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Comparison of passive cooling techniques in improving thermal comfort of occupants of a pre-fabricated building

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ABSTRACT

Pre-fabricated composite buildings are proposed as sustainable sheltering and housing solutions for developing countries. This work compares different passive cooling techniques of shading, natural ventilation, cool painting and increase in thickness of interior gypsum plaster for these buildings to tackle overheating in hot climates. The studied techniques are measured and compared in terms of indoor air temperature by calculating four indicators of maximum, minimum, average of highest 5% and average of lowest 5% temperatures as well as thermal comfort of the occupants based on two acceptability rates of ASHRAE 55 and three acceptability limits of EN 15251 standards in three climates: Porto, Nairobi and Mumbai. The findings of this comparison bring insights into the effectiveness of passive cooling techniques, that can be highly beneficial at design level. Results point out improvements by all studied techniques, even if these quantitatively depend on the presence of the occupants and the choice of the performance indicators. Finally, further indicators such as stored heat, solar radiation heat gain and surface temperature are analyzed, to explain causes and effects associated with studied passive cooling techniques. Results of these comparisons pointed out that the combined implementation of all techniques combined is effective enough to provide thermal comfort of the occupants during almost all annual occupancy in Nairobi measured by acceptability rate of 80% of ASHRAE 55 and Category III of EN 15251.

1. Introduction

At the start of the millennium, more than one billion people lived in inadequate housing, particularly in poor countries [1]. By 2030, this number may increase to 3 billion, i.e. 40% of the global population, mainly in Sub-Saharan Africa and south Asia [2]. Moreover, noting the climate change and consequent drastic increase in natural disasters [3,4], there is a growing interest in development of sheltering and temporary housing for post-disaster situations. Considering the importance of economic viability of sheltering and housing solutions, the concept of affordable housing has been developed and investigated in recent years. Furthermore, environmental concerns of using natural resources for construction and operation of buildings have been widely vented. Linking affordable and environmental friendliness with well-being of the occupants, as social aspect of sustainability, have led to development of the concept of "sustainable building" as a basic requirement for the construction industry.

Advantages such as rapid construction, minimal handling, improved surface quality, lower need for resources and less waste have led to growth of pre-fabricated (off-site) construction [5,6]. There is also a rising interest in use of composite wall systems in pre-fabricated buildings due to benefits such as light weight and better health and safety for workers [6]. Hence, pre-fabricated composite buildings are being proposed as sustainable solutions for where there is a huge need for affordable housing (such as Sub-Saharan African countries) [2] and as a rapid post-disaster sheltering where there is high vulnerability to natural disasters (such as south Asian countries) [7]. However, considering high outdoor

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Abbreviations: ASHRAE, american society of heating; CTF, conduction transfer function; EMPD, effective moisture penetration depth; GHI, global horizontal irradiance [kWh m^{-2} day^{-1}]; GWP, global warming potential; HVAC, heating, ventilating, and air conditioning; IWEC, international weather for energy calculations; NPL, neutral pressure level; PPD, predicted percentage of dissatisfied; UHI, urban heat island; WMO, world meteorological organization.

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Nomenclature

A	Surface area [m^2]
A_o	Opening area of window [m^2]
C_d	Discharge coefficient for opening
C_w	Opening effectiveness
d_{EMPD}	Effective moisture penetration depth [m]
ε	Thermal absorptance
F_s	Open area fraction
g	Standard gravity [m s^{-2}]
h_m	Airside convective mass transfer coefficient [kg m^{-2} s^{-1}]
Q	Ventilation flow rate due to wind and stack effects [m^3 s^{-1}]
Q_s	Volumetric air flow rate due to stack effect [m^3 s^{-1}]
Q_w	Volumetric air flow rate driven by wind [m^3 s^{-1}]
T	Temperature [°C]
t	Time-step
T_c	Comfort temperature [°C]
T_{mo}	Monthly mean outdoor air dry-bulb temperature [°C]
T_o	Outdoor air dry-bulb temperature [°C]
T_{ot}	Operative temperature [°C]
T_{rm}	Weighted mean of the previous 7-day outdoor air dry-bulb temperature [°C]
T_z	Zone air dry-bulb temperature [°C]
u	Moisture capacitance [kg kg^{-1}]
U-value	Overall heat transfer coefficient [W m^{-2} K^{-1}]
V	Outdoor wind speed [m s^{-1}]
α	Solar absorptance
ΔH_{NPL}	Height from midpoint of lower opening to the neutral pressure level [m]
ρ_m	Dry bulk density of material [kg m^{-3}]
ω	Humidity ratio [kg kg^{-1}]
ω_z	Zone humidity ratio [kg kg^{-1}]

air temperature in both of these regions, avoiding overheating in buildings is a big challenge that needs to be tackled.

Passive cooling is a set of sustainable techniques for cooling buildings by natural means [8]. It comprises any system that aims to minimize, or eliminate if possible, mechanical air conditioning and therefore reduces cooling energy demand [9,10]. Noting that refrigeration and air conditioning account for about 15% of global electricity consumption and may cause contamination problems due to presence of organic dust in cooling coils, fans and filters [11], passive cooling plays an important role in the sustainable development of the building industry. A widely accepted framework to engineer passive cooling systems consists of three steps: (1) prevention of heat gains; (2) modulation of heat gains and (3) heat dissipation [11]. Consequently, passive cooling techniques range from choosing the most favorable arrangements of fenestration to implementing thermal insulation, thermal mass or phase change materials. Ultimate goal of all these techniques is to reduce high indoor air temperatures and cooling energy consumption and provide acceptable thermal comfort and indoor air quality for the occupants [11–13].

Windows are the most significant components of buildings in terms of comfort and energy use per unit surface area [14]. Using shading devices is one of the most common strategies to decrease heat gains through fenestrations. Moreover, when the outdoor temperature is below the indoor temperature, e.g. during nighttime, natural ventilation through windows can be applied to dissipate the daily heat gain. Furthermore, radiation properties of the exterior surfaces of building envelope affect surface temperature and consequently heat flux [15]. Applying cool (high reflectance and emittance) paints in the façade and roof of buildings is another technique for reducing the indoor air temperature [16–18] since it reflects incident solar radiation away and radiates the heat at night [19]. Due to several characteristics such as sound insulation, fireproofing, thermal and moisture buffering and cost, gypsum plaster has been used for thousands of years in many buildings for both interior and exterior walls and ceilings [20–22].

In this article we compare the impact of different passive cooling techniques for a pre-fabricated building made of a sandwiched-structured composite. Toward this aim, the thermal performance of the building (located in Porto, Portugal) was firstly assessed with regards to annual variations of indoor air temperature of living room and sleeping room. Subsequently, the average daily indoor air temperature was calculated for three coldest and hottest days of year. These results demonstrated the relative and absolute effectiveness of four passive cooling techniques (shading, natural ventilation, cool painting and increased thickness of interior gypsum plaster) for indoor air temperature by calculating four indicators of maximum, minimum, average of highest 5% and average of lowest 5% temperatures. The impact of the best solution of each passive cooling technique was compared in different climates in terms of average indoor air temperature as well as thermal comfort of the occupants based on two acceptability limits of ASHRAE 55 and three acceptability limits of EN 15251 standards. The three cities of Porto (as representative of warm-summer Mediterranean climate), Mumbai (where there is a high potential need for post-disaster sheltering and as representative of tropical climate) and Nairobi (where 60% of the population lives in informal dwellings [2] and as representative of Sub-Saharan Africa) were selected for these comparisons[PS1] . The study also looks at the impact of the selected passive cooling techniques on the annual heat storage energies, maximum and average annual solar radiation heat gain per area and maximum surface temperature of exterior walls and roof.

2. Literature review

Several studies have addressed thermal comfort to demonstrate the impact of passive cooling in buildings. ASHRAE 55 [23] standard describes thermal comfort as a state of mind which expresses satisfaction with the thermal environment [24]. Firstly, Fanger [25] defined a predicted mean vote (PMV) index as a thermal comfort vote based on four parameters: air temperature, mean radiant temperature, air velocity and air humidity and two individual parameters of clothing insulation and activity level. The PMV index is a value on a 7-point scale that assigns −3 for cold, −2 for cool, −1 for slightly cool, 0 for neutral, +1 for slightly warm, +2 for warm and +3 for hot thermal sensations. Predicted percentage of dissatisfied (PPD) is a function of PMV index that identifies the percentage of the occupants that are dissatisfied with the thermal conditions [26,27]. Noting that the Fanger model was based on large sample of college age students, impact of factors such as age, gender and body fat on accuracy of the model is questionable [28]. De Dear and Brager [29] subsequently introduced adaptive model that, as its name explains, assumes people adapt to thermal conditions by modifying their clothing insulation, posture and activity.

In hot climates, a significant fraction of heat gain happens through exterior windows [30,31]. Windows normally have a *U-value* five to ten times higher than wall area [32], therefore proving that shading devices are particularly important in terms of energy saving and thermal and visual comfort [33,34]. There is a large volume of published studies describing the role of shading devices in improving thermal comfort of the occupants of buildings. These studies examined several factors such as area and angle of the shading device [33,35,36], shading effect of surrounding objects such as trees or buildings [12,17,37,38], the window to wall ratio [30,39], color of shading [40,41], use of overhang [30,31,33,34,42] and interaction with occupants [32,43–45]. Together, these studies provide important insights into optimum design of shading device as well as energy saving benefits of shading. Nonetheless, considering low thermal inertia of the studied prefabricated building and limited space for the occupants, investigating the impact of different types of shading draws our attention to their effectiveness in comparison with other selected passive cooling techniques.

Natural ventilation, also known as free cooling, has been used for centuries. However, there is a growing interest in the use of natural ventilation not only to reduce cooling energy consumption, but also to increase indoor air quality by reducing mechanical ventilation [46–51]. This technique is especially effective for hot-dry climates and can do much to achieve the ideal indoor air temperature [49]. Overall, these studies have mainly pointed out the importance of natural ventilation in managing high indoor air temperatures. In addition to experimental, analytical and theoretical models, more contemporary trends such as computational techniques and software simulations have been used to study impact of natural ventilation on thermal performance of buildings [47]. However, modeling of natural ventilation and reliability of simulation results have been questioned by countless scholars [13,50,52,53].

Several studies have highlighted benefits of using cool painting for façades and roof of buildings. Many studies [15–17,19,54] have discussed how cool painting can contribute in diminishing urban heat island (UHI) effect in densely inhabited environments. Susca [55] has drawn our attention to impact of cool roof on global warming potential (GWP). On the other hand, results of studies by Rossi et al. [56] and Sproul et al. [57] prove that cool roof is a suitable approach to tackle global warming. Longer life than hot roofs of same material [17] and null cost for implementation [17,56] are other discussed advantages of this technique while increasing heating energy is concluded as its drawback [18]. Therefore, for climates with long winter period, it is suggested that application of cool paint should be associated with higher insulation level of the building envelope [16,58]. In addition to energy demand, other indicators such as thermal comfort [59,60], heat flow [60], heat flux [15,61,62] and surface temperature [15,61–63] have been measured to highlight the impact of cool painting. Taken together, these studies indicate that exclusive evaluation of energy consumption would not be sufficient for the impact assessment of cool painting as it is highly dependent to type of building and insulation.

Perhaps because gypsum plaster is a traditional material which is commonly used to allow wall finishing has meant that far less attention has been paid to it in buildings, even though it possesses significant thermal, acoustic and fire resistance properties [22,64,65]. Former studies show that gypsum plaster can play a vital role in the moisture buffering [66,67] and improving thermal insulation [21,68] of buildings, there are relatively few studies discussing how use of gypsum plaster can improve thermal comfort of the occupants though. Knowing advantages of moisture buffering of gypsum plaster, this lack of interest can be due to neglecting moisture transfer in the used heat balance algorithms in some models. Woods et al. [69] and Qin et al. [70] have argued while moisture sorption of materials is one of the main factors affecting indoor humidity, it is often neglected in energy models of buildings. Moreover, Firląg and Zamada [71] and Zhang et al. [72] have pointed out that this element has the largest and most immediate influence on indoor air humidity. Liu et al. [73] have mentioned that the effect of moisture buffering is even more significant in hot-humid climates. Overall, these studies outlined the need to consider moisture transfer and storage in building models. Moreover, they indicate the importance of interior layers of building envelope on energy demand and thermal comfort of the occupants. This consideration may highlight the benefits of using interior gypsum plaster in buildings for improving indoor thermal comfort of occupants.

The former studies on applying passive cooling technique to improve indoor thermal comfort can be categorized into two groups: the first group comprises those attempts that were applied on existing buildings (retrofitting) with the ultimate goal of improving thermal comfort of the occupants and decreasing energy demand such as [26,31,36,37,48,74–76]. The second class consists of those studies that compared different techniques for a specific building, but in different climate conditions and mainly different cities of a country such as Australia [24], Brazil [62,77], France [78], Greece [79], Italy [16,30], Portugal [18] and the United States [51]. While results of the first group can be beneficial for the buildings with same characteristics in similar climates, generalization of outcomes for other climates is yet questionable. Therefore, using different climate types for each case study, especially those buildings that are at design stage, is suggested.

The influence of simulation tools on the accuracy of models is another issue noted in these studies. Various studies have used available simulation tools such as *EnergyPlus* [16,36,39,52,79,80], *TRNSYS* [13,50,58,71,73,78,81], *ESP-r* [18,35,37,38] and *IES* [42,75,82] to simulate thermal performance of buildings. Johnson et al. [83] have compared different simulation tools for air flow network of natural ventilation and concluded that there would be up to 30% error in their modeling. Noting that accuracy and capabilities of different simulation tools can vary depending on the object of study, selection of correct simulation tool for that specific purpose is essential. Moreover, the importance of different heat and mass transfer algorithm, numerical models and presumed coefficients that are often neglected.

3. Methodology

3.1. Reference building

In this research, a $6\,\mathrm{m}^2 \times 5\,\mathrm{m}^2$ one-story house, lined up with north, consisting of one living room, one sleeping room and a service room was considered as shown in Fig. 1. All walls, floors and roofs of the studied buildings are made of a sandwich-structured composite comprising two glass-fiber reinforced laminates sandwiching a light core. The core material is extruded polystyrene and Equibiaxial (EBX) woven roving of fiberglass with $\pm 45^\circ$ orientation was considered as reinforcement and epoxy as resin. Mechanical, thermal, acoustic and fire performance tests were performed to assure the proposed panel has required properties to be used as building material. Results of these tests and material selection process are presented in Samani et al. [84]. Exterior walls, roofs and floors are coated with a 10 mm layer of interior gypsum plaster making total thickness of 92 mm and *U-value* of $0.445\,\mathrm{W\,m^{-2}\,K^{-1}}$. Interior walls are covered with gypsum plaster on both side (each 10 mm) resulting in total thickness of 102 mm and *U-value* of $0.44\,\mathrm{W\,m^{-2}\,K^{-1}}$. Windows are made of double clear glazing with thickness of 32 mm and *U-value* of $2.67\,\mathrm{W\,m^{-2}\,K^{-1}}$ and doors are wooden with thickness of 30 mm and *U-value* of $5\,\mathrm{W\,m^{-2}\,K^{-1}}$.

Different parameters must be set in order for thermal behavior of the building to be modelled appropriately. Infiltration, i.e. flow of outdoor air into a building through exterior doors, cracks and other unintentional openings [85], was set to 0.6 air changes per hour and air velocity of indoor space was set to $0.2\,\mathrm{m\,s^{-1}}$. Internal gains from lighting, home appliances and occupants are notable elements in indoor thermal balance of the building. These gains contain sensible (convective plus radiative) and latent heat. For each zone, internal gains consisting of home appliances, lighting and occupants were defined with a daily schedule recurring all days

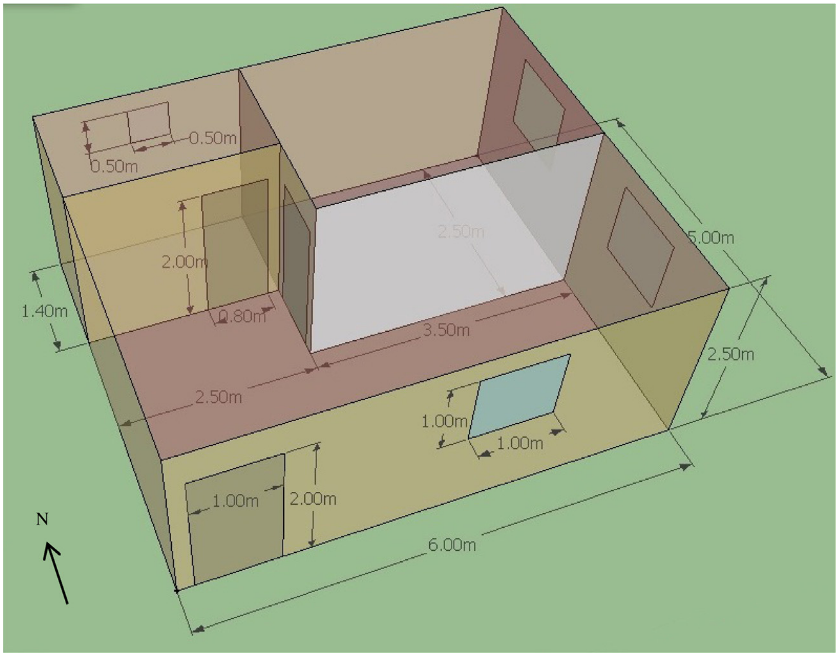

Fig. 1. Schematic model of the studied building.

Table 1
Internal gains of the studied building.

Thermal zone	Area [m^2]	Daily schedule	Type of internal gain	Activity level per person/power [W]
Living room	17.75	7:30–8:30 and 18:30–22:30 during weekdays, 7:30–22:30 during weekend	4 People seating	108
Living room	17.75	7:30–8:30 and 18:30–22:30	Lighting	36
Living room	17.75	7:30–8:30 and 18:30–22:30 during weekdays, 7:30–22:30 during weekend	Home appliances	160
Living room	17.75	24 hours	Refrigerator	28
Sleeping room	8.75	22:30–23:00	4 People reclining	81
Sleeping room	8.75	22:30–23:00	Lighting	36
Sleeping room	8.75	23:00–7:30	4 People sleeping	72
Service room	3.50	7:30–8:30 and 18:30–22:30	0.1 Person (average)	126
Service room	3.50	7:30–8:30 and 18:30–22:30	Lighting (average)	3.6

of year as set out in Table 1. Power of home appliances and lights were selected based on available commercial products and fraction radiant and metabolic rate of different activities of occupants were defined based on American society of heating, refrigerating and air conditioning engineers (ASHRAE) handbook of fundamentals [85].

3.2. Simulation

EnergyPlus ver 8.1 was used as the main simulation tool and *OpenStudio ver. 1.4* as an auxiliary interface. While the simulation was performed on a yearly basis, time was discretized into a series of bins and, for each of these moments, the model equations were solved by the software [86]. As some previous works such as by Corbin et al. [87] and by Hong et al. [88] have highlighted the impact of time-step on accuracy of simulation results, number of time-steps per hour was set to 60 to run the model at each minute. Specifications of materials of the building were provided either by the manufacturer or building component library and dataset of the software.

As mentioned in the literature review, considering moisture transfer in the thermal model of the building is relevant. Therefore, conduction transfer function (CTF), as a sensible heat diffusion technique, coupled with effective moisture penetration depth (EMPD), as an inside surface moisture storage, was selected as heat and moisture transfer technique for surface assemblies of the building. Furthermore, an integrated analytical solution was used to calculate zone air temperature and humidity ratios. Regarding convective heat transfer, Costanzo et al. [80] have compared applicable techniques for calculating exterior convective heat transfer coefficient in *EnergyPlus* and concluded that adaptive technique provides more reliable results. Therefore, in this research the adaptive technique was selected for calculating both interior and exterior convective heat transfer coefficients. This technique classifies surfaces into four different categories based on wind and heat flow directions and defines two types of forced and natural convective heat transfer coefficients for each group. Furthermore, a predictive dynamic clothing insulation technique as a function of outdoor air temperature, as approved by the ASHRAE, was considered for clothing of the occupants.

The simulations were performed in free-floating mode which considers no HVAC (heating, ventilating, and air conditioning) system. Two main thermal zones of the building, i.e. living room and sleeping room, were analyzed in each simulation using different indicators. Prior to applying passive cooling techniques, annual variations of indoor air temperature were calculated for the studied building in Porto climate. These variations provided a baseline relating the instants during the day and throughout a year, when indoor air temperature is excessively high or low. Moreover, the indoor air temperature was compared with outdoor air dry-bulb temperature of coldest and hottest days of the year. Obtaining from weather data, July 6th, August 10th and August 31st were identified as three hottest and January 2nd, January 3rd and December 16th as three coldest days of year in Porto. Results of each of these three

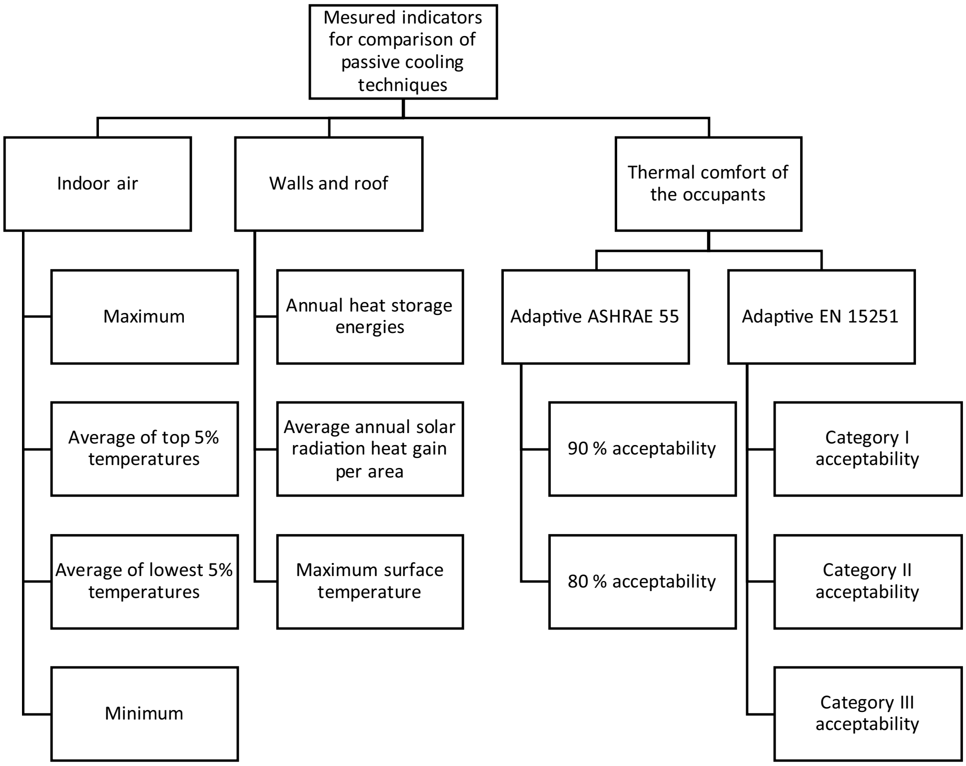

Fig. 2. Indicators assessed in the simulations.

days were measured and averaged to assess thermal performance of the building in the hottest and coldest days of year.

As mentioned in the literature review, different indicators have been used in former studies to assess thermal behavior of buildings. In this work, the impact of passive cooling techniques was inspected though (1) average indoor air temperature of living room and sleeping room; (2) thermal comfort of the occupants; (3) heat storage, solar gain and surface temperature at the exterior walls and roof. For the indoor air temperature, maximum, minimum, average of highest 5% and average of lowest 5% temperatures were calculated. For the walls and roof, annual heat storage energies, annual average solar radiation heat gain per area and maximum surface temperature were inspected. Furthermore, thermal comfort of the occupants was analyzed based on two adaptive models of the most widely used standards, i.e. ASHRAE 55 [23] and EN 15251 [89]. For ASHRAE 55 standard, both 80% and 90% acceptability limits were observed and three acceptability limits of category I (90%), category II (80%) and category III (65%) were considered based on EN 15251 standard. Fig. 2 presents breakdown of the measured indicators in this study. For annual variation of indoor air of living room and sleeping room and relation with outdoor air temperature for three coldest and hottest days of year as well as heat storage, solar gain, and surface temperature, the building was placed in Porto. For comparison of best solution of each passive cooling technique in terms of average indoor air temperature and thermal comfort of the occupants, all three climates of Porto, Mumbai and Nairobi were investigated to highlight impact of climate type on effectiveness of passive cooling techniques. Table 2 provides climate characteristics of these three cities.

3.3. *Passive cooling techniques*

3.3.1. *Shading*

Different types of shading were investigated in this study to assess their impact on indoor air temperature, i.e. average indoor air temperatures for living room and sleeping room and thermal comfort of the occupants. The same shading material was considered for all shading types with thickness of 10 mm, thermal conductivity of 0.1 W m^{-1} K^{-1} and distance of 5 mm to the glazing. Three examined types of shading were inside of the window (interior shade), outside of the window (exterior shade) and between glass layers (middle shade). Activation of shading was conditioned to indoor air temperature reaching 24 °C and applied to all fenestrations of the building.

3.3.2. *Natural ventilation*

Natural ventilation is normally simulated through opening of windows [53]. Wind and stack effects are two types of physical phenomena that induce natural ventilation in buildings. Natural ventilation because of the wind effect is explained by the pressure difference generated by the wind while the stack effect (thermal buoyancy) is based on density and temperature difference between the indoor and outdoor air [48,78]. The previous studies have mainly used wind-driven, buoyancy-driven and the combination of both effects to model natural ventilation in buildings. In this study, both wind and stack effects were considered in accordance with ASHRAE handbook of fundamentals [85] to assess their impacts on indoor air temperature and thermal comfort of the occupants. Hence, flow driven by wind Q_w and flow due to stack effect Q_s were calculated using Eqs. (1) and (2), respectively [85,86].

$$Q_w = C_w A_o F_s V \tag{1}$$

$$Q_s = C_d A_o F_s \sqrt{2g\Delta H_{NPL}(|T_z - T_o|/T_z)} \tag{2}$$

where A_o refers to the opening area of window and was set to 0.05 m^2 for all the windows of living room and sleeping room. F_s is the open area fraction representing the fraction of time defined for activation of opening and V is the outdoor wind speed. g refers to the standard gravity and ΔH_{NPL} represents the height from midpoint of lower opening to the neutral pressure level (NPL) which was set

Table 2
Characteristics of adapted climates in simulations.

Location	Porto, Portugal	Mumbai, India	Nairobi, Kenya
Weather file	IWEC, WMO 085450	IWEC, WMO 430030	IWEC, WMO 637400
Latitude [deg]	N 41° 13′	N 19° 7′	S 1° 19′
Longitude [deg]	W 8° 40′	E 72° 50′	E 36° 55′
Elevation [m] Cooling	73	14	1624
degree days (base 25 °C)	36	1197	67
Heating degree days (base 18 °C)	1433	0	305
Highest average monthly temperature [°C]	19.4	30.0	20.8
Lowest average monthly temperature [°C]	9.4	23.3	16.7
Annual average solar global horizontal irradiance (GHI) [kWh m^{-2} day^{-1}]	4.35	5.90	5.93
Köppen classification	Csb (warm-summer Mediterranean climate)	Aw (tropical savanna climate)	Cwb (subtropical highland variety of Oceanic climate)
ASHRAE climate zone	3C (warm-marine)	1B (very hot-dry)	3A (warm-humid)

to 0. T_z and T_o refer to air dry-bulb temperatures of respectively thermal zone and outdoor.

Several studies such as by Heiselberg et al. [53], Johnson et al. [83] and Breesch and Janssens [50] have highlighted the importance of coefficients in modeling natural ventilation. Breesch and Janssens [50] have determined that discharge coefficient C_d and opening effectiveness C_w have the largest impact on reliability of results. While many studies have considered these two factors constant, the results obtained by Heiselberg et al. [53] suggest that by changing the opening area, window type and temperature difference, the discharge coefficient is different and therefore cannot be considered constant. Therefore, C_w was calculated based on the angle difference between wind direction and effective angle using Eq. (3) [86] that is basically a linear interpolation utilizing the values for different wind directions recommended by ASHRAE handbook of fundamentals [85]. Furthermore, C_d was calculated by Eq. (4) as suggested by ASHRAE handbook of fundamentals [85].

$$C_w = 0.55 - \frac{|Angle \quad difference|}{180} \times 0.25 \tag{3}$$

$$C_d = 0.40 + 0.0045|T_z - T_o| \tag{4}$$

The activation of opening was not based on fraction of time (F_s was set to 1) and three following requirements were assigned: (1) $T_z > 24\,°\mathrm{C}$; (2) $T_z > T_o$ and (3) $V < 20\,\mathrm{m\,s^{-1}}$. Therefore, whenever the indoor air temperature was above 24 °C and outdoor air temperature was less than indoor air temperature, natural ventilation was activated while outdoor wind speed was less than 20 m s^{-1}. Consequently, total ventilation flow rate Q was calculated through superposition process combining both wind and stack effects calculated using Eq. (5) [85,86].

$$Q = \sqrt{{Q_s}^2 + {Q_w}^2} \tag{5}$$

3.3.3. Cool painting

ASHRAE first credited cool roofs in the Standard 90.1 [90] in 1999 characterizing them by minimum initial solar reflectance of 0.70 and minimum initial thermal emittance of 0.75 [91]. The high solar reflectance results in reduction of the amount of absorbed solar radiation in daytime and high emittance helps to dissipate the heat accumulated during day through a major radiant heat exchange at night [15–17]. In *EnergyPlus*, materials are characterized by thermal absorptance, solar absorptance and visible absorptance. Thermal absorptance ε is defined as fraction of incident long wavelength radiation that is absorbed by the material and is equal to thermal emittance for long wavelength radiant exchange. Solar absorptance α represents fraction of incident solar radiation that is absorbed by the material and is equal to 1 minus solar reflectance for opaque materials. Visible absorptance is defined as fraction of incident visible wavelength radiation that is absorbed by the material and is equal to 1 minus visible reflectance. Solar absorptance and visible absorptance are marginally different as solar radiation consists of visible spectrum along with infrared and ultraviolet wavelengths [92]. Color of exterior surfaces can be characterized by their solar absorptance [60]. Moreover, in heat transfer and radiant exchange of exterior surfaces, characteristics of most exterior layer of the surface must be considered [89]. Therefore, applying cool painting to exterior walls and roof was examined in this study by changing solar absorptance of the most exterior layer of these surfaces, i.e. exterior glass fiber laminate, and evaluating its impact on the indoor air temperature. Initial value of solar absorptance of exterior glass fiber laminate, before applying cool painting, was set to 0.3 and subsequently varied from 0.1 to 0.5 to assess the impact of color on the indoor air temperature of the building. It must be noted that EnergyPlus considers default values for thermal, solar and visible absorptance of building component library materials and these values need to be checked before utilization.

3.3.4. Thickness of interior gypsum plaster

All exterior and interior walls, roof and floor of the studied building are considered coated with interior gypsum plaster. Concerning thermal and moisture buffering advantages of gypsum plaster, impact of the gypsum plaster thickness on indoor air temperature was examined in this study. Initial thickness of gypsum plaster was set to 10 mm and subsequently varied from 2.5 mm to 20 mm. As mentioned before, EMPD coupled CTF model was selected as heat balance algorithm for surface assemblies of the building. The EMPD model considers a thin layer of uniform moisture content with thickness d_{EMPD} that dynamically exchanges moisture with the air while exposing to cycling air moisture loads. This model calculates the time derivative of moisture content by Eq. (6) [69]:

$$\frac{du}{dt} = \frac{\partial u}{\partial \omega}\frac{d\omega}{dt} + \frac{\partial u}{\partial T}\frac{dT}{dt} \tag{6}$$

where u is the moisture capacitance of the material, ω is humidity ratio of air in equilibrium with the material, T is temperature and t is time. Moreover, uniform moisture content is a function of ω and is calculated by Eq. (7) [69]:

$$\rho_m A d_{EMPD}\frac{du}{dt} = h_m A(\omega_z - \omega) \tag{7}$$

where ρ_m is the dry bulk density of the absorbing material, i.e. gypsum plaster in this study, A is the surface area, d_{EMPD} is effective moisture penetration depth, h_m is the airside convective mass transfer coefficient and ω_z is the humidity ratio of zone [69]. The

d_{EMPD} can be determined from either experimental or detailed simulation data [86]. In this research, values for moisture properties of gypsum plaster were extracted from the software dataset.

3.4. Thermal comfort models

In this study, thermal comfort of the occupants was analyzed and compared for studied passive cooling techniques based on two adaptive models of the most widely used standards, i.e. ASHRAE 55 [23] and EN 15251 [89]. For ASHRAE 55 standard, both 80% and 90% acceptability limits were observed and three acceptability limits of category I (90%), category II (80%) and category III (65%) were considered based on EN 15251 standard. ASHRAE 62.2 standard [93] requires satisfaction of at least 80% of the occupants for acceptable indoor air quality. Both ASHRAE 55 and EN 15251 standards define comfort temperature T_c based on allowed operative temperature T_{ot} (average of the indoor dry-bulb temperature and the mean radiant temperature of zone inside surfaces) related to the mean outdoor air dry-bulb temperature [86]. Therefore, ASHRAE 55 standard defines comfort temperature T_c by Eq. (8) where T_{mo} is the monthly mean outdoor air dry-bulb temperature [23,86].

$$\text{ASHRAE 55} \quad T_c : \begin{cases} T_{\text{mo}} < 10\,^\circ\text{C} & \text{Not applicable} \\ 10\,^\circ\text{C} < T_{\text{mo}} < 33.5\,^\circ\text{C}, & T_c = 0.31 \times T_{\text{mo}} + 17.8 \\ T_{\text{mo}} > 33.5\,^\circ\text{C} & \text{Not applicable} \end{cases} \tag{8}$$

Consequently, T_{ot} for acceptability limits of 90% and 80% of ASHRAE 55 standard were respectively calculated by Eqs. (9) and (10) [23,86].

$$90\%\ \text{acceptability limits}\ T_{\text{ot}} = T_c \pm 2.5 \tag{9}$$

$$80\%\ \text{acceptability limits}\ T_{\text{ot}} = T_c \pm 3.5 \tag{10}$$

In order to include all hours of occupants' presence in this study, for those temperatures when T_{mo} was less than 10 °C, T_c was modified based on T_{mo} of 10 °C that resulted in T_c of 20.9 °C. Similarly, for those temperatures when T_{mo} was higher than 33.5 °C, T_c was modified based on T_{mo} of 33.5 that led to T_c of 28.185 °C. Hence, the percentage of time during annual occupancy that meets thermal comfort criteria was calculated for each passive cooling technique based on 80% and 90% acceptability limits of the ASHRAE 55 standard.

For the EN 15251standard, comfort temperature T_c was calculated by Eq. (11) where T_{rm} is weighted mean of the previous 7-day outdoor air dry-bulb temperature [86,89].

$$\text{EN 15251}\ T_c : \begin{cases} T_{rm} < 10\,^\circ\text{C} & \text{Not applicable} \\ 10\,^\circ\text{C} < T_{rm} < 15\,^\circ\text{C}, & \text{For lower limits},\ T_c = 23.75\,^\circ\text{C} \\ 10\,^\circ\text{C} < T_{rm} < 15\,^\circ\text{C} & \text{For upper limits},\ T_c = 0.33 \times T_{rm} + 18.8 \\ 15\,^\circ\text{C} < T_{rm} < 30\,^\circ\text{C} & T_c = 0.33 \times T_{rm} + 18.8 \\ T_{rm} > 30\,^\circ\text{C} & \text{Not applicable} \end{cases} \tag{11}$$

Accordingly, three acceptability limits of category I (90%), category II (80%) and category III (65%) were respectively calculated by Eqs. (12), (13) and (14) [86,89].

$$\text{Category I (90\%) acceptability limits}\ T_{ot} = T_c \pm 2 \tag{12}$$

$$\text{Category II (80\%) acceptability limits}\ T_{ot} = T_c \pm 3 \tag{13}$$

$$\text{Category III (65\%) acceptability limits}\ T_{ot} = T_c \pm 4 \tag{14}$$

In this study, to consider all hours of occupants' presence and those temperatures when T_{rm} was less than 10 °C, T_c was modified based on T_{rm} of 10 °C that led to T_c of 23.75 °C. Likewise, for those temperatures when T_{rm} was higher than 30 °C, T_c was modified based on T_{rm} of 30 °C that resulted in T_c of 28.7 °C. Therefore, the percentage of time during annual occupancy that meets thermal comfort criteria was calculated for each passive cooling technique based on three acceptability limits of categories I, II and III of the EN 15251 standard.

4. Results and discussion

4.1. Reference building

Figs. 3 and 4 show annual variations of indoor air temperature of respectively living room and sleeping room of the reference building, before applying any passive cooling technique. These graphs illustrate at what time of the day and when in the year the indoor air temperature reaches high and low values. Moreover, how different periods of presence of occupants and presence of home appliances affect the indoor air temperature. However, regarding the time of the year both living room and sleeping room have presented similar thermal performance.

Figs. 5 and 6 present average indoor air temperature of living room and sleeping room as well as outdoor air temperature for respectively the three coldest and the three hottest days of year in Porto. The results show overall correspondence between outdoor and indoor air temperatures. One interesting finding of these results is high influence of presence of occupants on indoor air temperature. While in summer due to high outdoor temperature and subsequent increase in indoor air temperature this effect is less visible, the effect is more significant in winter due to lower outdoor temperature. Noting Fig. 6 and daily schedule of presence of occupants presented in Table 3, at 7.30 (marked by line A) occupants move from sleeping room to the living room. As a consequence, there is a slight boost in indoor air temperature of living room while outdoor and sleeping room air temperatures start decreasing at this instant. Similarly, when occupants shift from the living room to the sleeping room at 22.30 (marked by line B) there is an increment in indoor air temperature of the sleeping room and a reduction in indoor air temperature of the living room.

4.2. Shading and natural ventilation

Table 3 compares the impact of different shading techniques and natural ventilation on average indoor air temperature of the studied building in Porto. As all of these passive cooling strategies were aimed at decreasing indoor air temperature, none has affected minimum or average of lowest 5% temperatures significantly. Among different types of shading, exterior shade presented highest impact on reducing the indoor air temperature followed by middle shade and interior shade. Regarding impact of each technique on reduction of high temperatures, analogous decline was observed for both average of highest 5% and maximum indoor air temperatures. However, comparing exterior shade and natural ventilation, while both have nearly equal value for average of highest 5% temperatures, exterior shade has reduced maximum temperature 1.3 °C more than natural ventilation.

4.3. Cool painting

Table 4 presents impact of solar absorptance α of exterior walls and roof on average indoor air temperature of the studied building in Porto. The results point out the reduction of both maximum and average of highest 5% temperatures by decreasing α, i.e. painting them with a brighter color. However, a slight decrease in both minimum and the average of lowest 5% temperature was also detected that can be considered a disadvantage of this passive cooling technique. Regarding indicators of indoor air temperature, values of

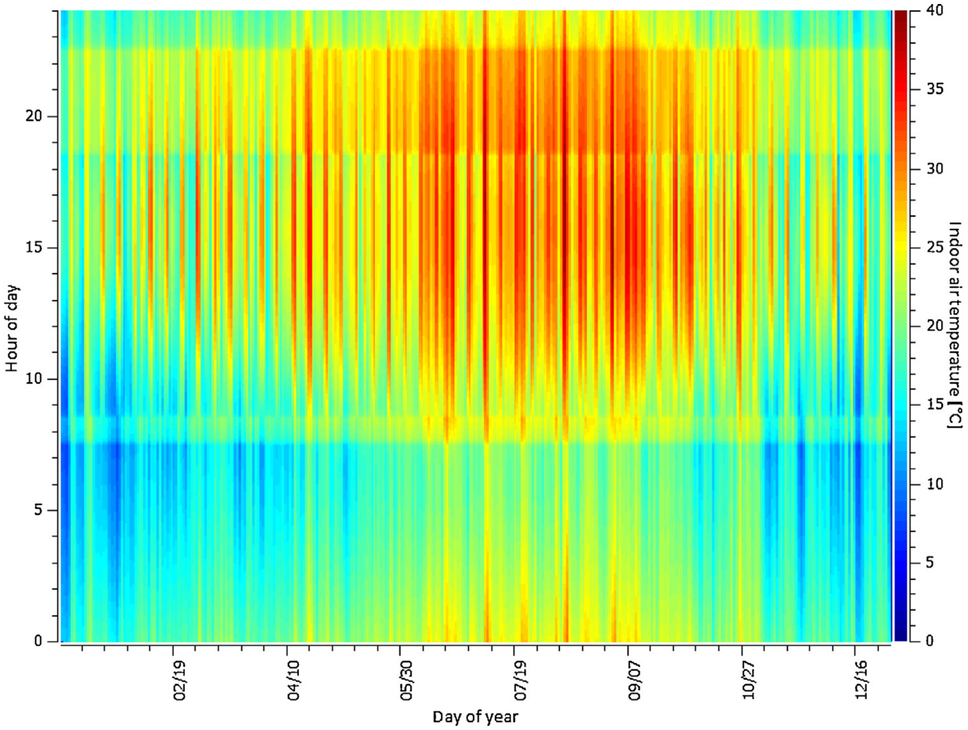

Fig. 3. Indoor air temperature of living room of the reference building—virtual location: Porto.

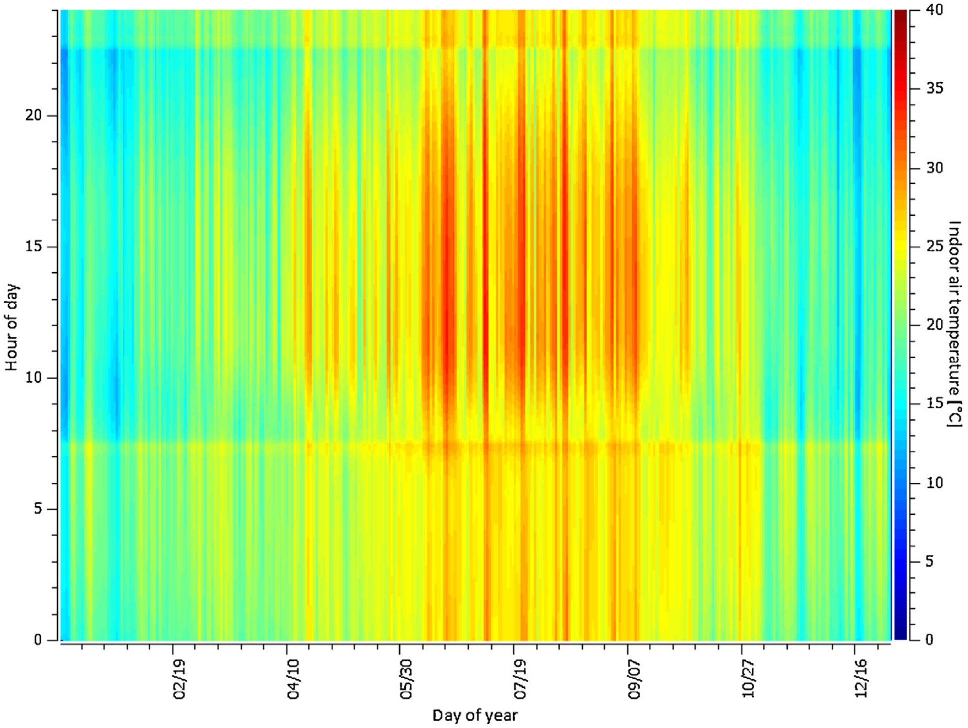

Fig. 4. Indoor air temperature of sleeping room of the reference building—virtual location: Porto.

Table 3
Impact of different shading techniques and natural ventilation on indoor air temperature—virtual location: Porto.

	Maximum temperature [°C]	Average of highest 5% temperatures [°C]	Average of lowest 5% temperatures [°C]	Minimum temperature[°C]
Reference building	36.9	32.0	13.0	9.0
Interior shade	35.3	30.8	13.0	9.0
Middle shade	33.1	29.3	12.9	9.0
Exterior shade	32.8	29.2	12.9	8.9
Natural ventilation	34.1	29.1	13.0	8.9

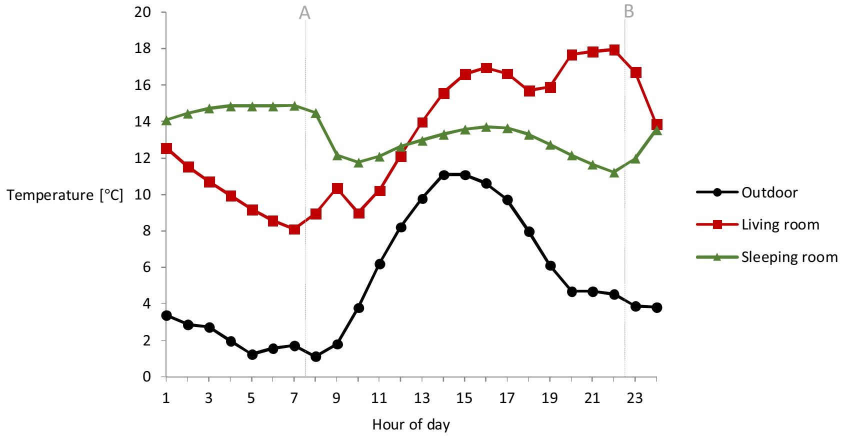

Fig. 5. Average daily indoor air temperature of the reference building in three coldest days of year—virtual location: Porto.

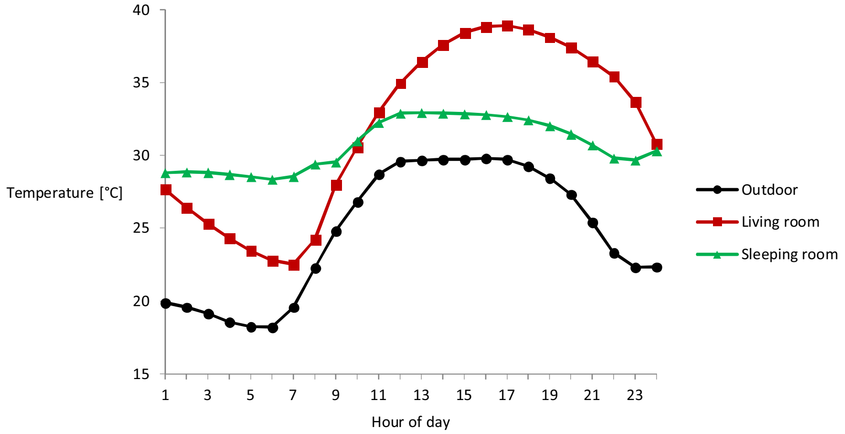

Fig. 6. Average daily indoor air temperature of the reference building in three hottest days of year—virtual location: Porto.

Table 4
Impact of solar absorption (α) of exterior walls and roof on indoor air temperature—virtual location: Porto.

Solar absorptance (α) of exterior walls and roof	Maximum temperature [°C]	Average of highest 5% temperatures [°C]	Average of lowest 5% temperatures [°C]	Minimum temperature[°C]
0.50	37.8	32.9	13.2	9.2
0.45	37.5	32.7	13.2	9.1
0.40	37.3	32.5	13.1	9.1
0.35	37.0	32.2	13.0	9.0
0.30	36.9	32.0	13.0	9.0
0.25	36.5	31.7	12.9	8.9
0.20	36.2	31.5	12.8	8.8
0.15	35.9	31.2	12.7	8.7
0.10	35.6	31.0	12.7	8.6

maximum and average of highest 5% temperatures presented reasonable compatibility as well as those for the minimum and average of lowest 5% temperatures.

4.4. *Thickness of interior gypsum plaster*

Table 5 illustrates the impact of the interior gypsum plaster thickness on the average indoor air temperature of the studied building in Porto. The results point out that rise in thickness of interior gypsum plaster decreases high and increases low indoor air temperatures. Concerning indicators of indoor air temperature, values of maximum and average of highest 5% temperatures showed fitting conformity as well as those for minimum and average of lowest 5% temperatures.

4.5. *Comparison of techniques*

After evaluating the impact of each passive cooling technique on the average indoor air temperature of the studied building, the best solution of each technique, i.e. the one resulted in topmost reduction of high indoor air temperatures, was identified to be compared in three different climates of Porto, Mumbai and Nairobi. Consequently, exterior shade was selected as the best shading technique. Moreover, cool painting of exterior walls and roof to achieve α of 0.1 and increasing thickness of the interior gypsum plaster to 20 mm were concluded as two other most advantageous techniques. Applying these three techniques in addition to natural ventilation integrated was evaluated to attain optimized model of the studied building featuring passive cooling techniques.

Table 5
Impact of thickness of interior gypsum plaster on indoor air temperature—virtual location: Porto.

Thickness of interior gypsum plaster [mm]	Maximum temperature [°C]	Average of highest 5% temperatures [°C]	Average of lowest 5% temperatures [°C]	Minimum temperature[°C]
2.5	39.7	33.5	11.7	7.3
5.0	38.5	32.8	12.2	8.0
7.5	37.5	32.4	12.6	8.5
10.0	36.9	32.0	13.0	9.0
12.5	36.1	31.7	13.2	9.3
15.0	35.6	31.5	13.4	9.6
17.5	35.2	31.3	13.6	9.9
20.0	34.8	31.1	13.8	10.1

Table 6
Comparison of impacts of different passive cooling techniques on average indoor air temperature—virtual location: Porto.

	Maximum temperature [°C]	Average of highest 5% temperatures [°C]	Average of lowest 5% temperatures [°C]	Minimum temperature[°C]
Reference building	36.9	32.0	13.0	9.0
Exterior shade	32.8	29.2	12.9	8.9
Natural ventilation	34.1	29.1	13.0	8.9
Cool painting	35.6	31.0	12.7	8.6
Increase in thickness of interior gypsum plaster	34.8	31.1	13.8	10.1
All techniques combined	31.0	26.5	14.7	9.7

Table 7
Comparison of impacts of different passive cooling techniques on average indoor air temperature—virtual location: Mumbai.

	Maximum temperature [°C]	Average of highest 5% temperatures [°C]	Average of lowest 5% temperatures [°C]	Minimum temperature[°C]
Reference building	40	37.4	25.3	21.9
Exterior shade	36.3	34.5	23.9	20.7
Natural ventilation	37.9	35.0	24.4	20.9
Cool painting	38.6	36.2	24.8	21.2
Increase in thickness of interior gypsum plaster	38.5	36.4	26.3	23.3
All techniques combined	34.5	32.2	23.7	21.3

Table 8
Comparison of impacts of different passive cooling techniques on average indoor air temperature—virtual location: Nairobi.

	Maximum temperature [°C]	Average of highest 5% temperatures [°C]	Average of lowest 5% temperatures [°C]	Minimum temperature[°C]
Reference building	35.1	32.4	20.1	17.1
Exterior shade	32.0	29.8	19.8	17.0
Natural ventilation	31.4	28.6	19.7	16.9
Cool painting	33.9	31.5	19.6	16.8
Increase in thickness of interior gypsum plaster	33.4	31.4	20.8	18.2
All techniques combined	29.3	26.7	20.0	17.6

4.5.1. *Comparison of techniques in terms of indoor air temperature*

Tables 6–8 compare the impact of each and all of passive cooling techniques on the studied building in terms of average indoor air temperature for respectively Porto, Mumbai and Nairobi climates. These results point out that all these passive cooling techniques have decreased high indoor air temperatures in all climates comparing with the reference building. Overall, exterior shading and natural ventilation showed better performance than increase in thickness of gypsum plaster and cool painting. Moreover, applying all techniques combined to the reference building proved to be highly effective to be considered as an optimized model for the building. For instance, it resulted in reduction of around 6 °C for both average of highest 5% and maximum temperatures in climate of Nairobi.

The results indicate that the ranking of these techniques depends on climate and use of either average of highest 5% or maximum temperatures though. Comparing exterior shading with natural ventilation, exterior shading demonstrated better performance in Mumbai while natural ventilation proved to be more effective in climate of Nairobi. Furthermore, average of highest 5% and maximum temperatures did not demonstrate compatibility for comparison of exterior shading and natural ventilation in climate of Porto as already discussed in the Section 4.2. While none of these techniques were aimed at changing the low indoor air temperatures of the building in winter, considerable findings were detected regarding this matter. Increase in thickness of gypsum plaster resulted in rise of minimum and average of lowest 5% temperatures while cool painting influenced them adversely.

4.5.2. *Comparison of techniques in terms of thermal comfort*

Figs. 7–9 compare passive cooling techniques in terms of selected adaptive comfort models for respectively Porto, Mumbai and Nairobi climates. This comparison points out that effectiveness of the studied techniques depends on the climate as well as the adapted thermal comfort models. Similar to the results of indoor air temperature, natural ventilation and exterior shading proved to be highly effective in improving thermal comfort of the occupants in all climates measured by all adapted thermal comfort models. Regarding cool painting, although it has decreased hours of thermal discomfort at high temperatures, noting its negative impact on low temperatures, the overall influence is less signifi-

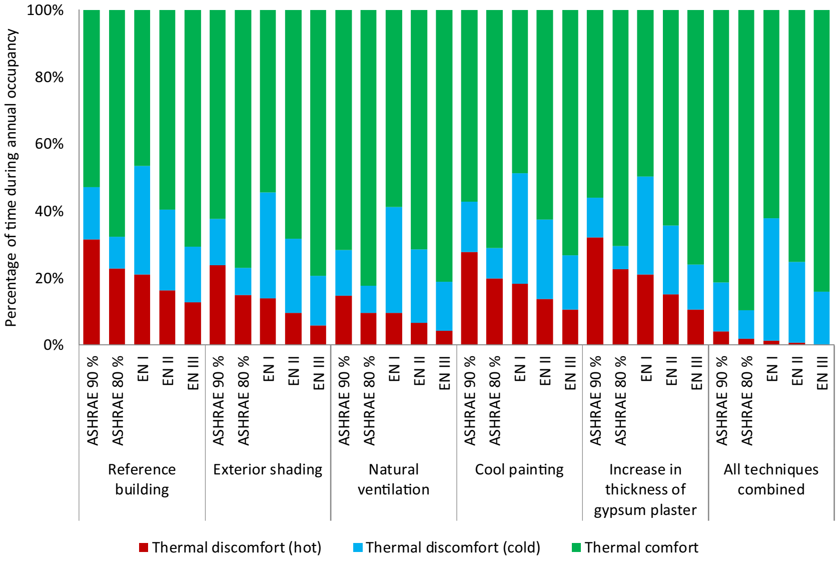

Fig. 7. Comparison of thermal comfort of the occupants for different passive cooling techniques—virtual location: Porto.

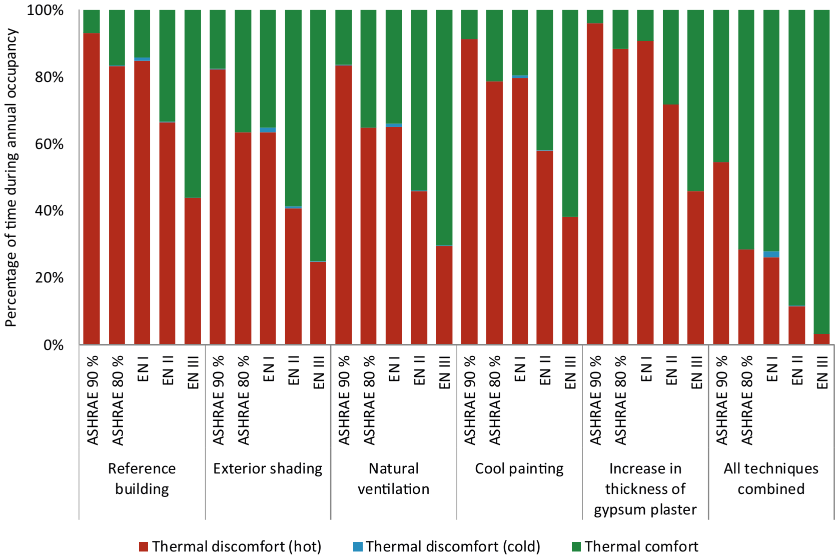

Fig. 8. Comparison of thermal comfort of the occupants for different passive cooling techniques—virtual location: Mumbai.

cant in comparison with natural ventilation and exterior shading. Another important finding was that even though increase in thickness of interior gypsum plaster demonstrated positive impact on indoor air temperatures in all the studied climates, thermal comfort assessment showed the contrary for the climate of Mumbai. However, it presented positive influence of this technique for the climate of Porto. This can be explained by the fact that this technique increases low indoor air temperatures that does not seems to be fully advantageous in a climate such as Mumbai where the lowest average monthly temperature is 23.3 °C. Moreover, unlike exterior shading and natural ventilation that perform upon high indoor air temperature, the impact of higher thermal inertia provided by this technique is not necessarily concurrent with hours of occupancy. It must also be noted that the annual occupancy refers to around 70% of the year when the occupants are in either living room or sleeping room. This period consists of all nights and does not include weekday afternoons. Therefore, this can affect the impact of studied passive cooling techniques in terms of adaptive thermal comfort compared with the indoor air temperature.

4.5.3. Comparison of impact of techniques on exterior walls and roof

Studying other indicators in addition to indoor air temperature and thermal comfort can enlighten causes and effects associated with passive cooling techniques. Table 9 compares passive cooling techniques in terms of annual heat storage energies, average annual solar radiation heat gain per area and maximum surface temperature for exterior walls and roof in climate of Porto. The comparison of heat storage energies explains how increased thickness of gypsum plaster has decreased indoor air temperature by storing the heat. Moreover, the results points out how cool painting of exterior walls and roof, i.e. change of α from 0.3 to 0.1, has lowered solar radiation heat gain per area by 44%. Furthermore, applying cool painting has resulted in reduction of 8.9 °C in maximum surface temperature of walls and roof.

5. Conclusions

This article compared different passive cooling techniques for a pre-fabricated building made of a sandwiched-structured compos-

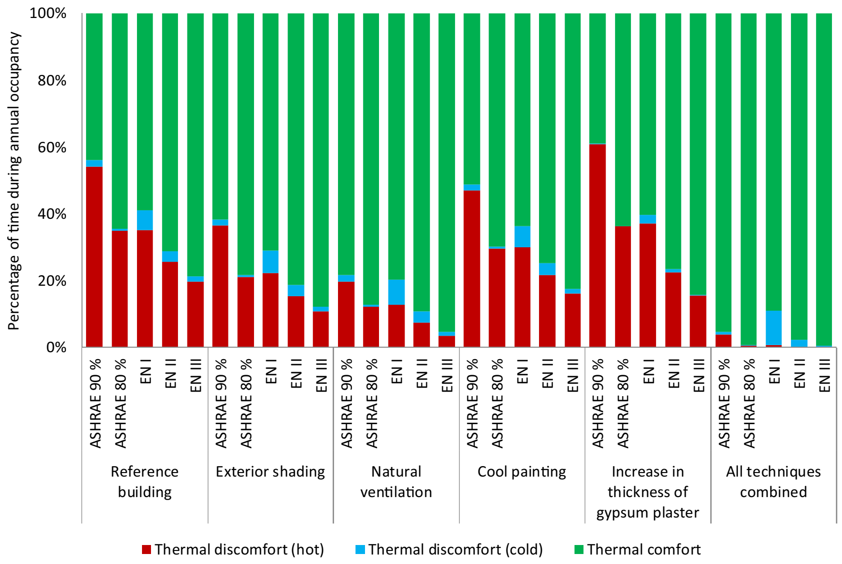

Fig. 9. Comparison of thermal comfort of the occupants for different passive cooling techniques—virtual location: Nairobi.

Table 9
Impact of passive cooling techniques on exterior walls and roof.

	Reference building	Exterior shading	Natural ventilation	Cool painting	Increase in thickness of gypsum plaster	All techniques combined
Annual heat storage energies [MJ]	2.03	2.02	2.04	2.07	2.68	2.84
Average annual solar radiation heat gain per area [$\mathrm{W\,m^{-2}}$]	36.78	36.78	36.78	16.22	36.78	16.22
Maximum surface temperature [°C]	45.5	45.3	45.5	36.6	45.5	34

ite. The thermal performance of the building was firstly assessed by simulating average indoor air temperature annually and daily for the three coldest and the hottest days of year. Calculating four indicators of maximum, minimum, average of highest 5% and average of lowest 5% temperatures, four different passive cooling techniques (shading, natural ventilation, cool painting and thickness of interior gypsum plaster) were investigated in terms of their impact on average indoor air temperature. Afterwards, the impact of the best solution of each passive cooling technique was compared in three different climates of Porto, Mumbai and Nairobi in terms of average indoor air temperature as well as thermal comfort of the occupants based on two acceptability limits of ASHRAE 55 and three acceptability limits of EN 15251 standards. Furthermore, annual heat storage energies, average annual solar radiation heat gain per area and maximum surface temperature were inspected to assess causes and effects associated with the studied techniques. By combining the best solution of each technique, the results show that thermal comfort of the occupants is achieved during almost all annual occupancy in Nairobi climate.

Thermal analysis of the building showed a substantial impact of the presence of occupants on indoor air temperature, especially in winter. A possible explanation for this observation is the low thermal inertia of the building and limited space for the occupants. Moreover, studying indoor air temperature confirmed the positive influence of all studied passive cooling techniques on decreasing high temperatures. However, our study demonstrated the superiority of natural ventilation and exterior shading followed by cool painting and increase in thickness of gypsum plaster. Regarding performance at low temperatures, exterior shading and natural ventilation were shown to have little or no impact. Cool painting slightly decreased low temperatures, which can be explained by lower solar absorptance of exterior walls and roof. Furthermore, an increase in gypsum plaster thickness raised the lower temperature, which can be justified by the increase in thermal mass and heat storage of the building in this situation. An interesting finding on the impact of the thickness of gypsum plaster was its positive effect on both high and low temperatures, due to an increase of the thermal storage effect.

The results also highlighted significant impact of climate on effectiveness of the studied passive cooling techniques. For instance, exterior shading demonstrated larger influence in Mumbai while natural ventilation proved to be more effective in climate of Nairobi. Moreover, while increase in thickness of plaster proved to be beneficial in improving thermal comfort of the occupants in Porto by decreasing high and increasing low indoor air temperatures, it did not seem to be fully advantageous in climate of Mumbai, where the lowest monthly average temperature is 23.3 °C. It must be noted that while exterior shading and natural ventilation are normally actuated upon high indoor air temperature, cool painting and increase in thickness of gypsum plaster are not contingent upon indoor air or comfort of the occupants.

Considering high indoor air temperatures, two indicators of maximum indoor air temperature and average of highest 5% indoor air temperatures indicated different preeminence for some of the studied techniques. Therefore, inspecting sets of top temperatures instead of peak temperature is suggested for future studies. Considering thermal comfort of the occupants, adaptive thermal comfort models depend on presence of occupants and the hours of occupancy is around 70% of the year including all nights and excluding weekday afternoons. Hence, it may slightly affect the impact of studied passive cooling techniques in terms of adaptive thermal comfort compared with the indoor air temperature. Moreover, ASHRAE 55 considers mean outdoor air temperature based on the last month whereas EN 15251 only considers the previous 7 days. Therefore, minor differences between hours of thermal comfort based on these two standards were expected.

Inspecting further indicators helped better explanation of the causes and effects associated with passive cooling techniques. The comparison in terms of heat storage energies showed how an increase in thickness of gypsum plaster contributes to both decreasing high and increasing low temperatures. Considering the low thermal inertia of the building, gypsum plaster increased heat storage of walls and roof and consequently balanced energy in day time and night time. Furthermore, observing solar radiation heat gain illustrated how cool painting can decrease high temperatures in hot scenarios by means of preventing heat gain. Inspecting surface temperatures also pointed out that cool painting can reduce maximum surface temperature by up to 8.9 °C in climate of Porto. Lowering surface temperature can be important for manufacturing requirement of panels and may provide new opportunities for using alternative materials. Observing the results of this study and reviewing three types of passive cooling techniques mentioned in introduction, it can be summed up that shading and cool painting contribute in reduction of high indoor air temperatures through prevention of heat gains, increase in thickness of gypsum plaster via modulation of heat gains and natural ventilation by heat dissipation.

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