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Evaluation of environmental comfort in a social housing prototype with bioclimatic double-skin in a tropical climate

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A R T I C L E I N F O

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A B S T R A C T

The aim of this paper is to broaden understanding of the social housing prototype that students and researchers at the University of Seville developed in response to tropical climate conditions to achieve the maximum level of hygrothermal comfort through the use of passive retrofit strategies.

This prototype, known as Aura 1.0, was presented at the Solar Decathlon competition where hygrothermal conditions inside the prototype were monitored over a ten-day period. Nevertheless, as the monitoring period of the environmental conditions was so reduced, the aim of this research is to assess the environmental behaviour of the prototype for a full year, under tropical climate conditions. To do so, energy and environmental simulation instruments will evaluate the performance of the architectural proposal and its passive construction systems, in particular the double skin designed with different objectives (architectural, construction, socio-economic).

The simulation model has been verified by the data monitored during the exhibition phase and the performance of the building. Various hypotheses have been analysed which demonstrate that employing a double skin in the dwelling contributed to improving interior thermal comfort, especially in the roof area as opposed to the facades, given the sun's path at a latitude close to the equator.

1. Introduction

The AURA 1.0 prototype was designed and built by a team made up of teachers, researchers, and final year students and recent graduates from the University of Seville's School of Architecture (Spain) [1], in collaboration with the University of Santiago de Cali, (Colombia). This prototype was developed to participate in the first Latin American edition of the Solar Decathlon competition which took place in Santiago de Cali (Colombia) in 2015. Various editions of this contest had already been held in the US (origin of the contest) [2], as well as in Europe [3] and Asia [4].

In this competition, dwelling prototypes are built and then exhibited [5]. They are presented and explained by the participating university teams who are previously chosen in a competition process. These prototypes undertake 10 tests whose scores are either awarded by a jury of experts (Architecture, Engineering and Construction, Sustainability, Communication and Marketing, Urban design, Innovation) or through objective measurements (Comfort conditions, Energy efficiency, Energy balance, House functioning).

This foments interdisciplinarity as researchers and students from different branches of knowledge work together with a common objective: design, build and test a sustainable dwelling with optimal interior environmental conditions [6].

This means that the dwelling prototypes can be used to carry out research into the suitability of different prefabricated construction systems [7], broadening visual comfort through natural lighting [8], the behaviour of specific installation systems from different prototypes in the same edition of the competition [9], or testing whether a particular system of energy production for self-consumption is marketable from an investment-performance perspective [10]. Other research has aimed for an adequate integration of energy efficient systems into the developed architectural concept [11].

The competition is also a good context for the introduction of reflections and debates as to whether comfort in a sustainable dwelling

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should be entrusted solely to passive strategies or whether, on the other hand, it is worth employing technology for active retrofitting when environmental conditions are extreme [12,13]. This aspect has been analysed in the different climates where the competition has been held: both tropical, in Colombia [14], and continental Mediterranean climates, such as Madrid (Spain) [15], highlighting that a combination of active-passive retrofitting strategies gives better results.

Nevertheless, Solar Decathlon has a few limitations related to the long term analysis of housing behaviour [16].

This is due to the fact that the prototypes built for the competition are assessed in two phases: a first phase which tests the prefabricated construction system designed by each team because the assembly of each prototype dwelling unit must be carried out in a maximum of fifteen days in the so-called “solar city”; the second, 10-day long phase when the prototype is exhibited to the public and when the different contests are assessed, among them the comfort conditions. This means that environmental behaviour is only monitored for ten days, which also, logically, coincides with a very specific climate period, depending on the time of year and the climate in which the competition is being held. .

The AURA 1.0 prototype took part in the first edition of the Latin American and Caribbean Solar Decathlon competition which was held in Santiago de Cali (Colombia) in 2015. The monitored data in two of its interior spaces (living room and bedroom) were very appropriate in terms of hygrothermal comfort [17] which led to this prototype winning the “Comfort Conditions” contest. Nevertheless, this is a social housing project, the aim of which is to achieve long term hygrothermal comfort for inhabitants, thereby minimizing energy poverty while guaranteeing that people with fewer resources can reside in an adequate space from the perspective of health and hygiene [18].

Consequently, the main objective of this article is to analyze what the environmental behaviour of the AURA 1.0 prototype would be over a year-long period. To this end, a simulation model was developed, verified by the monitored data, which allowed us to carry out calculations for the prototype’s hygrothermal behaviour based on five different hypotheses.

Firstly, these hypotheses consist of the evaluation of the prototype with simulation instruments in the same conditions of use, interior loads and natural ventilation as were given in the competition (exhibition phase open to the public) but extrapolating them to a full year. Next, its behaviour during normal residential use (dwelling for a family of three or four occupants) will be analysed. In this case natural ventilation is limited as openings are adjusted to the usual use of the dwelling. Finally, the effect that one of the prototype’s key bioclimatic design strategies produces: the double skin that acts as a solar protection system and was designed for both the roof areas and the south facade. The aim is to quantify the impact of this double skin if it is used solely on the roof or solely on the south facade.

As this is a temporary structure which was disassembled after the competition, there is no monitored data available for a year-long period which would give greater knowledge of behaviours. Neither is it possible to monitor other hypotheses related to thermal load or design. Therefore, the aim of this research centres around the analysis of the comfort conditions in the AURA 1.0 prototype in the city of Cali, with a tropical climate, according to Köppen climate classification [19], in the long term and using proven simulation instruments which make it possible to calculate the different proposed hypotheses.

During the exhibition period in Cali, the organisation’s assessment of the interior environmental conditions of the habitable spaces was made in a simple manner. Interior environmental conditions (dry temperature and relative humidity) only had to be maintained in a specific range. Outside of this static range, scores for the contest were lower or void. For the temperature, the range for maximum scores was between 24 °C and 28 °C. Relative humidity had to be below 60%.

For this research, assessment of environmental conditions for the three simulated hypotheses has been carried out with widely recognised, adaptive comfort criteria which are set out in the European Standard EN 16798-1:2019 “Energy performance of buildings. Ventilation for buildings. Part 1” [20].

1.1. Description of AURA 1.0: from urban scale to dwelling unit

The AURA 1.0 prototype is a dwelling unit which resulted from the urban planning of one of the most socially and environmentally excluded areas of the city of Santiago de Cali. It was here that the AURA strategy was developed, focusing on reconditioning deprived urban spaces, with the premise of progressive and sustainable growth, and participative, guided self-construction.

AURA 1.0 is developed at four scales: urban scale, building scale, housing scale, and exhibition prototype. A network of basic services is woven between them (again, at different scales) which makes the two base strategies of the project possible: sustainable growth in phases and participatory construction.

Thus, the prototype which was built in the Solar City is the representation of a dwelling unit extracted from a project whose aim is the urban and social regeneration of the urban fabric in one of the most deprived areas in Cali. This dwelling has a 50 m^2 surface area and an 18 m^2 private hallway which opens onto the common areas.

Access to the dwelling is through the north facade, where there is a covered gallery. The south facade is protected from solar radiation thanks to a double skin which acts as ventilated façade made out of cane (Fig. 1). This double skin also extends over the roof.

The inside of the dwelling can be configured in different ways thanks to its flexible design in which spaces can have different functions throughout the day, depending on domestic needs.

Thanks to the multifunctional furniture (Fig. 2), a space could be a bedroom at night, but a study or games room during the day, or it could serve to increase the space in the living or dining room. However, during the competition, the dwelling was exhibited as a completely diaphanous space; the furniture was set out in a way that meant the rooms were not compartmentalised.

The AURA 1.0 prototype was therefore designed to overcome the characteristic tropical climate conditions in Santiago de Cali [21,22], located in the Northern hemisphere at a latitude of 3° 27″ N, a longitude of 76° 32″ W and 995 m above sea level.

Based on the Givoni diagram [23] (Fig. 3), it is possible to analyze graphically the conditioning strategies required [24,25] in the climatic conditions of Santiago de Cali: on the one hand, internal gains will be necessary in the hours where the temperature is lower and, on the other hand, solar protection mechanisms must be available in the hours where there is greater radiation.

With that in mind, a series of passive retrofit strategies, consistent with the location, were included such as protecting the south facade from the sun or creating a covered but open space like the entranceway which acted as both a sound barrier between houses and encouraged social relationships among neighbours.

The competition was held in December, for this reason two solar protection strategies were designed in the prototype: to the North (facade without solar radiation in this month) a flight that served as protection to the entrance gallery to the house was arranged and, to the South (facade that receives direct solar radiation in the period of the year), a double skin was designed that continues on the roof, due to the verticality of solar radiation at this latitude.

1.2. Double skin on the south facade and roof

The design of a double skin facade (DSF) is a passive conditioning strategy successfully tested in tropical climates [26,27], not only as solar protection but also to promote natural ventilation [28], although its performance is directly related to the materials used [29]. However, in the case of Santiago de Cali, not only the tropical character of its climate should be taken into account, but also its latitude.

Fig. 1. South elevation of the AURA 1.0 prototype and cane panels as solar protection.

Fig. 2. Multifunctional furniture.

The impact of the equatorial latitude on architecture [30], as in the case of Cali, makes it necessary to analyze, among other aspects, the repercussion of the double skin on the roof [31,32], due to the high inclination of solar radiation, in addition to assessing the best orientation where to place the double skin on the facade (DSF), since both the North and South facades will receive direct solar radiation in different months of the year (Fig. 4).

In the AURA 1.0 building scale design, a skin was developed and handcrafted from local materials (Fig. 5) which gave uniformity to the south elevation of a building based on safe, guided self-construction, guaranteeing that the final elevation would not be personalised by the tenant of each dwelling.

Furthermore, this skin fomented the local economy, using natural materials which are not usually being used to generate wealth among the population. As a consequence, value is added to the work of the local carpenter who made the pieces for the facade.

These pieces consist of different sized frames which make up the design of the facade. They were made from carved natural wood to which pieces of cane were attached mechanically, having previously been treated with antibacterial varnish and linseed oil.

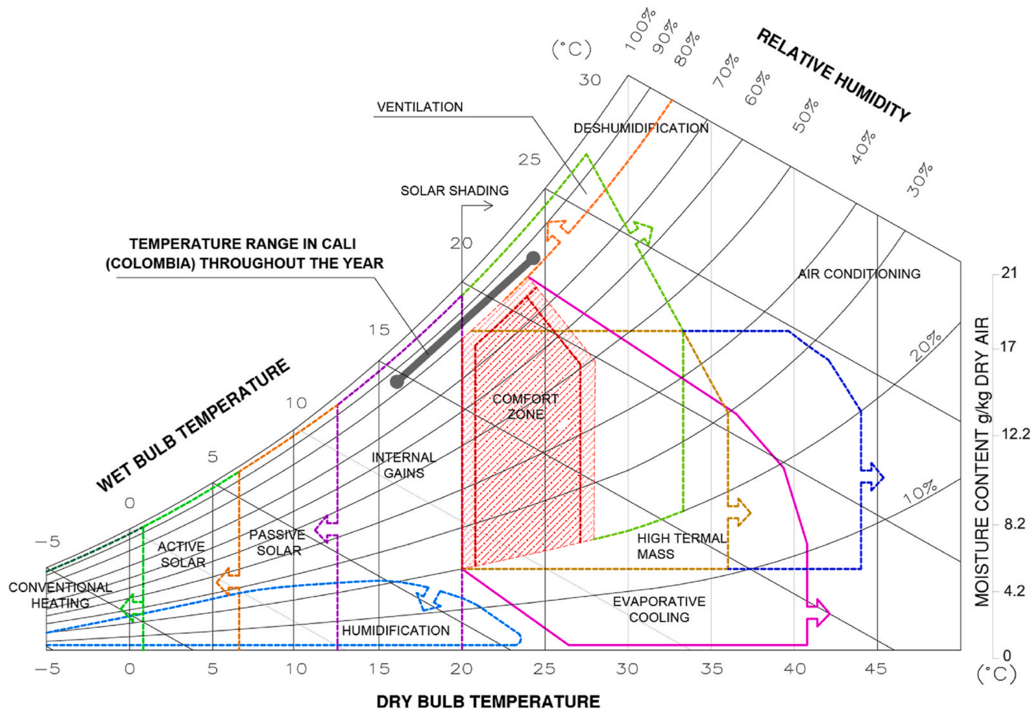

Fig. 3. Givoni diagram for Santiago de Cali's climate.

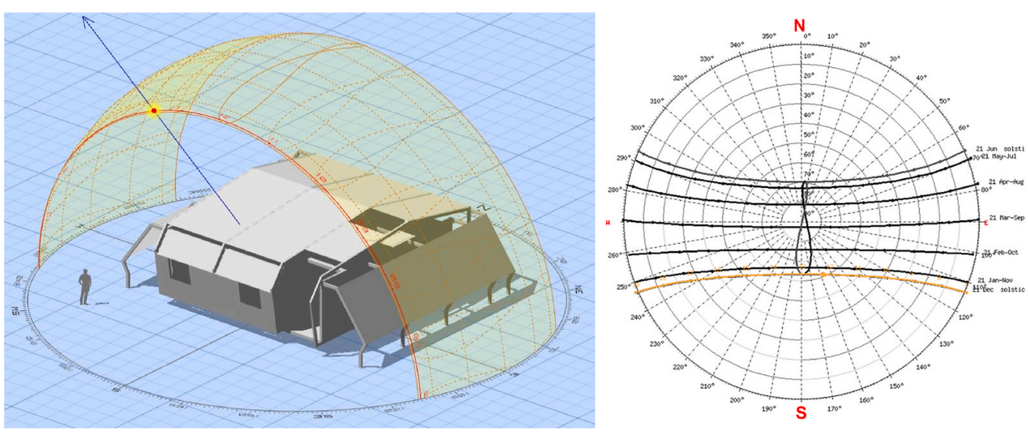

Fig. 4. Recorrido solar en Santiago de Cali.

2. Materials and methods

2.1. Data monitored by the competition organisers

The measurement process was carried out by the competition organisers during the 10 days that the contests lasted (from 5th to December 14, 2015). To do so, two temperature sensors were installed inside the prototype and three humidity sensors were placed in strategic locations in the dwelling (Fig. 6).

During the competition, the prototype was considered an "exhibition pavilion" as it was visited in particular timeslots by a variable number of people, both expert and non-expert in the field. During the period of public exhibition, it was a completely open, ventilated space. Outside of this period, the prototype was closed, and this is when its interior environmental conditions were assessed. As energy consumption was measured and was scorable in another of the contests (Energy Balance), the heating and cooling systems were activated, or not, depending on needs. The best buildings, from an environmental aspect, were those that maintained interior conditions in a range with the lowest possible use of the active systems.

The constructive solutions used (Table 1) were designed with the objective of using local resources, carrying out a study of existing companies within a radius of less than 100 km in order to propose solutions that could be transferred to society.

Outside of visiting times, the dwelling was usually occupied by members of the team, for example, during the celebration of one of the competition's contests. On the other hand, these timetables and this activity changed between weekdays and weekends. The prototype timetable on exhibition days is set out in Fig. 7.

The number of visitors in the dwelling was not the same at 10am as 3pm, so although this timetable established by the competition organisers helps us to interpret the data obtained and verify the simulation data, it should be considered that they were achieved under very variable conditions.

On the other hand, to measure exterior conditions, the organisation had a weather station which collected the values of temperature, humidity and lighting in real time on the site where the competition was held. It should be highlighted that during the competition period, there

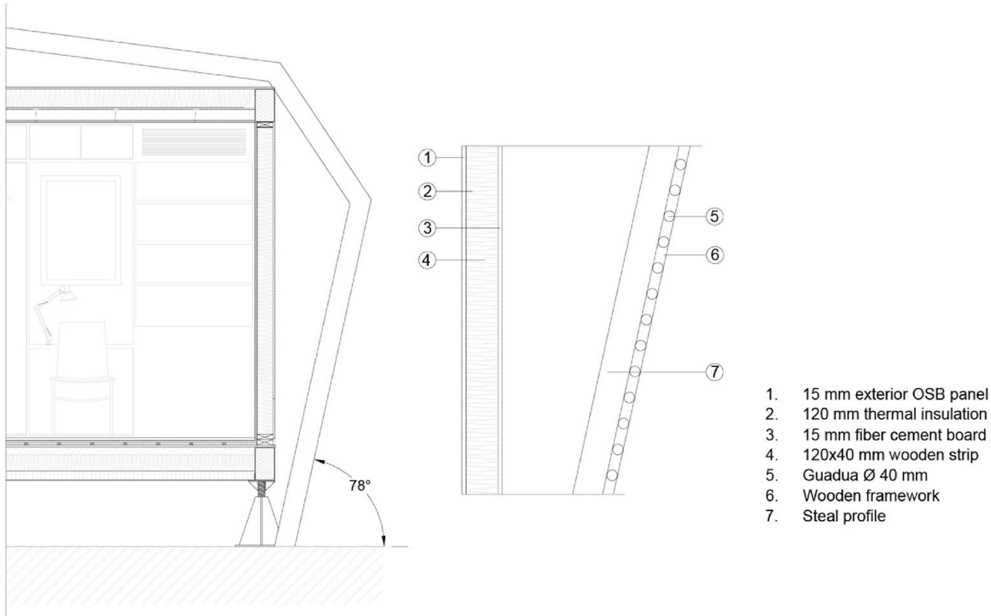

Fig. 5. Construction section of the double skin façade.

was no precipitation.

Fig. 8 shows the starting data for the development of the validated simulation model: outdoor temperature and indoor temperature measured by the sensors placed by the organization. An average was made with the interior temperature values taken from each of the sensors located in the dwelling.

2.2. Simulation model

To address the proposed objective, a simulation model of the study's prototype, AURA 1.0 was developed. This model has been verified according to the temperature data obtained from the measurements taken by the competition organisers via a system of monitoring implemented in all the participating prototypes.

SG SAVE version 2.9.2.1 was used to generate the simulation model. This uses the EnergyPlus [33,34] calculation engine, considered to date, the most advanced software in existence. It was developed by the U.S. Department of Energy's National Renewable Energy Laboratory [35, 36]. The calculation methodology used by EnergyPlus, as well as the governing equations for heat and mass transfer [37,38] are available online [39].

SG SAVE uses Sketchup 2017 modelling software which makes it possible to model the spaces to be simulated in a very intuitive manner.

A single space has been generated for the simulation model because, as previously explained in the prototype description, the rooms were not compartmentalised. The corresponding openings and shade elements used on the south facade have been added to the single space.

To verify the simulation model and calculate the different hypotheses, a climate record from the Alfonso Bonilla Aragón International Airport located 20 km to the northwest of Cali (Colombia) was used. This is available on the web http://climate.onebuilding.org managed by the researchers Dr. Drury B. Crawley (Bentley Fellow/Director Building Performance Research at Bentley Systems, Inc., ASHRAE Director-At-Large, Vice President at IBPSA) and Dr. Linda Lawrie (Principal Software Design Engineer, Vice President at IBPSA).

ASHRAE: American Society of Heating, Refrigerating & Air-Conditioning Engineers.

IBPSA: International Building Performance Simulation Association.

2.3. Verification of the simulation model

To calibrate the model, the temperature values collected by the competition organisers from the weather station, on the days chosen to verify the simulation model were used.

Working with a space whose conditions, in regard to interior loads, were very variable for the previously mentioned reasons, the days on which the building had free evolution without active heating and cooling systems have been taken as the reference to carry out the verification.

The simulation instrument has recreated the prototype's operational conditions on the chosen days, bearing in mind the occupation and loads that these provided, as well as the renewal of interior air and the equipment and lighting loads. The exterior conditions used in the climate record were the same as those registered by the competition organisers' weather station on the days selected for the verification of the model. Fig. 9 shows the comparison of temperatures measured in situ and the simulated temperatures.

Although the graph shows how the data extracted from the simulation model follows the trend of the data of temperatures measured in the prototype, an analytical verification is also carried out.

This is to ensure the model's verification complies with the demands of ASHRAE Guideline 14:202 (ASHRAE) [40], which indicates that the calibrated model must have a normalized mean error (NMBE) of 55 and a Coefficient of Variation of Root-Mean Squared Error (CV)(RMSE) of 15% when monthly data is used for calibration, or requirements of ±10% or 30% respectively when hourly data is used, as in this case [41].

To calculate both coefficients, the expressions stated in section 5.2.11.3 of the guideline.

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

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

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

NMBE = - 0,393%
CV(RMSE) = 2,357%

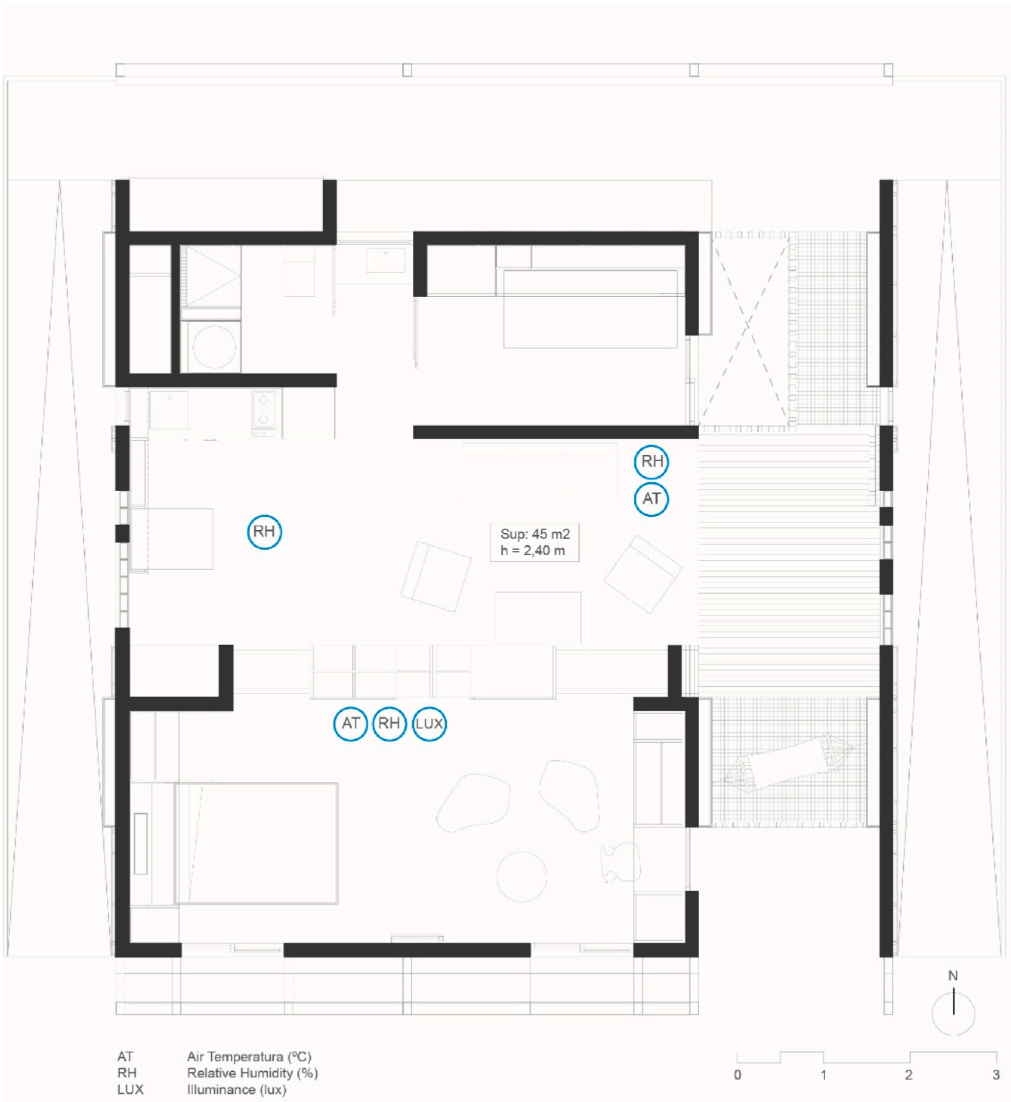

Fig. 6. Location of sensors in the AURA 1.0 prototype.

Table 1
Materials and thermal properties of the construction elements.

Element	Layer	U (W/m^{2}K)	Espesor (m)
Enclosure	Fiber cement panel	0.30	0.15
	Insulation		
	OSB Board		
Floor	Corrugated sheet	0.29	0.159
	Cellulose insulation		
	Corrugated sheet		
	Foamed polyethylene sheeting		
	Fiber cement panel		
	Wood		
Ceiling	Asphalt blanket	0.29	0.165
	Fiber cement panel		
	Insulation		
	OSB Board		
	Textile false ceiling		

Therefore, and according to the values mentioned previously, we can confirm that the simulation model is verified by the said method.

2.4. Hypothesis for the case study

Once the simulation model is verified with the results obtained from the monitoring carried out during the exhibition period in the "Solar Decathlon City" in Cali (Colombia), different operational conditions were defined in accordance with each hypothesis:

- Hypothesis nº1 (Exhibition mode): Prototype AURA 1.0 in the same operational conditions as during the competition. Building with high occupancy and open to the exterior.
  Parameters: 2 ren/h constant infiltration - Maximum ventilation 60 ren/h but variable depending on time of day.
- Hypothesis nº2 (Dwelling Mode): Operational conditions of residential use. Limited and controlled openings. Low occupancy.
  Parameters: Constant ventilation: 0.85 ren/h - Summer night-time ventilation: 3.15 ren/h
- Hypothesis nº3 (Effect of the double skin solely on the south facade): This hypothesis is based on hypothesis nº 2 (closed mode dwelling), but solar protection is limited to the south facade.
  Parameters: Same as Hypothesis nº2

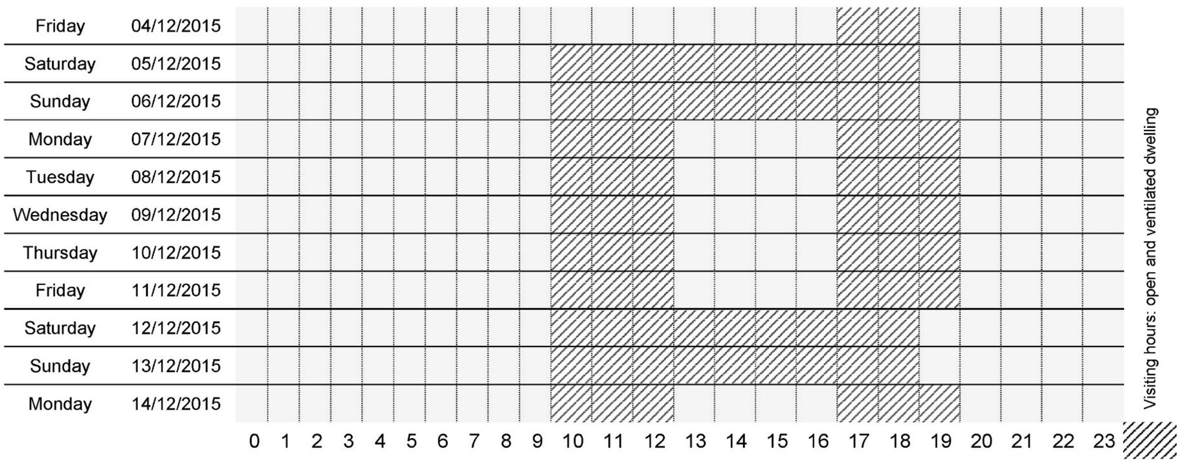

Fig. 7. Activity times in the prototype.

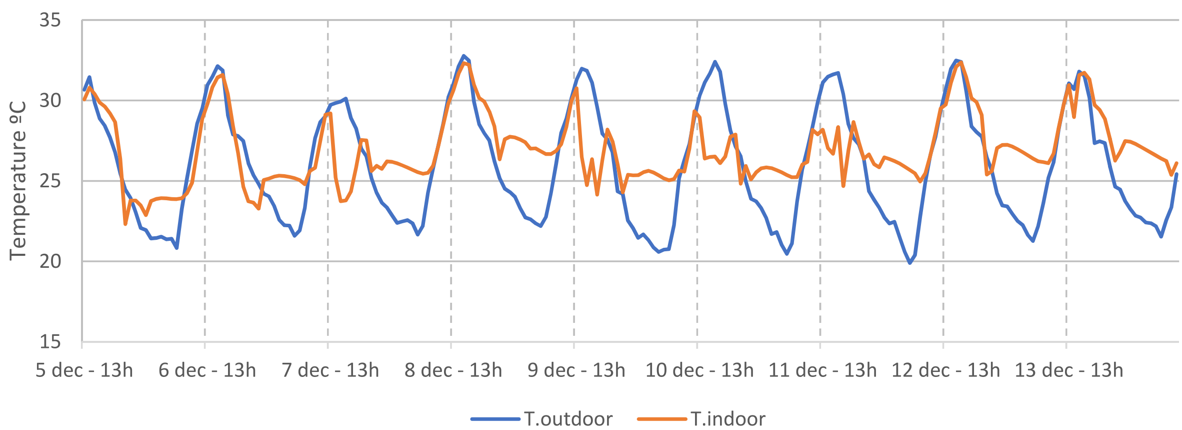

Fig. 8. T.outdoor and T.indoor measured by the weather station and sensors inside the dwelling during the monitoring period.

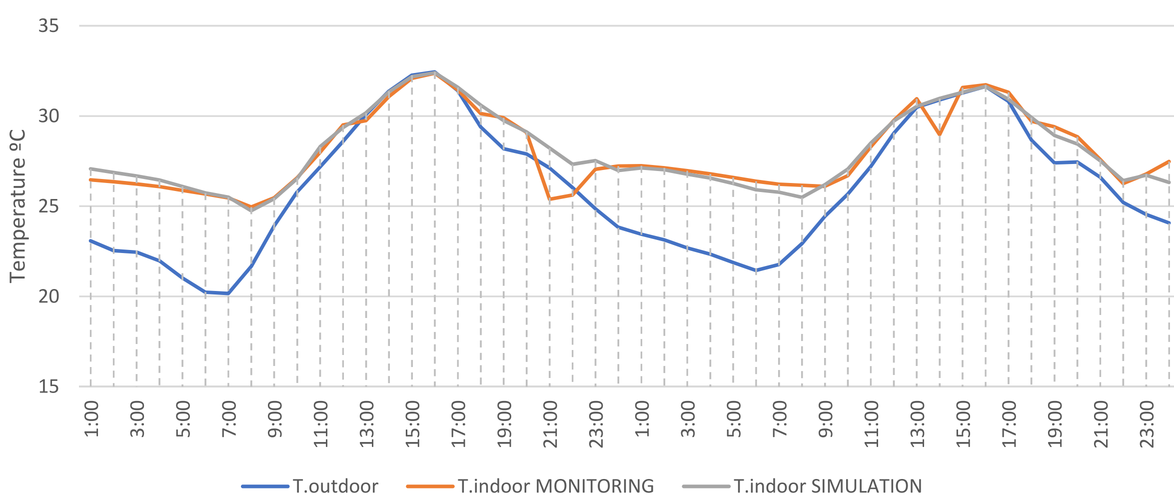

Fig. 9. T.outdoor and T.indoor in free evolution, in comparison to the simulation model T.indoor.

- Hypothesis nº4 (Effect of the double skin solely on the roof): This hypothesis is based on hypothesis nº 2 (closed mode dwelling), but solar protection is limited to the roof.
  Parameters: Same as Hypothesis nº2
- Hypothesis nº5 (Total elimination of the double skin): This hypothesis is a combination of nº 3 and nº 4 and therefore the double skin is eliminated from both the south facade and the roof.
  Parameters: Same as Hypothesis nº2

In the 5 hypotheses that were studied, the behaviour of the prototype is analysed on the basis of the following parameters: occupancy, ventilation and design of the solar protection on the roof and south facade. All hypotheses have been studied for a full one-year period to analyze the thermal condition behaviour in the long term and in different seasonal

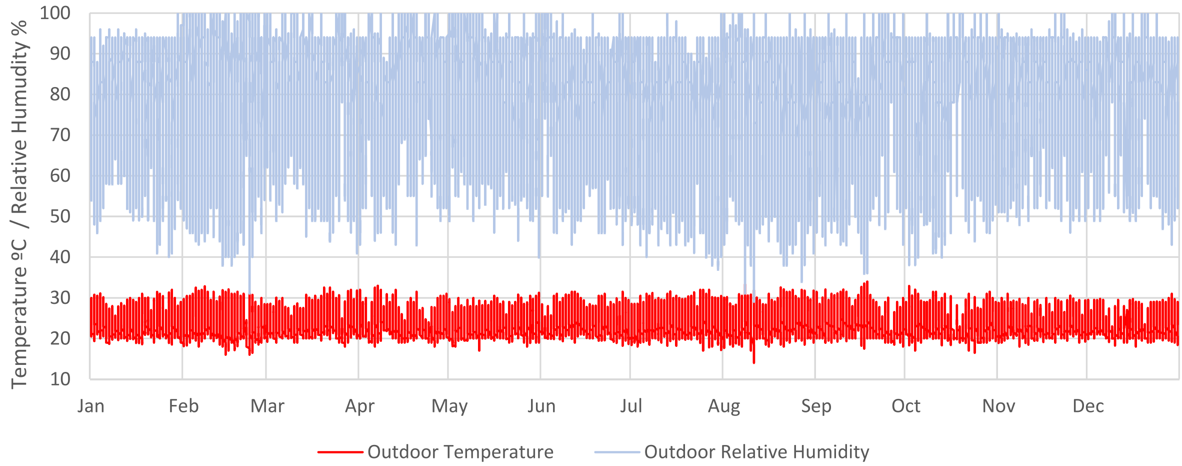

Fig. 10. Graph showing hygrothermal condition statistics in the city of Cali over a one-year period, obtained from the climate record detailed in point 2.2.

weather conditions. However, it should be pointed out that given the characteristics of a tropical climate, there are no large hygrometric oscillations between seasons (Fig. 10).

Hypothesis nº1 aims to assess the AURA prototype over a year long period under the same operational conditions as the exhibition prototype and with which the verification model was carried out.

For hypothesis nº2, the dwelling's ventilation stream was modified with respect to hypothesis nº1. A maximum occupancy of **20 m^2/person** (in this case that would correspond to 3 people), and a **70 W/person** load were determined appropriate for this type of housing. The profile occupancy timetable was as shown in Fig. 11 for weekdays, while a maximum constant occupancy was considered at weekends. This would be the standard hypothesis for social housing use.

Hypothesis nº3, nº4 and nº5 are based on the operational conditions of hypothesis nº2, but different parts of the solar protection have been eliminated to see the effectiveness of this on the prototype's thermal envelope (facade and roof).

Specifically, in Hypothesis nº 3, the double skin would only be on the south facade. In Hypothesis nº4, the double skin would only be on the roof. Finally, in Hypothesis nº5 the double skin would be eliminated from the façade and the roof (Fig. 12).

The results of the interior temperature obtained in these hypotheses are evaluated according to the adaptive comfort methodology set out in European Standard EN 16798-1:2019 "Energy performance of buildings. Ventilation for buildings. Part 1" [20], and a range of comfort is established supposing a value of 10% dissatisfaction.

Regarding the relative humidity results, the same standard establishes a maximum relative humidity of 60% and minimum relative humidity of 25%.

3. Results and discussion

After the calculation of the 5 hypotheses, the data obtained for temperature and humidity are analysed. This analysis will be carried out on a monthly basis, since atmospheric conditions are very stable throughout the year and there are no significant differences between the different seasons. However, it is convenient to take into account the solar path, since depending on the seasons of the year, the facade that receives direct solar radiation will vary: South in the months closest to the winter solstice, and North in the months close to the summer solstice.

3.1. Hypothesis nº1

In this hypothesis, a simulation is carried out with an open use of the dwelling, as it was exhibited in the competition. The results obtained simulating the thermal behaviour of the AURA 1.0 prototype over a full year are as follows (Fig. 13):

The percentage of hours of comfort per month are shown in Table 2, indicating that behaviour is usually homogenous. From the thermal perspective, October and November stand out while July and August are more relevant when looking at relative humidity data.

In this hypothesis, the thermal behaviour of the dwelling guarantees an average number of thermal comfort hours per year of over 40%. Relative interior humidity should stay, where possible, under 65%, this is achieved in more than 55% of the hours of the year.

It is a relevant fact that in the months close to the solstices (December–January and June–July), the percentage of hours of thermal comfort is lower than the annual average.

It should be pointed out that the occupancy load is very high in this hypothesis. This is due to the fact that the aim is to evaluate the prototype with the same load conditions as the exhibition phase where the average flow of public was high.

3.2. Hypothesis nº2

In this case, a simulation is carried out for a conventional use of a

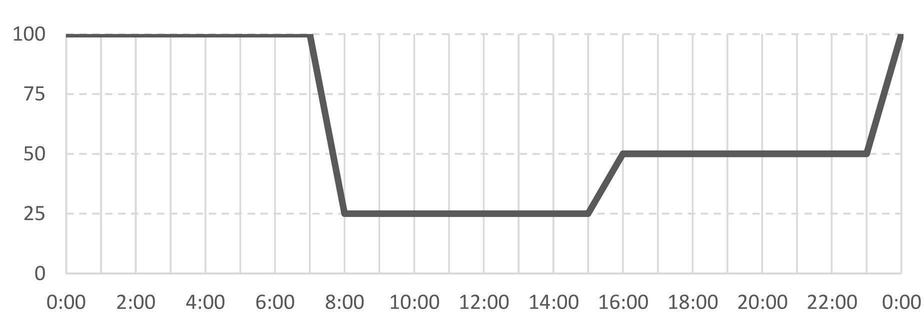

Fig. 11. Occupancy profile on weekdays.

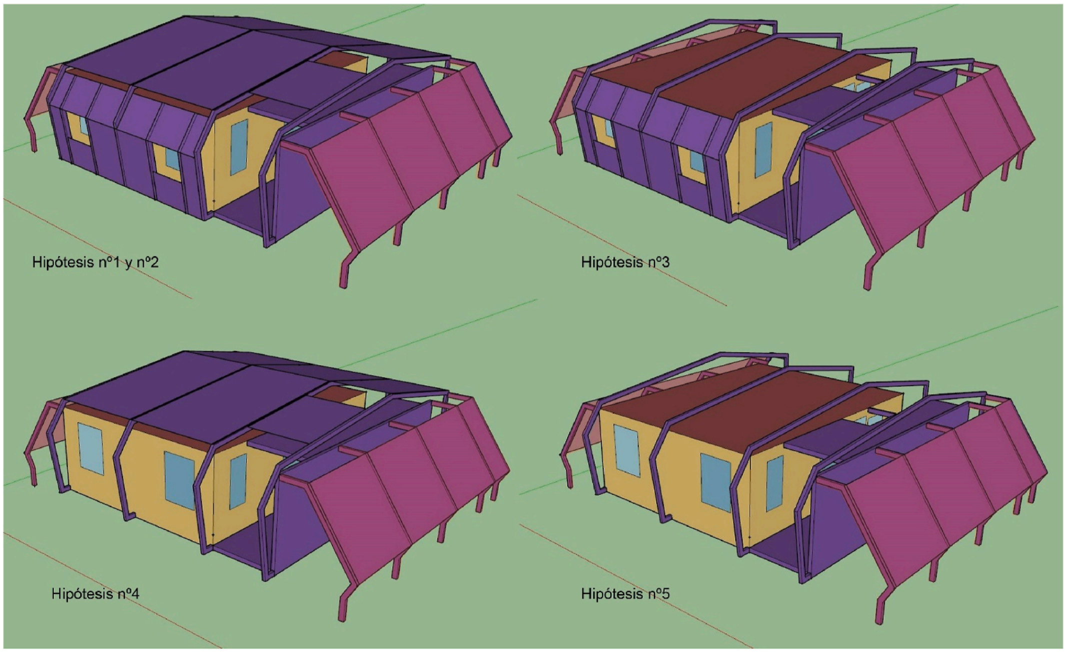

Fig. 12. Exterior geometry of the 5 hypotheses in this study.

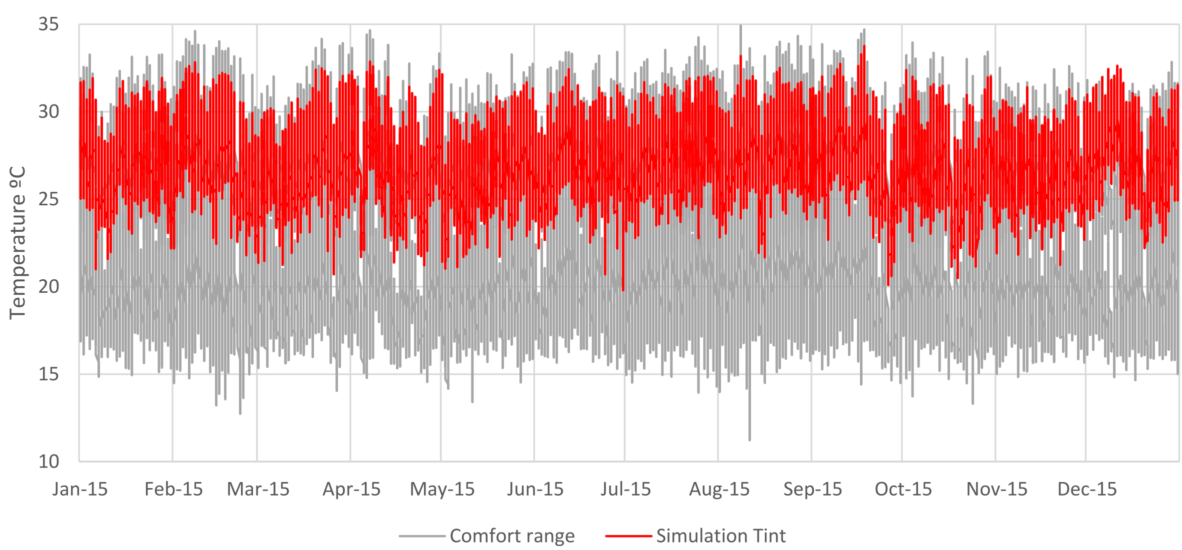

Fig. 13. Hypothesis nº1, thermal behaviour over a full year.

Table 2
Monthly hygrothermal behaviour of hypothesis nº1.

	nº hours within the thermal comfort range	% Hours within the thermal comfort range	nº hours RH < 65	% Hours RH < 65
January	307	41.26	457	61.42
February	266	39.58	448	66.67
March	357	47.98	312	41.94
April	331	45.97	331	45.97
May	353	47.45	323	43.41
June	300	41.67	402	55.83
July	289	38.84	544	73.12
August	325	43.68	519	**69.76**
September	314	43.61	447	62.08
October	358	48.12	436	58.60
November	350	**48.61**	281	39.03
December	276	37.10	370	49.73
Total	**3826**	**43.68**	**4870**	**55.59**

dwelling and a much lower occupancy load than in hypothesis nº1 (20 m^2/persona). The result, graphically (Fig. 14), is as follows:

According to the data shown in Table 3, for hypothesis nº2, where a more closed dwelling use is calculated, the thermal behaviour of the dwelling guarantees a percentage of thermal comfort hours of around 55%, where the dwelling behaves better in the summer months. Regarding relative interior humidity of the dwelling, there is also a percentage of almost 55% of hours per year in which the dwelling has a humidity of less than 65%.

In this hypothesis, the months close to the summer solstice have better thermal performance, and in the months close to the winter solstice (when the south façade receives direct solar radiation) the prototype has a worse thermal performance.

3.3. *Hypothesis nº3*

In this case, a simulation is carried out with the same operational

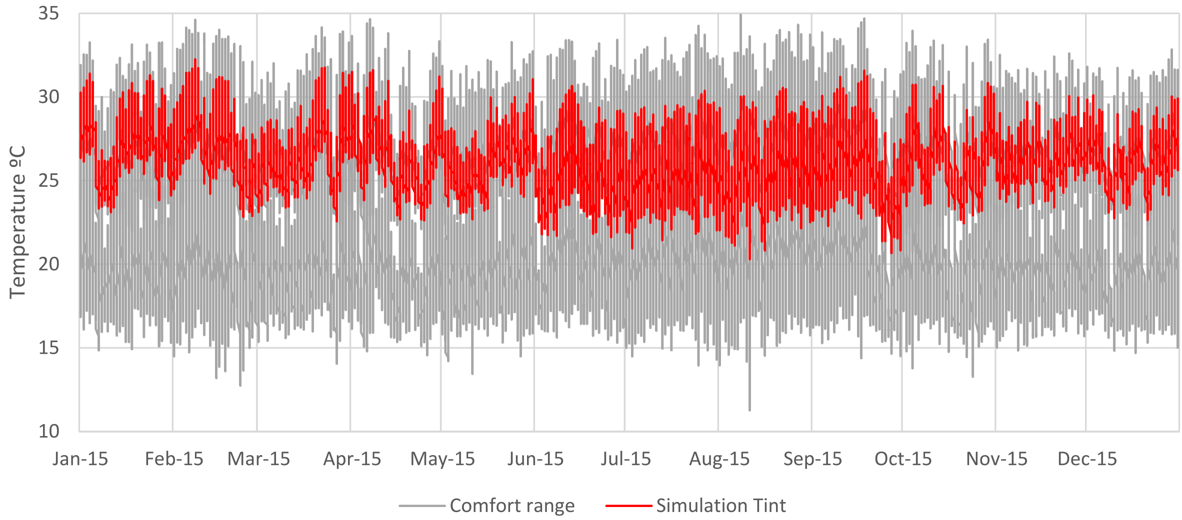

Fig. 14. Hypothesis nº2, thermal behaviour over a full year.

Table 3
Monthly hygrothermal behaviour of hypothesis nº2.

	nº hours within the thermal comfort range	% Hours within the thermal comfort range	nº hours RH < 65	% Hours RH < 65
January	298	40.05	491	65.99
February	272	40.48	494	73.51
March	330	44.35	299	40.19
April	341	47.36	346	48.06
May	362	48.66	324	43.55
June	532	**73.89**	315	43.75
July	532	71.51	428	57.53
August	537	72.18	417	56.05
September	505	70.14	375	52.08
October	342	45.97	444	59.68
November	322	44.72	351	48.75
December	333	44.76	413	55.51
Total	**4706**	**53.72**	**4697**	**53.62**

conditions as in hypothesis nº2 but eliminating the double skin on the roof and maintaining it solely on the south facade. The result, graphically (Fig. 15), is as follows:

Table 4
Monthly hygrothermal behaviour of hypothesis nº3.

	nº hours within the thermal comfort range	% Hours within the thermal comfort range	nº hours RH < 65	% Hours RH < 65
January	203	27.28	607	81.59
February	206	30.65	559	**83.18**
March	241	32.39	423	56.85
April	236	32.78	481	66.81
May	245	32.93	507	68.15
June	387	53.75	417	57.92
July	379	50.94	528	70.97
August	438	**58.87**	487	65.46
September	397	55.14	447	62.08
October	254	34.14	525	70.56
November	241	33.47	505	70.14
December	230	30.91	526	70.70
Total	**3457**	**39.46**	**6012**	**68.63**

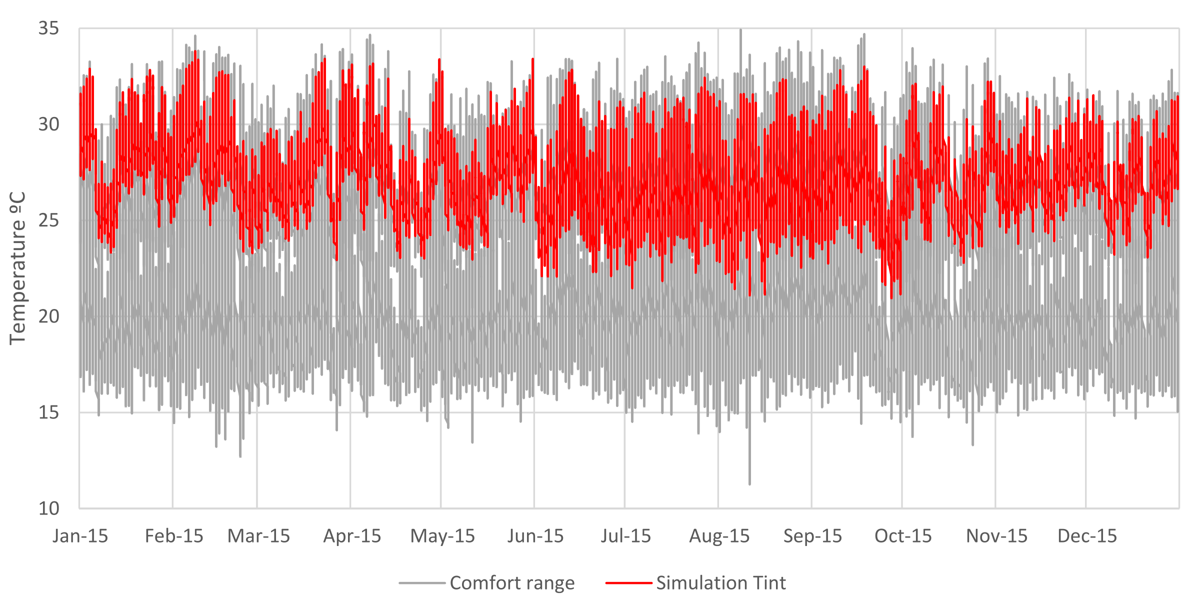

Fig. 15. Hypothesis nº3, thermal behaviour over a full year.

In Table 4, it can be seen that in this hypothesis the summer months have better thermal results, although in the overall calculation of the percentage of annual hours in which the dwelling is in thermal comfort is 40%.

With regards to relative humidity, this hypothesis presents a percentage greater than 60% of the total hours per year in which relative humidity in the interior of the prototype is lower than 65%.

If the results are analysed according to the solar chart, as in hypothesis 2, the months with the best thermal performance are those close to the summer solstice, whose difference with the winter solstice is almost 23% points. However, the fact of having eliminated the double skin on the roof, penalizes the annual percentage of hours in thermal comfort.

3.4. Hypothesis nº4

In Hypothesis nº4, the same operational conditions as the previous hypothesis are employed, but the double skin is eliminated on the south facade and left solely on the roof. The result, graphically (Fig. 16), is as follows:

This hypothesis achieves interior thermal comfort conditions in almost 45% of the total number of hours in the year. It functions better in the summer months than in the winter ones. In terms of relative humidity, in over 65% of the total number of hours in the year, the interior of the dwelling is below 65% relative humidity, as can be seen in Table 5.

The best thermal performance results are also obtained for the summer solstice; however, it can be seen that by eliminating the double skin on the south façade, the percentage of thermal comfort hours in the months close to the winter solstice (direct radiation on the south façade) has been significantly reduced. In this sense, the difference in percentage of thermal comfort hours between the summer solstice month (June) and the winter solstice month (December) is more than 47% points.

3.5. Hypothesis nº5

In this last hypothesis, a simulation with the same operational conditions as hypotheses nº2, nº3 and nº4 is carried out, but eliminating the double skin both on the roof and south facade. The result, graphically (Fig. 17) is as follows:

In hypothesis nº5, as seen in Table 6, the percentage of hours of annual thermal comfort is relatively low, not reaching 30%. However,

Table 5
Monthly hygrothermal behaviour in hypothesis nº4.

	nº hours within the thermal comfort range	% Hours within the thermal comfort range	nº hours RH < 65	% Hours RH < 65
January	157	21.10	625	**84.01**
February	202	30.06	547	81.40
March	285	38.31	360	48.39
April	307	42.64	392	54.44
May	324	43.55	380	51.08
June	503	**69.86**	340	47.22
July	509	68.41	448	60.22
August	514	69.09	432	58.06
September	473	65.69	405	56.25
October	272	36.56	499	67.07
November	214	29.72	509	70.69
December	165	22.18	558	75.00
Total	**3925**	**44.81**	**5495**	**62.73**

relative humidity stays below 65% in 75% of the yearly hours.

This is the most unfavorable hypothesis, although if we take into account, once again, the solar path, the months where the south façade receives direct radiation again have worse performance (December–January), compared to the months close to the winter solstice.

It should be emphasized that in this scenario there is no solar protection either to the north or to the south, since the double skin of the prototype has been completely eliminated, so the percentage of hours of annual thermal comfort is much lower than in the other hypothesis.

3.6. Comparison of results of the developed hypotheses

Analysing the results obtained in each hypothesis, we can see that hypothesis nº2 has the highest percentage of annual hours within the thermal comfort range. This hypothesis corresponds to the typical operational conditions of the dwelling use, with a bioclimatic double skin on all areas of the thermal envelope exposed to solar radiation.

Nevertheless, if this percentage of hours is analysed by month (Fig. 18), partial data can be obtained which helps to improve understanding of AURA 1.0's thermal behaviour, especially where the double skin is concerned. In this section, the percentage of comfort hours per month, in each of the respective hypotheses studied, are set out graphically as a form of comparison.

On the basis of these results, it has been found that oscillations in temperatures occur between day and night times and not between

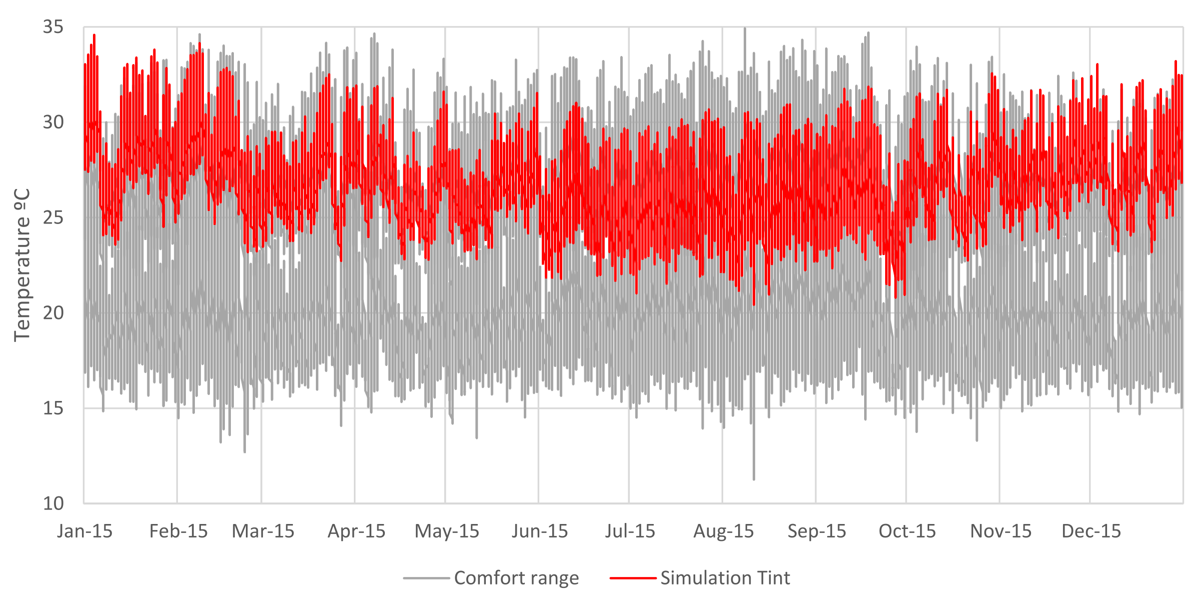

Fig. 16. Hypothesis nº4, thermal behaviour over a full year.

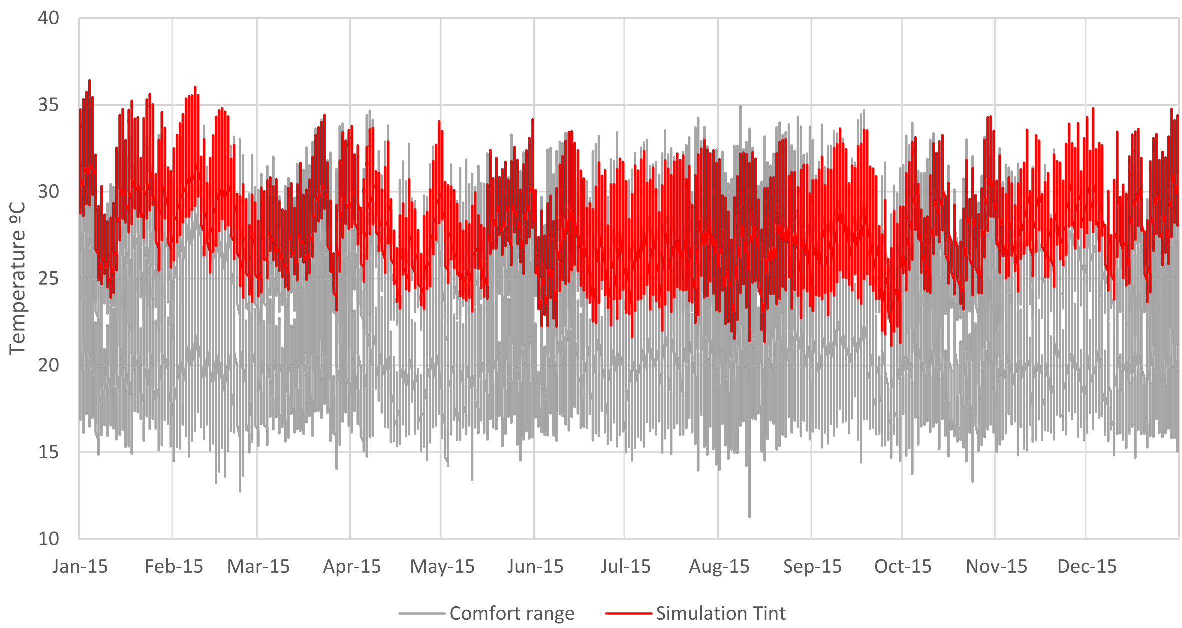

Fig. 17. Hypothesis nº5, thermal behaviour over a full year.

Table 6
Monthly hygrothermal behaviour in hypothesis nº5.

	nº hours within the thermal comfort range	% Hours within the thermal comfort range	nº hours RH < 65	% Hours RH < 65
January	68	9.14	668	89.78
February	122	18.15	605	**90.03**
March	182	24.46	497	66.80
April	197	27.36	514	71.39
May	192	25.81	551	74.06
June	325	45.14	443	61.53
July	323	43.41	550	73.92
August	384	**51.61**	513	68.95
September	340	47.22	477	66.25
October	182	24.46	579	77.82
November	113	15.69	615	85.42
December	80	10.75	632	84.95
Total	**2508**	**28.63**	**6644**	**75.84**

seasons. This is standard in a tropical climate. Nevertheless, thermal behaviour differs significantly when we compare the hypotheses with each other.

In the months of December, January and February, highly deficient results can be appreciated in hypothesis nº5 in which a double skin is not employed. As hypothesis nº3 obtained a better result than hypothesis nº4, the double skin is found to have more relevance when used on the south facade. However, in view of the results from hypothesis nº2, the full double skin (both on the facade and the roof) plays an important role from a thermal perspective.

In regard to the months of March, April and May, it can be seen that the dwelling in hypotheses nº1 and nº2 has a similar thermal behaviour. In any case, once the double skin is removed, the results worsen. Nevertheless, when the double skin is maintained on the roof (Hypothesis nº4), the results are better than Hypothesis nº3. This indicates that in these months, it is more important to place a double skin on the roof than on the façade. This is one of the periods of the year when solar radiation is most vertical.

In the months of June, July and August, the results of hypothesis nº2 stand out above the rest. As the results of hypothesis nº2 and nº4 are similar, it can be seen that the double skin on the roof plays an important role from a thermal perspective. In other words, the double skin is of more relevance on the roof than on the facade in the months from March to August. It is important to point out that at this time of the year the north façade receives solar radiation and by eliminating the double skin on the roof, the overhang that protects the north gallery of the prototype from the sun is eliminated.

Finally, with regard to the months of September, October and November, the results of the previous quarters are confirmed. In September the results between hypothesis nº2 and nº4 are similar, demonstrating the relevance of the double skin on the roof. In the months of October and November, the double skin on the facade has the same level of importance as on the roof.

It should be pointed out that in the months between March and September, the double skin on the roof is necessary from a thermal perspective but less relevant on the south facade. However, the rest of the year, the dwelling's thermal behaviour is not as great when the double skin is eliminated either on the roof or the facade.

This difference arises because of the sun's path in Cali, the months of November to February the solar radiation has a greater incidence on the south façade.

With regards to relative humidity, hypothesis nº5 produces better results with almost 76% of yearly hours below 65% relative humidity. The percentage of annual hours in which hypotheses nº1 and nº2 are below 65% relative humidity is 55% and 53% respectively. However, there is a difference if we study the monthly data, as occurs with thermal comfort.

3.7. Relevance of orientation in the design of the AURA1.0 prototype

As explained at the beginning of this document, in the "Introduction" section, this prototype was designed to compete and be monitored in the month of December in Santiago de Cali. This city is located close to the equator, therefore, the inclination of solar radiation is very high, having months of the year where there is radiation on the South façade and, others, on the North façade.

As the solar chart of Santiago de Cali indicates, in the month of December, the façade that suffers the most solar radiation is the south façade, and for this reason a double skin oriented to this orientation was designed. In addition, as the results shown above indicate, the double skin façade (DSF) South helps to improve the interior thermal comfort in December.

However, this research tries to analyze the behavior of the prototype

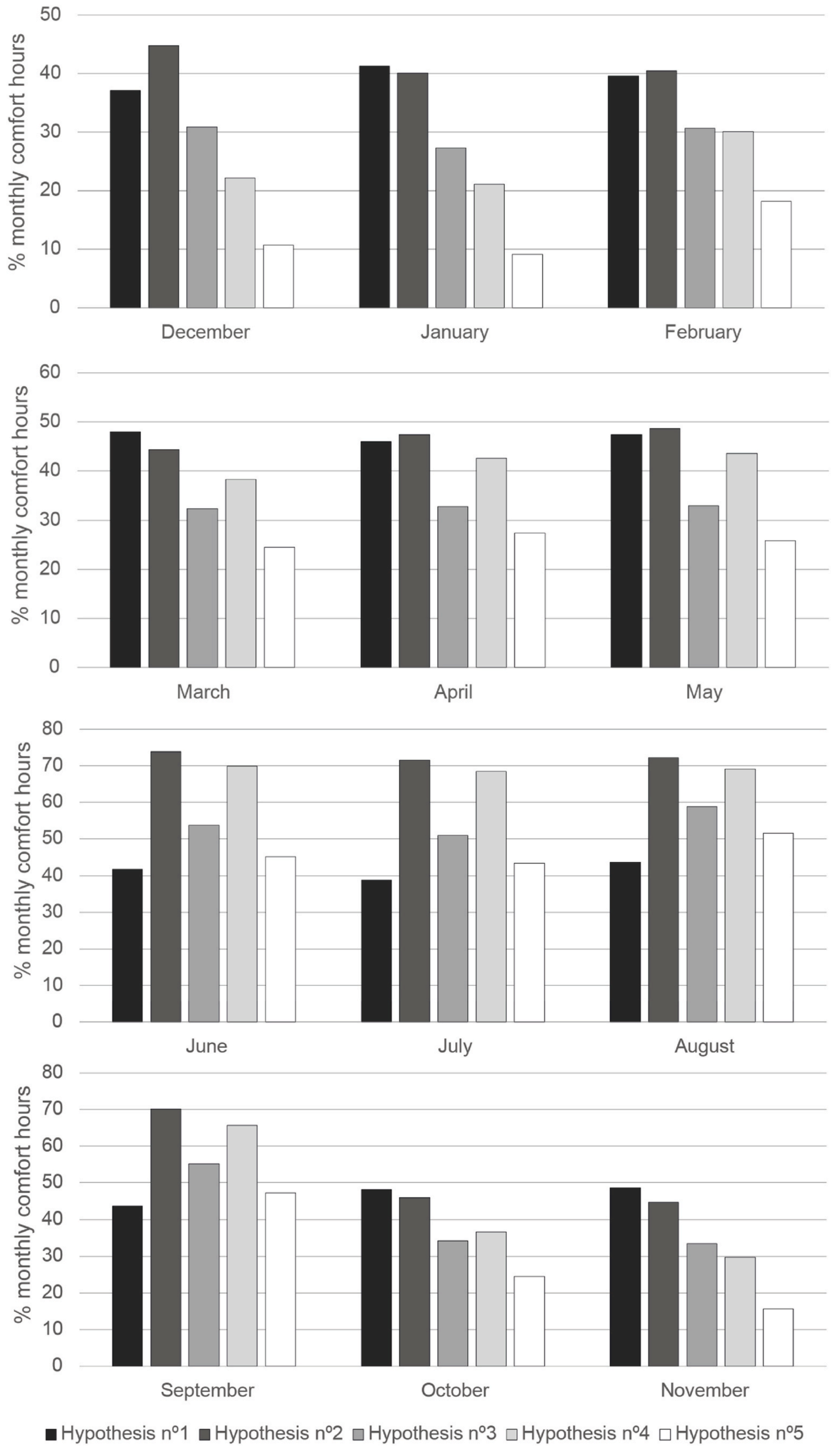

Fig. 18. Comparison monthly of thermal result in the 5 hypotheses.

throughout the year, therefore, it is convenient to check which is the most optimal orientation for the designed prototype. For this purpose, the hypothesis nº2 has been used, simulated previously and obtaining the best results, and the simulation has been carried out for the four orientations, rotating the prototype 90° (East), 180° (north) and 270° (West) (Table 7).

Table 7 shows the percentage of monthly hours in the comfort range in which the prototype would be throughout the year. It can be seen how, thermally, the prototype does not suffer great variations depending on its orientation.

However, it is in the original orientation (double skin to South) where the best results are obtained, especially in the months close to the summer and winter solstices.

4. Conclusions

The aim of this publication is to extend the hygrothermal performance data of the AURA 1.0 prototype to a full year, by developing a validated simulation model, which uses the data extracted from the monitoring carried out by the Solar Decathlon competition organization.

In Fig. 10 of this document, it can be seen that in Santiago de Cali there are no significant oscillations of temperature or outdoor humidity between the different months of the year. In other words, the outdoor hygrothermal conditions are very stable. This is to be expected in a tropical climate with an almost equatorial latitude.

However, it has been found that the indoor environmental behavior of the house varies when we compare the results between the different scenarios according to the different months of the year. This data indicates that there is a clear relationship between the results obtained and the solar path in the different stages of the year.

Therefore, this research is justified because, although the climate is very stable, the incidence of solar radiation does vary throughout the year. This means that the results obtained in December, during the competition, cannot be extrapolated to a full year and, therefore, a long-term analysis of the environmental performance of the AURA 1.0 prototype is necessary.

Based on these long-term analyses, it has been found that the double skin designed and built as a passive conditioning strategy is crucial to maintain adequate thermal conditions throughout the year. The use of the complete double skin, on the south façade and on the roof (Hypothesis nº2) guarantees 25% more hours of thermal comfort per year in the house than when this double skin is not used (Hypothesis nº5).

However, although the double skin plays a crucial role in the thermal comfort of the house, it has been checked that, depending on the time of the year, it is more relevant if it is placed on the roof or on the south façade:

Table 7
Thermal behaviour in hypothesis nº2, in differents orientations.

	% Hours within the thermal comfort range			
	South (Original orientation)	East	North	West
January	**40.05**	39.11	38.84	31.18
February	40.48	**40.77**	39.43	36.61
March	44.35	**46.51**	40.99	45.83
April	47.36	48.75	40.28	**49.31**
May	**48.66**	45.70	45.30	48.52
June	**73.89**	69.58	72.92	**73.89**
July	**71.51**	67.20	69.76	70.97
August	72.18	72.98	71.77	**74.19**
September	70.14	**73.06**	67.36	**73.06**
October	45.97	**46.77**	42.74	44.76
November	44.72	**44.86**	44.58	38.19
December	**44.76**	43.95	43.95	32.39
Total	**53.72**	53.31	51.54	51.62

- Summer solstice: In the month of June, the percentage of hours of thermal comfort is 20% points higher when a complete double skin is used (Hypothesis nº2), compared to when only this double skin is used on the South façade (hypothesis nº3).

On the other hand, if the double skin is removed from the South façade and is kept only on the roof (hypothesis nº4), the prototype has 14% less thermal comfort hours than if the complete double skin is used (hypothesis nº2). Therefore, it has been found that, in the months close to the summer solstice, the double skin has more relevance placed on the roof.

- Winter solstice: in the month of December, it was found that, on the one hand, Hypothesis No. 3 is worse than Hypothesis No. 2 by 16% points, on the other hand, Hypothesis No. 4 is worse than Hypothesis No. 2 by 22.5% points. Therefore, in the month of December, it is more penalized to eliminate the double skin on the South façade.
- Equinoxes: for the month of March, the percentage of thermal comfort hours in Hypotheses 2, 3 and 4 are 44%, 32% and 38%, respectively. For the month of October, the percentages are: 46%, 34% and 37%, respectively. With these results, it is confirmed that if the double skin on deck is eliminated (Hypothesis 3), the results suffer a greater penalty.

This means that, in the months close to the winter solstice, it is more relevant to place the double skin on the south façade; however, during the rest of the year, it provides more thermal comfort if it is kept on the roof. However, it is advisable to maintain the complete double skin all year round.

To sum up, it was found that for latitudes close to the equator and with a tropical climate, the use of a double skin as a passive air-conditioning strategy is suitable for optimizing thermal comfort inside the houses.

Similarly, it was found that the orientation of the AURA 1.0 prototype in the Solar Decathlon competition was the most suitable (double skin on the south façade), both in the long term (a full year) and for the month of December (the month of the competition).

However, with the objective of foreseeing a future urban fabric designed with high-rise buildings with different orientations and formed by this type of housing, it can be confirmed that this prototype presents an adequate and similar thermal behavior in all orientations (above 50% of annual hours in the thermal comfort range), with a maximum difference between them of 2% points. The south orientation is the most favorable and the north orientation the most unfavorable.

Taking into account the numerical data provided, but making a more socioeconomically contextualized analysis, it can be confirmed that these passive conditioning strategies are relevant in social housing typologies, where the occupant does not have the resources to employ on actions for hygrothermal comfort that require energy consumption.

Furthermore, hygrothermal comfort goes beyond the wellbeing of the dwelling's inhabitants. Optimal hygrothermal conditions guarantee levels of health and hygiene and are therefore to the benefit of the user's health and the prevention of illnesses related to excess levels of damp or an insufficient interior temperature.

In terms of the impact of the integration of a double skin in the passive design of residential architecture, the results of this paper are, without doubt, interesting for new buildings. From the perspective of sustainable architecture, they are even more relevant as they give rise to new solutions for urban regeneration in obsolete slum neighbourhoods.

CRediT authorship contribution statement

Álvaro López-Escamilla: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Conceptualization. **Rafael Herrera-Limones:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Conceptualization. **Ángel Luis León-Rodríguez:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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