THERMAL PERFORMANCE OF OPAQUE VENTILATED FACADES: A SYSTEMATIC REVIEW

DESEMPENHO TÉRMICO DE FACHADAS VENTILADAS OPACAS: UMA REVISÃO SISTEMÁTICA

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Abstract

Ventilated facades have been identified as a viable solution to improve the thermal performance of buildings, thereby upgrading their energy efficiency. The literature points out a lack of studies on opaque ventilated facades among the different types of these facades. Thus, this study aims to present research on the thermal performance of opaque ventilated facades using a Systematic Literature Review (SLR), considering where the research was carried out, the method used and the main parameters that influence the thermal performance of these facades. The SLR proved efficient in outlining the desired panorama, indicating that this facade model consists of a technology only recently explored in academia with research concentrated in Europe, mainly in Spain, Italy and Portugal, highlighting the Mediterranean climate as the focus of the research. Most of the studies were conducted using computer simulations, followed by experimental methods that validated the mathematical models of the simulation programs. The SLR identified the outdoor conditions and aspects of the facade geometry that have a higher influence on the thermal performance of these facades. Considering the outdoor environment conditions, solar radiation and the year's seasons were the most discussed parameters in the literature. Considering the facade geometry, the ventilated facade openings (presence or absence of joints and grilles), the cavity height, and the outer skin material were the most studied variables.

Keywords: thermal performance, opaque ventilated facade, systematic literature review.

Resumo

As fachadas ventiladas têm sido apontadas como uma solução viável para melhoria do desempenho térmico de edifícios, beneficiando, assim, sua eficiência energética. Dentre os diversos tipos desse sistema, a literatura aponta uma escassez de estudos acerca das fachadas ventiladas opacas. Assim, este trabalho tem como objetivo reunir pesquisas sobre o desempenho térmico de fachadas ventiladas opacas por meio da Revisão Sistemática da Literatura (RSL), considerando o local onde as pesquisas foram feitas, o método utilizado e os principais parâmetros que influenciam no desempenho térmico dessas fachadas. A RSL se mostrou eficiente em traçar o panorama desejado, indicando que este modelo de fachada consiste em uma tecnologia explorada apenas recentemente no meio acadêmico, com pesquisas concentradas no continente europeu, principalmente na Espanha, Itália e Portugal, evidenciando o clima mediterrâneo como foco das pesquisas. A maior parte das pesquisas foi realizada com simulações computacionais, seguidos pelos métodos experimentais, que validaram os modelos matemáticos dos programas de simulação. Com a RSL, identificaram-se as condições externas e os aspectos da geometria que mais influenciam no desempenho térmico dessas fachadas. Dentre as condições do meio externo, a radiação solar e as estações do ano foram os parâmetros mais abordados nas pesquisas. Em relação à geometria da fachada, as aberturas na fachada ventilada (presença ou ausência de juntas e grelhas), a altura da cavidade e o material que compõe a camada externa foram as variáveis mais estudadas.

Palavras-chave: *desempenho térmico, fachada ventilada opaca, revisão sistemática da literatura.*

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Introduction

According to the sixth report produced by the Intergovernmental Panel on Climate Change (IPCC) in 2014 (IPCC, 2014), buildings are responsible for 6.4% of greenhouse gas emissions, which shows the need to consider design strategies to manage climate change impacts. Changes in building codes, incorporating more efficient systems into building designs, changes in user behavior and lifestyle are pointed out as examples of mitigation measures in the building sector. Within this context, new technologies have emerged to meet the demand for more sustainable buildings, combining comfort and energy efficiency.

The external sealing element, comprised by the walls, roof and openings, influences the comfort conditions inside buildings as it controls the air passage from the outdoor/indoor environment, ensuring adequate levels of temperature, ventilation, lighting and noise. The behavior of the external envelope against solar radiation, wind, rain, thermal variations, among others, determines the good performance of the facade. The annual consumption spent on heating and cooling buildings is strongly influenced by heat losses and gains through the facades, especially tall buildings, as most of the heat exchange takes place on the surface exposed to the outdoor environment. Therefore, architects have currently considered the building facades as sophisticated membranes that require careful design (APARICIO-FERNANDEZ *et al*., 2014).

Ventilated facades are characterized by a ventilated channel between the internal and external layers of the building envelope. A careful design of these systems must consider functional and performance concerns, as well as aesthetic and architectural issues (SÁNCHEZ *et al*., 2020). There are several studies in the literature related to ventilated facades, especially focusing on: Double-skin Ventilated Facades, Building Integrated Photovoltaic, Trombe and Solar Walls, Facade Solar collectors, as well as some studies on light weight ventilated facades. However, little attention has been paid to opaque ventilated facades, whose typology differs from the previous ones due to their geometry, architectural application and energy purpose, in addition to differences in fluid dynamics characteristics (SANJUAN *et al*., 2011c). In this article, the focus of the research refers to opaque ventilated facades, terminology used to designate a double skin facade consisting of two opaque layers and a ventilation channel in between. Table 1 shows the most used opaque ventilated facade compositions, according to Ibañez-Puy *et al.* (2017).

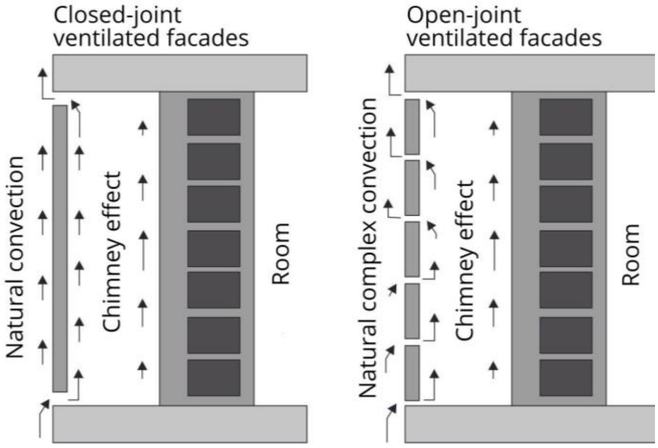
Table 1 - Different types and materials for opaque ventilated facades

Layer	Types	More frequently used
Outer skin	Heavy	Ceramic, stone, concrete panels...
	Light	GRC panels (cement and fine sand mortar reinforced with fiberglass), metallic, composite panels...
Air cavity	Naturally ventilated	From 4-10cm
Thermal insulation	The thickness depends on each country´s standards	MW (mineral wool), EPS (expanded polysterene), XPS (extruded polysterene), PUR (polyurethane)
Inner skin	Heavy	Brick, concrete...
	Light	Sandwich panels, gypsum boards...

Source: Ibañez-Puy *et al*. (2017), adapted by the authors.

Concerning facade openings, there are closed- and open-joint ventilated facades, as can be seen in Figure 1. When the panels are continuous and the spaces in between them are closed with openings only in the lower and upper part of the facade, they are called closed-joint opaque facades, as can be seen on the left in Figure 1. Sanjuan *et al*. (2011c) can be mentioned for publishing one of the first studies that addresses the thermal performance of open-joint ventilated facades, when there are small openings between one slab and another that comprise the external envelope of the facade, which allows air to enter and leave at the same time along the entire facade, characterizing another type of fluid dynamic inside the ventilated cavity (to the right of Figure 1).

Figure 1 – Types of opaque ventilated facades: closed joints (left) and open joints (right)



Source: Sanjuan *et al*. (2011c), adapted by the authors.

Opaque ventilated facades originate in northern European countries and, more recently, the main interest has been to reduce cooling thermal loads in southern European countries. The thermal performance of opaque ventilated facades is strongly dependent on the facade design (geometry, materials, etc.) and external parameters (climate conditions: solar radiation, wind direction and speed, and temperature) (IBAÑEZ-PUY *et al.,* 2017). Therefore, existing analyses on the European climate serve as a reference for the assessment process, but the results cannot be extended to all types of the climate. In Brazil, the first buildings that used this technology on their facades were built around 2010 (ROCHA, 2011) and since then, there has been a growing number of buildings built with opaque ventilated facades, mainly with ceramic or porcelain tile closures. Academically, however, there are not many studies that attest that it is a strategy that offers benefits related to passive thermal conditioning for the climate of Brazil.

This study aims to carry out a Systematic Literature Review on the thermoenergetic performance of opaque ventilated facades, considering the place where the research was performed, the investigation method used to assess the thermal behavior and the main parameters that influence the thermal performance of these facades. Using this literature review, we aim to fill a research gap that identifies the main parameters that must be taken into account when designing an opaque ventilated facade and for which types of climates it is suitable.

Method

This study was carried out using the Systematic Literature Review (SLR) method, a type of secondary research that aims to map, identify, critically evaluate, consolidate and aggregate primary studies relevant to a specific topic, in addition to identifying gaps to be filled (DRESCH; LACERDA; ANTUNES, 2015). The advantage of the systematic review is that the method is designed to be unbiased, accurate, auditable, replicable and updatable. Based on the steps described by Dresch, Lacerda and Antunes (2015), the SLR was divided into 4 steps, namely:

1. Definition of the research question. How is the thermoenergetic performance of buildings that use opaque ventilated facades?

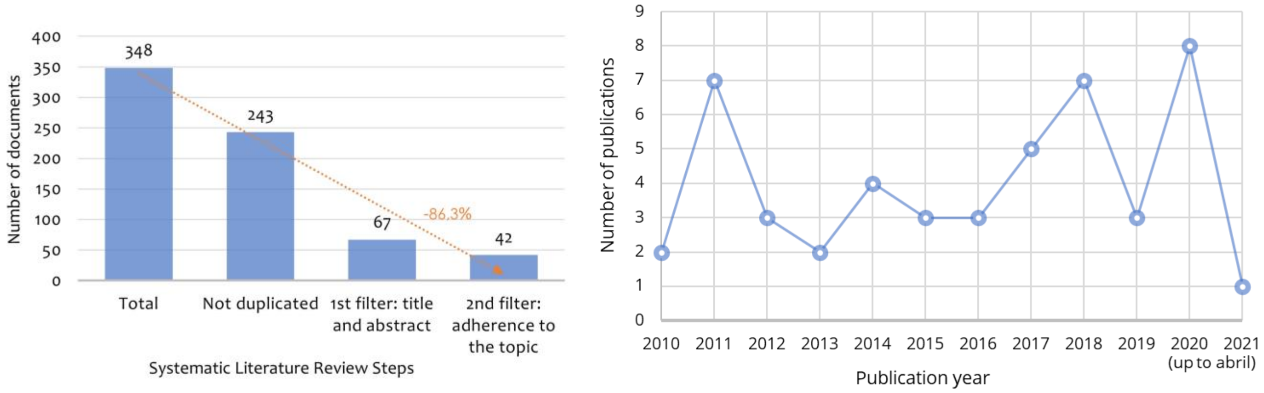
2. Definition of search strategies. The search terms were searched in the title, abstract and keywords and the search was performed in April 2021. The search string was: Perform* AND (*"ventilated fa?ade"* OR *"double fa?ade"* OR *"opaque fa?ade"*). The asterisk (*) shows all the results with that prefix, and words such as *performance*, *performed*, etc. can be found. Expressions between quotation marks ("") are sought in their exact form. The question mark looks for words in which the letter can be changed, making the search easier as the translation of "fachada" into English accepts the spelling of both "*facade*" and "*façade*". Aiming at the greater scientific rigor of the research and also looking for studies from Brazil, the works indexed in the Scopus, Web of Science and Scielo databases were selected. Articles in English and Portuguese were included, selecting scientific articles published in journals and conferences from 2010 to the date of the research. An exclusion criterion included excluding articles that analyze typologies of facades that are not, specifically, opaque ventilated facades and articles that deal with other aspects of these facades, other than thermal performance.
3. Research, selection and coding of primary studies. The search results were exported into Excel spreadsheets for data processing and analysis. The author, title, year, journal and abstract information were saved. Therefore, duplicate articles were first excluded. Afterwards, the titles and abstracts of the articles were read, excluding articles that met the exclusion criteria. Next, potential articles were read and analyzed mainly focusing on understanding the type of facade. Thus, articles that analyzed typologies of facades whose thermal behavior differed substantially from that of opaque ventilated facades were excluded, for example: double skin facades, ventilation facade cavity with active systems, phase-change materials in double skin facade inside the cavity, building integrated photovoltaics, adaptable facades, in addition to fire resistance studies, mechanical and structural performance and impact of thermal bridges on opaque ventilated facades. After the final selection, the data of interest was extracted, such as: the main focus of the article, the main contributions, the research years, the location, type of climate, analyzed season, building type, analysis method, software used and other facade geometry data such as height, thickness of the air layer, outer skin material, type of joint, etc.
4. Synthesis and presentation of results. The synthesis process consists of joining the results to generate new knowledge. Thus, the data were systematized in graphs and tables for better visualization of the results that would lead to a more in-depth understanding of the thermal performance and fluid dynamic behavior of the opaque ventilated facades.

Research overview

This item aims to present the results as the most quantitative part of the analysis of the articles, such as the number of documents, year and place in which they were published, and the method used to evaluate and identify the main variables that influence the thermal performance of opaque ventilated facades.

Figure 2 (on the left) shows the number of documents found at each stage of the search. In the Scopus database, 180 studies were found, in the Web of Science, 158 studies and in Scielo 10 studies, totaling 348 articles. Of these, there were 105 duplicate articles, resulting in 243 articles. After filtering the title and abstract, 67 articles remained; and after the second filter due to the typology of the ventilated facades, 42 articles were obtained that addressed the research topic. A reduction of 86.3% in the number of articles can be observed. Regarding the number of publications over the years, Figure 2 (on the right) shows greater amounts of publications in 2011 and 2020, demonstrating that it is a recent topic, enhancing interest in research.

Figure 2 - Number of documents and evolution of SLR (on the left) and number of publications over the years (on the right)



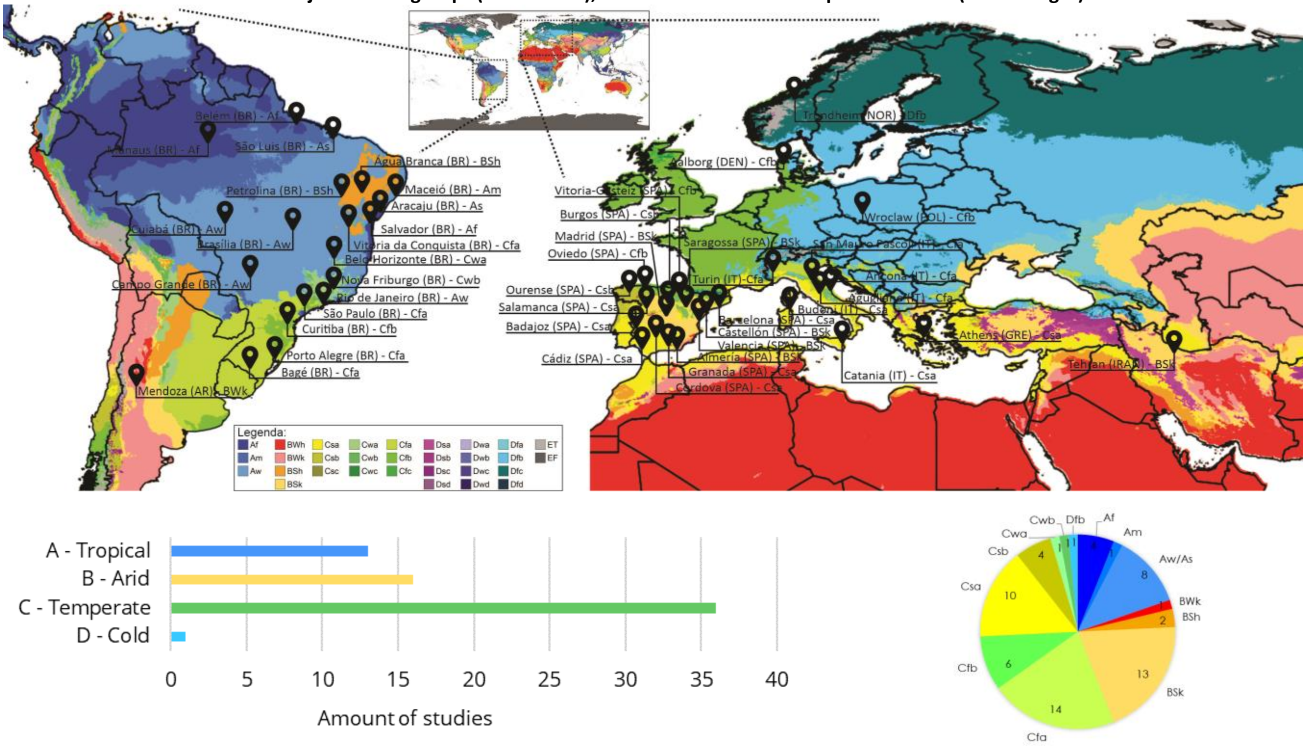
Source: the authors.

Figure 3 (top) shows two clippings of the world map illustrating part of South America and Europe with the climate classification according to Köppen-Geiger (BECK *et al.*, 2018). Moreover, points were plotted in black, which indicate the approximate location where the surveys were carried out and the type of climate according to the legend. In the graph in Figure 3 (bottom left), we can see the prevalence of studies in temperate climates, more specifically, in the chart in Figure 3 (bottom right), we can see the prevalence in Cfa climates (Temperate climate, without dry season with hot summer), Csa (temperate climate with dry and hot summer) and BSk (arid, steppe and cold climate). The initial studies of this type of facade took place in Italy and Spain and with the advancement of facade technology to several countries around the world, there is a growing interest in researching this typology in other climates, highlighting two studies in Brazil, as well as a study in the city of Trondheim (Dfb – cold, (continental), without dry season with warm summer), Norway; in Wroclaw (Cfb – temperate climate, without dry season with warm summer), a city in Poland; in Tehran (BSk), a city in Iran; and in Aalborg (Cfb), Denmark.

The 19 cities evaluated in Brazil are the result of the analyses of two studies: Maciel and Carvalho (2019) and Gregorio-Atem *et al.* (2020). The former carried out simulations in 16 Brazilian cities chosen according to the Köppen-Geiger climate classification: Manaus, Belém and Salvador (Af); Maceio (Am); São Luís and Aracaju (As); Rio de Janeiro, Brasília, Cuiabá and Campo Grande (Aw); Água Branca (BSh); Porto Alegre and São Paulo (Cfa); Curitiba (Cfb); Belo Horizonte (Cwa) and Nova Friburgo (Cwb). The article by Gregorio-Atem *et al.* (2020) also analyzed, through computer simulation, the performance of ventilated facades in eight cities, each belonging to the eight Brazilian bioclimatic zones: Curitiba (ZB1), Bagé (ZB2), São Paulo (ZB3), Brasília (ZB4), Vitória da Conquista (ZB5), Campo Grande (ZB6), Petrolina (ZB7) and Belém (ZB8).

Regarding the methods used to evaluate the different types of ventilated facades of the articles, it can be observed in Figure 4 (left) that they were varied. The "yellow" color family represents the studies that only had computer simulations and represent most of the studies (38%). The "blue" color family (27%) represents the studies that only carried out experimental studies. The "orange" color family (31%) shows the studies that carried out experimental research and computer simulations. The "green" family (4%), in smaller numbers, shows the studies that carried out an experimental and analytical study. The studies that carried out experimental research consist of measurements in a real building, scaled-down models in the laboratory (where all variables are controlled) or measurements in outdoor test buildings.

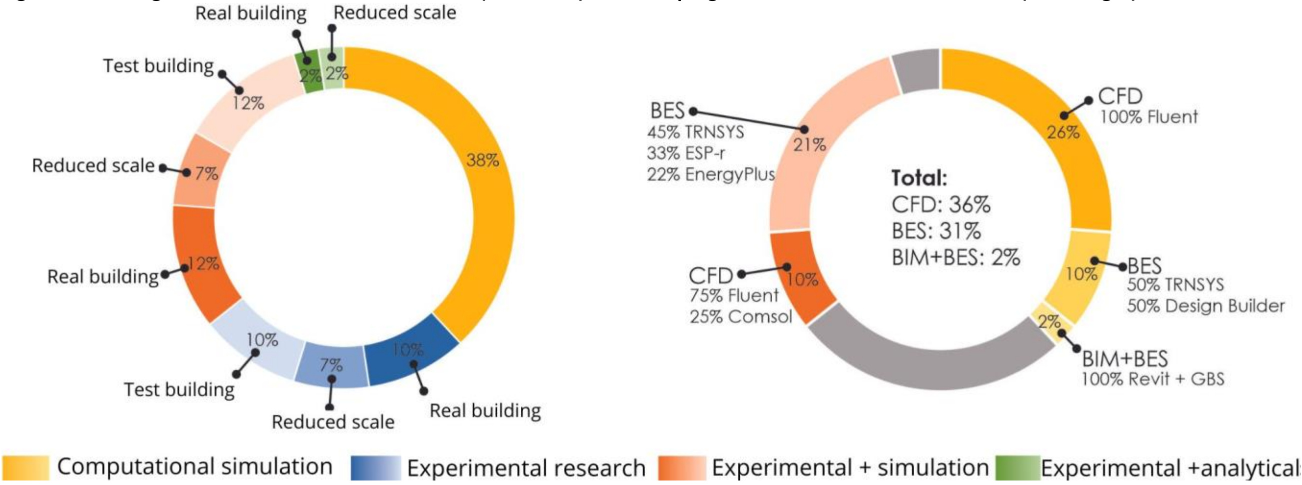
Figure 3 – Clipping of the world map showing the location of the surveys and the climate according to the Köppen-Geiger classification (top); number of studies divided into major climatic groups (bottom left); amount of work in each specific climate (bottom right)



Source: adapted from BECK *et al*. (2018) (top) and the authors (adaptation from the map and graphs).

The graph in Figure 4 (on the right) shows the different programs used in studies with computer simulations (exclusively or with an experimental stage). When analyzing the studies that only used simulation, most of them (26%) worked with computational fluid dynamics (CFD) software, in which the greatest interest is in the visualization of the phenomenon of air movement inside the ventilated cavity of the facade. This type of method demonstrates a difficulty in validating experimental results as the phenomena involved are more complex. When analyzing the studies that performed simulations with experimental data validation, most of them use Building Energy Simulation (BES) software, in which the focus is on the thermal performance of the building and the heat exchanges between the outdoor and indoor environment are more important. Among the most used BES programs are TRNSYS, ESP-r, EnergyPlus and Design Builder. Concerning CFD programs, there is a predominance of the use of Fluent software. The studies that performed data validation found satisfactory levels of convergence between experimental and simulation data. From the authors who used the ESP-r, Marinosci *et al.* (2011) and Seferis *et al.* (2011) found greater discrepancies in temperatures at night, when there is no solar radiation, and Fantucci *et al.* (2017) scored the impact of input data such as surface convection coefficient and component thermal conductivity on the results. Among the studies that carried out validation with Fluent, Sánchez *et al.* (2020) found small differences in the behavior of cavity air, Giancola *et al.* (2012) highlighted the importance of including ground-reflected radiation, and Sanjuan *et al.* (2011b) defined the best turbulence (*RNG K-epsilon*) and radiation (Discrete Ordinate) models available for simulation.

Figure 4 – Investigation methods used in the research (on the left) and main programs used in the simulation cases (on the right).



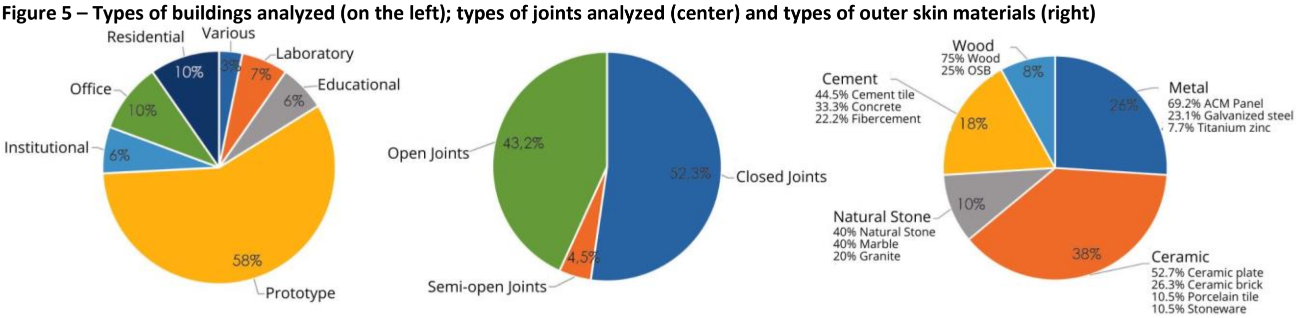
Source: the authors.

Figure 5 (on the left) shows the most analyzed building types in studies that evaluate the thermal performance of opaque ventilated facades. Most of the studies use prototypes, that is, a test model in a real or reduced scale, carried out especially for the purpose of the research. In the remainder of the studies, no predominance of any type was observed. Moreover, office and residential buildings were the most cited. It is important to report that not all the articles present the use of the building studies. For some authors who worked with simulation, this data was not important, but rather the geometry of the facade itself.

Regarding the way air enters and leaves the ventilated facade, the studies were classified as: closed joints with openings only in the lower and upper parts of the cavity; open joints with openings along the entire facade; and semi-open joints, with only one opening below or above. In the graph in Figure 5 (at the center), a slight predominance of closed joints was observed.

In the studies, a wide variety of outer skin materials that make up the ventilated facade was observed. In the graph in Figure 5 (on the right), a predominance of ceramic materials can be observed, followed by metallic ones. In fact, the market for opaque ventilated facades is dominated by companies that have the experience and technique necessary for making ceramic tile, porcelain tile, and aluminum composite (ACM) facades.

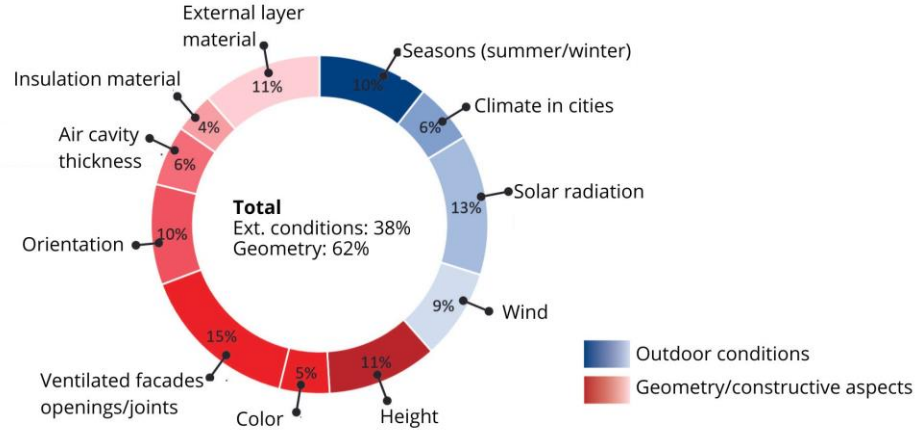
Figure 5 – Types of buildings analyzed (on the left); types of joints analyzed (center) and types of outer skin materials (right)



Source: the authors.

Identifying the parameters that impact the thermal performance of these facades is important as this technology allows different arrangements and configurations that influence the result of the energy behavior. In the studies researched, it was found that the performance of the facade depends on external conditions, such as climate, seasons and climate variables, in which solar radiation and wind speed and direction were the most cited in the analyses. In addition to the outdoor environment, the articles analyze the influence of the geometry itself and the constructive aspects in the way the air circulates through this facade and will be able to represent some energy savings in the final performance of the building. The graph in Figure 6 shows the percentage of times each parameter was investigated in the research, in which geometry (62%) was more studied than the external conditions (38%).

Figure 6 - Identification of parameters influencing the thermal performance of opaque ventilated facades



Source: the authors.

Influence parameters on the thermal behavior of opaque ventilated facades

Outdoor conditions

The list of studies that differentiate the analyses by seasons (summer and winter), analyze more than one type of climate or analyze the impact of environmental variables on the thermal behavior of facades can be seen in Table 2. Peci López and Santiago (2015) stands out as it is one of the few European studies that simulated in different climate zones, corresponding to 12 cities in Spain. In a sensitivity analysis, in which they analyzed the combination of the effects of climate variables - temperature, radiation and wind speed, they concluded that solar radiation was the variable with the greatest influence, corroborating all the authors who analyze this variable. Climates with hot summers and milder winters proved to be better for installing ventilated facades, although research has been seen in moderate climates.

Alonso *et al.* (2016) concluded that for hot climates, a study carried out during the summer in Madrid with facades exposed to solar radiation, the ventilated facade was 13.3% more efficient than the conventional one (double skin facade with non-ventilated air chamber). For climates with a predominance of winter, a facade system with greater thermal insulation proved to be more effective than ventilated facades. Suárez *et al.* (2011) observed an annual energy savings of 9% compared to the sealed air cavity facade for climates with hot summers and moderate winters, such as Madrid. Giancola *et al.* (2012) developed research in Almeria, a city in southern Spain, and corroborated that in hot climates with high levels of solar radiation, ventilated facades can play an important role in reducing the thermal loads of heating and cooling, as long as external temperatures are not extreme. The authors summarize the behavior of ventilated facades in hot climates: in winter, the facade acts as good thermal insulation when the radiation values are high because the air temperature leaving the facade joints is higher than the temperature of the indoor environment, causing the environment not to lose heat. When the solar radiation and external temperature are low, the air temperature leaving the facade is lower than the internal temperature and the energy balance on the facade is negative. In summer, the air that leaves the facade removes part of the thermal load from the facade, reducing heat gain in the indoor environment, however, when the outdoor temperature and solar radiation are very high, there can be internal heat gain. Soto Francés *et al.* (2013) validated a numerical model with tests in a variety of climate conditions (hot, cold, sunny and cloudy days) in Castellón, Spain and highlighted that the impact of solar radiation is greater than the outdoor temperature and wind, corroborating with the aforementioned research. Gagliano and Aneli (2020) studied the influence of outdoor conditions in a study carried out in Catania, Italy, and compared a ventilated facade with a non-ventilated facade. The authors concluded that the ventilated facade ensures energy savings of 20 to 50% in winter and 40 to 50% in summer, depending on the facade orientation and wind incidence.

Table 2 - Identification of the parameters (outdoor conditions, geometry and constructive aspects) evaluated

References	Seasons	Climate in cities	Solar radiation	Wind	Height	Color	Ventilated facade openings	Orientation	Air cavity thickness	Insulation material	Outer skin material
Alonso *et al.* (2016)	X										
Aparicio-Fernandez *et al.* (2014)					X			X			
Balter *et al.* (2019)					X		X	X	X	X	X
Balter, Barea and Ganem (2020)					X			X			X
Fantucci *et al.* (2017)	X		X								
Fantucci, Serra and Carbonaro (2020)	X		X		X	X	X				
Gagliano and Aneli (2020)	X			X			X				
Gagliano, Nocera and Aneli (2016)				X							
Giancola *et al.* (2012)	X		X								
Gregório-Atem *et al*. (2020)		X				X				X	X
Guillen *et al.* (2014)										X	
Harnane, Bouzid and Brima (2018)							X				
Iribarren, Castelló and Maestre (2018)											X
Iribar-Solaberrieta *et al.* (2015)		X						X			X
Maciel and Carvalho (2019)		X									
Mandavinejad and Mohammadi (2018)		X			X						
Marinosci *et al.* (2011)				X			X		X		
Marinosci, Semprini and Morini (2014)						X	X	X	X		X
Nore, Blocken and Thue (2010)				X							
Pastori *et al.* (2021)			X		X	X					
Patania *et al.* (2010)			X	X				X			X
Peci López and Santiago (2015)	X	X	X	X							
Peci López *et al.* (2012)			X	X							
Pergolini *et al.* (2019)							X				X
Petritchenko *et al*. (2017)							X		X		
Petritchenko *et al.* (2018)	X				X				X		
Sánchez *et al.* (2013)			X				X				
Sánchez *et al.* (2017)			X				X				
Sánchez *et al.* (2020)							X				
Sanjuan *et al.* (2011a)			X				X				
Sanjuan *et al.* (2011b)			X		X		X				
Sanjuan *et al.* (2011c)			X				X	X			
Schabowicz and Zawislak (2020)		X					X				
Seferis *et al.* (2011)	X										X
Soto Francés *et al*. (2013)	X		X	X		X					
Stazi *et al.* (2011)					X			X			
Stazi *et al.* (2018)											X
Stazi *et al.* (2020)	X										X
Stazi, Veglio and Di Perna (2014)			X	X	X			X			X
Suárez *et al.* (2011)					X				X		
Suárez et al. (2012)	X						X	X			
Zurro García *et al.* (2020)										X	
TOTAL NUMBER OF STUDIES	11	6	14	9	11	5	16	10	6	4	12

Source: the authors.

Two authors analyzed the ventilated facade for moderate climates: semiarid and cold in Tehran, Iran (MANDAVINEJAD; MOHAMMADI, 2018) and temperate oceanic facade in Wroclaw, Poland (SCHABOWICZ; ZAWISLAK, 2020) and it proved to be efficient. The first authors point out 40% of energy savings in summer compared to the same facade, however, with no ventilation, as long as there is enough solar radiation on the facade.

Regarding authors who studied different cities, the Brazilians authors Maciel and Carvalho (2019) and Gregorio-Atem *et al.* (2020) can be mentioned. The former performed an energy analysis, quantifying annual operating energy for heating and cooling systems in 16 Brazilian cities. The ventilated granite facade was compared with a cladding facade of the same material, using simulations in BIM (*Revit*) and BES (*GBS - Green Building Studio*) programs. The results indicated great benefits using ventilated facades for hot climates (A and B, according to the Koppen-Geiger classification), mainly in the cities of Belém, Manaus and Salvador; and the ventilated facade solution was encouraged by the authors as most of Brazil is in a hot zone. The study analyzed only one type of closed-joint facade with openings at the bottom and top of the facade. The study by Gregorio-Atem *et al.* (2020) analyzed buildings in 8 Brazilian cities with open-joints facades using TRNSYS software simulations and considered material and color variation for the outer layer (ceramic, stone and aluminum composite material), inner layer (plasterboard with mineral wool and ceramic) and presence or absence of thermal insulation. The results showed that the best settings can be selected for each climate condition in Brazil. In general, for zones 1 and 2, the coldest Brazilian zones, external envelope of plasterboard with mineral wool and dark colored ceramic tiles was indicated for the outermost layer of the facade. For zone 3, the best configuration was solid brick wall with insulation in the ventilated layer and light-colored ceramic tiles as outer material. Zones 4, 5, 6 and 8 showed the best results with plastered solid brick walls, without thermal insulation and with a light-colored ceramic tile. Zone 7 presented the same configuration as zones 4, 5, 6 and 8 as the best solution, however, using natural stone instead of ceramic tile. The authors corroborate with Maciel and Carvalho (2019) in which lower values of energy demand were found for the hottest zones (zones 4, 5, 6, 7 and 8).

Regarding wind, Peci López *et al.* (2012) showed that wind speed and direction are variables that directly influence the performance of ventilated facades. The higher the wind speed, the higher the airflow rates. When the wind speed is low, the buoyancy effect predominates. According to Gagliano, Nocera and Aneli (2016) in the wind scenario, a forced convection is generated within the cavity, while in the leeward, the flow is influenced by both the buoyancy effect and the wind forces and a mixed convection is generated within the cavity. The ventilated facades showed energy savings in the range of 47% (windward 5m/s) to 51% (no wind) compared to the non-ventilated facade for the study carried out in the city of Catania, Italy. Wind increases airflow, but it also increases convection heat losses in the environment. Stazi, Veglio and Di Perna (2014) showed that wind pressure influenced the airflow rates of lower facades, while for higher facades it did not appear to have much effect.

Thus, it was found that all the authors who evaluated the importance of external conditions highlighted solar radiation as the variable that most impacts the performance of ventilated facades. The airflow in the ventilated cavity is highly potentiated by the incident radiation. Energy savings increase as solar radiation increases.

Geometry and constructive aspects

One of the great challenges of studying opaque ventilated facades is that there are numerous possibilities for assembling and composing the system. Each aspect will change the behavior of the air inside the ventilated cavity, with greater or lesser intensity, directly impacting the thermoenergetic performance of these facades. The list of authors who analyze the impact of the height of the facade, color of the external element, openings (inlet and outlet of air in the ventilated cavity), facade orientation (north/south or east/west), air cavity thickness, presence or absence of the insulation material in the cavity and the outer skin material can also be seen in Table 2.

The air flow inside the cavity is influenced by the height of the ventilated channel, but few authors have evaluated the influence of this variable. In general, the higher the facade, the greater the air flow rate and velocity within the cavity and the greater the energy saving potential of these facades (FANTUCCI; SERRA; CARBONARO, 2020; SANJUAN *et al.,* 2011b; STAZI *et al.,* 2011). Stazi, Veglio and Di Perna (2014) showed that lower facades perform worse because they receive ground-reflected radiation and, due to the reduction in the air column, there is an increase in the temperature of the channel, reducing the internal-external temperature difference. Pastori *et al.* (2021) conclude that it is essential to consider the efficiency of the facade along its height to correctly design the energy performance of the building.

Fantucci, Serra and Carbonaro (2020) carried out a sensitivity analysis in which they tested several possibilities: grill opening percentage, facade height, external surface color, in which the color was the parameter that most influenced the energy performance of ventilated facades. The light color reduced the thermal load by 80% and the dark one by 31% compared to a non-ventilated facade. According to Pastori *et al.* (2021), the light color (α=0.4) allowed a heat flux reduction of 40% when compared to the dark color (α=0.8). Marinosci, Semprini and Morini (2014) highlight that the thermal performance of facades is very sensitive to the radiant properties of the outer layer. Adopting a high value of solar absorption coefficient increases the temperature of the outer wall during sunny days, which not only increases the air velocity inside the cavity due to the buoyancy effect, but also the long-wave thermal radiation inside the cavity. These authors indicated that using lower solar absorption coefficients was beneficial to reduce summer heat loads. Gregorio-Atem *et al.* (2020) suggest using light colors for hot climates, especially in facades without thermal insulation.

In general, studies on the performance of ventilated facades tended to analyze the air inlet and outlet openings in more depth. Balter *et al.* (2019); Petritchenko *et al.* (2017); Marinosci, Semprini and Morini (2014) compared closed and open joints and found better results when the joints along the facade are closed and the air opening occurs only through the lower and upper portions of it. In these authors' studies, open joints reduce the thermal load reduction capacity of ventilated facades during the summer, as the buoyancy effect is greater without open joints. The greater the percentage of the open joint area, the greater the air velocity in the cavity, but this velocity is greater when you only have the bottom and top openings.

Complementarily, some authors point out advantages in open joints, when compared to a sealed facade, that is, without ventilation (HARNANE; BOUZID; BRIMA, 2018; SUÁREZ *et al.,* 2011; SANJUAN *et al.,* 2011c). Open joints allow effective ventilation flow into the cavity, reducing heat transfer. The comparison between a ventilated facade with horizontal open joints and one with a sealed cavity, that is, without openings, showed that the air velocity in the cavity is 5 times greater in the ventilated facade, and the flow pattern is different: while the air flow in the sealed facade is in a loop, in the ventilated facade, it is always ascendant (SUÁREZ *et al.,* 2011). Sanjuan et al. (2011a); Sánchez *et al.* (2013) and Sánchez *et al.* (2017) performed experiments to describe the cavity airflow when using slabs with open joints. Using PIV (Particle Image Velocimetry) methods, they measured the air velocity field within the cavity of an open-joint ventilated facade, under laboratory conditions. Heating the slabs caused an ascending flow of ventilation inside the cavity, which was non-homogeneous and asymmetrical. Speed and turbulence increased with the forces of the buoyancy effect, that is, with temperature differences, regardless of the number of slabs, air enters through the lowest joints and leaves through the highest. The flow tends to move close to the heated slabs and develops an upward movement, interrupted by the presence of the joints. The maximum flow rate takes place at the central height of the facade. Sanjuan *et al.* (2011b, 2011c) and Sánchez *et al.* (2020) used data from previous experimental work to validate fluid dynamics simulation models in Fluent software, which the authors argue is mandatory in these cases, as they can describe the details of internal airflows and exchange heat phenomena. Marinosci *et al.* (2011), who used the ESP-r software, concluded that open joints can be ignored, as there was no significant change in the results and the simulation is simpler and faster.

Fantucci, Serra and Carbonaro (2020) concluded that the ventilation grill opening ratio, which prevents insects, leaves, etc. from entering (when there is only an opening at the bottom and top of the facade) has a moderate impact on facade performance. Marinosci, Semprini and Morini (2014) pointed out that the best performances were achieved the lower the pressure losses along the cavity, therefore the combination of grills at the ends of the air cavity and low cavity thickness should be avoided.

Regarding the orientation of the evaluated facades, most studies analyze south-facing facades (which receives more hours of direct solar radiation in the northern hemisphere, where most of the research was carried out; equivalent to the northern facade for the southern hemisphere), ensuring more energy savings compared to other facades. According to Gagliano and Aneli (2020), east/west facades ensure greater energy savings during summer days and the south facade performs better on winter days. Stazi *et al.* (2011) related orientation and height and concluded that the lower east/west facades (6m) reach higher temperatures due to lower solar radiation in the early morning and late afternoon, while higher facades (12m) and those facing the south should be preferred because they perform better in terms of air velocity. Sanjuan *et al.* (2011a) point out that the ventilated facade gains less heat on the south facade during the summer but loses more heat on the north facade at night. These authors highlight the importance of an annual study that considers the costs and price of energy used for heating and cooling. The results of the study conducted by Marinosci, Semprini and Morini (2014) showed similar performances on south or west facades. Finally, Iribar-Solaberrieta *et al.* (2015) concluded that it is necessary to analyze the thermal behavior of all facades as the thermal performance depends on the amount of radiation incident on each facade.

The thickness of the air cavity influences the air velocity within the cavity. Narrower cavities tend to have higher air velocities, but there are few studies on this topic. Marinosci *et al.* (2011) attributed the low values of air velocity within the cavity to the large cavity width (24 cm). In a study by Marinosci, Semprini and Morini (2014), similar performances were obtained when the thickness of the air chamber was in the order of 10 to 24 cm, concluding that the thickness cannot be too small to reduce pressure losses along the air cavity.

Another variable that has been underexplored in the studies on this subject is the issue of the presence of insulation material within the cavity, as in most European countries using thermal insulation in the cavity is required, due to climate conditions. The study by Zurro García *et al.* (2020) points to a 26.7% reduction in heat flow with the addition of 15 cm of insulation material in the air cavity, showing energy savings. Despite this, for the climate in Brazil, Gregorio-Atem *et al.* (2020) point out that in warmer areas it is more beneficial not to use insulation material.

Pergolin *et al.* (2019), Stazi *et al.* (2018) and Stazi *et al.* (2020) tested different configurations of outer material in relation to thermal mass: light, with thermal mass in the innermost and outermost layer. When the greatest thermal mass is in the outermost layer, the results were better, with lower external surface temperatures, limiting the overheating of air inside the cavity. These results were corroborated by Patania *et al.* (2010), who observed better performance when the outer layer has a low value of thermal conductivity, high density values and specific heat and low values of thermal diffusivity. Stazi, Veglio and Di Perna (2014) also demonstrated that thermal inertia influences the period in which the buoyancy effect becomes more effective: at night for coatings with low thermal inertia and during the day for coatings with high thermal inertia. Regarding the different types of materials analyzed, when comparing ceramic plates with composite aluminum panels, ceramics had better results (IRIBARREN; CASTELLÓ; MAESTRE, 2018; MARINOSCI; SEMPRINI; MORINI, 2014), including for the climate in Brazil, as shown by Gregorio-Atem *et al.* (2020). Seferis *et al.* (2011) included a radiant barrier (aluminium) between the outermost layer and the air chamber and obtained beneficial results, as this barrier helped keep the air in the air chamber warmer in winter, especially at night, and cooler during the summer.

Conclusion

Based on the results presented in this literature review, it can be inferred that studies on this topic are recent, which demonstrates novel research interest. Regarding the research location, the concentration is on the European continent, mainly in Spain, Italy and Portugal, highlighting the Mediterranean climate as the focus of the research. Only two studies from Brazil were found, thus showing evidence of the lack of indexed research in the Southern Hemisphere, showing a gap in more in-depth research on the subject in the Brazilian context. The analysis methods varied, being exclusively computer simulations or research that validated the simulations with experiments or experimental studies. Most of the articles that used CFD software used Fluent; in the studies that used energy simulation software, TRNSYS predominated.

As a characterization of the objects of the studies, it can be concluded that most types of buildings analyzed are prototypes, followed by residential and office buildings. Regarding facade joints, practically half of the studies examined closed joints, and the other half analyzed open joints. The materials used for the external envelope of the most studied facades were ceramic and metallic. Regarding the seasons, the studies conclude that in the summer, the ventilated facade presented lower heat flow and greater energy savings compared to other systems, such as the conventional facade system (non-ventilated). In summer, the air purged by the facade removes part of the thermal load, reducing the heat gain in the indoor environment. However, there can be internal heat gain when the external temperature and solar radiation are high. In winter, the ventilated facade can act as a good thermal insulator when radiation values remain high. Therefore, an annual thermal analysis is recommended. The studies conclude that the best places to install ventilated facades are in hot climates, with high temperatures in the summer and low-severity winters. Unanimously, solar radiation is the external factor that determines the thermal behaviour of the ventilated facade. The airflow in the ventilated cavity is highly potentiated by incident radiation. Energy savings increase as solar radiation increases.

Each aspect of the facade's geometry will change the behaviour of the air inside the ventilated cavity, with greater or lesser intensity, directly impacting the thermoenergetic performance of these facades. The height of the ventilated channel influences the airflow inside the cavity. Generally, the higher the facade, the greater the air velocity inside the cavity and the greater the energy-saving potential of buildings that use this technology. The results of studies that evaluated color indicated that using lower solar absorption coefficients was beneficial in reducing summer heat loads. Regarding the openings, the closed-joint facades presented better results, in which the air opening occurs only through the lower and upper portions of the facade. Most of the studies analyze the performance of the south-facing facade since they are in the northern hemisphere, where the south facade is the one that receives the most solar radiation. Some authors emphasize the importance of considering all facades as the general performance of the building depends on the amount of solar radiation each face receives. Regarding the thickness of the air cavity, it was found that the narrower it is, the higher the air velocity. However, there are not many studies that specifically analyze this variable. Another parameter not yet explored is the presence of insulation material as it is widely used in the countries studied; however, its use is not recommended for warmer climates. Finally, considering the external envelope material, some authors have found improvements when there is greater thermal mass in this layer, decreasing surface temperatures and limiting superheating inside the cavity. Thus, the ceramic material had better results in terms of thermal performance when compared to composite aluminum panels, which is low thermal material mass.

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