Highlights

- A house prototype, developed for an international competition, is analysed
- Hygrothermal, air quality comfort conditions and energy consumption were assessed
- Controlled and passive strategies provided the best adapt to the comfort bands
- Considering international standards, adaptive comfort band would reach almost 80 %

Improving comfort conditions as an energy upgrade tool for housing stock: analysis of a house prototype

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Abstract

Given the role of the building sector as one of the current main causes of pollution in cities, the promotion of research on energy efficiency and sustainable strategies is key. At the Solar Decathlon international competition, different university teams design optimized energy-efficient and prefabricated houses, integrating passive and active solutions to achieve the best environmental and energy performance. This study analyses hygrothermal and air quality comfort conditions through a real-scale housing prototype developed by the University of Seville; this is then compared with the more widely used solely energy-related assessment. Different environmental variables (temperature, relative humidity, carbon dioxide concentrations and electricity consumption) were monitored during the competition. The aim was to provide useful information to optimize building performance at the design stage, minimizing the performance gap prior to its implementation on a district scale. Results show that the strategies implemented in the prototype developed provided the best comfort conditions for the longest periods of time, resulting in zero energy consumption during passive days and approximately 50 kWh during active days. Steady-state comfort conditions were achieved in around 45 % of the hours. However, adaptive comfort conditions, which are more closely linked to the level of tolerance and socio-cultural conditions, were met in approximately 80 % of the hours.

Keywords: passive strategies, thermal comfort, indoor air quality, oceanic climate, house prototype competition.

1. Introduction

1.1 Energy and regulation framework

Energy use, indispensable to the development of life on earth, has been increasing significantly over time as a result of technological advances and demographic growth. In fact, in 2019 final energy consumption in the European Union accounted for 935 Mtoe, with the building sector among the top three dominant energy consumers [1]. A major contributor to climate change [2] is greenhouse gas emission, as demonstrated in 2020 when emissions from energy use accounted for around three quarters of all man-made CO_2 emissions [3]. The European building sector is responsible for 36% of global final energy use and 39% of energy-related CO_2 emissions [4]. Thus, higher energy efficiency and the development of sustainable strategies are vital for the promotion of reduced energy consumption.

Around 75% of the entire European stock is made up of residential buildings [5] and close to a third of these are over 50 years old [6]. The vast majority of these buildings are therefore considered to be energetically obsolete [7] and, taking into consideration new-built construction rate [8], by 2050 they are expected to represent around 70% of the future stock [9].

Energy retrofitting the existing social housing stock is of the utmost importance and should be highlighted as a major objective for undertaking building decarbonization. In this regard, the challenging measures put forward in the European Green Deal (EGD) aim to cut down greenhouse gas emissions by at least 55% by 2030 and to preserve natural environments. The implementation of these ambitious policies is expected to make Europe a climate-neutral continent by 2050.

However, with current strategies focusing mainly on energy consumption and emissions, solutions for improving comfort conditions have been relegated to the background. In the case of low-income dwellings, the widespread lack of Heating, Ventilation and Air Conditioning (HVAC) systems [10] is linked to energy poverty, with users unable to afford electricity costs to meet comfort and energy requirements [11]. Major efforts are therefore required to prioritize the improvement of indoor comfort conditions over energy savings provided by active systems in social dwellings [12]. Furthermore, passive low-cost strategies and low thermal inertia retrofit solutions allow a controlled exchange between outdoor-indoor conditions, fundamental for the social stock.

Unlike in the case of steady-state models [13], comfort models have to be reformulated taking into account user adaptability. Adaptive models consider the capacity of building occupants to adapt to relationships between indoor-outdoor climate, giving rise to a more environmental response [14]. According to Nicol and Humphreys [15] adaptive models applied to free-running buildings allow a better estimation of the indoor temperature in which occupants are most likely to be in comfort compared to static models. In recent years, several adaptive approaches have been developed in international standards [16,17], including adaptive models for naturally ventilated buildings where users can freely control windows and modify clothing. This improved adaptation to ambient conditions leads to a reduction in the perception of discomfort [18].

1.2 Performance assessment through housing prototypes

While climate change must be addressed from different perspectives, a special emphasis is required on social aspects in order to enhance social awareness and guarantee adequate living conditions worldwide in the future. In order to tackle this problem, the social initiative of the Solar Decathlon (SD) international competition aims to promote the implementation of innovative strategies and renewable energy sources when constructing zero-energy and sustainable houses. One of the main goals of this competition is to present the effectiveness of exemplary energy efficiency housing prototypes with the highest level of self-sufficiency. Notable SD experiences from previous years have highlighted innovative strategies, microclimate organization, renewable energies, passive and active element integration and prefabricated systems.

In the ReStart4Smart project, presented at the SD Middle East 2018 competition in Dubai (BWh – a hot desert climate according to Köppen's updated classification [19]) the energy strategies, architectural concepts and technological solutions adopted [20] emphasized the combination of passive cooling strategies (central patio, wind tower, fountain, green wall, adaptive shading systems) with active systems (photovoltaics, water recycling, smart house automation). Simulation and monitoring analysis were used to assess the electricity consumption and production forecast. In the same edition, the KNOW HOWse project [21] presented optimized functional and size requirements for enhancing passive energy strategies (shading systems, compact shape, passive ventilation, low thermal mass envelope, etc), merging traditional environmental strategies (cross-ventilation, wind tower and chimney effect) with innovative consumption technologies. Lin et al. [22] presented design optimization strategies for a net-zero energy SD house assessing different technologies using water-based thermal energy storage and phase change materials as a starting point.

In 2017, another SD house competition entry in Dezhou, China (Cwa – dry-winter humid subtropical climate [19]) highlighted the need to configure the appropriate energy system during the design phase to achieve energy efficiency in the design of HVAC systems, by means of energy simulation [23]. Ferrara et al. [24] worked on an optimization-based energy model of the SD SCUTxPoliTo house to improve competition results, optimizing points earned in indoor temperature, relative humidity and air quality tests following competition rules. The predicted results were later compared with real measurements, proving the usefulness of the methodology followed. At SD 2017 in Denver, Colorado (Bsk – semi-arid climate [19]), the University of Switzerland proposed a well-insulated prototype, combining natural ventilation techniques, solar protection and electricity production through integrated PVs [25], previously analysed through simulation and later compared with on-site data recorded during the competition.

The STILE prototype competing in Irvine (Csb – Mediterranean warm summer climate [19]) at SD 2015 was used to calibrate and validate a simulation model subsequently used for critical analysis of the house design in different locations [26]. This confirmed that this house required less energy to operate HVAC systems in cooler climates than in warmer areas. Also at SD 2015, the University of Buffalo presented the Grow Home [27], comparing the results measured during the competition with those obtained through energy simulations, mainly in terms of electricity production and consumption.

Likewise, several studies have provided detailed analyses of previous SD experiences: Yu et al. [28] present a critical review on passive design and active systems for 33 prototypes proposed during the European SD 2010 and 2012 projects, held in Madrid, Spain (Csa – Mediterranean climate [19]), showing the technological process towards an optimized Zero Energy Solar House through experimental competition. Ma et al. [29] reviewed the HVAC systems in 212 solar-powered houses developed in 13 different SD competitions, highlighting the use of a wide range of energy technologies to reduce the electricity consumption of systems.

So far, most of the SD competition studies published have focused on energy demand, production and consumption, obtained through prior simulation and later monitored during the competition. However, indoor environmental quality assessment has not been addressed in such depth, despite its prime importance when considering competition rules and scores. At SD 2015 in Cali, Colombia (Aw – a Tropical Savanna climate [19]), Ocupa et al. [30] designed the Ayni House based on passive design (natural ventilation, solar protections, low thermal mass envelope AND reflective surfaces), comparing on-site indoor temperatures recorded in the competition and energy simulation outputs. At SD Europe 2019, held in Szentendre, Hungary (Cfb – Oceanic climate [19]), the Faculty of Engineering of Bangkok presented the Resilient Nest, a net positive electrical balance and lightweight house with low-thermal conductivity insulation and several active systems (heat recovery ventilation, solar thermal and PV panels). This prototype was awarded second place in comfort conditions in the competition [31],analysing indoor temperatures under energy balance. Also at SD Europe 2019, Landuyt et al. [32] analysed the impact of the embedded energy of the materials used in the Mobble prototype and the energy used in the operation through energy simulations and life cycle assessment.

This research aims to address the research gap identified in the assessment of thermal comfort and indoor air quality conditions, contrasting this with the more common analysis focusing solely on energy and consumption. At SD Europe 2019 in Szentendre (oceanic climate) the indoor thermal comfort and air quality of the Aura 3.1 project presented by the University of Seville (Spain) were assessed. The specific approach of this research examines experimental techniques and a real-scale housing prototype in order to optimize the building's performance during the design phase and minimize the performance gap prior to any district- or city-scale intervention. Monitoring values were provided for several ambient variables (temperature, relative humidity and carbon dioxide values), as well as electricity consumption data for the comparison of results with those obtained by other contestants. The variables monitored were evaluated in accordance with the static-state comfort bands stipulated in the competition rules and international standards, providing new results of the prototype's thermal performance towards adaptive comfort models.

2. The Aura 3.1 project.

At the 2019 SD edition (Figure 1a) held in July in Szentendre (Hungary), emphasis was placed on the retrofitting of existing buildings, focusing on environmental indoor comfort and implementing sustainable technologies and a mix of modern and reclaimed materials. The competition was divided into two stages: the assembly, which took place over two weeks, and the exhibition, developed in the following two weeks. This paper analyses the Aura 3.1 Project housing prototype designed and developed by the University of Seville at SD 2019 (Figure 1b).

(a)

(b)

Figure 1: a) View of the Solar Decathlon Europe Village during the competition week held in Szentendre, Hungary, 2019; b) Aura 3.1 Pavilion-prototype during the contest phase.

It should be emphasized that SDE competitions evaluate ten contests, each of which can be awarded up to 100 points in terms of indoor comfort assessment, with one of the categories specifically targeting indoor environmental comfort. For this, each house must be equipped with technologies to test the capacity for indoor comfort provision through the measurement of environmental parameters such as temperature, humidity, acoustics, lighting, and indoor air quality (IAQ). Energy performance and environmental performance are continuously monitored during the final phase of the competition, when all houses are open to the public. Thus, the evaluation of comfort should not be based solely on hygrothermal parameters but should also assess other relevant issues, taking into account repercussions on people's health. In fact, Herrera et al. [33] present a survey-based methodology which provides complementary information on comfort and health to be considered in further editions.

2.1 Urban strategy

The prefabricated construction of the Aura 3.1 full-scale housing-pavilion prototype, designed by the University of Seville team, is based on the idea of urban regeneration and sustainable construction. Both ideas stem from the recycling of energy-obsolete residential neighbourhoods built in the Mediterranean climate. The main characteristics and benefits promoted by this sustainable approach include the reuse of existing buildings, in turn reducing the carbon footprint of the construction process and extending their useful life.

Interventions carried out improved the thermal envelope characteristics and the operation of facility systems, making it possible to conserve all the fundamental construction elements of buildings while also offering an improved use of materials and energy resources during the construction phase. Thus, the main retrofitting proposal is based on the addition of new technological features to the existing building using two components: a connection envelope and prefabricated modular extensions (Figure 2).

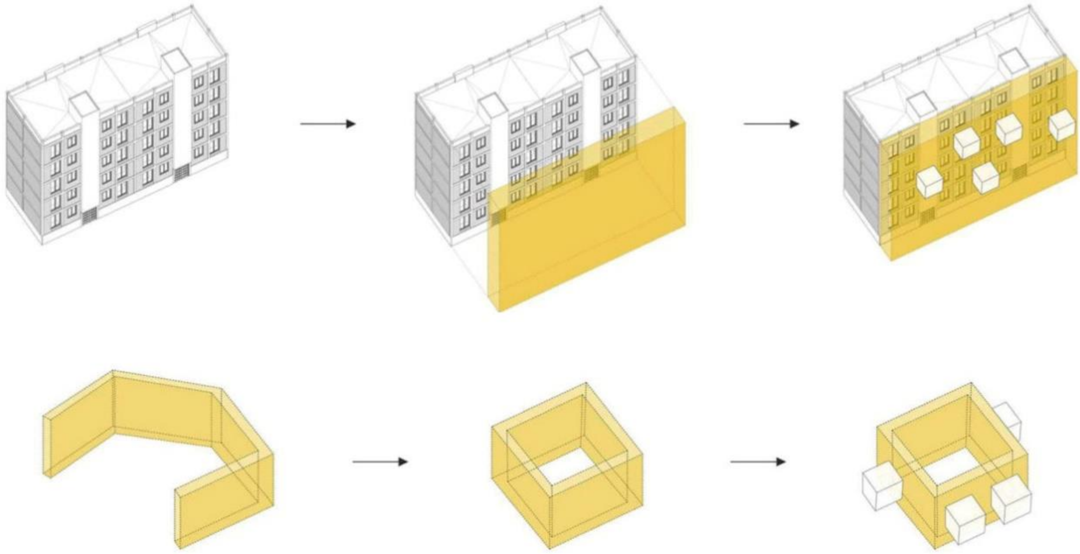


Figure 2. Above from left to right: existing building, connection envelope (in yellow) and gadgets. Below from left to right: folded connection envelope (in yellow) and modular extensions in the configuration of the competition prototype.

The first component is the connection envelope, an independent load-bearing structure consisting of a double-layered framework. The first layer is connected to the existing building, while the second is a separate layer located approximately 1.5 m away from the building. The prefabricated modular extensions can be hung using the connection envelope. The space within the double-layered framework incorporates new communal elements for the existing building, including elevators, staircases, galleries, terraces and technical facilities networks. This envelope also allows existing buildings to be connected, improving urban public spaces through new shared facilities and accesses.

The prefabricated modular extensions create additional spaces for existing homes. These extensions hang from the connection envelope, and positions can be modified freely depending on the new needs of individual dwellings. This makes it possible to incorporate a bedroom, a workspace, a bathroom, a storage space or a kitchen garden. These modular extensions can be added progressively without causing interference with other homes.

This retrofitting-building system could be applied to existing residential neighbourhoods in any number of configurations. For the purposes of this intervention project, the San Pablo neighbourhood in Seville (Spain), which was built in the 1960s and 70s, was chosen (Figure 3).

Figure 3. Implementation of the Aura 3.1 project in the San Pablo neighbourhood in Seville.

2.2 Description of the Aura 3.1 housing-prototype

The Aura 3.1 prototype was interpreted as an exhibition pavilion providing visitors with a meeting place during the two weeks of the competition.

As this proposal arises from the urban strategy described in subsection 2.1, in which the new intervention is added to an existing building, the configuration had to be adapted to the prototype presented in the competition. Therefore, the envelope-structure connection was produced as an independent element to fold in on itself, forming a square plan. In the project a series of additional modules or gadgets hung at different heights, and varying in scale to adapt to the type of space (bedroom, living room, kitchen, bathroom, workspace, orchard and facility room), are attached to this connection envelope. In the interstitial space of the connection envelope, a system of stairs allows access to the gadgets (Figure 4). The empty indoor space resulting from the folding of the envelope-structure is configured as a *patio*, a distinctive feature of Mediterranean architecture.

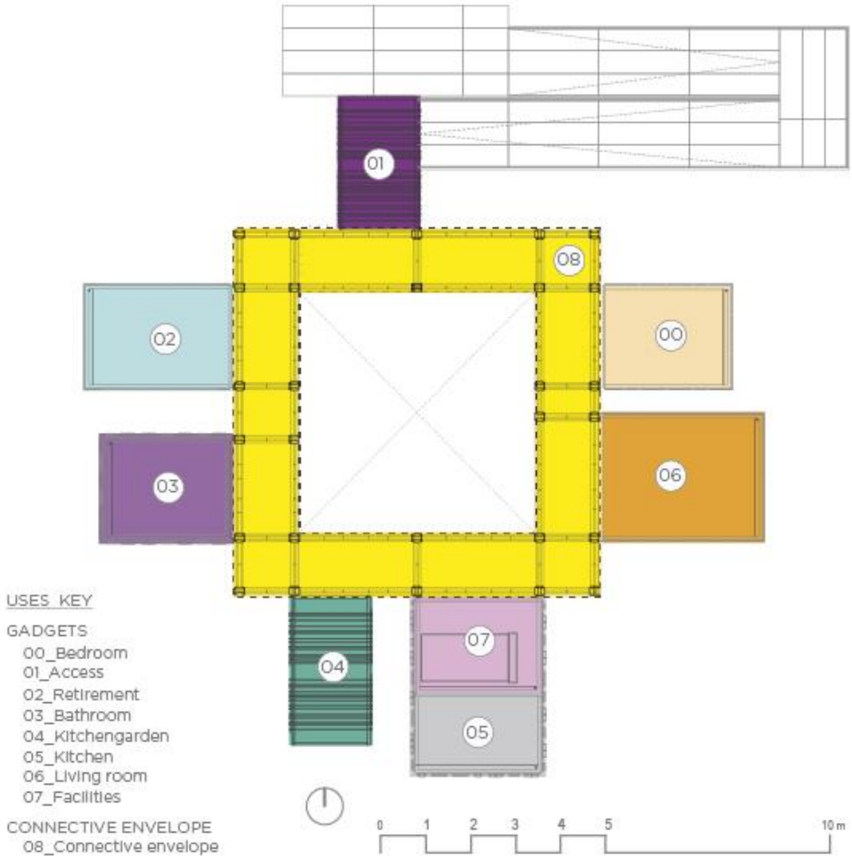


Figure 4. Schematic floor plan of the Aura 3.1 Pavilion-prototype. Connection envelope and modular extensions (gadgets)

The envelope composition and thermal properties of the Aura 3.1 are shown in Table 1. The envelope-structure connection is made up of a double semi-permeable textile material. The 100-cm-thick air chamber between both layers accommodates the layout of facilities and accesses to the extension modules.

Table 1. Aura 3.1 housing-prototype envelope composition and thermal transmittance value (U).

	Building envelope (Out - In)	**Thickness (cm)**	**U (W/m²K)**
Wall	Cellulose-cement panel Aquapanel, MW rock wool [0.04 W/[mK]] 50 mm, air chamber, MW rock wool [0.04 W/[mK]] 45 mm, laminated drywall panel 15 mm.	17.5	U_W= 0.35
Roof	Waterproof Sika film onsite, OSB 03 board 19 mm, MW rock wool [0.04 W/[mK]] 100 mm, laminated drywall panel. 15 mm.	12.5	U_R= 0.34
Floor	OSB 03 board 19 mm, MW rock wool [0.04 W/[mK]] 100 mm, OSB 03 board 19 mm	13.8	U_F = 0.33
Door	OSB 03 board 15 mm, EPS expanded polystyrene [0.037 W/[mK]] 30 mm, OSB 03 board 15 mm	6	U_d= 0.83
Window	Double-glazing 4.8.4. Wood frame (no T.B.)		U_0 = 2.75

The lightweight thermal envelope of the housing modules is made up of a sandwich panel with rock wool insulation (MW) and a non-ventilated chamber where the facilities are located. The inner skin of the modules is made of laminated drywall while the outer skin is composed of prefabricated cement / cellulose panels. Two types of exterior finish can be identified depending on the type of module:

- Modules that must guarantee controlled environmental conditions are reinforced with external thermal insulation (ETICS) prefabricated panels, finished in a lime mortar coating.
- Modules that do not need to guarantee controlled environmental conditions have a light coating made of recycled aluminium can waste from the industrial sector.

For the HVAC systems, a hydronic system consisting of an external heat pump operating both in heating and cooling modes was implemented in the Aura 3.1 housing prototype, combined with two internal fan coil units (one in the bedroom and another in the living room). The installation scheme and general technical data can be seen in Figure 5. Additionally, for the mechanical ventilation system, a low-consumption heliocentrifuge fan (Brand: Soler & Palau, Model: TD-Ecowatt) was installed in both the bedroom and living room and activated to guarantee a proper indoor air quality renovation depending on outdoor temperatures and relative humidity.

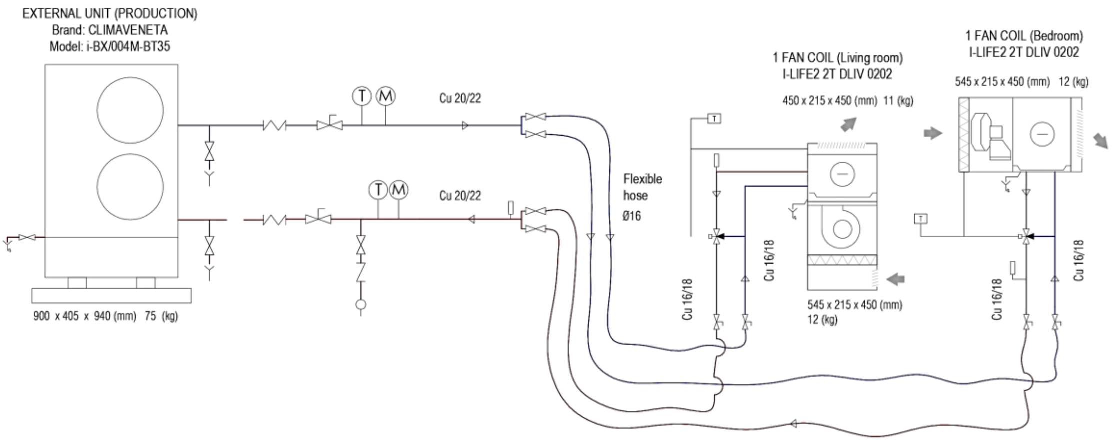


Figure 5. Scheme of heating and cooling systems implemented in the Aura 3.1 Pavilion-prototype.

3. Methodology

The comfort conditions of the Aura 3.1 housing prototype were analysed during two weeks of the SDE19 competition (July 15-24 2019) to determine the validity of the project strategy and to test the qualities and benefits of a real case study of a social housing retrofit. Quantitative data for environmental parameters were recorded using a monitoring system for thermal comfort and IAQ conditions. Judges could assign a top score of 100 points in the assessment of the monitored performance.

3.1 Monitoring system

The experimental technique is based on on-site measurements of indoor and outdoor environmental temperature conditions (T), relative humidity (RH) and CO_2 levels. A Netatmo Weather Station monitoring device, configured for measurements at 5-minute intervals, was used for data collection. Table 2 summarizes the characteristics of the equipment and sensors used in the measurement process. Monitoring devices were placed in two different rooms/gadgets of the house, away from direct solar radiation and air currents to avoid distortions in the data collection. Figure 6 shows an interior view of the gadgets and the position of monitoring devices.

Figure 6. Indoor view of the Aura 3.1 Pavilion-prototype and position of monitoring devices.

Table 2. Characteristics of the measuring equipment.

Netatmo Weather Station				
Parameter	**Units**	**Limit range**	**Accuracy (%)**	**Measuring interval**
CO_2 concentration	ppm	0 – 5000	± 5.0 (50 ppm)	5 min
Indoor temperature (T)	°C	0 – 50	± 0.3	
Outdoor temperature (T)	°C	-40 – 65	± 0.3	
Relative humidity (RH)	%	0 – 100	± 3.0	

3.2 Indoor comfort and air quality assessment

During the competition the housing prototype's capacity for guaranteeing adequate comfort conditions was determined by controlling different indoor ambient variables (temperature, relative humidity, air quality, lighting and acoustics). The aim of the comfort test is to achieve the best indoor comfort conditions possible, following the scoring system for specific comfort bands established by the organizers. The monitoring process of the ambient variables was two-fold. Firstly, temperature, relative humidity, and indoor air quality were assessed through continuous monitoring, reporting data over a long-term period. Secondly, aspects related to natural lighting and acoustics were analysed through occasional measurements.

Since practically 60% of the score for the comfort test depends on the control of hygrothermal variables, this paper focuses on the assessment of monitored hygrothermal variables (temperature and relative humidity), as well as indoor air quality, all recorded over long periods of time. Comfort conditions were thus determined following the criteria established in the competition rules, explained in detail below:

- In the case of indoor temperature, all available points are earned in the competition by maintaining indoor air temperatures within a static-state comfort band of 23-25 ºC. Points are reduced when indoor temperatures are between 21-23 ºC and 25-27 ºC. If temperatures do not fall within these bands, no points are earned.
- In the case of indoor relative humidity, the comfort band is fixed at 40-55%. Likewise, points are reduced if relative humidity values are 25-40% or 55-60%. Zero points are earned if relative humidity values do not fall within these bands.
- In order to guarantee adequate indoor air quality conditions, CO_2 concentrations must be below 800 ppm and points are reduced if indoor carbon dioxide levels are 800-1200 ppm. Carbon dioxide concentrations which do not meet these values are awarded zero points.

In addition to the above, this paper presents a more extensive thermal comfort assessment, conducted following EN 16798-1:2019 [34]. This international standard defines an adaptive thermal comfort model for buildings under free-running conditions, with window operation freely controlled by users. It considers a metabolic rate between 1.0-1.3 met and thermal value resistance of 0.5 clo and 1.0 clo in summer and winter, respectively. The adaptive comfort temperature (T_{com}) is based on the running mean dry bulb outdoor temperature ($T_{o,ref}$), which depends on the daily mean dry bulb outdoor temperature for the previous 1 to 7 days ($T_{o,ref1}$ to $T_{o,ref7}$:) (Equations 1 and 2). Three acceptability ranges can be defined based on building category. In this research, category II was considered, representing a normal level of expectations (predicted percentage of dissatisfied below 10%), setting a temperature adaptive comfort interval of +3 °C (upper limit) and –4 °C (lower limit).

$$T_{com} = 0.33\times T_{o,ref} + 18.8 \qquad (1)$$

$$T_{o,ref} = (T_{o,ref1} + 0.8\ T_{o,ref2} + 0.6\ T_{o,ref3} + 0.5\ T_{o,ref4} + 0.4\ T_{o,ref5} + 0.3\ T_{o,ref6} + 0.2\ T_{o,ref7})/3.8 \qquad (2)$$

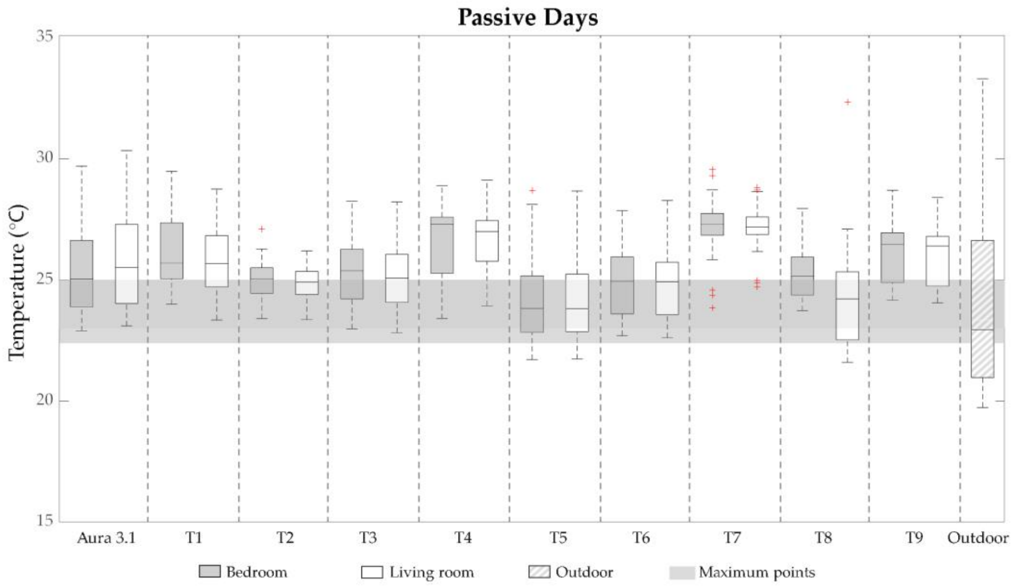
4. Results and Discussion

This section describes the monitoring results recorded during the competition period, showing a comparison of the comfort conditions obtained by each contestant. The indoor temperatures (ºC), relative humidity (%) and carbon dioxide levels (ppm) recorded by the individual teams are presented, and the values are compared to the comfort bands required for each competition variable.

During two consecutive days (20 % of the competition period), the comfort conditions of the participant prototypes were evaluated under passive strategies, in which competition rules did not allow the use of any form of thermodynamic cycle or internal heating / cooling production devices. Aiming to justify the effectiveness of the comfort conditions in the prototype designed, the comfort results were analysed in terms of energy consumption, for both passive (only consumption of passive ventilation systems is allowed) and active (HVAC systems are allowed) competition days. This assessment permitted the comparison of the different participating entries, taking into consideration energy strategies.

4.1 Comfort conditions and energy consumption assessment: passive days.

Figure 7 shows the boxplots for indoor air temperature, relative humidity and CO_2 values registered in the different participant house prototypes during the passive days of the competition. The comfort band established by the competition rules is shown in grey for each variable analysed. The results for Aura 3.1 were compared with those of the other contestants (Team 1 to Team 9 – T1 to T9).



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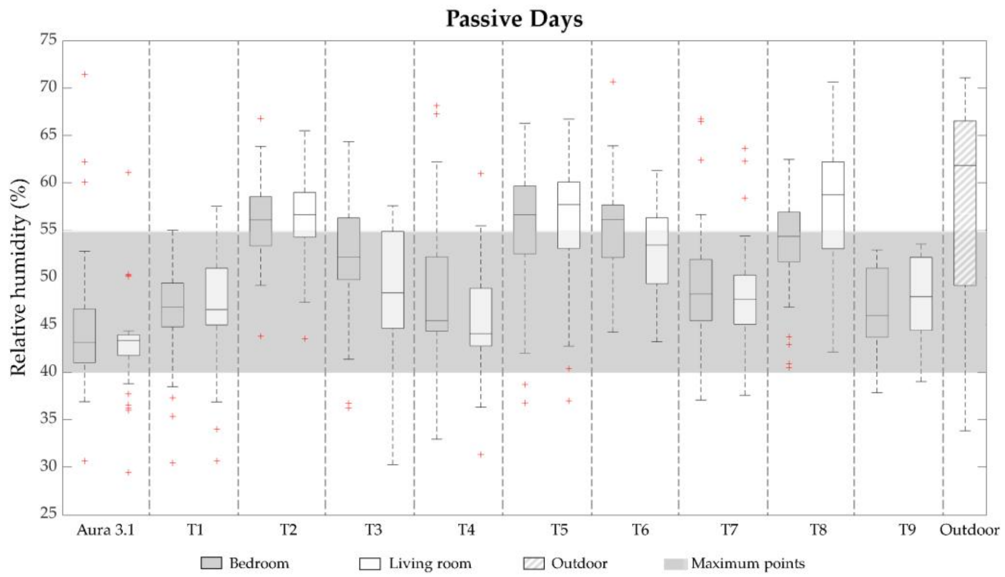

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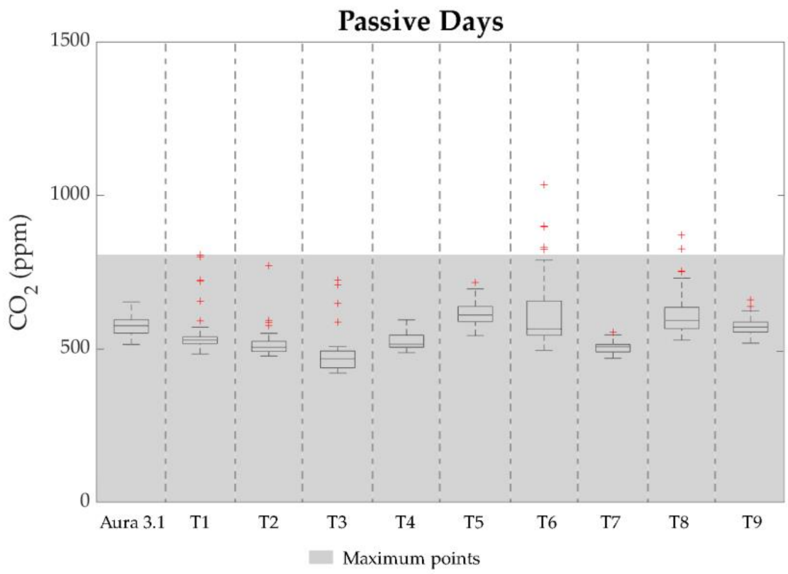

(c)

Figure 7. Boxplots of measurements during passive competition hours (22-23 July) for all house prototypes. T means Team. Comfort bands according to competition rules are shown in grey: a) Air Temperature (ºC); b) Relative Humidity (%); c) Carbon dioxide levels (ppm).

Figure 7a shows indoor air temperatures recorded in both the living room and bedroom, as well as outdoor temperatures. Around 40-50 % of the indoor temperature values registered by the Aura 3.1 team and by T2, T3, T5 and T6 meet comfort conditions. This is seen in the quartile representation in the boxplot (horizontal lines represent the four quartiles, dividing the sample into four sections, so that each section indicates 25 % of the values of the sample), mostly within the comfort band. The percentage of comfort hours is 45.8 % and 52.8 % for the Aura 3.1 team and T2, respectively. The other three teams mentioned recorded values around 42.9 % of comfort hours. Another interesting observation is the temperature range: the difference in indoor air temperature between maximum and minimum values (corresponding to the whiskers or upper and lower horizontal lines). The lowest thermal ranges were registered by T2 and T7 teams, with the latter also showing the lowest percentage of thermal comfort hours (9.7 %). The remaining teams recorded temperatures which led to comfort hours between 20.8 % and 38.9 %.

Likewise, in Figure 7b relative humidity values recorded in the living room and bedroom are indicated for each team, along with outdoor relative humidity results. In this case, it can be seen that the comfort percentages are generally higher than those obtained for the temperature assessment, especially for the Aura 3.1 team and T1, T3, T4, T7 and T9 teams. In these prototypes, most of the boxplot form is within the comfort band, corresponding to 76.4 %, 83.3 %, 66.7 %, 75.0 %, 84.7 % and 95.8 % of the hours under comfort conditions, respectively. The other teams reach percentages of 29.2 % (T5), 30.6 % (T2), 47.2 % (T8) and 48.6 % (T6) of comfort hours.

Lastly, in Figure 7c it can be observed that practically all carbon dioxide values recorded by the participants during passive hours are within the comfort band. Several specific values related to the interquartile values of the samples (in red) of T1, T6 and T8 teams do not meet comfort conditions. The smallest range (difference between minimum and maximum values of the sample), 85 ppm, is registered by T7, showing that indoor concentrations are quite constant and uniform. The Aura 3.1, T4, T5 and T9 teams show ranges between 107 and 142 ppm. The remaining teams exceed 300 ppm of minimum and maximum value difference, leading to considerable oscillation in indoor carbon dioxide concentrations. T6 records the highest oscillation with a difference of 540 ppm between minimum and maximum concentrations.

The lack of use of thermal systems in the social housing stock of southern Europe, built in a time when thermal standards were not required, make it difficult to obtain indoor comfort conditions when applying current legislation. The energy-poverty conditions of the residential social stock with low-income users and the limited possibilities for tackling high energy consumption have prompted the development of low-cost solutions and energy retrofit interventions which prioritize habitability conditions for users.

Figure 8 represents the score distribution of each team during passive days, taking into account energy consumption linked to the passive ventilation systems implemented by each participant. It should be noted that in the Aura 3.1 prototype the comfort results obtained during passive days were reached without using mechanical devices and, thus, with zero energy consumption. This strategy is in contrast with those chosen by the remaining teams, which generally implemented mechanical ventilation systems with heat recovery. This gave rise to energy consumption values higher than 5 kWh for half of the teams (T2, T4, T5, T7 and T9), even exceeding values of 10 kWh (T9), but with no clear improvement of indoor hygrothermal conditions.

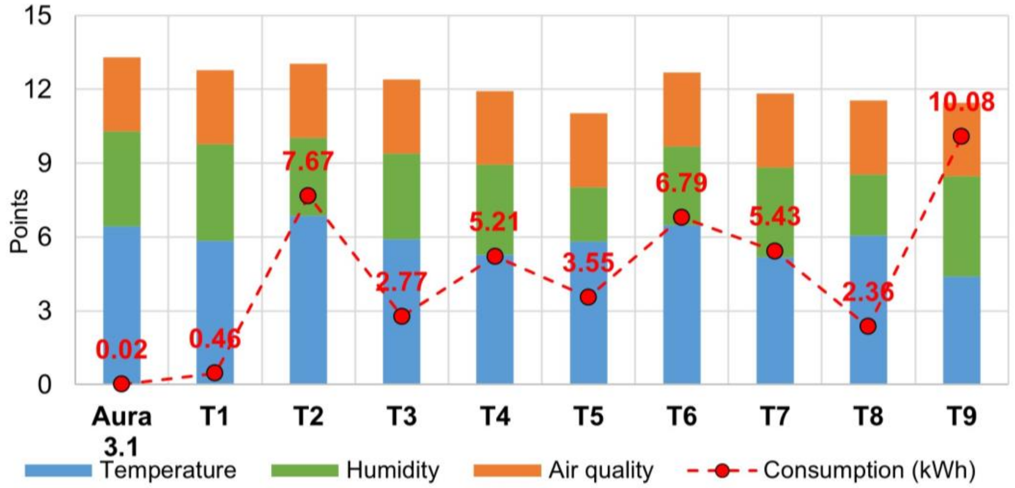

Figure 8. Scores obtained by each team during passive competition hours (22-23 July). Evolution of energy consumption of the ventilation systems.

Table 3 shows the percentage of hours in which the Aura 3.1 house prototype reached comfort conditions during the passive days. In light of the results, it can be stated that the Aura 3.1 team attained significantly better indoor comfort levels than other teams, with comfort values above 44 % and almost 74 % for temperature and relative humidity, respectively. This in turn led to zero energy consumption and an average comfort value of 60 %, which earned Aura 3.1 second place in the comfort competition, after T9, the team recording the highest energy consumption.

Table 3. Percentage of comfort hours during passive days (22-23 July) for the Aura 3.1 team

Parameter in Aura 3.1	Average (%)	Bedroom (%)	Living room (%)

Temperature	Non comfort	> 25 ºC	52.8	55.6	50.0
	Comfort	23 - 25 ºC	44.4	44.4	44.4
	Non comfort	< 23 ºC	2.8	5.6	0.0
Humidity	Non comfort	> 55 %	5.6	8.3	2.8
	Comfort	40-55 %	73.6	69.4	77.8
	Non comfort	< 40 ºC	20.8	22.2	19.4
CO2	Non comfort	> 800 ppm	0.0		
	Comfort	≤ 800 ppm	100		

It should be stressed that in the percentage of hours in which the Aura 3.1 house is outside the comfort range, the indoor temperature generally remains above 25 ºC, with relative humidity values under 40 %. This may be partly due to the fact that the competition was held during summer. In the indoor air quality assessment, most of the house prototypes reached CO_2 concentrations below 800 ppm during the entire competition period, continuously registering values within the comfort band.

4.2 Comfort conditions and energy consumption assessment: non-passive days.

Figure 9 represents the score distribution for each team during the non-passive days, showing the energy consumption of the HVAC systems implemented in individual house prototypes. Unlike the most commonly used energy approaches focusing on high energy efficiency systems and the reduction of energy consumption, the Aura 3.1 prototype enhances the development of interventions which provide optimum comfort conditions for users. As stated previously, the best results are registered in the evaluation of the parameters monitored during long-term periods (temperature, relative humidity and air quality), obtaining the maximum score of 53.92, similar to that obtained by T2 and quite close to that reached by T1 (53.65).

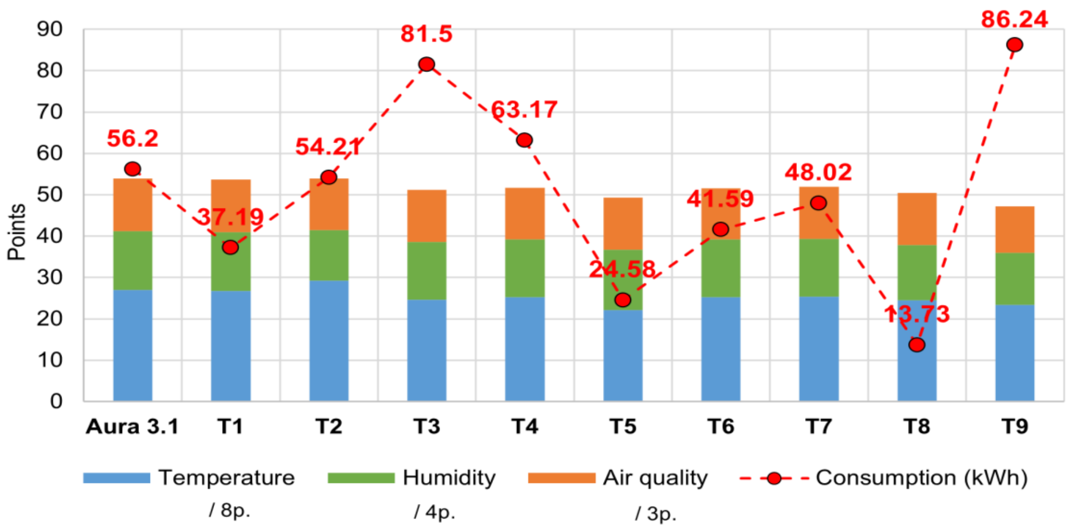

Figure 9. Scores obtained by each team during the non-passive competition days. Evolution of energy consumption of the HVAC systems.

4.3 Assessment of the strategies used in Aura 3.1

Figure 10 presents the outdoor and indoor hourly air temperatures monitored in the living room (red line) and bedroom (blue line) in the Aura 3.1 prototype during the passive hours in the competition period. If these values are analysed in relation to the thermal comfort band proposed in the competition (23 ºC to 25 ºC in solid grey), only 45.8 % of the hours are within comfort conditions, that is, 17 hours out of 36 registered in the living room and one less (16) in the bedroom. 51.4 % of discomfort hours exceed the upper static-state comfort band. The average indoor temperature is quite similar in both spaces: 25.3 ºC in the living room and 25.7 ºC in the bedroom. However, the maximum peak temperature in the bedroom is 30.03 ºC (13:00h on 22 July) while in the living room it is 22.9 ºC (9:00h on 23 July).

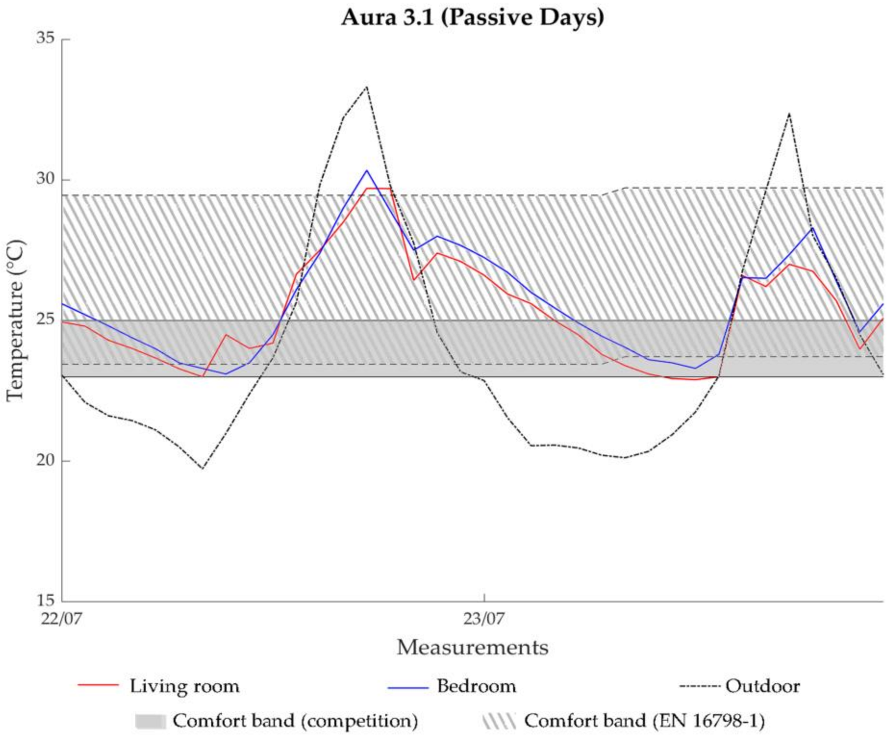

Figure 10. Indoor and outdoor air temperature (ºC) registered in Aura 3.1 during the passive days (22-23 July). Only competition hours are represented.

If indoor air temperatures were analysed according to the adaptive comfort established in EN 16798-1:2019 [34], described in section 2, the comfort band would depend on outdoor temperatures, as indicated with the striped grey shading. In this case, the percentage of adaptive comfort hours would reach 79.2 %, corresponding to 27 comfort hours in the living room and 30 comfort hours in the bedroom (from a total of 72 hours analysed, 36 hours in each space). This highlights the importance of considering adaptive comfort conditions given that people adapt to environmental conditions and interact with the environment and the feeling of discomfort is reduced [15].

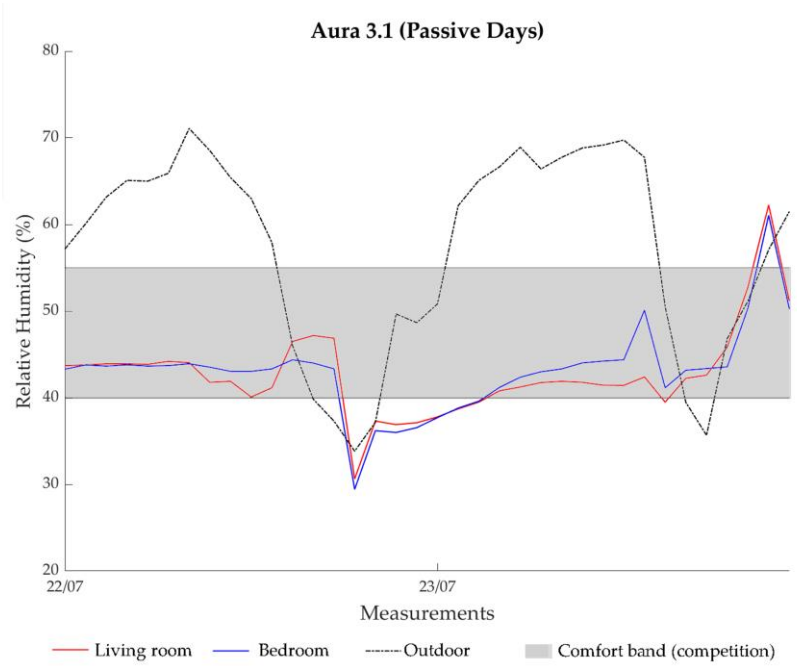

Figure 11. Indoor and outdoor relative humidity (%) registered in Aura 3.1 during the passive days (22-23 July). Only competition hours are represented.

The hourly relative humidity measurements recorded during the passive days both in the living room (red line) and bedroom (blue line) of the Aura 3.1 house are represented in Figure 11. It can be observed that 76.4 % of hours are within the comfort band (considering total measurements of both spaces), so that relative humidity values are between 40.0 % and 55.0 %. Discomfort hours are registered late at night, between 20:00 h and 2:00 h, exceeding the upper limit of the comfort band only during 2.8 % of the hours. Average relative humidity in the living room is 42.7 %, quite similar to the average value monitored in the bedroom (43.0 %). The maximum relative humidity peak is recorded in the living room (62.0 %) and the minimum peak in the bedroom (29.4 %), both at 22:00 h on 23 and 22 July, respectively.

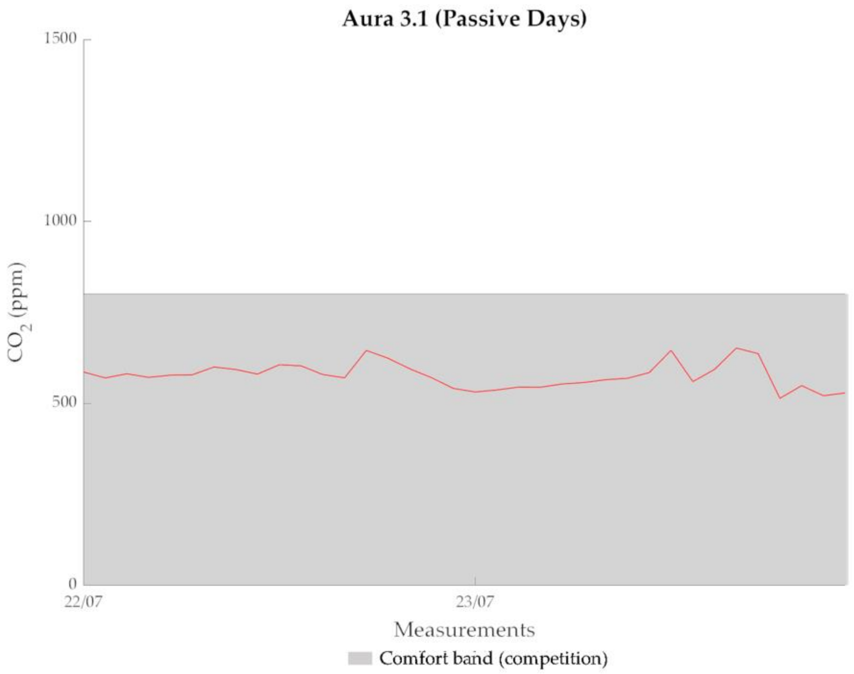

Figure 12. Carbon dioxide levels (ppm) registered in Aura 3.1 during the passive days (22-23 July). Only competition hours are represented.

As can be seen in Figure 12, showing carbon dioxide levels monitored inside the Aura 3.1 prototype during the passive competition days, in 100 % of the hours CO_2 concentrations meet the comfort conditions, limited to a maximum value of 800 ppm. Average indoor CO_2 levels inside the Aura 3.1 house are 576 ppm. Although no data were recorded on outdoor carbon dioxide levels, minimum and maximum indoor CO_2 peaks were 514 ppm and 652 ppm, reached on 23 July at 20:00 h and 12:00 h, respectively.

In light of these results, the energy strategy proposed by the Aura 3.1 team has made it possible to globally guarantee the best comfort conditions (88.11 points), especially during the continuous monitoring of temperature, relative humidity and indoor air quality. Only T2 secured a higher score in the temperature test (37.84 points), when compared with the Aura 3.1 team (32.96 points), which translates into an energy consumption significantly higher than that of T2 (7.67 kWh), in contrast to the zero-energy consumption of the Aura 3.1 prototype during the passive days.

Based on a comparative assessment of the results obtained by the different teams, it can be concluded that energy and comfort strategies implemented in the Aura 3.1 prototype provided the indoor results that best adapt to the comfort bands and for the longest periods of time. Moreover, this meant that the Aura 3.1 prototype secured the maximum score in the comfort test, while energy consumption was in line with the average values obtained by other teams during non-passive days (51 kWh), with no consumption during passive days. In fact, the Aura 3.1 is the only prototype with zero energy consumption during passive days.

All this being said, the hygrothermal performance of the Aura 3.1 prototype has proven to be quite effective, thanks to the controlled and passive outdoor-indoor exchange proposed. This proposal reported significant results during the evaluation period for passive strategies, and was awarded the highest competition rating for minimum energy consumption.

5. Conclusions

This paper highlights the importance of comfort in an energy improvement scenario which aims to minimize consumption and maximize indoor comfort. In addition, there is an assessment of daily energy strategies adopted, which favour exchanges when outdoor conditions display greater oscillation. This commonly occurs in warmer climates, unlike seasonal models of colder climates where temperatures remain stable. The results of comfort conditions are analysed and compared with those of other teams, according to both the static-state comfort bands required by the competition rules and the adaptive comfort models established in international standards. The monitoring process of hygrothermal and air quality variables makes it possible to determine the capacity to guarantee the best indoor comfort conditions in the design housing prototype. From what was observed at the SD competition, it seems logical to apply adaptive comfort models, more closely linked to the degree of tolerance and socio-cultural conditions. It should also be noted that these models generally extend the range of percentage of hours in comfort conditions.

Results show that during the non-passive days when it was possible to use any form of heating / cooling production equipment that led to any thermodynamic cycle, the Aura 3.1 project obtained the maximum score in the comfort test while maintaining energy consumption within the average values obtained by other teams during the eight non-passive days (51 kWh). Furthermore, the house-pavilion designed by the University of Seville was the only prototype with zero energy consumption during passive days, when no thermodynamic cycle equipment was allowed.

Considering international standards and adaptive comfort models, the percentage of adaptive comfort band would reach almost 80 % in the case of temperature variables and 76 % when analysing relative humidity. Based on these considerations, it can be concluded the hygrothermal performance of the Aura 3.1 prototype has proven to be quite effective, thanks to the proposal of a controlled and passive outdoor-indoor exchange. However, this strategy would have to be validated not only in a housing prototype, but in a real case of residential building retrofit, in order to also assess the impact on the existing spaces.

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Appendix A.

Table A.1 shows the score distribution of the comfort band for each monitored parameter in the comfort test, as well as the highest possible score and reduced points which may be obtained.

Table A.1. Distribution of scores in tests for monitoring comfort conditions according to SDE19 competition rules.

Comfort conditions	Parameters	Total points	No points	Reduced points	Maximum points	Reduced points	No points
Temperature	Indoor temperature (ºC)	40	≤ 21	21÷23	23÷25	25÷27	≥ 27
Humidity	Indoor relative humidity (%)	20	≤ 25	25÷40	40÷55	55÷60	≥ 60
Indoor air quality	CO_2 concentration (ppm)	15		800÷1200	≤ 800	800÷1200	≥ 1200
Lighting	Natural lighting (Daylight factor %)	15	≤ 2.5	2.5÷4.0	≥ 4		
Acoustics	$D_{ls,2m,nT,w}$ (dB)	10	≤ 30	30÷42	≥ 42		
	Equipment and HVAC sound level		≥35	35÷25	≤ 25		