apartment without HVAC systems.
- Solve the need to design a passive cooling solution to mitigate the overheating that characterizes the social housing districts of southern Spain: this study provides the design of a ventilated roof solution whose heat dissipation can be enhanced by integrating an evaporative cooling system.
- The designed roof solution is integrated into more than 2500 m^2 of roof surface as a real example of the integration of high-tech components.
- Finally, this study evaluates the energy impact of the renovation project selected through the life cycle cost analysis and the additional improvement that can be achieved thanks to the integration of the ventilated roof solution in different modes of operation.

Finally, in line with the goals defined, the present paper is organised as follows sections. Section 2 describes the case study and justifies the need for intervention in regard to indoor temperatures and thermal discomfort. Section 3 describes the set of improvement measures proposed for the conventional renovation of the district, in addition to the evaluation and selection of the optimal solution. Section 3 describes the implementation of the solution in the district and its impact on energy efficiency. Section 4 defines the conceptual ventilated roof solution proposed as a passive cooling technique and the details of its design. Finally, it shows the final situation of the district and the assessment of its impact on cooling needs.

2 Case study

2.1 Description of the case study

The social housing district under study is the property of the Andalusia Housing and Renovation Agency. It consists of 150 apartments distributed in 14 buildings (see Figure 1). It is located in Mengíbar (Jaén, Spain) and was built in 1984. The thermal efficiency of the buildings is poor (for example, U_{walls}=1.4 W/m^{2}K and $U_{openings}$=5.6 W/m^{2}K), which, along with the low income of the occupants, means that the apartments live in fuel poverty. There is a social assistant of the Andalusian Social Housing Agency for the district. She has generated data for the analysis of the economic-social situation of the district. The social assistant is responsible for helping social housing tenants and intervening in possible problems related to paying rent, bills, or other vital expenses. The data provided by this assistant are: 56% of families have a monthly income below € 900, not exceeding the remaining 44% of € 1600. However, there is a 34% with income below € 600 per month. The neighbourhood has a considerable unemployment rate that markedly exceeds the limit of vulnerability established by 1.5 times the state average. Another relevant indicator is that more than 35% of households survive on public pensions. Additionally, tenant surveys reveal that more than 64% of households say they do not have money to install a heating system in their homes, and 23% indicate that they put it less than they think they need it due to the high expense it would entail in their family economy.

Figure 1. View of the district before the renovation

According to the climate classification for Spain, Mengibar belongs to zone C4 (Ministry of Development, 2019). Since Köppen-Geiger, the climate zone of Mengibar is Csa (Carver, Mikkelsen, & Woodward, 2002). On the other hand, its severity climate index is 0.52 for winter and 1.5 for summer (Guerrero Delgado, Sánchez Ramos, & Álvarez Domínguez, 2020). The region is characterised by extreme summer and winter climate conditions. Summers are short, torrid, dry, and mainly cloudless. Winters are cold, dry, and partly cloudy. Figure 2 shows the monthly average of outdoor air temperature, relative humidity, solar radiation, and rainfall level for Mengibar during 2019. Also, Figure 3 shows the mean daily and hourly outdoor temperature. All climate data are obtained from the climate station near the district and are owned by the Spanish government (open and accessible data). They show that the hot season lasts four months, from approximately June to September, when the average maximum temperature at the time of day is generally above 28 ° C. The winter season also lasts four months, from November to March, when the average maximum temperature at daytime is below 10 ° C. During the year, the hourly temperature generally ranges between 2 ° C and 37 ° C, but temperatures sometimes drop below -2 ° C or rise above 41 ° C. Since Figure 3, the hottest day of the year 2019 is 22th July, with a mean daytime temperature of 33 ° C and a maximum hourly temperature of 42 ° C.

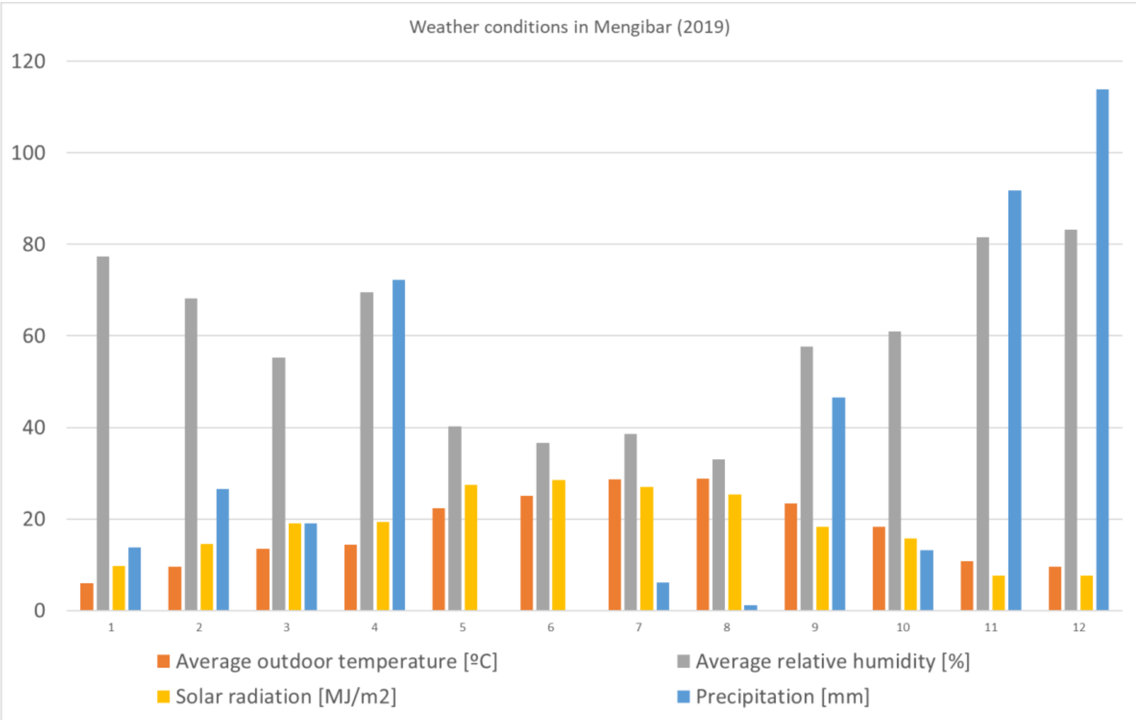


Figure 2. Weather Conditions in Mengibar (2019)

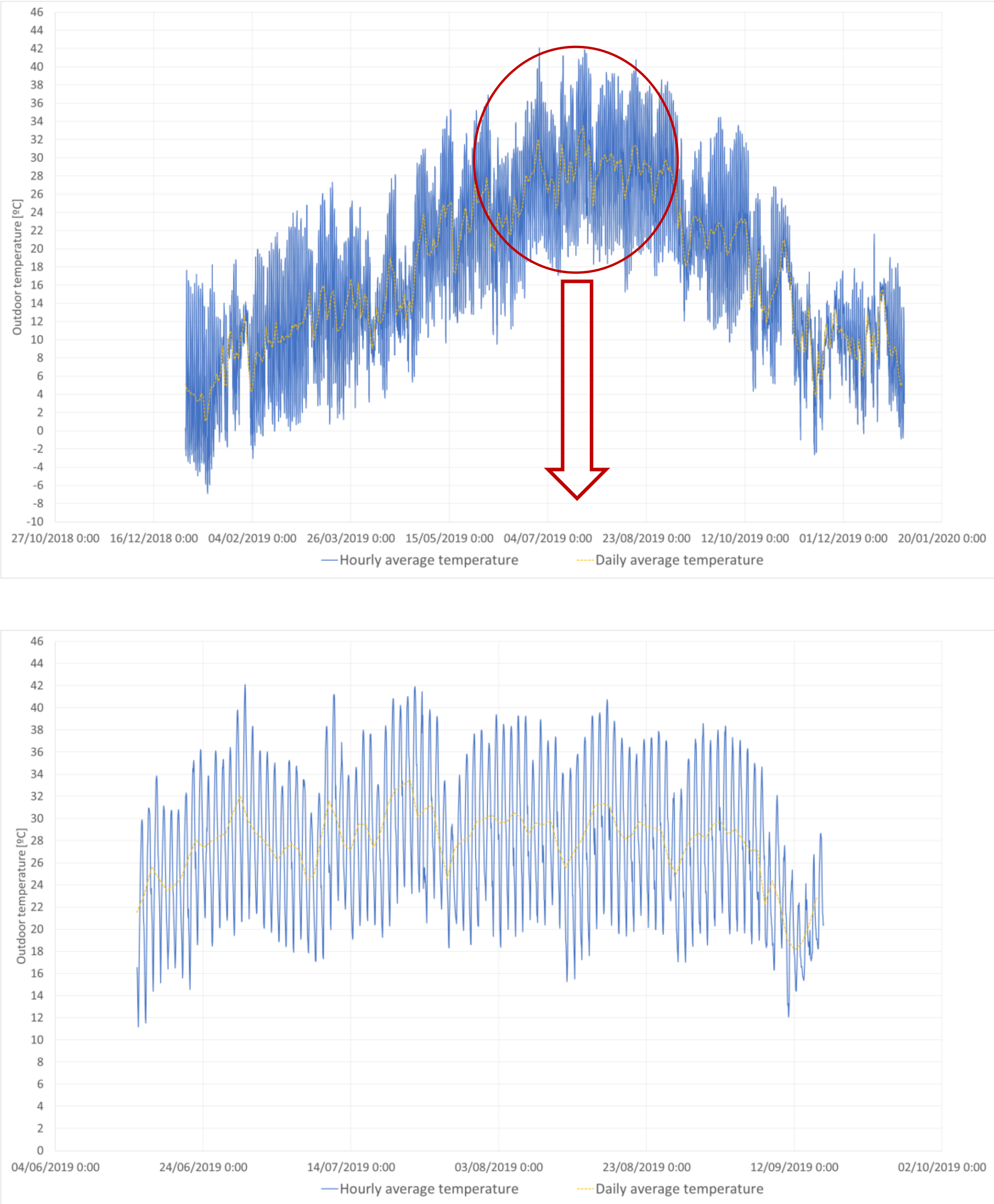


Figure 3. Weather conditions in Mengíbar (2019)

2.2 Justification for the intervention

Models and indicators of thermal comfort are used to measure the habitability of apartments, compare the level of discomfort of different apartments, or even evaluate the impact of renovation by comparing initial and improved energy situations (Machrafi, 2012). In Section 2.2.1, we describe the indicators that make it possible to assess the initial thermal behaviour of the buildings (before the renovation) and form the basis for the justification for the intervention.

2.2.1 Indicators of habitability and thermal comfort

Thermal comfort is understood when people who live in a house do not experience a sensation of heat or cold, or, in other words, when the conditions of humidity, temperature and air movement are pleasant and appropriate to the activity carried out inside. The complexity of evaluating thermal comfort, related to people's subjective sensations, allows for study variables such as air temperature, radiant temperature, air humidity, and air velocity. The PassivHaus standard ("Passivhaus Institut," n.d.) interprets for the average air temperature a minimum comfort value in winter of 20º and summer a maximum value of 25º and humidity between 40 and 70% can provide a feeling of comfort (Echarri-Iribarren, Sotos-Solano, Espinosa-Fernández, & Prado-Govea, 2019). Comfort in buildings has been based on the studies of Fanger (P.O. Fanger, 1970) in which the human being is considered the result of a series of heat exchanges. This method has now given rise to the ISO 7730 UNE-EN (Standardization, 2005). This regulatory framework applies a static comfort model, which establishes that the interior design conditions of operating temperature and relative humidity are set based on metabolic activity, clothing insulation, and expected percentage of dissatisfaction. On the other hand, adaptative comfort is based on the outdoor temperature. In this way, the dynamic models ASHRAE Standard 55-2017 (ASHRAE, 2017)and UNE-EN 15251 (UNE standards, 2008). In this line, Brager et al. (Brager & De Dear, 1998) propose that, in general terms, adaptation can be described as the gradual reduction of the response of an organism to repetitive stimulation of the environment outside the ranges predicted using mathematical models of comfort. On the other hand, according to Nicol (McCartney &

Fergus Nicol, 2002) the primary hypothesis of adaptive comfort is that if a change generates thermal discomfort, people react by carrying out actions to return to comfort. Therefore, the environmental conditions that people find comfortable will depend on their interaction and the environment.

Traditionally, different magnitudes are defined based on the above models and used to measure an apartment's degree of comfort or discomfort. The first commonly used scale is the number of hours the apartment or building spends in thermal discomfort. However, it seems logical that the hours when it is significantly hotter than the comfort temperature should not be weighed equal to the hours when the variation is minimal. Although it seems obvious, this reasoning, which is based on the percentage of unsatisfied people (PUP) according to the temperature difference proposed by Fanger himself, has not been presented by some authors until very recently (Kordjamshidi, 2011). Following this reasoning, the scale for assessing the degree of comfort would go from a sum of hours to a sum of temperature differences expressed in accumulated degrees-hour, or a sum of temperature differences weighted by the percentage of unsatisfied people. Therefore, the most common indicators for thermal comfort are listed below. These scales will be the indicators used in this study to assess the thermal habitability of the district.

- Hours of discomfort [h].- number of hours where the indoor temperature is outside the thermal comfort range.
- Degrees–hours of discomfort [ºC·h].- Sum of the temperature differences when the indoor temperature is outside the thermal comfort range.
- Weighted degrees-hour of discomfort [ºC·h·ppi].- Sum of the temperature differences in the hours in which the indoor temperature is outside the thermal comfort range, weighted by the percentage of unsatisfied people.

The analysis of these indicators allows for the thermal evaluation of the initial situation of the district. That is to say, knowing the energy situation of the district and justifying the need for the intervention. Section 2.2.2 below shows the monitoring campaign that took place.

2.2.2 Experimental assessment

The monitoring campaign is designed to assess and validate the level of thermal comfort in the apartments. The monitored apartments appear in Figure 4. They are called using a code: BX PY Z (where BX is the ID of the block, PY is the number of the entrance in this block and Z is the number of the apartment). For example, B5_P3_3C is apartment 3C, in block 5 (B5), entrance P3. Likewise, the associated description details the orientation, situation, or plant of location and number of occupants.

Figure 4. Apartments representative of the district

2.2.2.1 *Description of the monitoring system*

The monitoring system for each apartment consists of a temperature and humidity sensor in the living room and master bedroom. This monitor system is the USB Elitech RC-5.

Its resolution is 0.1 ºC, and its precision is +-0.5 ºC. The monitoring campaign began in April 2019 and continues to this day. The campaign made it possible to obtain values for the air temperature and relative humidity of the six apartments with 10-minute sampling periods. The weather data explained above is obtained from the weather station near the district, which provides hourly values of outdoor air temperature, relative humidity, wind velocity and direction, and solar radiation. Finally, it highlights that the citizen participation process was organised to encourage the occupants to allow their apartments to be used for the experiments. To this end, regular meetings were held so that they could participate in the solution.

2.2.2.2 Experimental results

First, Figure 5 shows the hourly temperature values measured between June and September 2019 (months before the intervention) for two monitored apartments. One of them is situated on the top floor (B5_P3_3C), and the homologous is in the same orientation but on the middle floor (B5_P3_3C). The figure shows that the indoor temperatures in both apartments were constantly high for many consecutive days. Door-to-door surveys revealed that unbearably high temperatures in the occupants' bedrooms at night made it impossible to get a good night's sleep. Figure 5 shows that the apartment on the top floor below the roof had higher temperatures than the apartment on the middle floor, with differences ranging up to 7 ° C. It is due to the result of heat gains produced through the roof.

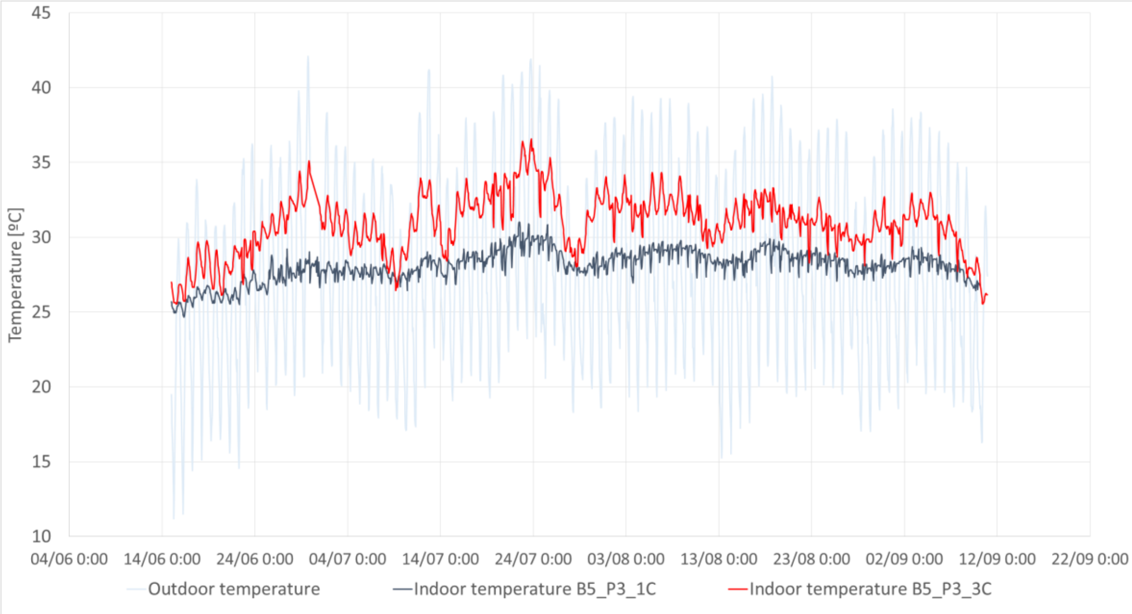


Figure 5. Comparison of apartment on the upper floor and apartment on the middle floor

2.2.2.3 Evaluation of the initial thermal situation of apartments

The assessment of the initial situation of the apartments in terms of thermal discomfort is shown below. To this end, the number of hours of thermal discomfort was calculated for the six apartments monitored during the four months with a high cooling need before the intervention (June to September). Table 1 shows the number of hours of thermal discomfort and the percentage of these hours four months before the district renovation. The results are distinguished by housing groups: (Group 1: B5-P1-1B (intermediate floor), B5-P1-3B (upper floor); Group 2: B5-P2-2B (intermediate floor), B5-P2-3B (upper floor); Group 3: B5-P3-1C (intermediate floor), B5-P3-3C (upper floor)). Each group (cluster) consists of an apartment on the intermediate floor and an apartment on the top floor, located in the same block, portal, and orientation. As seen in Table 1, the number of hours during which the apartments experience thermal discomfort is very high, reaching values of up to 97% in July and August in all the apartments studied.

		Middle floor	Nº discomfort hours [h]	Discomfort hours [%]	Top floor under roof	Nº discomfort hours [h]	Discomfort hours [%]
G1	JUNE	B5-P1-1B	572	79	B5-P1-3B	636	88
	JULY	B5-P1-1B	720	97	B5-P1-3B	720	97
	AUGUST	B5-P1-1B	720	97	B5-P1-3B	720	97
	SEPTEMBER	B5-P1-1B	285	40	B5-P1-3B	334	46
G2	JUNE	B5-P2-2B	623	87	B5-P2-3B	700	97
	JULY	B5-P2-2B	720	97	B5-P2-3B	720	97
	AUGUST	B5-P2-2B	720	97	B5-P2-3B	720	97
	SEPTEMBER	B5-P2-2B	446	62	B5-P2-3B	567	79
G3	JUNE	B5-P3-1C	656	91	B5-P3-3C	699	97
	JULY	B5-P3-1C	720	97	B5-P3-3C	720	97
	AUGUST	B5-P3-1C	720	97	B5-P3-3C	720	97
	SEPTEMBER	B5-P3-1C	322	45	B5-P3-3C	562	78

Table 1. Initial thermal comfort situation (cooling)

Finally, the roof's contribution to the apartment's thermal discomfort was assessed by comparing the weighted measure of degrees of discomfort [ºC·h·ppi]. As mentioned above, this measure considers the number of hours that the apartment is in thermal discomfort and considers the importance of the difference between the temperature and thermal comfort temperature. Table 2 shows the measurements obtained for all apartments in the cooling months before the intervention.

The results measured show the negative effect of the roof. The contribution of the roof to thermal discomfort varies from 15-33% for the group of apartments in the south-west orientation. However, the contribution of the roof in the increase in groups 2 and 3 in the weighted degrees of discomfort reached values of up to 50%. However, the minor differences obtained between apartments with the same orientation (G2 and G3) are due to the behaviour of the user. It is relevant and, consequently, the intervention is of interest.

		Middle floor	Weighted hours [ºC h ppi]	Top floor under roof	Weighted hours [ºC h ppi]	**Roof contribution [% of ºC h ppi]**
G1	JUNE	B5-P1-1B	1287	B5-P1-3B	1935	**33**
	JULY	B5-P1-1B	4103	B5-P1-3B	4907	**16**
	AUGUST	B5-P1-1B	4117	B5-P1-3B	4800	**14**
	SEPTEMBER	B5-P1-1B	873	B5-P1-3B	1026	**15**
G2	JUNE	B5-P2-2B	1845	B5-P2-3B	3377	**45**
	JULY	B5-P2-2B	4653	B5-P2-3B	6040	**23**
	AUGUST	B5-P2-2B	4635	B5-P2-3B	6061	**24**
	SEPTEMBER	B5-P2-2B	1034	B5-P2-3B	1675	**38**
G3	JUNE	B5-P3-1C	1657	B5-P3-3C	3335	**50**
	JULY	B5-P3-1C	4763	B5-P3-3C	6024	**21**
	AUGUST	B5-P3-1C	4724	B5-P3-3C	6033	**22**
	SEPTEMBER	B5-P3-1C	1058	B5-P3-3C	1637	**35**

Table 2. Contribution of the roof to the increase in thermal discomfort

It is used as a building energy simulation tool to define the best solution for mitigating the problem before. For that, the district was modelled, and the model was validated. The district was modelled to calculate the indicators of habitability, compensating for the role of the occupants of the apartments, which is essential to obtain an assessment of the energy impact that is a true reflection of the actual situation.

2.2.3 Modelling and validation

The constructive geometric model was created in the LIDER-CALENER Unified tool (HULC) (see Figure 6). It is the official tool for energy certification of buildings in Spain ("Ministry of Development. Unified LIDER-CALENER software Tool (HULC); 2019.," n.d.). It has been used in many recent studies in the literature (Gallego Sánchez-Torija, Fernández Nieto, & Gómez Serrano, 2021; Las-heras-casas, Olasolo-alonso, Luis, & Luis, 2021). The actual construction solutions were used. The calculation procedure has been validated by the Bestest (Lab, 1995). This calculation method allows two types of simulation: the spaces behave at a controlled temperature or in free oscillation (during periods in which the temperature is spontaneously between the set values and during periods without occupation). The boundary conditions can be particularized according to the use of the building and the behaviour of the occupants. This tool contains a database of standard climate files with which it performs energy simulation and certification of buildings in Spain. It is possible to use any climate data for the simulation. In the present study, the energy simulation of the buildings is carried out with the actual climate obtained from the climatic station near the district under study. However, the tool contains a database or standard climate files with which it performs energy simulation and certification of buildings in Spain. On the other hand, the tool allows one to define a personalized time profile of the occupant's behaviour with the actual occupant's behaviour.

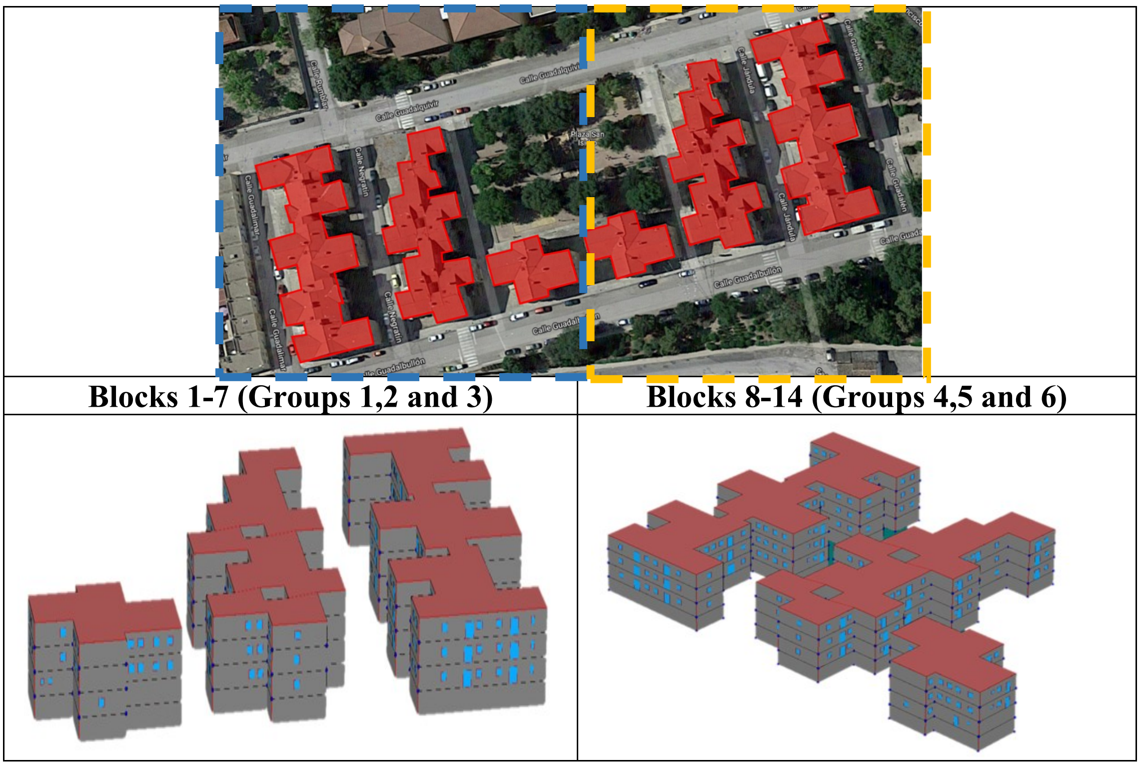


Figure 6. Modelling of the district

The apartment model developed in HULC was used as the baseline reference model to assess the energy impact of integrating the passive improvement strategies (Salmerón, Álvarez, Molina, Ruiz, & Sánchez, 2013). The validation process involved comparing the measured hourly indoor temperature with the hourly indoor temperature estimated by the model according to the use of the apartments and the actual temperature. Figure 7 shows the results obtained for the six apartments monitored. The relative error (absolute value) is below 5% in 96% of the cases. So, the modelling procedure is considered acceptable.

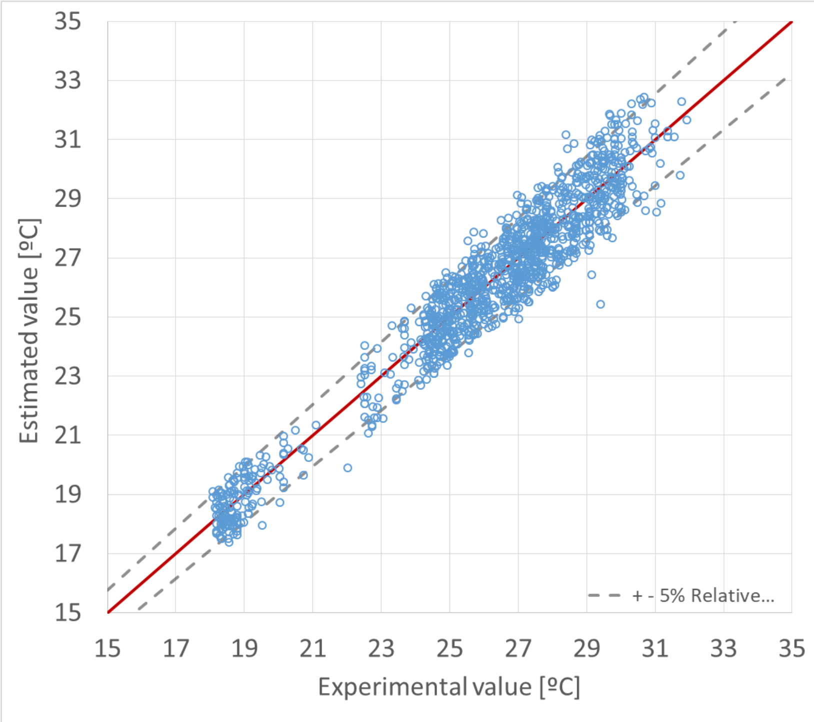


Figure 7. Validation

Furthermore, Figure 8 shows the details of the validation of the apartment B5-P2-3B model in May 2019, typically a transition month in terms of heating and cooling needs. The results provided by the software are accurate, and it is acceptable to use the models.

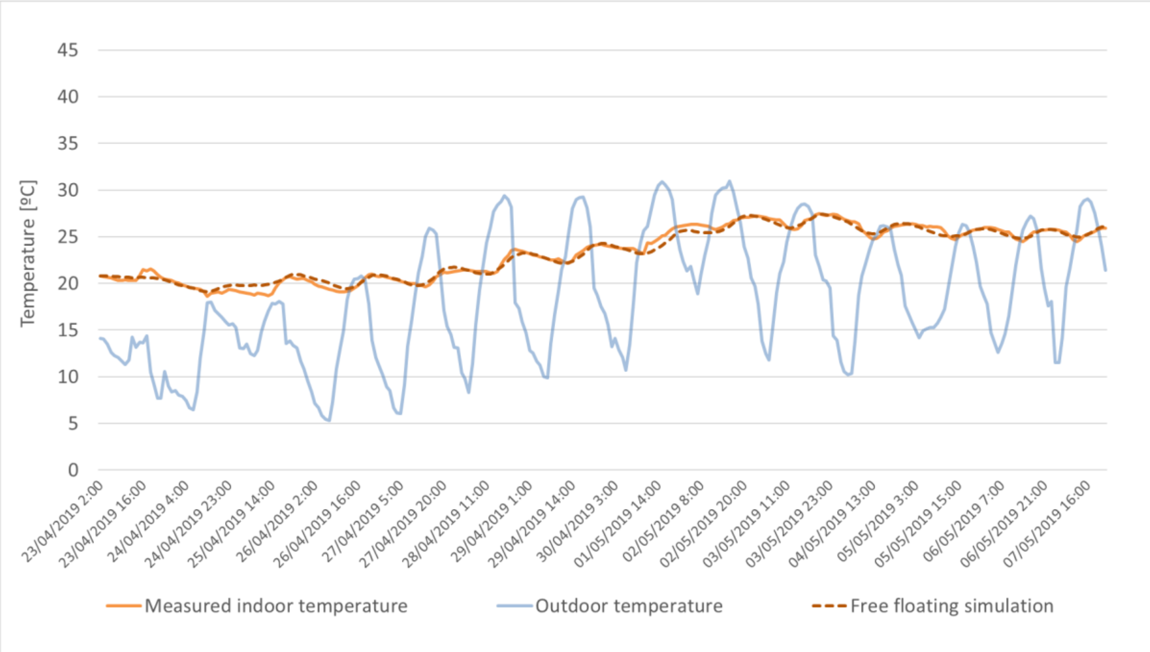


Figure 8. Example of validation of the simulation model for apartment B5-P2-3B.

3 Improvement measures

Improving the habitability of social housing districts is achieved through passive strategies adapted to the reality of the occupants, a population with limited financial resources. Along these lines, different passive improvement strategies are proposed in this study to reduce the heating and cooling needs. A study methodology must accompany the proposal and choose the best measure to be incorporated to create a catalogue of measures that can be applied to building renovations, from which the best solution can be found. The passive renovation measures proposed in the present study are as follows:

- Envelopes: Insulating the envelopes. In the case of the roof, a double-skin roof was the solution considered, which can be found in Section 4. Integrating this roof involves creating an air chamber and insulating the exterior skin. Thermal mass activation for heating was not considered (non-ventilated air chamber).
- Doors and windows: Replacing the existing windows was proposed, considering that this would decrease the transmittance and the solar factor (g-value).

- Thermal bridges: Improvements to thermal bridges have been considered.
- Infiltrations and ventilation: Different strategies were proposed to improve the airtightness of buildings and ventilation systems to reduce air changes per hour due to air infiltration.

In addition to the ventilated roof (detailed in Section 4), solar control and night ventilation are considered to reduce cooling needs. Regarding solar control strategies, the most commonly studied options are fixed systems and mobile solar protection systems (Huo, Xu, Li, Lv, & Liu, 2021; Kirimtat, Koyunbaba, Chatzikonstantinou, & Sariyildiz, 2016). Night ventilation focuses on taking advantage of free cooling potential using low nighttime temperatures to cool the thermal mass of the building and reduce cooling needs (H. Zhang et al., 2021). As shown in Figure 7, outdoor air temperatures at night in Mengíbar reach much lower temperatures than during the day. Therefore, the cool nights in summer make it possible for this study to benefit from this mitigation strategy. The options considered in this study involve activating ventilation for eight hours from midnight.

Table 3 shows the catalogue of improvement measures proposed in this study. The first row of the table corresponds to the base scenario (starting situation). The different levels of improvement proposed are defined following the cost-optimal methodology defined by the EPBD (Energy Performance of Buildings Directive) for the transposition of the same in the member countries. This methodology is based on the definition of levels of improvement by coherent measures. The packages of measures defined in the present study are the following: 1: Improvement of the thermal transmittance of elements of the envelope; 2: Reduction of thermal bridges; 3: Reduction of infiltrations; 4: Reduction of solar gains; 5: Increase heat losses by night ventilation. For each of the packages described, different levels of improvement are defined. Package 1 presents the base case at level 1. Level 2 corresponds to the minimum energy qualities, level 3 corresponds to the recommended energy qualities, and level 5 corresponds to the high energy efficiency values. These levels are defined in the Technical Building Code of Spain for the corresponding climatic zone (Ministry of Development, 2019), in this case, C4. Level 4 corresponds to an intermediate additional assessment level between 3 and 5. The second package (reduction of thermal bridges) considers three levels: level 1 is the base case, level 2 is the first improvement, and level 3 corresponds to the most remarkable improvement. These levels 2 and 3 are defined by the Technical Building Code of Spain. The most significant difference between levels 2 and 3 is that level 3 implies improvement in the thermal transmittance of windows.

The third package of measures (reduction of infiltrations) considers in level 1 the starting situation, level 2 corresponds to the tightness requirement defined in the Spanish Technical Building Code, and level 3 corresponds to compliance with the minimum tightness level required and the presence of a ventilation system with operation controlled by the energy needs of the building.

The fourth package of measures (reduction of solar gains) presents in level 1 the base case, level 2 the integration of solar control elements that reduce solar gains by half compared to the base case, and the third level corresponds to the high-efficiency level defined in UNE 14501 (14501: 2021, 2021). Finally, in the package of measures 4 (increase in losses in cooling by night ventilation), three levels of progressive increase of the renewals hour of outdoor air to the maximum level defined in 10 ren / h are evaluated to avoid discomfort problems.

The set of options in Table 2 generates 540 possible combinations, all of which were simulated in the building simulation tool (HULC) to obtain a value for the energy savings of each in the initial situation. Finally, it should be mentioned that the impact of operating the ventilated roof for cooling was not considered in the choice of optimal measures for the renovation of the district. The energy impact of the operation of the roof for cooling was quantified and evaluated after it was designed. This design is defined as an innovative passive cooling technique that acts as a backup to improve habitability with regard to the cooling needs, especially on the floor under the roof.

	Heating reduction alternative						Cooling reduction alternative	
Level of improvement	Walls [W/m^{2}K]	Roof [W/m^{2}K]	Floor [W/m^{2}K]	Windows [W/m^{2}K]	Linear transmittance of Thermal Bridges	Infiltrations + Ventilation	Solar control (g-value of Windows in summer)	Night ventilation [1/h]
1	1.42	0.68	1.90	5.6	Base case	n50=5.2	0.8	4
2	0.56	0.44	0.56	3.1	50% reduction	n50=3	0.4	8
3	0.42	0.33	0.44	2.6	75% reduction	n50=3 (with demand control ventilation)	0.1	10
4	0.35	0.27	0.38	2.1				
5	0.28	0.22	0.32	-1.8				

Table 3. Proposal of renovation options considered

The cost-optimal methodology proposed in European regulations was followed to find the optimal renovation solution from the catalogue of options (EU, 2010). The cost-optimal methodology aims to minimize the life cycle cost (LCC) of a building by applying a set of renovation measures. The proposed methodology optimises the performance of the building envelope and its facilities, taking into account energy savings and investment and operating costs. This methodology offers a complete analysis of environmental impact over 30 years (Commission, 2012). Next, the application of the optimal cost methodology is shown, as well as the results obtained.

3.1 Cost-optimal

The life cycle cost of a building is the total cost of the building over its entire life. However, the European Commission decided that this study period would be 30 years

(Economidou et al., 2020). The total cost of the building includes the cost of the building and the cost of operation. The base cost and the cost of the improvements to be made are considered from the envelope. For the aim of this study, we are only interested in the second term (extra cost or investment cost). The cost of acquiring and installing the conditioning equipment for the initial situation is considered for the systems. Also, the operation costs take into account the energy consumption for heating and cooling. These costs may vary due to changes in energy prices (inflation). Equation 1 shows the calculation formula of the LCC indicator in the present study, and eq. 2 defines the calculation of effective interest.

$$LCC\ (€) = Investment\ (€) + Operation\ cost\ \left(\frac{€}{yr}\right) \cdot \sum_{k=1}^{30} \frac{1}{(1+ief)^k} \quad \text{(eq.1)}$$

$$(1 + ief) = \frac{(1+i)}{(1+inf)} \quad \text{(eq.2)}$$

Where i is the interest rate, inflation inf and the effective interest, the cost values are determined for one year and are supposed to be repeated for everyone, with no variation other than inflation. The values of the discount rate and inflation are average values for the entire life cycle. The primary energy consumption of heating or cooling necessary for the calculation of the operating cost was calculated as the relationship between the heating and cooling energy needs and the performance of the reference system defined in the Spanish regulations (Ministry of Development, 2019) to focus the study on the reduction of energy needs by neutralizing the facilities. The reference system of domestic heat water and heating is a natural gas boiler with a nominal efficiency of 0.92. In the case of cold production, the reference system is characterized by consuming electricity and having an energy efficiency ratio of 2.6. The energy cost of heating was €0.08/kWh, obtained for natural gas, and the cost of electricity was €0.25/kWh. These prices are obtained from the fuel and fuel prices report carried out by IDAE (Institute for Energy

Diversification and Saving) for 2021. The interest rate was assumed to be 3.5%, and the inflation (inf) was 2%, following the suggestions of the associated regulation. In this line, the value of the effective interest is 1.5%. Finally, the investment costs used in the present study are detailed below (Table 4). These costs come from national databases, prices obtained from manufacturers, and various real experiences.

Energy Efficiency measures	Cost/ additional cost
Wall insulation	(2.7325 x Thermal resistance [$m^2 \cdot K/W$] + 2.004 (€/m^2)
Roof insulation	(1.7019 x Thermal resistance [$m^2 \cdot K/W$] + 1.948 (€/m^2)
Floor insulation	(4.135 x Thermal resistance [$m^2 \cdot K/W$] + 2.38 (€/m^2)
Improve windows	Linear interpolation in function of windows U-Value o. First point - U-value 1: 15.7 W/$m^{2 \cdot}$K, cost 1: 182 €/m^2 ; second point - U-value 2: 0.8 W/ $m^{2 \cdot}$K, cost 2: 499.83 €/m^2
Reduction of transmittance of Thermal Bridges defined as level 2 in table 3	6.0 €/ m of lineal thermal bridges
Reduction of transmittance of Thermal Bridges defined as level 3 in table 3	7.0 €/m of lineal thermal bridges
Improvement of windows permeability (n_{50}= 3h^{-1}) – level 2 in table 3	60 €/m^2 of windows
Improvement of windows permeability (n_{50}= 3h^{-1}) and demand-controlled ventilation – level 2 in Table 3 -m level 3 in Table 3	60 €/m^2 of window + 600 € per apartments
Solar control – level 2in table 3	90 €/m^2 of windows
Solar control – level 3 in table 3	140 €/m^2 of windows
Mechanical Night ventilation	8 €/m^2 for 10 ACH and proportional for other airflows

Table 4. Investment costs

3.2 Selection of the optimal solution

As mentioned previously, the cost-optimal methodology aims to minimize the building life cycle cost (LCC). This section shows how the methodology is implemented to select the optimal profitability alternative. First, Figure 8 shows the life cycle cost (LCC) versus total primary energy consumption for the 540 combinations of improvement measures defined in Table 3. The initial situation is shown in red. The combination of characteristic parameters that define the initial situation is defined in the first row (level 1) of Table 3.

If it was not subject to restrictions, choosing the optimal profitability alternative would minimize LCC (marked orange in Figure 9).

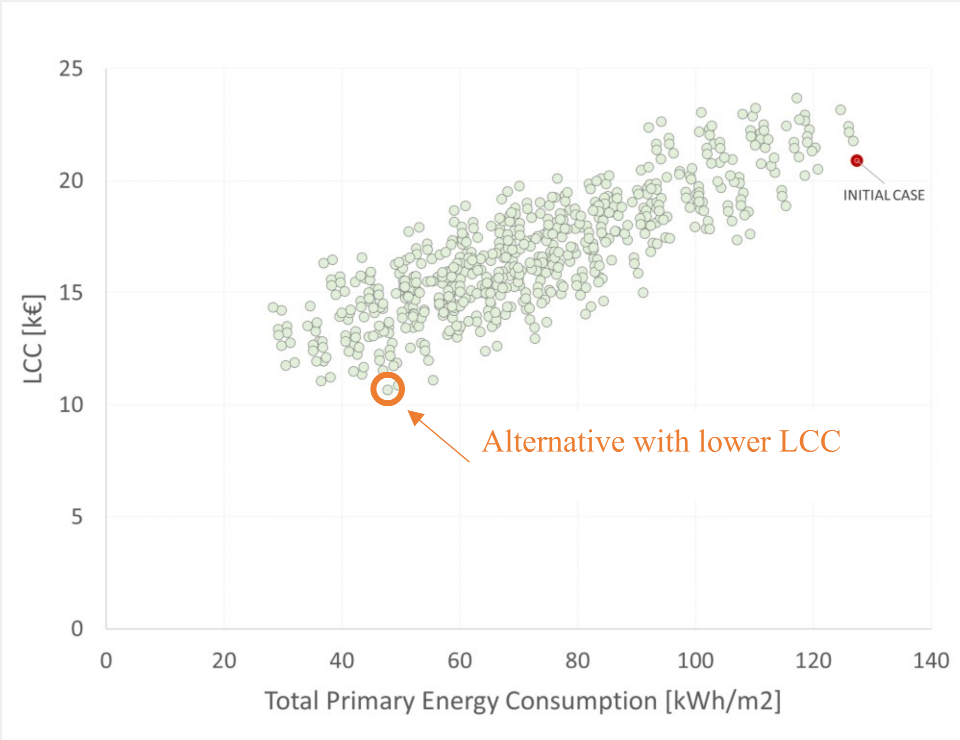


Figure 9. Cost-optimal (total primary energy consumption)

However, each country's choice of the optimal case is subject to regulatory restrictions associated with energy needs and consumption for the climate zone in question (Ministry of Development, 2019). Therefore, Figure 10 shows the combinations that comply with the energy needs measures established by the directive (points in dark green). Finally, in addition to the restrictions on energy needs, consumption restrictions are applied. Figure 10 shows the consumption limit established through the blue line. The combination of measures to be implemented complies with the energy needs and consumption restrictions and presents the lowest LCC (shown in black).

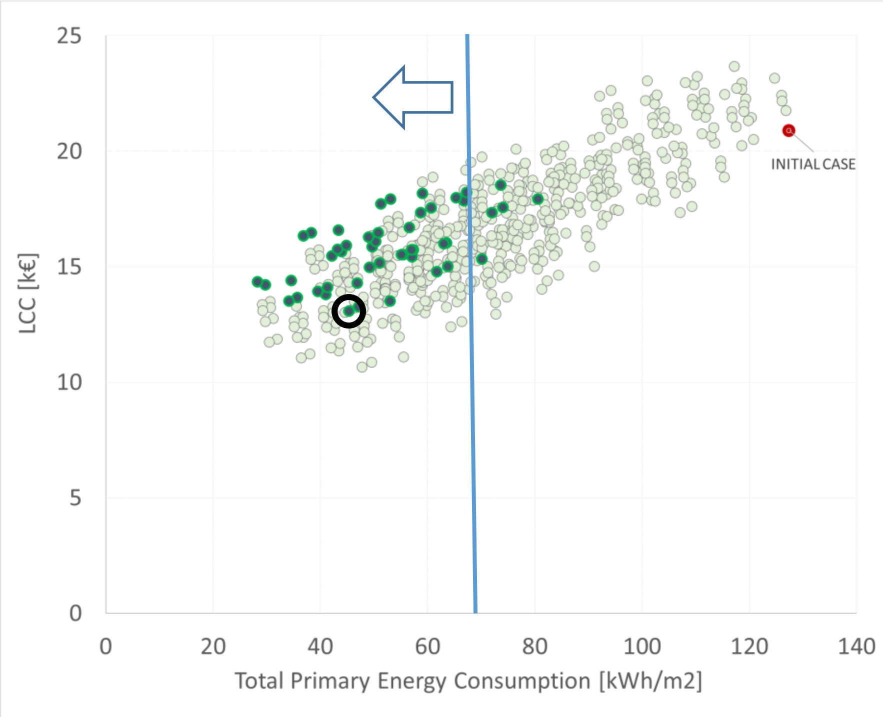


Figure 10. Cost-optimal with regulatory restrictions

The optimal case selected corresponds to the combination of parameters defined in Table 5:

	Heating reduction alternative						Heating reduction alternative	
	Walls [W/m²K]	Roof [W/m²K]	Floor [W/m²K]	Windows [W/m²K]	Linear transmittance of Thermal Bridges	Infiltrations + Ventilation	Solar control (g-value of windows in summer)	Night ventilation [1/h]
Selected combination	0.28	0.22	0.32	2.0	75% reduction	3	Base	4

Table 5. Renovation measure selected

This combination of renovation measures was integrated into the apartments studied. Regarding the envelope, an exterior insulation finishing system (EIFS) was installed on the exterior walls of the façade of the buildings, including the inner courtyard. The optimum transmittance of the roof appears in table 5. This value is the requirement applied in the design of the ventilated roof (maximum value of the thermal transmittance of the roof), which is detailed in Section 4. Given the poor condition of the windows, they were replaced with thermal breaks and thermoacoustic glass 4+15+6b. By installing the exterior insulation system and also sealing the windows, the airtightness of the buildings improved to a value of three air changes per hour. The intervention decreased the thermal transmittance due to thermal bridges according to the reduction considered in Table 5. Figure 11 shows the condition of the district after the renovation work was completed.

Figure 11. Condition of the district after renovation

3.3 Results: assessment of the energy impact

Tables 6 and 7 show the decrease in the energy needs obtained after applying the comprehensive renovation plan described in Table 5 for the individual apartments that represent the whole housing district. Table 6 shows how the renovation has a significant impact in terms of the heating needs of the district. The decrease in these needs is around 50% for the district. However, the decrease in the cooling needs is only approximately 2%. This result shows that the application of conventional passive strategies is insufficient in the extremely hot and arid climate of Mengibar. In these climates, innovative solutions and natural cooling techniques are required to promote heat dissipation.

	Heating needs in the apartments [KWh/m^2]						Heating needs of the district [KWh / year]
	B5_P1_1B	B5_P1_3B	B5_P2_2B	B5_P2_3B	B5_P3_1C	B5_P3_3C	
Initial situation	54.0	84.9	61.3	109.0	64.6	97.0	703331.3
Selected combination (see table 4)	21.0	43.6	25.0	56.9	26.7	49.7	370531.9
Reduction [%]	61.1	48.6	59.3	47.8	58.7	48.8	**47.3**

Table 6. Heating needs

	Cooling needs in the apartments [KWh/m^2]						Cooling needs of District [KWh/year]
	B5_P1_1B	B5_P1_3B	B5_P2_2B	B5_P2_3B	B5_P3_1C	B5_P3_3C	
Initial situation	16.0	24.7	20.3	17.2	20.9	28.3	231851.0
Selected combination (see table 4)	14.8	21.5	19.3	17.0	20.1	25.6	227897.6
Reduction [%]	7.3	13.1	5.1	1.5	4.0	9.7	**1.7**

Table 7. Cooling needs

4 Passive cooling: ventilated roof

As mentioned above, the initial thermal comfort study carried out in the district highlighted how the roof played an important role in the thermal discomfort of the apartments. Therefore, the present study evaluates a ventilated roof solution for buildings. The ventilated roof consisted of two main layers or sheets between which there is a space or air chamber through which the fans force air. Ventilation is automated so that it is activated only when it is convenient from an energy point of view. Active ventilated roofs are indicated for areas with a cooling dominated climate and low-rise buildings. Ventilated roofs reduce solar gain and cool the spaces under the roof. To this end, the roof has three operating modes and they are detailed in figure 12.

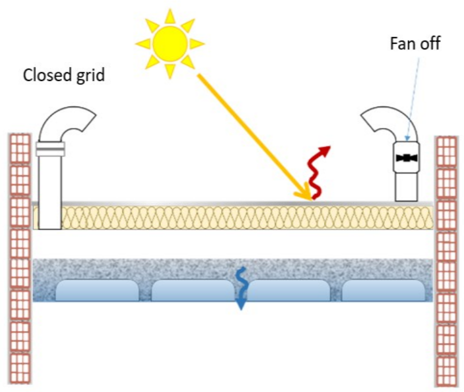
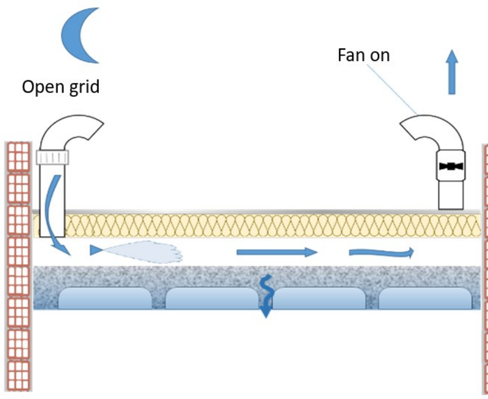
Mode 1 – Winter and Summer daytime	**Mode 2 - Summer nighttime** 2A Only ventilated Roof 2B Evaporative ventilated roof
	

Figure 12. Roof operating modes

Figure 12 shows that the roof has two operating modes. The second mode can be divided into 2A and 2B, but mode 2B is linked to mode 2A.

<u>Mode 1.</u> During the day, when solar radiation and the outdoor temperature are high, the air circulation is stopped (fan off, and the grids closed). Therefore, the roof behaves like a well-insulated roof. The outer layer repels heat and simultaneously prevents the heating of the thermal mass of the roof. Consequently, the ceiling of the apartment absorbs indoor heat gains (cools the space). This mode can be called the period of cold discharge from the thermally active roof.

<u>Mode 2A.</u> The air circulation is activated when the outdoor air temperature is lower than 22ºC (fan takes on and the grids open). It happens during the night. The heat is dissipated from the inner layer of the roof, which cools as a consequence. This mode is called the cold charge.

<u>Mode 2B.</u> If the minimum nighttime temperature is not low enough to dissipate heat from the roof, the cold charge mode described in 2 is ineffective. Under these circumstances, an evaporative cooling system is operated to obtain an additional decrease in the air temperature.

The details of its design and how it was integrated into the buildings are shown below.

4.1 Design and integration of the ventilated roof

The roof system is composed of a double layer and a ventilated chamber of 5 cm in the middle. The outer layer is on top, and its function is to insulate the system from the outside conditions. This outer layer must be insulated and have a thermal transmittance below or equal to 0.7 [W/(m^{2}K)] (value based on indoor and outdoor convection and radiation heat transfer coefficients of 0.10 [m^{2}K/W] and 0.04 [m^{2}K/W] respectively (Ministry of Development - Government of Spain, 2015)). The insulation must have a thickness of approximately 6 to 8 cm to achieve the required value (Girma & Tariku, 2021; Kovac & Vojtus, 2015). To this end, the present design was insulated with an EPS sandwich panel with a total thickness of 8 cm. The inner sheet is on the bottom side, one of its surfaces bordering the inside of the building. The inner element has the thermal mass of the roof. It is cooled during the night to cool the space during the daytime. Therefore, it should have a high thermal mass and be a good heat conductor. In the case under study, the inner layer is the existing roof, consisting of a 25 cm layer of concrete with a density of 1330 kg/m^3. The ventilated roof has partitions over it to create a uniform flow of air over its whole surface. The design of the partition distribution is carried out by studying the air distribution of the system in the Computational Fluid Dynamics (CFD) software. The designed layout must ensure a uniform flow from the central air inlet and outlet throughout the roof. Hot or cold spots must be avoided.

The analysis of air movement in the different design typologies proposed through the CFD simulation considers the following general points. First, the mesh is defined using the Meshing of ANSYS software (Ansys, n.d.). The characteristics and typology of the distribution of nodes for meshing have been chosen, optimising computational savings and ensuring high accuracy in the results obtained. Once the mesh is defined, it is exported to Ansys Fluent for simulation. The turbulence model adopted for resolution is the k-ε (Wright & Easom, 2003), used to optimise airflow through the ventilated roof. Finally, the boundary conditions are defined. In all the cases studied, the boundary condition is exhaust airflow to simulate the fan extractor. Air extraction is carried out using fans, which must generate airflow in the chamber such that the speed is around 1.7 m/s to avoid high-pressure losses. Figure 14 shows an example of the CFD study for a type of module. It is possible to verify the air chamber's air velocity for the channels' final design.

The spray nozzles must be located inside the air chamber, near the inlet and arranged to favour the evaporation of the water in the air current. Finally, the spraying system must generate drops with a minimum size of 20 micrometres (Guerrero Delgado, Sánchez Ramos, Cabeza et al., 2020) and a total water flow of more than 2.5 l/h per metre of the width of the roof. Figure 13 shows the final assembly and the details of the air chamber construction. The cost of the roof solution described has a value of 110 €/m^2 of the roof, considering the components' investment and implementation.

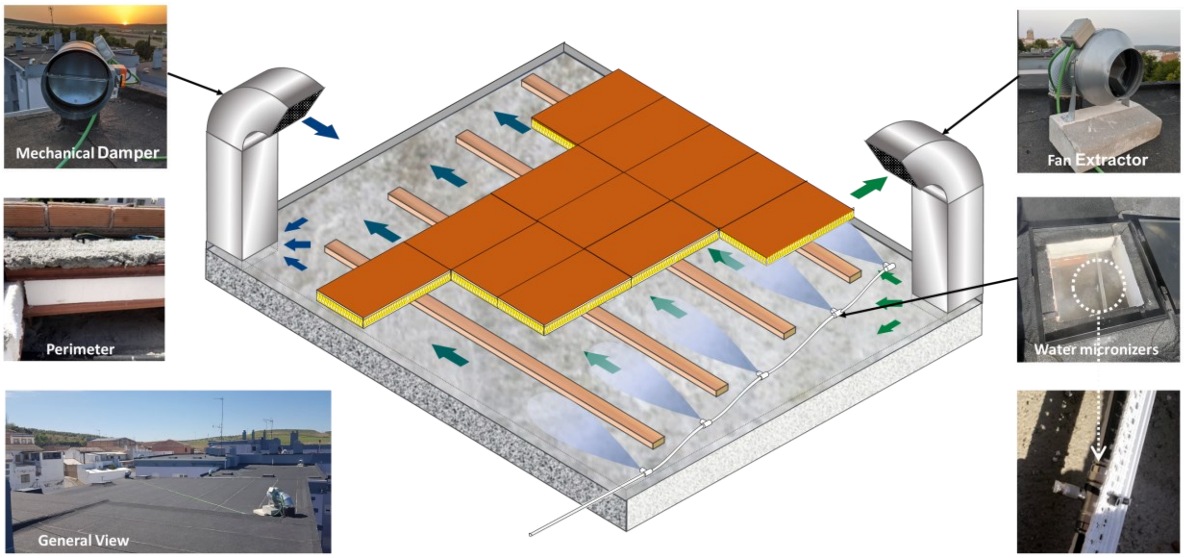


Figure 13. Construction details of the roof

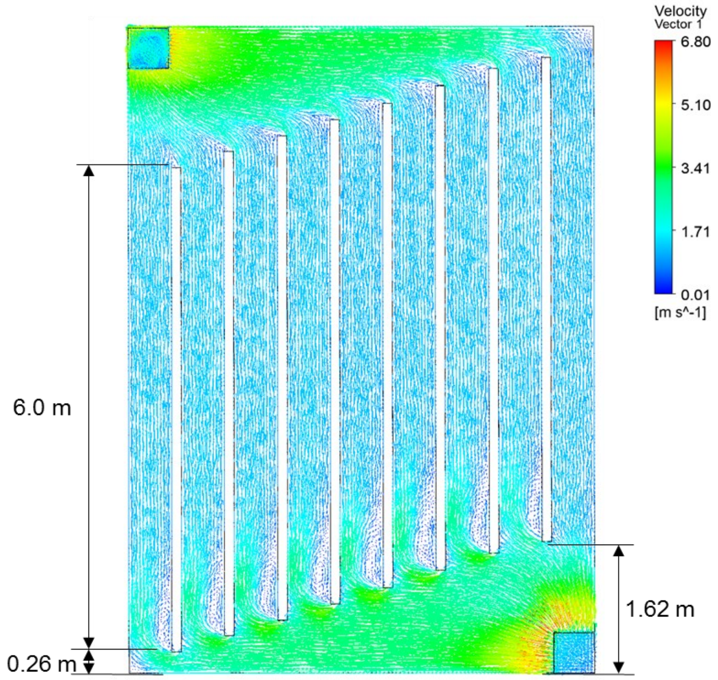


Figure 14. Example of an airflow study of roofs

Three types of modules were designed to integrate into the roofs of the 14 buildings. Each has different dimensions and geometries. The design aimed to adapt the concept to the roofs of the buildings taking into account the design restrictions mentioned above. Figure 15 shows the geometric details of the design for the three types of design integrated into the district. In addition, Figure 16 shows the modules used in the different apartment blocks in the district. The areas where the roof modules are not integrated contain the necessary facilities for their operation. These areas are generally adjacent to common areas of the buildings and have access to the roof.

Design type 1	**Design type 2**	**Design type 3**

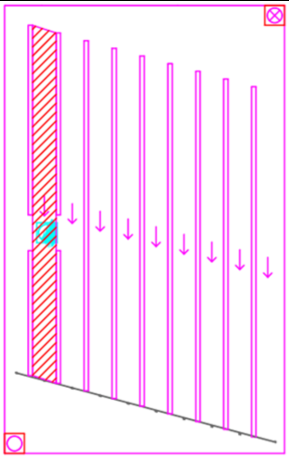
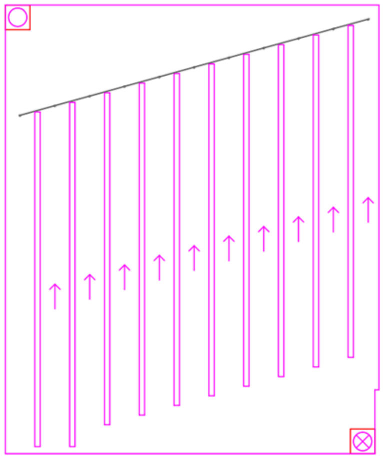
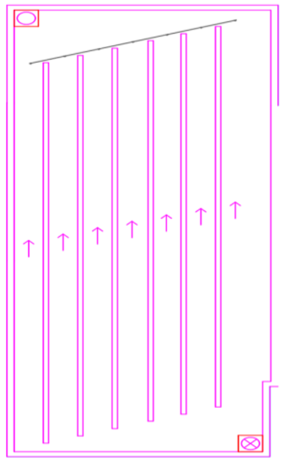
		
Roof surface: 78.8 m^2 No. of channels: 8 Channel width: 50 mm Channel length: 600 mm	Roof surface: 69.2 m^2 No. of channels: 10 Channel width: 50 mm Channel length: 600 mm	Roof surface: 68.8 m^2 No. of channels: 7 Channel width: 50 mm Channel length: 500 cm

Figure 15. Types of modules

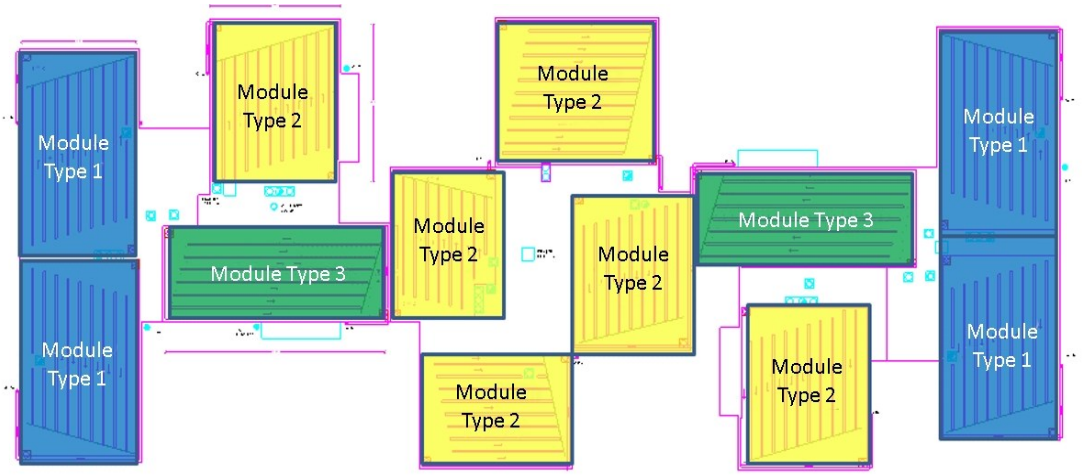


Figure 16. Distribution of types of modules on roofs

Finally, Figure 17 shows the current condition of the district after incorporating all the roof modules.

Figure 17. Condition of the district after renovation

4.1 Results: assessment of the energy impact

The evaluation below shows the energy impact of incorporating the proposed ventilated roof design as a passive cooling technique. To this end, to obtain a good comparison of the energy impact achieved with the different solutions studied, it is necessary to assess them under identical climate conditions. This comparison requires the baseline energy needs of the apartment or building, widely used in recent studies (Díaz et al., 2018; Granderson, Price, Jump, Addy, & Sohn, 2015). To this end, the present study used the HULC software as a baseline comparison. As shown above, in the validation (Section 2), this software produces very accurate results. An analysis was performed for one of the apartments on the upper floor (B5-P1-3B) of the effect of using the ventilated roof solution for cooling in different operating modes: ventilation for eight hours at night; ventilation and evaporative cooling for eight hours at night; and ventilation and evaporative cooling throughout the day. Table 5 shows that using the ventilated roof leads to a more significant reduction in cooling needs: 28% when it operates at night in ventilation mode and 65% when it uses ventilation and evaporative cooling 24 hours a day. Therefore, using the ventilated roof in ventilation mode with evaporative cooling, cooling needs decrease 14 kWh/m^2 per year compared to the renovation project without the cooling system on the roof (65% improvement). These results can be compared with the literature review discussed in the introduction section. Santamouris et al. (Santamouris et al., 2007) report that it is possible to decrease the cooling needs by between 20 and 70% through the use of cool roofs. However, A. Synnefa et al. (Synnefa et al., 2007) suggest that incorporating cool roofs may lead to a heating penalty of up to 17 kWh/m^2 year. The solution proposed in this paper can achieve the maximum decrease in cooling load suggested in the literature without a heating penalty. Table 8 shows that the comprehensive roof renovation. It highlights how the solution allows reducing the heating needs by approximately 50% (see table 6).

Retrofitting plans (See table 4)	Cooling needs (kWh/m^2·year)	Improvement [%]
Case 0-Initial situation	24.7	-
Case 1-Selected combination of table 4 (cost-optimal; ventilated roof off)	21.5	13
Case 1 + Ventilated Roof (ventilation 8h)	15.56	**28**
Case 1 + Ventilated Roof (ventilation + evaporative 8h)	13.19	**39**
Case 1 + Ventilated Roof (ventilation + evaporative 24h)	7.66	**65**

Table 8. Comparison of different operating modes

The impact of the ventilated roof is shown in figure 18 and table 9. Figure 18 shows the fluctuations in the values of inside air temperature for a flat on the top floor in June corresponding to the different operating modes of the roof system. It shows how the indoor temperature of the apartment can be up to four degrees lower when the roof system operates in ventilation and evaporative cooling mode throughout the day.

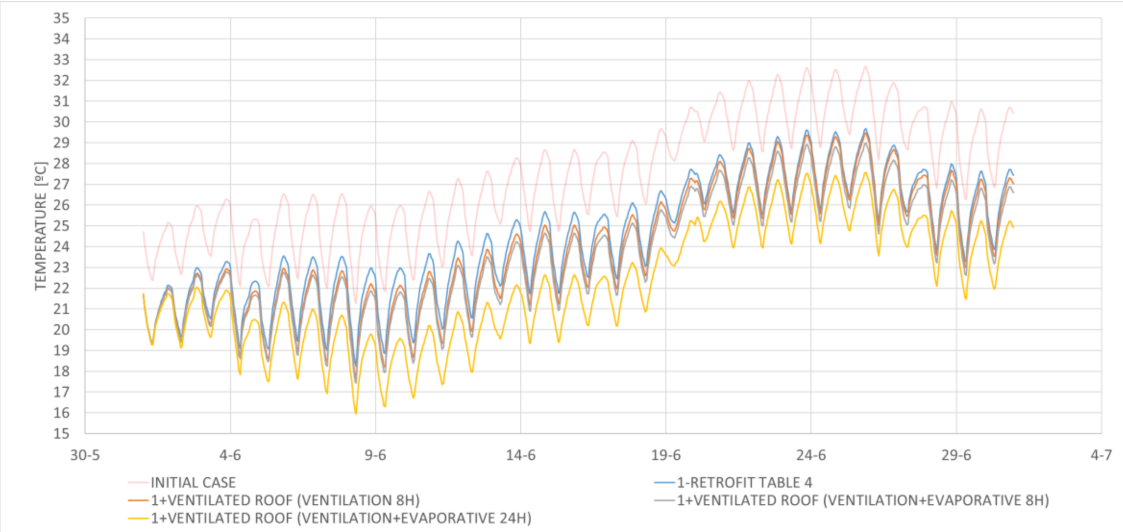


Figure 18. Fluctuations in the indoor temperature of the apartment on the upper floor with the use of different improvement measures

Similarly, Table 8 shows the results of the impact on thermal comfort obtained in the apartment under the roof (B5-P1-3B). There are four cases in table 9. Case 1 is the optimal case of Table 4 (conventional retrofitting plan) with the integration of the ventilated roof, but it does not operate. Cases 2, 3 and 4 show the influence of the different operating hours of the ventilated roof. When the roof is operating in ventilation mode during the night, a decrease in thermal discomfort of up to 9% can be achieved in the situation after only conventional improvement measures (not ventilated roof). Using the evaporative cooling system improves thermal comfort, 36% when it only operates during the night but 80% if the system operates with ventilation and evaporative cooling during the whole day. The results obtained show the importance of incorporating the ventilated roof solution and how it works best.

	Case 1 The optimal solution of table 4 + ventilated roof OFF			Case 2 Case 1 + Ventilated roof (operation during nigh 8h)			Case 3 Case 1 + Ventilated roof (operation during 16h)			Case 4 Case 1 + Ventilated roof (operation during 24h)		
	[ºC h]	[ºC h ppi]	[h]	[ºC h]	[ºC h ppi]	[h]	[ºC h]	[ºC h ppi]	[h]	[ºC h]	[ºC h ppi]	[h]
June	667	292	323	573	233	280	458	152	259	166	29	162
July	1883	1213	640	1730	1102	617	1405	795	574	688	273	364
August	2157	1392	682	2042	1289	672	1673	893	650	848	282	495
September	1201	707	502	1096	662	460	881	465	400	475	165	254
Summer	5908	3604	2147	5441	3286	2029	4417	2305	1883	2177	749	1275
Improvement [%]				**8**	**9**	**5**	**25**	**36**	**12**	**63**	**79**	**41**

Table 9. Evaluation of the impact on thermal comfort of renovation improvements and ventilated roof in different operating modes

5 Discussion and conclusions

Spain is a country that has a primarily obsolete residential park in terms of construction quality and energy efficiency. 75% of the 18 million homes were built between 1960 and 2007, which means that they do not comply with any regulations on energy efficiency in buildings or meet deficient levels of efficiency and habitability compared to current comfort standards. This fact and its correlation with the impossibility of almost 3.3 million households to get a comfortable temperature in winter and 4.5 million in summer for socioeconomic reasons lead to living conditions of greater vulnerability to climatic conditions, something that will worsen as the impact of climate change in our country advances. In addition, to these data, it is added that the percentage of the population over 65 years in the country reaches 25%, this social group being very vulnerable to extreme climatic phenomena. The OMS attributes 30% of mortality to inadequate housing conditions and consequent thermal discomfort. Improvement of habitability through energy rehabilitation, such as the one carried out in the present study, can improve the thermal comfort of houses. In addition, as previously mentioned, the social housing districts of southern Spain are subject to two well-known serious problems: energy poverty and overheating of buildings. The mitigation of overheating in the Mediterranean climate is not possible with the integration of conventional rehabilitation techniques. So, the design proposal of this study of the ventilated roof solution as a passive cooling technique presents high interest. Energy impact analysis shows that implementing the roof solution as a passive cooling technique can reduce cooling needs by 65% without a resulting heating penalty.

Furthermore, the measures significantly improve habitability, with thermal discomfort decreasing by up to 80% when used for cooling. The results obtained also reveal the importance of the operating mode of the roof system and the need to optimise it to maximise the improvement in thermal comfort and minimise energy consumption. Taking these lines into account, as the solution has the infrastructure necessary for the roof system to be intelligently controlled, future studies could assess the actual performance of the roofs when in operation according to the climate conditions and the real needs of the buildings. The roof solution has been integrated into more than 2500 m^2 of building roofs, and it is one of the first times such a critical study has been performed on actual buildings. Lastly, the occupants of the apartments were visited after the renovation work, and they expressed their deep gratitude and satisfaction with the measures taken in the district. The proposed solution has been designed taking into account the reality of tenants (low incomes and energy vulnerability). Integrating the energy rehabilitation proposal and the roof as a passive cooling technique in the Mediterranean climate can reduce morbidity and mortality figures and, therefore, reduce health costs, improving the health of citizens and quality of life. Finally, these benefits reduce the environmental impacts produced by housing and adaptation to climate change.

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