

Improving the livability of lightweight emergency architectures: a numerical investigation on a novel reinforced-EPS based construction system

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ABSTRACT

In the aftermath of catastrophic events, lightweight construction systems are often used to build temporary emergency architectures. However, if suitable environmental control systems are not present, as may occur in post-disaster scenarios, these buildings provide poor indoor thermal conditions, especially in hot climates, which may jeopardize the occupants' physical and mental health in case of longer periods of occupations. In these contexts, passive cooling techniques are the preferred strategies to improve the indoor thermal environment. However, only a few papers evaluated the effectiveness of these measures on emergency buildings, also considering calibrated simulations, different climates, costs, and operational feasibility. In this work, the thermal performance of a novel emergency construction system, still not sufficiently studied in the literature and based on the assembly of 3D-reinforced EPS panels, is examined. First, a numerical model of an experimental unit is calibrated on experimental data. Then, the thermal performance in hot and temperate climates of a reference building, recently adopted in emergency scenarios, is numerically evaluated and improved through passive cooling measures, i.e. shading, thermal buffering, natural ventilation, and cooling materials. Results show high summer thermal discomfort in all climates. The efficacy of the different measures depends on climatic contexts, with natural ventilation, combined with cool roof materials or blinds (for temperate and hot climates, respectively), providing the best trade-off between thermal comfort, costs, and feasibility. However, the summer indoor thermal discomfort cannot be completely reduced. This study helps decision-makers and people to correctly improve the living conditions and sustainability of emergency architectures.

KEYWORDS

Emergency architecture; Temporary housing; Affordable housing; Reinforced EPS; Lightweight construction system; Passive strategy.

27 NOMENCLATURE

28 λ	Thermal conductivity
29 ς	Specific heat capacity
30 ϱ	Density
31 All_a	All strategies combined in aged conditions
32 All_n	All strategies combined in not aged conditions
33 AN	Ancona
34 B	Shading (slatted blinds)
35 CR	Cool roof passive strategy
36 CRa	Cool roof passive strategy in aged conditions
37 CRn	Cool roof passive strategy in not aged conditions
38 CRW	Cool roof and walls passive strategy
39 CRWa	Cool roof and walls passive strategy in aged conditions
40 CRWn	Cool roof and walls passive strategy in not aged conditions
41 $CVRMSE$	Coefficient of Variation of the Root Mean Square Error
42 $EMPD$	Effective moisture penetration depth
43 G	Internal thermal inertia increasing (gypsum boards)
44 GHI	Global horizontal irradiance
45 ND	New Delhi
46 MBE	Mean Bias Error
47 NV	Natural ventilation
48 $RMSE$	Root Mean Square Error
49 SP	Sao Paulo
50 SR	Solar reflectance
51 T_c	Thermal comfort limits
52 $T_{i_{exp}}$	Experimental indoor air temperature
53 $T_{i_{num}}$	Numerical indoor air temperature
54 T_{max}	Maximum numerical indoor air temperature

55	$T_{max,5\%}$	Average of the highest 5% numerical indoor air temperatures
56	T_{min}	Minimum numerical indoor air temperature
57	$T_{max,5\%}$	Average of the lowest 5% numerical indoor air temperatures
58	T_{rm}	Weighted mean of the previous 7-day outdoor air dry-bulb temperature
59	$T_{si_{exp}}$	Experimental indoor surface temperature
60	$T_{si_{num}}$	Numerical indoor surface temperature
61	$T_{o_{exp}}$	Experimental outdoor air temperature
62	$U-value$	Thermal transmittance

63 1 INTRODUCTION

64 In recent years, dramatic events such as anthropogenic and natural disasters are increasingly frequent (CRED 2017;
65 Eurostat 2018; UNHCR 2019a). These events often lead to severe urban destruction, which renders cities unusable
66 and affects the sustainable development of the urban environment and society (Rouhanizadeh and Kermanshachi
67 2020).

68 Housing provision has a crucial role in the recovery process, allowing displaced people to re-establish some
69 normalcy in their life, providing the conditions to live with protection, security, comfort, and privacy, also preventing
70 the rising of deaths and the spread of diseases (Félix et al. 2014). However, in a chaotic post-disaster situation,
71 providing new houses (or repairing damaged ones) may take time. Thus, it is mandatory in the meanwhile to provide
72 temporary accommodations where locating people as quickly as possible (Arslan and Cosgun 2008; Félix et al. 2014;
73 Seike et al. 2018).

74 Prefabricated, lightweight, modular construction systems are increasingly used to build temporary
75 accommodations and field hospitals in emergency scenarios thanks to their high speed of construction, portability,
76 cheapness, and adaptability (IFRC 2013; Félix et al. 2013, 2014; Chang-Richards et al. 2014; Arouri et al. 2015; Barreca
77 and Tirella 2017; Tanyer et al. 2018). The importance of such construction techniques for emergency has been recently
78 emphasized also by the COVID-19 pandemic, during which, to face the sanitary emergency, most countries were
79 forced to build new emergency hospitals, housing or to enlarge existing ones in a matter of few weeks to add
80 thousands of beds for treatment or quarantine (Luo et al. 2020; Megahed and Ghoneim 2020). However, being mainly
81 designed for rapid construction and short periods of occupancy, these construction systems often provide poor
82 thermal comfort conditions during the stay of people (especially due to summer indoor overheating) if a suitable

83 environmental control system is not present, as may occur in post-disaster scenarios (due to the lack of facilities or
84 energy supply), or for economic restrictions (Pearlmutter and Meir 1995; Bernstein et al. 2011; Wallbaum et al. 2012;
85 Barbosa et al. 2017; Gan et al. 2017; Thapa et al. 2018). This phenomenon occurs especially in countries characterized
86 by hot climates, where these buildings are more and more frequently adopted (Huang et al. 2015; Kim et al. 2015;
87 Wang et al. 2016; Albadra et al. 2018; Thapa et al. 2018; D’Orazio and Maracchini 2019), but it is also increasingly
88 frequent in temperate climates, also considering the rise in atmospheric temperature due to global warming. As a
89 result, the physical and mental health of the occupants may be further jeopardized by this condition, leading to
90 diseases and mortality when prolonged exposure is concerned (Wang et al. 2015). This notwithstanding, it is not
91 uncommon that forcibly displaced people may end up living in these buildings for years or even decades, turning
92 temporary camps into (semi-)permanent habitats (UNHCR 2012; UNRWA 2021). This is the case, for example, of
93 the Dadaab refugee camp in Kenya, which hosted Somali refugees from 1991 and which has continued to grow to
94 the point that, if today it were a city, it would be the fourth-largest city of Kenya (UNHCR 2019b). Overall, to date
95 about 60 million displaced people live in temporary accommodations all around the world (IDMC 2018, 2019a;
96 UNHCR 2019c).

97 An accurate investigation of the indoor thermal environment of these construction systems, also considering the
98 possible implementation of suitable measures to reduce indoor overheating and improve livability, is then strongly
99 needed to allow displaced people to improve correctly the indoor building thermal comfort during buildings service
100 life and to provide more comfortable and healthier living spaces (IFRC 2013; Lee et al. 2016; Albadra et al. 2017;
101 Shinohara et al. 2017).

102 In the absence of a suitable environmental control system, passive cooling techniques are the preferred measures
103 to reduce indoor overheating in hot climates (Santamouris and Kolokotsa 2013; Bhamare et al. 2019). However, while
104 there are a lot of studies focused on the use of passive strategies in traditional buildings (see e.g. (Santamouris and
105 Kolokotsa 2013; Harkouss et al. 2018; Del Rio et al. 2019; Firfiris et al. 2019; Tuck et al. 2019; Bhamare et al. 2019;
106 Belmonte et al. 2021; Jung et al. 2021; Wang et al. 2021)), only a few and recent works investigate the impact and
107 effectiveness of these measures when applied in low-cost/emergency construction systems (Wang et al. 2013, 2017,
108 2019; Marin et al. 2016; Samani et al. 2016). In (Samani et al. 2016), a numerical evaluation of the effectiveness in
109 different hot climates of several passive cooling techniques (such as cool painting, increase in the thickness of interior
110 gypsum plaster, shading, and natural ventilation), applied to a prefabricated lightweight building made of sandwiched-

structured composite panels (two glass-fiber-reinforced laminates sandwiching a light core of XPS and equibiaxial woven roving of fiberglass), was carried out. The results pointed out that the combined implementation of all the techniques provides thermal comfort during almost all annual occupancy in Nairobi. This notwithstanding, even in this case, a validation of the numerical model was not carried out. In (Wang et al. 2013) and (Wang et al. 2019), the thermal performance of lightweight prefabricated houses placed in Chengdu city, China, was improved by using phase change materials (PCM). Similarly, in (Marin et al. 2016) the possible use of PCM-enhanced gypsum board to increase the thermal performance of relocatable, lightweight buildings was numerically evaluated under different climatic conditions. Finally, in (Wang et al. 2017), different passive cooling measures (window blind, screens, moveable fabric with high reflectance applied to wall and roof) were applied to a prefabricated house made of insulated color metal sheet sandwich panels, placed in Chengdu city, China. The numerical results indicated that the maximum reduction of unacceptable hours of about 30% can be obtained by simultaneously using movable fabrics and window blinds, i.e. without using all passive measures together (thus, saving implementation costs).

However, these studies mainly focused on the application or optimization of a single passive strategy and in a specific climate (Wang et al. 2013, 2019; Marin et al. 2016), while only a few carried out a comparison between different strategies (Samani et al. 2016; Wang et al. 2017) or considered their effectiveness in different climatic scenarios (Marin et al. 2016; Samani et al. 2016). In addition, few studies also considered costs or operational feasibility aspects in their comparison (Borge-Diez et al. 2013b). Finally, most of these works mainly rely on the use of not validated numerical models, thus requiring further experimental investigations to verify the accuracy of the modeling assumptions and the reliability of the numerical results (Borge-Diez et al. 2013b; Marin et al. 2016; Samani et al. 2016).

Among low-cost, prefabricated, and lightweight construction systems, those based on synthetically produced materials (such as EPS walls) present several advantages in terms of sustainability and affordability and are then potentially suitable for temporary and affordable accommodations (Wallbaum et al. 2012; Ramli Sulong et al. 2019). However, to the best authors' knowledge, there are no works that try investigating the indoor environment of these systems in different climates and the effectiveness of passive cooling techniques in improving their indoor livability.

For these reasons, in this work, the effectiveness of several passive cooling strategies in reducing indoor overheating and thermal discomfort of a novel EPS-reinforced based emergency architecture was evaluated in different climatic locations through calibrated numerical simulations. The passive measures are also compared in terms of costs and operational feasibility to provide suggestions on how to correctly improve the livability of these

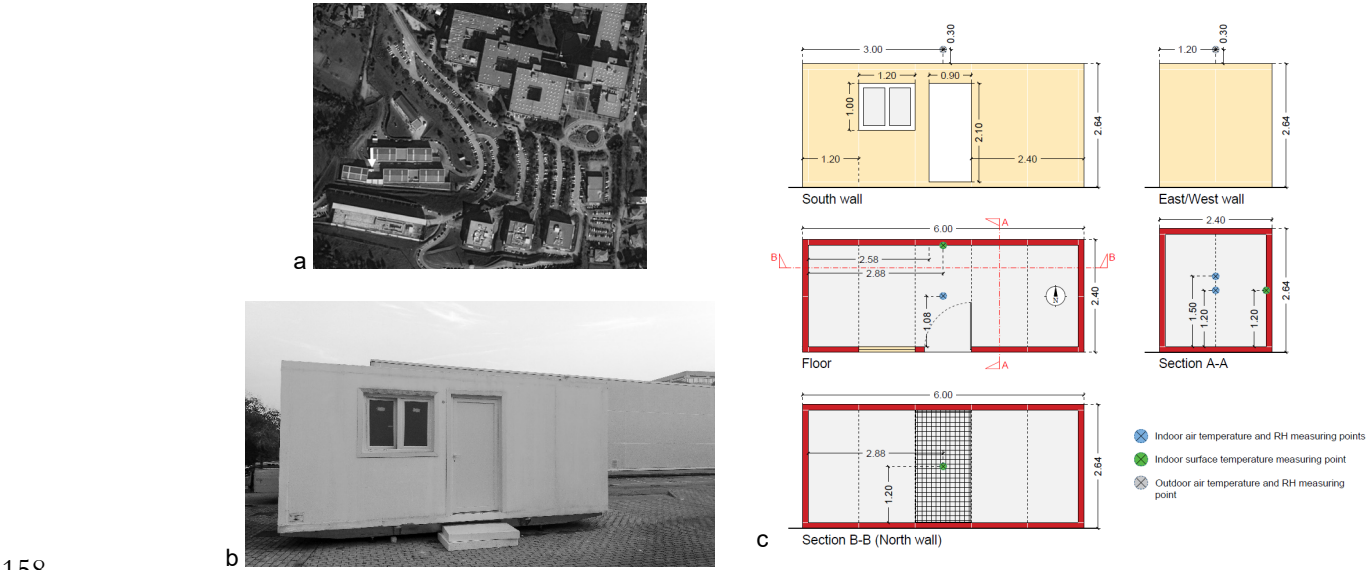
139 systems to allow a safer long-term use and a more sustainable urban regeneration.

140 **2 PHASES, MATERIALS, AND METHODS**

141 **2.1 Phases**

142 The present study can be subdivided into three main phases:

- 143 • in the first phase, a reinforced EPS-based temporary unit (referred to as “experimental unit” in the following) is
144 purposely built, and its indoor thermal environment is monitored (see Fig. 1). The collected experimental data
145 are then used to calibrate a numerical model to verify the accuracy of modeling assumptions, and to provide
146 reliable input parameters for the numerical analysis;
- 147 • then, the summer thermal response of a housing module (referred to as “reference building” in the following,
148 see Fig. 2) recently adopted as both temporary and affordable housing solutions in emergency camps and
149 developing countries (see e.g. (Sferra 2017)) is evaluated through a numerical model (created based on the
150 outcomes of the calibration phase) considering a free-running mode and different climatic locations. The
151 reference building is a temporary housing solution, then it is intended to be occupied for several years by
152 displaced people (Félix et al. 2013);
- 153 • finally, to provide suggestions for the correct improvement of the livability of lightweight construction systems
154 adopted in emergency scenarios, the effectiveness of several low-cost, easy-to-apply passive cooling measures in
155 reducing indoor thermal discomfort due to overheating (such as natural ventilation, shadings, increasing of
156 indoor thermal inertia, and cooling finishing materials) is evaluated, also considering the negative effect on
157 minimum indoor air temperatures, their costs and operational feasibility, and also their possible combination.



158 **Fig. 1. Experimental unit.**

Fig. 1. a) Location of the experimental unit inside the laboratory campus; b) experimental unit; c) geometrical description of the experimental unit and sensors measuring points (dimensions in meters).

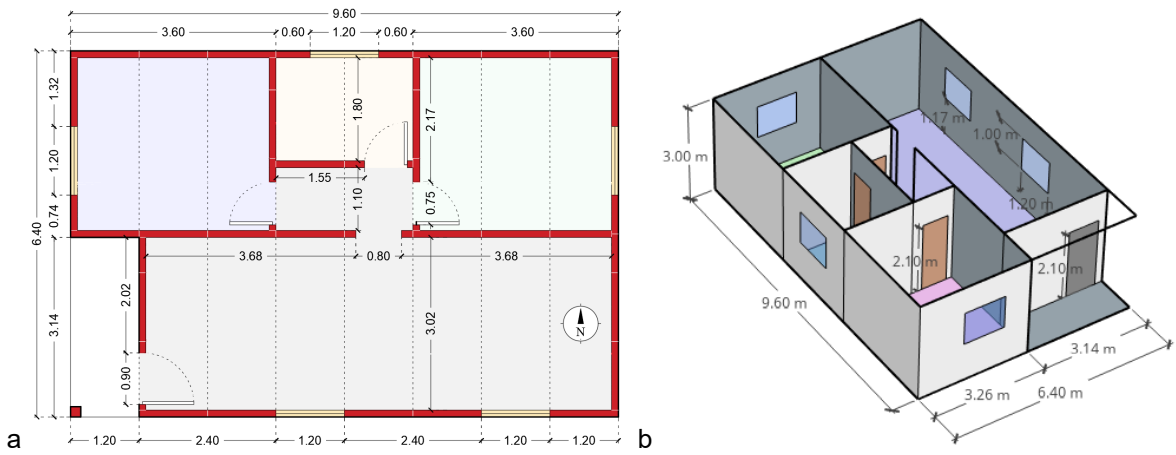


Fig. 2. a) Floor and b) schematic model of the reference building adopted for the numerical simulations. Each color corresponds to a different thermal zone. Dimensions in meters.

2.2 The construction system

The construction system investigated in this study, named HOMEDONE, has been recently used as re-locatable temporary housing in Italy after a recent earthquake (Central Italy earthquakes, 2016), as a specialty field hospital to increase the admission capacity of a designated hospital during the recent COVID-19 pandemic in the Italian Marche region, and as affordable housing solutions in developing countries with increasing affordable housing demand (Sferra 2017). It is based on the assembly of prefabricated structural reinforced-EPS panels (Fig. 3), consisting of high-strength tridimensional electro-welded galvanized steel wires (S235JR steel bars with a diameter of 3 mm) embedded in high-density EPS panels (from 45 kg/m³ to 65 kg/m³).

The composite panels can be provided with different lengths (generally 1.2m), widths (from 10 to 16 cm), and heights (from 2.4 to 3.4 m), allowing great adaptability to different uses. The limited size and weight of the panels allow easy transportation of the panels without the help of cranes. Then, the panels can be manually assembled by using a simple Allen wrench thanks to a patented steel hooking system. As a result, units can be provided both as readymade units, i.e. totally made off-site, or as kit supplies, i.e. totally assembled on-site to optimize and reduce transportation costs (Félix et al. 2014). This allows realizing building even where work-site vehicles do not have easy access and specialized workers are not present, as may occur in emergencies or developing countries.

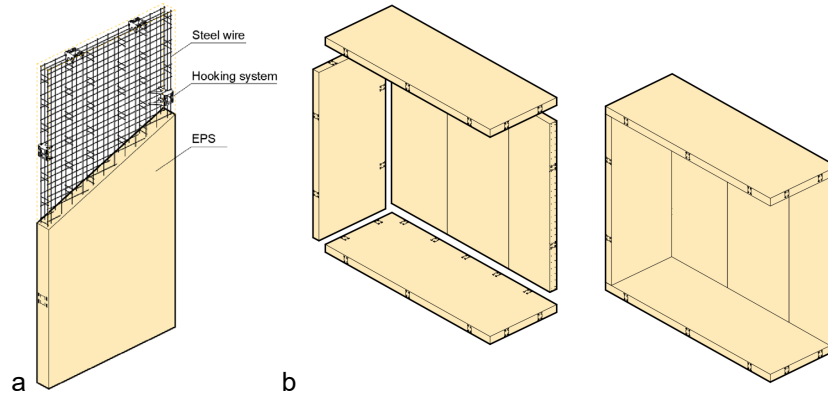


Fig. 3. a) Reinforced-EPS panel and b) assembly process of reinforced-EPS panels.

Air and water impermeability are ensured by applying silicone glue in the junctions between panels. A bituminous covering can be also used to improve roof impermeability. Finally, based on requests, an internal and external finishing layer can be applied, generally made of plastic sheets, steel sheets, or a multi-layer cementitious based finishing system (D’Orazio et al. 2020), the latter being also able to avoid moisture-related issues due to its moisture buffering capacity, as evidenced in (D’Orazio and Maracchini 2019).

The foundation can be made of a set of steel beams with steel rods allowing horizontality regulation. This allows reducing the polluting impact on the site where the unit is placed and to restore more easily its original condition as in pre-disaster. Besides, the modularity of the system permits not only high adaptability to any spatial requests but also progressive modification, expansions, upgrading, re-use, and re-location from temporary sites to permanent locations (IFRC 2013). In this way, when they are no longer needed, the module can be disassembled, sold, re-used for other purposes, or even included in permanent constructions (Wagemann 2017) without any waste of resources (Arslan 2007; Arslan and Cosgun 2008; Seike et al. 2018).

2.3 Building energy simulation tool

The graphical interface *DesignBuilder ver. 6.0* (Cockcroft 2021) was used to model both the experimental unit (see Section 2.4) and the reference building (see Section 2.5), while the building energy performance simulation tool *EnergyPlus ver. 8.9* (DOE 2017) was used for the numerical simulations. The latter were carried out considering 6 time-steps per hour for calculation. Concerning the heat balance algorithm, recent studies have outlined the importance of considering moisture transfer in building energy models, since moisture buffering of the internal layers of the building envelope can have an important role in reducing energy demand and improving the occupants’ thermal comfort (Firlag and Zawada 2013; Zhang et al. 2014; Liu et al. 2015). For this reason, a conduction transfer function combined with an effective moisture penetration depth (EMPD) was adopted as a heat and moisture transfer technique for

surface assemblies (Samani et al. 2017; Woods and Winkler 2018). The moisture properties of all the indoor surfaces, needed for the EMPD model (Woods et al. 2013), were directly extracted from the *DesignBuilder ver. 6.0* software dataset (Cockcroft 2021). Finally, as made in other works (Samani et al. 2017), an adaptive convection algorithm was considered for computing both internal and external convective heat transfer coefficients, since generally more reliable for calculating convective heat transfer coefficients when compared to other techniques (Costanzo et al. 2014).

2.4 Experimental activities and model calibration

An experimental single-room unit, with a single window and a single door, was purposely built to provide the experimental information needed for the calibration of the related numerical model (see Fig. 1). The experimental unit, exposed to the hot-summer Mediterranean climate of Ancona (Italy) (Kottek et al. 2006), represents the smallest available unit that can be used in an emergency scenario or for seasonal working purposes and can be also used to realize multi-unit houses with more rooms. The geometrical characteristics of the experimental unit are reported in Fig. 1. The panels are characterized by a thickness of 12 cm, an EPS density of 45 kg m^{-3} , and a thermal conductivity (λ) of the homogenized material of $0.0288 \text{ W m}^{-1} \text{ K}^{-1}$ (D’Orazio and Maracchini 2019). The window consists of double clear glazing with a total solar transmission equal to 0.40, a light transmission equal to 0.63, and a surface-to-surface *U-value* equal to $1.420 \text{ W m}^{-2} \text{ K}^{-1}$. The external door consists of a 24 mm thick glass fiber slab sandwiched between two thin layers of PVC and is characterized by a surface-to-surface *U-value* of $1.305 \text{ W m}^{-2} \text{ K}^{-1}$.

The experimental unit is placed on two longitudinal external steel beams provided with external studs to allow horizontality regulation. Thus, the floor is not in direct contact with the soil but about 30 cm above the external ground. Near buildings were also modeled as component blocks, to consider their shading action on the experimental unit.

No electrical, architectural, water, and air systems components are present. As a result, and also due to the presence of few openings, a very good airtightness performance was obtained, mainly ensured by the silicone glue in panel junctions, with an air change rate at 50Pa (n_{50}) equal to 2.55 h^{-1} , as experimentally observed in (D’Orazio and Maracchini 2019). To model infiltration rate, the Flow Coefficient model implemented in EnergyPlus is adopted (DOE 2017). The parameters needed to characterize the model have been derived from the results of the experimental campaign (Blower Door Test) carried out by the authors in (D’Orazio and Maracchini 2019) and from (DOE 2017).

To focus the calibration process on the panel characteristics only, no finishing materials were applied on the panels

of the experimental unit. Thence, the physical properties of the panels are the main input values to be tuned in the calibration process.

During the monitoring campaign, the experimental indoor air temperature (T_{iexp}), the indoor air relative humidity, and the surface temperature of the north wall (T_{siexp}) were recorded (see Fig. 1 for the positioning of the indoor monitoring point). Climate data needed for calibration were also recorded. The measuring instruments for outdoor air temperatures (T_{oexp}) and relative humidity were placed above the unit and accurately shielded from rain, wind, and solar radiation, while horizontal global solar radiation, horizontal diffuse radiation, and atmospheric pressure, were obtained from a near meteorological station. The characteristics of the adopted measuring instrumentation are reported in Table 1. No occupants, electric appliances and HVAC systems were present inside the building during the monitoring period (i.e. no internal loads), and the opening was kept closed. In this way, the indoor environment was only affected by environmental factors such as outdoor air temperatures and solar radiation.

The numerical model was calibrated by comparing T_{iexp} and T_{siexp} with the same quantities obtained through the numerical simulation (T_{inum} and T_{sinum} , respectively). To ascertain the model accuracy, the Root Mean Square Error (RMSE), the Coefficient of Variation of the Root Mean Square Error (CVRMSE), and the Mean Bias Error (MBE) were computed and compared to those obtained in the literature for the calibration of other temporary housing and naturally ventilated buildings (Fabrizio and Monetti 2015; Wang et al. 2017, 2019; O’ Donovan et al. 2019). In particular, in the literature, the RMSE ranged between 0.9 and 2.9 °C (with a maximum absolute error between 1.0 and 21.9°C), the MBE from -5.9% to 1.9%, and the CVRMSE from 1.7% to 20.3% (Wang et al. 2017, 2019; O’ Donovan et al. 2019).

Table 1. Equipment characteristics for each measured quantity.

Measure	Model	Measurement uncertainty	Sampling rate / Storing rate
T_{iexp} , RH_{iexp}	LSI Lastem DMA 572.1	0.1°C at 0°C and 1.5% RH	-
T_{oexp} , RH_{oexp}	thermohygrometer		
T_{siexp}	LSI Lastem PT-100 thermocouple	0.1°C at 0°C	-
Datalogger	LSI Lastem ELO105	-	1 min / 10 min

2.5 Reference building and climatic locations

To investigate the impact of different passive cooling strategies on the indoor environment of a building in a real use condition, a numerical model of a reference building, i.e. a temporary house recently adopted in emergency camps, and also used as affordable housing in developing countries, was created (Sferra 2017). The geometrical characteristics of the reference building are summarized in Fig. 2. All external and internal walls (partitions), as well as roof and

floor, are made of reinforced EPS panels with hygrothermal characteristics directly derived from the numerical calibration of the experimental unit. Windows and external doors have the same thermal properties as those adopted in the experimental unit (see Section 2.4). Internal doors, instead, are wooden, with a thickness of 35 mm and a λ of 0.099 Wm⁻¹K⁻¹. The floor panels are considered directly in contact with a concrete slab used as a foundation, and internally covered by an 80 mm thick lightweight casted concrete slab ($\lambda=0.38$ Wm⁻¹K⁻¹, $\varsigma=1000$ J kg⁻¹K⁻¹ and $\rho=1200$ kg m⁻³) and a 10 mm thick layer of stoneware tiles as finishing ($\lambda=1.3$ Wm⁻¹K⁻¹, $\varsigma=1000$ J kg⁻¹K⁻¹, and $\rho=2200$ kg m⁻³), to simulate the real use finishing condition defined by the manufacturer.

In the baseline case (i.e. the case without passive cooling strategies), a continuous thin rendering layer is considered in the external and internal sides of the walls and the internal side of the roof, with an overall thickness of 4 and 3 mm in the external and internal sides, respectively. The conductivity λ , specific heat ς and density ρ of the render are equal to 0.72 Wm⁻¹K⁻¹, 840 J kg⁻¹K⁻¹, and 1800 kg m⁻³, while the thermal, solar, and visible absorptances were set to 0.9, 0.6, and 0.6, respectively.

Due to the uncertainties characterizing the internal activities in emergency scenarios (see for example the different assumptions made in (Samani et al. 2016), (Wang et al. 2017) and (Borge-Diez et al. 2013a)), in this work a standard use of the building is considered according to (UNI 2019), useful to compare buildings regardless of their actual use. Thence, a constant power density for internal gains equal to 6.15 W m⁻² for all of the rooms (UNI 2019) (each of which is assumed to be a different thermal zone, see Fig. 2a) and a constant infiltration rate equal to 0.6 air changes per hour is assumed according to (UNI 2019) and as made in similar works (see e.g. (Borge-Diez et al. 2013b; Samani et al. 2017)). The infiltration rate is higher than that obtained for the experimental unit since the presence of more exterior openings, cracks and unintentionally opening (such as those from lighting and home appliances (ASHRAE 2013)) is taken into account, increasing the building air permeability. Finally, no HVAC is assumed to be present in the building, as may occur in emergency scenarios or developing countries due to economic restrictions.

Three different climatic contexts have been considered in the simulation, representing the different locations in which these buildings can be placed. The adopted climates, characterized by a different annual average solar global horizontal irradiance (GHI) that constitutes the main thermal load in hot climates due to the absence of an HVAC system, are the following:

- Ancona, Italy, (where the experimental unit is placed), which is representative of hot-summer Mediterranean climates characterized by a GHI of 3.25 kWh m⁻² day⁻¹, and where, recently, there was a need for temporary

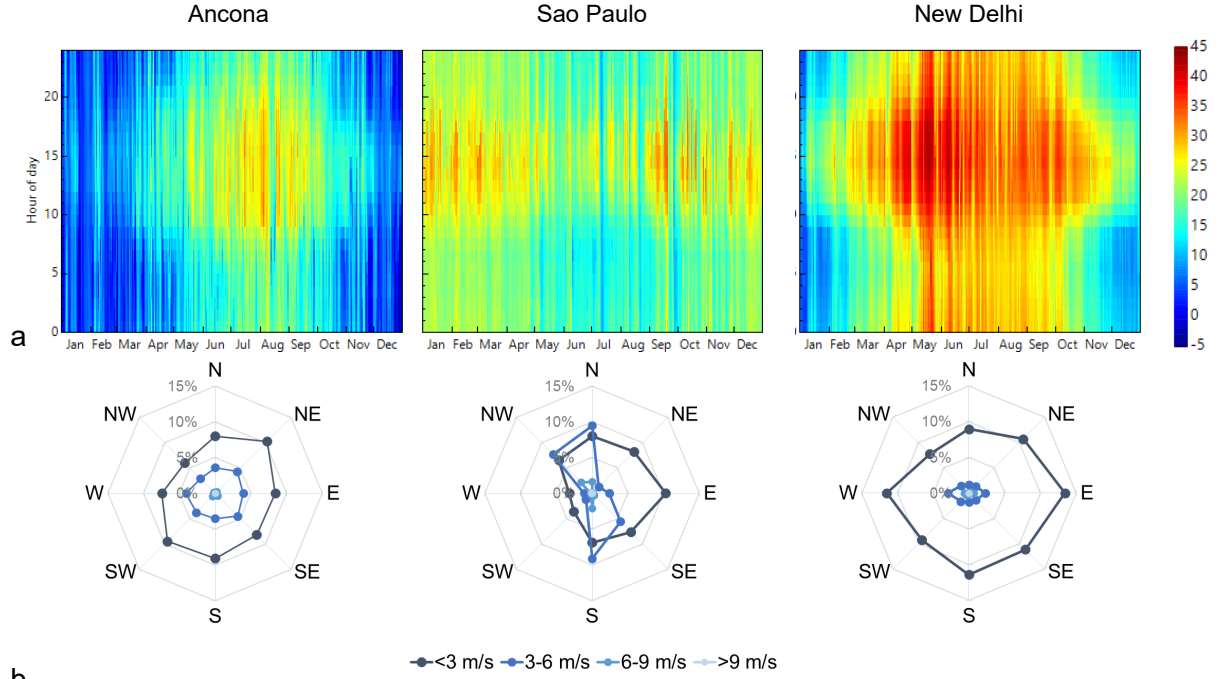
housing solutions due to a near seismic event (Central Italy Earthquake 2016, see (Sferra 2017));

- Sao Paulo, Brazil, as representative of hot-humid subtropical climates characterized by a GHI of 4.77 kWh m⁻² day⁻¹ and where there is a need for low-cost housing solutions due to the high affordable housing demand;
- New Delhi, India, as representative of very hot-dry climates and South Asia, characterized by a GHI of 5.23 kWh m⁻² day⁻¹, and where the highest number of new internal displacement people was recorded in the first half of 2019 due to natural disasters such as floods and monsoons (IDMC 2019b).

A detailed characterization of the climatic locations can be found in Fig. 4 and Table 2. In Fig. 4a, the annual temperature variations for each climate are shown, while other climate characteristics are reported in Table 2. Besides, since the wind velocity, frequency and direction are determinants for the natural ventilation passive strategy, in Fig. 4b the wind data related to the summer season are also reported for each location.

Table 2. Characteristics of the climate files adopted in the numerical simulations.

Location	Ancona, Italy	Sao Paulo, Brasil	New Delhi, India
Weather File	ASHRAE/IGDG, WMO 161910	ASHRAE/IWEC, WMO 837800	ASHRAE/ISHRAE, WMO 421820
Latitude [deg]	N 43.62	S 23.63	N 28.58
Longitude [deg]	E 13.52	W 46.65	E 77.20
Elevation [m]	105	802	216
Cooling degree days (base 25°C)	6	190	1118
Cooling degree days (base 10°C)	1750	3808	5457
Heating degree days (base 18°C)	2062	20	329
Highest average monthly temperature [°C]	22.0	23.5	32.6
Highest average daily temperature [°C]	27.3	28.2	38.6
Highest temperature [°C]	34.1	34.0	43.7
Average of highest 5% temperatures [°C]	28.0	30.0	39.0
Lowest average monthly temperature [°C]	5.5	17.5	12.1
Lowest average daily temperature [°C]	0.0	9.6	6.6
Lowest temperature [°C]	-4.0	8.8	3.6
Average of minimum 5% temperatures [°C]	0.5	12.4	7.89
Annual average solar global horizontal irradiance (GHI) [kWh m ⁻² day ⁻¹]	3.25	4.77	5.23
Average normal solar irradiance for the hottest month [kWh m ⁻² day ⁻¹]	4.26	3.38	4.71
Köppen classification	Csa (hot-summer Mediterranean climate)	Cfa (Humid subtropical climates)	CWa (Monsoon-influenced humid subtropical climate)/BSh (Hot semi-arid climates)
ASHRAE climate zone	4A (mixed-humid)	2A (hot-humid)	1B (very hot-dry)



b

297

298 Fig. 4. a) Annual hourly dry-bulb air temperatures of the three different climates; b) Wind direction, speed, and frequency during the year in the locations
299 during summer.

300 2.6 Thermal comfort

301 The adaptive thermal comfort model proposed in EN 16798-1 (EN 2019) for a normal level of expectation was
302 considered for thermal comfort calculation, which is a widely used comfort model for naturally ventilated buildings,
303 already applied on temporary housing solutions (see e.g. (Samani et al. 2016; D’Orazio and Maracchini 2019)). Some
304 modifications on the safe side to the original EN 16798-1 (EN 2019) relationship used to compute comfort limits
305 (T_c) were made to include days with a weighted mean of the previous 7-day outdoor air dry-bulb temperature (T_{rm})
306 lower than 10°C and higher than 30 °C, as suggested in (Samani et al. 2016; D’Orazio and Maracchini 2019). The
307 adopted formulation is reported in Eq (1). The long-term assessment of the thermal comfort condition is made
308 according to EN ISO 7730 (ISO 2005) based on the method of “Percentage outside the range”, as made in (Harkouss
309 et al. 2018). In particular, to avoid uncomfortable hot feelings due to indoor overheating, the percentage of hours
310 with thermal discomfort should not surpass 3% in each room from May to September (included), i.e. 1.25 % of the
311 whole year (CIBSE 2013).

$$T_c = \begin{cases} (21.6 \pm 3.5) ^\circ C & T_{rm} < 10^\circ C \\ (0.33T_{rm} + 18.3 \pm 3.5) ^\circ C & 10^\circ C < T_{rm} < 30^\circ C \\ (28.2 \pm 3.5) ^\circ C & T_{rm} > 30^\circ C \end{cases} \quad (1)$$

312 2.7 Passive cooling techniques

313 Different passive cooling strategies can be used to reduce building energy consumption and improve occupants'
314 indoor thermal comfort in hot climates. These strategies are usually classified into heat dissipation techniques, heat
315 modulation techniques, and heat protection techniques (Bhamare et al. 2019). In the field of emergency temporary
316 buildings, low-cost and easy-to-apply measures are usually adopted to guarantee large-scale delivery and fast
317 applicability even by non-specialized workers. Due to this, in this work, low-cost and easily implemented passive
318 cooling measures that do not involve significant changes to the building layout have been adopted and compared.
319 These are natural ventilation and cooling finishing materials (as heat dissipation techniques), shadings (as heat
320 protection techniques, including both overhangs with lateral fins and slatted blinds), and the increase of indoor
321 thermal inertia by adding interior gypsum boards (as heat modulation technique). A detailed description of the
322 modeling approaches adopted for each passive strategy is reported in the following sections. The metrics adopted to
323 compare the effectiveness of the different solutions are finally described in Section 2.7.5.

324 2.7.1 Natural ventilation

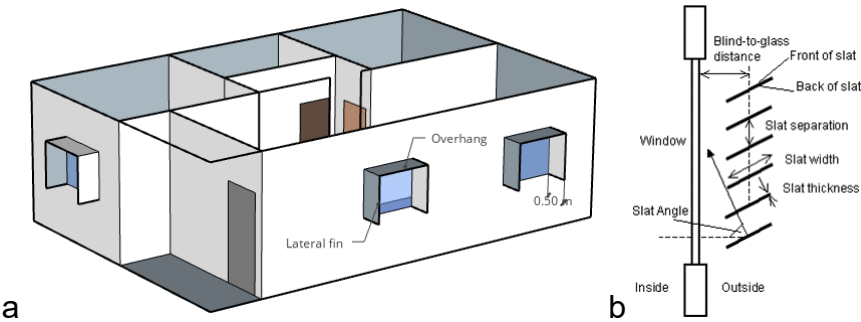
325 A passive natural ventilation strategy (NV) was adopted to consider the manual opening of the windows by the
326 occupants to enable space cooling. In this study, the activation of the windows occurs when all the following
327 conditions are met: $T_{i_{num}} > 26\text{ }^{\circ}\text{C}$; $T_{i_{num}} > T_{o_{exp}}$; $V < 10\text{ m s}^{-1}$. According to the ASHRAE book of fundamentals
328 (ASHRAE 55 2017), both the flow driven by wind Q_w and the flow due to stack effects Q_s should be considered in
329 the space cooling calculation. However, when the vertical distance between the midpoints of the inlet and outlet
330 windows is equal to 0, as in our case (see Fig. 2), the flow due to stack effects can be neglected (Samani et al. 2016;
331 UNI/PdR 13.1:2019 2019). Thus, only the flow driven by the wind was considered in this study, computed as follows
332 (ASHRAE 55 2017; DOE 2019):

$$Q_w = C_w A_o V \quad (2)$$

333 where: A_o is the opening area of the window, set equal to 5% of the total window area (i.e. 0.06 m^2 for each window)
334 to simulate the worst scenario in terms of windows obstructions as may occur in high-density emergency camps
335 (Menberg et al. 2016); V is the outdoor wind speed; C_w is the opening effectiveness, calculated based on the angle
336 difference between wind direction and effective opening angle according to (Heiselberg et al. 2001; ASHRAE 55
337 2017; DOE 2019).

338 2.7.2 Shading

339 Two different types of shading are considered and applied to south-, east- and west-facing windows. These are
340 external overhangs with lateral fins, characterized by a projection of 0.5m (see Fig. 5a), and external slatted blinds (see
341 Fig. 5b), both currently used by the manufacturer of the construction system. These solutions are directly applicable
342 to the window frames, thence without requiring the skills of specialized workers for their installation (which could be
343 not available in an emergency scenario). The slatted blinds are horizontally oriented for the south-facing windows
344 and vertically oriented for the other windows to maximize shading efficiency. Slats are inclined at 45° and spaced
345 0.018m, with a width of 0.025m and a distance to the glazing of 0.05 m. A thickness of 0.01m is considered for all
346 the shading elements, with a λ of 0.1 W m⁻¹ K⁻¹. Concerning the modeling approach, a preliminary set of simulations
347 were carried out to identify the correct indoor temperature set point for the activation of the shading. In particular,
348 it was seen that, for all climatic contexts, considering an activation setpoints lower than 26 °C does not provide any
349 improvement in reducing thermal discomfort due to overheating while leading to a detrimental reduction of solar
350 beam penetration in coldest periods (i.e. when the solar beam has a beneficial effect on indoor thermal comfort).
351 Then, an activation set point equal to 26 °C was assumed.



353 Fig. 5. a) Schematic representation of model with external overhangs and lateral fins; b) schematic representation of the external slatted blinds (adapted
354 from (Cockcroft 2021)).

355 2.7.3 Cooling materials

356 Cooling materials are external finishing materials characterized by high solar reflectance (SR) (equal or higher than
357 0.70 (Akbari and Levinson 2008)), help to reduce the amount of absorbed solar radiation during the daytime, and
358 high thermal emittance ϵ (equal or higher than 0.75 (Akbari and Levinson 2008)), which allows at night to quickly
359 dissipate the heat accumulated during the day in the form of infrared radiation (de Brito Filho et al. 2011; Zinzi and
360 Agnoli 2012; Bhamare et al. 2019). Among the existing cooling materials (such as cool tiles, asphalt shingles, metal
361 roofs, elastomeric coatings, etc.), white coatings with nanotechnological and microtechnological additives are

362 considered in this study since able to reduce overheating without requiring high investment costs (see Section 2.7)
363 and the involvement of specialized workers for their application. Two different configurations are adopted, i.e.
364 application on the roof only (Cool roof, CR (Borge-Diez et al. 2013b)), and application to all external surfaces (Cool
365 roof and walls, CRW (Samani et al. 2017)).

366 Based on results of other studies (de Brito Filho et al. 2011; Lapisa et al. 2013), the impact of cooling finishing
367 materials on indoor air temperatures and thermal comfort can be considered by increasing the SR value of the external
368 finishing system from the initial value of 0.4 (related to the adopted external finishing system in the reference building)
369 to the value of 0.9 (related to the maximum SR values adopted in literature, see e.g. (Borge-Diez et al. 2013b; Wang
370 et al. 2017)), corresponding in decreasing the solar absorptance from 0.6 to 0.1. However, cool finishing materials
371 may incur a consistent loss of performance over time due to chemical and physical stress, weathering, organic and
372 inorganic matter deposition, and microbial growth over time. This loss may occur even right after a few months in
373 very polluted contexts due to dirt deposition (Sleiman et al. 2011; Cheng et al. 2012; Paolini et al. 2017, 2020; D’Orazio
374 et al. 2020). Then, this aspect should be accurately taken into account in the analyses. Considering the different
375 contexts where emergency buildings can be placed (urban and rural; developed and developing countries; polluted
376 and not polluted scenarios), and the possible cleaning activities that the occupants may carry out in summer to restore,
377 partially or totally, the initial SR of the surfaces after dirt deposition (Levinson et al. 2005), two “extreme” scenarios
378 have been considered in our study. In the first scenario, a not aged SR of the cooling materials (0.9) is adopted for
379 the whole yearly simulation. In this case, the CR and CRW strategies are referred to as CR_n and CRW_n in the text
380 and the results are representative of unpolluted contexts (whole period of simulation), polluted contexts before aging
381 (summer results), and consider the possible cleaning activities of the occupants in polluted contexts (summer results).
382 In the second scenario, an SR=0.6 is assumed (aged conditions) for the whole yearly simulation (CR_a and CRW_a)
383 (Sleiman et al. 2011; Cheng et al. 2012; Paolini et al. 2017, 2020). The results are representative of polluted contexts
384 (i.e. mainly urban contexts) after one or more years of occupation or of an end-of-life scenario.

385 2.7.4 Internal thermal inertia increase

386 Among the different measures adopted in the literature to increase the thermal inertia of lightweight affordable
387 construction systems, the use of internal gypsum board layer and phase change materials (PCM) are the most used
388 ones (see e.g. (Wang et al. 2013; Marin et al. 2016; Samani et al. 2017)). In this study, the effect on the indoor thermal
389 environment of increasing the internal thermal inertia of the housing solution is evaluated by considering the

390 application of a gypsum board layer to all internal surfaces (walls and roof).

391 Different board thicknesses were considered at this aim, ranging from 5 to 25 mm, the latter considered as the
392 maximum thickness usually implemented in this kind of buildings (see e.g. (Samani et al. 2017; D’Orazio and
393 Maracchini 2019)). Since a metallic frame is used to connect the gypsum boards to the reinforced-EPS wall, 50mm-
394 thick and 100mm-thick air gaps were considered between the wall and the boards and between the roof and the
395 boards, respectively, also useful for placing electric cables in real use conditions. The adopted internal gypsum boards
396 are characterized by a λ of $0.32 \text{ W m}^{-1}\text{K}^{-1}$, a ς of $1100 \text{ J kg}^{-1} \text{ K}^{-1}$, and a ρ equal to 1150 kg m^{-3} . Moisture properties of
397 the gypsum boards were directly extracted from the *DesignBuilder ver. 6.0* software dataset (Cockcroft 2021).

398 2.7.5 Performance indicators and costs

399 The effectiveness of each technique in reducing indoor overheating was evaluated by using different cooling
400 performance indicators, such as the maximum indoor air temperature (T_{max}), the average of the highest 5% indoor air
401 temperatures ($T_{max,5\%}$), and the percentage of time with indoor thermal discomfort due to hotness (see Section 2.6)
402 during a whole year (Samani et al. 2016). Moreover, because some of these measures may cause indoor air temperature
403 variations also during the coldest periods, to allow a more comprehensive comparison among different techniques,
404 the minimum indoor air temperature (T_{min}), the average of the lowest 5% indoor air temperatures ($T_{min,5\%}$), and time
405 with thermal discomfort due to coldness were also computed and compared. Since the financial parameters are of
406 paramount importance in an emergency scenario to inform decisions about possible investments, the actual costs of
407 each solution are also considered. The total and specific costs for each solution are reported in Table 3. These values
408 are the sum of the additional costs (materials and labor) incurred by the manufacturer before selling the system as a
409 ready-made unit due to the implementation of the passive measures. Running costs are not considered in this work
410 since no HVAC system is considered in this work (as may occur in hot climates or emergency scenarios), while
411 maintenance costs are neglected. The higher investment cost required by the internal thermal inertia increase strategy
412 (about 10-15% of the unit construction cost) is due to the higher amount of material needed, the need for specialized
413 workers for its application (due to the several phases needed to complete the system), and the higher quality of the
414 housing solution reached after the installation (thanks to the possible use of the new air gaps for placing electric cables
415 and other equipment).

416 Table 3. Manufacturer’ additional costs for the implementation of the passive solutions to the reference building. Concerning cool painting, the possible
417 re-painting needed to restore the original solar reflectance (SR) value after UV aging is not considered since generally needed at a later time (after more

than 10 years), i.e. when temporary buildings should be no more used (Sleiman et al. 2011; Cheng et al. 2012; Paolini et al. 2017; D’Orazio et al. 2020).

Passive strategy	Shadings	Cool roof (SR=0.9)	Cool roof and walls (SR=0.9)	Gypsum board (25mm)
Cost [€]	900	600	2200	6100
Specific cost [€ m ⁻²]	16	10.5	38.1	106

3 RESULTS AND DISCUSSION

3.1 A Model calibration

The results of the model calibration are shown in Fig. 6, where the comparison between experimental measurements and numerical outcomes are reported in terms of indoor air temperature (T_{iexp} and T_{inum}) and indoor surface temperatures of the north wall (T_{siexp} and T_{sinum}). A good agreement is obtained between the simulated and the measured indoor temperatures, with only very small variations in terms of peak temperatures. The $RMSE$, $CVRMSE$ and MBE values (equal to 0.57 °C, 4.88 % and -2.29% for indoor air temperature and 0.64 °C, 5.65 % and -4.33% for indoor surface temperature, respectively) were similar or even lower than those obtained in other calibration works regarding temporary housing and naturally ventilated buildings (see Section 2.4). A good match between initial input values and calibrated numerical ones was found in our case since only the solar absorptance value was varied from 0.4 to 0.1, which is in line with the high reflectivity for other white surfaces observed in the literature (Taleghani et al. 2014). These results denoted a good consistency between the numerical model assumptions (such as the absence of thermal bridges at junctions) and the real characteristics of the construction system. Then, the modeling assumptions can be considered accurate enough to be used in the modeling of such a construction system (Coakley et al. 2014; Martínez et al. 2020).

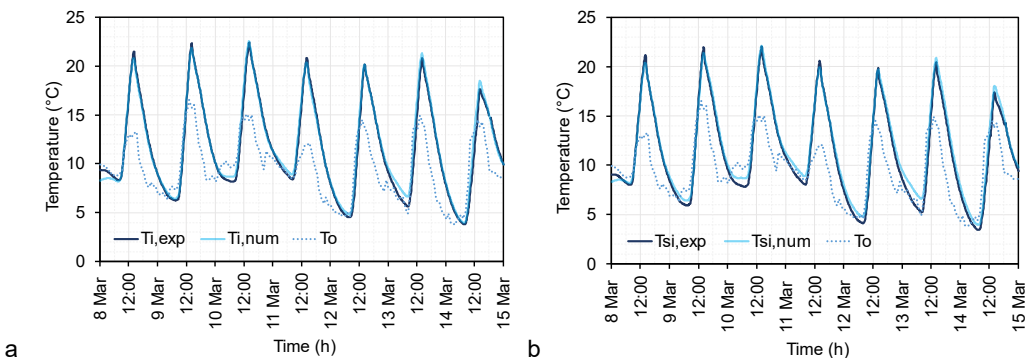


Fig. 6. Comparisons between experimental (*exp*) and numerical (*num*) results in terms of (a) indoor air temperatures T_i and (b) indoor surface temperatures of north wall T_{si} of the experimental unit. T_o : outdoor air temperature.

438 **3.2 Reference building**

439 **3.2.1 Indoor air temperatures**

440 In Fig. 7, the indoor air temperatures of each thermal zone (room), obtained during the hottest (Fig. 7a) and coldest (Fig. 7b) day of the year in Ancona, are shown. The overheating of the indoor environment (i.e. indoor air temperature higher than outdoor ones) in summer is quite evident in this climate location, with maximum indoor air temperatures 5-10°C higher than maximum outdoor ones (Fig. 7a). Even on the coldest day, the overheating of the indoor environment can be noted in terms of mean temperature values (Fig. 7b), with a shift of the daily mean temperature from 2.21 to about 6.72 °C. The lower increase obtained in this case can be attributed to the lower amount of solar beam penetrating the indoor environment on this day.

447

448

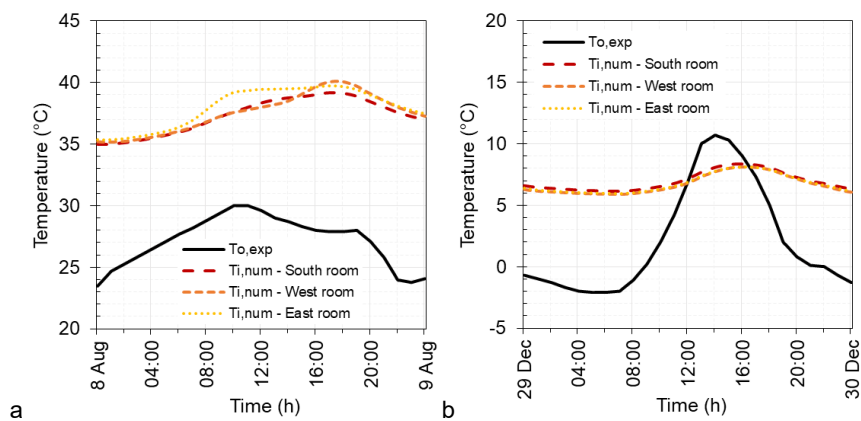


Fig. 7. Numerical indoor air temperatures of the reference buildings in the hottest (a) and coldest (b) days of the year of Ancona, Italy.

449 Comparing the response of the different rooms, a quite similar thermal behavior is observed, with only slight differences in summer due to the different window orientation (see Fig. 2) that causes a shift of the maximum indoor air temperature at a different time of the day. Moreover, slightly higher temperatures can be observed in the west room during summer. This is probably because, when the solar beam starts to penetrate inside the west room through the window, i.e. at the end of the day, the indoor air temperature is already quite high due to the heat coming from the other rooms during the previous hours. Thus, a higher temperature is obtained in this zone.

455 The results obtained in the climate of Ancona can be extended to the other climates and times of the year (see also Fig. A.1 in Appendix). For the sake of brevity, only the results related to the west room are reported and discussed henceforth. In Fig. 8, a comparison between indoor and outdoor air temperatures of the west room is reported for each climate condition. Concerning the amount of overheating (i.e. the thermal gradient between indoor and outdoor air temperature), the lowest thermal gradient between indoor and outdoor air is obtained for Sao Paulo despite being

the second hottest climate. This is mainly due to the lower normal solar irradiance in this location (average value equal to $3.38 \text{ kWh m}^{-2} \text{ day}^{-1}$ in the hottest month, see Table 2), which leads to lower solar radiation penetrating through the windows.

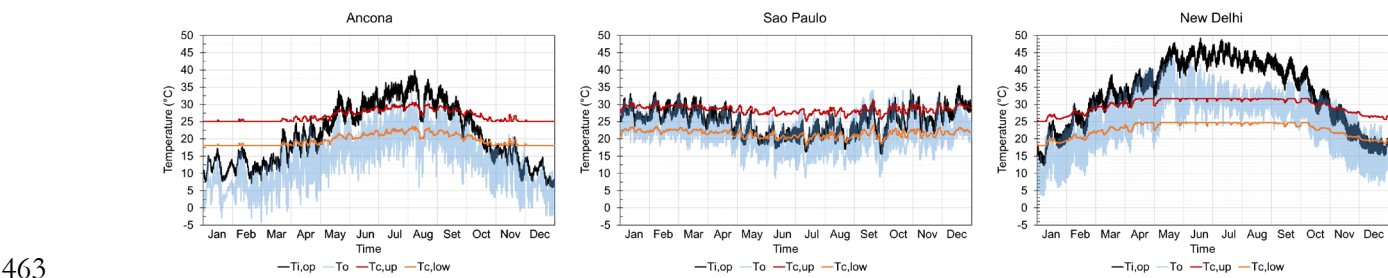


Fig. 8. For each climatic context, indoor operative temperatures of the west room of the reference buildings ($T_{i,op}$), outdoor air temperatures ($T_{o,exp}$), and upper and lower comfort limits ($T_{c,up}$ and $T_{c,low}$, respectively).

3.2.2 Indoor thermal comfort

In Fig. 8, for each considered climatic context, the thermal comfort limits, computed as described in Section 2.6, are also compared with the outdoor air temperatures and indoor operative air temperatures. The outdoor comfort condition (obtained by comparing comfort limits with outdoor temperatures) can be considered as a comfort limit condition corresponding to the no-overheating situation for the studied building. In our cases, both Ancona and Sao Paulo are characterized by a quite null percentage of time with “outdoor” thermal discomfort due to hotness in summer (1.0% and 2.9 %, respectively). Conversely, in New Delhi, a higher number of hours in summer above the comfort limits can be observed, equal to 23.8 % of hours of the year.

Differently, concerning the indoor environment, higher periods with thermal discomfort are obtained due to indoor overheating. In particular, the lower percentage of time with thermal discomfort due to extreme hotness is obtained in Sao Paulo (11.2%), mainly due to the lower thermal gradient between indoor and outdoor air. In Ancona and New Delhi, this value reaches 29.5 and 68.3%, respectively. In all cases, however, the indoor overheating leads to a time with thermal discomfort higher than the threshold defined in (CIBSE 2013) to avert hot feeling (i.e. 3% from May to September included), denoting the need for implementing passive cooling strategies to reduce indoor overheating in all considered climates.

3.2.3 Summer heat gain characteristics

Given the highlighted needs of improving indoor thermal comfort in summer in all the considered climatic locations, in Fig. 9 a breakdown of summer heat gain of the reference building is reported for each climate, constituting a useful reference in studying the application of the different passive cooling techniques.

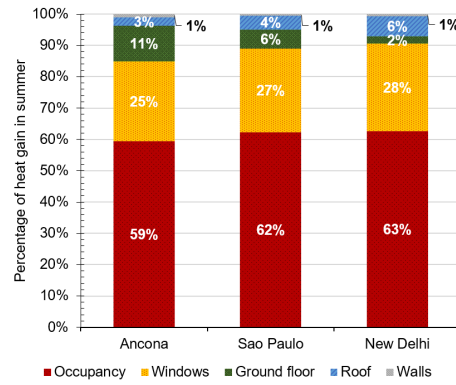


Fig. 9. The detailed breakdown of the reference building heat gain during a summer month in Ancona (August), Sao Paulo (December) and New Delhi (June).

As expected, in all the climatic contexts, the highest share of heat gains is due to the internal gains (i.e. occupant related activities, ranging from 59 to 63% of the total heat gain depending on the climatic context), followed by solar gains through windows (from 25 to 28%), ground floor (from 2 to 11%) and roof (from 3 to 6%). This means that windows are the constructive feature with the highest share of the total heat gain in summer (as also seen for other lightweight construction systems used in emergency scenarios (Wang et al. 2017)) and, consequently, should have priority when studying the possible application of passive cooling techniques. The heat gains through the ground floor are relevant only in those contexts where the indoor night temperature reaches values below the ground temperature in summer (i.e. Ancona and Sao Paulo), while heat gains through roof elements seem proportional to the GHI of the considered location (the higher the GHI the higher the importance of improving roof elements, see Table 2). Wall elements are liable only for 1% of total heat gains in summer. This result strongly differs from what has been achieved in other studies (Wang et al. 2017), where the heat gains through walls of common temporary units have a higher share in total gains (29%), even higher than that of windows in absolute terms. This difference can be attributed, on one hand, to the less compact layout adopted in our study, with a surface-to-volume ratio lower than that adopted in (Wang et al. 2017) (1.18 and 1.46 m^{-1} , respectively), which leads to a lower impact of walls elements on the total heat gain due to their lower relative extension. On the other hand, the lower *U-value* of the panels, equal to $0.24 \text{ W m}^{-2} \text{ K}^{-1}$ in our study and 0.82 in (Wang et al. 2017), allows a low amount of inwards heat to pass through these elements when the outdoor surface temperatures are higher than the indoor ones (mainly in the morning). The low contribution of the opaque constructive elements to the total amount of heat released into the indoor environment also justifies the high share of heat gains due to the internal gains (occupancy, lighting, and other appliances), which is higher than that obtained in [48] (about 60 and 28%, respectively).

508 **3.3 Passive cooling techniques**

509 3.3.1 Natural ventilation

510 The results obtained by adopting the natural ventilation cooling strategy (NV) are reported in Table 4. Its effectiveness
511 in reducing overheating in summer (T_{max} and $T_{max,5\%}$) is quite evident (Table 4). In particular, the higher decrease in
512 terms of $T_{max,5\%}$ is obtained for New Delhi, followed by Sao Paulo and Ancona. The different reductions obtained in
513 the three climates can be attributable to the different climatic characteristics, and, in particular, to the different wind
514 speeds and the different thermal gradients between indoor and outdoor air in summer. On one hand, indeed, the
515 higher the thermal gradient between outdoor and indoor air (i.e. the higher the amount of overheating), the higher
516 the capacity of the natural ventilation in cooling down the indoor environment. On the other hand, the higher the
517 wind speed, the higher the amount of fresh air that will penetrate inside the building to cool down the indoor
518 environment. In our case, the higher and lower thermal gradients were obtained in New Delhi and Sao Paulo,
519 respectively (see Fig. 8). Conversely, the highest wind speed was observed in Sao Paulo (average wind speed in
520 summer of 2.84 m/s), while a lower wind speed was observed in New Delhi and Ancona (average wind speed in
521 summer of 1.43 and 1.64 m/s, respectively, see also Fig. 4b). As a result of the combined action of these two factors,
522 the worst results of NV in terms of indoor air temperature reduction were obtained in Ancona, due to low wind
523 speed in summer and the quite low indoor/outdoor thermal gradient (if compared with that obtained in New Delhi).
524 Better performance was obtained in New Delhi, due to the high thermal gradient, and Sao Paulo, due to the high
525 wind speed. This denotes a quite marked dependence of the effectiveness of this strategy on climatic and site-specific
526 conditions.

527 3.3.2 Shading

528 Concerning the shading strategy, the two different devices considered in this study (slatted blinds and overhang with
529 fins) provide similar results in terms of reduction of $T_{max,5\%}$ regardless of the location (Table 4). In particular, slatted
530 blinds perform slightly better in all the climatic conditions, mainly due to their better capacity to prevent solar heat
531 gains through the windows in the east and west rooms (i.e. where the solar beams easily penetrate during the summer
532 days). As for the NV strategy, these solutions do not affect the thermal behavior of the building during the coldest
533 periods.

534

535 Table 4. Performance indicators for natural ventilation and shading strategies under different climatic conditions (AN: Ancona; SP: Sao Paulo; ND: New

536 Delhi) of the west room.

537

538 3.3.3 Cooling materials

539 In Fig. 10, the impact of cooling materials on T_{max} , $T_{max,5\%}$, T_{min} , and $T_{min,5\%}$ is reported. For both cool roof (CR) and
540 cool roof and walls (CRW) strategies, the results show a quite linear decrease of both maximum and minimum indoor
541 temperatures due to the reduction of the solar absorptance value of the external surfaces. As expected, a higher
542 cooling potential (in terms of decrease of both $T_{max,5\%}$) is obtained for the CRW solution.

543

544 Fig. 10. Impact of solar absorptance on indoor air temperature of the living room in the three different climates. CR: Cool roof; CRW: Cool roof and
545 walls.

546 3.3.4 Internal thermal inertia increasing

547 In Fig. 11, the results obtained by increasing the thermal storage capacity of the module through the addition of
548 different thicknesses of interior gypsum boards (G) are reported. As expected, the higher the thickness of the boards,
549 the more the decrease of summer temperatures ($T_{max,5\%}$ and T_{max}) and the increase of the winter ones ($T_{min,5\%}$ and T_{min}).
550 A non-linear, inverse relationship between maximum summer temperatures and board thickness is observed. The
551 decrement of $T_{max,5\%}$ obtained by increasing the board thickness gets smaller and smaller at each thickness increment.
552 This indicates that, beyond a certain threshold, further increasing the board thickness will not cause more effects on
553 indoor temperatures. Thus, this threshold should be accurately checked before using this strategy.

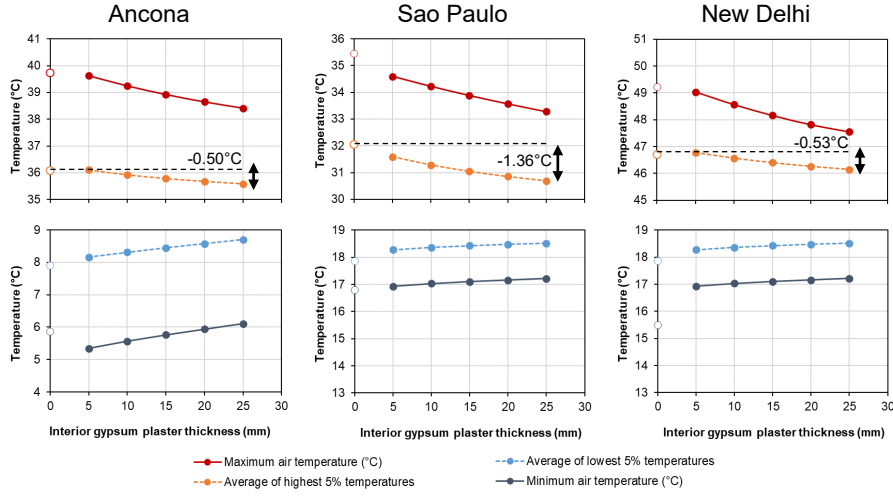


Fig. 11. Impact of interior gypsum layer on the indoor air temperature of the living room in the three different climates.

The maximum decreases in $T_{max,5\%}$ is obtained in Sao Paulo, denoting higher effectiveness of this technique in this location due to the lower amount of overheating, resulting in a higher capacity of the board to dynamically interact with the indoor environment by releasing heat and storing cold energy during the night. Concerning the winter temperatures, the increase in minimum temperature can be considered a positive side effect of this cooling strategy.

3.4 Comparison and combination of passive strategies

3.4.1 Indoor air temperature and thermal comfort

In this section, the different passive measures are compared also considering their possible combination. Concerning the cooling materials, both CR and CRW in aged (CRa and CRWa, SR=0.6) and not aged (CRn and CRWn, SR=0.9) conditions are considered. Regarding the other strategies, for the sake of brevity, only the solution resulting in the topmost reductions of $T_{max,5\%}$ are considered, i.e. slatted blinds for the shading strategy (B), and a thickness of 25 mm for the G strategy.

In general, the best results in terms of both $T_{max,5\%}$ reduction (Table 5) and reduction of discomfort hours due to hotness (Fig. 12) were obtained by adopting the two heat dissipation strategies NV and CRWn, followed by the heat protection strategy (B), the CRn strategy, and, finally, CRWa and CRa and the heat modulation strategy G. The NV strategy always provides the best results excepting for Ancona where the lower wind speed (if compared with that in Sao Paulo) and the lower amount of overheating (if compared with that in New Delhi) makes this strategy less effective than the CRWn strategy. However, if we also consider the detrimental side effect that cooling materials may have in winter, and its possible quick decrease of performance right after a year of occupation in some urban contexts (CRWa), it can be said that NV is the best performing strategy in all cases.

575

576 Table 5. Comparison between different techniques in terms of T_{max} , $T_{max,5\%}$, T_{min} and $T_{min,5\%}$ variations, and solutions ranking in terms of effectiveness in
577 reducing $T_{max,5\%}$ (in round brackets). All_n: All strategies combined in not aged conditions; All_a: All strategies combined in aged conditions.

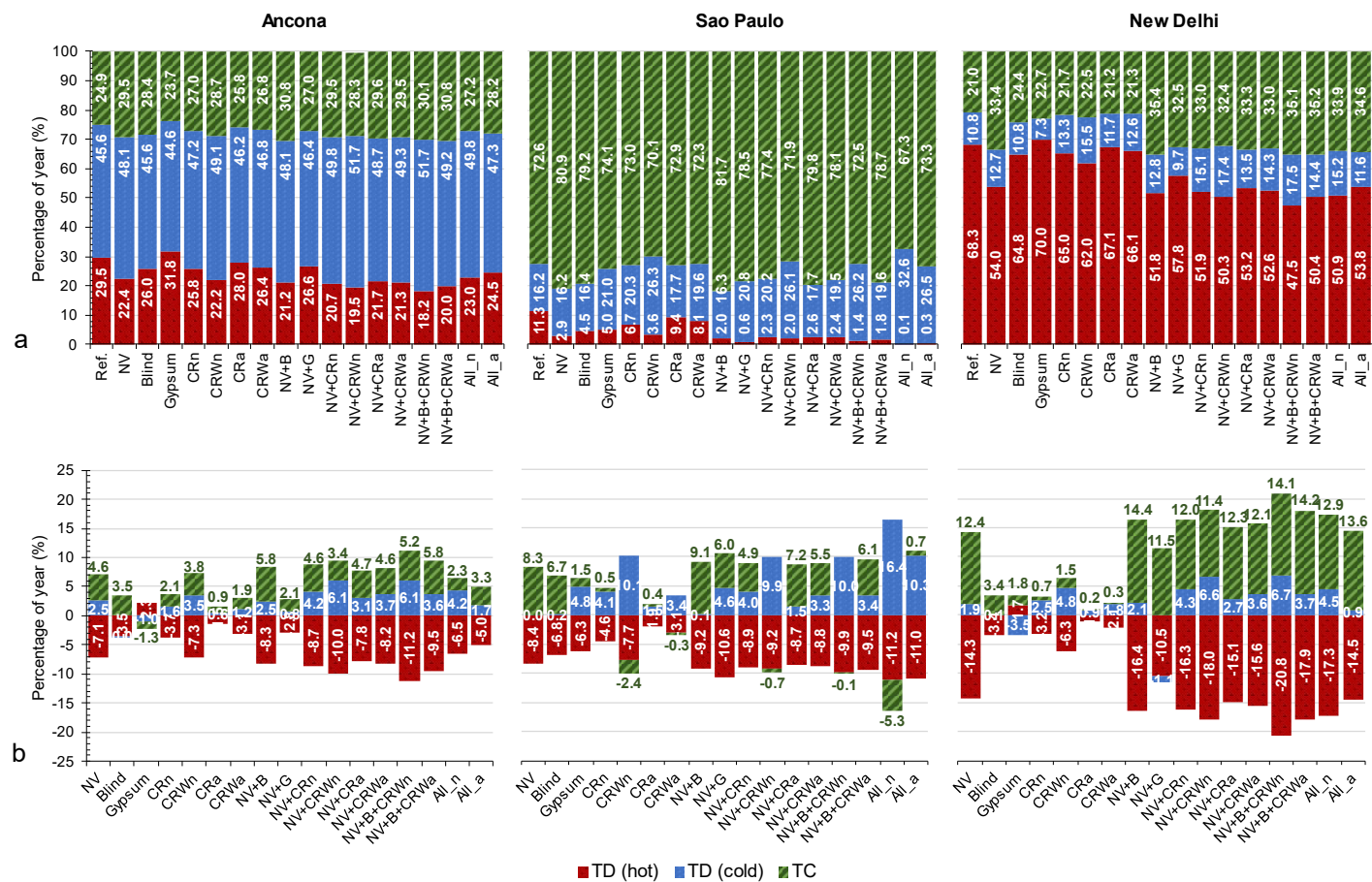
	T_{max} [°C]			$T_{max,5\%}$ [°C]			T_{min} [°C]			$T_{min,5\%}$ [°C]		
	AN	SP	ND	AN	SP	ND	AN	SP	ND	AN	SP	ND
Ref. building	39.73	35.45	49.22	36.08	32.05	46.70	5.88	15.49	12.23	7.91	17.86	15.67
NV	0.03	-1.45	-0.41	-1.24 (2)	-2.23 (1)	-2.48 (1)	0.64	-0.05	0.00	0.34	0.00	0.10
B	-1.10	-1.49	-1.56	-1.05 (3)	-1.37 (3)	-1.44 (3)	-0.05	0.00	0.00	-0.01	0.00	0.00
G	-1.32	-2.17	-1.67	-0.50 (6)	-1.36 (4)	-0.56 (6)	0.92	0.53	1.04	0.79	0.66	0.90
CRn	-1.25	-1.23	-1.75	-0.99 (4)	-0.94 (5)	-1.21 (4)	5.8	15.35	11.78	7.73	17.66	15.07
CRWn	-2.25	-2.03	-2.80	-1.77 (1)	-1.63 (2)	-2.15 (2)	-0.14	-0.27	-0.90	-0.40	-0.45	-0.99
CRA	-0.50	-0.49	-0.70	-0.39 (7)	-0.38 (7)	-0.48 (7)	-0.03	-0.05	-0.18	-0.07	-0.08	-0.24
CRWa	-0.83	-0.81	-1.07	-0.69 (5)	-0.65 (6)	-0.80 (5)	-0.06	-0.09	-0.33	-0.15	-0.16	-0.36
NV+B	-0.05	-2.08	-0.89	-1.23 (2)	-2.61 (3)	-2.99 (2)	0.64	-0.06	0.00	0.34	0.00	0.10
NV+G	-0.35	-3.56	-0.23	-1.04 (5)	-3.14 (1)	-1.35 (6)	2.19	1.48	1.04	1.34	0.58	2.49
NV+CRn	-0.13	-2.06	-0.92	-1.20 (3)	-2.53 (4)	-2.96 (3)	0.52	-0.30	-0.46	0.15	-0.21	-0.38
NV+CRWn	-1.38	-2.51	-1.20	-1.79 (1)	-2.77 (2)	-3.27 (1)	0.40	-0.42	-0.90	-0.08	-0.46	-0.87
NV+CRA	0.23	-1.67	-0.60	-0.97 (6)	-2.35 (6)	-2.66 (5)	0.59	-0.15	-0.16	0.27	-0.08	-0.07
NV+CRWa	-0.92	-1.84	-0.72	-1.08 (4)	-2.45 (5)	-2.79 (4)	0.54	-0.23	-0.33	0.18	-0.16	-0.24
NV+B+CRWn	-1.40	-3.12	-1.72	-2.07 (1)	-3.10 (2)	-3.70 (1)	0.40	-0.42	-0.90	-0.08	-0.46	-0.87
All_n	-1.38	-4.38	-1.57	-1.51 (2)	-3.84 (1)	-2.52 (2)	1.95	1.36	0.01	0.93	0.22	0.11
NV+B+CRWa	-0.43	-2.47	-1.20	-1.47 (1)	-2.81 (2)	-3.28 (1)	0.54	-0.23	-0.33	0.18	-0.17	-0.24
All_a	-0.34	-4.15	-1.18	-0.58 (2)	-3.62 (1)	-2.12 (2)	2.08	1.47	0.66	1.18	0.47	0.68

578

579 Conversely, the G and CRA strategies are the worst-performing solutions in both Ancona and New Delhi. The G
580 case, in particular, even leads to an increase of hours with thermal discomfort due to overheating in these contexts
581 (Fig. 12). This is because the average indoor daily temperatures in summer are already above the upper comfort limit
582 in both Ancona and New Delhi (see Fig. 8). Then, even after the dampening of the temperature oscillations obtained
583 with the increase of the thermal storage capacity, the maximum temperatures remain higher than the upper comfort
584 limit, while the minimum temperatures already within the comfort limits rise above the upper comfort limit, leading
585 to a reduction of the total hours of thermal comfort. In Sao Paulo, instead, the summer average indoor daily
586 temperatures of the reference building are already within the thermal comfort limits (see Fig. 8). Then, both the
587 maximum and the minimum temperatures can easily fall within the comfort limits due to the dampening of the indoor
588 temperature oscillations, leading to a better performance of the G strategy in this location.

589 In Table 5 and Fig. 12, the results obtained by combining the NV strategy with the other passive cooling techniques
590 are also reported, i.e. NV + B, NV + G, NV + CRn, NV + CRWn, NV + CRA, NV + CRWa. The best result is
591 obtained, as expected, by combining the two best performing techniques, i.e. NV and CRWn, except for the Sao
592 Paulo case, where the NV + G strategy is the best option due to the better performance of the G strategy in this
593 climatic location. In the aged scenario, however, the NV+B strategy performs slightly better than that of the

594 NV+CRWa strategy, becoming the best strategy in both Ancona and New Delhi.



595
596 Fig. 12. a) Occupants thermal comfort and discomfort computed according to EN 16798-1 (EN 2019) for single and combined passive cooling strategies
597 in different locations; b) Absolute differences in terms of percentage of time with thermal comfort/discomfort between the reference building and the
598 building after the application of the different measures.

599 The results obtained by combining all the strategies are also reported in Table 5 and Fig. 12, with and without
600 considering the G strategy in the combination due to its very different behavior in the different climatic locations. As
601 can be seen, combining all the different strategies does not always provide the best results. In Ancona and New Delhi,
602 indeed, the NV + B + CRW strategy (in both aged and not aged scenarios) performs better than considering all the
603 strategies together, denoting the possibility of avoiding implementing all passive measures to obtain the best results,
604 thus saving the implementation costs. Conversely, the combination of all strategies provides the overall best results
605 for the Sao Paulo case only (in both aged and not aged scenarios), i.e. where the gypsum board strategy has a better
606 performance.

607 It should be noted that only in the Sao Paulo case the application of the passive strategies allows reaching the
608 levels of thermal discomfort due to hotness related to the outdoor air (i.e. 1.0, 2.9 and 23.8% for AN, SP and ND,
609 respectively, see Section 3.2.2), as well as a percentage of hours with thermal discomfort due to hotness lower than

the threshold defined in (CIBSE 2013) to avert hot feeling (i.e. 1.25 % of the whole year), and in particular by adopting the NV + G and the “All combined” strategy in both aged and not aged scenarios.

Finally, a comparison between the different solutions can also be made in terms of thermal comfort increase. In this case, the best solution for all the three climatic locations is obtained with the NV + B strategy, with an overall number of hours that are no more characterized by thermal discomfort (due to both hotness and coldness) equal to 5.8, 9.1, and 14.4% of the total hours of the year for Ancona, Sao Paulo, and New Delhi, respectively.

3.4.2 Cost-effectiveness and operational feasibility

Given the paramount importance of economic and financial aspects in emergency scenarios, in Fig. 13 a comparison between passive solutions in terms of both cost and cooling effectiveness is reported to define the best strategy. In particular, the passive cooling effectiveness is reported in terms of $T_{max,5\%}$ reduction (Fig. 13a), and reduction of thermal discomfort due to hotness (Fig. 13b). Costs are referred to the additional costs incurred by the manufacturer for the implementation of the passive measures before selling the unit (see Table 3).

Since the objectives of minimizing costs and maximizing passive cooling effectiveness are contrasted with one another, it is not possible to identify a single optimal solution that minimizes/maximizes simultaneously both objectives. Then, in these situations, the best solution is generally represented by the best trade-off. The latter is chosen among the Pareto optimal solutions, i.e. a set of solutions that, taken individually, have no other solutions with better performance in terms of both cost and cooling effectiveness (not-dominated solutions) (Harkouss et al. 2018). The set of Pareto optimal solutions constitute the so-called Pareto front. Accordingly, for each climatic context, two Pareto fronts are identified and shown in Fig. 13a and b, referred to the aged and not aged scenario, respectively.

In all climatic locations and scenarios, the Pareto front is constituted of NV-based solutions, i.e. the NV solution combined with the other strategies. In particular, in the not aged scenario, NV, NV + CR, NV + B, NV + CRW, and NV + B + CRW are always Pareto optimal solutions, and then constitute the Pareto front of all climatic scenarios. The NV + G and All strategies, instead, are Pareto optimal solutions only in the SP case. In the aged scenario, a similar result is obtained, except for NV + CRW, which is dominated by NV+B and then it is no more an optimal solution.

As already said, it is difficult to define the best trade-off among optimal solutions. However, some general considerations can still be made.

First, the NV strategy is the solution with the highest cost-effectiveness due to the null investment cost for all the

638 considered climates. Thus, it can be considered as the first optimization of the no-investment scenario.

639 Conversely, the solutions implementing the G strategy (“All” and NV + G) are characterized by the highest costs,
640 due to the high cost of the G strategy. As can be seen in Fig. 13, these high costs are never justified by an adequate
641 and proportional reduction of indoor overheating (even for the Sao Paulo case). For this reason (and since these
642 solutions are not included in the Pareto front of Ancona and New Delhi), increasing the internal thermal inertia
643 cannot be considered an appropriate choice for improving the indoor environment of temporary lightweight
644 construction systems when placed in these climates, unless the costs for the application of this solution are reduced.
645 The G-based strategies are also the worst solutions in terms of operational feasibility for the specific construction
646 system, due to the need for specialized workers for their installation (that could not be available in an emergency
647 scenario), the transportation issues that can arise due to the higher massiveness and volume of the materials, and the
648 reduction of the indoor space that the adoption of this solution entails when compared with other strategies.

649 Comparing the other cases, the NV + CR and NV + B solutions have the lowest costs in all climatic contexts and
650 scenarios, thus representing the cost-optimal solutions. In particular, in the not aged scenario, NV + CR outperforms
651 other strategies in terms of both cost and cost-effectiveness, the latter computed as the ratio between cost and cooling
652 effectiveness parameter, graphically identifiable in Fig. 13 as the slope of the lines connecting the data markers with
653 the NV marker representing the optimized no-investment scenario (the lower the slope, the higher the cost-
654 effectiveness). In the aged scenario, however, NV + B becomes the best solution in terms of cost-effectiveness in all
655 climatic contexts. Moreover, considering that in some climatic locations higher importance can be attributed to the
656 minimization of thermal discomfort due to coldness, such as in Ancona due to the colder winter (see Fig. 4), the NV
657 + B solution could represent a better option than NV + CR also in not aged conditions, since the higher cost can be
658 justified by the quite null increase of thermal discomfort due to coldness (see Table 5 and Fig. 12).

659 Thence, in hot climates, the NV + CR solution can be considered as the optimal trade-off between thermal
660 comfort, economic and operational feasibility, but only if its performance is not expected to be strongly reduced by
661 aging during the building service life, or, in case of polluted scenarios, only if a periodic cleaning and maintenance of
662 the surfaces is carried out by the occupants. If rapid aging is expected, indeed, the NV + B strategy represents the
663 best trade-off. NV + B represents the best trade-off also in temperate climates in both aged and not aged scenarios.
664 Then, it should be considered as the first choice for improving the indoor thermal environment of lightweight
665 temporary units.

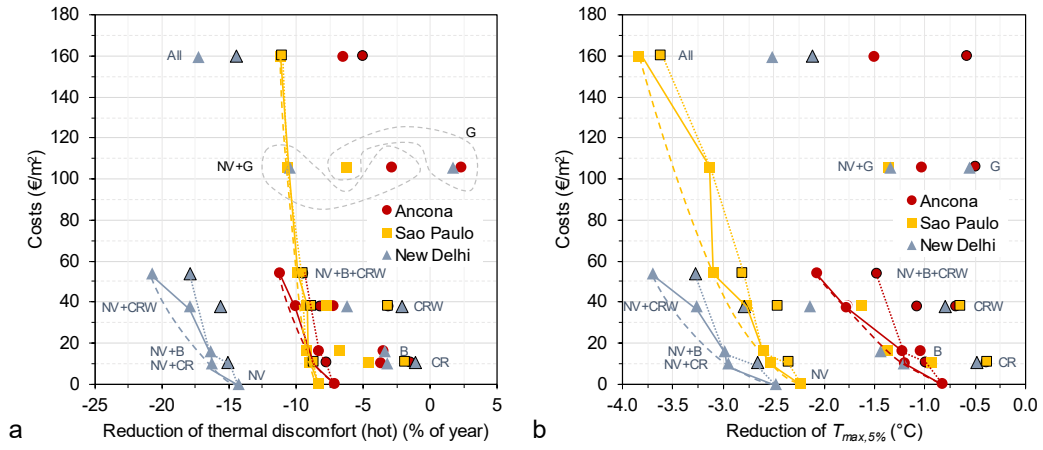


Fig. 13. Comparison of different passive strategies in terms of a) cost and reduction of $T_{max,5\%}$; b) cost and reduction of thermal discomfort due to overheating. Markers with black contours are referred to the strategies with cooling materials in the aged scenario. Solid and dotted lines represent Pareto fronts with optimal solutions for each climatic location in the not aged and aged scenarios, respectively. Dashed lines are theoretical (convex) Pareto fronts.

4 CONCLUSION

In this paper, calibrated numerical simulations have been carried out to investigate the thermal performance of a novel, lightweight, construction system, recently used as temporary units, affordable housing solutions, and specialty field hospitals. The possible application of several passive cooling measures was investigated to provide suggestions for the correct improvement of the indoor livability of temporary lightweight buildings in hot and temperate climates.

The numerical analyses showed high indoor summer overheating and high thermal discomfort due to hotness in all the considered climates. Summer heat gains analysis suggests that windows are the constructive feature responsible for the highest share of the total heat gain. Conversely, walls have the lowest impact on indoor heat gain due to the low thermal conductivity.

The effectiveness of passive cooling strategies may depend on the characteristics of the climatic locations. This notwithstanding, in all the considered climates, the results suggested that combining natural ventilation with shading or cooling materials constitutes a good trade-off between thermal comfort, costs, and operational feasibility aspects. However, it is found that passive strategies cannot completely reduce the thermal discomfort due to indoor overheating.

The main limitation of this study was to consider only a few representative climatic contexts, building layouts, and orientation. Future works will then investigate the possible optimization of geometrical features in a wider number of climates, also considering the possible combination of both passive and active cooling measures to allow safer use when long periods of occupation are concerned.

689 **APPENDIX. REFERENCE BUILDING RESULTS**

690 In Fig. A.1, the annual variations of indoor air temperatures in the south, west, and east rooms are plotted and
691 compared for each climatic location from which the highest indoor temperatures are reached in the west room for
692 all the locations. These plots provide an insight into the instants during the year and the hours of the days when
693 indoor air temperatures are excessively low or high. For example, it can be noted that, in Sao Paulo, the indoor air
694 temperatures are characterized by a more limited oscillation during the year, due to a temperature variation similar in
695 both hot and cold seasons (see Fig. A.1).

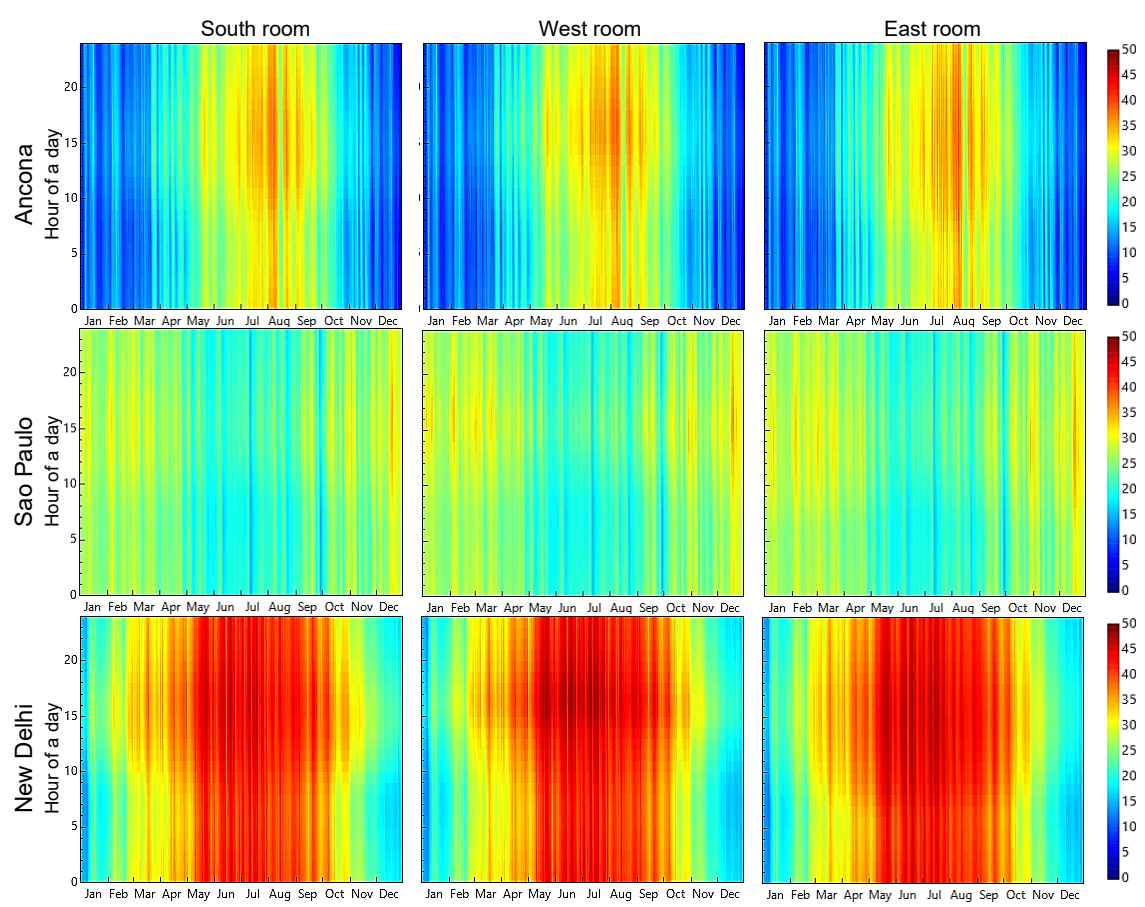


Fig. A.1. Hourly indoor air temperatures of the monitored rooms of the reference building in the three different climates.

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