Low-cost architectural strategies to reduce heat stress in social housing for hot desert climates

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Abstract. Achieving thermal comfort inside buildings in a region with a hot desert climate is challenging, especially in social housing, which is generally not designed or built suitably for these climates. Two well-known architectural strategies for reducing heat stress in these houses are thermal insulation and solar protection by shading. However, under free-running conditions, doubts arise about the effectiveness of these strategies. The social housing of the city of Hermosillo is exclusively single-family housing. The city has a hot desert climate with an average annual temperature of 25ºC and a mean oscillation of 15ºC. During the hot season, there are recurring peaks above 48ºC. This study aims to evaluate three low-cost architectural strategies to reduce heat stress in a single-family social house under free-running conditions; adding thermal insulation to walls and windows, adding sun protection to windows, and solar protection to the roof. The results show that both the use of thermal insulation and solar protections achieve improvements in the indoor thermal conditions of the house. However, when considering the warmer months, the solar protection strategies perform better in reducing indoor heat stress in terms of discomfort hours.

Keywords: Thermal Behavior, Social Housing, Hot Desert Climate Architecture.

1 Introduction

Climate change is taking us to an increase in ambient temperatures and the frequency, duration, and intensity of extreme heat events worldwide [1]. This effect is particularly severe in the desert climate regions. At present, more than 40% of the Earth's surface is considered dryland and concentrates about one-third of the world population; further, approximately 70% of the drylands are located in developing countries. Within the drylands, the arid and hyper-arid regions (deserts) are home to almost 6% of the world's population [2]. The extreme conditions of desert climates pose a series of challenges from an energetic and social development perspective.

Achieving thermal comfort inside buildings is complicated in regions with extreme climates, such as hot deserts. There are several studies on different strategies to improve the indoor environment in this climate. Some of the strategies are the increment of the reflectance of surfaces [3,4] and solar protection on both windows and roofs [5,6]. Other passive design strategies such as evaporative cooling, natural night ventilation, solar chimneys, wind towers, and thermal mass [7] have also been studied. Regarding the use of thermal insulation, these studies usually consider the presence of refrigeration, while the parameters analyzed are usually its placement and thickness [8-10].

This task is even more challenging when it comes to social housing, usually poorly built and equipped, since the owners of these single-family houses are low-income citizens. These houses have characteristics that make them unsuitable for the climate, generally lacking thermal insulation and solar protection. This problem persists despite the existence of different official standards on the energy efficiency of buildings, such as NORM-020-ENER-2011 [11] that establishes the U-values and solar protection factors for different regions of Mexico and is not put into practice by the social housing private developers.

Since a large part of this population cannot afford the installation and the use of air conditioning systems, it is necessary to provide economical and robust solutions to improve the thermal conditions of the house in free-running conditions.

2 Objective

This study aims to compare the effectiveness of three common low-cost architectural strategies to improve indoor thermal conditions: thermal insulation and two different approaches to solar protection. In a hot desert climate, solar radiation is the main source of heat gains in buildings, making it a key parameter to consider in achieving indoor thermal comfort [12]. The study is carried in a dispersed and low-density city with a hot desert climate, characterized by almost exclusively single-family houses with a high air conditioning demand during the hot season [13].

3 Case study

3.1 Site description

This study takes place in Hermosillo (lat. 29N), a city located in the Sonoran desert in northwestern Mexico (see Fig. 1). This city has a hot desert climate (BWh in the Köppen climate classification), with an average annual temperature of 25ºC, a mean oscillation of 15ºC, and precipitation of 387 mm (Table 1) [14,15].

Although Hermosillo's climate may seem mild on average, it presents extreme climate conditions for more than half the year. During the hot season, which lasts between May and October, the average maximum temperatures range between 34ºC and 40ºC, and peaks above 48ºC are recurrent. As a desert city, it has high levels of solar radiation. Hermosillo has an annual mean solar radiation of 5,85 kWh/m^2 per day. Though, during the hot season, the mean solar radiation is 6,7 kWh/m^2 per day.

Fig. 1. Location of Hermosillo in relation to Mexico (left), and the urban area of the city (right). Author’s elaboration on Google Earth.

Table 1. Monthly data of average maximum temperature (AMT), mean temperature (MT), average minimum temperature (AmT), relative humidity % (RH), and global horizontal radiation (kWh/m²).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AMT ºC	24.2	25.8	28.7	32.3	36.3	39.8	39.3	38.3	37.5	33.9	28.6	24.0
MT ºC	17.2	18.5	20.9	24.1	27.9	31.8	32.5	31.9	31.0	26.9	21.3	17.1
AmT ºC	10.2	11.3	13.1	15.9	19.4	23.8	25.8	25.6	24.6	19.8	14.0	10.2
HR (%)	48	44	40	34	31	34	48	53	48	42	43	49
kWh/m²	3.88	4.76	6.34	7.45	7.73	7.59	7.07	6.88	5.74	5.23	4.11	3.25

For the last century in this region of North America, there has been an increase in the average temperature. In Hermosillo, this increase is more noticeable during the hot season. In the last fifty years, there has been an increase of around 2ºC in the average temperature this season (see Fig. 2).

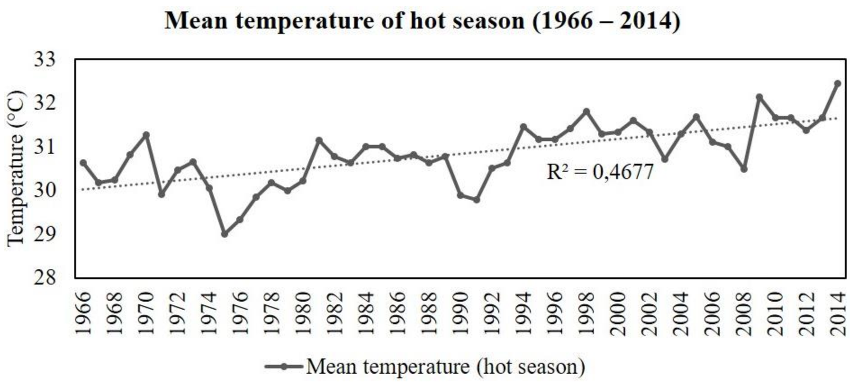

Fig. 2. Chart that shows the mean temperature change, from 1966 to 2014. There is an increase of almost 2ºC. Authors’ elaboration with data from the Municipality of Hermosillo [16].

3.2 The single-family social house

Hermosillo has a high percentage of social housing built in the last three decades, made up exclusively of single-family homes. A worker can acquire a house through a loan granted by the government (INFONAVIT, FOVISSSTE) and pay for it through monthly installments taken from the worker's salary. These houses are classified into three basic categories: social-interest, medium-interest, and residential housing. The one with the greatest presence and the largest number of inhabitants is the social-interest housing [17]. These houses are the smallest (25 - 90 m^2) and the construction is cost-effective since they are produced in mass, causing that the quality of the house and an efficient energy design are not a priority, resulting in excessive use of energy with high air conditioning costs [18]. This represents a serious problem for the 41% of the population that lives with less than 3 minimum wages monthly (less than 300 euros), and the 23% receives a monthly income between 300 – 500 euros [19].

The house analyzed in this work is located in a plot 8 x 14 m (112 m^2). It has a living area of 51 m^2 and an interior height of 2,5 m. Like most houses, it has light colors on its façade and white roof, an outdoor parking space, and a backyard. The lack of vegetation to shade the living areas, the façade and the parking area is a constant in this type of housing (see Fig. 3).

Fig. 3. Photograph of a social housing neighborhood, our model is based in these houses. Photograph taken from Google Earth.

4 Methodology

This study assesses the thermal behavior of a single-family social house during the hot season (May 1st – October 31st) in four different cases:

1. Base case (walls of concrete block of 0,15 m thickness, the roof has a 0,12 m of thickness, and consists of precast concrete joists and EPS vaults that act as thermal insulation, and simple 4 mm clear glass for the windows);

2. Case "A": Adding thermal insulation on walls and windows (roof + walls + windows);
3. Case "B": Adding solar protection on windows;
4. Case "C": Adding solar protection over the roof.

The analysis consists of dynamic thermal simulations using DesignBuilder (with EnergyPlus as the calculation engine) [20]. The parameter used to analyze the results is the indoor air temperature. The weather data used from the EPW file is from the Hermosillo International Airport. We evaluated the performance of each intervention based on the number of hours of discomfort and the accumulated degree-hours. These mean the number of hours with an indoor temperature exceeding a temperature value considered "neutral" for people acclimated to this climate (32ºC) [21] and the degrees accumulated for each hour above 32ºC. We quantified these values throughout the hot season and during the two warmest months (July and August).

The geometry, materials, orientation, and the architectonic distribution of the model used for the simulations, respond to the predominant building typology (see Fig. 4). The thermal transmittance, U (W/m^2K), of the different elements of the house envelope is as follows: for the Base Case, the walls have a U-value of 2,75 W/m^2K; the roof has a U-value of 1,35 W/m^2K; the ground floor U-value is 2,80 W/m^2K, and the U-value of the windows is 5,80 W/m^2K. For Case A, these U-values are modified in the walls (0,91 W/m^2K) by adding a 0,025 m XPS plate (extruded polystyrene); and on windows (3,08 W/m^2K) by changing the 4mm single clear glass to a 6mm double clear glass + 6mm air gap. We decided not to insulate the ground floor since its effect is counterproductive in non-conditioned buildings in a hot desert climate [22].

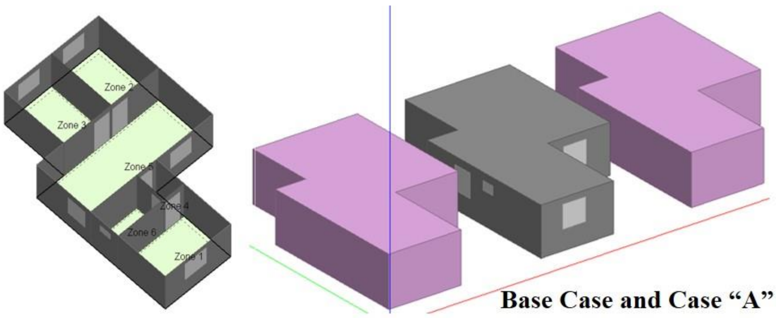

Fig. 4. Simulation model. It has a north-south orientation, with no adjacency between houses.

In Case "B", we used a system of gray color metal louvers, overhangs, and side fins to provide solar protection on the windows. In Case "C", for the solar protection of the roof, we added a double roof (a white light metal hat), large enough to protect the concrete roof and south façade windows (see Fig. 5). This system also allows for ventilation between the roofs.

The level of solar protection on windows provided by these two strategies is different. In Case B, with the louvers system, the house receives 209 kWh of direct solar gains throughout the hot season, while in Case C, the windows have a solar gain of

1185 kWh during the same period. Thus, considering that the Base Case receives 1793 kWh, these strategies represent a reduction of 88% and 34% respectively.

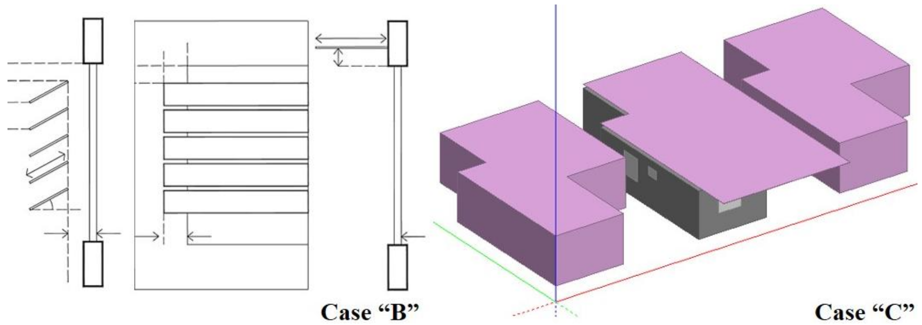

Fig. 5. Windows solar protection system for Case "B" (used in all windows), and simulation model with a double roof used for Case "C" (shading the roof and south-facing windows).

We utilized the work that Irene Marincic [23] carried out in Hermosillo during August and September (daily from 8:00 to 19:00) to validate the simulations in this study. They measured and collected hourly data on indoor air temperature, relative humidity, wind speed, and mean radiant temperature from 143 houses and calculated the operating temperature (see Fig. 6). In all cases, the measured values are in a range between 25ºC and 40ºC. We used the air temperature (T_a) and the operative temperature (T_{op}) data to validate our simulations. To do this, we utilized two models of social housing with different living areas (51 m^2 and 41 m^2), and we simulated their thermal behavior during August and September. To calculate the operative temperature, we used the simplified formula $T_{op} = (T_a + MRT)/2$, where MRT is the mean radiant temperature.

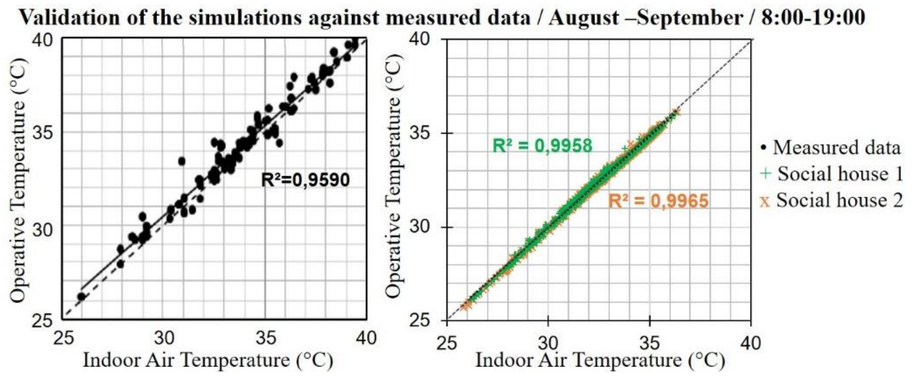

Fig. 6. Simulation results of two houses (R^2=0,9958, R^2=0,9965) contrasted against the data measured in 143 houses (R^2=0,959) during August and September.

The graph on the right shows the mean indoor air temperature and operative temperature data for the two houses. Both houses have similar behavior to the measured data (chart on the left). In these cases, the values obtained through simulations are also in the same temperature range (25ºC – 40ºC).

5 Results and discussion

To ease the discussion the four cases analyzed will be referred to as the base case, case "A" (insulation in roof, walls and windows), case "B" (solar protection on windows), and case "C" (solar protection over the roof). All the cases present the same occupation (4 users, as the only internal gain) and a ventilation rate of 4 ac/h, with an infiltration rate of 0,7 ac/h. It was necessary to analyze the indoor thermal behavior of the four cases during the entire hot season. Figure 7 shows that the three thermal improvement strategies have similar performance, with a seasonal mean indoor air temperature of 30,2ºC. The base case averages an indoor air temperature of 30,5ºC.

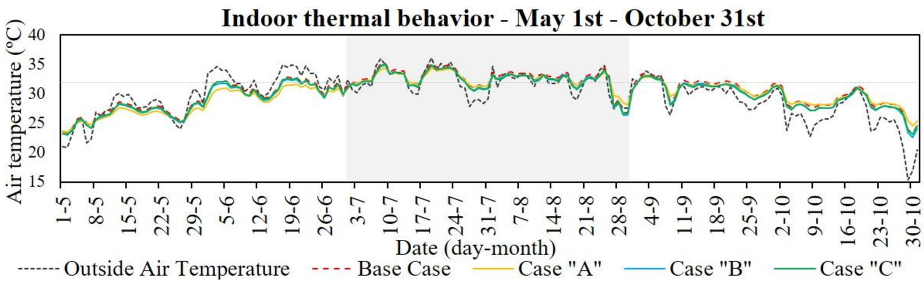

Fig. 7. Chart with the outside air temperature, the 32ºC for indoor "neutral" temperature, and the indoor temperature behavior for all cases.

These similarities are more evident during July and August. Figure 8 shows that in the three interventions, the house is out of comfort (hours above 32ºC) for around 30% (1.288-1.325 hours), while the base case is for 37% (1.570 hours) of the season. Nevertheless, when analyzing the accumulated degree-hours, the differences among the strategies can be observed. Case "A" represents a reduction of 40% to the base case, the case "B" a 25%, and the case "C" reduces a 30%.

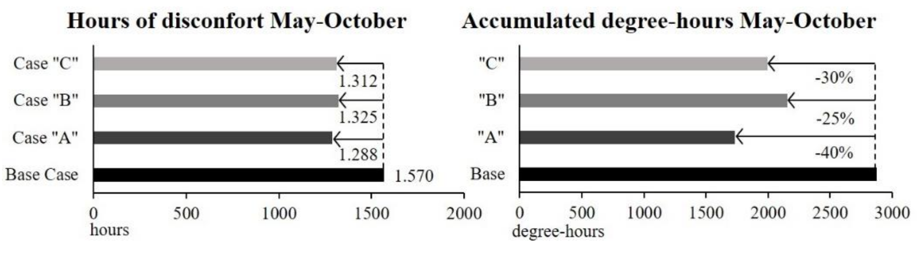

Fig. 8. These charts show the results of the two comfort indicators for the entire hot season.

However, when considering only the warmest months (July and August), different results are produced between the three thermal improvement strategies (Figure 9). The two interventions that increase solar protection, whether on the windows (case “B) or roof (case “C”), manage to decrease discomfort, passing from the 63% (941 hours) of the time out of comfort in the Base Case to a 56% (844-851 hours) in the refurbished scenario. In contrast, the intervention with higher thermal insulation maintains the initial 63% (938 hours) over the neutral temperature of 32°C.

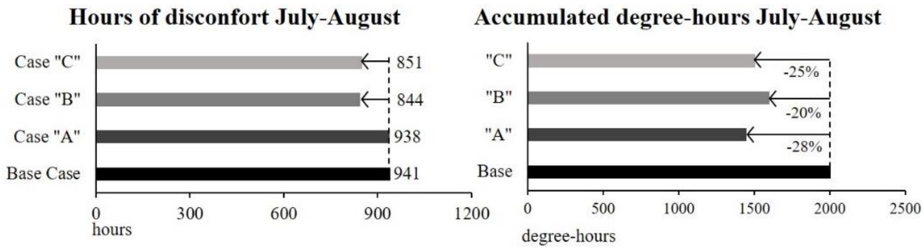

Fig. 9. These charts show the results of the two comfort indicators for July and August.

Nonetheless, when comparing the accumulated degree - hours, the results are different. Case “A” (+ thermal insulation) reduces this indicator by around 28% regarding the base case. Cases “B” and “C” represent a reduction of 20% and 25% each in order.

Based on the results obtained, some doubts about the use of thermal insulation arise. On the one hand, the use of thermal insulation (case "A") reduces the oscillation of the indoor air temperature (see Fig. 10), thus is beneficial when considering the number of accumulated degree-hours (above 32ºC). However, on the other hand, thermal insulation does not allow an easy heat dissipation in the house, thus maintaining an indoor air temperature above 32ºC for more hours. This behavior is more noticeable during the warmest months, though is present in the last 4 months of the hot season (see Fig.7).

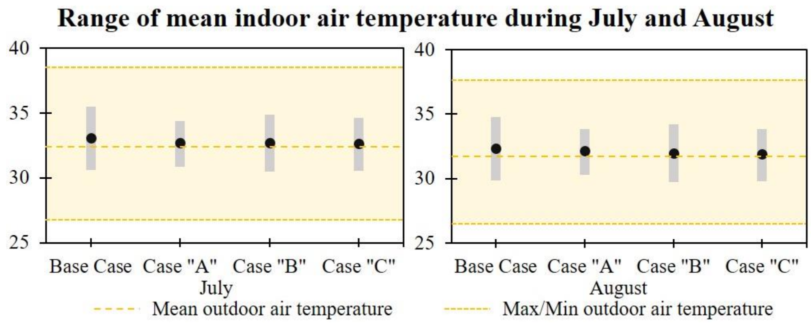

Fig. 10. These two charts show the range of mean air temperature during the hottest months.

In the case of architectural strategies based on solar protection, it can be said that case "C" with a double roof, has a slightly better performance than case "B" (solar protection on the windows). During the hot season, both have a similar number of hours above 32ºC (“B” 1.325 and “C” 1.312), and a difference of around 5% in the number of accumulated degree-hours in favor of case “C”. In July and August, case “B” has

844 hours and case “C” 851, but the latter maintains the difference of 5% in the number of degrees accumulated.

6 Conclusions

This paper studied the effectiveness of three low-cost architectural strategies to reduce heat stress in social housing under free-running conditions in a hot desert climate.

The methods used to evaluate the strategies' performance (hours of discomfort and accumulated degree-hours) are useful to understand the difference in the thermal behavior of each case. The results obtained indicate that before making a decision, it is necessary to analyze the socio-economic situation and the user's profile of each household.

On the one hand, thermal insulation may not be the best option for a home that can't afford air conditioning. Although the temperature peaks are not as high as in the other strategies, the thermal insulation itself favors maintaining a high indoor temperature. On the other hand, solar protection strategies allow an oscillation of the indoor temperature, reaching higher temperatures, but at the same time, arriving to lower temperatures than a house with thermal insulation. However, if the house is refrigerated, the strategy based on thermal insulation will be the most effective. It will maintain a suitable indoor temperature and lower energy consumption.

The findings of this paper help to prioritize architectural interventions aimed at improving thermal conditions in social housing. Analysis under free-running conditions is essential to decrease the risk of energy poverty in vulnerable populations.

Acknowledgements

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References

1. Garcia-Nevado, E., Duport N., Bugeat, A. and Beckers, B.: Benefits of street sun sails to limit building cooling needs in a Mediterranean city. Building and Environment 187, 107403 (2020).
2. Safriel, U., et al. Chapter 22: drylands systems. In: Ecosystems and Human Well-being: Current state and Trends, Vol. 1. Island Press, Washington, DC (2005).
3. De Boeck, L., et al.: Improving the energy performance of residential buildings: A literature review. Renewable and Sustainable Energy Reviews, 52, 960–975 (2015)
4. Alpuche Cruz, M. G., et al.: Influence of Absorptance in the Building Envelope of Affordable Housing in Warm Dry Climates Energy Procedia, 57, 1842–1850 (2014)

5. Sherif, A., El-Zafarany, A., & Arafa, R.: External perforated window Solar Screens: The effect of screen depth and perforation ratio on energy performance in extreme desert environments. Energy and Buildings, 52, 1–10 (2012)
6. Galindo Duarte, M., et al.: Sistema De Protección Del Aislamiento E Impermeabilización De Techos Evaluación De Viviendas Del Desierto. Energética, (40), 5–12 (2008)
7. Osman, M, Sevinc, H.: Adaptation of climate-responsive building design strategies and resilience to climate change in the hot/arid region of Khartoum, Sudan. Sustainable Cities and Society 47 (2019)
8. Idris, Y., Mae, M.: Anti-insulation mitigation by altering the envelope layers' configuration. Energy and Buildings 141, pp. 186-204 (2017)
9. Calderón, R., et al.: Electrical consumption and CO2 reduction using saving systems and thermal insulation applied to dwellings in arid lands of Mexico. Información Tecnológica, 22(2) (2011)
10. Friess, W. A., et al.: Wall insulation measures for residential villas in Dubai: A case study in energy efficiency. Energy and Buildings, 44(1) (2012)
11. Normas Oficiales Mexicanas en Eficiencia Energética -Edificaciones-, https://www.gob.mx/conuee/acciones-y-programas/normas-oficiales-mexicanas-en-eficiencia-energetica-edificaciones/, last accessed 2021/06/08
12. Coch, H.: Bioclimatism in vernacular architecture. Renewable and Sustainable Energy Reviews 2 (1-2), 67-87 (1998).
13. Wegener, M., Lopez-Ordoñez, C., Isalgue, A., Malmquist, A. and Martin, A.: How much does it cost to go off-grid with renewables? A case study of a polygeneration system for a neighborhood in Hermosillo, Mexico. In: Littlewood, J., Howlett, R., Capozzoli, A., Jain, L. (eds.) Sustainability in Energy and Buildings. Smart Innovation, Systems and Technologies, Vol 163. Springer, Singapore (2020).
14. Servicio Meteorológico Nacional (SMN).: Normales Climatológicas, Hermosillo II (DGE), https://smn.conagua.gob.mx/es/informacion-climatologica-por-estado?estado=son, last accessed 2021/03/30
15. LEMA, Estación Meteorológica, https://lema-arq.unison.mx/, last accessed 2020/11/20
16. IMPLAN Hermosillo, http://www.implanhermosillo.gob.mx, last accessed 2021/03/30
17. Lopez-Ordoñez, C.: Planificación urbana en ciudades dispersas de clima desértico: La densificación vertical como estrategia para la mejora ambiental. El caso de Hermosillo (México). Universitat Politècnica de Catalunya, Barcelona (2020).
18. Marincic, I., Ochoa, J.M. and Alpuche, G.: Passive house for a desert climate. In: Brebbia, C.A., Pulselli, R. (eds.) Eco-Architecture V. Harmonization Between Architecture and Nature 2014, pp. 13-24. WIT press, Southampton (2014).
19. INEGI, https://www.inegi.org.mx/, last accessed 2021/03/30
20. DesignBuilder Software Ltd, https://www.designbuilder.co.uk/, last accessed 2021/03/30
21. Marincic, I., Ochoa J.M. and Del Rio, J.A.: Confort térmico adaptativo dependiente de la temperature y la humedad. ACE Architecture, City and Environment 07 (20), 27-46 (2012).
22. Lopez-Ordoñez, C., Crespo Cabillo, I., Roset Calzada, J. and Coch Roura, H.: The role of thermal insulation in the architecture of hot desert climates. In: Littlewood, J., Howlett, R., Capozzoli, A., Jain, L. (eds.) Sustainability in Energy and Buildings. Smart Innovation, Systems and Technologies, Vol 163. Springer, Singapore (2020).
23. Gomez-Azpeitia, L., Bojorquez-Morales, G., Ruiz, R.P., Marincic, I., Gonzalez, E. and Tejeda, A.: Extreme adaptation to extreme environments in hot dry, hot sub-humid and hot humid climates in Mexico. Journal of Civil Engineering and Architecture 8 (8), 929-942 (2014).