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25 Years of cooling research in office buildings: Review for the integration of cooling strategies into the building façade (1990–2014)

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ABSTRACT

This paper seeks to present a panorama of cooling related research in office buildings, categorising reported research experiences from the past 25 years in order to identify knowledge gaps and define current paths and trends for further exploration. The general goal behind this research is to support the design of sustainable office buildings in warm climates through examination of past experiences, thus the paper focuses on strategies at building level and specially related with façade design.

Peer reviewed journal articles were selected as the source for the study, given the reliability of the information published under peer-review processes. Several queries were carried out throughout three online journal article databases (Web of Science, SCOPUS and ScienceDirect), considering published papers from 1990 onwards. The resulting article database was then explored trough descriptive analysis and in-depth review of some articles to expand on specific topics in order to thoroughly visualise scientific interest and tendencies within the field of study for the last 25 years.

As results of the review it is possible to state the high current relevance of cooling research, having experienced an increase of publications under different climate contexts and varied topics ranging from passive to solar cooling, which is seen as a research field on its own. Also, in terms of research methods, software simulations seem to be the primary tool for cooling research, which makes sense for performance driven developments. On the other hand, the main knowledge gaps identified are the need for specific research regarding possibilities for application and architectural integration of cooling systems; the lack of articles addressing some specific cooling strategies, such as the use of evaporative and ground cooling; and the need for more information about the operation of cooling systems, especially taking users' perception and their behaviour into account.

1. Introduction

Buildings have an important role in worldwide energy consumption compared to other economic sectors. According to studies performed in the EU, buildings account for 40–45% of the total energy demand [1]. As a result, several initiatives are being put into place to reduce the operational energy demand in buildings. In Europe, the Energy Performance of Buildings Directive was approved in 2002, and then updated in 2010, considering new challenges for the building sector, and specially requesting all new buildings in the EU to consume "nearly zero" energy after 2020 [2].

As result of the application of energy saving measures and the development of new technologies, the thermal performance of buildings during winter period has been greatly improved. However, due to a number of reasons such as increasing standards of life, affordability of air-conditioning, temperature increase in the urban environment and global climate change; the energy needs for cooling have increased drastically [3]. This scenario is even more pressing considering energy projections for the next decades, which show the impact of emerging economies from outside the Organisation for Economic Cooperation and Development (OECD) on worldwide energy consumption. Estimates show that energy consumption will increase by 34% between 2014 and 2035, mostly due to demands from fast-growing emerging economies [4]. Indeed, it has been stated that just Non-OECD Asia (including India and China) will account for more than half of the world's total increase in energy consumption between 2012 and 2040

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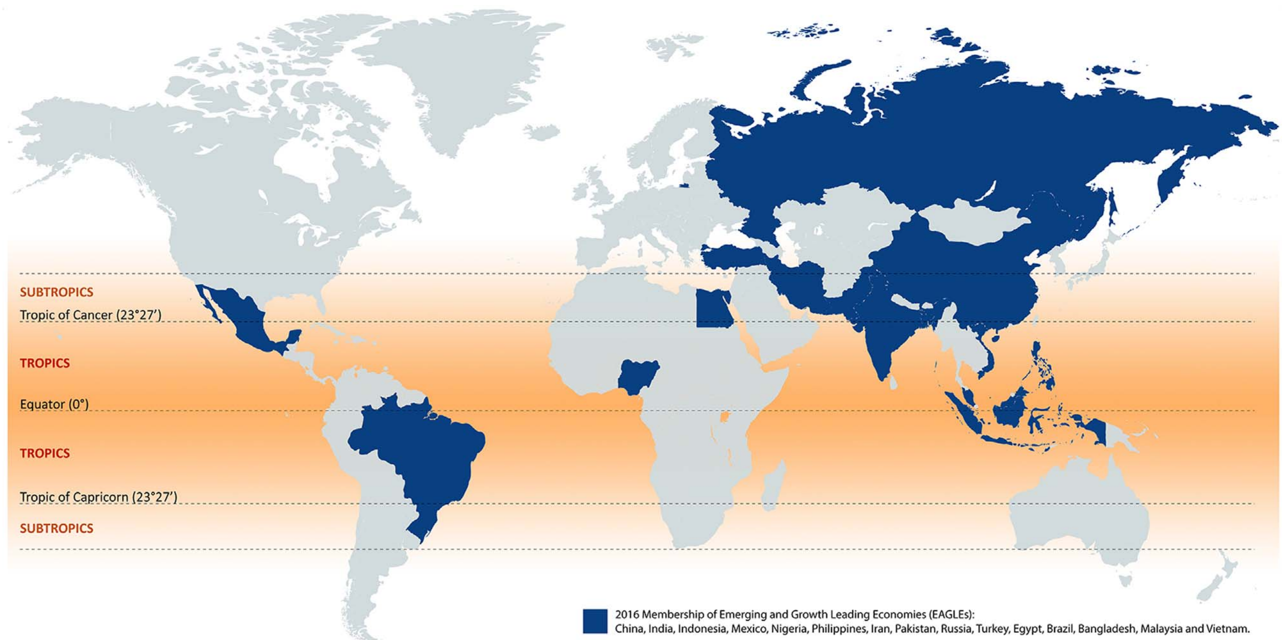

Fig. 1. Emerging and Growth Leading Economies (EAGLEs) and their relative location compared to tropical and subtropical world zones.

[5]. The fact that most emerging and growth leading economies (EAGLEs) experience warm climates [6] (Fig. 1) puts pressure on the need for buildings specifically designed to minimise cooling loads.

In this sense, the design of office buildings presents a particular challenge due to the relative importance of heating, ventilation and air-conditioning equipment in their total energy usage. Fig. 2 shows the disaggregated energy consumption for an average high-rise office building located in USA [7], and for an average office building in a tropical climate (Singapore) [8]. The energy used for heating and cooling in the former sums up to 33%; while it increases up to 51% in the latter, basically responding to cooling demands [9]. Furthermore, the widespread use of AC units in buildings has been proven to have an important impact on total energy consumption. Some studies even show that refrigeration and air conditioning are responsible for about 15% of the total electricity consumption in the world [10]. The relevance of cooling demands in office and commercial buildings responds to high internal gains (occupation density and equipment) in general, which is aggravated by the impact of solar radiation and high external temperatures in warm climates [11,12].

The fact that office building designs usually favour the use of lightweight building components and high transparency in façade systems, following an international look associated with success and corporate imagery [13], only exacerbates the discussed problems. Indeed, these building types heavily rely on active air-conditioning equipment in order to function, replacing the traditional role of the building envelope with the application of energy driven systems to cope with the resulting demands. Opposing this widespread trend, several authors advocate for sustainable or climate responsive designs as the first step for energy efficiency. Lechner stated that a sustainable building could accomplish up to 60% of its heating, cooling and lighting demands by itself, compared to a reference case. Moreover, the author proposed a three-tier design approach for sustainable buildings. The first tier deals with basic building design strategies such as orientation, insulation and the use of exterior shading. If this is not enough to meet the requirements, which it is often the case in warm climates, then a second tier of passive or hybrid systems based on natural energies should follow, considering the use of evaporative cooling, earth coupling, or diurnal/nocturnal ventilation. Lastly, mechanical equipment could be incorporated into the building in the third tier, if needed, within an already passively optimised building design [14].

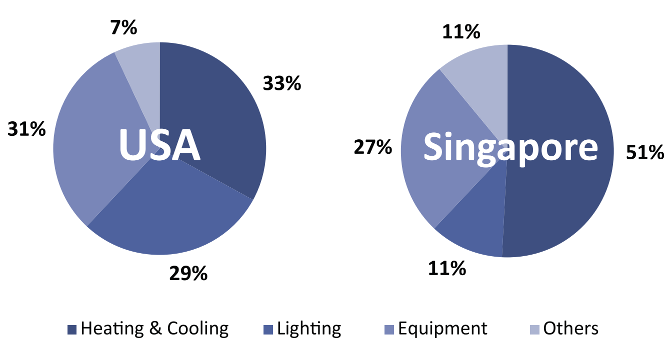

Fig. 2. Disaggregated energy consumption of an average high-rise office building located in USA and Singapore.

Similarly, Herzog et al. defined two sequential sets of strategies to cope with the regulatory functions of the façade. The authors considered the application of supplementary measures, such as thermal insulation, sun shading or even vegetation, as a first resource; and then suggested the use of supplementary building services such as artificial lighting and air conditioning only if needed [15]. The authors also considered the use of thermal collectors or PV panels as supplementary services for energy generation, which relates to the hybrid use of natural energies expressed by Lechner as an alternative to the use of fossil fuels. In fact, the use of environmental heat sources and sinks as drivers for high temperature cooling systems has been reported by several researchers, supporting the use of low-exergy sources [16]. This definition also comprehends the heat and electrical output from solar thermal collectors and PV systems, even though solar radiation itself is regarded as a high exergy source from a technical standpoint [17,18].

Solar cooling systems have gained increased attention these last years, for their potential to lower indoor temperatures using renewable energy [19,20]. Several initiatives supported by private developers and public organisations such as the Solar Heating & Cooling Programme of the IEA [21], have been promoting the use of these technologies by showing their advantages while increasing the efficiency of the systems to allow for massive commercial application [22,23]. In the current scenario of increasing cooling demands, it is highly unlikely that purely passive strategies are enough to cope with comfort requirements, and downright impossible in the case of warm climates, so these hybrid solar based technologies are regarded as an interesting complement to bridge the gap in passively optimised office buildings.

This paper seeks to present a panorama of cooling related research in office buildings, categorising reported research experiences from the past 25 years in order to identify knowledge gaps and define current paths and trends for further exploration. The general goal behind this research is to support the design of sustainable office buildings in warm climates through examination of past experiences, thus the paper focuses on strategies at building level and specially related with façade design. Although there have been important advances in strategies at larger scales, such as the use of district cooling [24,25] or the concept of smart energy grids [26], these are out of the scope of the present document.

Peer reviewed journal articles were selected as the source for the study, given the reliability of the information published under peer-review processes. Several systematic queries were carried out throughout three online journal article databases (Web of Science, SCOPUS and ScienceDirect), considering published papers from 1990 onwards to gather enough cooling related research experiences to detect trends and knowledge gaps. The resulting article database was then explored trough descriptive analysis and in-depth review of some articles to expand on specific topics in order to thoroughly visualise scientific interest and tendencies within the field of study for the last 25 years.

The results and discussion section of this paper is structured in three parts: first, a general panorama of cooling related research is presented, discussing the gathered experiences in terms of main research topics, representation of different climate contexts, and tools and methods used by researchers. Then, in the second and third part, the discussion is focused on the respective assessment of two particular sets of cooling strategies: passive cooling and solar cooling. The application of passive cooling strategies was mentioned as the first step for the design of sustainable office buildings in warm climates, while solar cooling technologies are regarded as a promising alternative to provide supplementary cooling driven by renewable energy sources. These sets of strategies are explored through the literature, presenting an overview of the available information while showing examples of advances within the field.

2. Material and methods: review of journal articles from 1990 to 2014

2.1. Definition of parameters for the search queries

Research experiences from peer review journal articles were considered as base material for the review. In order to gather relevant articles within the scope of the study, some parameters were defined as input for their search (Table 1). The constraints served the purpose of limiting the results to the most corresponding articles, and at the same time limiting the number to a manageable amount which allowed an initial review and categorisation of the information.

The parameters shown in Table 1 correspond to the final query performed after an iterative process to narrow down the results to a manageable number, excluding outliers. So, the search was focused on articles published from 1990 onwards considering only title, abstract and keywords match (not entire document). Besides the use of keywords that matched the declared focus, such as 'office buildings', 'cooling', and 'façade', it was decided to avoid particular keywords that conducted to misleading information. Chemical related research was discarded because of its specific focus in material science rather than building applications. Moreover, the keyword 'nuclear' was avoided, in order to rule out nuclear plant cooling systems, which considered a large number or matches but fell out of the proposed scope.

The search query was performed on three online journal article databases: Web of Science, SCOPUS and ScienceDirect obtaining the results shown in Table 2. However, in the case of the ScienceDirect database search, another string of parameters was added in order to narrow down the results (marked with ** in Table 1).

Table 1
Parameters used for journal database searches.

Type of search	Title / abstract / keywords	
Publication date	> 1989	
SEARCH KEYWORDS	AND	(PASSIVE or LOW-TECH or LOW-ENERGY or ACTIVE or MECHANICAL or SOLAR) (COOLING or REFRIGERATION or AIR-CONDITIONING) (FAÇADE or ENVELOPE or CURTAIN-WALL) (OFFICE or NON-RESIDENTIAL or COMMERCIAL or TERTIARY) (BUILDING) (COST or PERFORMANCE or EVALUATION or MONITORING or SIMULATION)**
	AND NOT	(HOUSE or HOUSING or DWELLING) (NUCLEAR or CHEM*)

Table 2
Online journal databases consulted.

Online databases	Matches found
WEB OF SCIENCE	127
SCOPUS	236
SCIENCE DIRECT	11.017 / 1.062**

After an initial review of the results, filtering outliers and avoiding repeated results, a consolidated database of journal articles was generated using a reference manager software (ENDnote). The queries were performed during September 2014; ending up with a consolidated database of 861 journal articles at October 1st, 2014. Hence, the overview presented on this document is based on a sample of 861 research articles, considering mostly original research but also reviews conducted by other researchers. All articles' abstracts were reviewed for the evaluation, while some relevant articles were reviewed in detail to provide examples of interesting advances in the field.

2.2. Building a reference database: assignment of new keywords for categorisation

The second step after gathering relevant journal articles was to categorise them for further exploration of the information. To accomplish this, new keywords were assigned to each article within the database. This was done through a review of the abstracts, considering topics, methods and focus of each article. All 861 abstracts were checked and categorised according to the newly defined keywords. This categorisation fulfilled two goals: it structured the information in an accessible manner, generating a organised reference database; while at the same time it provided the means to explore the information through descriptive analysis.

The new keywords used for categorisation are shown in Table 3 grouped into topics, methods and deliverables addressed in each article. The definition of the new keywords was carried out by developing families of concepts relevant to the field of study after an initial review of reference articles and books. As it was stated before, the review explicitly addressed some specific topics in more depth, such as passive strategies and solar cooling systems due to their potential for achieving low-energy cooling in office buildings. Thus, their families of concepts are larger than other topics'.

Table 3
Selected keywords within the families of concepts.

TOPICS			
COOLING		FAÇADE	COMFORT
- PASSIVE COOLING	- ACTIVE COOLING	- PASSIVE FAÇADE	- PHYSICAL COMFORT
		- SINGLE FAÇADE	- THERMAL
- HEAT PREVENTION	- SOLAR COOLING	- AIR-TIGHT	- PMV
- MICROCLIMATE		- VENTILATED	- ADAPTIVE
- SOLAR CONTROL	- ELECTRIC (PV)	- DOUBLE FAÇADE	- ACOUSTIC
- ORIENTATION	- PV	- AIR-TIGHT	- VISUAL
- GLAZING	- THERMO ELECTRICAL	- VENTILATED FAÇADE	- HYGIENIC (IAQ)
- SHADING	- PELTIER MODULES	- BOX-WINDOW	- PSYCHOLOGICAL COMFORT
- HEAT MODULATION	- THERMAL (COLLECTORS)	- CORRIDOR	
- THERMAL MASS	- THERMO MECHANICAL	- SHAFT-BOX	CLIMATES
- HEAT DISSIPATION	- RANKINE	- ALTERNATING	- TEMPERATE CLIMATE
- VENTILATION	- EJECTOR	- OTHERS	- HOT-ARID CLIMATE
- CROSS VENT	- STIRLING ENGINE	- SOLAR CHIMNEY	- HOT-HUMID CLIMATE
- SINGLE SIDED VENT	- THERMAL (HEAT)	- ATRIUM	
- BUOYANCY VENT	- CLOSED CYCLE	- TROMBE WALL	OTHERS
- NIGHT VENTILATION	- ABSORPTION	- ACTIVE FAÇADE	- ENERGY EFFICIENCY
- EVAPORATIVE COOL	- ADSORPTION	- INTEGRATED FAÇADE	- CLIMATE CHANGE
- GROUND COOLING	- OPEN CYCLE	- MECHANICAL VENT	- LIFE CYCLE
- RADIATIVE COOLING	- SOLID DESICCANT	- SOLAR TECH	- MARKET
	- LIQUID DESICCANT	- PV	- OPERATION
		- COLLECTORS	

METHODS
- REVIEW
- MONITORING
- SIMULATION
- VALIDATION
- SURVEY
- COST EVALUATION
- STATISTICAL ANALYSIS

DELIVERABLES
- REGULATION
- DESIGN GUIDELINES
- MODELS
- PROTOTYPE
- BENCHMARK
- PERFORMANCE / COP

CATEGORIES

FAMILIES OF CONCEPTS

SELECTED KEYWORDS

Afterwards, some of the concepts were selected as new keywords for categorisation (highlighted in Table 3), trying to avoid over specification in issues out of the main scope (such as the specific type of double façade), or to avoid redundancy in the categories (to state that an article addresses absorption chillers also implies that it considers closed cycle thermally driven solar cooling).

Finally, these new keywords were used as main input for a descriptive analysis of the database. The keywords represent the information contained in each article, thus they are presented as a valid mechanism for the generation of an overview and the evaluation of research trends over time. It is important to point out though, that all conclusions should lie within the scope of the search queries and the defined categorisation method in order to be valid. This of course means that it is only possible to analyse and state valid conclusions about topics and concepts specifically addressed in the database.

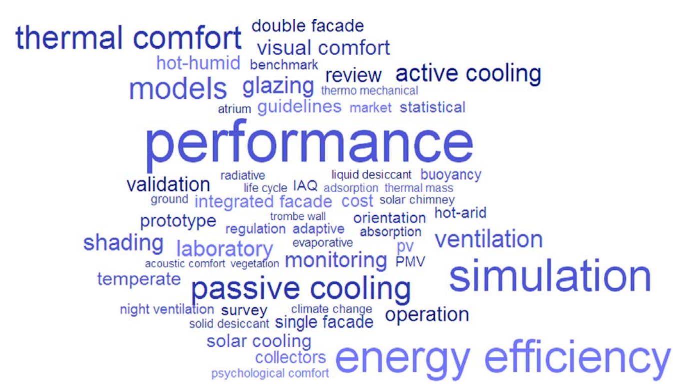

Fig. 3. Word cloud of the assigned keywords. Size of the word equals the number of articles that contain it.

3. Results and discussion: descriptive analysis and article review

The article database was explored through descriptive analysis, to generate a panorama of the field of study for the last 24 years. This analysis was complemented with in-depth review of some of the articles in order to understand certain topics in a more detailed way. The main topic addressed on the article search was the use of façade related cooling strategies in office buildings, thus all interpretation of the results must consider this specific focus.

Fig. 3 shows an initial approach to the matter, by counting the number of articles that consider each keyword (the size of the word expresses the number of articles). Therefore, the figure shows the weight of each concept within the database, showing also the direction of the scientific interest on the subjects for the past couple of decades.

Research about performance of cooling strategies and systems has the higher results (577 matches), which makes sense by also stating the fact that “energy efficiency” is the second most repeated topic (417). Overall, cooling related research is focused on developing energy efficient systems and strategies. Therefore, performance assessment of existing technologies as well as performance evaluation of new cooling systems are key aspects for the improvement of the technical possibilities.

Besides energy aspects, the performance of cooling systems and strategies has to take thermal comfort into account. While some of the studies specifically focus on this subject (258), it is indeed a subject at least indirectly considered while discussing thermal control of indoor spaces.

In terms of the methods used for research purposes, simulation seems to be the leading one (407). The continuous development of energy simulation software during the last two decades has improved both the accuracy of the results and the speed of the calculation processes, which has made possible their widespread use. Nonetheless, there is an important number of articles that seek to develop new energy consumption prediction models (239) to be used in early design stages, simplifying energy calculations even more for easier application.

Specific analyses of the database were carried out focusing on particular topics, in order to understand their relevance and explore their evolution over time. The results are presented organised into three topics: an overall assessment of cooling research, and two particular explorations into the state of research in passive cooling and solar cooling technologies.

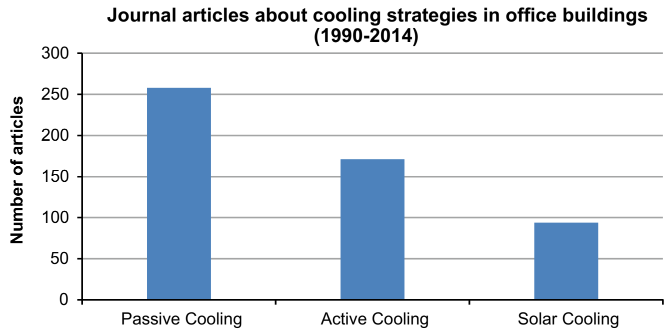

Fig. 4. Different types of cooling articles between 1990 and 2014.

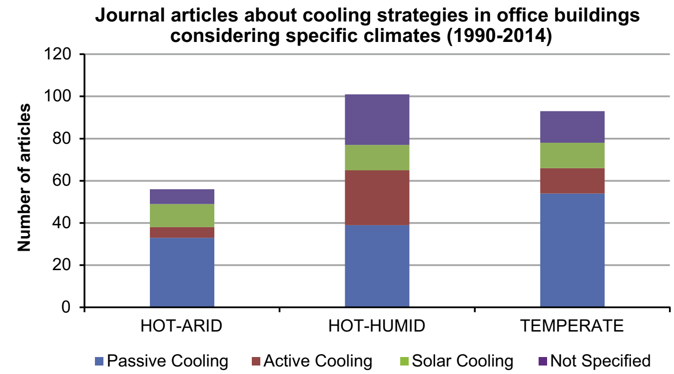

Fig. 6. Cooling research considering specific climates.

3.1. Cooling research: general overview of gathered experiences

First of all, a general panorama of cooling research in office buildings is presented. It is possible to see in Fig. 4 that passive cooling strategies have been studied more than active and solar cooling. However, all three strategies have experienced increased scientific interest over the years (Fig. 5). This is especially true in the case of solar cooling research, which became noticeable in the turn of the century due mostly to the support of several initiatives developed by the Solar Heating & Cooling programme of the International Energy Agency.

When considering cooling research focused on a particular climate, results vary. In general terms, there is less recognizable research focused on hot-arid contexts (Fig. 6), but Fig. 7 shows that this is currently changing due to research projects being carried out in middle eastern countries such as Bahrain, Saudi Arabia, Kuwait and United Arab Emirates. Topics being researched consider mostly the evaluation of passive cooling strategies, like the energy performance of shading systems [27,28], evaluation of glazing properties [29], or possibilities for the application of multi-façade systems in hot-arid climates [30,31].

Also in temperate climate contexts passive cooling research has leaded scientific interest. Among relevant experiences in this subject it is possible to highlight the studies carried out by Santamouris and Kolokotsa [3] about passive heat-dissipation techniques, the research done on night ventilation performance by Pfafferott [32] and Kolokotroni [33] and the extensive studies carried out by Gratia and De Herde on the potential for natural ventilation on double-skin facades [34,35].

In the case of hot-humid climate cooling research, there is also a big number of passive driven studies related to the design of naturally ventilated façades [36–38], evaluation of atrium performance [39,40] and the assessment of adaptive thermal comfort levels in hot-humid conditions [41–43]. However, unlike other climate specific research discussed, there is a considerable amount of experiences focused on active cooling technologies.

Topics of interest concerning active technologies are the development of energy use estimation models for the design of HVAC systems [44–46], analyses of current policy related with the design and operation of air-conditioned offices [47] and the evaluation of specific systems and prototypes such as decentralised AC units [48] or mechanical ventilation units [49,50].

In terms of solar cooling research, it is worth mentioning that it is possible to encounter experiences on all three specific climate regions, which is evidence that there is scientific interest and potential for application in all these contexts.

Besides the initiatives supported by the Solar Heating & Cooling Programme and the research projects carried out by organisations such as Fraunhofer to define and promote solar cooling technologies [19,23], there are other analyses on the performance and economic aspects of these systems, like the studies carried out in the Stuttgart University of Applied Sciences (HFT) on thermal and photovoltaic solar cooling [51,52] or the generation of a technology roadmap for future development of these technologies by the Austrian Institute of Technology (AIT) [53].

Among solar cooling experiences in hot-humid climates, it is possible to recognize the studies carried out in Australia by Baniyounes, Liu [54] and experimental testing of solar desiccant technologies for application in office buildings of Hong Kong, performed by Fong [55,56]. On the other hand, concerning hot-arid climate experiences, studies are concentrated either in middle east, such as assessments of possibilities for implementation in Jordan [57] and Qatar [58]; or in Spain. Among Spanish experiences in the subject, there are studies concerning about the development of new models and simulation tools [59,60] and studies focused on optimisation of existing technologies considering the overall system [61] or components, such as air handling units [62].

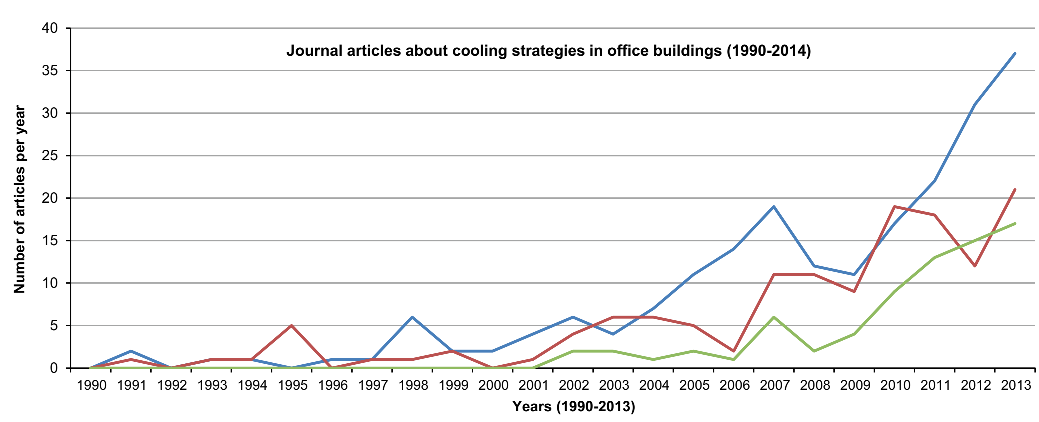

Fig. 5. Cooling articles between 1990 and 2013.

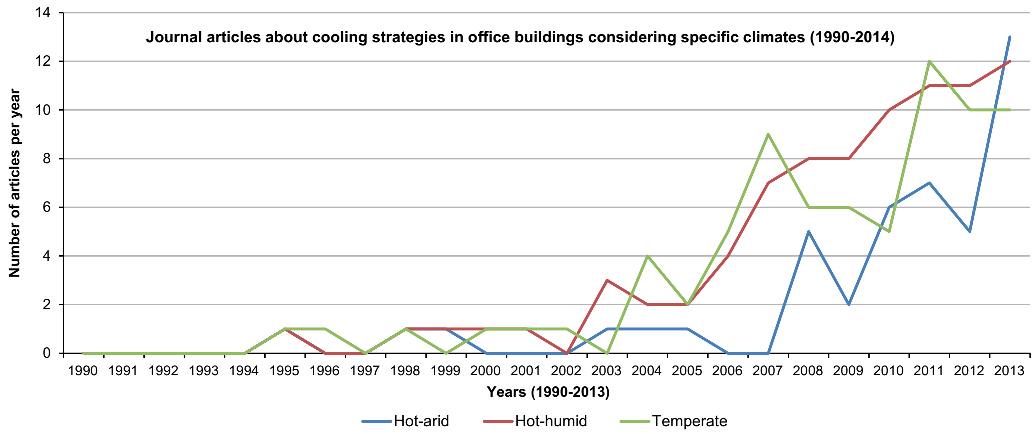

Fig. 7. Cooling articles on specific climates.

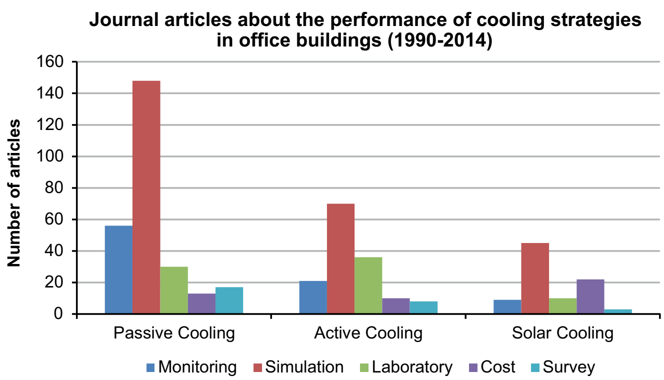

Fig. 8. Cooling articles considering diverse research methods.

The methods used in the documented experiences are also noteworthy. As it was stated before, simulation is the preferred alternative in order to assess the performance of different cooling strategies or systems (Fig. 8). This seems to be the case for all types of strategies, given the possibility of easily testing different alternatives within a cheap and controlled experimental setup when compared with built prototypes and field studies.

Monitoring is also seen as a relevant method, especially in the case of passive cooling studies, however the lack of existence of a great number of built projects using solar cooling is probably the main cause for the low number of studies that consider this approach as main input. Furthermore, the existence of studies relying in experiments being conducted in laboratories is relevant for the development of new technologies and systems not yet used on buildings. This approach seems to be relevant in the case of active cooling systems development, building prototypes for the evaluation of new solutions.

Finally, it is possible to see that cost analysis have particular importance in solar cooling evaluation. This of course shows that cost is a relevant issue for the current development of these technologies, aiming to generate not just high-performance solutions, but also cost-effective ones.

3.2. Passive cooling: building design strategies

Passive cooling strategies for buildings are categorised into three types: (a) heat prevention, (b) heat modulation and (c) heat dissipation. Heat prevention strategies are mostly related with solar radiation control, avoiding the entrance of heat from the external environment. Heat modulation strategies consider heat storage techniques in order to control heat flux indoor, also working as a complement for heat dissipation strategies, which seek to remove indoor heat releasing it into a natural reservoir (air, water, ground).

Fig. 9 shows the amount of experiences that address different passive cooling strategies considering diverse methods for evaluation. It can be seen that solar control strategies (orientation, glazing and shading) are the most evaluated passive strategies, and particularly shading analysis have the highest results among them.

It is commonly stated that the best method for solar radiation control is to apply proper external sunshade, intercepting direct solar radiation before it falls over the window of a given wall [63]. Sun shading systems have been studied since the 60 s, establishing criteria for the proper design of the shadow according to the latitude of a given location [64]. By the end of the 20th century, sun shading systems have been properly classified and described in existing literature. One common initial distinction is made regarding control possibilities of

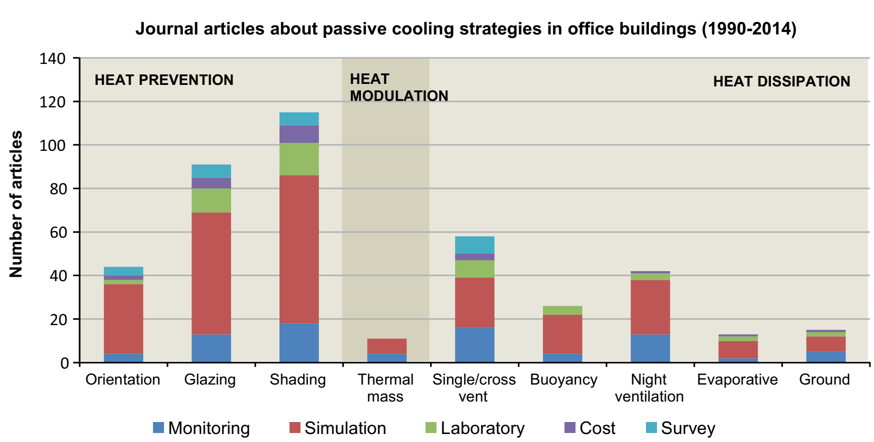

Fig. 9. Passive cooling strategies in articles considering diverse research methods.

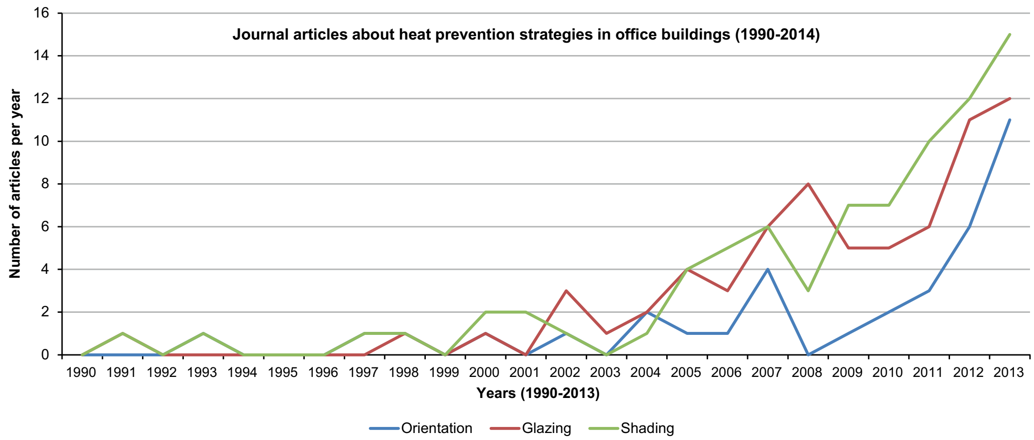

Fig. 10. Heat prevention strategies in journal articles.

the system, separating them between movable or fixed systems [65]. The first ones give more possibilities for the users but have high maintenance costs, while the second ones are seen as more efficient (if well designed) but consider no possibility of control from the user and could have varying performance during the day. (Fig. 10).

Studies regarding sun shading systems have focused on optimisation of the design of the components to improve its performance, along with the development of software for multi-variable analysis and parametric design [66–68]. The reported performance of sun shading systems greatly varies among the reviewed experiences, encountering cooling demand reduction values ranging from 10% to 50% compared to reference cases. Hwang and Shu showed the impact of overhangs of different lengths on the cooling demands of a south facing office in a lightweight office building located in Taiwan, with 72% window-to-wall ratio. Their results showed a reduction of cooling loads between 7% and 11% [69]. Ferrari and Zanotto reported cooling reduction values ranging from 10–27% by using external venetian blinds in different south facing offices located in several Italian cities. The worst values correspond to office buildings with low window-to-wall ratio, due to the limited action of sun shading on an already optimised façade, and vice versa [70]. Manzan evaluated the impact of the application of flat screens parallel to the window in south facing offices in Italy, obtaining cooling savings ranging from 49–56% in the case of Trieste and from 30–46% in the case of Rome [68]. Similarly, Pino et al. reported cooling savings of up to 54% following the application of louvres at north, east and west orientations of a fully glazed office building located in Santiago, Chile [71].

Besides energy performance, comfort levels of occupants have been a growing issue of concern, regarding mostly daylighting and glare problems reported on office buildings with facades with high window-to-wall ratio [72,73]. Recently, research focused on occupant comfort has expanded its area of interest, considering the interaction of the user with shading systems. Occupancy patterns are seen as relevant input for the assessment of both performance of the shading system and comfort of the user, improving the knowledge regarding indoor comfort (considering not just thermal or lighting inputs, but actual human response to the environment) and at the same time refining predictive methods such as software simulation by giving real information [74].

It is usual to find studies that address both shading and glazing solar strategies considering also different orientations. Some experiences seek to address the overall performance of entire fenestration systems, like the monitoring campaigns conducted in Chile by Bustamante [12], or the studies carried out through simulations in USA [75] and South Korea [76]; while others seek to establish comparisons between the resulting performance of the application of glazing or shading technologies [77].

Studies focused specifically in glazing performance seek to understand the influence of glazing in the indoor thermal conditions and energy consumption, considering both the type of glazing used [78,79] and the window-size or window-to-wall ratio of a specific façade system [80,81]. Eskin and Turkmen reported cooling demand savings of up to 16% by using low-e double glazing instead of clear double glazing in a simulated office building located in several cities in Turkey [82], while Hamza found a reduction of 13% by using reflective glazing instead of clear single glass in a south facing office located in Egypt [30]. Regarding the impact of window-to-wall ratio, Lee et al. stated savings of 27–30% in buildings 50% glazed and between 41% and 44% in buildings with a window-to-wall ratio of 0,25, compared with a fully glazed reference case located in China and The Philippines [83].

On the other hand, there is also a considerable amount of research focused on developing and testing new technologies. Among them, it is possible to highlight the evaluation of solar film coatings [84–86], vacuum glazing [87] and “smart” adaptive glass, such as electrochromic or aerogel glazing [29,88,89]. Aldawoud evaluated the use of electrochromic glass in a building located in Phoenix, USA; obtaining solar heat gain values 57% lower than a reference building with double clear glazing [27]. Similarly, Bahaj et al. reported a cooling demand reduction of 45–49% by using different electrochromic glass panes instead of a low-e double glass unit in a simulated office building located in Dubai, United Arab Emirates [29].

Passive heat dissipation strategies have also been researched in the recent years, focusing on natural ventilation. Besides research on single and cross-ventilation in office buildings [90–92], continuous research regarding buoyancy-driven stack ventilation has been carried out by several authors, considering the performance of multi-layered facades [34,93] or whole-building scale strategies such as atriums and solar chimneys [94]. Radhi et al. stated that the use of a ventilated double skin façade could lower cooling demands by up to 17% through the simulation of a real university building located in the United Arab Emirates [31]. Nevertheless, Gratia and De Herde have claimed that even if the use of double skin facades may be beneficial in some cases, they need to be carefully designed according to ventilating patterns to avoid overheating in the cavity [95,96].

Within ventilation strategies, night ventilation has been consistently researched as a specific subject for the last 15 years. Some early experiences dealt with the evaluation of these strategies via on-site measurements [32,33,97], while others used simulations to assess the energy saving potential of their application [98,99], even discussing possibilities for implementation in different climate contexts [100,101]. Campanico et al. evaluated the application of several night cooling strategies in an office building located in Geneva, obtaining cooling savings between 41% and 66% compared to a non-ventilated reference [98]. Similarly, Ferrari and Zanotto found cooling savings of up to 64% after simulating the impact of 5 air changes per hour (ach) from 23:00 to 07:00 in office buildings located in several Italian cities [70]. Better results were reported by Roach et al. for night ventilation

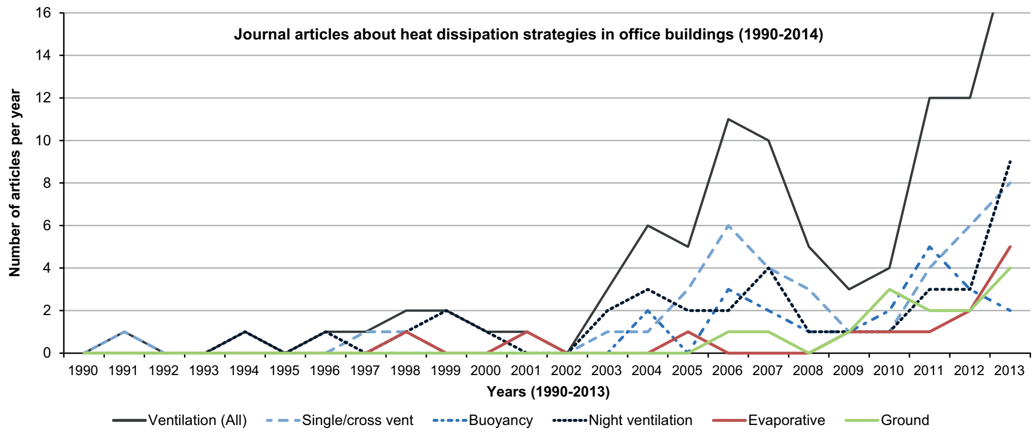

Fig. 11. Heat dissipation passive cooling strategies in journal articles.

application in the Australian context. The authors claimed cooling savings ranging from 69–83%, depending on the air change rate in a simulated entire floor of an office building located in Adelaide [99].

Besides energy assessments, some studies focus in specific aspects in an attempt to understand the impact of different variables in the overall performance, such as surface convection during night cooling [102] or window-use patterns [103]. In terms of optimisation, it has been stated that night ventilation effectiveness is greatly improved when it is combined with heat modulation strategies like the use of exposed thermal mass, storing heat to be released into the ambient during night time [104,105].

Additionally to ventilation strategies, studies about evaporative and ground cooling strategies are worth mentioning due to the current interest on alternative cooling systems. The application of these strategies in office buildings falls into the definition of hybrid systems based on passive environmental heat sinks discussed in the introduction, due to the incorporation of low energy equipment such as fans and small size pumps. Although these strategies have not been studied as much as the others mentioned, it is possible to see that scientific interest on both subjects has increased during the last years (Fig. 11) probably as a result of efforts to find new cost-effective strategies for cooling.

Evaporative cooling techniques have been researched mostly for hot-arid climate applications, considering them along with ventilation strategies in order to bring pre-cooled fresh air into the buildings. Experimental applications have been developed and tested, either integrated in façade modules [106] or integrated in larger structures like solar chimneys [107]. Also, the efficiency of evaporative cooling is being analysed under different climate contexts, in order to explore the potential for implementation in other regions [108,109]. Ezzeldin and Rees studied total energy savings related to the use of evaporative cooling combined with ventilation in several hot arid locations (Australia, Bahrain, Egypt and Saudi Arabia). Their results showed energy savings ranging from 43–60% and from 52–66% considering high and low internal gains respectively [110].

Regarding ground cooling techniques, the studies are focused on the development of heat exchangers, either for stand-alone application [111,112], or coupled with other strategies such as thermal storage [113], evaporative cooling [114] or ventilation through the use of solar chimneys [115–117]. Pardo et al. encountered energy savings in electrical consumption of up to 40% by comparing the application of several combinations of ground coupled heat pumps and thermal storage devices, to a referential HVAC system driven by an air to water heat pump in the Mediterranean coast [113]. Li et al. proposed a coupled system consisting of a solar collector enhanced solar chimney and an earth-to-air heat exchanger, and measured its performance in Omaha, USA. The results showed that the system was capable to maintain indoor air temperatures between 21,3 and 25,1 °C, with a maximum cooling capacity of 2.582 W, which almost covered the building design cooling load [116]. The discussed findings related to these hybrid technologies are regarded as promising, achieving relevant energy savings as complement to the building design strategies previously mentioned. Nonetheless, further research is needed in order to promote their development as competing alternatives to conventional vapour based cooling technologies.

3.3. Solar cooling: renewable sources for complementary cooling

Solar cooling systems may be classified according to their energy input into two main groups: solar electric process systems (using PV cells to transform solar radiation into electric energy) and solar thermal process systems (using heat transformation process as base for cooling purposes). Furthermore, solar thermal process systems may be classified into solar thermo-mechanical systems, thus transforming thermal energy into mechanical power; and solar thermal systems, using the stored heat directly in sorption based cooling technologies [23].

Fig. 12 shows the amount of studies within the database that address each type of the mentioned solar cooling systems. Thermal cooling systems appear to be much more researched than the rest, however it is important to state that all studies grouped under "Electric" only consider the application of PV cells used explicitly for solar cooling purposes, given the explained search parameters. PV cells are used to generate energy, and cooling is only one of the possibilities for using this energy. So, research related with the integration of PV cells in the façade is not restricted nor specifically related to the development of solar electric cooling systems.

Evidence of this is the fact that all specific solar electric cooling studies reviewed also addressed thermal solar cooling. These studies consist either of the development of a PV/thermal mixed-mode solar cooling system [118–120] or comparative analyses between electric and thermal driven solar cooling considering both energy performance

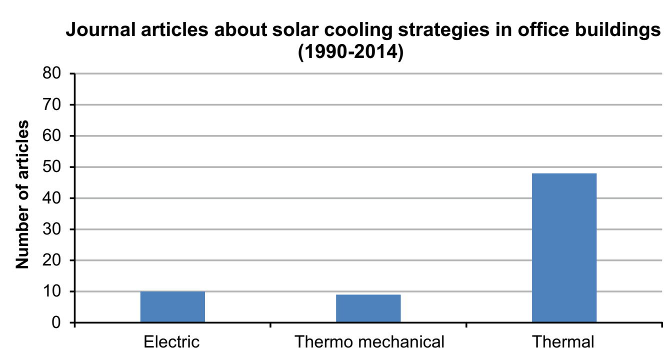

Fig. 12. Solar cooling systems in journal articles.

and economic assessment [51,121–123].

On a side note, besides specific cooling application, the integration of PV cells in facades has been driven by the development and evaluation of new façade concepts such as photovoltaic double-skin façades [124,125], semi-transparent PV glazing [126,127] or PV integrated shading devices [128–130]. Furthermore, there are studies carried out on laboratories focused on specific aspects for PV application and operation, such as the technical development of new optimised concentrators [131] or studies about the effect of over-heating in PV cell efficiency and the use of ventilation alternatives to avoid it [132,133].

Regarding thermo-mechanical cooling systems, most of them are mentioned in review articles that address different possibilities for solar cooling [134–136]. However, there are also research experiences concerned with the development of cooling systems based on these principles. Main examples of this are the studies on solar ejector refrigerating [137–139] and the exploration of Rankine cycle systems for cooling application [140,141]. In 1998, Huang measured COP values of 0,22 on a prototype of a solar ejector system at a temperature of 88 °C and solar radiation levels of 700 W/m^2 [142], while Buyadgie stated that even though COP values of 0,25-0,3 were considered high years ago, nowadays it is common to obtain COP values of 0,5 or higher using ejector based technologies [137]. Regarding the application of rankine cycles, Wu simulated the performance of a façade integrated prototype, being able to cope with cooling requirements from a hot and humid climate, with an annual solar fraction of about 13% [143]. The thermal efficiency of steam rankine cycles was studied by Zandian and Ashjaee, recombining a dry cooling tower with a solar chimney. CFD simulation results showed an increase of up to 37% in the thermal efficiency of a power plant located in Iran, selected as case study [141].

As mentioned before, solar thermal systems are most studied within solar cooling related articles. Even built examples have been evaluated as part of research projects such as SACE and SOLAIR. Solar thermal systems are generally divided into two categories: closed and open cycles. Closed-cycle systems are based mainly on the absorption cycle, considering absorption and adsorption; while open-cycle systems consider desiccant materials in either solid or liquid state [22].

Absorption systems are the most studied among solar thermal cooling technologies (Fig. 13). Energy performance of these systems is assessed either via numerical simulations and modelling [144–146] or via empirical validation through monitoring of built examples [147,148]. Also, there are documented experiences considering all three selected climates: hot-humid [149], hot-arid [59,61] and temperate [150,151], which shows scientific interest on the development and application of these systems on diverse contexts. Pando simulated the performance of an hybrid solar-gas absorption heat pump of 17,6 kW of cooling capacity in Mexico, showing a reduction in gas consumption of 24% during the evaluated period [152]. Qu et al. used monitoring and simulation tools to assess the performance of a LiBr/H2O absorption chiller with a cooling capacity of 16 kW in Pittsburgh, USA. It was found that the system could potentially supply 39% of the

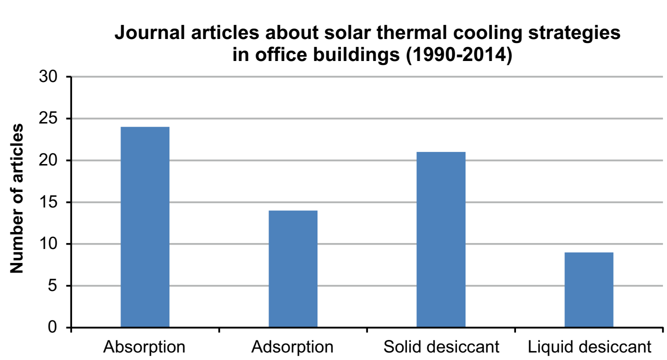

Fig. 13. Solar thermal cooling strategies by type in journal articles.

cooling demands, if it included properly sized storage tanks and low diameter connecting pipes [153]. Rosiek and Batlles also monitored the performance of a LiBr/H2O absorption chiller in a building located at Spain, under different operation modes. Experimental results showed that in practice it is highly possible to obtain COP values around 0,6 [148].

During the last years, there has been increasing interest on adsorption systems as well. Besides some studies carried out to evaluate their performance considering materials such as activated carbon and ammonia [154,155]; there are also studies focused on the development of compact units with small range capacity in order to promote widespread use of adsorption driven solar cooling systems [156]. This seems relevant for further exploration on the possibilities of architectural integration of solar driven systems. Fadar et al. simulated the performance of a Carbon/ammonia adsorption chiller, obtaining a refrigeration cycle COP of 0,43 by producing a daily useful cooling effect of 2.515 kJ per 0,8 m2 of thermal collector area [157]; while Sim evaluated the performance of a small size adsorption system of 4,5 kW cooling capacity in Doha, Qatar. The results from numerical models showed that the system could reduce the electricity consumption by 47% compared to a compression cooling system, being labelled as promising for further development [58].

On the other hand, open-cycle systems have been studied as well, focusing either on monitoring some built experiences [158,159], or performance optimisation via simulation of new concepts [62,160]. The use of evaporative cooling as complement of desiccant systems also has been studied given its impact on the cooling performance of the systems [161,162]. Mei et al. reported an average COP of 0518 over summer season with a solar fraction of 75% for a solar powered desiccant cooling system coupled with evaporative cooling in Barcelona [120]. Similarly, Cejudo et al. studied the energy performance of solar desiccant air handling units, finding up to 35% savings in two warm climates in Spain [62]. A solid desiccant system was also monitored by Eicker et al. in Stuttgart, reporting an average seasonal COP close to 1,0 and an electrical COP between 1,7 and 4,6, with a dehumidification efficiency of 80% [159].

Lately, liquid desiccant systems have gained attention, because of their lower heat requirements. Furthermore, these systems can work with temperatures below 80 °C, which makes them more effective than solid desiccant systems in terms of heat input [136]. Research is being done in order to develop commercial cooling systems mostly through experimental evaluation of prototypes [163–165]. Qi et al. studied the cost –effectiveness of a liquid desiccant system coupled to an air handling unit for cooling for application in hot-humid climates (Houston and Singapore). The results showed that the system could reduce up to 40% of the total energy consumption during cooling seasons, with a calculated cost payback period of approximately 7 years [166]. A similar payback period (7 years and 8 months) was calculated by Keniar et al. for the use of a liquid desiccant unit in Beirut, compared to investment costs of vapour compressor units [167].

Table 4 shows cooling capacities and coefficients of performance (COP) of market ready solar thermal technologies, reported by several research projects [20,22,168–171]. It is possible to observe that even though COP values have remained stable for commercial applications over time, the ranges of cooling capacity have been expanded, particularly in the case of absorption and adsorption heat pumps. The fact that smaller capacities have been pursued seems especially promising regarding possibilities for integration in building components, and widespread application at lower implementation costs [168].

Given that solar thermal collectors play a fundamental role in the application of solar thermal cooling technologies, there is also research that deals specifically with their development and evaluation. As it was stated when discussing PV related research, also in this case the point is to explore specific issues regarding solar collectors which can be used (or not) for cooling purposes. It is possible to see studies focused on

Table 4
Cooling capacities and Coefficients of performance (COP) of market ready solar thermal technologies reported by several research projects over time.

Refrigerant cycle	Cooling principle	Typical cooling capacity					
		SACE (2002–2004) [22]	ClimaSol (2002–2005) [171]	Keepcool (2005–2007) [170]	SOLAIR (2007–2009) [169]	SHC IEA Task 38 (2006-2010)[b] [168]	Kohlenbach & Jakob (2014) [20]
CLOSED CYCLE	ABSORPTION[a]	–	15 – 5.000 kW	15 – 5.000 kW	4,5 – 5.000 kW	4,5- kW	10 – 20,500 kW
	ADSORPTION	–	50–430 kW	50–430 kW	5,5–500 kW	2,5- kW	19 – 1.000 kW
OPEN CYCLE	SOLID DESICCANT	–	20–350 kW	20–350 kW	20–350 kW	–	6 – 300 kW
	LIQUID DESICCANT	–	–	–	–	–	–
		Typical coefficient of performance (COP)					
CLOSED CYCLE	ABSORPTION[a]	0,6–0,7	0,6–0,75	0,6–0,75	0,6–0,75	0,6–0,78	0,5–0,7
	ADSORPTION	0,55–0,65	0,5–0,7	0,5–0,7	0,5–0,7	0,5–0,6	0,5–0,65
OPEN CYCLE	SOLID DESICCANT	–	0,5- > 1	0,5- > 1	0,5- > 1	–	0,5–1
	LIQUID DESICCANT	0,5	> 1	–	> 1	–	1

[a] Considering only single-effect absorption chillers.
[b] Review focused on market available systems with cooling capacity below 20 kW.

evaluating the performance of different types of collectors, such as flat plate [172], evacuated tube heat pipe [173,174] and unglazed transpired solar air collectors [175].

Nevertheless, it is also possible to see studies that address aesthetical aspects of solar collectors, that is of course, without compromising performance issues. Examples of these are the studies carried out by Andreas Schüler to develop coloured glazed thermal collectors through the use of multilayer films [176,177] or the development of selective paint coatings [178,179]. Furthermore, the so called "architectural quality" of thermal collectors has been explored in research projects conducted by the IEA, understanding its importance in achieving a successful architectural integration in buildings [180].

The mentioned studies show that there have been advances on the architectural integration of solar collectors, even proposing façade design concepts using curved collectors [181], integrating evacuated tubes into fenestration systems [182] or even using shading devices as solar thermal collectors [183]. However, there is little research about façade integration of solar cooling systems, except for some scattered experiences.

Among some interesting examples it is possible to mention the experiences conducted by Wu [143] and Chan [184] in the University of Melbourne and the National University of Malaysia respectively. The first one considers the use of evacuated tube collectors within the cavity of a double-skin façade, coupled with an organic Rankine cycle turbine (ORC) which drives the compressor of a vapour compression cycle (VCC) chiller. Although a chiller is used, it is an interesting exploration on the role of the façade as part of an ORC-VCC coupled cooling system.

The second example is a 3-layered façade system that consists of: an external aluminium transpired plate (solar collector), an intermediate sandtile wall (evaporative pad) and the internal building wall. The operation of the system is based on the use of indirect evaporative cooling, that is cooling the air without adding moisture to it. This system was evaluated via mathematical models and experimental setup obtaining similar energy performance than other solar indirect evaporative cooling and desiccant cooling systems [184].

Given the presented overview, it is possible to state that there is potential for the design of solar cooling integrated façade systems. However, there are various issues, either technical requirements (size and performance of the components and systems), or the so-called "architectural" aspects (design and operation of integrated façades), that need to be further studied in order to conceive a roadmap for the development of new architectural façade products.

4. Conclusions

The main purpose of this paper was to promote the development of façade related strategies and systems for low-energy cooling in office buildings, by presenting a panorama of research experiences from the last twenty five years. Given the nature of the paper, it is possible to state conclusions about both the methods used in the review and the content of the discussion itself.

The analysis of the information was done through a review of journal articles from three online databases. The amount of available information called for the use of a systematic approach, from the definition of search parameters and new keywords to the use of descriptive analysis in order to explore the data. The proposed method was successful in its attempt to categorise and visualise high amounts of information in broad levels, while providing examples through in-depth reviews of some of the experiences. However, there are also limitations in this approach. The most important one is that the analysis of the database, and thus, the main findings of the paper are inherently linked to the defined parameters and keywords. As mentioned before, it is only possible to perform an analysis and state valid conclusions about topics and concepts specifically addressed as keywords and search parameters.

In terms of the content, the presented review sought to visualise existing knowledge concerning cooling strategies and systems for office building application, in order to detect research trends and discover knowledge gaps for further development. Thus, main findings may be classified following the same logic.

4.1. Research trends

Cooling research: High relevance and increasing interest. it is relevant to state that cooling research is currently a very active field, having experienced an important increase of related publications up to date, especially since the last ten years. There is interest in cooling research not only in warm climates, but temperate climates as well, which seems to be true for passive, active and solar cooling systems. In that aspect, solar cooling research is seen as a particular field on its own, dealing with specific issues while gathering special attention from researchers.

Research methods: Simulating performance. Software simulations seem to be the primary tool for cooling research, which makes sense for performance driven developments. However, there is also an increasing number of monitoring campaigns which may present invaluable information about the actual performance of strategies and systems under operation. This allows for feedback in a very clear performance driven research field.

Passive cooling: Solar control and ventilation. There are clearly two main sub fields within passive cooling research: research about solar control strategies (shading, glazing and building orientation), and research on ventilation strategies (single-sided and cross ventilation, buoyancy effect and nocturnal ventilation). There is substantial information and specialized interest in these areas to identity them as particular and differentiated research fields.

4.2. Knowledge gaps

Cooling systems: Application and architectural integration in the built environment. Even though there is an increasing amount of cooling research, there is need for specific research regarding possibilities for application and architectural integration of cooling systems, without neglecting performance issues, of course. This need for practical information is particularly true in the case of low-energy active technologies and solar cooling, in order to promote accessible guidelines for a wide spread use of these systems by architects and building professionals.

Technological development: Performance and application of less explored systems. An obvious gap is seen in the lack of articles addressing some specific cooling strategies, such as the use of thermal mass, evaporative and ground cooling, when comparing with sun shading or ventilation strategies. Even though these strategies have also experienced an increase in terms of number of related articles, there is room for much more growth regarding both performance and application issues. The same could be said for solar cooling systems. There is room for exploration of thermomechanical systems, along with research about compact sized adsorption chillers and liquid desiccant based technologies. Furthermore, the smaller potential sizes of these systems present favourable possibilities for architectural integration in office buildings.

Feedback: Operation and implementation data. As stated, cooling research has mostly relied on software simulation methods and monitoring in a lesser extent. While monitoring provides invaluable information about the actual performance of running systems, there is need for more information about their operation, especially taking users' perception and their behaviour into account. Survey based studies should be promoted along with studies about implementation and maintenance costs for new cooling technologies. Clear information about costs would facilitate the decision making process related with building systems design and operation, for both clients and architects.

As a final remark, it is important to reaffirm that even though there is increasing scientific interest in cooling research, much more information is needed to facilitate a wide spread use of low-energy cooling technologies in office buildings. Issues such as the performance limits of passive strategies in hot climates, the use of renewable sources of energy for cooling, or the energy efficiency of low-energy active systems are tasks which, without being knowledge gaps, still require further attention to achieve the goals of nearly zero energy consumption in office buildings.

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