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Passive cooling design strategies as adaptation measures for lowering the indoor overheating risk in tropical climates

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ABSTRACT

Year-round high temperatures and humidity in the Tropics, coupled with poor design decisions and climate change, can cause indoor environments to overheat, affecting health and increasing energy demand and carbon emissions. Passive cooling could help lower the indoor overheating risk. Given the gap in the relative influence of passive cooling design strategies on lowering the indoor overheating risk in tropical locations, this study investigated their impact in two warm tropical cities (i.e., Tegucigalpa and San Pedro Sula), considering both current and future climate scenarios, with a total of 3840 thermal simulations performed. Indoor overheating risk in apartment-type dwellings was assessed using two metrics (i.e., hours of exceedance and the indoor overheating degree), and considering fixed and adaptive thermal comfort limits. Simulation results show that the overheating risk can be significantly lowered in these tropical contexts using solely passive cooling strategies as heat adaptation measures. Multivariate regression models demonstrate that *natural ventilation*, *wall absorptance*, the *solar heat gain coefficient*, and *semi-outdoor spaces* have the greatest impact in lowering the risk in vertical social housing projects. This study emphasizes the importance of passive cooling and overheating protection design strategies in tropical building codes and building design while considering current and future risk.

1. Introduction

1.1. Background

According to the Intergovernmental Panel on Climate Change (IPCC) global warming will likely reach 1.5 °C between 2030 and 2052, putting vulnerable communities at a disproportionately increased risk to climate-related adverse consequences [1]. Climate change will have a substantial impact on tropical nations, which have a large percentage of the world's poorest and most vulnerable inhabitants [2]. The tropical region is home to 43% of world's population, and is expected to increase to more than half of the world's population by 2050 [3–5]. The Tropics has warmed by 0.7–0.8 °C over the last century, however, climate models predict for this region a further 1–2 °C warming by 2050 [6]. In the Tropics, high-heat stress days and nights are very pronounced in urban areas [7], which may cause buildings to overheat; however, indoor overheating is reduced when proper building design strategies for these climatic regions are adopted, according to case studies in tropical contexts (e.g., Honduras, Thailand, Uganda, Myanmar) [8–12]. At least 1 billion people worldwide are facing cooling access risk, and more than 2.2 billion are likely to purchase inefficient cooling devices, resulting in a dramatic increase in energy and associated carbon emissions [13,14]. Climate change and income growth will cause an increase in global cooling energy demand in the world's warmest regions by 2100 [15], therefore, building sector adaptation measures are urgently needed considering the challenges posed by future growth on the global cooling energy demand and of the increase of climatic vulnerability [16].

In Latin America and the Caribbean despite the fact that floor area growth and demand for energy services have increased considerably since 2010, and that active cooling is in high demand due to high temperatures and humidity, progress on building codes with thermal comfort and energy efficiency requirements has been poor [17,18]. For instance, only 6 out of 33 countries had mandatory or voluntary building energy codes in place as of 2018 [19]. In Honduras, there is currently no mandatory national or city-level code requiring residential buildings to meet thermal comfort targets. However, the development of a *Sustainable Construction*

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Nomenclature

α	Constant between 0 and 1 that controls the speed at which the running mean ($T_{pm(out)}$) responds to outdoor temperature
AC	Air conditioning
ACH	Air changes per hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CIBSE	Chartered Institution of Building Services Engineers
DB_{AVG}	Average outdoor dry bulb temperature
GVIF	Generalised variance inflation factor
He	Hours of exceedance
He_F	Hours of exceedance, calculated with a fixed thermal comfort limit
He_A	Hours of exceedance, calculated with an adaptive thermal comfort limit
IEA	International Energy Agency
IOD	Indoor overheating degree
IOD_F	Indoor overheating degree, calculated with a fixed thermal comfort limit
IOD_A	Indoor overheating degree, calculated with an adaptive thermal comfort limit
IPCC	Intergovernmental Panel on Climate Change
KG	Köppen-Geiger climate classification
MN7	Meteonorm version 7.3
N_{occ}	Total number of occupied hours
NV_{ACH}	Natural ventilation, air change rates
SHGC	Solar heat gain coefficient of windows
SOS	Semi-outdoor space
SOS_{PB}	Perimeter buffer type of semi-outdoor space
SOS_{PB_NONE}	No semi-outdoor space
SOS_{PB_S}	Perimeter buffer type of semi-outdoor space. Only at south
SOS_{PB_N}	Perimeter buffer type of semi-outdoor space. Only at north
$SOS_{PB\_S\&N}$	Perimeter buffer type of semi-outdoor space. At both south and north
SPS	San Pedro Sula
TGU	Tegucigalpa
$T_{e(d-1)}$	Mean daily temperature of the previous day
$T_{e(d-2)}$	Mean daily temperature of the day before the previous day
$TL_{comf,i,z}$	Thermal comfort temperature limit in each zone (z) and each time step (i)
T_{max}	Upper 80% acceptability limit according to ASHRAE 55
T_{max_a}	Actual maximum operative temperature on each simulated case
$T_{op,i,z}$	Free running indoor operative temperature in each zone (z) and each time step (i)
$T_{pm(out)}$	Prevailing mean outdoor temperature
VIF	Variance inflation factor
W_A	Wall solar absorptance
W_U	Wall thermal transmittance
WWR	Window-to-wall ratio
Z	Total building zones

Guide for Tegucigalpa, Central District Municipality in 2019 was a great step forward [20], though no explicit mention of the indoor thermal comfort targets that Tegucigalpa dwellings must meet is made. Nonetheless, a green building code could be a significant step forward for Honduras in order to follow the roadmap outlined in the Honduras Decarbonisation Plan 2020–2050, which aims to decarbonize building operations by 2050 [21]. Therefore, research is required to provide support.

According to the last national census in Honduras's two largest cities, the total number of households with air conditioning (AC) in Tegucigalpa has increased from 3.9% to 9.3% between 2001 and 2013; in San Pedro Sula from 11.6% to 26.9 % in the same time period [22]. Even though Tegucigalpa has a mild tropical climate and is not as hot as other tropical cities are, dwellings may suffer from indoor overheating and may lead its occupants to install AC units. A recent study conducted in the city of Tegucigalpa found that the percentage of overheating hours (calculated with ASHRAE 55 upper 80% acceptability limit) in apartment-type dwellings can go up to 9.9 – 12.0% during occupied hours, and that in dwellings with higher risk of overheating occupants have already installed an air conditioning (AC) device [8]. Passive cooling design strategies (e.g., natural ventilation, high albedo, external shading, low solar heat gain coefficient) might help dwellings in ensuring thermally comfortable indoor conditions in the present and in the future, as well as reducing the need of AC cooling devices. AC is not an affordable solution for all households in a low-income country like Honduras, the second poorest country in Latin America and the Caribbean after Haiti [23].

1.2. Research gap and objectives

Passive cooling design – explicitly as a way to reduce indoor overheating risk – is seldom discussed in climates such as the warm tropical ones exposed all year long to high temperatures and humidity levels.

Existing studies draw different conclusions about which parameters are the most important to strengthen in warm tropical contexts, as they individually study only a subset of the key design parameters. A study conducted in Bangkok, Thailand, found that roof insulation and balcony openings for natural ventilation are the most influential building design parameters on reducing indoor overheating risk, while window shading and wall material are the least effective [10]; however, no mentioned is given on the effect of glazing properties and envelope solar absorptance. According to studies conducted in the low-income tropical context of Kampala, Uganda, (i) solar shading is not effective enough to meet thermal comfort criteria, (ii) insulation of floors and internal walls should be avoided, and (iii) priority should always be given to roof and ceiling insulation, followed by external wall insulation, and by white painting roofs with low-absorptance [24–26]; however, natural ventilation was not studied. Another study examined the overheating risk provided by various building forms in Katunayake, Sri Lanka; however, the findings focus on the effect of window-to-wall ratio (WWR) on indoor thermal comfort [27]. According to a study conducted for the warm tropical climate of Kuala Lumpur, Malaysia, shading is the most important strategy for reducing overheating in this context [28].

The literature on passive cooling design to reduce the risk of indoor overheating focuses on other climates (e.g., warm temperate climates) rather than the warm-humid tropical climate. A study on passive design optimization found that for cooling dominant climates, among them warm-humid tropical ones (i.e., Indore, Caracas, Douala and Singapore), passive cooling strategies (i.e., blinds during daytime, natural ventilation of 1–1.5 air change rates) are necessary to avoid indoor overheating risk [29]; however, no specific conclusion is given for warm tropical climates of the benefits of parameters such as WWR, solar absorptance, or solar heat gain coefficients (SHGC). Another study examined whether insulation as a passive strategy increases or decreases the risk of indoor overheating in eight different climates, none of which are warm-humid tropical, and concludes that insulation does not significantly increase the risk of indoor overheating, especially when a proper purge ventilation strategy is used (i.e., window opening at the right time) [30].

Only a few studies explicitly discuss the effects of passive design on the indoor overheating reduction in current and future scenarios of warm tropical or subtropical climates. Studies conducted in Myanmar show that high nocturnal ventilation rates have higher potential of decreasing overheating hours than lower roof U-values; however, current ventilation practices are not able to provide the required thermal comfort both for typical weather year and when considering future climate change scenarios [12,31,32]. A study conducted using Hong Kong as reference – a warm subtropical climate – studied a typical mixed-mode residential building (both AC and natural ventilation are used) and found that: (i) the importance of airtightness is expected to increase in future climate change scenarios for mechanically cooled dwellings, (ii) natural ventilation will continue to be an efficient way to cool buildings but its cooling potential will decrease in time, and (iii) solar protection is the most significant strategy for avoiding overheating [33].

There is still a gap in the relative influence of key passive cooling strategies as adaptation measures in lowering the risk of indoor overheating in warm tropical locations, as well as the extent to which they reduce the need for AC today and in the future. Using a Central American tropical context as case study, the following research objectives are proposed: (1) assess the risk of indoor overheating based on simulations, taking into account multiple passive combinations, different tropical locations, and different climate change scenarios; and (2) determine the most influential passive cooling strategies on the risk of indoor overheating in the selected tropical locations and climate scenarios using inferential statistics. Given the economic burden that the installation and use of AC can impose on many Honduran households, as well as the lack of a regulation requiring minimum indoor thermal comfort conditions, this study seeks to demonstrate the limits of passive design in lowering the indoor overheating risk in Honduras's two largest cities with typical warm tropical climates, both today and in the future.

2. Methodology

2.1. Locations and climate scenarios

Two Central American tropical locations were selected (see Table 1), each corresponding to the two main cities of Honduras: Tegucigalpa (*TGU*) and San Pedro Sula (*SPS*). As shown in Table 2, cities in Honduras experience two major meteorological seasons: rainy season (hottest months) and dry season (coolest months), with *SPS* experiencing higher dry bulb temperature, rainfall, relative humidity, and global horizontal solar radiation levels than *TGU*. The city of *TGU* has a tropical highland climate (similar to Brasilia, Bangalore, Caracas or San José); and *SPS* has a tropical lowland climate (similar to Miami, Dhaka, Dar-es-Salaam, Mombasa or Havana) [8]. For each city two climate scenarios were studied based on weather datasets generated with Meteonorm version 7.3 (MN7) [34]: current (20-year period for solar radiation: 1986–2005; 10-year period for temperature: 2000–2009) and future (IPCC 2050 A2 scenario). For the future scenario, the IPCC 2050 A2 scenario was selected so to consider a medium-term worst-case scenario.

2.2. Thermal simulations

A residential linear block building typology with a building floor plan that promotes cross ventilation and connects two dwellings per floor via staircases was used as reference for the building thermal simulations. This residential building typology (see Fig. 1) was selected based on the first vertical social housing project in Honduras recently built in the city of *SPS* and considering that it could continue to be used for future vertical social housing projects in Honduras. Typical vertical multifamily housing projects in cities of Honduras are mostly between four and twelve-storey high [38].

The building used as reference was modelled as a five-story residential building (four dwellings per floor) with its main facades facing north and south was modelled considering it as the best case scenario for avoiding high indoor overheating and having maximum good illuminance levels [39]. In these tropical climates, the south facade receives direct solar radiation for the majority of the year, while the north receives it for 3–3.5 months (e.g., in SPS: approximately from May 3 – August 11). As illustrated in Fig. 2, and similar to simulation-based study on the effectiveness of passive cooling design strategies in high-rise buildings [40], a mid-floor dwelling was studied considering that in vertical housing projects that is the most representative dwelling when compared top-floor dwellings. The west sided mid-floor dwelling was selected considering that it is the most affected by solar radiation, especially during afternoon hours. The dwelling was considered as one thermal zone without indoor partitions. All adjacent apartments were considered adiabatic. Using EnergyPlus simulation engine within DesignBuilder [41] 3840 simulations were performed using dynamic thermal simulations at hourly timesteps, considering different passive cooling design strategies and dwelling characteristics, as explained in **Section 2.2.1** and **Section 2.2.2**, and summarised in Table 3.

2.2.1. Passive cooling design measures

Based on literature review, different passive cooling design strategies were considered in order to determine their relative impact on the indoor overheating risk of dwellings located in the tropical contexts of *TGU* and *SPS*: natural ventilation (air changes per hour, NV_{ACH}), wall absorptance (W_A), the shading effect of the semi-outdoor space (*SOS*) as perimeter buffers (e.g., balconies), the solar heat gain coefficient of windows (*SHGC*), the wall U-value (W_U) and the window-to-wall ratio (*WWR*).

Table 1
Climatic data of Tegucigalpa and San Pedro Sula, Honduras.

Location	Lat.	Long.	KG [1]	ASHRAE [1]	Scenarios	DB_{AVG} [2]
Tegucigalpa (*TGU*)	14.05	−87.93	Aw	2A	Current	22.0 °C
					Future, 2050 A2	23.5 °C
San Pedro Sula (*SPS*)	15.45	−87.22	Af	0A	Current	26.7 °C
					Future, 2050 A2	27.9 °C

[1] Köppen-Geiger climate classification [35] & ASHRAE 169–2020 climate classification[36]
[2] Annual average dry bulb temperatures, obtained from .stat file of MN7 weather file

Table 2
Weather data from Tegucigalpa and San Pedrol Sula taken from .MN7 file, except precipitation.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tegucigalpa (*TGU*)												
Daily Average dry bulb temperature (°C)	19.8	20.9	22.5	23.6	23.8	22.5	22.7	23.0	22.3	21.9	20.2	20.3
Maximum dry bulb temperature (°C)	29.0	31.6	33.8	34.6	32.4	30.7	32.1	32.3	30.5	30.3	29.7	29.3
Minimum dry bulb temperature (°C)	10.2	10.9	12.4	14.4	15.6	15.8	15.6	15.6	15.1	15.0	12.0	11.9
Relative humidity (%)	73	67	61	61	69	79	74	74	79	81	80	76
Total precipitation (mm) *	5	5	10	43	144	159	82	88	177	109	40	10
Global horizontal solar radiation (Wh/m^2)	4124	4759	5240	5115	4839	5024	5176	5155	4759	4327	3915	3750
San Pedro Sula (*SPS*)												
Daily Average dry bulb temperature (°C)	23.6	24.9	26.5	27.5	28.7	28.2	28.1	28.3	28.0	27.0	24.7	24.4
Maximum dry bulb temperature (°C)	31.9	33.6	37.5	39.0	37.7	36.7	36.2	35.4	36.5	34.9	33.0	32.9
Minimum dry bulb temperature (°C)	16.5	16.8	17.2	19.7	21.9	22.3	21.7	22.5	21.8	20.4	17.7	17.6
Relative humidity (%)	86	81	75	76	75	80	80	80	82	84	87	86
Total precipitation (mm) *	72	60	32	32	63	142	110	106	152	148	135	122
Global horizontal solar radiation (Wh/m^2)	3984	4938	5257	5657	5279	5495	5472	5709	5206	4534	3720	3504

* Precipitation data for TGU and SPS retrieved from ASHRAE Climatic Design Conditions Database[37]

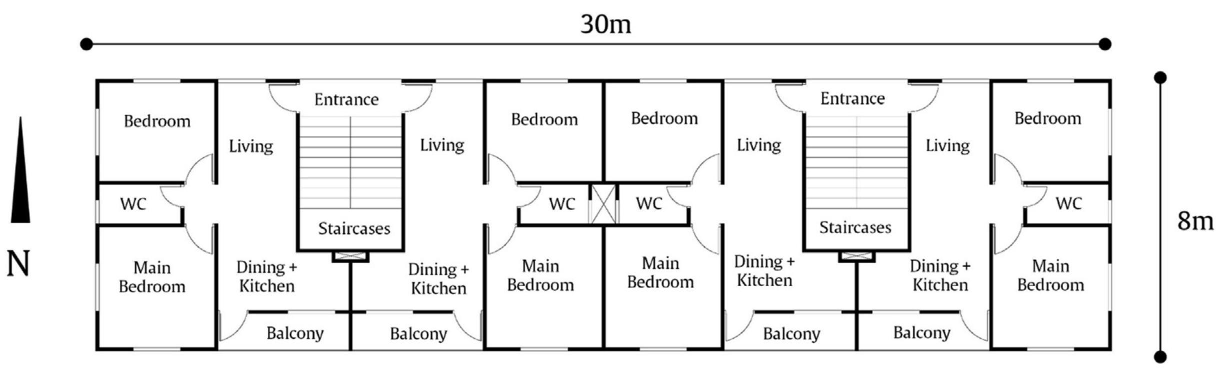

Fig. 1. Floor plan of the first vertical social housing project in Honduras, located in the city of San Pedro Sula.

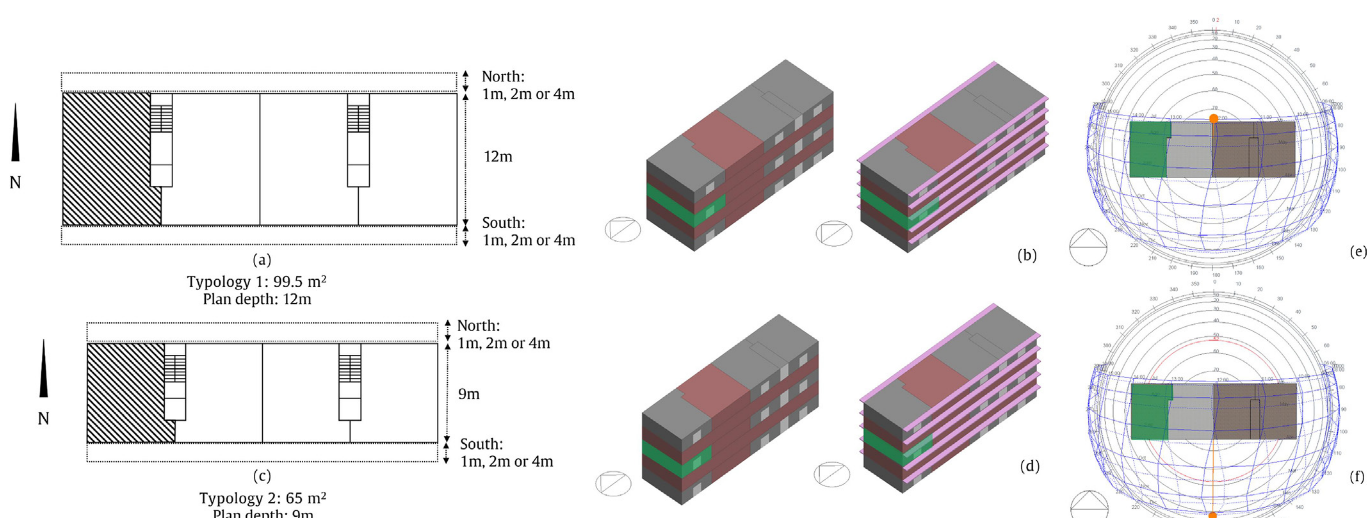

Fig. 2. (a) Floor plan of Typology 1 (99.5 m^2); (b) 3D model showing location of Typology 1 dwelling without/with SOS_{PB}; (c) floor plan of Typology 2 (65 m^2); (d) 3D model showing location of Typology 2 dwelling without/with SOS_{PB}; (e) solar angle at noon during summer solstice (June 20): 81.9°; (f) solar angle at noon during winter solstice (December 21): 51.0°.

2.2.1.1. Natural ventilation. Two options of natural ventilation (NV_{ACH}) were considered based on the values established in the Brazilian code and its computational simulation method for assessing the indoor thermal performance: (i) 1 air change per hour (1 ACH), and (ii) 5 air changes per hour (5 ACH) [42]. This simulation method of using air changes per hour allows to control the influence that this passive cooling design strategy exerts on the indoor thermal performance.

A previous study found that purge ventilation lowers the indoor overheating risk when indoor spaces are occupied (especially at night) and when natural ventilation is 'sensibly used', avoiding warm air to enter indoor spaces [30]. Based on the latter, in this study natural ventilation (whether 1 ACH or 5 ACH) is turned on

Table 3
Parameters in this study (total combinations: 3840).

Parameter	Options
Climatic location	Tegucigalpa (TGU) San Pedro Sula (SPS)
Climate scenario	Current Future (2050 A2)
Floor area (F_{AREA})	65 m^2 99.5 m^2
Average infiltration rate	1 ACH
Natural ventilation (NV_{ACH}) *	1ACH 5ACH
Wall absorptance (W_A)	30% 50% 70%
Semi-outdoor space – perimeter buffer (SOS_{PB})	SOS_{PB_NONE}: No shading SOS_{PB_N}: North shading (1 m, 2 m or 4 m) SOS_{PB_S}: South shading (1 m, 2 m or 4 m) $SOS_{PB\_S\&N}$: North & South shading (1 m, 2 m or 4 m)
Solar heat gain coefficient (*SHGC*)	0.86 (single glazed: 3–4 mm, 5.9 W/m^2K) 0.39 (double-glazed with air gap and exterior reflective coating: 6/12/6mm, 2.6 W/m^2K)
Wall U-values (W_U)	2.5 W/m^2K 1.5 W/m^2K
Window-to-wall ratio (*WWR*)	20% 40%

* 0.5 ACH when criteria are not met (see Section 2.2.1.1)

only when the following requirements are met: (i) if indoor spaces are occupied (see Appendix **Section**, **Table A. 1**); (ii) if indoor operative temperature is above 19 °C (based on Brazilian building code [43]); (iii) and if outdoor temperature is below indoor operative temperature. When one of these criteria is not met natural ventilation is 0.5 air changes per hour (0.5 ACH) so to ensure good indoor air quality and constant air renovation. This minimum value approximates the minimum outdoor air flow per person (in ACH) outlined by ASHRAE 62.1 [44].

2.2.1.2. Wall absorptance. Considering that a low wall absorptance (W_A) value is said to be the most effective and economic strategy to reduce indoor temperature in hot-humid climate [45], it was selected as an important parameter for assessing the indoor overheating risk in *TGU* and *SPS*. The Brazilian building code outlines three alternatives when assessing the W_A by a simulation method: (i) light colour (a = 30%), (ii) medium colour (a = 50%), and (iii) dark colour (a = 70%) [42]. These three options were considered as parameters for this simulation study.

2.2.1.3. Semi-outdoor spaces for solar protection. Literature agglomerates several design strategies for protecting indoor spaces from solar radiation: semi-outdoor spaces (e.g., balconies [10,46–49], veranda [50–52]), exterior shading devices (i.e., overhangs, exterior louvers, solar screens [11,53,54]), and vegetation (i.e., trees, green facades or living walls [55–57]). This study focuses on the influence that the semi-outdoor space (*SOS*) has as a shading element on lowering the indoor overheating risk, since they not only provides thermal comfort and energy use outcomes but also extend the living space, favour social relations [58], and promotes social interaction in vertical social housing [59–61]. For instance, a previous study demonstrated that the *SOS* works as a thermal buffer reducing indoor thermal discomfort as well as cutting down energy use and promoting social interaction [59,60].

From all types of *SOS* found in literature (e.g., perimeter buffers, sky terraces, breezeway atria [61]) this study focuses on assessing the influence that perimeter buffers (SOS_{PB}), such as balconies, have on reducing the indoor overheating risk. When compared to the other types, the SOS_{PB} was selected for this study since it could be the most cost-effective, replicable type of *SOS* for Honduras. Regardless of whether SOS_{PB} are in the north, south or both, three depths were considered for each orientation: 1 m, 2 m and 4 m.

A total of 10 combinations resulted, however, were condensed down to four for the analysis: (i) no semi-outdoor space (SOS_{PB_NONE}) as the worst-case scenario since it means that simulated model has no external solar protection, (ii) 1 m, 2 m or 4 m semi-outdoor spaces only at north (SOS_{PB_N}) considering it as a small improvement to not having solar protection, (iii) 1 m, 2 m or 4 m semi-outdoor spaces only at south (SOS_{PB_S}) considering it as a large improvement since south facades receive high levels of solar radiation throughout the year; (iv) and 1 m, 2 m or 4 m semi-outdoor spaces at both south and north ($SOS_{PB\_S\&N}$) as the best-case scenario since it cuts down solar radiation on both facades.

2.2.1.4. Window-to-wall ratio and solar heat gain coefficient of windows. Two options of *WWR* were considered. Based on a previous study [8], a WWR of 20% was assumed to be the typical value for apartment-type dwellings in Honduras. Based on ASHRAE 90.1 [62], a WWR of 40% was defined as the maximum allowable value, with the understanding that future vertical social housing projects in Honduras may seek to provide higher architectural quality indoor spaces (e.g., larger windows).

Two options of solar heat gain coefficients (*SHGC*) were evaluated for windows: (i) a value of 0.86 considered as the typical one in Honduras (and worst-case scenario), which corresponds to 3 mm – 4 mm single glazed windows (5.9 W/m^2K); and (ii) an improved value of 0.39 which would meet the set by the *Sustainable Construction Guide* developed for Tegucigalpa [20] or the *Philippine Green Building Code* [63] for a *WWR* of 40%, and corresponds, for instance, to a double-glazed windows with air gap (6/12/6mm, 2.6 W/m^2K) with an exterior reflective coating. This study does not intend to define the limits of *WWR* and *SHGC* values in the two tropical climatic contexts under analysis, but rather to demonstrate the degree of overheating risk considering different combinations of *WWR* and *SHGC* values with other parameters.

2.2.1.5. Wall thermal transmittance. Two options of wall thermal transmittance (W_U) were considered in this study: (i) a value of 2.5 W/m^2K which corresponds to the common type of wall in Honduran dwellings, typically built with 20 cm hollowed concrete blocks, plastered with mortar (2.5 cm) in both sides; and (ii) a value of 1.5 W/m^2K, which corresponds to the same wall construction system, however, insulated in the external face with 1 cm of expanded polystyrene plus mortar plaster.

Lower W_U values were not considered attending to literature and existing building codes on naturally ventilated dwellings in warm-humid tropical contexts. In Brazil, W_U values up to 3.7 W/m^2K (if $W_A \leq 0.6$) and 2.5 W/m^2K (if W_A greater than 0.6) are allowed for those bioclimatic zones similar to that in *TGU* and *SPS* [64,65]. In Guadeloupe, Martinique, and Guyana (French overseas territories) W_U values must be less than 2 W/m^2K [66] and in Jamaica's climatic zone 1 less than 3 W/m^2K [67]. In Singapore, a study found that depending on the *WWR* and orientation W_U values ranging from 1 to 3 W/m^2K are acceptable for naturally ventilated dwellings Singapore [68].

2.2.2. Dwelling characteristics

Except for the dwelling floor area (F_A), the following dwelling characteristics remained constant throughout all simulations: average infiltration rates and occupation and lighting schedules. Two options of F_A were considered. A F_A of 65 m^2 (Typology 1) was considered the typical value (with a building floor depth 9 m), based on the vertical social housing project built recently in the city of *SPS*. A F_A of 99.5 m^2 (Typology 2) was considered as

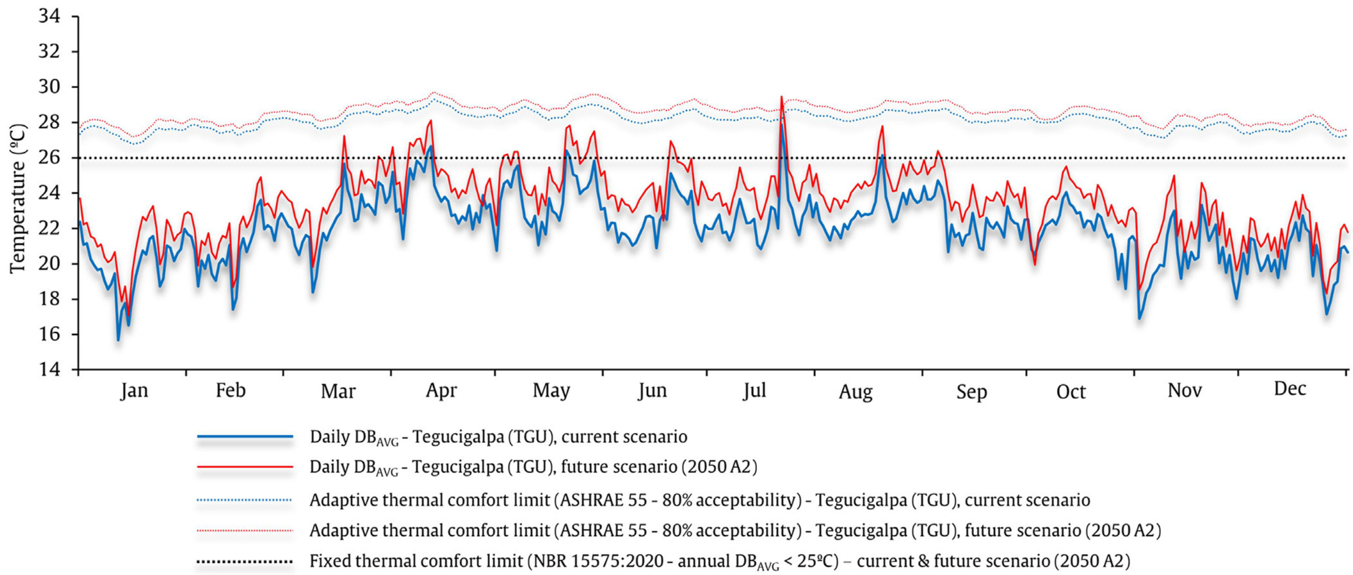

Fig. 3. Average dry bulb temperature (DB_{AVG}) & thermal comfort temperature limits for present and future scenario in *TGU*.

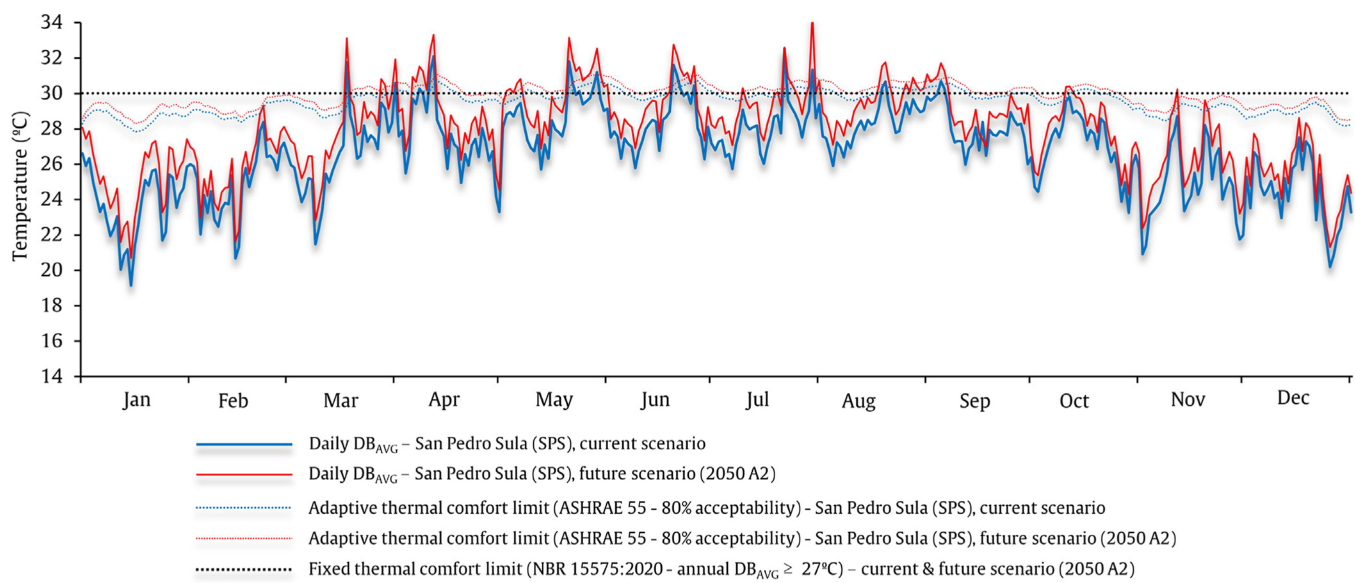

Fig. 4. Average dry bulb temperature (DB_{AVG}) & thermal comfort temperature limits for present and future scenario in *SPS*.

a second option (with a building floor depth 12 m) assuming that future vertical social housing projects in Honduras will provide larger apartments. An average infiltration rate of 1 ACH was assumed for all simulations based on the Brazilian building code, assuming that Brazil has a context similar to that of Honduran. The Brazilian building code outlines that dynamic thermal simulations should be carried out with an air infiltration rate of 1 ACH [42]. Occupation and lighting schedules, shown in **Table A. 1** in the Appendix section, were defined based on the Brazilian building code [43] assuming that in the context of Honduras no study exists, and that the occupation profile defined for the Brazilian context might be similar to other Latin American countries such as Honduras.

2.3. Data analysis

The overheating risk for each of the 3840 simulations was calculated based their respective indoor operative temperature outputs for all 8760 h in a year. **Section 2.3.1** and **Section 2.3.2** explains how calculations were performed, using different metrics and different thermal comfort limit. **Section 2.3.3** identifies the best and worst performance cases and explains through descriptive statistical analysis data behaviour. **Section 2.3.4** identifies through inferential statistical analysis the passive cooling design strategies with higher influence on lowering the indoor overheating risk in the present and future scenario.

2.3.1. Overheating risk metrics

This study assesses overheating risk with two metrics: (i) the exceedance hours (*He*), that quantifies the number of occupied hours in which the environmental condition in an indoor occupied space is outside the thermal comfort zone [69]; and (ii) the indoor overheating degree (*IOD*), that quantifies overheating risk taking into account the intensity and the frequency of indoor overheating risk [70]. In this study, both metrics are measured considering a fixed and adaptive thermal comfort temperature limit, as explained in **Section 2.3.2.** Both metrics were selected considering that both are endorsed by literature. For instance, *He* is found in international building codes (e.g., ASHRAE 55 [69], EN 16,798 [71], CIBSE [72,73]). Although each building code computes it differently it is always quantified without considering the overheating intensity/severity. In this regard, *IOD* is proposed in the *IEA Annex 80: Resilient Cooling for Buildings* since it assesses passive and active technologies as solutions of resilient cooling and overheating protection considering both the intensity and the frequency in one sole metric [74]. As defined in **Equation 1**, the intensity is quantified by the temperature difference between the free-running indoor operative temperature and a chosen thermal comfort temperature limit (TL_{comf}). On the other hand, the frequency is calculated by integrating the intensity of overheating during the occupied period (N_{occ}) into the different building zones (z) to present the overall overheating in a building.

$$\mathrm{IOD}\ (^{\circ}\mathrm{C}) = \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ(z)}}\left[\left(T_{op,i,z} - TL_{comf,\ i,\ z}\right)^{+} \times t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ(z)}} t_{i,z}} \quad (1)$$

Where t is the time step (typically it is 1 h), i is occupied hour counter, Z is total building zones, N_{occ} is the total number of occupied hours, $T_{op,i,z}$ is the free-running indoor operative temperature in zone z at time step i, and TL_{comf} is the comfort temperature in zone z at time step i. Only positive differences of $(T_{op,i,z} - TL_{comf,i,z})^{+}$ are considered. For simplification purposes this study simulates the dwelling as one thermal zone.

2.3.2. Thermal comfort limits

This study adopted thermal comfort temperature limits (TL_{comf}) based on the two most common approaches of studying indoor thermal comfort: a fixed and an adaptive approach. Thermal comfort limits for *TGU* and *SPS* are illustrated in Fig. 3 and Fig. 4, for both the current and future scenario.

For the fixed approach two TL_{comf} were considered, one for Tegucigalpa (*TGU*) and other for San Pedro Sula (*SPS*), based on the Brazilian building code that establishes a TL_{comf} depending on the outdoor average dry bulb temperature (DB_{AVG}) [43]. The maximum T_{op} allowed for buildings located in locations with an annual DB_{AVG} below 25 °C is 26 °C. The maximum T_{op} for locations with an annual DB_{AVG} above or equal to 27 °C is 30 °C.

The selection of the adaptive approach is based on field experiments that have shown that in occupant-controlled naturally conditioned spaces the subjective notion of comfort is influenced by the occupants' thermal experiences, preferences, expectations, and availability of control [69,75]. As defined in **Equation 2**, the upper 80% acceptability limit was selected to allow a lower standard of thermal comfort as a less strict approach according to ASHRAE 55:

$$(\text{upper } 80\% \text{ acceptability limit})\ t_{max}\ (^{\circ}\mathrm{C}) = 0.31\ \bar{t}_{pm(out)} + 17.8 + 3.5 \quad (2)$$

The prevailing mean outdoor temperature ($\overline{t_{pm(out)}}$) was calculated as defined in **Equation 3**. In this equation the mean daily temperature for the previous day is represented with $t_{e(d-1)}$, and the mean daily temperature for the day before that $t_{e(d-2)}$, and so on. The α was set to 0.9 since ASHRAE 55 suggests it could be more appropriate for climates in which synoptic-scale (day-to-day) temperature dynamics are relatively minor, such as the humid tropics [69]:

$$\bar{t}_{pm(out)}(^{\circ}\mathrm{C}) = (1-\alpha)\left[t_{e(d-1)} + \alpha t_{e(d-2)} + \alpha^{2} t_{e(d-3)} + \alpha^{3} t_{e(d-4)} + \ldots\right] \quad (3)$$

2.3.3. Overheating risk quantification

Best and worst performance cases were identified for each overheating risk metric, whether calculated with a fixed or an adaptive approach, for each *climatic location* and each *climate scenario*. To understand how related both overheating risk metrics (i.e., *He*, *IOD*) are a correlation test was performed. Prior to this descriptive statistical test, a normality test was performed for each of the overheating risk metrics using the one-sample Kolmogorov-Smirnov test in R software (*ks.test* function). Correlation between both overheating risk metrics was performed using Spearman's rank correlation test, with *cor.test* function, since none of both follow a normal distribution as explained in the **Results section**. The actual maximum operative temperature (T_{max_a}) for the best and worst cases was also identified, in addition to *He* and *IOD*.

2.3.4. The influence of passive design measures on the overheating risk

The influence of different passive cooling design strategies (NV_{ACH}, W_A, SOS_{PB}, *SHGC*, W_U, and *WWR*) and the dwelling characteristics of F_{AREA} on the indoor overheating risk was studied performing stepwise multivariate regression analysis. Together with aforementioned parameters the multivariate regressions also included as predictors the *climatic location* (i.e., *TGU* or *SPS*) and the *climate scenario* (i.e., current or future 2050 A2). The indoor overheating risk metrics of *He* and *IOD* were considered as the response (dependent) variable. Four multivariate regression models were performed corresponding to both overheating risk metrics, whether calculated with a fixed or an adaptive thermal comfort limit. The multivariate regression analysis was performed using the *lm* function and *stepAIC* function (*MASS* package) in R software. In order to capture the relative influence of each predictor on the indoor overheating risk *lm.beta* function (*lm.beta* package) was used to calculate the standardised coefficients of each predictor. Multicollinearity in the multivariate regression models was tested using the *VIF* function (*regclass* package) in R software so to determine if the independent variables in a regression model are correlated to each other. Considering that all four models include a categorical independent variable (SOS_{PB}) the generalised variance inflation factor (GVIF) for all predictors in regression models was provided. For each multivariate regression model, an R-squared value (R^2) was also provided, which represents the proportion of the variance that is explained by the independent variables (climatic location, climate scenarios, dwelling characteristics and passive design measures).

3. Results

This section presents the results of 3840 simulations, of which 960 cases are simulations that combine different passive cooling design strategies in 2 tropical climatic contexts - Tegucigalpa & San Pedro Sula - and in 2 different climate scenarios: current & future '2050 A2'. The indoor overheating risk is assessed following two metrics: a metric that quantifies the frequency of indoor overheating risk (*He*: percentage of exceedance hours) and a metric that quantifies both intensity and frequency of indoor overheating risk (*IOD*: indoor overheating degree). Both metrics are measured considering a fixed and adaptive thermal comfort limit (see **Methodology** 2.3.1 and 2.3.2 sections).

3.1. Overheating risk

The one sample Kolmogorov-Smirnov test identifies that none of the overheating risk metrics – neither *He* nor *IOD* – follow a normal distribution ($p < .05$) in both climate scenarios. As shown in Table 4, Spearman's rank correlation test indicates a strong association between *He* and *IOD* for both fixed and adaptive thermal

Table 4
Spearman's correlation coefficient (rho) between *He* and *IOD*.

Spearmans's rank correlation rho	
He_F, IOD_F	rho = 0.986, p < .001
He_A, IOD_A	rho = 0.996, p < .001

comfort limits (i.e., He_F and IOD_F; He_A and IOD_A), this means, as the hours of exceedance (*He*) increase, so does the indoor overheating degree (*IOD*), and vice versa. Fig. 5 illustrates this correlation between overheating metrics where each point represents one simulation.

Regardless of whether passive cooling strategies are used or not, results show that the overheating risk is higher when measured with a stricter thermal comfort limit. Table 5 and Table 6 summarize the results in terms of *He*, *IOD*, and T_{max_a} for the best and worst performance cases, and **Fig. A 1.** in Appendix illustrate results for all 3840 simulation cases. **Table A. 2.** and **Table A. 3.** in Appendix show that the overheating risk metrics, whether measured with a fixed or adaptive thermal comfort limit, identify as best performance cases those that include especially passive design measures such as a high natural ventilation rate (NV_{ACH} = 5), a low solar absorptance in walls (W_A = 0.3), a low solar heat gain coefficient (*SHGC* = 0.39), and a low window-to-wall ratio (*WWR* = 0.2); however, depending on the overheating risk metric, the best and worst performance cases differ, particularly in terms of SOS_{PB}, W_U, and F_{AREA}.

3.2. Influence of passive design strategies and dwelling characteristics on the overheating risk

This section shows the relative influence of each design parameters on the risk of overheating based on a multivariate regression analysis. The GVIF of all variables in all regression models is 1 which means that no multicollinearity (high correlation between independent variables) is detected in multivariate regression models. Four stepwise multivariate regression models were performed, as shown in Table 7, each corresponding to an overheating risk metric.

As shown in Table 8 (Model 1), Table 9 (Model 2), Table 10 (Model 3) and Table 11 (Model 4), results show that all passive design strategies considered in this study (NV_{ACH}, W_A, SOS_{PB}, *SHGC*, W_U, and *WWR*), as well as the dwelling characteristic of F_{AREA}, the *climatic location* (*TGU* or *SPS*) and the *climate scenarios* (current or future) significantly influence the risk of overheating.

In Model 1 and Model 2 the three independent variables with the strongest effect on the indoor overheating risk are NV_{ACH}, *climate scenario* and W_A, respectively by their order of importance. In Model 3, they are *climatic location*, NV_{ACH} and *climate scenario*. In Model 4, *climatic location*, NV_{ACH} and W_A. The three independent variables with the weakest effect on the overheating risk are the following: F_{AREA}, SOS_{PB_N} and W_U.

All positive and negative signs of the standardized and unstandardized coefficients remain the same throughout all four regression models. The independent variable NV_{ACH} has a negative coefficient, which means that the higher the air changes per hour of natural ventilation the lower the overheating risk. W_A has a positive coefficient, which means that the higher the wall absorptance value the higher the overheating risk. All SOS_{PB} independent variables (SOS_{PB_N}, SOS_{PB_S} & $SOS_{PB\_S\&N}$) have a negative coefficient, meaning that the overheating risk decreases if perimeter buffers (SOS_{PB}), such as balconies, are incorporated to the building, with greater effect especially if located in both south and north ($SOS_{PB\_S\&N}$), or only in south (SOS_{PB_S}). *SHGC* has a positive coefficient, which means that the higher the solar heat gain coefficient in windows the higher the overheating risk. F_{AREA} and W_U have a negative coefficient, which means that the greater the floor area of the dwelling and the wall thermal transmittance, the lower the overheating risk. The window-to-wall ratio (*WWR*) has a posi-

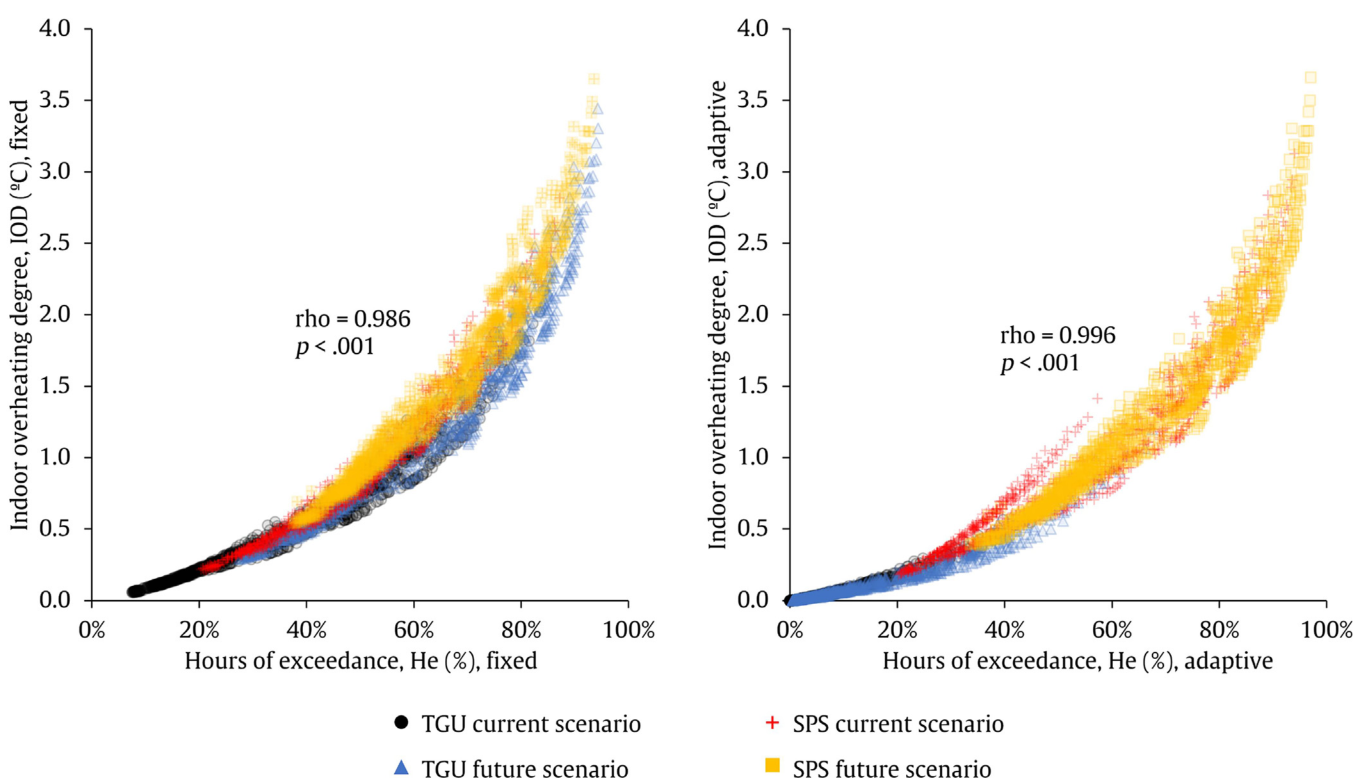

Fig. 5. Correlation between the percentage of exceedance hours (*He*) and the indoor overheating degree (*IOD*).

tive coefficient, which means that the greater the *WWR* the higher the overheating risk. Evidently, the independent variable of *climatic location* has a positive coefficient, which means that the higher the outdoor dry bulb temperature of the city the higher the overheating risk (i.e., higher overheating risk in *SPS*); and the independent variable of *climate scenario* has a positive coefficient, which means that the overheating risk is higher in the future scenario and lesser in the current scenario.

4. Discussion

These results demonstrate that it is possible to achieve low levels of overheating risk in tropical contexts such as Tegucigalpa (*TGU)* and San Pedro Sula (*SPS)* using only passive cooling design strategies as adaptation measures to heat. Findings complement and extend the work performed in similar studies on the role of passive design in preventing buildings from overheating [30,40,76], but focus on warm Central American tropical climates: *TGU*: (Aw/2A) and *SPS* (Af/0A). The findings of the present study suggest that the indoor overheating risk in *TGU* and *SPS* – whether measured with two different overheating metrics (*He*: hours of exceedance and *IOD*: indoor overheating degree) and following two different thermal comfort limits (fixed and adaptive) – can be lowered significantly by only passive means, as shown in Table 5 and Table 6.

Considering the multivariate regression models (Model 1 – Model 4) only for explanatory purposes it was found that all passive cooling design strategies considered in this study explain the variations in the overheating metrics of He_F, He_A, IOD_F and IOF_A, by 94%, 95%, 91% and 83%, respectively. Each coefficient in the multivariate regressions has a physical meaning, for instance, in Model 2 when NV_{ACH} increases one unit IOD_F decreases 0.210 (21.0% of a unit). Positive and negative signs of the predictors are in line with what literature suggest. Correlation found between *He* and *IOD* does not imply causation. Among studied passive design cooling strategies to prevent buildings from indoor overheating, natural ventilation (NV_{ACH}), wall absorptance (W_A) and solar heat gain coefficient (*SHGC*) of windows stand out as the three most effective ones in all multivariate regression models shown in **Results section** (Table 8 - Table 11). All regression models show that although passive design adaptation measures are important and provide significant improvements on indoor thermal comfort conditions, the change in outdoor temperature expected for 2050 (i.e., *climate scenario*) for both cities (i.e., *climatic location*) has a significant weight on the indoor overheating risk and must not be overlooked.

In contrast to a previous study [40], solar protection was not found to be the most effective passive cooling design strategy in providing indoor thermal comfort, but natural ventilation (NV_{ACH}). Although NV_{ACH} is in this study the passive strategy with the strongest effect in the current and future scenario, its cooling potential will decrease in time as a previous study suggests [40]. It is very likely that NV_{ACH} appears consistently in all regression models as the passive cooling design strategy with the strongest effect due to the mean daily temperature oscillation of both cities (10.8 °C and 9.4 °C in *TGU* and *SPS*, respectively [37]), this means, indoor thermal conditions may enormously benefit from free cooling (especially at night) especially when occupants open windows to let outdoor cool air to replace the indoor warm air. These results are in line with a previous study carried out for different cities with other climate classifications – except tropical ones (i.e., Af, Am, Aw) – which found that natural ventilation (purge ventilation) is the strategy with higher importance on reducing the frequency and severity of the indoor overheating risk [30]. Natural ventilation's ability to reduce the risk of indoor overheating is highly dependent not only on the window area or the percentage of openable window area, but also on when occupants manually open windows (i.e., time of the day, natural ventilation setpoint) [30]. That is why this simulation study prioritised the assessment of the natural ventilation effect on the indoor overheating risk considering only a 'sensible use' of it as best case scenario, this means, (i) when indoor spaces are occupied; (ii) when indoor operative temperature is above 19 °C (based on Brazilian building code [43]); (iii) and if outdoor temperature is below indoor operative temperature. Based on results, policymakers and designers should prioritise this passive cooling design strategy in the building codes and building forms, respectively, so to ensure that occupants can rely on opening windows without having security concerns, or limitations due to mosquitoes, noise, or pollution (aspects not considered in this study). Otherwise, occupants will not be able to take full advantage of this passive strategy.

Given that the building codes of some tropical countries primarily focus on parameters such as thermal transmittance (e.g., in Mexico warm-humid tropical locations, W_U values between 0.5 W/m^{2}K and 1 W/m^{2}K) [77], greater emphasis should be placed on the wall absorptance (W_A), as the Brazilian and Jamaican building codes do [64,67]. W_A is the passive cooling design strategy with the second strongest effect in reducing the indoor overheating risk of naturally ventilated dwellings, after natural ventilation (NV_{ACH}). Concerns have been raised about the use of the W_U as a passive cooling design parameter because it has been linked to a higher risk of indoor overheating in climates ranging from warm temperate ones (i.e., London) to subtropical ones (e.g., Sao Paulo). For instance, a previous study found that higher insulation levels are associated with higher overheating risk, particularly when dwellings lack an adequate ventilation strategy; however, if purge ventilation is used wisely, better insulation levels tend to result in both lower overheating risk [30]. The current study suggests that the latter is also true for warm tropical climates, as many simulation cases revealed that many dwellings with a low W_U value but a high NV_{ACH} value of 5 ACH have a low overheating risk. However, even with an adequate ventilation strategy of 5 ACH, *TGU* and *SPS* results show that a low W_U value is not always associated with a low overheating risk, especially if there is no south solar protection and if W_A, *SHGC* and *WWR* values are high. The latter means that even if walls are insulated with a W_U of 1.5 W/m^{2}K, air change rates of 5 ACH are insufficient to provide thermal comfort when the walls are dark, and the windows are large with no solar heat gain treatment and unshaded. It should also be noted that in the current study, U-values are discussed in terms of walls rather than roofs, as several studies have linked lower roof U-values to higher thermal comfort [78].

A previous study that examined 576,000 building variants found that shading is the least important strategy for reducing the frequency and severity of indoor overheating risk in climates ranging from warm temperate (i.e., London) to subtropical ones (e.g., Sao Paulo) [30]; however, another study found that for the subtropical climate of Hong Kong it is one of the most important parameters for providing indoor thermal comfort in future scenarios. [40]. Nonetheless, based on the current study's findings and building codes in other tropical countries (e.g., Jamaica, Singapore, India, and the Philippines), shading must be prioritized [63,67,79,80]. In the present study, shading by a semi-outdoor space at both north and south ($SOS_{PMB\_S\&N}$) is the passive cooling design strategy with the third strongest effect on the indoor overheating risk shown in Model 1 (**Results section,** Table 8). Because the current study only oriented the building's main facade to the north and south – as a best-case scenario – it is likely that external solar shading would have appeared as a parameter with a greater influence on reducing the risk of indoor overheating, for instance, if facades were oriented to the west and east. This study found that semi-outdoor spaces (*SOS*), such as the perimeter buffers (SOS_{PB}),

Table 5
Results of *He*, *IOD* and T_{max_a} for the best (B) and worst (W) simulation cases in Tegucigalpa (*TGU*). Corresponding values of passive cooling design measures and dwelling characteristics are shown in **Table A. 2**.

	CurrentScenario (2020)	FutureScenario (2050 A2)
He		
B – fixed	7.5%	27.4%
B – adaptive	0.0%	0.4%
W – fixed	84.1%	94.3%
W – adaptive	47.9%	67.5%
IOD		
B – fixed	0.1 °C	0.3 °C
B – adaptive	0.0 °C	0.0 °C
W – fixed	2.2 °C	3.4 °C
W – adaptive	0.7 °C	1.2 °C
T_{max_a}		
B	29.0 °C	30.2 °C
W	33.5 °C	35.3 °C

Table 6
Results of *He*, *IOD* and T_{max_a} for the best (B) and worst (W) simulation cases in San Pedro Sula (*SPS*). Corresponding values of passive cooling design measures and dwelling characteristics are shown in **Table A. 3**.

	Current scenario (2020)	Future scenario (2050 A2)
He		
B – fixed	20.4%	37.5%
B – adaptive	20.2%	33.6%
W – fixed	87.1%	93.6%
W – adaptive	94.0%	97.0%
IOD		
B – fixed	0.2 °C	0.5 °C
B – adaptive	0.2 °C	0.4 °C
W – fixed	2.8 °C	3.7 °C
W – adaptive	3.1 °C	3.7 °C
T_{max_a}		
B	33.7 °C	34.9 °C
W	38.5 °C	39.5 °C

Table 7
Summary of the models having *He* and *IOD* as dependent variables.

Model	Dependent variable	R^2	p-value (*p*)
Model 1	Hours of exceedance, fixed (He_F)	0.94	$p < .001$
Model 2	Indoor overheating degree, fixed (IOD_F)	0.91	$p < .001$
Model 3	Hours of exceedance, adaptive (He_A)	0.95	$p < .001$
Model 4	Indoor overheating degree, adaptive (IOD_A)	0.83	$p < .001$

significantly reduce the indoor overheating risk especially when located in both south and north ($SOS_{PB\_S\&N}$), and in a lower extent if located only in a south orientation (SOS_{PB_S}). Among the best performance cases the *He* or *IOD* values are not significantly different between having 2 m or having 4 m of depth at both south and north orientations, therefore, having a 2 m-depth SOS_{PB} might represent a more cost-effective measure for Honduras than having a 4 m-depth SOS_{PB}.

The identification of the most relevant passive cooling design strategies on reducing the indoor overheating risk represents an important step on the understanding of what means to deliver a thermally comfortable home in tropical contexts – such as *TGU* and *SPS* – without or with reduced need for AC, however, additional work still needs to be done. Although *TGU* and *SPS* are both typical tropical highland and lowland climates, more research is needed to assess the impact of studied passive cooling design measures as adaptation strategies, particularly in tropical lowland climates near the Equator (e.g., Singapore, Bangkok), where daily temperature oscillation is lower and outdoor temperature is higher [8]. Further research is still needed on the cooling (sensible and latent) energy demand implications of adopting passive cooling design strategies in these contexts. Although several studies exist on the assessment of the indoor overheating risk using ASHRAE 55, EN 16987, and CIBSE TM52 and TM59 metrics [69,71–73] still field work is needed especially on the use of the novel metric of *IOD* on assessing overheating risk. Although *IOD* is a multizonal metric, this means, measures overheating risk for more than two zones [70,74], for simplification purposes this research work considered the studied dwelling as one thermal zone. The influence that the relative humidity plays on the indoor thermal comfort is not consider in this study and should be further investigated considering studies that emphasize its importance [81,82]. Cost-effectiveness studies should also be conducted to determine the economic impact of the most relevant passive cooling design strategies identified in this study; however, the work behind the development of the *Sustainable Construction Guide* for *TGU* indicates that they may not represent a significant capital cost [20]. As this study focuses on how SOSs such as balconies improve indoor thermal comfort, future research may investigate the benefits of alternative passive protection and glazing solutions. Although literature suggests that top-floor dwellings are more prone to overheat [30,83,84] in this study mid-floor dwellings were selected as they are more representative at the building level in dense urban contexts; however, future research should investigate the risk of overheating on upper floor dwellings when roof properties (e.g., U-value, albedo, roof ventilation) come into play. Future studies may also consider the average infiltration rate not as a constant parameter. Regarding the latter, highly air tight buildings are uncommon in the tropical contexts where occupants culturally valuate more the idea of openness and constant air movement [85,86]. However, it is worth noting that its significance may grow by the end of the century in conjunction with external wall insulation [40], where external conditions may become unfavourable to the use of natural ventilation and thermal comfort conditions must rely on cooling systems [87].

Table 8
Multivariate regression measuring the influence of all parameters on He_F (Model 1).

Variables	Unstandardized coefficients Coefficients	Std. Error	Standardized Coefficient	p-value (*p*)
(Intercept)	3.615e-01	7.376e-03	–	–
Scenario	2.013e-01	1.666e-03	0.49448556	$p < .001$
City	8.838e-02	1.666e-03	0.21711373	$p < .001$
SOS_{PB_N}	−2.192e-02	3.041e-03	−0.04935301	$p < .001$
SOS_{PB_S}	−6.750e-02	3.041e-03	−0.15196683	$p < .001$
$SOS_{PB\_S\&N}$	−9.075e-02	3.041e-03	−0.20430818	$p < .001$
NV_{ACH}	−7.006e-02	4.164e-04	−0.68837034	$p < .001$
W_U	−3.435e-02	1.666e-03	−0.08437078	$p < .001$
W_A	3.191e-01	5.100e-03	0.25603229	$p < .001$
SHGC	1.699e-01	3.544e-03	0.19617254	$p < .001$
WWR	3.700e-01	8.328e-03	0.18179241	$p < .001$
F_{AREA}	−2.924e-04	4.828e-05	−0.02478062	$p < .001$

Table 9
Multivariate regression measuring the influence of all parameters on IOD_F (Model 2).

Variables	Unstandardized coefficients		Standardized Coefficient	p-value (p)
	Coefficients	Std. Error		
(Intercept)	0.1701027	0.0285972	–	–
Scenario	0.6354768	0.0064581	0.47538375	$p < .001$
City	0.3450230	0.0064581	0.25810274	$p < .001$
SOS_{PB_N}	−0.1243341	0.0117908	−0.08524613	$p < .001$
SOS_{PB_S}	−0.1990603	0.0117908	−0.13647997	$p < .001$
$SOS_{PB\_S\&N}$	−0.3173321	0.0117908	−0.21756960	$p < .001$
NV_{ACH}	−0.2101779	0.0016145	−0.62891448	$p < .001$
W_U	−0.0979387	0.0064581	−0.07326537	$p < .001$
W_A	1.1801487	0.0197737	0.28833389	$p < .001$
SHGC	0.6914391	0.0137406	0.24310639	$p < .001$
WWR	1.5273533	0.0322904	0.22851469	$p < .001$
F_{AREA}	−0.0010841	0.0001872	−0.02797984	$p < .001$

Table 10
Multivariate regression measuring the influence of all parameters on He_A (Model 3).

Variables	Unstandardized coefficients		Standardized Coefficient	p-value (p)
	Coefficients	Std. Error		
(Intercept)	1.533e-02	1.001e-02	–	–
Scenario	1.074e-01	2.260e-03	0.17948211	$p < .001$
City	5.009e-01	2.260e-03	0.83678104	$p < .001$
SOS_{PB_N}	−2.347e-02	4.126e-03	−0.03594224	$p < .001$
SOS_{PB_S}	−5.788e-02	4.126e-03	−0.08862636	$p < .001$
$SOS_{PB\_S\&N}$	−8.187e-02	4.126e-03	−0.12536428	$p < .001$
NV_{ACH}	−5.745e-02	5.650e-04	−0.38389610	$p < .001$
W_U	−3.420e-02	2.260e-03	−0.05714082	$p < .001$
W_A	2.832e-01	6.920e-03	0.15454090	$p < .001$
SHGC	1.598e-01	4.809e-03	0.12550918	$p < .001$
WWR	3.513e-01	1.130e-02	0.11737695	$p < .001$
F_{AREA}	−2.505e-04	6.551e-05	−0.01444059	$p < .001$

Table 11
Multivariate regression measuring the influence of all parameters on IOD_A (Model 4).

Variables	Unstandardized coefficients		Standardized Coefficient	p-value (p)
	Coefficients	Std. Error		
(Intercept)	−0.3483907	0.0430915	–	–
Scenario	0.2404485	0.0097313	0.16648181	$p < .001$
City	1.0802916	0.0097313	0.74797274	$p < .001$
SOS_{PB_N}	−0.0869522	0.0177669	−0.05517789	$p < .001$
SOS_{PB_S}	−0.1557362	0.0177669	−0.09882663	$p < .001$
$SOS_{PB\_S\&N}$	−0.2363096	0.0177669	−0.14995666	$p < .001$
NV_{ACH}	−0.1363122	0.0024328	−0.37751953	$p < .001$
W_U	−0.0524819	0.0097313	−0.03633742	$p < .001$
W_A	0.8196112	0.0297959	0.18533909	$p < .001$
SHGC	0.4990096	0.0207049	0.16238709	$p < .001$
WWR	1.1004830	0.0486566	0.15239057	$p < .001$
F_{AREA}	−0.0008629	0.0002821	−0.02061258	$p = .002$

5. Conclusions

This study investigated the influence of different passive cooling design strategies and dwelling characteristics on the indoor overheating risk of an apartment-type dwelling in two Central American tropical *climatic locations* (Tegucigalpa and San Pedro Sula), through 3840 simulation cases. These strategies and characteristics are natural ventilation (air change rates, NV_{ACH}), wall absorptance (W_A), perimeter buffer type of semi-outdoor space (SOS_{PB}), solar heat gain coefficient of windows (*SHGC*), wall thermal transmittance (W_U), window-to-wall ratio (*WWR*) and the dwelling's floor area (F_{AREA}). The analysis used two indoor overheating risk metrics – hours of exceedance (*He*) and indoor overheating degree (*IOD*) – and two thermal comfort limits (adaptive and fixed). The findings of this study are the following:

- Passive cooling design strategies significantly help reduce the overheating risk in the warm-humid tropical context of Tegucigalpa (*TGU*) and San Pedro Sula (*SPS*) in both current and future climate scenarios.
  - o In the current scenario of *TGU*, the best performance case appears to have no overheating risk with both metrics. In the future scenario, it appears to experience a low risk of *He* (i.e., 0.4%) and no risk of *IOD*. The latter is based on the adaptive model of thermal comfort.
  - o In the current scenario of *SPS*, the best performance case appears to experience a risk of 20.4% of *He* and 0.2 °C of *IOD*. In the future scenario, it appears to experience a risk of 37.5% of *He* and 0.5 °C of *IOD*. The latter is based on the fixed model of thermal comfort.

- As shown in the multivariate regression analysis, variations in the indoor overheating risk (whether *He* or *IOD*) can be explained by all considered parameters: NV_{ACH}, W_A, SOS_{PB}, *SHGC*, W_U, *WWR*, F_{AREA}, *climatic location*, and *climate scenario*, with a R-squared (R^2) value that ranged between 0.83 and 0.95.
- From all passive cooling design strategies NV_{ACH} appears to be the parameter with the strongest effect on lowering the indoor overheating risk, followed by the parameter of W_A. In some models $SOS_{PB\_S\&N}$ and *SHGC* appear to be the parameters with the third strongest effect. The parameters of F_{AREA} and SOS_{PB_N}, and W_U are the three parameters with the lowest effect on lowering the indoor overheating risk.

In these tropical contexts, passive cooling design strategies are effective adaptation measures for both the current and future (2050 A2) scenarios. However, it becomes clear that providing indoor thermal comfort solely through the most effective passive means is more difficult in cities with higher mean outdoor temperature (e.g., San Pedro Sula), where air conditioning (AC) is required for at least 20.4% of annual occupied hours for the best performance case, and in the future scenario for at least 37.5%. As a result, it is critical to prepare the residential building stock of Honduras and Central America's largest cities so that it can be resilient now and in the near future, when temperatures are expected to rise. In these tropical contexts, it is necessary to adapt current national building codes for this purpose, or for local governments to develop a local building code for their respective city. The prompt adoption of an updated or new building code that considers indoor thermal comfort requirements and the aforementioned passive cooling design strategies according to each climatic location might benefit Honduras and other countries with warm tropical cities (e.g. Central American countries): (a) avoid excessive overheating, which can have a negative impact on the health of vulnerable populations (i.e., elderly people, infants and children, low-income households); (b) reduce cooling energy demand, which is expected to rise globally in the coming decades due to income growth and global warming; and (c) guide towards decarbonizing building operations by 2050 (e.g., as set out in the Honduras Decarbonisation Plan 2020–2050). This study is relevant for all building professionals as well as to the building sector policymakers seeking to create thermally comfortable indoor environments in vertical social housing projects of tropical warm-humid contexts.

CRediT authorship contribution statement

Juan Gamero-Salinas: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing - review & editing, Visualization, Project administration. **Aurora Monge-Barrio:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision. **Nirmal Kishnani:** Conceptualization, Methodology, Supervision. **Jesús López-Fidalgo:** Methodology, Formal analysis, Writing - review & editing. **Ana Sánchez-Ostiz:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision.

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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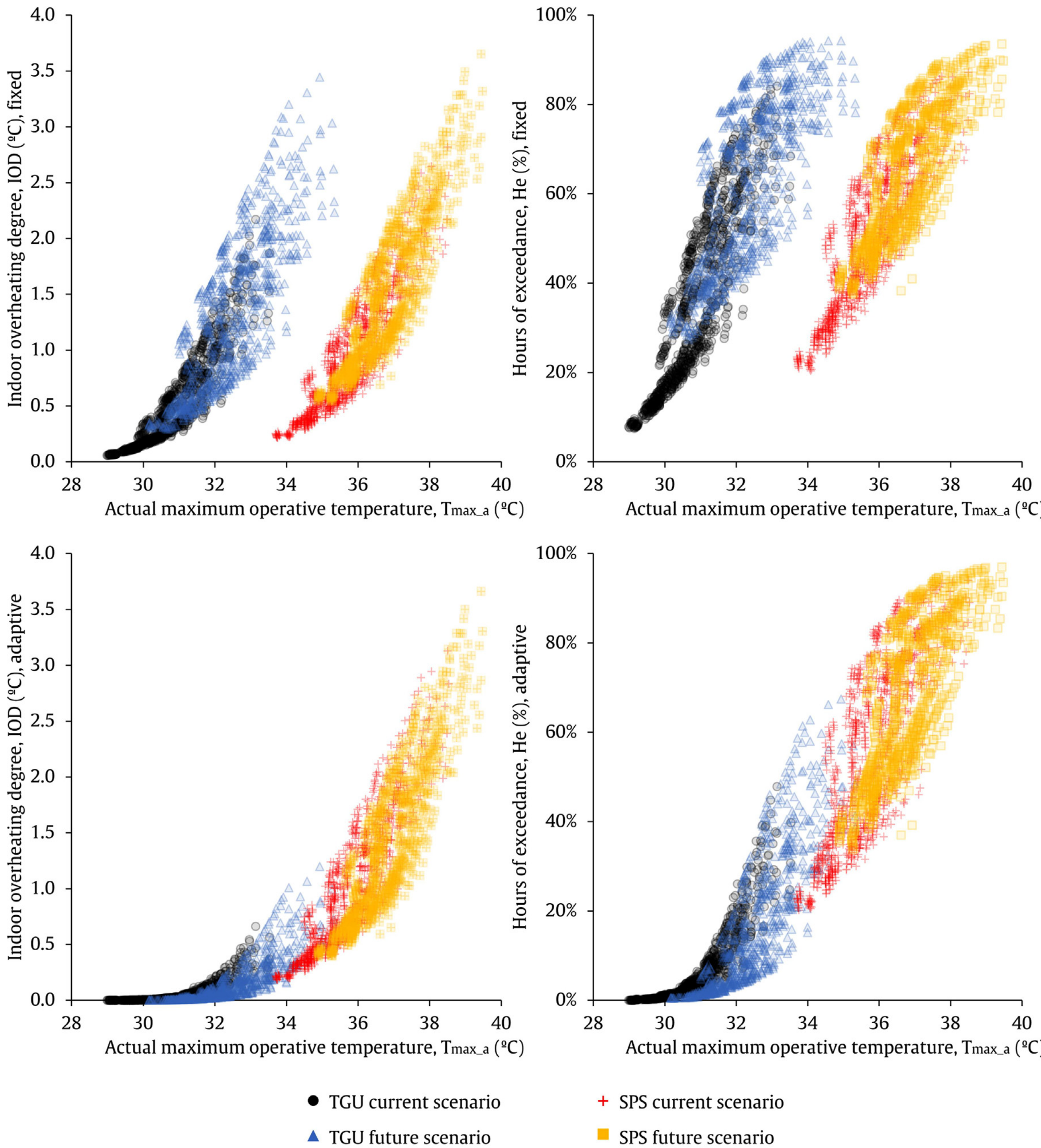

Fig. A1. Correlation between the actual maximum operative temperature (T_{max_a}) and the indoor overheating risk metrics: percentage of exceedance hours (*He*) and the indoor overheating degree (*IOD*).

Table A1
Occupation and lighting schedule as defined in Brazilian building code [42]

Hours	Occupation	Lighting
00:00 – 00:59	100%	0%
01:00 – 01:59	100%	0%
02:00 – 02:59	100%	0%
03:00 – 03:59	100%	0%
04:00 – 04:59	100%	0%
05:00 – 05:59	100%	0%
06:00 – 06:59	100%	100%
07:00 – 07:59	100%	100%
08:00 – 08:59	0%	0%
09:00 – 09:59	0%	0%
10:00 – 10:59	0%	0%
11:00 – 11:59	0%	0%
12:00 – 12:59	0%	0%
13:00 – 13:59	0%	0%
14:00 – 14:59	50%	0%
15:00 – 15:59	50%	0%
16:00 – 16:59	50%	100%
17:00 – 17:59	50%	100%
18:00 – 18:59	50%	100%
19:00 – 19:59	50%	100%
20:00 – 20:59	50%	100%
21:00 – 21:59	50%	100%
22:00 – 22:59	100%	100%
23:00 – 23:59	100%	100%

Table A2
Best (B) and worst (W) performance cases in *TGU* in terms of passive cooling design measures and dwelling characteristics. Corresponding values of *He*, *IOD* or T_{max_a} are shown in Table 5.

	NV_{ACH} (ACH)	W_A (%)	SOS_{PB}	SHGC	W_U (W/m^2K)	WWR (%)	F_{AREA} (m^2)
He							
B – current (2020), fixed	5	30	4 m S/ 4 m N	0.39	2.5	20	99.5
W – current (2020), fixed	1	70	0 m S/ 0 m N	0.86	1.5	40	65
B – future (2050 A2), fixed,	5	30	4 m S/ 4 m N	0.39	2.5	20	99.5
W – future (2050 A2), fixed	1	70	0 m S/ 0 m N	0.86	1.5	40	99.5
B – current (2020), adaptive	5	30	*	0.39	1.5	20	*
W – current (2020), adaptive	1	70	0 m S/ 0 m N	0.86	1.5	40	65
B – future (2050 A2), adaptive	5	30	4 m S/ 4 m N	0.39	1.5	20	65
W – future (2050 A2), adaptive	1	70	0 m S/ 0 m N	0.86	1.5	40	65
IOD							
B – current (2020), fixed	5	30	4 m S/ 4 m N	0.39	1.5	20	99.5
W – current (2020), fixed	1	70	0 m S/ 0 m N	0.86	1.5	40	65
B – future (2050 A2), fixed,	5	30	4 m S/ 4 m N	0.39	2.5	20	99.5
W – future (2050 A2), fixed	1	70	0 m S/ 0 m N	0.86	1.5	40	65
B – current (2020), adaptive	5	30	*	0.39	1.5	20	*
W – current (2020), adaptive	1	70	0 m S/ 0 m N	0.86	1.5	40	65
B – future (2050 A2), adaptive	5	30	0 m S/ 4 m N	0.39	1.5	20	99.5
W – future (2050 A2), adaptive	1	70	0 m S/ 0 m N	0.86	1.5	40	65
T_{max_a}							
B – current (2020)	5	30	4 m S/ 4 m N	0.39	1.5	20	65
W – current (2020)	1	70	0 m S/ 0 m N	0.86	2.5	40	65
B – future (2050 A2)	5	30	0 m S/ 2 m N	0.39	1.5	20	99.5
W – future (2050 A2)	1	70	4 m S/ 0 m N	0.86	2.5	40	65

* Overheating risk is the same regardless of the option.

Table A3
Best (B) and worst (W) performance cases in *SPS* in terms of passive cooling design measures and dwelling characteristics. Corresponding values of *He*, *IOD* or T_{max_a} are shown in Table 6.

	NV_{ACH} (ACH)	W_A (%)	SOS_{PB}	SHGC	W_U (W/m^{2}K)	WWR (%)	F_{AREA} (m^2)
He							
B – current (2020), fixed	5	30	4 m S/ 4 m N	0.39	2.5	20	99.5
W – current (2020), fixed	1	70	0 m S/ 0 m N	0.86	1.5	40	65
B – future (2050 A2), fixed,	5	30	4 m S/ 4 m N	0.39	2.5	20	99.5
W – future (2050 A2), fixed	1	70	0 m S/ 0 m N	0.86	1.5	40	99.5
B – current (2020), adaptive	5	30	4 m S/ 4 m N	0.39	1.5	20	99.5
W – current (2020), adaptive	1	70	0 m S/ 0 m N	0.86	1.5	40	65
B – future (2050 A2), adaptive	5	30	4 m S/ 4 m N	0.39	2.5	20	99.5
W – future (2050 A2), adaptive	1	70	0 m S/ 0 m N	0.86	1.5	40	99.5
IOD							
B – current (2020), fixed	5	30	4 m S/ 4 m N	0.39	1.5	20	99.5
W – current (2020), fixed	1	70	0 m S/ 0 m N	0.86	1.5	40	65
B – future (2050 A2), fixed,	5	30	4 m S/ 4 m N	0.39	2.5	20	99.5
W – future (2050 A2), fixed	1	70	0 m S/ 0 m N	0.86	1.5	40	99.5
B – current (2020), adaptive	5	30	4 m S/ 4 m N	0.39	1.5	20	99.5
W – current (2020), adaptive	1	70	0 m S/ 0 m N	0.86	1.5	40	65
B – future (2050 A2), adaptive	5	30	4 m S/ 4 m N	0.39	1.5	20	99.5
W – future (2050 A2), adaptive	1	70	0 m S/ 0 m N	0.86	1.5	40	65
T_{max_a}							
B – current (2020)	5	30	1 m S/ 0 m N	0.39	1.5	20	65
W – current (2020)	1	70	0 m S/ 0 m N	0.86	2.5	40	65
B – future (2050 A2)	5	30	4 m S/ 4 m N	0.39	1.5	20	65
W – future (2050 A2)	1	70	0 m S/ 0 m N	0.86	2.5	40	65

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