Passive cooling & climate responsive façade design

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Passive cooling & climate responsive façade design exploring the limits of passive cooling strategies to improve the performance of commercial buildings in warm climates

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1. Introduction

The energy required to provide cooling for commercial buildings is an issue of concern in the current global agenda for sustainability. It has been stated that refrigeration and air conditioning account for about 15% of the total electricity consumption in the world [1], while cooling may be responsible for over half of the overall energy needs for the operation of an average office building in warm climates [2]. The relevance of cooling demands in commercial buildings responds to high internal gains (occupation density and equipment) in general, which is aggravated by the impact of solar radiation in commonly lightweight and highly glazed façades [3]. On a global scale, the relevance of cooling demands will keep increasing, considering climate change and the impact of fast growing economies from warm climates, such as India and China, on energy consumption projections for the next decades [4–6].

Several initiatives have been put in place to tackle this situation, focusing on the energy savings potential of the building sector. Good practices and benchmarks are being extensively promoted for referential purposes [7,8], while regulation is being enforced to reduce the operational energy demands in buildings [9]. To accomplish this goal, it is widely agreed that the first step in the design of an energy efficient building should be the application of passive strategies under a climate responsive design approach [10–12], before considering mechanical equipment driven by fossil fuels. Therefore, understanding the potential benefits from passive design strategies and the limits for their application has become a relevant research field, particularly concerning façade design, as the main filtering layer between outside and inside [13].

The performance of passive cooling strategies in office buildings has been increasingly studied over the last couple of decades, mostly through the use of computer simulations [14]. Most experiences focus on specialised evaluations of one or more strategies, such as ventilation or solar control, under selected parameters. Regarding ventilation, relevant examples are the studies carried out by Kolokotroni et al. [15,16] on night ventilation performance and the extensive studies carried out by Gratia and De Herde on the potential for natural ventilation on double-skin facades [17,18]. Solar control studies have mostly focused on design optimisation of sun shading components to improve their performance, through multi-variable analysis and parametric design [19–21]. Although these experiences are regarded as highly valuable referential information, their results are constrained to the particularities defined for each evaluation setup, namely climate context or assumptions from the base model; hindering their direct translation under different conditions. On the other hand, it is possible to find more comprehensive approaches that explore the potential of different passive cooling strategies in various climates, throughout the review of climate factors [22,23], or by developing and testing multi-objective assessment tools [24,25]. Nonetheless, these studies mainly focus on the general suitability of passive strategies based on climatic considerations, but do not fully explore their potential limits and expected performance considering particularities of the building.

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This paper discusses the expected performance of selected passive cooling strategies in commercial buildings from warm climates, to explore the extents of passive design optimisation under varying conditions. Hence, the main goal of the article is to define ranges of performance for each addressed strategy, in terms of energy savings potential, identifying borderline situations and optimal scenarios based on previous research experiences. The decision to use results from the literature as main information source was driven by the desire to contrast multiple scenarios and parameters, to account for variability present on real conditions. A secondary reason was an aspiration to organise valuable scientific data in a systematic way in order to provide useful referential guidelines for passive design of commercial buildings, instead of generating redundant new data. The review and statistical analysis of the information was followed by a controlled series of simulations in order to explore certain aspects in more detail.

Therefore, the assessment was structured in two main consecutive stages: first, a review of research experiences was conducted, to establish performance ranges based on available information; followed by a sensitivity analysis to evaluate the different strategies in a controlled environment. The review served as referential information considering a wide array of variables, cases and contexts, while the sensibility analysis was used to understand the potential impact of selected variables and their interaction, on the cooling savings for a particular case in humid and dry warm climates. The variables for the detailed analysis were selected from the referential information gathered through the review of research experiences. The results from each stage are discussed individually, while the boundaries and defined parameters for the overall assessment are presented on a separate section dealing with material and methods.

1.1. Passive cooling: definitions and selection of strategies to be evaluated

Passive cooling is commonly understood as a set of natural processes and techniques to reduce indoor temperatures, in opposition to the use of 'active' mechanical equipment. Nonetheless, this binary distinction present problems in practice, addressed by several authors when stating that the use of minor mechanical equipment such as fans and pumps is allowed under the term 'passive' if their application might result in a better performance [26]. Therefore, it is possible to find two distinct groups within passive cooling concepts, based on the use of auxiliary equipment. On the one hand, strategies such as solar control, building layout, orientation, and control of internal heat sources, are presented in the literature as 'bioclimatic design strategies' [26], 'basic building design' [11], or simply 'passive cooling' [27]. On the other hand, concepts which benefit by the use of pumps or fans, such as geothermal, evaporative and radiative cooling or night flush ventilation, are defined as 'natural cooling' [27] or most commonly 'passive cooling systems' [11,26,28]. Nevertheless, the common attribute of all mentioned strategies is that they are driven by low valued energy, in the form of environmental heat sources and sinks (low-exergy instead of high-exergy sources such as electricity) [29,30]. Thus, an extra layer in the discussion was added by Kalz and Pfafferott by categorising the discussed groups in 'passive low-ex' and 'active low-ex' cooling systems, in a declared effort to propose less ambiguous terminology [31].

From a physics standpoint, cooling strategies are also categorised in the literature according to the way they handle heat, basically distinguishing heat avoidance/protection, heat modulation, and heat dissipation principles and according strategies [27,32]. The fact that heat modulation techniques do not reduce cooling loads by themselves has been discussed by some authors, choosing to present them as a complement of heat dissipation/heat rejection cooling strategies [11,26], storing heat indoors to be released outside at a more convenient time. Hence, basic passive cooling principles seek to primarily avoid unwanted heat, while dissipating the surplus throughout environmental heat sinks. These two sets of principles define different technical possibilities, which match the distinction between building design strategies and passive systems, allowing a comprehensive categorisation of passive cooling principles (Fig. 1).

Fig. 1 shows an overview of passive cooling strategies and systems mentioned in the literature, categorised according to the discussed variables. Consequentially, two main groups were identified: passive design strategies and passive cooling systems, dealing with heat avoidance and heat dissipation respectively. The different possibilities are shown within the groups, with reference to the authors who mentioned them. Moreover, the overview also considers indirect strategies, which do not particularly provide a cooling effect, but their correct application could result on reduced cooling demands (use of daylight, air-tightness), or serve as a complement

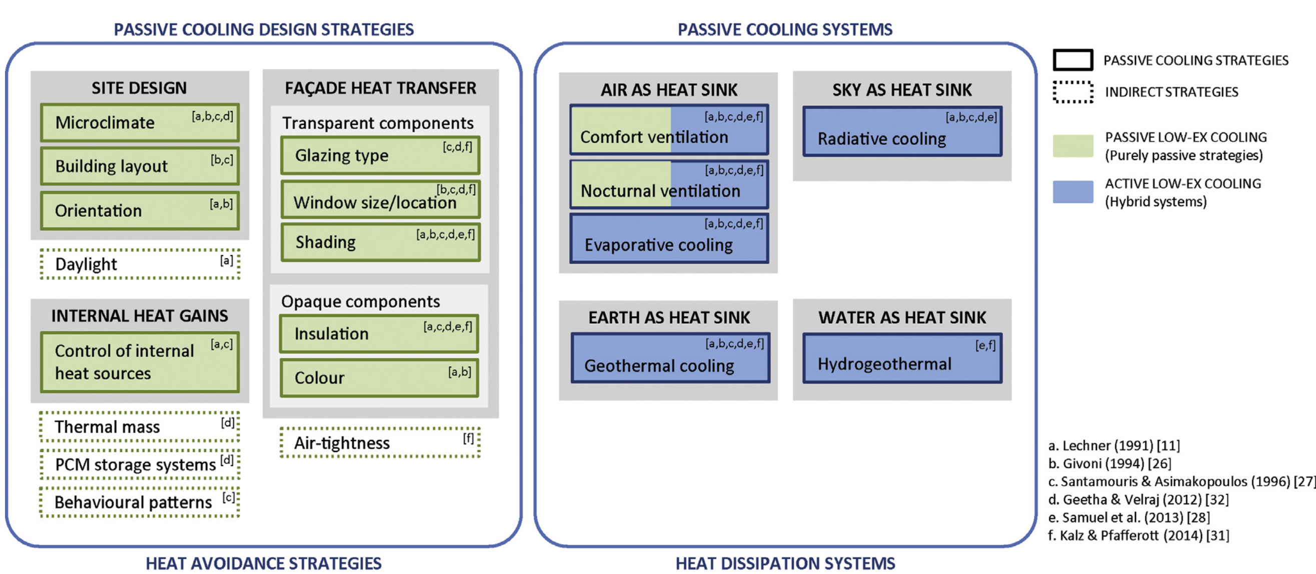

Fig. 1. Categorisation of passive cooling principles based on the literature review.

for heat dissipation strategies (thermal mass, PCM storage). Cooling strategies are further categorised within the main groups, in terms of their working principles. Hence, passive systems are classified according to the heat sinks they employ, being air, earth, water or sky; and passive design strategies are distinguished by their effect at whole building or site design level, management of internal heat gains, or design decisions concerning heat transfer through the façade, either through opaque or transparent components.

For purposes of the analysis, it was decided to focus on passive low-ex cooling strategies, as they represent the first step of building design optimisation, before adding additional equipment. Furthermore, the evaluation sought to consider relevant heat prevention and heat dissipation strategies for commercial buildings, so a second decision was to focus on solar control and ventilation cooling strategies. On the one hand, diurnal and nocturnal ventilation have been proven to be effective and simple heat dissipation strategies, driven either by natural or mechanical means. Of course, in the latter case, the potential operational benefits derived from using fans have to surpass the inconvenient extra energy required for their operation. On the other hand, the impact of solar radiation on the cooling demands of commercial buildings is a particularly important aspect to consider in warm climates. Moreover, façade design is specially determinant in urban contexts, where site restrictions and orientations are set beforehand, so the potential for passive optimisation falls on an adequate design of the building envelope, according to the particular climate context, with emphasis on the treatment of its transparent components.

2. Strategy and methods

As explained before, the evaluation was conducted in two sequential steps. First, a review of performance results from previous research experiences was carried out, to define performance ranges for each passive cooling strategy considering multiple scenarios. This was followed by a sensitivity analysis through the use of an energy simulation software, to discuss and compare the general results under a controlled experimental setup, in order to assess the impact of certain variables on the expected cooling performance. The methods, boundary conditions and parameters set for each evaluation stage are presented separately.

2.1. Review of passive cooling research experiences

Published results in peer reviewed scientific articles were considered as source material for the evaluation. The articles were selected from several journal online databases, following initial search queries to explore the field, presented and discussed in an earlier work [14]. The review considered research experiences conducted on cooling dominated climates in tropical, dry and temperate zones (class A, B and C in Koppen's classification), focusing exclusively on passive cooling. As mentioned before, the strategies considered in the evaluation were ventilation and solar control strategies, namely shading, glazing type, and window-to-wall ratio.

Given that the goal of the review was to define performance ranges for several cooling strategies, it was necessary to consider the same type of output from the findings to allow for comparisons. Because of its referential value for design purposes, cooling demands savings was chosen as the unit for comparison, understood as the reduction (in percentage) from the cooling demands of a base case scenario, after the application of a particular cooling strategy. This decision directly influenced the article selection process, considering research experiences which analysed the performance of diverse cooling strategies in terms of cooling demands, instead of temperature differential, or perceived thermal comfort. In some cases, cooling savings were directly given, while in some others were calculated based on the reported total cooling demands of several scenarios before and after intervention. Moreover, the goal was to assess the reduction potential of different cooling strategies, so it was a prerequisite to be able to isolate their specific influence from the available information published in the papers. Hence, the research methods and published data had to be comprehensive enough to allow for correct interpretation. As an additional fact, all selected articles used energy simulation software for evaluation purposes, clearly detailing the experimental setup. So, in all selected research experiences, it was possible to define a primary strategy being tested, in which case only parameters related with that particular strategy were modified from base case to the intervened scenario. In some cases, a secondary strategy was identified, but they were regarded as auxiliary to the main strategy evaluated, such as the increase of thermal mass to further improve night ventilation strategies. The possible impact of these secondary strategies on cooling demand reduction was considered when discussing the results.

Table 1 shows the selected articles for the review, based on the criteria discussed above. Besides references, the table shows the climate zones referred in each document and the passive cooling strategies evaluated by the authors. These articles were reviewed to generate a database which considered not only the reported results in terms of cooling demand savings, but also relevant information about the experimental setups and parameters set by the researchers. The database consists of 526 rows of data, from 41 scientific articles [33–73]. Each data row in the database corresponds to one reported experiment, based on the evaluation of the effect of a particular parameter in the performance of a passive strategy in a given climatic context. This meant that if the evaluation was carried out in more than one climate, or multiple strategies were analysed, this resulted in separated data rows for each one of the cases. Likewise, if several parameters were evaluated for a particular strategy, such as the performance of different shading types, it also resulted on separate rows for each one of the defined types, associated with each different reported cooling demand savings. Results from evaluations conducted on cold climates were not considered in the databased, even if they were reported in the reviewed articles.

The database was categorised and explored through descriptive analysis techniques with the use of IBM SPSS Statistics software. An initial overview of the sample was conducted, to characterise the gathered information and present the array of research experiences considered in the database, accounting for climate variations and the share of each passive cooling strategy in the total amount of data rows ($n = 526$). The graph in Fig. 2 shows the amount of results per climate context, classified in four groups: tropical (Af, Am, Aw), dry (BWh, BWk, BSh, BSk), humid temperate (Cfb, Cwb, Cfa, CWa), and dry temperate climates (Csa, Csb), representing 16%, 21%, 21% and 42% of the total sample respectively. Considering humidity as a defining parameter, warm dry climates comprehend 63% of the sample ($n = 331$), while warm humid climates account for the remaining 37% ($n = 195$).

The composition of the sample in terms of selected passive strategies is shown in Fig. 3, considering an initial distinction between warm dry and warm humid climates. It is possible to see that even though the sample considers more research conducted on dry climates, all strategies are covered in both main climate groups. Performance ranges for each passive cooling strategy are defined and discussed separately, in Section 3, considering climate variation. Furthermore, relevant experiences are discussed in detail, identifying average performance values and borderline scenarios, to assess expected savings from each strategy and reported limits of their impact in different warm climates.

Table 1
Articles considered in the review, with climate zones and passive cooling strategies evaluated by the authors.

BASIC INFORMATION				PASSIVE COOLING STRATEGIES			
REF	AUTHOR	YEAR	CLIMATE ZONES (KOPPEN)	SHADING	GLAZING TYPE	GLAZING SIZE	VENT.
[33]	Ahmed & Wongpanyathaworn	2012	Cfa				■
[34]	Appelfeld et al.	2012	Cfb/Csa/Dfb	■			
[35]	Assem & Al-Mumin	2010	BWh	■	■		
[36]	Aste et al.	2012	Cfa	■	■		
[37]	Bahaj et al.	2008	BWh	■	■		
[38]	Baldinelli	2009	Csa	■		■	
[39]	Bellia et al.	2013	Csa/Cfa	■		■	
[40]	Ben-David & Waring	2016	Aw/BWh/BWk/BSk/Csa/Cfa				■
[41]	Chiesa & Grosso	2015	Cfa/BSh/Csa/BWh/BSk				■
[42]	Eskin & Türkmen	2008	Dsa/Csa	■	■		
[43]	Ezzeldin & Rees	2013	BWh				■
[44]	Fathoni et al.	2016	Aw	■			
[45]	Favoino et al.	2015	Csa		■		
[46]	Ferrari & Zanotto	2012	Cfa/Csa	■			■
[47]	Geros et al.	1999	Csa				■
[48]	Goia	2016	Cfb/Csa			■	
[49]	Hammad & Abu-Hijleh	2010	BWh	■			
[50]	Hamza	2008	BWh		■		
[51]	Hee et al.	2015	Af/Cfa		■		
[52]	Huang & Niu	2015	Cwa		■		
[53]	Hwang & Shu	2011	Am	■	■	■	
[54]	Ji et al.	2009	Cfa				■
[55]	Kolokotroni & Aronis	1999	Cfa				■
[56]	Lau et al.	2016	Af	■	■		
[57]	Lee et al.	2013	Af/Cfa			■	
[58]	Manzan	2014	Cfa/Csa	■	■		
[59]	Chaiwiwatworakul et al.	2012	Aw		■	■	
[60]	Moretti & Belloni	2015	Cfa		■		
[61]	Pino et al.	2012	Csb	■	■	■	
[62]	Roach et al.	2013	Csa				■
[63]	Samaan et al.	2016	BWh	■	■	■	■
[64]	Schulze & Eicker	2013	Csa/Cfa/Cfb	■		■	■
[65]	Sherif et al.	2012	BWh	■			
[66]	Solgi et al.	2016	BWh				■
[67]	Stazi et al.	2014	Cfa	■			
[68]	Tsikaloudaki et al.	2012	Csa	■			
[69]	Wan Nazi et al.	2015	Af		■		
[70]	Wan Nazi et al.	2017	Af		■		
[71]	Wang & Greenberg	2015	Cfa				■
[72]	Yang & Li	2008	Cwa				■
[73]	Yoon et al.	2014	Cwa	■	■		

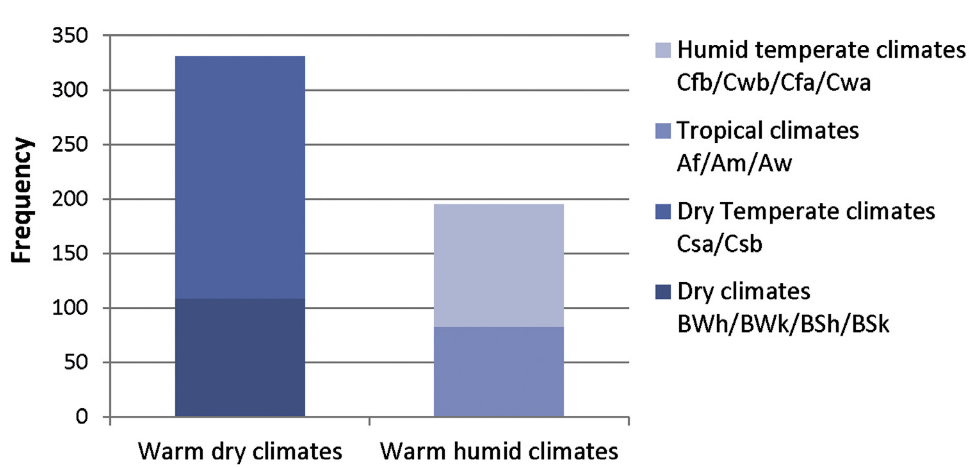

Fig. 2. Number of reviewed results per climate context.

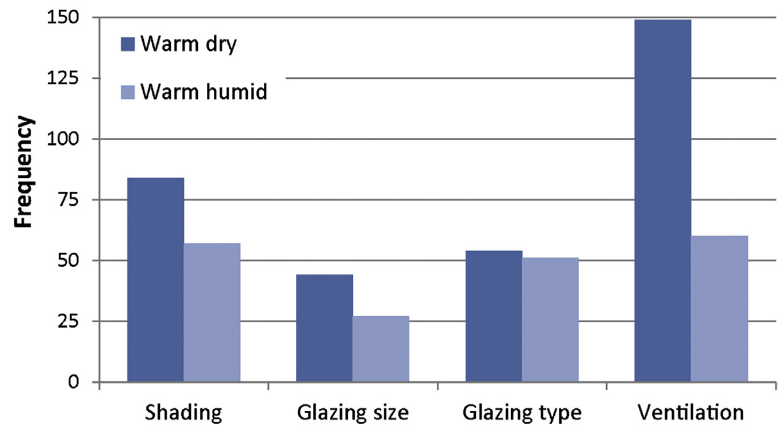

Fig. 3. Number of results per strategy and main climate groups.

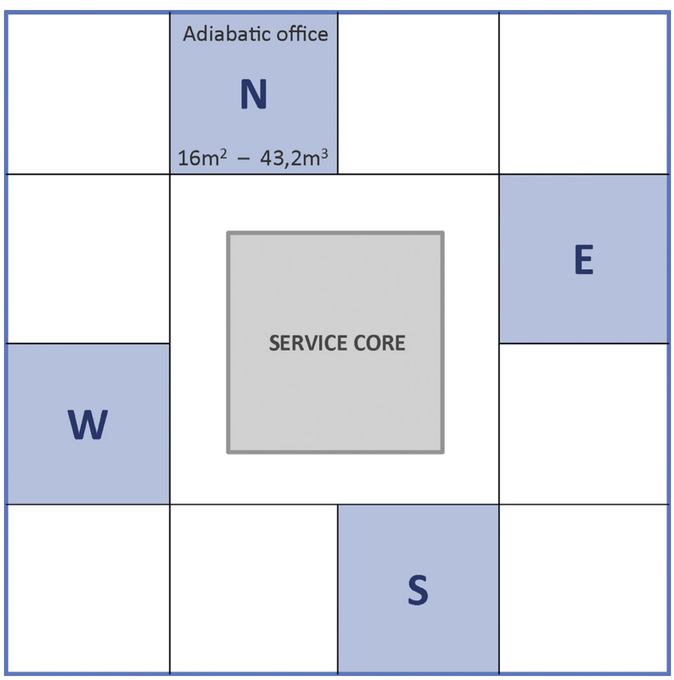

Fig. 4. Office floor plan used as base case.

2.2. Sensitivity analysis of passive cooling strategies

The sensitivity analysis sought to complement the results from the review with results obtained under a controlled setup, isolating the impact of the evaluated strategies on two different reference buildings, located on representative cities from selected warm climates. While the review aimed to provide overall performance ranges considering a high variation of scenarios, the sensitivity analysis allowed to directly compare cooling savings potential of the evaluated strategies and possible relations between them on two reference cases. Furthermore, it allowed to compare not only cooling reduction in terms of percentage, but also discuss brute cooling demands per square meter before and after the application of each strategy.

DesignBuilder v4.7 was used for the analysis, as the graphical interface of EnergyPlus v8.3. The base model consisted of a complete office floor of 2.7 m high and a plenum of 0.7 m, with perimeter offices of 4 × 4 m each as shown in Fig. 4. Only highlighted offices were considered in the analysis, using their cooling demand values to define a floor average as unit for comparison during the evaluation. Basic building parameters and internal heat gains were set based on referential values commonly used in the reviewed research experiences. Hence, occupancy was set at 0.1 people/m^2, equipment loads at 11.77 W/m^2 and infiltration rate was set at 0.2 air changes per hour (ach). Ventilation was kept at a minimum rate for hygienic purposes (10l/s per person), while lighting was controlled, with a target illuminance of 400 lx and a lighting power density of 3 W/m^2 for 100 lx. Thermal comfort ranges considered a maximum temperature of 26 °C and relative humidity between 25 and 55%.

To define the scenarios to be simulated, two conditions were set for each passive cooling strategy: an initial condition (0), where the strategy is not applied in the building, and a second condition (1), considering its application by changing a specific parameter, as shown in Table 2. Simulated parameters were based on the reviewed experiences, considering high energy savings potential as reported by the researchers. Consequentially, different combinations of these parameters were considered in a matrix, for the definition of the simulation scenarios, as shown in Table 3. Ten different scenarios were defined: an initial case without the application of any passive cooling strategy (0000), a case which considered all strategies (1111) and all combinations resulting from the single application of each evaluated strategy (1000–0001), and the application of all others with the exemption of the one to be evaluated (0111–1110). This set of scenarios allowed for the assessment of the isolated impact of each strategy on a case without any other passive measure, and a case where other measures were already in place. It is relevant to point out that the application of all strategies is not necessarily presented as an optimal scenario, acting only as an example of the application of several passive cooling strategies into a reference building, without a process of conscious optimisation or integral design.

The scenarios were simulated in representative cities from each climate group. It was decided to consider two examples instead of one in the case of temperate climates, to account for variations in climate severity within the group. Hence, six representative cities were selected for the evaluation, as shown in Table 4 along with their cooling degree days (CDD) considering 26 °C as base temperature. In summary, the total number of simulations was set at 60, comprising 10 scenarios in 6 representative cities, for a comprehensive evaluation and comparison of the results.

Table 2
Simulated parameters for each passive cooling strategy.

Cooling strategy	Simulated parameters	
	0	1
Shading	NO	Dynamic exterior shading (high reflectivity slats) on operation over 100 W/m^2 of solar irradiance on facades.
Glazing size (WWR)	100%	25%
Glazing type	Double clear glass	Double reflective glass (6–13–6 mm with air in cavity)
Ventilation	NO	5 ACH max when it's thermodynamically feasible (external temperature below internal temperature)

Table 3
Simulated scenarios based on the application of the evaluated strategies.

Simulated scenarios per climate	Passive cooling strategies			
	Shading	Glazing size (WWR)	Glazing type	Ventilation
No strategies applied	0	0	0	0
Only shading applied	1	0	0	0
Only WWR applied	0	1	0	0
Only glass type applied	0	0	1	0
Only ventilation applied	0	0	0	1
All strategies applied	1	1	1	1
No shading applied	0	1	1	1
No WWR applied	1	0	1	1
No glass type applied	1	1	0	1
No ventilation applied	1	1	1	0

Table 4
Representative cities per climate group.

Climate group	City	CDD (26C)
Desert	Riyadh	1583
Tropical	Singapore	992
Temperate humid	Hong-Kong	602
Temperate dry	Athens	212
Temperate humid	Trieste	88
Temperate dry	Lisbon	69

3. Results and discussion

3.1. Definition of performance ranges for passive cooling strategies: exploration of a database of research experiences

As explained before, the first part of the evaluation was based on the statistical exploration of a database comprising performance results obtained from several scientific articles. Table 5 shows basic statistical data to assess the energy savings potential of the selected strategies, for two main climate groups: warm-dry and warm-humid climates. A first issue worth mentioning is the fact that reported energy savings reach higher values in the case of warm-dry climates, evidenced by the large difference between maximum reported values (from 22 to 37 percentage points depending on the strategy), and the higher average and median values for all strategies, with the exemption of the use of shading devices, which average similarly on both groups. This means that the application of passive cooling strategies has more potential for lowering cooling demands on warm-dry climates, instead of warm-humid ones; which corresponds with the well-known complexity and particular challenges associated with high humidity contexts and tropical regions.

Furthermore, the reported energy savings in both climate groups vary differently among the evaluated strategies. In the case of warm-dry climates, the best average results are experienced through the use of ventilation strategies (50%) and the reduction of the window-to-wall ratio (34%); while in the case of warm-humid climates, it is through ventilation and shading strategies, with lower values of 33% and 28% respectively. The use of natural ventilation has been largely considered as a feasible cooling strategy for dry climates, but its application in humid climates presents more challenges due to specific humidity control requirements, which clearly affects its expected performance. On the contrary, the results from the use of shading devices present the lowest variation between both climate groups, which seem to position them as suitable alternatives with comparable effectiveness regardless the context. These statements are based on the initial assessment of general statistical data, so they will be expanded and compared when discussing particular cases in detail in subsequent sections.

Fig. 5 shows all reported energy savings data in a box-plot graph to visualise the range of action of all evaluated passive cooling strategies, in the two main defined climate groups: warm-dry and warm-humid climates. On the one hand, it is possible to identify short ranges, which mean that there is consistency between the gathered results for a particular strategy. This is the case of window-to-wall ratio and glazing type reported energy savings for warm-humid climates. On the other hand, long ranges mean more dispersion among the results, such as the case of ventilation strategies in both climate groups, and window-to-wall ratio in warm-dry climates. Furthermore, a long performance range means that the expected energy savings of a given strategy varies considerably within the sample, thus, it depends on other factors and variables to ensure a satisfying performance. Therefore, it is important to detect and discuss boundary cases in order to isolate the characteristics that make higher energy savings possible. The same goes for the existence of outliers with markedly higher savings, identifying and assessing their uniqueness within the larger sample, and possibilities for replicability. In that sense, the fact that all strategies considered minimum cooling savings from 0 to 5%, means that the mere application of a passive strategy is not always enough to ensure a satisfying performance, but it depends on several parameters that need to be carefully controlled to achieve the expected results.

Each evaluated passive strategy is discussed separately, exploring the gathered information to provide context to the results and identify relevant parameters for performance optimisation. The discussion focuses on the best reported result, comprising variables such as the climate severity of each evaluated context (variations based on different climates within the climate groups), characteristics of the intervention (internal parameters related to the

Table 5
Statistical values to assess cooling demand savings per evaluated strategy.

Strategies	Warm dry					Warm humid				
	N	Mean	Median	Minimum	Maximum	N	Mean	Median	Minimum	Maximum
Shading	84	26%	25%	4%	93%	57	28%	24%	5%	56%
Glazing size (WWR)	44	34%	34%	2%	76%	27	18%	14%	−2%	44%
Glazing type	54	22%	15%	1%	70%	51	12%	10%	1%	40%
Ventilation	149	50%	52%	6%	91%	60	33%	30%	2%	69%

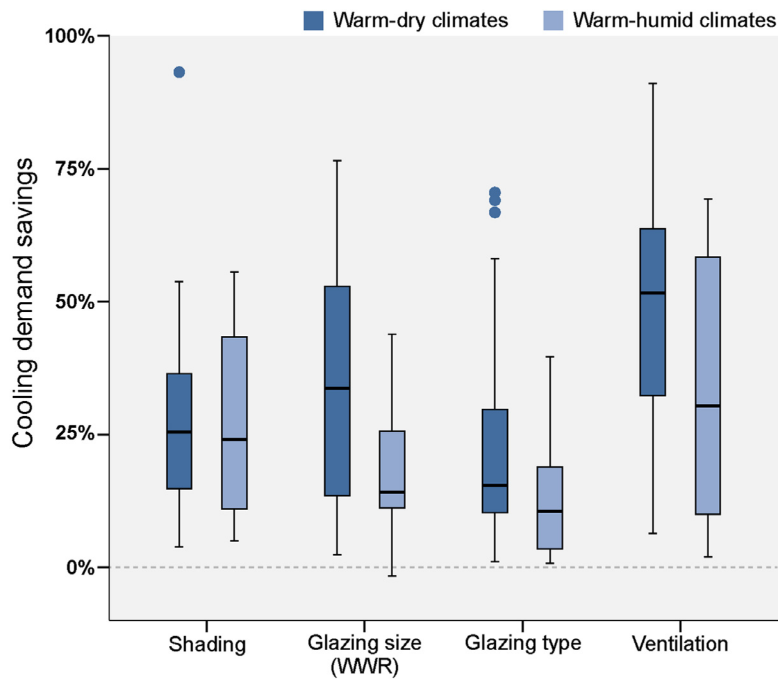

Fig. 5. Performance ranges considering all reviewed results per passive cooling strategy and main climate groups.

evaluated strategy), and characteristics of the base case (external parameters related to the experimental setup and defined base scenario).

3.1.1. Shading

The results obtained by the application of shading systems show higher mean and median values, compared to cooling demands savings from glazing type improvements. In general, shading reported values are consistent in both major climate groups, averaging around 25% in potential cooling demand savings for warm-dry and warm-humid contexts. Similarly, best reported results are comparable, reaching maximum values of 55.6% and 54.6% in the warm-humid climates of Bangkok (Aw) [44] and Trieste (Cfa) [58]; and 53.8% and 45.2% in the hot-summer mediterranean climate of Santiago, Chile (Csb) [61] and the hot desert climate of Dubai (BWh) [37], respectively. The 93.2% cooling savings reported by Baldinelli for a case in central Italy (Csa) [38] was identified as an outlier considering its large difference and uniqueness compared to the rest of the sample. Hence, it should be excluded from expected performance ranges from the application of shading strategies.

Table 6 shows all shading related research experiences considered in the database, detailing their climate context, reported range of cooling savings, information from the base case and details of the intervention and evaluated parameters. Exploring the differences from the evaluated cases, it could be seen that in general, equator facing offices have larger cooling savings potential, basically due to the high solar incidence in the north and south façade in southern and northern hemispheres respectively. Maximum reported values for equator facing offices are 55.6% [44] while maximum savings reach 39% in the case of east-west oriented rooms in the humid subtropical climate of Turin [64].

Regarding evaluated shading types, it is possible to state that the use of different shading systems does not categorically result on markedly different cooling demand savings. Nonetheless, reported results seem to hint at louvers and screens having more savings potential than the use of overhangs, which make sense considering the amount of exposed window area. Maximum reported cooling savings are 55.6%, 53.8% and 41.1% for the use of screens [44], external louvres [61], and overhangs [61], respectively. In any case, further information would be needed for a detailed evaluation of several shading types in different climate zones, besides considering particularities from each case and shading design. It is the authors' opinion, that especially in the case of shading strategies, referential information is useful and relevant for early design stages but it should always be contrasted with a detailed analysis of the actual devices being used, due to design particularities and dynamic shading patterns of a specific location and orientation.

3.1.2. Glazing size (WWR)

The results of glazing size evaluations show a considerable difference between warm-dry and warm-humid climate groups. In the first group, average cooling demand savings are 34%, while in the second they only reach 18%. The fact that median values are lower than the average in the latter (14%), mean that expected average cooling savings for warm-humid climates could be

Table 6
Research experiences about shading, considering experimental setup, climate zones and reported cooling savings ranges.

Ref	Climate zones (KOPPEN)	Country	Software	Reference case details	Evaluated parameters	Cooling savings
[34]	Hot summer mediterranean (Csa)	Italy	ESP-r	Test office room with low-e double glazing, WWR of 32% and temperature comfort range between 20–26 °C	Evaluation of microperforated steel screen, roller shade, and venetian blinds, as shading devices between the glass panes.	18%–24%
[35]	Hot desert (BWh)	Kuwait	EnergyPlus	North-west facing office with clear double glazing and 100% WWR.	Overhang of 1 m width	8%–9%
[36]	Humid subtropical (Cfa)	Italy	EnergyPlus	South facing office room with Low-e double glazing (Argon in the cavity) and 17% WWR. Temperature comfort range between 20–26 °C.	External automated aluminium venetian blind.	18%
[37]	Hot desert (BWh)	UAE	TRNSYS	North facing office room with clear low-E double glass as glazing unit with undisclosed window-to-wall ratio, and temperature set-point defined at 23 °C.	External blinds with 0% transmission	45%
[38]	Hot summer mediterranean (Csa)	Italy	CFD simulation	South facing office room with clear double glazing and 100% WWR.	Movable aluminium horizontal slats within the cavity of a double skin façade prototype.	93%
[39]	Hum Subtrop (Cfa) Hot-summer mediterra (Csa)	Italy	EnergyPlus	Complete typical office building with double glazing and 30% WWR. Temperature comfort range between 20–26 °C.	Overhangs on south façade (1 m) and fixed louvers on east-west facades	26%–30%
[42]	Hot summer mediterranean (Csa)	Turkey	EnergyPlus	Complete office building with aspect ratio of 1:36, clear single glazing and 40% WWR. Temperature comfort ranges between 22–24 °C and 18–26 °C for day and night time respectively. Infiltration of 0.2 ACH	Internal light color curtain (close weaved).	4%–7%
[44]	Tropical savanna (Aw)	Thailand	Visual Basic 6	South facing office room with variable depth. Heat reflective single laminated glazing with 53% WWR and temperature setpoint of 25 °C.	Horizontal slats in the cavity of a double glazing unit.	37%–55%
[46]	Humid subtropical (Cfa) Hot-summer mediterranean (Csa)	ITALY	TRNSYS	South facing room in five different office building types, based on decade of construction and WWR. Glazing type considers clear and tinted double glazing, with 23%, 63% and 100% WWR according to each building type. Temperature setpoint of 26 °C, infiltration rate of 0.2 ACH	Light colored external venetian blinds, with shading factor of 0.3. Shadings are manually activated when direct solar radiation exceeds 100 W/m^2.	10%–27%
[49]	Hot desert (BWh)	UAE	IES-VE	Isolated office room with clear double glazing, window-to-wall ratio of 60% and a temperature set-point of 24 °C. South, west and east orientations were considered in the analysis	Evaluation of fixed vertical (west-east) or horizontal (south) lovers at 0*, and dynamic louvers for all orientations	25%–38%
[53]	Monsoon (Am)	China	EnergyPlus	South facing room of a real building, with tinted-blue single glazing and 72% WWR.	Evaluation of overhangs with different width (1.2; 2.4; 3.6; 4.8)	7%–11%
[56]	Tropical rainforest (Af)	Malaysia	IES-VE	Complete high-rise office buildings with clear single and low-e clear double glazing, and 100% WWR. Operative temperature set at 23 °C.	Evaluation of horizontal and vertical louvres and egg-crate shading devices.	5%–10%
[58]	Hum subtrop (Cfa) Hot-summer mediterra (Csa)	Italy	ESP-r	South facing office room of 20 m^2, with low-e clear double glazing and 45% WWR. Window with and without reveal were used as base scenarios.	Flat panel positioned parallel to the window, inclined by its horizontal axis and widths of 1 and 2 m.	30%–56%
[61]	Hot-summer mediterranean (Csb)	Chile	EDSL TAS	Evaluation of an entire office floor. Considering different reference cases, based on the use of different glazing types (clear single and double, and tinted single and double glazing) and window-to-wall ratios (20%, 50%, 100%)	The evaluation considered blinds at west and east orientations, and the use of either overhangs or blinds facing north.	22%–54%
[63]	Hot desert (BWh)	Egypt	EnergyPlus	Evaluation of real office rooms in an University Campus, facing north, south and west orientations. Clear single glazing and 50% WWR is considered. Operative temperature is set to 23 °C.	Shading devices evaluated consider horizontal louvres (0.5 m) and the use of overhang of diverse width (0.5 m; 1 m; 1.5 m)	4%–20%
[64]	Humid subtropical (Cfa) Hot-summer mediterra (Csa)	Italy Turkey	EnergyPlus	Evaluation of 18 office rooms in a referential building, facing east and west orientations, with low-e double glazing and 50% WWR. Temperature cooling setpoint is 25 °C during work hours and 30 °C during night time.	External venetian blinds with slat angle of 45*, 50% reflectivity, slat separation and width of 4 and 5 cm respectively. Automated shading system depending on solar intensity on façade (250 W/m^2).	36%–39%
[65]	Hot desert (BWh)	Egypt	EnergyPlus	Isolated office room with low-e clear double glass and 20% WWR. Evaluation was conducted for all four orientations separately. Operative temperature set at 23 °C	Wooden solar screen (oakwood) of 2.7 × 1.8 m at 50 mm from the wall. Perforation area: 90% Depth ratio:1.0	7%–30%
[67]	Humid subtropical (Cfa)	Italy	EnergyPlus	Single west facing office room of 28 m^2, with low-e double glass and 57% WWR. Temperature comfort range between 20–26 °C.	External aluminium slats with different angles, width and separation.	18%–29%
[68]	Hot summer mediterranean (Csa)	Greece	EnergyPlus	South and east facing office rooms within a reference building defined in ISO15265 and ISO13790. Operative temperature setpoint is 24.5 °C and infiltration rate is 0.5 ACH. WWR and Glazing types varies (WWR from 10–100% and 9 glazing units are tested).	Movable shading device, activated when incident solar radiation on vertical plane exceeds 300 W/m^2. Evaluation of shading factors of 25%, 50% and 75%	9%–45%
[73]	Humid subtropical (Cwa)	South Korea	EnergyPlus	South facing office room of 100% WWR and various glazing types (clear single, double and triple, and low-e double and triple glazing). Temperature comfort range between 22–26 °C.	External slats (25 mm slat separation, width and distance to glass). Reflectance of 0.1	9%–14%

Table 7
Research experiences about glazing size (wwr), considering experimental setup, climate zones and reported cooling savings ranges.

Ref	Climate zones (KOPPEN)	Country	Software	Reference case details	Evaluated parameters	Cooling savings
[38]	Hot summer mediterranean (Csa)	Italy	CFD simulation	South facing office room with clear double glazing and 100% WWR.	50% WWR	49%
[39]	Hot-summer mediterr (Csa) Hum subtrop (Cfa)	Italy	EnergyPlus	Complete typical office building with double glazing and 60% WWR. Temperature comfort range between 20–26 °C.	30% WWR	34%–36%
[48]	Hot-summer mediterranean (Csa)	Italy Greece	EnergyPlus	Complete office building with low-e clear triple glazing, 80% WWR and external automated venetian shading. Separated evaluations per orientation are considered. Temperature comfort range is set between 20–24 °C	Several WWR values were evaluated from 20% to 37% (optimised values per orientation)	11%–17%
[53]	Monsoon (Am)	China	EnergyPlus	South facing room of a real building, with tinted-blue single glazing and 60% WWR.	36% and 48% WWR. Additionally, the use of 2.4 m overhang was evaluated for both cases.	6%–12%
[57]	Trop rainforest (Af) Hum subtrop (Cfa)	The Philippines China	EnergyPlus COMFEN	Complete building consisting of 4 perimeter zones with 5 office rooms each. Clear double glazing on windows with 100% WWR.	Several WWR values (25%, 50%, 75%)	5%–44%
[59]	Tropical savanna (Aw)	Thailand	Numerical calculations	South facing office room with several glazing types (heat reflective, tinted and low-e laminated glazing) and either 40% or 68% WWR. Six external slats per glass pane are used as shading device.	WWR values of 40% and 20% were evaluated	−2%–24%
[61]	Hot-summer mediterranean (Csb)	Chile	EDSL TAS	Evaluation of an entire office floor. Considering different reference cases, based on the use of different glazing types (clear single and double, and tinted single and double glazing) and 100% WWR. Variations considered no shading device and the use of overhang or louvres in north, east and west orientations.	WWR values of 50% and 20% were evaluated	21%–76%
[63]	Hot desert (BWh)	Egypt	EnergyPlus	Evaluation of real office rooms in an University Campus, facing north, south and west orientations. Clear single glazing and 50% WWR is considered. Operative temperature is set to 23 °C.	Several WWR values (40%, 30%, 20%)	2%–12%
[64]	Hot-summer mediterranean (Csa) Humid subtropical (Cfa)	Italy Turkey	EnergyPlus	Evaluation of 18 office rooms in a referential building, facing east and west orientations, with low-e double glazing and 50% WWR. External venetian blinds are used as shading device. Temperature cooling setpoint is 25 °C during work hours and 30 °C during night time.	25% WWR	19%–20%

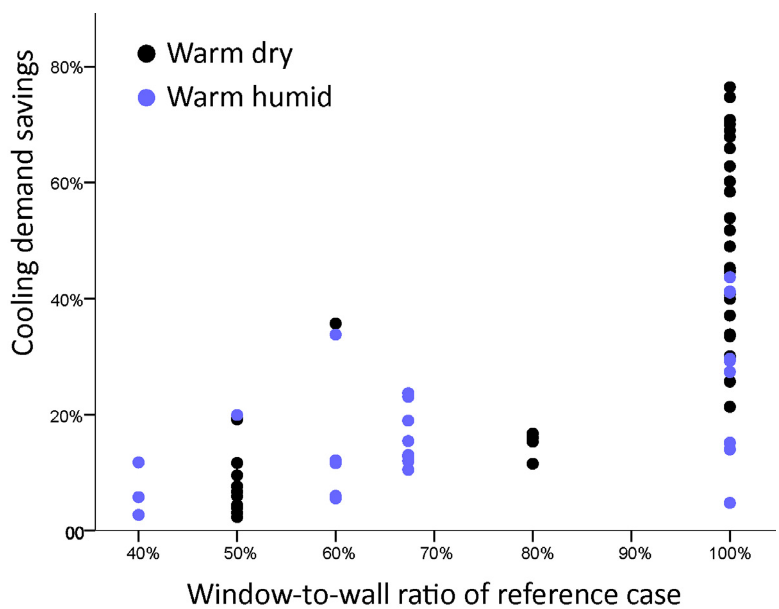

Fig. 6. Cooling demand savings compared to reference case WWR.

assumed to be lower (around 14%−18%), based on the analysed sample. In terms of maximum reported values, the difference grows apart, evidenced by the 76.4% savings obtained for the warm-dry climate of Santiago, Chile (Csb) [61] and the 43.7% and 41.1% registered by Lee et al. for warm-humid cases in Shanghai (Cfa) and Manila (Af), respectively [57]. It is relevant to point out that the research experiences that reported higher cooling savings, also considered a reference case of 100% window-to-wall ratio (WWR), by looking at the detailed information in Table 7 and the graph in Fig. 6. Of course this is not a coincidence, because any intervention conducted on a 'worst case' base scenario, should have higher potential savings in terms of percentage, so this needs to be considered when looking at the results. Nonetheless, as Fig. 6 shows, there are low savings values regardless of the initial reference case, explained by different WWR values evaluated in the second scenario.

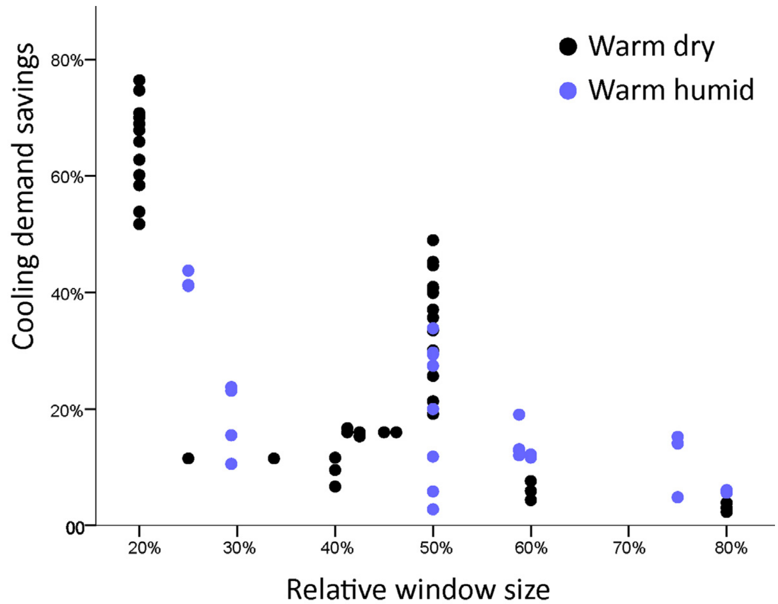

Fig. 7. Cooling demand savings compared to relative window size.

The fact that the reviewed experiences considered different WWR values in both the reference case and the intervened scenario, makes a direct comparison of energy savings troublesome. Hence, a dimensionless unit named 'relative window size' was introduced, as a way to visualise the savings impact of varying WWR under a normalised unit which simply shows the proportion of the new window compared to the reference case Eq. (1).

$$\frac{WWR_{intervention}}{WWR_{reference}} = relative\ window\ size \quad (1)$$

Fig. 7 shows the reported results compared to the 'relative window size', differentiating both major climate groups. As expected, highest cooling demand savings tend to be related to the smallest relative window sizes; however, again it is relevant to consider the WWR of the reference case to explain reported differences on cooling savings. For instance, comparing results from cases which considered a relative window size of 50% (highest frequency within the sample), it is possible to see that reported savings are between 21% and 49% for $WWR_{reference}$ of 100% [38,57,61], while they reach maximum values of 36%, 20%, and 12% in cases with $WWR_{reference}$ of 60% [39], 50% [64] and 40% [59] respectively. The differences within each range depend on the application of other strategies, such as considering tinted glass or shading in both the base case and the intervention (the only changed parameter being WWR). However, there is no clear correlation between the application of extra strategies in the base case and expected cooling savings, for cases with the same relative window size and $WWR_{reference}$. The relation between different cooling strategies and the impact of their combined application will be further discussed in Section 3.2, considering a normalised base case for comparison. This issue is highly relevant for design purposes, optimising an integral solution or building element, avoiding redundant passive strategies or even counterproductive effects. The latter are evidenced by the reported results from Chaiwiwatworakul et al. showing an increase of 2% in cooling demands by reducing the WWR from 40% to 20% in a reference case with tinted low-e double glass and external slats as shading device [59].

3.1.3. Glazing type

Results seem to show that the use of different glazing types has the lowest energy savings potential among the reviewed strategies. This is the case for both main climate groups, although the reported performance is higher in the case of warm-dry contexts, following the general trend discussed before. Results for warm-dry climates show average and median values of 22% and 15% respectively, with maximum reported savings of 58%, considering in-range experiences, and three identified outliers with values up to 70%. All best cases (in-range and outliers), correspond to the same evaluation for the hot-summer Mediterranean (Csa) climate of Rome [45]. Mean and median values for warm-humid climates are 12% and 10% respectively, while maximum values reached 39% for the humid subtropical (Cfa) climate of Milan [36].

Differences in reported performance may be further explained by looking at distinct parameters considered to define the glazing types. By looking at detailed information of each research experience in Table 8, it is possible to identify five different types of interventions, based on the change of specific glazing parameters between the initial case and the evaluated scenario: number of layers, glass colour, use of coatings, a combination of these variables, and the replacement of conventional static glazing for switchable or dynamic glazing technologies. As expected, the sole increase of the number of glass layers do not carry relevant cooling demand savings, evidenced by the 1%–2% reported savings by replacing clear single with clear double glazing in both warm-humid [51] and warm-dry [63] climate contexts.

The change in colour properties and the use of coatings seem to achieve similar cooling savings, obtaining peak values around 30%. Pino et al. reported a maximum value of 32% evaluating the use of a tinted double instead of a clear double glazing unit in Santiago, Chile [61]; while Manzan obtained the same value applying a low-e coating on a clear double glass, in the humid subtropical (Cfa) context of Trieste, Italy [58]. Moreover, Moretti and Belloni found cooling savings up to 29% through the use of solar control films on glass, in the same climate of Perugia [60]. Interestingly, higher savings values were reported by using glazing types which combined both parameters. The results from Favoino et al. showed savings up to 53% by comparing the use of clear double glass to the application of a tinted double low-e glazing unit in Rome, Italy [45]. Nevertheless, in this case it is important to highlight that the glazing unit evaluated was the result of a design optimisation process, so it could be regarded as a best case scenario. In this sense, a comparison could be made to the 19% obtained by Wan Nazi et al.

Table 8
Research experiences about glazing type, considering experimental setup, climate zones and reported cooling savings ranges.

Ref	Climate zones (KOPPEN)	Country	Software	Reference case details	Evaluated parameters	Cooling savings
[35]	Hot desert (BWh)	Kuwait	EnergyPlus	North-west facing office with clear double glazing and 100% WWR.	Evaluation of different glazing types (clear, tinted and reflective low-e glazing).	7%–27%
[36]	Humid subtropical (Cfa)	Italy	EnergyPlus	South facing office room with Low-e double glazing (Argon in the cavity) and 17% WWR. Temperature comfort range between 20–26 °C.	Electrochromic glass pane in double glazing unit.	39%
[37]	Hot desert (BWh)	UAE	TRNSYS	North facing office room with clear low-E double glass as glazing unit with undisclosed window-to-wall ratio, and temperature set-point defined at 23 °C	Several glazing types (reflective, aerogel, electrochromic, tinted glazing).	10%–49%
[42]	Hot summer mediterranean (Csa)	Turkey	EnergyPlus	Complete office building with aspect ratio of 1:36, clear single glazing and 40% WWR. Temperature comfort ranges between 22–24 °C and 18–26 °C for day and nighttime respectively. Infiltration of 0.2 ACH	Low-e clear double glazing	13%–16%
[45]	Hot summer mediterranean (Csa)	Italy	EnergyPlus GenOpt MatLab	Isolated office room with clear double glazing, 40% WWR and no shading. All orientations were evaluated separetely. Temperature comfort range set at 20–26 °C	Evaluation of an optimised glazing unit and the use of switchable glazing.	30%–70%
[50]	Hot desert (BWh)	Egypt	IES-VE	Office room with clear single glazing and 40% WWR. All orientations were evaluated separately. Temperature comfort range set between 22–24 °C	Reflective glazing	6%–12%
[51]	Trop rainforest (Af) Hum subtrop (Cfa)	Malaysia China	EnergyPlus	Isolated office room with clear single glass and undisclosed WWR. All orientations were considered separately.	Several glazing types (clear double, low-e double, reflective double, and thermotropic glazing).	1%–19%
[52]	Humid subtropical (Cwa)	China	EnergyPlus	Complete office building according to referential examples from Hong Kong guidelines. Clear double glazing on windows, 36% WWR and no shading devices. Temperature set at 25 °C	Clear double glass low-e and silica aerogel glazing are evaluated.	2%–6%
[53]	Monsoon (Am)	China	EnergyPlus	South facing room of a real building, with clear float glazing, 72% WWR and 2.4 m overhang as shading device.	Several glazing types (tinted-blue single, tinted-bronze single, film on clear pane, low-e single and reflective glazing).	3%–17%
[56]	Tropical rainforest (Af)	Malaysia	IES-VE	Complete high-rise office buildings with clear single glazing and 100% WWR. Evaluation considered no shading and the use of egg-crate, horizontal and vertical louvres separately. Operative temperature set at 23 °C.	Clear double glass low-e	10%–11%
[58]	Humid subtropical (Cfa) Hot-summer mediterranean (Csa)	Italy	ESP-r	South facing office room of 20 m^2, with clear double glazing and 45% WWR. Flat panel positioned parallel to the window, inclined by its horizontal axis was used as shading device for base case. Window with and without reveal were used as base scenarios.	Clear double glass low-e	2%–32%
[59]	Tropical savanna (Aw)	Thailand	Numerical calculations	South facing office room with heat reflective laminated tinted glass and either 40% or 68% WWR. Six external slats per glass pane are used as shading device.	Several glazing types were evaluated (laminated tinted green + clear, laminated tinted green + clear low-e, tinted double glass low-e)	17%–29%
[60]	Humid subtropical (Cfa)	Italy	EnergyPlus	South-west facing office room in the University of Perugia, with clear double glazing and 50% WWR, and no shading devices.	Solar control film on glazing	29%
[61]	Hot-summer mediterranean (Csb)	Chile	EDSL TAS	Evaluation of an entire office floor considering different base cases: variation of window-to-wall ratios (20%, 50%, 100%); the use of overhang or louvres in north, east and west orientations, or no shading at all; and clear single and clear double glazing as base case.	Tinted single and tinted double glass were compared to clear single and clear double glazing respectively.	9%–32%
[63]	Hot desert (BWh)	Egypt	EnergyPlus	Evaluation of real office rooms in an University Campus, facing north, south and west orientations. Clear single glazing and 50% WWR is considered. Operative temperature is set to 23 °C.	Several glazing types were evaluated (clear double, clear double low-e, and tinted single glazing).	1%–15%
[69]	Tropical rainforest (Af)	Malaysia	EnergyPlus	Complete medium sized office building with clear double glazing, undisclosed WWR and no shading. Operative temperature setpoint set at 24 °C.	Several glazing types were evaluated (reflective, tinted double, and tinted double low-e glazing).	12%–19%
[70]	Tropical rainforest (Af)	Malaysia	EnergyPlus	Complete medium sized office building with green tinted single glazing, 85% WWR and local shading. Operative temp. setpoint at 22 °C.	Low-E double glazing	3%
[73]	Humid subtropical (Cwa)	South Korea	EnergyPlus	South facing office room of 100% WWR and either double or triple clear glazing. Internal blinds are used for shading. Temperature comfort range between 22–26 °C.	Low-E double and triple glass were compared to clear double and triple glazing respectively.	4%–6%

through the evaluation of similar glazing units (clear double and tinted double low-e) for a building located in the tropical rainforest climate (Af) of Putrajaya, Malaysia [69].

Finally, the best results coincided with the application of dynamic glazing technologies. Both Aste et al. [36] and Bahaj et al. [37] evaluated the performance of electrochromic glazing, compared to the use of low-e double glazing, obtaining similar cooling demand savings. The former obtained 40% for a test office in Milan (Cfa), while the latter reported savings from 45% to 49% for a case study in Dubai, UAE (BWh). Moreover, Favoino et al. reported savings ranging from 58% to 70% related to the use of switchable glazing instead of clear double glass [45]. These results correspond to the outliers discussed earlier, so they are regarded as evidence of the higher potential performance ranges of these technologies, compared to 'static' solar control glazing. Nonetheless, their widespread application in façades is still restricted, mostly due to cost barriers and limited availability of products in the market.

3.1.4. Ventilation

The application of ventilation strategies achieved the highest cooling demand savings among all evaluated strategies. In general numbers, this seemed to be the case in both main climate groups, obtaining mean and median values of 50% and 52% for warm-dry climates, and 33% and 30% for warm-humid climate zones. Maximum values in each main group corresponded to research experiences in temperate climates. Chiesa and Grosso reported cooling savings up to 91%, based on the combined use of stack and wind driven ventilation in a simulated office building in the hot-summer Mediterranean (Csa) climate of Ankara, Turkey [41]. The same authors obtained savings up to 69.3% and 68.8% as the result from evaluating the building model in the humid subtropical climate of Plovdiv, Bulgary; and Rimini, Italy, respectively. The performance of ventilation strategies decreased in more harsh climates, particularly in the case of tropical environments. Maximum values in dry climates were 78% and 70%, reported by Ezzeldin and Rees, from evaluating the effect of night ventilation strategies and diurnal natural ventilation when applicable, in El Arish (Egypt) and Alice Springs (Australia); respectively [43]. In the case of tropical climates, maximum savings of 25.7% were found by Ben-David and Waring for a typical office in Miami (USA), after ventilating through the façade when it was thermodynamically favourable (mostly during night time) [40]. It is important to point out that this maximum value was obtained by also accepting a wider range in comfort temperatures, following the adaptive model proposed by Nicol et al. [74]. The authors also carried an evaluation under the same temperature ranges for both reference case and intervened scenario, obtaining cooling savings of only 8.5%, which seems to be more realistic for tropical climates based on the rest of the sample. The application of natural ventilation strategies is particularly challenging in tropical climates, due to high humidity levels which need to be controlled to prevent not only discomfort but also health issues and deterioration of building components through internal condensation.

Particular parameters considered in each research experience are shown in Table 9. Examining the results, it is noteworthy to point out that experiences that explicitly declared the use of high thermal mass obtained the highest cooling demand savings. The maximum value of 91% already discussed is an example of this, along with values up to 82.7% and 79.1% declared by Roach et al. [62] and Geros et al. [47] respectively. The former was obtained following the evaluation of a complete floor in the hot summer Mediterranean climate (Csa) of Adelaide, Australia; while the latter was the result of a TRNSYS model of a real building calibrated through on-site measurements in the similar climate of Athens, Greece.

Ventilation rates were also particularly addressed by some researchers, evaluating their impact on the overall effectiveness of the strategy. The graph in Fig. 8 shows the correlation between cooling demand savings and different ventilation rates, expressed in air changes per hour (ach). It is important to point out that information about ventilation rates was reported in just 60 out of the 209 total cases, so this particular analysis only considered a fraction of the sample (29% of all ventilation results). Ventilation rates considered in the evaluations range from 1 to 30 ach. Looking at the results, there is no direct correlation between reported savings and any given ventilation rate, so it does not seem to have a definitive impact on the overall performance. Results from applying 30 ach vary greatly, considering values between 36.2% and 79.1%, reported by Geros et al. [47] in Athens (Csa); and a minimum of 15.4% reported by Solgi et al. [66] in the hot desert climate of Yazd, Iran (BWh). On the other hand, savings up to 82.1% and 79% were reported by Roach et al. [62] under 6 and 3 ach respectively. Furthermore, most cases considered 5 ach in the evaluation, with a wide range of resulting savings (4–63%), so akin ventilation rates are judged as enough to achieve a good performance under adequate design considerations.

3.2. Impact of the evaluated strategies under a controlled setup: sensitivity analysis of selected parameters

As explained before, a sensitivity analysis was conducted to check the impact of selected parameters on the cooling demands of two reference cases, under a controlled experimental setup. Boundary cases were defined to assess the specific impact of the selected cooling strategies in extreme conditions: a scenario without any strategy applied on and another where all other strategies were applied.

Fig. 9 shows the results obtained from the simulations in terms of cooling demand savings, contrasted to the performance ranges obtained through the review of research experiences. The results are represented using different colours for the selected cities, and different symbols for the impact on the defined reference cases, according to the attached legend (Fig. 9). As a starting point, it was assumed that the impact from the application of the evaluated strategies would be higher in reference cases that did not consider any particular passive measures or bioclimatic design attributes, and vice versa. So, the comparison was useful to correlate the results from the simulation to the larger context of experiences, while also exploring the differences on the resulting performance of the strategies considering boundary reference cases.

From the graph it is possible to see that with the exemption of ventilation strategies, results from the simulations align with the identified performance ranges. Mean values obtained from the review for these strategies were between 22%–34% and 12%–28% for warm-dry and warm-humid climates; while the average values from the simulated scenarios were between 26%–33% and 17%–22% respectively. On the one hand, the results are mostly contained within the outer limits of each performance range, given that the reference cases represent somehow boundary cases. In the particular case of glazing types, the results from the simulation seem to be overestimated compared to the data from the review. This may be explained by the high reflectivity glass pane used in the simulations, with an assumed better behaviour than most of the examples from previous experiences, in order to test performance limits. On the other hand, most results are aligned in terms of the climate context they refer, which is particularly true in the worst case scenario comparisons (*). Hence, the impact of passive strategies on the mild temperate context of Lisbon and Trieste is higher (in percentage points) than the response of their application on extreme environments such as Riyadh or Singapore.

Table 9
Research experiences about ventilation, considering experimental setup, climate zones and reported cooling savings ranges.

Ref	Climate zones (KOPPEN)	Country	Software	Reference case details	Evaluated parameters	Cooling savings
[33]	Humid subtropical (Cfa)	Australia	IES-VE	Case considers a WWR over 50%, no shading devices and west orientation. Upper boundary for temperature comfort range set to 28 °C. No equipment and 1 person per 10 m^2.	Louvres are set to open automatically if temperature difference outside/inside is satisfactory. Operation mostly during nighttime.	61%
[40]	Tropical savanna (Aw) Hot desert (BWh) Semi-arid (BSk) Hot-summer mediterranean (Csa) Humid subtropical (Cfa)	USA	EnergyPlus	Entire floor of a typical office building in 14 representative locations with 14% WWR, undisclosed glazing type and no shading. Temp comfort ranges between 21–24 °C.Internal gains were 9 W/m^2 (lighting), 15 W/m^2 (equip.) and 5 persons per 100sqm. Minimal ventilation solely for hygienic purposes during work hours. Natural and mechanical ventilation were evaluated separately.	Evaluation considers natural ventilation through the façade, and mechanical ventilation though both façade and air-handling units (AHUs), when it is thermodynamically favourable (mostly during night time). Dynamic operation with cutbacks in the case of temperature and/or wind excess were considered.	4%–59%
[41]	Humid subtropical (Cfa) Semi-arid (BSk) Hot-summer mediterranean (Csa) Hot desert (BWh)	Several cities in southern Europe and Northern Africa	EnergyPlus	Complete office building with high thermal mass and south-north orientation, 28% WWR and overhang as shading. Mech. ventilation during work hours is kept at the minimum, just for hygienic reasons. Upper limit for temp. comfort range set to 26 °C. Internal heat gains are 11.77 W/m^2 (equip.) and 0.1 people/m^2.	Evaluation considered natural wind driven ventilation and stack + wind driven ventilation through vents automatically operated during all day, but mostly allowing fresh air over night time.	17%–91%
[43]	Hot desert (BWh)	Australia Bahrain Egypt Saudi Arabia	EnergyPlus	Entire floor of a typical office building. Glazing type complies with ASHRAE 90.1, with 30% WWR and 90% WWR on south and north façades. Adaptive temp. comfort ranges are assumed. Evaluation considers low (25 W/m^2) and high (50 W/m^2) int.l heat gains separately.	Natural ventilation during office hours when feasible, and night ventilation.	56%–78%
[46]	Humid subtropical (Cfa) Hot-summer mediterranean (Csa)	Italy	TRNSYS	South facing room in five different building types, based on decade of construction and WWR. Glazing type considers clear and tinted double glass, with 23%, 63% and 100% WWR according to each building type and no shading. Temp. setpoint of 26 °C, infiltration rate of 0.2 ACH and natural ventilation rate of 1.7ACH during occupancy hours.	Increase of air change rate to 5ACH between 23:00 and 07:00 for night ventilation purposes.	22%–62%
[47]	Hot summer mediterranean (Csa)	Greece	TRNSYS	Simulation of three office buildings with high and low to medium thermal mass, validated through monitoring campaigns. Glazing type and WWR were undisclosed, and no shading was considered. Evaluation considered an upper temperature limit of 25 and 27 °C.	Night ventilation from 23:00 to 07:00, considering several ACH values (5, 10, 20 and 30 air changes per hour).	14%–79%
[54]	Humid subtropical (Cfa)	China	IES-VE	Several rooms with different orientations, clear double low-E glazing, undisclosed WWR and shading. Temperature comfort range set at 20–27 °C. Heat gains range from 35 to 45 W/m^2, considering lighting (12 W/m^2), occupants (90 W each) and PCs (116 W each). Infiltration rate set at 0.2 ach. Ventilation rate at the minimum for hygienic purposes.	Night ventilation automatically operated considering temperature cutbacks, only for work days.	30%–38%
[55]	Humid subtropical (Cfa)	UK	3TC (BRE)	South facing office room with clear double glass, several WWR values (20%, 40%, 60%, 80%) and 0.2 shading coefficient. Temperature setpoint at 24 °C and several internal heat gain values (20, 30, 60 W/m^2)	Single sided night ventilation through the building façade. Air changes per hour (ACH) values of 1,3,5,7 and 9 were evaluated.	2%–15%
[62]	Hot summer mediterranean (Csa)	Australia	EnergyPlus	Entire floor of an office building with clear double glass, 60% WWR and no shading. Base case considers occupancy gains of 8 W/m^2 and no internal heat gains and 40 W/m^2 heat gains analysed separately. Minimum air supply for hygienic reasons was considered.	Night ventilation considering several ventilation rates (3,6,9,12 ACH) and direct contact with thermal mass indoors.	29%–83%
[63]	Hot desert (BWh)	Egypt	EnergyPlus	Rooms from an University Campus, facing north, south and west. Clear single glazing and 50% WWR was considered. Operative temperature is set to 23 °C. High occupancy (2.5 m^2/person) and base ventilation of 10 l/s.	Application of night ventilation and minimisation of diurnal ventilation during summer.	15%–19%
[64]	Humid subtropical (Cfa) Hot-summer mediterranean (Csa)	Italy Turkey	EnergyPlus	18 office rooms in a referential building, facing east and west, with low-e double glazing, 50% WWR and external venetian blinds. Temp. cooling setpoint is 25 °C during work hours and 30 °C during night. Occupancy of 2 persons and 7 W/m^2 for equipment. High thermal mass is considered with infiltration rate of 1.5 ACH.	Single sided night ventilation through sliding windows.	6%–10%
[66]	Hot desert (BWh)	Iran	EnergyPlus	Isolated south facing office room with clear single glass, undisclosed WWR and no shading. Base case considers the use of PCM (1 cm) on walls, roof and floor. Temperature comfort range of 21–28 °C.	Mechanical night ventilation from 00:00 to 07:00, automatically operated if outside temperature is lower than setpoint. Several ventilation rates were evaluated (5,10,15,20,25,30 ACH).	14%–19%
[71]	Humid subtropical (Cfa)	USA	EnergyPlus	Entire floor of an office building with clear double glass, 48% WWR and no shading. Internal heat gains are 16 W/m^2 and operative temperature setpoint is defined at 24 °C.	Mixed-mode vent. strategies (concurrent, change-over, and zone dependent operation). Automatic use of natural vent. when external conditions allow it).	17%–32%
[72]	Humid subtropical (Cwa)	China	Numerical model	Isolated office room with undisclosed glazing type and WWR values, and no shading. No thermal mass was assumed for the model.	Natural night ventilation	10%

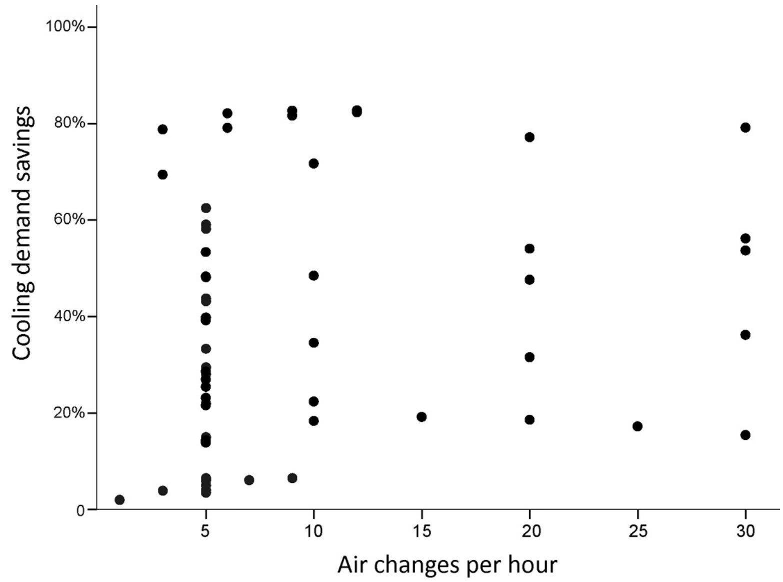

Fig. 8. Relation between cooling demand savings and reported ventilation rates used in the evaluations.

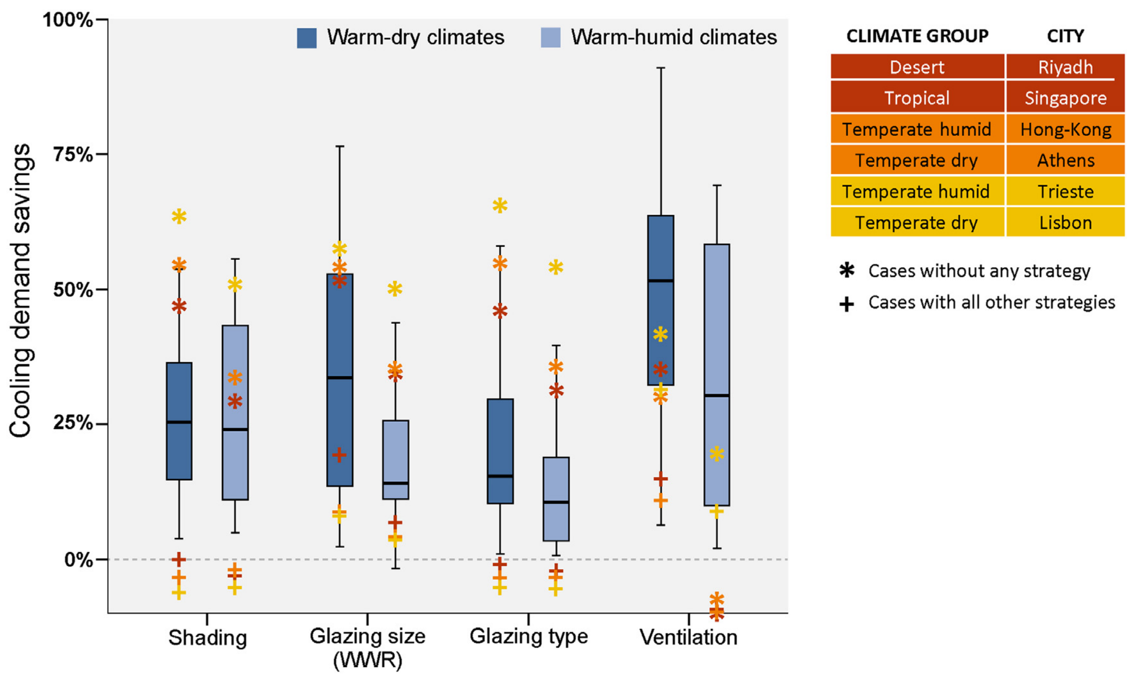

Fig. 9. Cooling demand savings from the simulations (in percentage points) contrasted to the performance ranges defined by the review. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The most evident difference between reviewed experiences and simulations occurs for ventilation strategies, with mean values dropping from 50% to 27% for warm-dry climates, and from 33% to −2% in the case of warm-humid climates. Two reasons may explain this mismatch. Firstly, the reviewed database considers more experiences located in temperate rather than extreme environments, which is especially true in the case of ventilation strategies on warm-humid climates. As the simulations show, the impact of ventilation strategies is markedly different from temperate to extreme warm-humid climates; while they may be beneficial in the former, they are largely counterproductive in the latter cases. Secondly, another explanation could be the possible disregard of dehumidification loads in some of the reviewed calculations. For the simulations, an upper relative humidity limit of 55% was set, keeping absolute humidity below 12 g/Kg of dry air at 26 °C [75]. This could also explain the larger difference between warm-dry and warm-humid climates, evidencing limits for the application of ventilation in highly humid environments, due to their high latent loads.

Interestingly, results from the application of ventilation strategies in four out of the six locations result on cooling savings in all events, either as a single strategy or applied in a case that already considers other passive strategies. The extra savings in the latter cases may be explained due to the fact that ventilation strategies are based on heat dissipation, serving as an important complement for heat prevention strategies. Nonetheless, simulation results show that the difference between reference cases is not as important as the difference between climate contexts for

Table 10
Average cooling demands for the entire floor, for each simulated scenario.

Scenarios		Code	AVG Cooling demands entire floor (kWh/m^2 year)					
			Riyadh	Singapore	Hong Kong	Athens	Trieste	Lisbon
*	No strategies	0000	288,36	366,73	234,12	181,75	108,27	168,20
	Only shading	1000	157,06	261,00	157,37	83,01	53,22	61,90
	Only WWR	0100	**138,76**	**242,06**	152,31	84,08	53,63	72,78
	Only glass type	0010	157,12	252,77	**150,77**	**81,09**	**49,91**	**58,15**
	Only Ventilation	0001	186,21	407,93	252,01	126,90	87,26	98,59
+	All strategies	1111	91,43	246,83	158,75	56,05	41,01	33,57
	No shading	0111	91,44	240,78	154,90	54,51	**38,92**	**31,73**
	No WWR	1011	112,85	264,71	165,03	61,45	42,92	36,31
	No glass type	1101	**90,93**	241,82	154,08	**54,48**	38,97	31,84
	No ventilation	1110	107,98	**223,11**	**141,15**	63,05	44,88	48,62

ventilation strategies. Thus, while it is true that passive ventilation strategies may improve the cooling performance of an optimised building in terms of heat prevention strategies, their efficacy is strongly limited by the climate context. So their application must follow an adequate assessment. The results advocate for the application of passive ventilation in warm-dry climates in any event, while also showing benefits in temperate humid climates to a lesser degree. However, counterproductive results were found not only for Singapore, but also for Hong Kong, evidencing high dehumidification requirements for air intake.

On the other hand, the behaviour of the heat prevention strategies (shading, window-to-wall ratio, glazing type) is similar among them, as pointed out in the scenarios with no strategies (worst case), with particular differences according to their specific impact on the evaluated climates. However, in the case that considers other strategies, the results show larger differences, particularly comparing the impact of glazing size (WWR) with the other two strategies. Most notably, results from glazing size show cooling demand savings in all events, while the use of shading and glazing type may have an adverse effect if all other strategies are applied. This means that regardless other parameters, to consider smaller glazed areas is always recommended in warm climates, and its application should be particularly prioritised in extreme climate zones due to its relative effectiveness. Contrarily, the application of shading and glazing type strategies at the same time either shows no difference or shows an adverse effect on cooling demands, due to an overplay of their performance, blocking too much solar radiation which in turn increases indoor lighting needs that have to be fulfilled by active equipment. Both strategies work under the same principle, so the decision to apply either one or the other may be subjected to other façade design requirements. Similarly, their combined use needs to be carefully assessed to achieve optimal results.

The examination of the cooling demands in terms of absolute values reinforces the idea of clashing strategies. Table 10 shows the average cooling demands for the entire floor in all analysed cases. Best results obtained in both sets of scenarios are highlighted (application of a single strategy or their combined use). Best results for Singapore and Hong Kong were obtained without using ventilation for cooling purposes (only maintaining minimum rates for indoor air quality), as previously discussed. In all other cases, the lowest overall cooling demands were obtained either using shading or a better glass unit (not both), along with an optimised window-to-wall ratio and ventilation strategies. It is important to point out that this comparison is based on cooling demands, so dynamic shading systems may present advantages regarding heating demands on temperate climates, supporting their application over reflective glazing units in particular contexts.

The relative impact from the application of a single strategy and their combined use is further presented in Fig. 10. The graph shows the average cooling demands for an entire floor for all evaluated cities, under three different scenarios. The first scenario considers the worst case used as reference, without considering any passive cooling strategy. Next to it, the highest impact from a single strategy is shown, presenting also the referred strategy. Finally, the best case is presented as third scenario, considering the combined action of several measures, thus showing the maximum cooling demand savings obtained within the boundaries of the experimental setup. The bars show the brute demands, while the cooling savings are expressed in percentage value compared to the first (worst) scenario.

It is possible to notice an important reduction in all cases by using only one strategy. In the extreme climates of Riyadh and Singapore, the best results were obtained by reducing the window-to-wall ratio, with a 52% and 34% of respective cooling demand savings. In all other contexts, the strategy with more isolated impact was the change from clear double glazing to reflective glazing. On a side note, the worst results considering isolated strategies were obtained through the application of ventilation strategies. This suggests an order for the application of passive cooling strategies, starting from heat prevention through a careful design of the building envelope, and then considering heat dissipation strategies such as diurnal or nocturnal ventilation if they apply. Ventilation strategies will not report important benefits without an adequate designed façade system already in place.

The relations between the different strategies are further evidenced by the results from the best case, which considers more strategies on top of the best single one already discussed. The difference between the second and third scenario is smaller in hot-humid climates when compared to dry climates, constraining further optimisation. The resulting improvement is due to the combined effectiveness of extra strategies. In all cases except Singapore and Hong Kong, the main strategy responsible for this was found to be ventilation. This fact reinforces the idea that even if ventilation is not the first strategy that needs to be applied, its complementary use along with heat prevention façade strategies, is highly advised, with a different range of benefits in all climates except highly humid environments.

The results from the application of combined strategies are evidence of the whole potential of passive measures on lowering cooling demands of commercial buildings. When compared to a worst case scenario, obtained cooling savings range from 40% up to 80%, with annual total cooling demands per square meter of 30 kWh/m^2 in the temperate climate of Lisbon. Therefore, the integration of passive cooling strategies under a climate responsive architectural concept is regarded as a minimum condition for the design of office buildings in warm climates. Even if these strategies are not capable of coping with comfort requirements entirely by themselves, it is proven that their adequate application will report relevant energy savings, along with the associated reduction of the

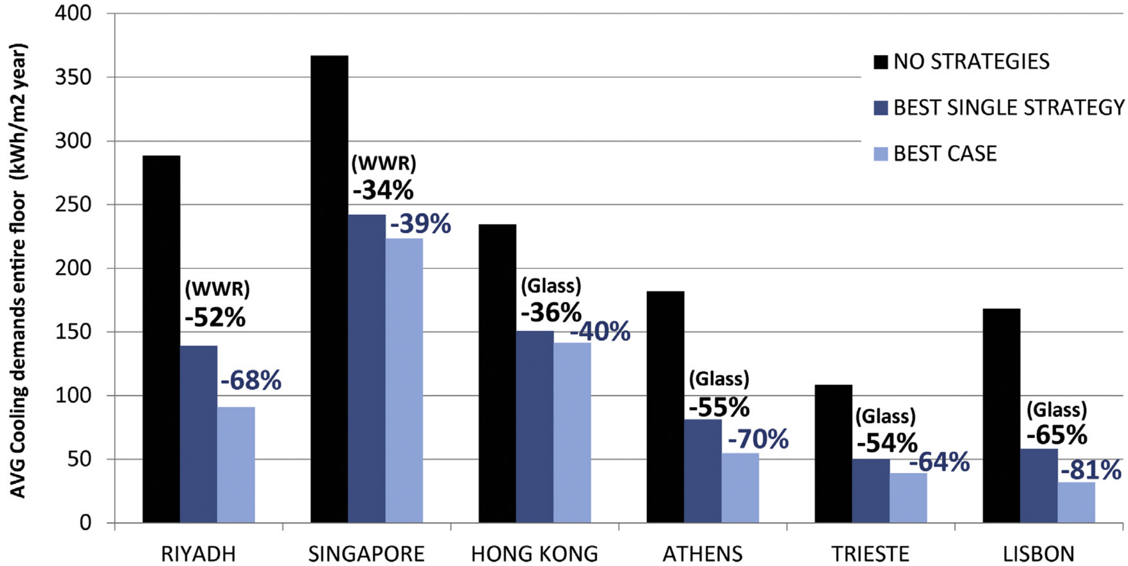

Fig. 10. Average cooling demands for each evaluated city, considering the worst case and best results obtained by the use of a single strategy and their combined application.

environmental impact derived by the use of smaller mechanical equipment and less overall consumption of fossil fuels.

4. Conclusions

This paper sought to explore the effectiveness of selected passive cooling strategies in commercial buildings from warm climates, defining performance ranges based on the assessment of multiple scenarios and climate contexts. This task was conducted through the statistical analysis of results from documented research experiences, to define overall ranges and boundary conditions; and through software simulation of selected parameters to isolate their impact under a controlled experimental setup.

First of all, it was corroborated by both the review and the simulations that passive cooling strategies are more effective in warm dry climates, reaching higher cooling demand savings in these contexts than in humid environments. Mean cooling demand savings considering all analysed strategies ranged between 22%–50% and 26%–33% based on the review and the simulations respectively in the case of warm dry climates, while the overall ranges obtained for warm humid climates were 12%–33% and −2%–22%. The potential effectiveness of all strategies was also found to be higher in temperate climates, in terms of percentage points, which holds true for both dry and humid climate groups. Nevertheless, the dispersion among the results showed that the mere application of passive strategies is not enough to guarantee relevant savings. Their effectiveness is conditioned to both the harshness of a given climate and different parameters that need to be carefully considered during the design of a specific building. Particular findings for each evaluated strategy are drafted below.

Regarding shading strategies, the review showed consistent average savings among warm-dry and warm-humid climate groups. Furthermore, the sample revealed that different types of shading devices do not categorically result on markedly different cooling demand savings, so it becomes important to promote further detailed studies on this topic, and advocate for a careful evaluation of different shading possibilities during the design of any given building on a particular context. Similarly, the application of shading devices must be analysed considering the glazing type used in the window, following an integrated approach for the design of the whole fenestration. Simulation results showed redundancy and negative effects by using both strategies at once without a conscious optimisation process. Looking exclusively at cooling demands, the compared effectiveness of using shading systems or reflective glazing was negligible in most cases. However, the use of dynamic shading devices may present advantages on temperate climates, considering lighting and heating demands.

Discussing window-to-wall ratio, highest cooling savings were unsurprisingly related to the smallest window sizes. However, it is necessary to consider lighting needs and the action of complementary heat prevention strategies when sizing a window, to prevent counterproductive effects. The review revealed a considerable difference in its expected performance between warm-dry and warm-humid climates, with average values of 34% and 18% respectively. Nonetheless, results from the simulation showed cooling savings on all evaluated scenarios, which added to previous results lead to recommend its application as an effective design strategy in all events, especially in extreme climate zones due to its specific relative performance.

According to the review, glazing type strategies had the lowest potential for cooling demand savings, although this is highly dependent on the type of glazing units being used. Changes on the number of layers do not report relevant improvements, while the combined use of coloured panes and reflective coatings was found to be promising. Dynamic glazing technologies evaluated in previous experiences reported the best results but their widespread application is still limited. The impact on cooling demands from the use of reflective glazing was found to be comparable to the use of external shading devices in the conducted simulations, being a matter of choice between them in all analysed cities.

In turn, ventilation strategies had the highest potential for cooling savings, based on the reviewed experiences, in desert, dry temperate and humid temperate climates. Best results were strongly related to the explicit use of thermal mass, to modulate heat during the day allowing for night-time ventilation. The examination of previous experiences also revealed no relevant correlation between cooling savings and ventilation rates, considering 5 air changes per hour to be enough to achieve good results, under the right conditions. The controlled simulated scenarios revealed that ventilation may indeed promote high cooling savings, especially improving the performance of cases that already considered heat prevention strategies, thus serving as a good complement to climate responsive façade design. Nevertheless, the overall effectiveness of ventilation strategies was found to be strongly dependent to the climate conditions instead of the building itself, reaching better performances in temperate climates, but actually making matters worse in highly humid environments.

The potential from the application of passive cooling strategies in commercial buildings is evidenced by both the review of experiences and the results from the simulations. Further studies should tackle the evaluated strategies in detail, assessing the impact of varying parameters under a combined integrated application. However, it feels important to reiterate that these or future general guidelines should not replace detailed analyses of a specific building in a particular context, but are being regarded as valuable referential information in early design stages. Another field worthy of exploration is the architectural integration of hybrid systems (active low-ex cooling) and renewable sources of energy, out of the scope of this document, to cope with the remaining cooling demands after a conscious process of passive design optimisation of new and refurbished buildings in warm climates.

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