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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

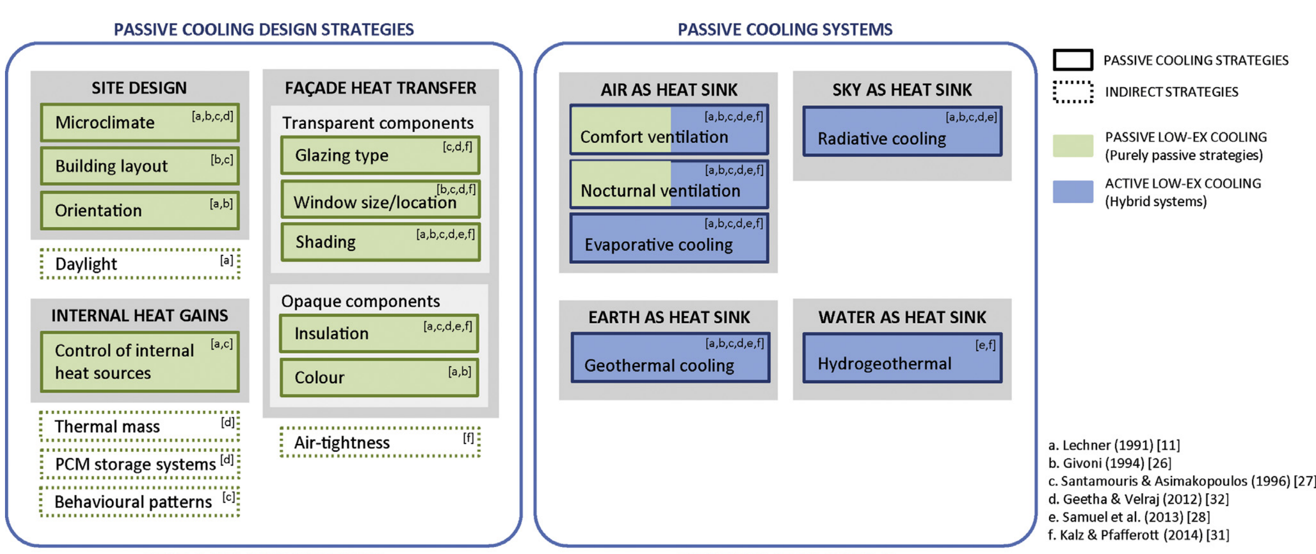

Fig. 1. Categorisation of passive cooling principles based on the literature review.