Influence of Automated Façades on Comfort and Energy: A Critical Review

de la Barra Luegmayer, P.; Brembilla, E.; Prieto, Alejandro; Vásquez, Claudio; Knaack, U.; Luna-Navarro, Alessandra

DOI
10.1016/j.enbuild.2025.116290

Publication date
2025

Document Version
Final published version

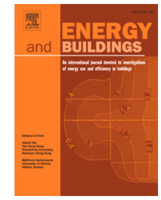
Published in
Energy and Buildings

Energy & Buildings 347 (2025) 116290

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild



Influence of automated façades on comfort and energy: A critical review

P. de la Barra [a,*], E. Brembilla [a], A. Prieto [b], C. Vásquez [c], U. Knaack [a], A. Luna-Navarro [a]

[a] Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, Delft, 2628, BL, The Netherlands
[b] Facultad de Arquitectura, Arte y Diseño, Universidad Diego Portales, Av. República 180, Santiago, 8370074, Región Metropolitana, Chile
[c] Facultad de Arquitectura, Diseño y Estudios Urbanos, Universidad Católica de Chile, El Comendador 1916, Providencia, 7500000, Región Metropolitana, Chile

ARTICLE INFO

Keywords:
Dynamic façade
Automated façade
Building envelope
Occupant
Comfort
Energy performance

ABSTRACT

In recent years, several studies have assessed the influence of automated façades on energy savings, IEQ, and occupant satisfaction. However, discrepancies exist between the expected advantages of automated façades predicted in research and the actual benefits observed in real-world tests. To assess how automated façade operation enhances building performance, in particular within office building contexts, this study reviews and analyzes current evidence on the influence of automated façades. In this review, 91 studies were identified presenting evidence of their performance. A total of 34 studies investigated performance in laboratory settings, 23 in real office buildings, and 34 in simulations. Only 13 laboratory studies and 17 real office building studies included human participants. Visual and thermal quality were the main indoor environmental domains investigated, with limited exploration of others. Existing studies show large variability in contextual factors (e.g., type of shading and control) or experimental designs (e.g., different benchmark scenarios), hindering the comparison of results. Consistent evidence shows the potential of automated façades for energy savings, particularly in lighting and cooling demands, which outperform manual control systems. Automated controls are more effective in reducing excessive daylight and glare, while evidence of the impact on thermal and air quality remains limited. Regarding occupant satisfaction, evidence is unclear since, in some cases, occupants prefer manually controlled façades and, in others, automated ones. Further research is suggested on human-centered studies in real office buildings to capture occupant behavior and preferences while exploring solutions that dynamically identify and integrate factors affecting occupant interaction with buildings.

1. Introduction

The façade or envelope of a building is essential to achieve high performance in buildings, as its design and operation directly affect energy demand and indoor environmental quality (IEQ) [1]. Previous studies have shown that dynamic facades can provide a means to adapt to transient requirements (for example, comfort of the occupant or changing weather) and improve the overall performance of the building [2] by regulating solar gains, natural ventilation, moisture, daylight, view and outside noise [3–5]. In particular, automated control of these dynamic and movable components (automated facades) has been associated with the reduction of energy demand [6,7] and the improvement of IEQ [8] compared to manually controlled dynamic facades [9] and static façade technologies [10].

Bilgen et al. [11] made one of the first attempts to investigate the effect of automated facades on building energy performance. Their study indicated that energy savings on automated façade operation are greater when cooling or ventilation is necessary to maintain IEQ compared to a regular window solution (a glazed facade). These findings were followed by other studies, such as those by Vine et al. [12] and Lee et al. [13], showing that an automated façade improves indoor daylight levels while reducing indoor overheating risk by blocking incoming sun radiation when needed. More recently, research on automated facade performance has focused on comparing different dynamic façade technologies, control logic, and levels of occupant interaction.

Current studies have increasingly focused on the multi-domain influence of automated facades. Simulation-based research has generated substantial evidence demonstrating the advantages of automated façades across multiple domains, including the optimization of daylight access [14,15], mitigation of discomfort glare [16], reduction of thermal loads [17], and enhancement of indoor air quality [8]. Notably, the work of researchers such as Loonen et al. shows the critical role of building performance simulation (BPS) in the development and com-

* Corresponding author.
E-mail address: p.delabarraluegmayer@tudelft.nl (P. de la Barra).

https://doi.org/10.1016/j.enbuild.2025.116290
Received 20 June 2025; Received in revised form 6 August 2025; Accepted 11 August 2025
Available online 14 August 2025

parative evaluation of innovative façade technologies [18]. Discrepancies emerge in laboratory and real office building studies, presenting the challenges posed by the simultaneous impact of facades on various indoor comfort domains [19,20]. For instance, controlling solar gains can have a detrimental impact on access to outdoor views or daylight availability. Inconsistencies are also shown when energy savings on artificial lighting, cooling, and heating achieved by automated systems have been studied in real settings where occupants interact with the building systems [21]. There is still no clarity on the balance of occupant requirements in façade operation to achieve satisfactory control and efficient building performance, as occupant requirements differ among individuals and depend on many contextual factors.

Three previous literature reviews have examined the performance of dynamic façades with a focus on occupant comfort and energy efficiency. Konstantoglou and Tsangrassoulis [22] analyzed automated controls for dynamic shading systems, finding that occupants are more likely to accept these systems when they have the ability to override controls, although this can reduce expected energy savings. The ease of system use also plays a crucial role in occupant acceptance. Moreover, strategies that optimize both visual and thermal performance tend to yield more balanced outcomes in terms of comfort and energy efficiency. Luna-Navarro et al. [23] explored interaction strategies and the requirements for effective occupant-façade interaction for dynamic façades, emphasizing the need for multidisciplinary approaches that foster communication between different fields of expertise. Shafaghat and Keyvanfar [24] investigated the state-of-the-art in dynamic façades, highlighting their physical performance in terms of thermal comfort, visual environment, ventilation, and electricity generation. This study demonstrated that dynamic façades can actively and selectively manage heat transfer and energy flow, thereby improving IEQ conditions and potentially reducing heating and cooling loads. However, none of these reviews has critically assessed the current evidence on the benefits of automated façades for improving energy savings in cooling, heating, and lighting, as well as overall environmental comfort and occupant satisfaction. While several studies suggest that automation could theoretically enhance these factors, the extent to which this is realized in practical applications remains unclear. This lack of clarity presents a barrier to the effective uptake of such façade technologies in the market.

The lack of understanding of occupant requirements, the scattered evidence on the impact of automated façade on building performance, and the absence of prior reviews highlight the need for a thorough study. Therefore, this review aims to evaluate the current evidence on the influence of automated facades on energy savings, IEQ, and occupant satisfaction to identify current opportunities and limitations of automated facades. This work reviews experimental, real office building, and simulation studies focusing only on office building contexts to evaluate current evidence on automated facades.

This literature review is relevant to inform and guide future research and industry efforts to improve office building energy and environmental performance. First, Section 2 explains the review methodology, including databases, selection criteria, and keyword clustering. Section 3 shows the general information on the current research landscape. Section 4 presents the current reported evidence on the effect of automated façades on energy savings, IEQ, and occupant response to automated façade operation. These results are then discussed in Section 5. Finally, Section 6 draws this paper's conclusion and highlights potential future challenges and investigations based on the conducted review.

2. Methodology

A systematic review was conducted to examine previous work on the influence of automated facades regarding energy savings in cooling, heating and lighting, indoor environmental conditions and occupant response in office building contexts. Advanced queries based on the keywords in Table 1 were performed. We selected papers that provided evidence from laboratory experiments, real office building assessments, and simulation studies on the impact of automated dynamic façade operations on energy demand, IEQ, and occupant response. In this literature review, we excluded studies that (i) solely examined manually controlled systems without any automated features, (ii) focused exclusively on façades that did not incorporate active and automated control strategies, and (iii) were conducted in building types other than office environments. The keywords were divided into three groups: (1) façade operation, (2) façade technology, and (3) type of study. The review was carried out by searching for laboratory and real office building studies separated from simulation studies in the following databases: Science Direct, Scopus, and Web of Science (WoS). A total of 6079 references were collected: (Science Direct (618), WoS (2481), and Scopus (2980)). The article selection process was performed in three steps: (1) screening titles and keywords, (2) screening abstracts, and (3) full-text assessment. After that process, only 91 studies met the selection criteria published between 1998 and 2025.

Table 1
Summary of keywords used for the systematic search of studies on automated façades (Search date: 15-12-2024). Keywords are categorized into three groups: (i) façade operation, (ii) façade technology, and (iii) study type. Separate queries were conducted for studies focusing on laboratory experiments, real-building assessments, and simulations.

Keywords groups	Inclusion searching criteria in title, abstract and keywords
Façade operation	(adaptive OR responsive OR dynamic OR kinetic OR intelligent OR advanced OR smart OR interactive OR active OR automated OR switchable) **AND**
Façade technology	(façade OR envelope OR skin OR shading OR glazing OR glazed OR window OR Venetian OR roller OR blind) **AND**
Type of study	**Keywords for laboratory and real office building studies** (laboratory OR on-site OR field OR experimental OR post-occupancy OR testbed OR test room OR campaign OR monitoring) **Keywords for simulation studies** (simulation OR model OR calculation)

3. Literature review results

3.1. Distribution of studies per time, aim and methodology

Fig. 1 illustrates the distribution of studies (1994–2025) on the impact of automated facades on energy savings, IEQ and occupant response. This figure classifies studies into laboratories, real office buildings, and simulations (Fig. 1a), further distinguishing those with and without participants (Fig. 1b).

The number of studies across real office building, laboratory, and simulation environments increased from 1 in 1994 to 79 in 2024. Initially, research was entirely laboratory-based (100 % in 1994). Real office building studies increased to 6̃0 % in 2000 before stabilizing at 25 %-33 %. Laboratory research remained dominant (50 %-60 %) until recently, declining to 41 %-44 %. Simulation studies emerged in 2007 and grew steadily, reaching 32 % in 2025. Over time, research shifted from a laboratory focus to a more balanced distribution across real office buildings and simulations. The increasing inclusion of human participants reflects a growing emphasis on human-centered research.

Fig. 2 presents the distribution of studies on automated facade systems by location. Europe has the highest number of studies with 41 studies, primarily in laboratories (n = 15) and simulations (n = 19). North America followed with 32 studies, mainly in real office buildings (n = 13). Asia has fewer studies, distributed across laboratories (n = 8), simulations (n = 10), and real office buildings (n = 2). Oceania and South America have four and three studies respectively, while Africa has no studies.

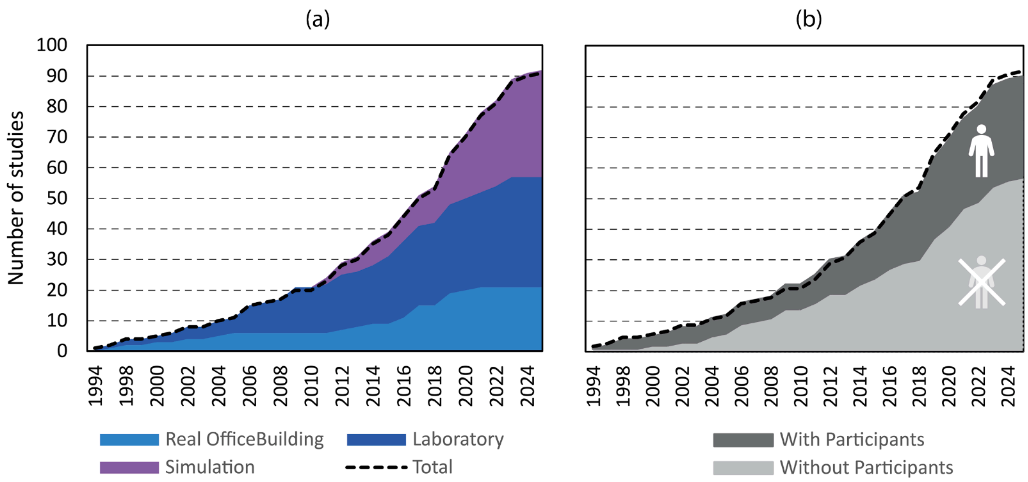


Fig. 1. Cumulative number of studies over time, presented in two stacked area charts: (a) Distribution of studies by laboratory, real office buildings, and simulation studies setting; (b) Distribution of studies according to the inclusion of human participants.

Fig. 2. Number of studies per world region divided by laboratory, real office building, and simulation setting. The plot shows that the majority of the studies have been carried out in Asia, Europe, and North America.

This distribution of studies shows the need for a broader geographical representation to ensure that automated façade research addresses diverse cultural contexts.

Most studies were conducted in laboratory settings (n = 34) and simulations (n = 34), while 23 were performed in real office buildings. As shown in Fig. 3, participant involvement is more frequent in real office buildings, likely due to the challenges of recruiting participants for laboratory environments. In fact, 74 % of real office building studies included human participants, compared to 38 % in laboratories. Real office building studies primarily monitor occupant behavior, comfort, satisfaction, acceptance, perception, and sensation, particularly in relation to façade operation and characteristics.

Among the laboratory studies, 21 did not involve human participants but assessed automated façade performance through physical measurements. Twelve of these used standard comfort models, such as Daylight Glare Probability (DGP), Predicted Glare Sensation Vote (PGSV), and Predicted Mean Vote (PMV), or environmental quality thresholds like work plane illuminance and indoor air temperature. Thirteen studies included participants, employing objective IEQ measurements, comfort models and questionnaires to analyze occupant behavior and perception.

In real office buildings, six studies did not include human participants, focusing solely on energy efficiency assessments or standard comfort models to evaluate façade impact. The 17 studies involving participants used questionnaires to examine occupant interaction with the façade, perceptions of automated systems, and their influence on indoor environmental satisfaction.

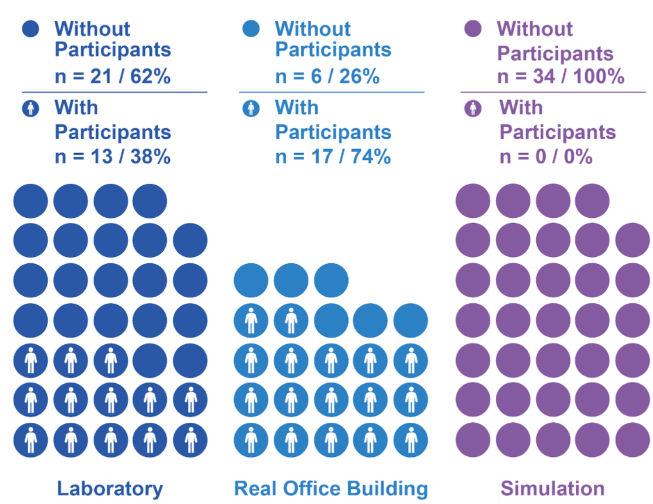


Fig. 3. The distribution of studies divided by laboratory, real office building, and simulation, indicating whether these studies involve human participants. Number of studies/percentage.

Fig. 4 illustrates the distribution of laboratory experiments, real office buildings, and simulations by research objective. Laboratory and real office building studies primarily addressed (i) control algorithm development, (ii) occupant impact, (iii) energy savings, and (iv) combined

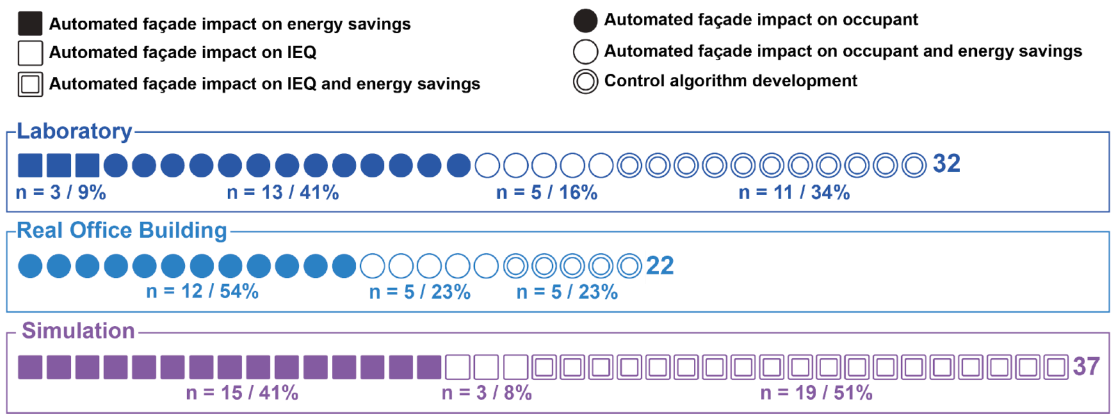


Fig. 4. Distribution of laboratory experiments, real office building assessment, and simulation according to their research aim, namely automated façade's impact on energy savings, impact on occupants, and control algorithms development. Additionally, several articles focused on the effect of automated facades on energy savings and occupant response. Number of studies/percentage.

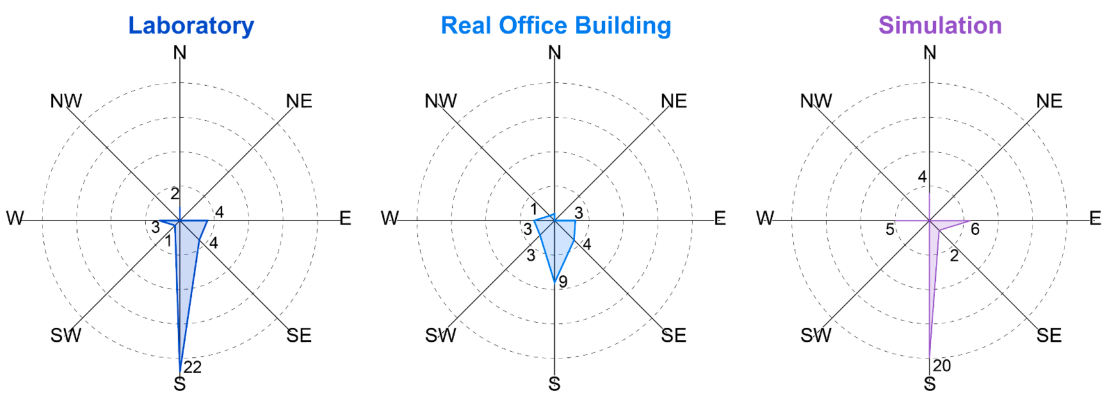


Fig. 5. Distribution of studies per orientation divided by laboratory, real office building, and simulation setting. The plot shows that most laboratory experiments have been conducted on south-oriented facades. Real office building orientations are distributed among west, south, and east orientations.

occupant and energy impact. In contrast, simulations focused on (i) energy savings and (ii) IEQ.

3.2. Orientation and climatic context of previous studies

Studies on dynamic facades have mainly focused on southern orientations, as shown in Fig. 5.

Real office building studies examined the orientations of the south (n = 9) and southeast (n = 4), with fewer studies in the east (n = 3), west (n = 3), north (n = 1), and northwest (n = 1). In laboratory experiments, south (n = 22) was most studied, followed by east (n = 4) and southeast (n = 4). The simulations showed a similar trend, focusing on the south (n = 28), then the east (n = 6), and the north (n = 5). Some studies covered multiple orientations, and four did not specify orientation. However, the limited investigation of other orientations, such as north-facing façades with diffuse daylight or west-facing façades with afternoon overheating risks, may result in gaps in understanding façade performance under different environmental conditions.

The climate context for laboratory experiments, real office building studies, and simulations is shown in Fig. 6. Most studies were conducted in Temperate Oceanic Climates (5 laboratories, 10 real office buildings, 14 simulations), Humid Subtropical Climates (8 laboratories, 4 real office buildings, 10 simulations), and Warm-Summer Mediterranean Climates (4 laboratories, 2 real office buildings, 1 simulation). Fewer studies were conducted in Hot Desert Climate (3 simulations) and Cold-Summer Mediterranean Climates (1 laboratory, 6 real office buildings). Other climate types, such as Tropical Monsoon (n = 2) and Warm Summer Humid Continental, were minimally represented (n = 7).

This shows a focus on temperate and subtropical climates, with arid and tropical regions underexplored in dynamic facade research.

3.3. The domain of investigation and type of façade technology investigated

Studies have examined IEQ across five domains: visual, thermal, acoustic, indoor air quality, and personal control (Fig. 7). Of these studies, 59 assessed the impact of dynamic façades using objective measurements, while 25 combined sensor data with subjective participant feedback. In the visual domain, studies focused on indoor daylight conditions (n = 64), view access (n = 15), discomfort glare (n = 30), and perceived privacy (n = 3). Thermal aspects investigated included indoor air temperature (n = 30) and solar gains (n = 12). Personal control and occupants' interaction were analyzed in terms of perceived control (n = 8), override options (n = 9), and control type (n = 4). Acoustic studies addressed noise levels and perception (n = 2). Indoor air quality was assessed through CO_2, VOC measurements, and occupant surveys (n = 5) [12,20,25–27].

The impact of automated façades on energy performance was analyzed in terms of cooling, heating, and artificial lighting. Thirty-four studies focused on lighting energy savings, while thirty-three examined cooling and twenty-one heating demands. Fig. 8 illustrates the distribution of studies considering energy savings across these domains,

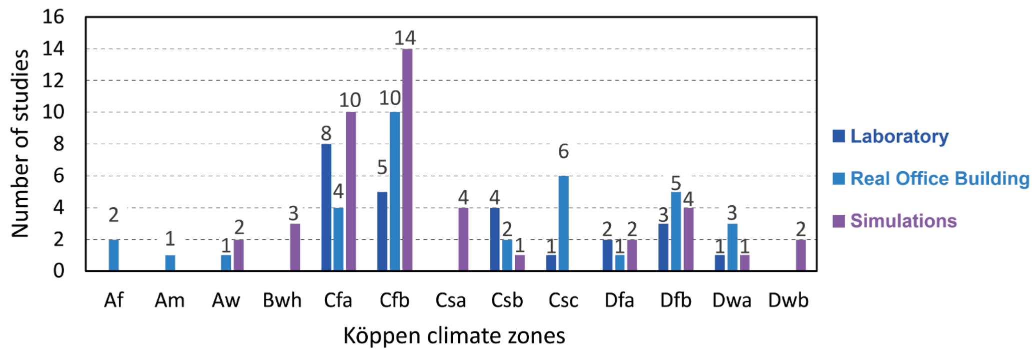


Fig. 6. Description of the frequency of climates considered by reviewed studies (classification according to the Koppen Climate). The climates are Tropical Rainforest Climate (Af), Tropical Monsoon Climate (Am), Tropical Wet and Dry Climate (Aw), Hot desert climate (BWh), Humid Sub-Tropical Climate (Cfa), Temperate Oceanic Climate (Cfb), Hot-Summer Mediterranean Climate (Csa), Warm-Summer Mediterranean Climate (Csb), Cold-Summer Mediterranean Climate (Csc), Hot-Summer Humid Continental Climate (Dfa), Warm-Summer Humid Continental Climate (Dfb), Humid Continental Climate (Dwa).

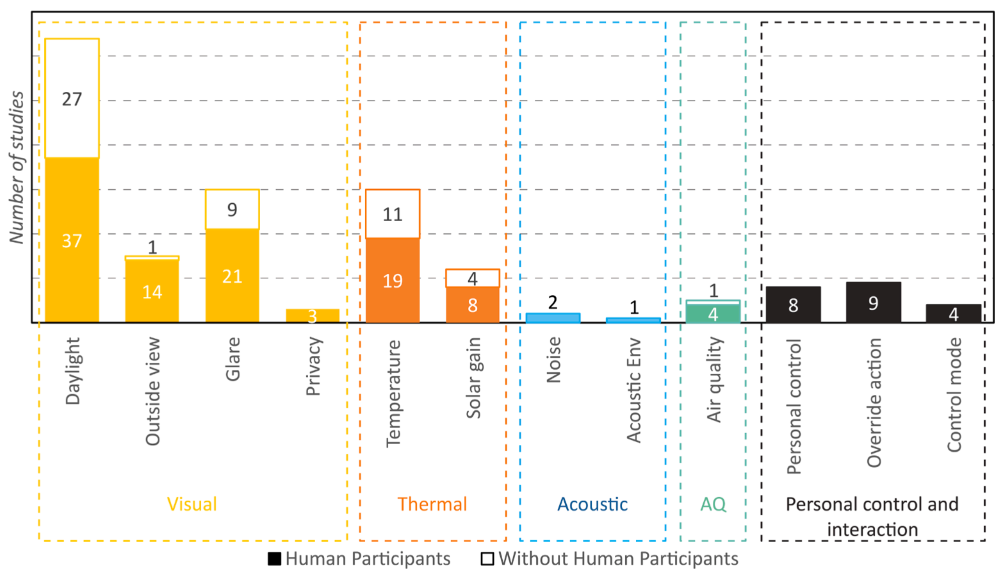


Fig. 7. Number of studies investigating indoor environmental domains with and without participants.

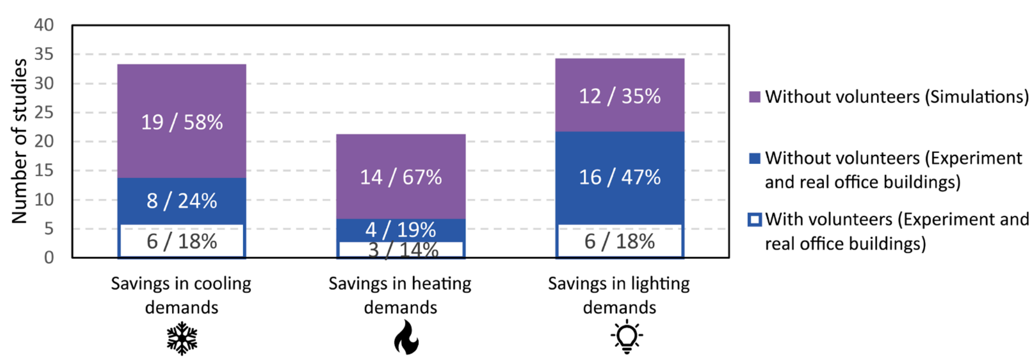


Fig. 8. Distribution of savings in energy demands in cooling, heating and artificial lighting assessed by studies with and without participants.

distinguishing cases with and without participants. Only three studies assessed occupant overrides, and none examined the impact on ventilation energy demand. Façade energy harvesting was investigated in one study featuring an automated system with integrated photovoltaics [28].

The reviewed studies on laboratory and real office buildings primarily examined four dynamic façade types: switchable glazing, roller shades, venetian blinds, and window openings. Simulation studies included additional variants such as switchable suspended particle devices (SPD), modular façades, PCM Trombe walls, switchable ethylene-tetrafluoroethylene (ETFE) foil cushions, and thermochromic glazing. These façades were tested using various control strategies categorized by (i) feedback ability, (ii) source of information, and (iii) data interpretation. Feedback ability distinguishes between closed-loop systems, which adjust based on real-time feedback, and open-loop systems, which operate without it. The source of information refers to sensor-based in-

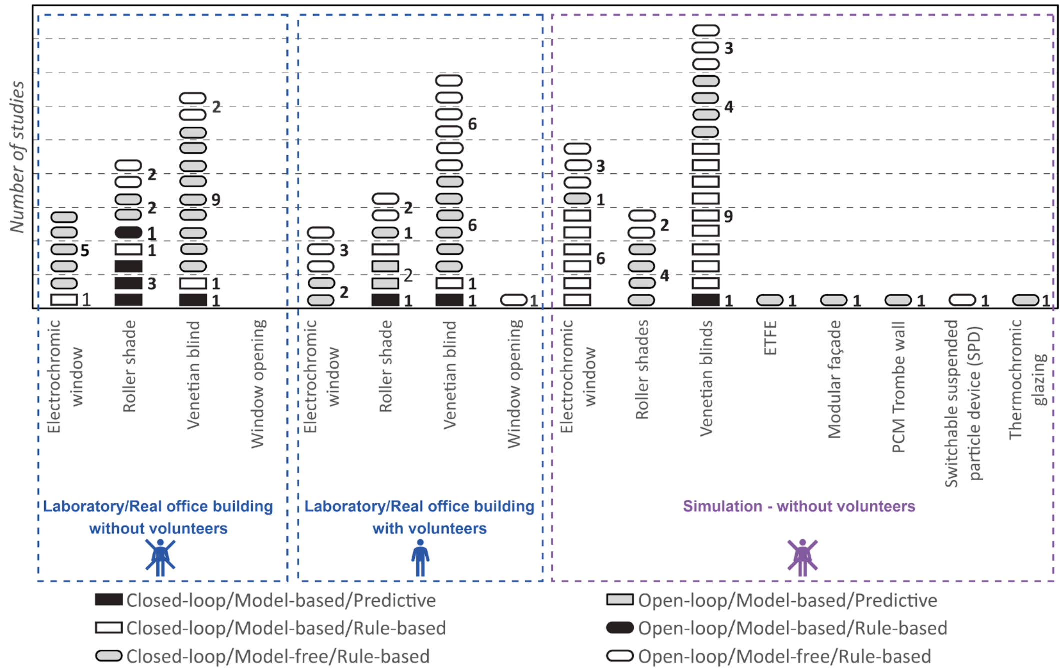


Fig. 9. Dynamic facades and control strategies investigated by studies. There were identified six control strategies that are the result of three aspects: (i) feedback ability (closed-loop/open-loop), (ii) source of information (sensor or digital model), and (iii) data interpretation (rule-based/predictive algorithm).

puts (from direct measurements) or model-based inputs (from digital simulations). Data interpretation can follow rule-based or predictive approaches: rule-based algorithms apply predefined actions, while predictive algorithms analyze data patterns to anticipate and optimize façade control.

Fig. 9 presents the distribution of studies on automated façades based on control strategies, categorized by feedback ability, information source, and data interpretation. Studies were classified based on whether human participants were involved. Most studies investigated closed-loop, model-free, rule-based control, with 9 studies involving participants and 29 without participants. Closed-loop, model-based, rule-based control was examined in 2 studies with participants and 17 without participants. Open-loop control was more common in studies without participants (n = 14), particularly model-free, rule-based approaches (12 with participants, 13 without). Predictive algorithms were used in 7 studies, mostly for venetian blinds and roller shades, including 3 studies with participants and 2 without.

3.4. Control objectives for automated facades tested

Fig. 10 summarizes automated façades control objectives, with most studies focusing on maximizing daylight (n = 28), of which 22 were conducted in laboratory or real office building settings and six through simulations. Glare prevention was examined in 15 studies (8 Laboratory/real office building, 7 Simulation), while maintaining indoor air temperature was explored in 16 studies (4 Laboratory/real office

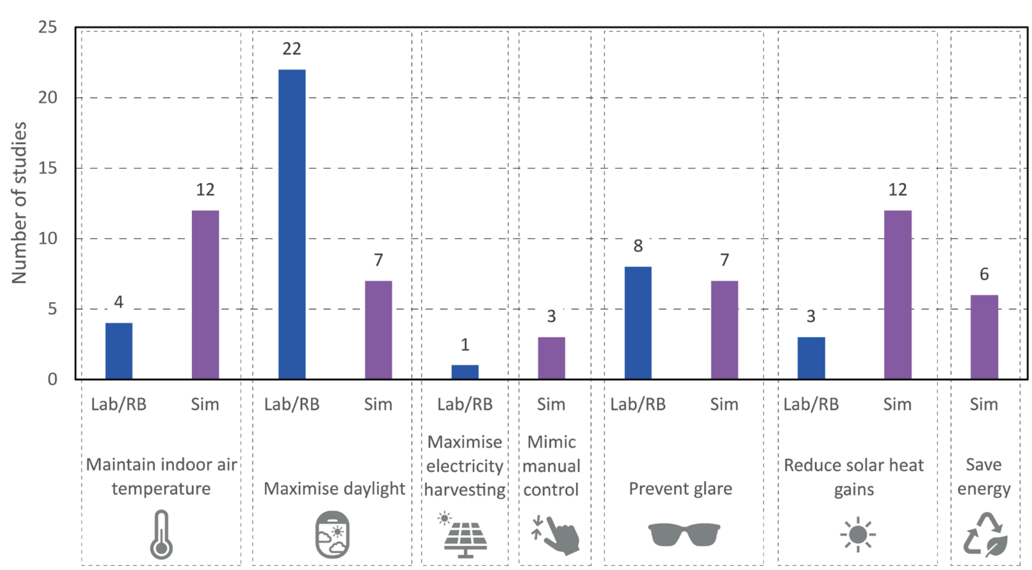


Fig. 10. Distribution of automated façade control objectives among the papers analyzed. Each control objective is described regarding simulation study and laboratory and real office building assessment.

building, 12 Simulation). Fewer studies investigated mimicking manual control (n = 3) or maximizing electricity harvesting (n = 1). Multi-objective strategies, combining daylight with glare control (n = 8) or temperature regulation (n = 4), aimed to enhance energy performance. There is a lack of control strategies that address occupant needs for privacy, improved views, or other aspects of occupant experience that directly impact the operation of façades. This gap may be attributed to the complexity of understanding and dynamically integrating occupant preferences into control strategies, a challenge that, if overcome, could significantly improve the effectiveness of automated façade systems.

4. Current evidence on the influence of automated façade on energy demand, IEQ and occupants

4.1. Automated façade influence on building energy demand

As shown in Fig. 11, the energy savings of automated facades in office environments were analyzed in 68 articles, comparing automated windows with unshaded windows (n = 34), static shading (n = 15), and manually controlled windows (n = 13). Additionally, five studies evaluated model-based and adaptive algorithms based on occupant illuminance preferences against conventional automated systems that use desk-level indoor illuminance controls.

Fig. 12 shows the number of studies where occupant interaction was considered, dividing them into simulations, laboratory and real office building assessments. Among the simulation studies, 29 did not account for occupant interaction with the building, while one included glare probability as a proxy of occupant interaction to compare automation against manual control [29]. In the laboratory and real office building assessments, 26 studies did not incorporate occupant interaction, whereas two studies allowed occupants to interact with façade elements.

Energy consumption findings are summarized in Fig. 13, categorizing evidence into cooling (blue), heating (orange), lighting (yellow), and overall energy consumption (grey) while distinguishing between simulation studies and laboratory or real office building assessments. Simulations indicate that automated façades can reduce cooling energy consumption by 0–40 %, depending on location and orientation [30–36], with reductions of 85 % in Riyadh [37] and 93 % in Nottingham [38], both for south-facing façades. However, no laboratory or real office building studies implemented control strategies specifically for cooling energy savings. Despite this, automated venetian blinds achieved reductions in cooling energy between 12 teKim2009AnSummer and 28 % [39] compared to static shading. Conversely, one study reported a 10 % increase in cooling energy consumption with automated roller shades [40]. While laboratory and real office building research on optimizing cooling energy use remains limited, existing evidence highlights the potential of automated façades to enhance cooling efficiency, particularly in high solar-gain climates.

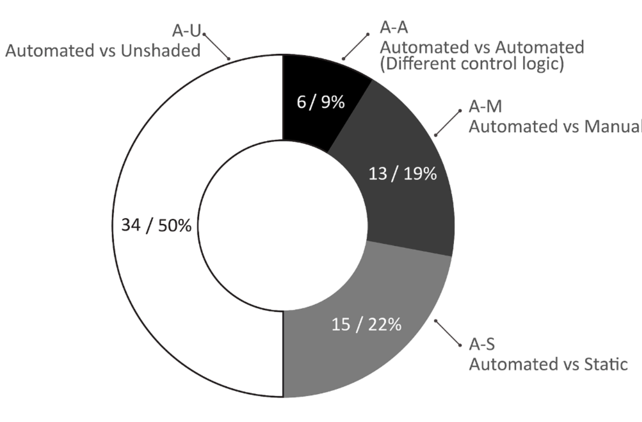


Fig. 11. Distribution of studies comparing automated facade control systems with other operational modes. The plot shows the proportion of studies that compare automated systems to unshaded facades (A-U), static facades (A-S), manual control (A-M), and different types of automated logic (A-A).

The impact of automated façades on heating energy consumption varies significantly across studies. Some simulations reported increases of up to 103 % when using ethylene-tetrafluoroethylene (ETFE) foil cushions [38], while others found reductions ranging from 77 % [41] and 42 % [37] (switchable suspended particle device (SPD) and roller shades with occupant interaction) to 5 % [31,42,43] (electrochromic windows, roller shades, and venetian blinds). Laboratory and real office building studies provide limited evidence on heating energy consumption. Two studies reported contrasting results: rule-based venetian blinds controlled by indoor illuminance increased heating energy consumption by 5 % compared to unshaded windows [11], while irradiance-controlled venetian blinds with photovoltaic cells achieved 6–14 % energy savings compared to similar automated blinds with different control logic [44]. These discrepancies may be due to insufficient solar gains with automated control compared to manual operation, while the second study compares different control logics for automated venetian blinds. Only one simulation study examined the effect of manual control or occupant interaction on heating energy demand.

When programmed for lighting energy savings, automated façades consistently reduce lighting energy consumption. Simulation studies report reductions from 31% with electrochromic windows compared to unshaded windows [30,45–49] to 81 % with venetian blinds compared to static louvers [16,50]. In laboratory and real office building studies, electrochromic windows achieved up to 68 % savings compared to static 15 % visual-transmittance glazing [41], while roller shades reduced up to 75 % [51] and venetian blinds reached 86 % [13,52–55]. However, the highest savings occurred in studies without occupant interaction. When occupoants could override automation, savings dropped to 10 % for venetian blinds [21,56], and 25 % for roller shades [57]. This raises uncertainty about whether similar savings would be achieved in real office buildings with occupant intervention.

Thirty-four of the 68 studies compared automated façades to static glazing without shading [34,58–64]. However, such comparisons are insufficient to demonstrate the benefits of automation, as unshaded windows are already known to increase energy demand and are rarely used in real office buildings. A more relevant comparison was made in 15 studies, which evaluated automated shading against manually controlled systems. However, these studies only considered automation without allowing occupants to override the system. Since previous research suggests that occupant overrides can significantly reduce the efficiency of automation [65], the reported benefits may not fully reflect real-world performance. Only two studies [21,57] accounted for occupant interaction in both manual and automated scenarios, providing a more robust comparison. Their findings suggest that automation, even with occupant interaction, can still lead to lower energy consumption.

Two laboratory studies and one simulation-based evaluation assessed model-based and adaptive control algorithms, primarily for reducing lighting energy consumption. A model-based system reduced lighting energy consumption by approximately 30 % compared to a strategy using desk-level indoor illuminance [66]. In a real office building, a predictive control strategy with occupant overrides achieved a 25 % reduction compared to a control based on desk illuminance and automated lighting switch-off [57]. Simulations reported an 81 % reduction when comparing predictive control to static shading. Although evidence is limited, these findings demonstrate the potential benefits of advanced control strategies such as model-based and predictive algorithms.

Fig. 14 illustrates the impact of automated façades on energy consumption by comparing studies that evaluated automation against manually controlled shading in laboratory, real office building, and simulation settings. Five studies provided relevant data, all indicating energy savings with automated control. Among laboratory and real office building studies, the greatest reduction was observed in lighting consumption for roller shades (39 % [40]), followed by venetian blinds (11 %

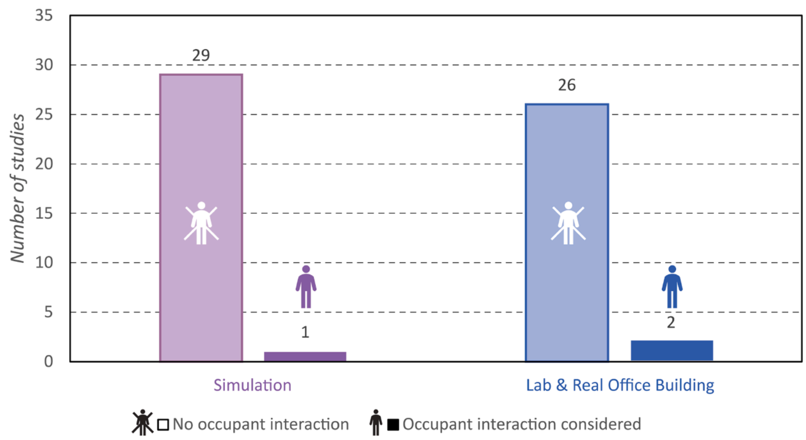


Fig. 12. Distribution of the studies considering occupant interaction when evaluating the energy performance of automated facades. The plot shows the number of papers in two categories: simulation, and laboratory and real office building experiments.

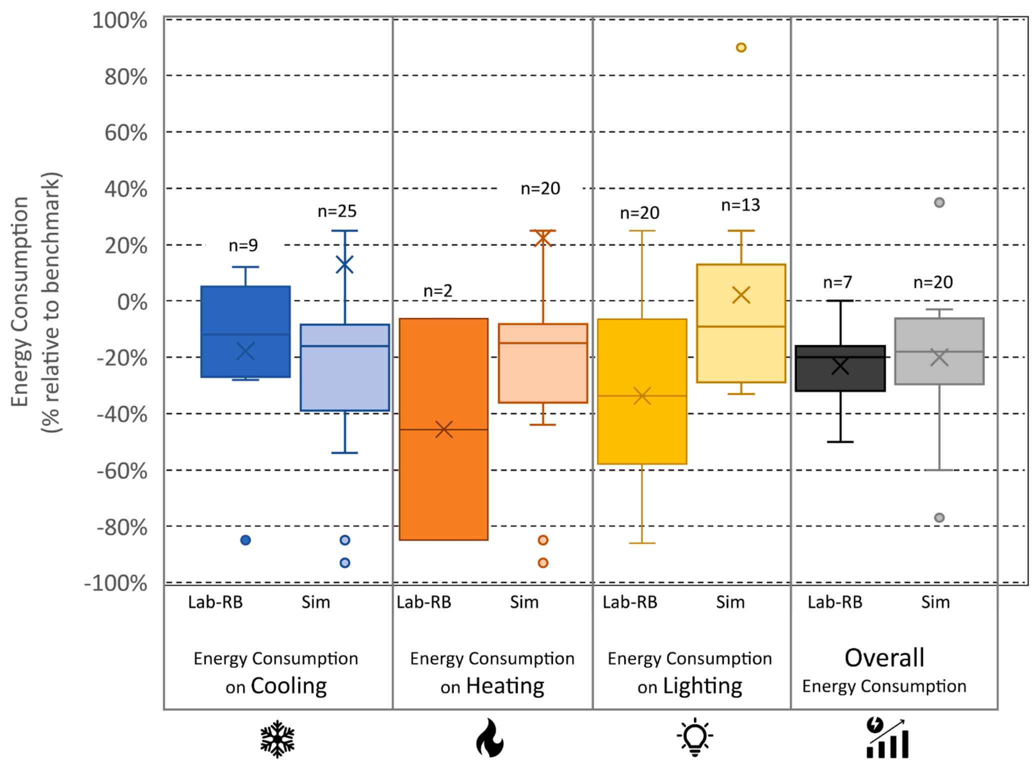


Fig. 13. Box plot illustrating the reported energy demand reduction (%) achieved by automated façades across different study types: Laboratory-Real office Building (Lab-RB) and Simulation (Sim). Each box represents the range of energy performance outcomes, with the horizontal line indicating the median and 'X' marking the mean. The number of studies included in each category (n) is shown above the respective box plot for context.

[67]). However, automated roller shades controlled by an external illuminance sensor increased cooling energy consumption by 10 % [40]. One simulation study [41] demonstrated that automated façades significantly improve energy efficiency, particularly when occupant behavior is suboptimal. Comparing three behavioral models ("careless user," "intermediate user," and "proactive user") the study found that automation reduced cooling energy consumption by up to 95 % in the "careless user" scenario. Even "proactive" users saw notable savings, highlighting the limitations of manual operation. Heating energy savings ranged from 0 % to 30 %, while lighting reductions were between 20 % and 48 %.

The overall energy savings indicate that automation yields greater energy savings in the summer [27] compared to winter [27,68], primarily due to the reduction in solar gains received by the façade during winter. Additionally, some occupant profiles can reduce the energy consumption gap between automated and manual control, influenced by individual control objectives or personal preferences. These findings underscore the significance of advanced control algorithms in optimizing the energy efficiency of automated façades. Moreover, effective strategies-whether model-based or rule-based-can result in substantial energy savings and improved IEQ, while inadequate manual control can undermine these benefits and lead to excessive energy consumption.

4.2. Automated façade influence on IEQ

The impact of automated façade operation on indoor environmental quality (IEQ) in office environments has been investigated through laboratory experiments (n = 15), real office building assessments (n = 7), and simulations (n = 13). Most studies employed rule-based con-

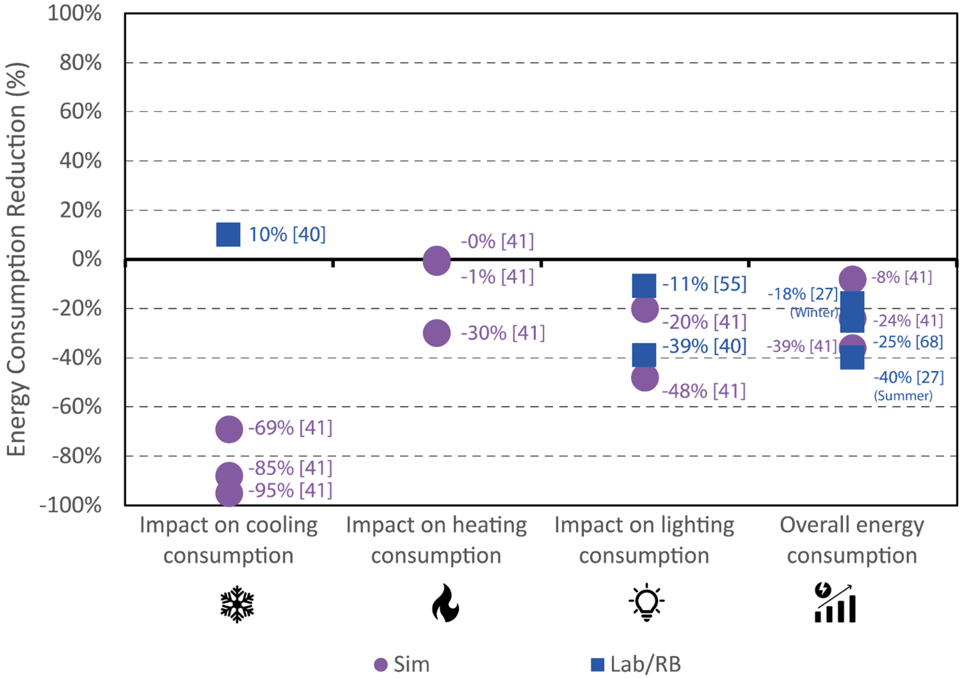


Fig. 14. Reported impact of automated façade operation on energy consumption, compared exclusively to manually controlled façades. Each point represents a study, with results shown as the percentage reduction in energy consumption for cooling, heating, lighting, and overall energy consumption. Circles indicate simulation studies, while squares represent laboratory or real office building (Lab/RB) studies. The figure highlights the general trend of automated façades reducing energy demand, though not all studies reported savings in every category.

trol strategies based on workplane illuminance, Daylight Glare Probability (DGP), indoor air temperature, solar irradiance, and air quality (Fig. 15). Automated façade control regulated the visual environment using workplane illuminance thresholds ranging from 510–700 lx to 500–3000 lx, ensuring glare probability remained below 0.35 (imperceptible rating). Thermal control targeted indoor temperatures between 21$^{\circ}C$ and 25$^{\circ}C$, with shading devices activated when solar irradiance exceeded 250 W/m^2. Air quality control was addressed in a single study, where window operation was triggered when CO_2 levels surpassed 1250 ppm. Only two studies evaluated the performance of predictive control systems [16,27].

Workplane illuminance thresholds, daylight glare probability, indoor air temperature, solar irradiance on the façade, and air quality are key environmental variables used to assess the performance of automated control strategies, as illustrated in Fig. 16. In some cases, operative temperature was evaluated alongside control strategies primarily focused on indoor illuminance, while metrics such as view out and workplane illuminance were used to assess strategies based on solar irradiance. These variations highlight the interdependence of IEQ parameters, demonstrating how control strategies targeting a single environmental variable can influence overall environmental comfort.

The interdependence of IEQ variables is supported by studies on multi-domain IEQ [44,69,70], which assessed automated façade performance in relation to both visual and thermal effects. These studies indicate that controlling one environmental domain influences others, impacting overall occupant comfort. However, no studies have examined how to balance these effects or identify key competing factors. Additionally, only two studies have investigated the impact of automated façades across all IEQ domains [20,71].

Regarding daylight access, a few studies have evaluated whether automated façade operation enhances visual conditions by comparing average workplane illuminance levels. These studies applied different target illuminance thresholds to assess visual performance, considering the duration within specific ranges: 510–700 lx [12], 484–538 lx [72] 484–538 lx [67], 570–670 lx [40], <2000 lx [73], 500–3000 lx [4,74–76], and 600-3000 lx [69,70,77]. Findings indicate that manually controlled scenarios tend to exhibit higher daylight levels and an increased risk of glare (e.g., [4,10]) compared to automated systems, which are typically programmed to minimise cooling loads [20] or mitigate excessive brightness [40,78] and glare [4,40,76,79]. For instance, Clear et al. [10] demonstrated that an automated electrochromic window reduced illuminance from 2990 ± 2165 lx to 830 ± 520 lx compared to manually controlled blinds. Similar results were reported by Vine et al. [12], Kim et al. [9], and Lee et al. [40] in comparisons with manual controls. Thus, automated systems effectively prevent excessive brightness by continuously adjusting the façade, which manual controls do not achieve with manual control. This trend was also present when a fully automated venetian blind was compared to a semi-automated control strategy with an override option, but with smaller differences, as described by Vine et al. [12], from 735 ± 162 lx (semi-automated) to 598 ± 60 lx (fully-automated).

Glare in indoor spaces was assessed using either DGP [4,74,76,79] or window luminance (cd/m^2) [10,73,78,80]. Automated control effectively reduced glare when operating venetian blinds and roller shades, outperforming manual systems [4,73]. However, electrochromic windows showed no substantial improvement over semi-automated operation [10,73], as their darkest tint state does not provide adequate protection when the sun is within the field of view. These findings indicate that the effectiveness of automated control depends on the façade typology and its ability to regulate specific environmental variables. Additionally, automated façades were compared to a fully closed roller shade, however, using either a fully raised or fully closed blind does not constitute a suitable reference scenario.

Regarding thermal quality, two studies found automated controls to be more effective in preventing overheating [71,81], while others reported no significant differences [20,69]. When compared to a static shade, an automated roller shade programmed to regulate indoor air temperature reduced overheating from 15 % to 8 % of the total time

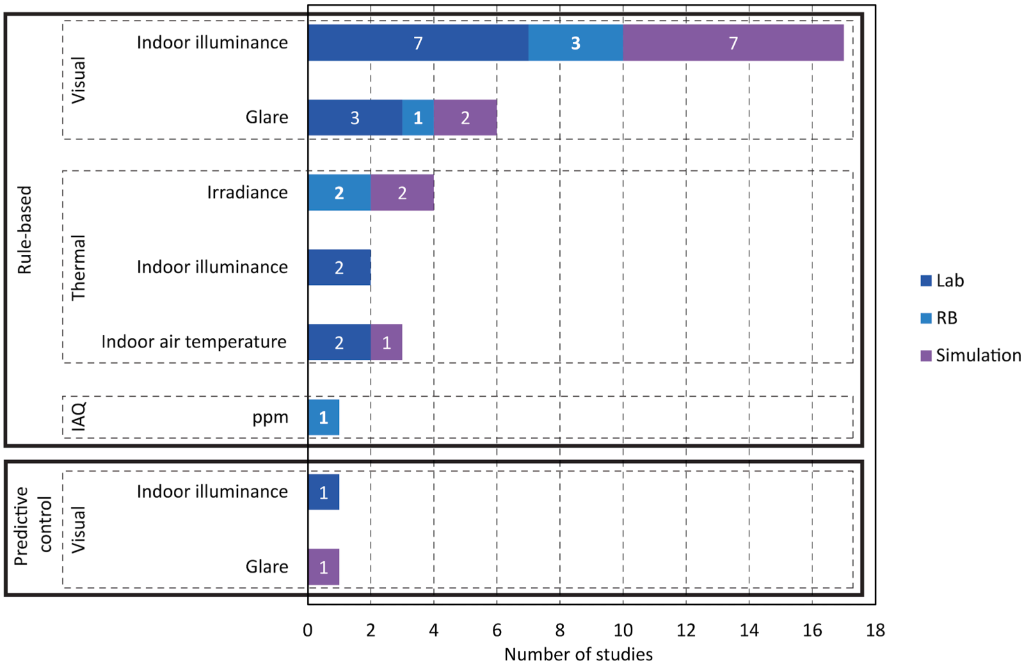


Fig. 15. Distribution of control strategies and evaluated environmental domains in the studies reviewed. The bar chart distinguishes between two control strategies: rule-based and predictive control. For rule-based control, studies are further grouped by environmental domain (visual, thermal, and IAQ), with the specific variables assessed indicated within each domain. For predictive control, only the visual domain is represented. Bar segments are color-coded by study type (laboratory, real building, and simulation), and the numbers within the bars indicate the count of studies addressing each variable.

[81]. However, air temperature alone is insufficient; operative temperature must also be considered [69,70], along with the impact of solar radiation on occupants' thermal comfort, as solar irradiance plays a key role in assessing façade influence on thermal comfort. Additionally, one study found no substantial difference in thermal comfort between manually controlled and semi-automated scenarios. Automated controls that disrupt occupants are frequently overridden and often fail to effectively regulate solar gains [23]. The only study that compared automated strategies to window openings or vents versus manual controls reported better air quality when the control was automatic [8]. The automated windows' opening overpasses the concentration of carbon dioxide ($CO^2 > 1500$ppm) for about 9 % of the time, compared to a manual window opening that showed 31 %. This means the automated control system better controlled the air quality inside the room tested.

There were no studies comparing different shading devices with the same control strategy, which is a valuable information for designing effective automated façade strategies. Only three studies allowed occupants to override the automated system, which was programmed to maintain illuminance under certain thresholds. Therefore, the semi-automated scenario measured higher indoor illuminance levels than expected [12]. Thus, there was a tendency in manually controlled strategies to provide brighter [4,9,12] or more glary indoor conditions [4], while only one study showed lower light levels [40] and poorer indoor air quality [8]. Regarding orientation and climate, east and west ori-

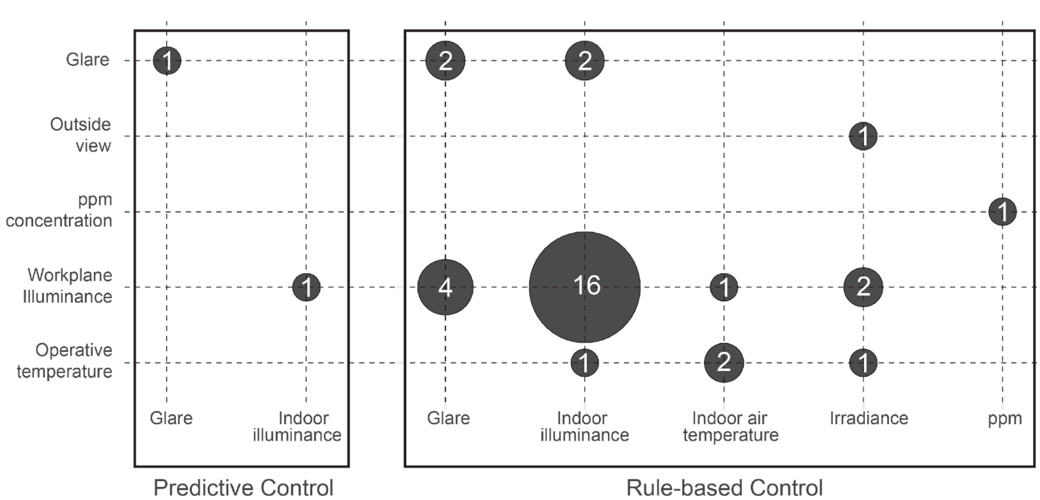


Fig. 16. Distribution of studies based on the environmental variables used to evaluate the performance of automated façades, visualized as a bubble plot. The y-axis lists the evaluation variables, such as glare, outside view, ppm concentration, workplane illuminance, and operative temperature. The x-axis categorizes the studies by control strategy, distinguishing between predictive control and rule-based control. The size of each bubble indicates the number of studies considering a given variable within each control strategy. Numeric labels within bubbles denote the study count.

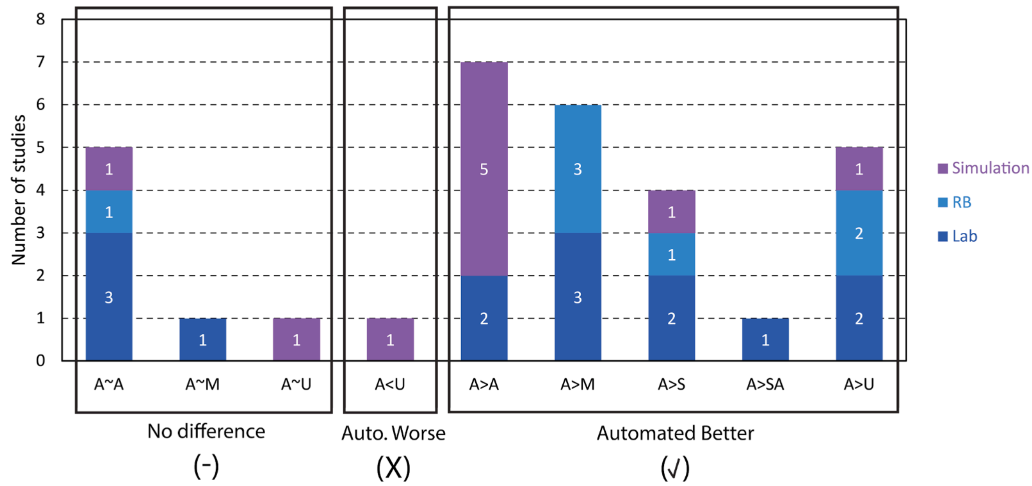


Fig. 17. Comparison of the environmental performance of automated façades relative to other control strategies, visualized as a stacked bar chart. The x-axis groups studies by performance outcome: "No difference," "Automated Worse," and "Automated Better." Subcategories indicate the control strategy used for comparison with automated facades, such as unshaded windows (A-U), static facade (A-S), manual shading (A-M), semi-automated (A-SA), and other automated controls (A-A). Bars are stacked and color-coded to represent study types: laboratory (Lab), real office building (RB), and simulation (Simulation). The height and composition of each bar indicate the number and type of studies reporting each performance outcome.

entations showed that the automated system was inadequate to balance competing indoor comfort domains (glare/view access, overheating and daylight) [9].

Fig. 17 summarizes the performance of automated façade systems relative to other control strategies across three categories: "No Difference," "Automated Worse," and "Automated Better." The y-axis represents the number of studies, while the x-axis distinguishes the comparisons: automated versus another automated system (A-A), manual control (A-M), unshaded conditions (A-U), and static shading (A-S). Most studies (n = 22) indicate that automation enhances environmental conditions compared to semi-automatic, manual, static, and unshaded windows. Cases showing no difference include comparisons between different automated control logics [15,27,73,82,83], studies where automation prioritized illuminance but was evaluated based on indoor temperature [69,70], and those focusing on solar heat gain control while assessing daylight availability [43,84]. One study found unshaded windows to outperform automated façades due to the evaluation criterion being the percentage of time with an unobstructed outdoor view [29].

4.3. Occupant response to automated façade operation

The impact of automated façades on occupants in office environments has been investigated across multiple environmental domains, including visual, thermal, acoustic, and air quality. Research methods, such as questionnaires, surveys, and interviews, have been employed to assess occupant satisfaction (n = 26), perception (n = 15), discomfort (n = 2), and interaction frequency (n = 7) with control systems. Studies have been conducted in both laboratory settings and real office buildings, often integrating monitoring systems to track occupant interactions and override actions.

The dynamic façade components analyzed were venetian blinds (n = 9), electrochromic glazing (n = 4), roller shades (n = 4), and window openings (n = 1). Occupant responses were compared across different operation modes: unshaded windows (n = 2), manually operated shading (n = 8), semi-automated shading with override options (n = 3), and manual window opening (n = 1). Additionally, six studies examined advanced control strategies, including adaptive [27], predictive [85], learning-based [86], and multi-variable algorithms [87], compared to conventional controls based on temperature, irradiance, and indoor illuminance measurements.

Table 2 presents evidence on the impact of dynamic facades in the visual domain, focusing on occupant satisfaction (n = 11), perception (n = 4), discomfort (n = 2), and dissatisfaction (n = 1). The studies assess indoor lighting, glare, brightness, and access to outdoor views. Findings regarding automated versus manual control are mixed. Three out of six studies comparing automated to manual facades reported improved satisfaction with automated daylight control [9,26,88]. In contrast, other studies found greater satisfaction with manually operated venetian blinds and roller shades [12,69,89]. While occupants appreciated automated daylight control, they preferred manual operation for selecting control modes and accessing outdoor views. However, one study [88] reported occupant satisfaction with automated control for view access.

Three studies compared fully automated to semi-automated controls. Semi-automated systems demonstrated improved satisfaction with lighting conditions compared to fully automated scenarios [12] and were more effective in reducing glare perception [6,12]. One study [90], which did not compare automation with other control modes, reported low brightness and glare perception under automated control.

When comparing rule-based controls to advanced automated systems capable of predicting occupant behavior and adapting to their preferences, the latter showed slightly better results for glare perception and access to outdoor views [91]. However, two studies reported higher dissatisfaction with daylight under advanced control operation, potentially indicating the impact of the control objectives over occupant satisfaction [66,91].

Thus, evidence on occupant response with the visual domain suggests that while automated facade can enhance occupant satisfaction, occupants prefer manual operation for selecting control modes and accessing outdoor views. Semi-automated systems offer a middle ground, improving satisfaction and reducing glare perception compared to fully automated controls. However, advanced automation, despite slight benefits in glare management and view access, can lead to increased dissatisfaction with daylight, indicating the need for carefully calibrated control objectives. The mixed results indicate the diversity of occupant preferences, underscoring the importance of adaptable control strategies that balance automation with personal control.

Occupant responses to the thermal environment were evaluated across four studies, focusing on thermal sensation (n = 1), satisfaction (n = 3), dissatisfaction (n = 1), and discomfort levels (n = 1). As summarised in Table 3, findings on the impact of automated con-

Table 2

Evidence on the visual domain. The table presents the type of occupant response reported, the control logic tested, the metrics used in each study, and the corresponding results. ([LA]: Level of Automation; [Res]: Result); [A]: Automated; [M]: Manual; [SA]: Semi-automated; [S]: Static; [PR]: Pre-program; [AD]: Advanced).

R.	Occupant response	Control logic	Metric	[LA] = Res
[9]	Satisfaction with lighting.	(1) Automated, (2) manual	Occupants satisfied (%)	[A] = 88 % [M] = 0 %
[10]	Perception of glare.	(1) Automated based on indoor illuminance (2), Semi-automatic, (3) fixed 60 % glazing.	1 = very dissatisfied 5 = very satisfied	[A] = 3.7 [SA] = 3.8 [S] = 3.2
[10]	Perception of lighting.	(1) Automated based on indoor illuminance, (2) Semi-automatic (3) fixed 60 % glazing.	1 = very dissatisfied 5 = very satisfied	[A] = 3.3 [SA] = 3.1 [S] = 3.5
[12]	Satisfaction with lighting.	(1) Automatic based on illuminance, (2) Semi-automated, (3) Manual mode.	Occupants satisfied (%)	[A] = 57 % [SA] = 71 % [M] = 64 %
[12]	Perception of glare.	(1) Automatic based on illuminance, (2) Semi-automated, (3) Manual mode.	Occupants perceiving glare (%)	[A] = 0 % [SA] = 0 % [M] = 14 %
[90]	Perception of brightness.	(1) Automated based on direct sunlight.	1 = never 5 = always	[A] = 1.9
[90]	Perception of glare.	(1) Automated based on direct sunlight.	1 = never 5 = always	[A] = 1.9
[90]	Perception of brightness.	(1) Automated based on direct sunlight.	1 = never 5 = always	[A] = 1.10
[90]	Perception of glare.	(1) Automated based on direct sunlight.	1 = never 5 = always	[A] = 2.1
[90]	Perception of brightness.	(1) Automated based on direct sunlight.	1 = never 5 = always	[A] = 1.8
[25]	Satisfaction with lighting conditions.	(1) Pre-programmed action, (2) illuminance-based automation.	100 = Too high -100 = Too low	[A] = -15.1 [PR] = 1.3
[25]	Satisfaction with glare.	(1) Pre-programmed action, (2) illuminance-based automation.	100 = Very much -100 = Not at all	[A] = 14.2 [PR] = 26
[25]	Satisfaction with view access.	(1) Pre-programmed action, (2) illuminance-based automation.	100 = very dissatisfied -100 = very satisfied	[A] = -1 [PR] = 21
[26]	Satisfaction with lighting.	(1) Automated based on exterior illuminance, (2) manual.	Occupants satisfied (%)	[A] = 56.8 % [M] = 37.3 %
[20]	Discomfort with lack of daylight.	(1) Automated based on exterior irradiance, (2) manual.	Discomfort events (n)	[SA] = 16 [M] = 7
[20]	Dissatisfaction with lack of view access.	(1) Automated based on exterior irradiance, (2) manual.	Interactions (n)	[SA] = 18 [M] = 7
[20]	Dissatisfaction with glare conditions.	(1) Automated based on exterior irradiance, (2) manual.	Interactions (n)	[SA] = 10 [M] = 4
[20]	Satisfaction with lighting.	(1) Automated based on exterior irradiance, (2) manual.	1 = dissatisfied 5 = satisfied	[SA] = 4.5 [M] = 4.2
[20]	Satisfaction with glare conditions.	(1) Automated based on exterior irradiance, (2) manual.	1 = dissatisfied 5 = satisfied	[SA] = 3.1 [M] = 4
[20]	Satisfaction with view access.	(1) Automated based on exterior irradiance, (2) manual.	1 = dissatisfied 5 = satisfied	[SA] = 3 [M] = 3.7
[66]	Satisfaction with lighting.	(1) Automated based on DGP and work plane illuminance, (2) control based on desk illuminance.	0 = very dissatisfied 10 = very satisfied	[AD] = 7.5 [A] = 7
[66]	Perception of glare.	(1) Automated based on DGP and work plane illuminance, (2) control based on desk illuminance.	0 = no perceived 10 = perceived	[AD] = 1.8 [A] = 2.2
[69]	Satisfaction with lighting.	(1) Automated based on indoor illuminance (2) manual.	% time of IR = 0.	[A] = 67 % [M] = 81 %
[71]	Discomfort with the visual env.	(1) Automated based on the sun of the field of view, (2) manual.	Discomfort events (n)	[SA] = 14 [M] = 1
[71]	Satisfaction with glare protection.	(1) Automated based on the sun of the field of view, (2) manual.	1 = agree 5 = disagree	[SA] = 4.5 [M] = 4
[71]	Satisfaction with daylight.	(1) Automated based on the sun of the field of view, (2) manual.	1 = agree 5 = disagree	[SA] = 3.7 [M] = 3.7
[71]	Satisfaction with view access.	(1) Automated based on the sun of the field of view, (2) manual.	1 = agree 5 = disagree	[SA] = 4.8 [M] = 4.3
[91]	Satisfaction with view access.	(1) Automation based on indoor illuminance, irradiance, and temperature (2) automated based on irradiance.	Satisfied subjects (n)	[AD] = 20 [A] = 5
[91]	Satisfaction with lighting.	(1) Automation based on indoor illuminance, irradiance, and temperature (2) automated based on irradiance.	Satisfactory answers (n)	[AD] = 22 [A] = 17
[91]	Satisfaction with lighting.	(1) Automated based on indoor illuminance, irradiance, and temperature (2) automated based on irradiance.	Satisfactory answers (n)	[AD] = 7 [A] = 13
[89]	Satisfaction with lighting.	(1) Manual, (2) automated (3) Semi-automated.	1 = dissatisfied 7 = satisfied	[A] = 4.5 [SA] = 5 [M] = 5.4
[89]	Satisfaction with view access.	(1) Manual, (2) Automated, (3) Semi-automated.	1 = dissatisfied 7 = satisfied	[A] = 5.3 [SA] = 5.9 [M] = 6.3
[88]	Satisfaction with view access.	(1) automated control, (2) fixed glazing.	1 = very poor 5 = excellent	[A] = 4.4 [M] = 3.7
[88]	Satisfaction with lighting.	(1) automated control, (2) fixed glazing.	1 = very poor 5 = excellent	[A] = 4.6 [M] = 4.3
[90]	Perception of glare.	(1) Automated based on direct sunlight.	1 = never 5 = always	[A] = 1.8

Table 3
Evidence on the thermal domain. The table presents the type of occupant response reported, the control logic tested, the metrics used in each study, and the corresponding results. ([LA]: Level of Automation; [Res]: Result); [A]: Automated; [M]: Manual; [SA]: Semi-automated; [AD]: Advanced).

R.	Occupant response	Control logic	Metric	[LA] = Res
[8]	Sensation of thermal env.	(1) Automated, (2) manual	TSV neutral votes (%).	[A] = 77 % [M] = 66 %
[20]	Dissatisfaction with thermal env.	(1) Automated based on exterior irradiance, (2) manual.	Interactions (n)	[SA] = 5 [M] = 1
[20]	Satisfaction with thermal env.	(1) Automated based on exterior irradiance, (2) manual.	1 = dissatisfied 5 = satisfied	[SA] = 3 [M] = 4
[66]	Satisfaction with thermal env.	(1) Automated based on DGP and work plane illuminance, (2) control based on desk illuminance.	1 = cold 10 = hot	[AD] = 5.2 [A] = 5
[71]	Discomfort with thermal env.	(1) Automated based on the sun of the field of view, (2) manual.	Discomfort events (n)	[SA] = 12 [M] = 7
[71]	Satisfaction with thermal env.	(1) Automated based on the sun of the field of view, (2) manual.	1 = agree 5 = disagree	[SA] = 3.2 [M] = 1

trol strategies on thermal responses are mixed. One study reported improved thermal sensation with automation compared to manual control [8], while another found no significant differences between adaptive and rule-based controls [66]. Studies on semi-automated controls consistently indicated higher satisfaction and fewer discomfort events compared to manual controls [20,71]. While semi-automated controls reliably enhance satisfaction and reduce discomfort, the effects of fully automated systems remain inconclusive, with some studies reporting benefits and others showing no significant differences. These discrepancies may be attributed to variations in façade types, control strategies (e.g., CO_2 concentration, solar irradiance, indoor illuminance), study settings (laboratory vs. real office buildings), and the limited number of studies examining occupant responses to automated façades in the thermal domain

Three studies have focused on acoustic satisfaction, perception and discomfort, as shown in Table 4. While Vine et al. [12] found no significant differences, Luna-Navarro et al. [20,71] reported increased acoustic discomfort due to actuator noise and background sound levels. Higher perceived noise levels were associated with semi-automated modes, possibly due to frequent system actuation resulting from occupant overrides [12].

Two studies [20,71] found no significant differences in perceived indoor air quality between semi-automated and manually controlled shading (Table 5). The limited impact on air quality may be due to automated shading primarily regulating solar radiation, daylight, and glare, rather than air quality. The only study examining automated openable vents did not assess air quality perception [8].

Table 4
Evidence on the acoustic domain. The table presents the type of occupant response reported, the control logic tested, the metrics used in each study, and the corresponding results. ([LA]: Level of Automation; [Res]: Result); [A]: Automated; [M]: Manual; [SA]: Semi-automated).

R.	Occupant response	Control logic	Metric	[LA] = Res
[12]	Perception of noise.	(1) Automatic based on illuminance, (2) Semi-automated, (3) Manual mode.	Occupants perceiving noise (%)	[A] = 14 % [SA] = 21 % [M] = 14 %
[20]	Satisfaction with acoustic env.	(1) Automated based on exterior irradiance, (2) manual.	1 = dissatisfied 5 = satisfied	[SA] = 4.5 [M] = 2
[71]	Discomfort with acoustic env.	(1) Automated based on the sun of the field of view, (2) manual.	Discomfort events (n)	[SA] = 3 [M] = 1

Table 5
Evidence on the indoor air quality domain. The table presents the type of occupant response reported, the control logic tested, the metrics used in each study, and the corresponding results. ([LA]: Level of Automation; [Res]: Result); [M]: Manual; [SA]: Semi-automated).

R.	Occupant response	Control logic	Metric	[LA] = Res
[20]	Satisfaction with air quality.	(1) Automated based on exterior irradiance, (2) manual.	1 = dissatisfied 5 = satisfied	[SA] = 4 [M] = 4.5
[71]	Discomfort with air quality.	(1) Automated based on exterior irradiance, (2) manual.	Discomfort events (n)	[SA] = 0 [M] = 1

Studies on occupant behavior, summarized in Table 6, examined interactions with automated façades in relation to specific occupant requirements, including increasing daylight availability (n = 1), reducing glare (n = 2), improving the view (n = 1), and regulating the thermal environment (n = 1). One study [92] did not provide a baseline for comparing occupant responses to the automated façade. Overall, findings indicate that occupants interact more frequently under manual control than in semi-automated scenarios [27,70,71,93]. This increased interaction under manual control is attributed to occupants' need to adjust their environment according to individual preferences. This aligns with the design of the automated systems studied, which were programmed to regulate daylight and minimize direct sunlight in the field of view, thereby reducing the need for occupant intervention. Additionally, studies suggest that interactions in semi-automated scenarios may

Table 6
Evidence on occupant behavior to automated facade. The table presents the type of occupant response reported, the control logic tested, the metrics used in each study, and the corresponding results. ([LA]: Level of Automation; [Res]: Result); [M]: Manual; [SA]: Semi-automated; [AD]: Advanced).

R.	Occupant response	Control logic	Metric	[LA] = Res
[27]	Interaction with control system.	(1) Adaptive control based on interactions, (2) temperature-based automation.	The number of interactions on average per day.	[AD] = 3.1 [SA] = 3.2
[92]	Interaction with control system.	(1) Automation based on exterior illuminance.	The number of interactions on average increasing daylight.	[SA] = 11
[92]	Interaction with control system.	(1) Automation based on exterior illuminance.	The number of interactions to reduce glare on average.	[SA] = 2
[70]	Interaction with control system.	(1) Automated based on indoor illuminance (2) manual.	Desired actions not executed (n)	[SA] = 0.5 [M] = 0.6
[70]	Interaction with control system.	(1) Automated based on indoor illuminance (2) manual.	Interactions (n) average	[SA] = 1.7 [M] = 2.8
[71]	Interaction with control system.	(1) Automated based on the sun of the field of view, (2) manual.	Interaction due to glare discomfort (n)	[SA] = 7 [M] = 18
[71]	Interaction with control system.	(1) Automated based on the sun of the field of view, (2) manual.	Interactions due to lack of view or daylight (n)	[SA] = 9 [M] = 11
[71]	Interaction with control system.	(1) Automated based on the sun of the field of view, (2) manual.	Interactions due to thermal discomfort (n)	[SA] = 1 [M] = 0
[93]	Interaction with control system.	(1) automated based on indoor temperature, (2) manual.	Interactions over the year (n)	[SA] = 9 [M] = 661

Table 7
Evidence on occupant perception of automated facade. The table presents the type of occupant response reported, the control logic tested, the metrics used in each study, and the corresponding results. ([LA]: Level of Automation; [Res]: Result); [M]: Manual; [SA]: Semi-automated; [AD]: Advanced).

R.	Occupant response	Control logic	Metric	[LA] = Res
[71]	Discomfort with control system.	(1) Automated based on the sun of the field of view, (2) manual.	Discomfort events (n)	[SA] = 4 [M] = 0
[71]	Discomfort with control system.	(1) Automated based on the sun of the field of view, (2) manual.	1 = agree 5 = disagree	[SA] = 2.6 [M] = 1.3
[12]	Satisfaction with control system.	(1) Automatic based on illuminance, (2) Semi-automated, (3) Manual.	Occupants satisfied (%)	[A] = 7 % [SA] = 29 % [M] = 57 %
[20]	Satisfaction with control system.	(1) Automated based on exterior irradiance, (2) manual.	1 = dissatisfied 5 = satisfied	[A] = 3 [M] = 4
[10]	Satisfaction with control system.	(1) Automated based on indoor illuminance, (2) Semi-automatic (3) fixed 60 % glazing.	1 = very dissatisfied 5 = very satisfied	[A] = 4.1 [SA] = 3.8 [S] = 3.5

result from automated actions triggering occupant responses, potentially disrupting concentration and productivity [20,92]. Luna-Navarro et al. [20] noted that gradual, silent automated controls are less likely to be overridden.

Control strategies significantly influence occupant satisfaction, as shown in Table 7. Manual control is generally preferred over fully automated systems [12,20,71]. However, findings on automated control are inconsistent. While some studies report lower satisfaction with automation [12,20], others indicate higher satisfaction [10]. Clear et al. [10] investigated an indoor illuminance-based automated control system using electrochromic windows, which adjust opacity gradually. Because these changes occur slowly, occupants may not immediately perceive them, resulting in minimal disruption. This characteristic may account for the differing findings on occupant satisfaction with automation.

Finally, shown in Fig. 18, no strong consensus emerges in favor of either manual or automated operation regarding overall occupant satisfaction. Instead, preferences vary across environmental domains, indicating the need to balance automation with manual control. In the visual domain, automated shading effectively reduces glare and excessive daylight, but manual control is preferred when maintaining an outdoor view is a priority. Semi-automated systems with override options provide a better balance, improving satisfaction. For thermal comfort, occupants favor manual or semi-automated control for temperature regulation via shading and ventilation, as predictive automation can optimize conditions but may cause dissatisfaction when actions are unexpected. In terms of acoustic comfort, automated windows can help control noise in urban settings, though manual control remains preferred for greater discretion. For indoor air quality, no clear preference exists due to limited research, though air quality sensors can trigger ventilation adjustments.

Satisfaction with control depends on perceived control, predictability, and alignment with occupant expectations. Systems that allow occupant overrides tend to be better received, whereas fully automated ones risk rejection due to loss of agency. Manual control results in higher interaction frequency, while automation reduces interaction, particularly when well aligned with expectations. However, unexpected system-driven changes, such as sudden shading adjustments, may lead to overrides, especially in work environments.

Thus, evidence indicates the importance of occupant-centered control to enhance the acceptance of automated facades. Although the role of automation in facade operation is not clearly defined yet, automated controls should support rather than replace occupant control, ensuring effectiveness when manually controlling the facade of the building.

5. Discussion

5.1. Energy performance of automated facades

Current evidence shows that automated controls can increase energy savings [13,27,37,41], in particular, in the lighting domain [4,21,57]. The highest energy savings were achieved when comparing fully automated shadings to unshaded windows [10,53,74,79,94,95] or static shading systems [13,78,79,81,96]. However, buildings rarely have unshaded windows, while the alternative to automated blinds or dynamic glazing is usually a manually controlled façade.
Nevertheless, in the few studies that compare fully automated facades to manually controlled ones, this trend is also confirmed in the lighting domain (from 10 % to 75 % [4,9,21,27,40,97]), and for both seasons (-18 % in summer and -40 % in winter [27]). Simulation-based studies tend to report higher energy savings than empirical studies, since discrepancies between predicted and actual performance are common in real office buildings [58].
While early design assessment of dynamic and automated façades required a dynamic simulation workflow to guide their technological developments [98], the discrepancy between predicted and monitored performance is now the bottleneck for automated facades up-scaled [99–101]. This requires empirical studies to: (i) increase practitioners, contractors and building owners' experience with automated facades, and (ii) provide confidence that these systems can provide a robust and reliable benefit in comparison with manually controlled facades for a

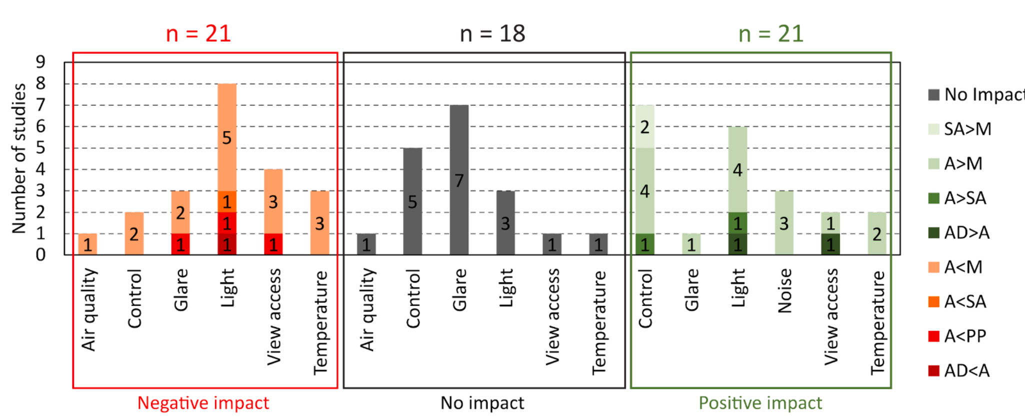


Fig. 18. Distribution of evidence provided by studies showing the cases in which the automated façade has a "negative impact" (n = 21), "no impact" (n = 18), and "positive impact" (n = 21). In each category, the evidence is divided by environmental domain. SA = Semi-automated control, M = Manual control, A = Automated, AD = Advance control, PR = Pre-programmed control.

wide number of buildings and occupants, thereby enabling sufficient generalization of research results. In this sense, the limited number of studies involving human participants (only 25 out of 91) is a barrier to up-scaling of these facade technologies. Moving forward, future research should focus on evaluating the performance of these technologies in real office building settings, particularly for façade technologies that are already well-developed and have a high level of technology readiness.

5.2. Balancing IEQ with automated façades

This review confirms that automated façades can effectively regulate indoor environmental quality (IEQ) parameters, particularly visual and thermal comfort. Automated shading systems have been shown to enhance daylight access [10,12,40] and mitigate glare [76,79] by controlling indoor brightness levels [13,40,41]. They can also reduce solar heat gains, thereby supporting thermal comfort [71,81].

A key challenge for automated control systems lies in managing trade-offs between competing IEQ parameters. For example, glare reduction strategies may limit daylight access, while optimizing thermal comfort can obstruct views to the outside [4,9,69,70]. Some studies have demonstrated that algorithms preventing glare effectively protect the occupants from excessive brightness [4,73]; however, this often comes at the cost of reduced indoor illuminance, which can lead to occupant dissatisfaction [12,20,89]. Similarly, while automated shading can reduce solar heat gain and enhance thermal comfort, its effectiveness may be compromised by obstructed views [8,66,71]. This limitation is particularly evident in systems that rely on single-parameter control strategies. In response, studies have proposed integrated control approaches that simultaneously account for glare, daylight, and temperature, in an effort to balance competing IEQ requirements [44,69,70]. Nonetheless, more research is needed to determine which IEQ parameters should be prioritized, particularly in dynamic and potentially personalized control scenarios.

5.3. Comparability of studies on occupant response to automated façades

The evaluation of automated façades in studies often relies on a variety of metrics, each targeting different aspects of indoor environmental performance. These include DGP [4,10], used to assess visual discomfort from glare, horizontal illuminance [12], which relates to task lighting levels, and the percentage of hours within comfort thresholds [71], which reflects overall performance over time. However, because these metrics are grounded in different physical principles and operational goals, direct comparisons between studies can be challenging unless the metrics address similar comfort dimensions.

In this context, the ISO 52016-3 [102] represents a step forward by offering standardized methods to assess the energy and indoor environmental performance of adaptive façades, covering heating, cooling, lighting demand, thermal comfort, visual comfort, and air quality. However, while this standard provides robust objective criteria, it does not fully capture the variability and subjectivity of occupant preferences, which may differ based on individual needs, cultural norms, or contextual factors. Several studies emphasize that acceptance of automation by occupants depends not only on environmental outcomes, but also on how the systems behave, how intuitive they are, and whether they respond appropriately to occupants' expectations [25,103]. To integrate the impact of dynamic façade operation with occupant preferences, performance assessments should go beyond physical metrics to include subjective and behavioral dimensions, such as perceived control, satisfaction, or acceptance of automation. This can be achieved through methods, such as post-occupancy evaluations, stated preference surveys, and behavioral monitoring that track occupants' interactions with the system. For example, adaptive algorithms could be designed to learn from occupants' overrides or feedback to adjust control strategies. This challenge aligns with recent work from IEA EBC Annex 79 by O'Brien et al. [104], which stresses the importance of integrating subjective and behavioral data with traditional metrics.

Furthermore, research should investigate potential disruptions caused by automation, such as noise from actuation mechanisms, limited accessibility to personal control, and delayed system response times, to strengthen the still-developing body of evidence on these issues [26,71]. This is essential to ensure that energy savings are not achieved at the expense of occupant comfort. For example, in the study by Luna-Navarro et al. [71], the noise generated by automated systems was identified as a potential source of dissatisfaction, detracting from the overall experience of occupants and diminishing their acceptance of the technology. Similarly, Meerbeek et al. [26] examined how occupants interact with automated shading systems, revealing that many preferred disabling automatic modes in favor of manual control. This suggests that automated systems may not always align with occupant preferences and comfort needs. These findings highlight the need to develop evaluation methodologies that recognize occupant comfort preferences and responses to automation, as understanding these factors is crucial for enhancing both comfort and acceptance of automated systems.

5.4. Occupant data collection to define personalization factors

Advanced control strategies, including adaptive approaches [27] and learning algorithms [57], have demonstrated the potential to improve occupant satisfaction and reduce override actions. By actively aligning automation with occupant preferences and control requirements, these systems enhance the occupant experience and address common concerns associated with automated controls. However, implementing these strategies presents barriers, particularly in defining and collecting occupant data and translating them into effective automation actions, such as determining system operation times or identifying conditions where manual control is more appropriate. For instance, five studies [10,27,70,92,93] suggest that frequent manual overrides may indicate dissatisfaction or the need for more refined automation strategies. Although overrides may also indicate a desire for personal control, a response to disruptions caused by automated actions, or a lack of understanding of the building control systems. The factors explaining these occupants' responses with automated systems [105–107], such as usability (e.g., ease of use, clarity of control interfaces), system responsiveness (e.g., speed of reaction, accuracy), personal control preferences (e.g., the need for manual overrides), trust in automation (e.g., reliability, transparency), and comfort-related factors (e.g., noise or environmental disruptions), are well-established in other fields. Nevertheless, the challenge remains in effectively transferring these data into control systems that can detect and respond to individual preferences in real-time, ensuring that automation remains aligned with occupants' needs and expectations.

6. Conclusion

A systematic review was conducted to examine current evidence from previous work on automated facades' influence on energy savings in cooling, heating and lighting, IEQ and occupant satisfaction. A total of 91 studies were analyzed, with 30 involving human participants. These studies showed that automation systems outperformed manual controls in energy savings. Automated facades also contribute to mitigating indoor environmental issues such as glare, controlling daylight, and preventing overheating. Although automated façades can effectively enhance indoor environmental conditions, no strong consensus was found on their overall impact on occupant satisfaction.

Despite the potential of automated facades to increase energy savings and improve IEQ without affecting overall occupant satisfaction with the control system, the review identified limitations in existing research that could hinder a broader adoption of such systems. The challenges include: First, methodological limitations, such as (i) the low number of empirical studies involving human participants, which are crucial for validating performance outcomes focused on occupant preferences and response, and (ii) the lack of standardization in metrics and experimental designs, including inconsistent illuminance and temperature thresholds, different benchmark scenarios (e.g., unshaded, static, or manual façades), and various control approaches, which limit the comparability and generalization of results. Second, performance trade-offs, including (iii) challenges in balancing competing IEQ parameters, such as glare reduction versus daylight access or thermal comfort versus outside views, and (iv) the critical role of control objectives, where prioritizing energy or visual comfort alone may fail to meet occupant needs for autonomy, view, or thermal conditions. Lastly, contextual constraints on performance outcomes, such as (v) the persistent discrepancy between simulation-based predictions and experimental results, where empirical outcomes are more variable, and (vi) the high contextual sensitivity of façade performance across different building orientations, climates, automated control strategies, and occupant profiles.

Future research should prioritize (a) empirical studies in real office buildings to capture occupant behavior, preferences, and override patterns; (b) developing multi-domain evaluation to describe façade control strategies' performance across the wide range of environmental domains; (c) establishing consistent metrics and benchmarks for evaluating automated façade systems to improve comparability between studies; (d) refining adaptive and learning-based systems to detect and respond to individual preferences in real-time, accounting for usability, trust, contextual disruptions, and manual override behavior; and (e) applying multi-criteria analyzis to determine which environmental parameters (e.g., glare, thermal comfort, energy savings) should be prioritized for automation under different building contexts. By addressing these gaps, future research can contribute to the development of automated façade systems that not only optimize energy efficiency and IEQ, but also meet the diverse and evolving needs of building occupants. These developments might help bridge the current disconnect between energy performance objectives and occupant satisfaction, ultimately improving the integration of automated façades into sustainable building operations.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

P. de la Barra: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; **E. Brembilla:** Writing – review & editing, Supervision, Methodology ; **A. Prieto:** Writing – review & editing, Supervision, Methodology; **C. Vásquez:** Writing – review & editing; **U. Knaack:** Writing – review & editing, Supervision; **A. Luna-Navarro:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Pedro de la Barra reports financial support was provided by National Agency for Research and Development. Pedro de la Barra reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study has received funding from the European Union under the Horizon Europe Research & Innovation Programme (Grant Agreement no. 101103956 SMARTeeSTORY). Pedro de la Barra also acknowledges support from the National Agency for Research and Development of Chile (ANID) through the Doctoral Scholarship Programme (Scholarship ID 72200582).

References

[1] S. Bianchi, C. Andriotis, T. Klein, M. Overend, Multi-criteria design methods in façade engineering: State-of-the-art and future trends, Build. Environ. 250 (2024) 111184. https://doi.org/10.1016/J.BUILDENV.2024.111184
[2] M. Barozzi, J. Lienhard, A. Zanelli, C. Monticelli, The sustainability of adaptive envelopes: developments of kinetic architecture, 2016.
[3] D.S. Noaman, S.A. Moneer, N.A. Megahed, S.A. El-Ghafour, Integration of active solar cooling technology into passively designed facade in hot climates, J. Build. Eng. 56 (2022) 104658. https://doi.org/10.1016/J.JOBE.2022.104658
[4] S. Babu, J. Zhou, M.P. Wan, A.S. Lamano, J.N. Sarvaiya, Z. Zhang, D.E.V.S.K. Kumar, C.p. Gao, S. Valliappan, A. Goh, A. Seoh, Investigation of an integrated automated blinds and dimmable lighting system for tropical climate in a rotatable testbed facility, Energy Build. 183 (2019) 356–376. https://doi.org/10.1016/J.ENBUILD.2018.11.007
[5] W.H. Ko, M.G. Kent, S. Schiavon, B. Levitt, G. Betti, A window view quality assessment framework, LEUKOS 18 (3) (2022) 268–293. https://doi.org/10.1080/15502724.2021.1965889
[6] R. Sullivan, E.S. Lee, K. Papamichael, M. Rubin, S.E. Selkowitz, Effect of switching control strategies on the energy performance of electrochromic windows, Optic. Mater. Technol. Energy Efficiency Solar Energy Convers. XIII 2255 (9) (1994) 443–455. https://doi.org/10.1117/12.185387
[7] A. Tzempelikos, A.K. Athienitis, The impact of shading design and control on building cooling and lighting demand, Solar Energy 81 (3) (2007) 369–382. https://doi.org/10.1016/J.SOLENER.2006.06.015
[8] F. Stazi, F. Naspi, G. Ulpiani, C. Di Perna, Indoor air quality and thermal comfort optimization in classrooms developing an automatic system for windows opening and closing, Energy Build. 139 (2017) 732–746. https://doi.org/10.1016/j.enbuild.2017.01.017
[9] J.H. Kim, Y.J. Park, M.S. Yeo, K.W. Kim, An experimental study on the environmental performance of the automated blind in summer, Build. Environ. 44 (7) (2009) 1517–1527. https://doi.org/10.1016/J.BUILDENV.2008.08.006
[10] R.D. Clear, V. Inkarojrit, E.S. Lee, Subject responses to electrochromic windows, Energy Build. 38 (7) (2006) 758–779. https://doi.org/10.1016/J.ENBUILD.2006.03.011
[11] E. Bilgen, Experimental study of thermal performance of automated venetian blind window systems, Solar Energy 52 (1) (1994) 3–7. https://doi.org/10.1016/0038-092X(94)90076-E
[12] E. Vine, E. Lee, R. Clear, D. DiBartolomeo, S. Selkowitz, Office worker response to an automated venetian blind and electric lighting system: a pilot study (1998). https://doi.org/10.2172/658295
[13] E.S. Lee, D.L. DiBartolomeo, S.E. Selkowitz, Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office, Energy Build. 29 (1) (1998) 47–63. https://doi.org/10.1016/S0378-7788(98)00035-8
[14] E. K1z1llörenli, F. Maden, Modular responsive facade proposals based on semi-regular and demi-regular tessellation: daylighting and visual comfort, Front. Archit. Res. 12 (4) (2023) 601–612. https://doi.org/10.1016/J.FOAR.2023.02.005
[15] C.T. Do, Y.C. Chan, Evaluation of the effectiveness of a multi-sectional facade with venetian blinds and roller shades with automated shading control strategies, Solar Energy 212 (2020) 241–257. https://doi.org/10.1016/j.solener.2020.11.003
[16] J. Xie, A.O. Sawyer, Simulation-assisted data-driven method for glare control with automated shading systems in office buildings, Building Environ. 196 (2021) 107801. https://doi.org/10.1016/J.BUILDENV.2021.107801
[17] A. Tabadkani, A. Roetzel, H.X. Li, A. Tsangrassoulis, Simulation-based personalized real-time control of adaptive facades in shared office spaces, Autom. Constr. 138 (2022) 104246. https://doi.org/10.1016/J.AUTCON.2022.104246
[18] R.C.G.M. Loonen, F. Favoino, J.L.M. Hensen, M. Overend, Review of current status, requirements and opportunities for building performance simulation of adaptive facades†, J. Build. Perform. Simul. 10 (2) (2017) 205–223. https://doi.org/10.1080/19401493.2016.1152303
[19] A.C. Boerstra, M.t. Kulve, J. Toftum, M.G.L.C. Loomans, B.W. Olesen, J.L.M. Hensen, Comfort and performance impact of personal control over thermal environment in summer: results from a laboratory study, Build. Environ. 87 (2015) 315–326. https://doi.org/10.1016/J.BUILDENV.2014.12.022
[20] A. Luna-Navarro, G.R. Hunt, M. Overend, Dynamic façades - an exploratory campaign to assess occupant multi-domain environmental satisfaction and façade interaction, Build. Environ. 211 (2022) 108703. https://doi.org/10.1016/j.buildenv.2021.108703
[21] G.R. Newsham, C. Arsenault, A camera as a sensor for lighting and shading control, http://dx.doi.org/10.1177/1477153508099889 41 (2) (2009) 143–160. https://doi.org/10.1177/1477153508099889

[22] M. Konstantoglou, A. Tsangrassoulis, Dynamic operation of daylighting and shading systems: a literature review, Renew. Sustain. Energy Rev. 60 (2016) 268–283. https://doi.org/10.1016/J.RSER.2015.12.246

[23] A. Luna-Navarro, R. Loonen, M. Juaristi, A. Monge-Barrio, S. Attia, M. Overend, Occupant-facade interaction: a review and classification scheme, Build. Environ. 177 (2020) 106880. https://doi.org/10.1016/j.buildenv.2020.106880

[24] A. Shafaghat, A. Keyvanfar, Dynamic façades design typologies, technologies, measurement techniques, and physical performances across thermal, optical, ventilation, and electricity generation outlooks, Renew. Sustain. Energy Rev. 167 (2022) 112647. https://doi.org/10.1016/J.RSER.2022.112647

[25] L.G. Bakker, E.C.M. Hoes-van Oeffelen, R.C.G.M. Loonen, J.L.M. Hensen, User satisfaction and interaction with automated dynamic facades: a pilot study, Build. Environ. 78 (2014) 44–52. https://doi.org/10.1016/j.buildenv.2014.04.007

[26] B. Meerbeek, M. te Kulve, T. Gritti, M. Aarts, E. van Loenen, E. Aarts, Building automation and perceived control: a field study on motorized exterior blinds in Dutch offices, Build. Environ. 79 (2014) 66–77. https://doi.org/10.1016/J.BUILDENV.2014.04.023

[27] A. Guillemin, N. Morel, Experimental results of a self-adaptive integrated control system in buildings: a pilot study ↑ 72 (5) (2002) 397–403. https://www.elsevier.com/locate/solener.

[28] A. Monteleone, G. Rodonò, A. Gagliano, V. Sapienza, SLICE: an innovative photovoltaic solution for adaptive envelope prototyping and testing in a relevant environment, Sustainability 13 (16) (2021) 8701. https://doi.org/10.3390/SU13168701

[29] S. Vanage, H. Dong, K. Cetin, Visual comfort and energy use reduction comparison for different shading and lighting control strategies in a small office building, Solar Energy 265 (2023) 112086. https://doi.org/10.1016/J.SOLENER.2023.112086

[30] N. Aste, J. Compostella, M. Mazzon, Comparative energy and economic performance analysis of an electrochromic window and automated external venetian blind, Energy Proc. 30 (2012) 404–413. https://doi.org/10.1016/J.EGYPRO.2012.11.048

[31] M.V. Nielsen, S. Svendsen, L.B. Jensen, Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight, Solar Energy 85 (5) (2011) 757–768. https://doi.org/10.1016/J.SOLENER.2011.01.010

[32] C. Gehbauer, E.S. Lee, T. Wang, An evaluation of the demand response potential of integrated dynamic window and HVAC systems, Energy Build. 298 (2023) 113481. https://doi.org/10.1016/J.ENBUILD.2023.113481

[33] S. Yeon, B. Yu, B. Seo, Y. Yoon, K.H. Lee, ANN based automatic slat angle control of venetian blind for minimized total load in an office building, Solar Energy 180 (2019) 133–145. https://doi.org/10.1016/J.SOLENER.2019.01.027

[34] A. Frattolillo, G. Loddo, C.C. Mastino, R. Baccoli, Heating and cooling loads with electrochromic glazing in Mediterranean climate, Energy Build. 201 (2019) 174–182. https://doi.org/10.1016/J.ENBUILD.2019.06.042

[35] A. Norouziasas, A. Tabadkani, R. Rahif, M. Amer, D. van Dijk, H. Lamy, S. Attia, Implementation of ISO/DIS 52016-3 for adaptive façades: a case study of an office building, Build. Environ. 235 (2023) 110195. https://doi.org/10.1016/J.BUILDENV.2023.110195

[36] P.F. Tavares, A.R. Gaspar, A.G. Martins, F. Frontini, Evaluation of electrochromic windows impact in the energy performance of buildings in Mediterranean climates, Energy Policy 67 (2014) 68–81. https://doi.org/10.1016/J.ENPOL.2013.07.038

[37] A. Mesloub, A. Ghosh, M. Touahmia, G.A. Albaqawy, B.M. Alsolami, A. Ahriz, Assessment of the overall energy performance of an SPD smart window in a hot desert climate, Energy 252 (2022) 124073. https://doi.org/10.1016/J.ENERGY.2022.124073

[38] J.F. Flor, D. Liu, Y. Sun, P. Beccarelli, J. Chilton, Y. Wu, Optical aspects and energy performance of switchable ethylene-tetrafluoroethylene (ETFE) foil cushions, Appl. Energy 229 (2018) 335–351. https://doi.org/10.1016/J.APENERGY.2018.07.046

[39] E.S. Lee, D.L. Dibartolomeo, E.L. Vine, S.E. Selkowitz, Integrated performance of an automated venetian blindlelectric lighting system in a full-scale private office, 1998.

[40] E. Lee, D. DiBartolomeo, J. Klems, R. Clear, K. Konis, M. Yazdanian, B.C. Park, Field measurements of innovative indoor shading systems in a full-scale office testbed, ASHRAE Trans. 115 (2) (2009).

[41] D.R. Hax, R.K. Leitzke, A.C.S.B. da Silva, E.G. da Cunha, Influence of user behavior on energy consumption in a university building versus automation costs, Energy Build. 256 (2022) 111730. https://doi.org/10.1016/J.ENBUILD.2021.111730

[42] D.K. Bui, T.N. Nguyen, A. Ghazlan, N.T. Ngo, T.D. Ngo, Enhancing building energy efficiency by adaptive façade: a computational optimization approach, Appl. Energy 265 (2020) 114797. https://doi.org/10.1016/j.apenergy.2020.114797

[43] A. Tzempelikos, H. Shen, Comparative control strategies for roller shades with respect to daylighting and energy performance, Build. Environ. 67 (2013) 179–192. https://doi.org/10.1016/J.BUILDENV.2013.05.016

[44] S. Hong, A. Choi, M. Sung, Impact of bi-directional PV blind control method on lighting, heating and cooling energy consumption in mock-up rooms, Energy Build. 176 (2018) 1–16. https://doi.org/10.1016/J.ENBUILD.2018.07.022

[45] E.S. Lee, C. Gehbauer, B.E. Coffey, A. McNeil, M. Stadler, C. Marnay, Integrated control of dynamic facades and distributed energy resources for energy cost minimization in commercial buildings, Solar Energy 122 (2015) 1384–1397. https://doi.org/10.1016/J.SOLENER.2015.11.003

[46] R. Tällberg, B.P. Jelle, R. Loonen, T. Gao, M. Hamdy, Comparison of the energy saving potential of adaptive and controllable smart windows: a state-of-the-art review and simulation studies of thermochromic, photochromic and electrochromic technologies, Solar Energy Mater. Solar Cells 200 (2019) 109828. https://doi.org/10.1016/j.solmat.2019.02.041

[47] E.S. Lee, D.L. DiBartolomeo, S.E. Selkowitz, E.S. Lee, D.L. DiBartolomeo, S.E. Selkowitz, Electrochromic windows for commercial buildings: monitored results from a full-scale testbed, in: 2000 ACEEE Summer Study on Energy Efficiency in Buildings, 2000, pp. 1–16.

[48] E.H. Suzuki, F.C. Lofrano, F.A. Kurokawa, R.T.A. Prado, B.C.C. Leite, Decision-making process for thermal comfort and energy efficiency optimization coupling smart-window and natural ventilation in the warm and hot climates, Energy Build. 266 (2022) 112110. https://doi.org/10.1016/J.ENBUILD.2022.112110

[49] E.S. Lee, D.L. Dibartolomeo, S.E. Selkowitz, Daylighting control performance of a thin-film ceramic electrochromic window: field study results, Energy Build. 38 (1) (2006) 30–44. https://doi.org/10.1016/J.ENBUILD.2005.02.009

[50] E. Lee, D. DiBartolomeo, S. Selkowitz, The effect of venetian blinds on daylight photoelectric control performance, J. Illum. Eng. Soc. 28 (1998) 3–23. https://doi.org/10.1080/00994480.1999.10748247

[51] H. Shen, A. Tzempelikos, Daylight-linked synchronized shading operation using simplified model-based control, Energy Build. 145 (2017) 200–212. https://doi.org/10.1016/J.ENBUILD.2017.04.021

[52] S.G. Colaco, C.P. Kurian, V.I. George, A.M. Colaco, Integrated design and real-time implementation of an adaptive, predictive light controller, Light. Res. Technol. 44 (4) (2012) 459–476. https://doi.org/10.1177/1477153512445713/ASSET/IMAGES/LARGE/10.1177{_}1477153512445713-FIG2.JPEG

[53] N. Kunwar, K.S. Cetin, U. Passe, X. Zhou, Y. Li, Energy savings and daylighting evaluation of dynamic venetian blinds and lighting through full-scale experimental testing, Energy 197 (2020) 117190. https://doi.org/10.1016/J.ENERGY.2020.117190

[54] H. Bülow-Hübe, Daylight in Glazed Office Buildings: A Comparative Study of Daylight Availability, Luminance and Illumince Distribution for an Office Room with Three Different Glass Areas, Ph.D. thesis, Lund University, Lund, Sweden, 2008. https://www.ebd.lth.se/fileadmin/energi_byggnadsdesign/images/Publikationer/Report_EBD_R_08_17_dagsljus.pdf.

[55] G. Newsham, S. Mancini, J. Veitch, R. Marchand, W. Lei, K. Charles, C. Arsenault, Control strategies for lighting and ventilation in offices: effects on energy and occupants, Intell. Build. Int. 1 (2) (2009) 101–121. https://doi.org/10.3763/INBI.2009.0004

[56] A.D. Galasiu, M.R. Atif, R.A. MacDonald, Impact of window blinds on daylight-linked dimming and automatic on/off lighting controls, Solar Energy 76 (5) (2004) 523–544. https://doi.org/10.1016/J.SOLENER.2003.12.007

[57] H.B. Gunay, W. O'Brien, I. Beausoleil-Morrison, S. Gilani, Development and implementation of an adaptive lighting and blinds control algorithm, Build. Environ. 113 (2017) 185–199. https://doi.org/10.1016/J.BUILDENV.2016.08.027

[58] G. Chiesa, S. Pizzuti, M. Zinzi, A new approach to assess the building energy performance gap: achieving accuracy through field measurements and input data analysis, J. Build. Eng. 102 (2025) 111941. https://doi.org/10.1016/J.JOBE.2025.111941

[59] K. Jens, A. Das, M.B. Kjaergaard, J.S. Gregg, Human-centered information for decision-making processes of future space designs, in: 2020 IEEE International Conference on Pervasive Computing and Communications Workshops, PerCom Workshops 2020, Institute of Electrical and Electronics Engineers Inc., 2020. https://doi.org/10.1109/PerComWorkshops48775.2020.9156227

[60] Y. Wu, J.H. Kämpf, J.L. Scartezzini, Automated 'Eye-sight' venetian blinds based on an embedded photometric device with real-time daylighting computing, Appl. Energy 252 (2019) 113317. https://doi.org/10.1016/j.apenergy.2019.113317

[61] X. Hong, M.K.H. Leung, W. He, Effective use of venetian blind in Trombe wall for solar space conditioning control, Appl. Energy 250 (2019) 452–460. https://doi.org/10.1016/J.APENERGY.2019.04.128

[62] B. Paule, E. Sok, S. Pantet, J. Boutiller, Electrochromic glazings: dynamic simulation of both daylight and thermal performance, Energy Proc. 122 (2017) 199–204. https://doi.org/10.1016/J.EGYPRO.2017.07.345

[63] Y. Sun, Y. Wu, R. Wilson, S. Lu, Experimental measurement and numerical simulation of the thermal performance of a double glazing system with an interstitial venetian blind, Build. Environ. 103 (2016) 111–122. https://doi.org/10.1016/J.BUILDENV.2016.03.028

[64] Y. Fang, P.C. Eames, Thermal performance of an electrochromic vacuum glazing, Energy Convers. Manage. 47 (20) (2006) 3602–3610. https://doi.org/10.1016/J.ENCONMAN.2006.03.016

[65] A.L. Navarro, J.D.B. Cadena, F. Favoino, M. Donato, T. Poli, M. Perino, M. Overend, Occupant-centred control strategies for adaptive facades: a preliminary study of the impact of shortwave solar radiation on thermal comfort, Build. Simul. Conf. Proc. 7 (2020) 4910–4917. https://doi.org/10.26868/25222708.2019.211013

[66] A. Motamed, L. Deschamps, J.L. Scartezzini, On-site monitoring and subjective comfort assessment of a sun shadings and electric lighting controller based on novel High Dynamic Range vision sensors, Energy Build. 149 (2017) 58–72.

[67] E.S. Lee, S.E. Selkowitz, The New York Times Headquarters daylighting mockup: monitored performance of the daylighting control system, Energy Build. 38 (7) (2006) 914–929. https://doi.org/10.1016/J.ENBUILD.2006.03.019

[68] A. Guillemin, N. Morel, An innovative lighting controller integrated in a self-adaptive building control system, Energy Build. 33 (5) (2001) 477–487. https://doi.org/10.1016/S0378-7788(00)00100-6

[69] N. Lolli, A. Nocente, J. Brozovsky, R. Woods, S. Grynning, Automatic vs manual control strategy for window blinds and ceiling lights: consequences to perceived visual and thermal discomfort, J. Daylight. 6 (2) (2019) 112–123. https://doi.org/10.15627/JD.2019.11

[70] N. Lolli, A. Nocente, S. Grynning, Perceived control in an office test cell, a case study, Buildings 10 (5) (2020) 82. https://doi.org/10.3390/BUILDINGS10050082

[71] A. Luna-Navarro, G. Lori, D. Callewaert, M. Overend, Semi-automated vs manually controlled dynamic facades: assessment through a field study on multi-domain occupant satisfaction, Energy Build. 286 (2023) 112912. https://doi.org/10.1016/J.

ENBUILD.2023.112912
[72] B. Bueno, J.M. Cejudo Lopez, A. Katsifaraki, H.R. Wilson, A systematic workflow for retrofitting office façades with large window-to-wall ratios based on automatic control and building simulations, Build. Environ. 132 (2018) 104–113. https://doi.org/10.1016/J.BUILDENV.2018.01.031
[73] J. Xiong, A. Tzempelikos, Model-based shading and lighting controls considering visual comfort and energy use, Solar Energy 134 (2016) 416–428. https://doi.org/10.1016/J.SOLENER.2016.04.026
[74] S. Yang, M.P. Wan, B.F. Ng, S. Dubey, G.P. Henze, W. Chen, K. Baskaran, Model predictive control for integrated control of air-conditioning and mechanical ventilation, lighting and shading systems, Appl. Energy 297 (2021) 117112. https://doi.org/10.1016/J.APENERGY.2021.117112
[75] Z. Luo, C. Sun, Q. Dong, A daylight-linked shading strategy for automated blinds based on model-based control and Radial Basis Function (RBF) optimization, Build. Environ. 177 (2020) 106854. https://doi.org/10.1016/J.BUILDENV.2020.106854
[76] I. Konstantzos, A. Tzempelikos, Y.C. Chan, Experimental and simulation analysis of daylight glare probability inoffices with dynamic window shades, Build. Environ. 87 (2015) 244–254. https://doi.org/10.1016/J.BUILDENV.2015.02.007
[77] E.S. Lee, D.L. DiBartolomeo, J. Klems, M. Yazdanian, S.E. Selkowitz, E.S. Lee, D.L. DiBartolomeo, J. Klems, M. Yazdanian, S.E. Selkowitz, Monitored energy performance of electrochromic windows controlled for daylight and visual comfort permalink https://escholarship.org/uc/item/76z069h7 publication date monitored energyperformance of electrochromic windows controlled for daylight and visua, 2006.
[78] E.S. Lee, D.L. DiBartolomeo, Application issues for large-area electrochromic windows in commercial buildings, Solar Energy Mater. Solar Cells 71 (4) (2002) 465–491. https://doi.org/10.1016/S0927-0248(01)00101-5
[79] N. Kunwar, K.S. Cetin, U. Passe, X. Zhou, Y. Li, Full-scale experimental testing of integrated dynamically-operated roller shades and lighting in perimeter office spaces, Solar Energy 186 (2019) 17–28. https://doi.org/10.1016/J.SOLENER.2019.04.069
[80] C. Goovaerts, F. Descamps, V.A. Jacobs, Shading control strategy to avoid visual discomfort by using a low-cost camera: a field study of two cases, Build. Environ. 125 (2017) 26–38. https://doi.org/10.1016/J.BUILDENV.2017.08.030
[81] P. La Roche, M. Milne, Effects of combining smart shading and ventilation on thermal comfort.
[82] Z. Luo, C. Sun, Q. Dong, J. Yu, An innovative shading controller for blinds in an open-plan office using machine learning, Build. Environ. 189 (2021) 107529. https://doi.org/10.1016/J.BUILDENV.2020.107529
[83] E. Shen, J. Hu, M. Patel, Energy and visual comfort analysis of lighting and daylight control strategies, Build. Environ. 78 (2014) 155–170. https://doi.org/10.1016/J.BUILDENV.2014.04.028
[84] H. Shen, A. Tzempelikos, Daylighting and energy analysis of private offices with automated interior roller shades, Solar Energy 86 (2) (2012) 681–704. https://doi.org/10.1016/J.SOLENER.2011.11.016
[85] C.D. Corbin, G.P. Henze, P. May-Ostendorp, A model predictive control optimization environment for real-time commercial building application, 10.1080/19401493.2011.648343 6 (3) (2013) 159–174. https://doi.org/10.1080/19401493.2011.648343
[86] Z. Cheng, Q. Zhao, F. Wang, Y. Jiang, L. Xia, J. Ding, Satisfaction based Q-learning for integrated lighting and blind control, Energy Build. 127 (2016) 43–55. https://doi.org/10.1016/J.ENBUILD.2016.05.067
[87] S.B. de Vries, R.C.G.M. Loonen, J.L.M. Hensen, Multi-state vertical-blinds solar shading - Performance assessment and recommended development directions, J. Build. Eng. 40 (2021) 102743. https://doi.org/10.1016/J.JOBE.2021.102743
[88] J.H. Choi, V. Loftness, D. Nou, B. Tinianov, D. Yeom, Multi-season assessment of occupant responses to manual shading and dynamic glass in a workplace environment, Energies 13 (1) (2019) 60. https://doi.org/10.3390/EN13010060
[89] S.A. Sadeghi, P. Karava, I. Konstantzos, A. Tzempelikos, Occupant interactions with shading and lighting systems using different control interfaces: a pilot field study, Build. Environ. 97 (2016) 177–195. https://doi.org/10.1016/J.BUILDENV.2015.12.008
[90] J.K. Day, B. Futrell, R. Cox, S.N. Ruiz, Blinded by the light: occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies, Build. Environ. 154 (2019) 107–121. https://doi.org/10.1016/J.BUILDENV.2019.02.037
[91] L. Karlsen, P. Heiselberg, I. Bryn, Occupant satisfaction with two blind control strategies: slats closed and slats in cut-off position, Solar Energy 115 (2015) 166–179. https://doi.org/10.1016/J.SOLENER.2015.02.031
[92] E.S. Lee, E.S. Claybaugh, M. Lafrance, End user impacts of automated electrochromic windows in a pilot retrofit application, Energy Build. 47 (2012) 267–284. https://doi.org/10.1016/J.ENBUILD.2011.12.003
[93] S.S. Korsavi, R.V. Jones, A. Fuertes, The gap between automated building management system and office occupants' manual window operations: towards personalised algorithms, Autom. Constr. 132 (2021) 103960. https://doi.org/10.1016/J.AUTCON.2021.103960
[94] L. Giovannini, F. Favoino, A. Pellegrino, V.R.M. Lo Verso, V. Serra, M. Zinzi, Thermochromic glazing performance: from component experimental characterisation to whole building performance evaluation, Appl. Energy 251 (2019) 113335. https://doi.org/10.1016/j.apenergy.2019.113335
[95] L. Karlsen, P. Heiselberg, I. Bryn, H. Johra, Solar shading control strategy for office buildings in cold climate, Energy Build. 118 (2016) 316–328. https://doi.org/10.1016/J.ENBUILD.2016.03.014
[96] M. Rabani, H. Bayera Madessa, N. Nord, Achieving zero-energy building performance with thermal and visual comfort enhancement through optimization of fenestration, envelope, shading device, and energy supply system, Sustain. Energy Technol. Assess. 44 (2021) 101020. https://doi.org/10.1016/j.seta.2021.101020
[97] X. Wu, B. Lin, G. Papachristos, P. Liu, N. Zimmermann, A holistic approach to evaluate building performance gap of green office buildings: a case study in China, Build. Environ. 175 (2020) 106819. https://doi.org/10.1016/j.buildenv.2020.106819
[98] T.E. Kuhn, S. Herkel, F. Frontini, P. Strachan, G. Kokogiannakis, Solar control: a general method for modelling of solar gains through complex facades in building simulation programs, Energy Build. 43 (1) (2011) 19–27. https://doi.org/10.1016/J.ENBUILD.2010.07.015
[99] M. Gonçalves, A. Figueiredo, R.M.S.F. Almeida, R. Vicente, Dynamic façades in buildings: a systematic review across thermal comfort, energy efficiency and daylight performance, Renew. Sustain. Energy Rev. 199 (2024) 114474. https://doi.org/10.1016/J.RSER.2024.114474
[100] G. Jamilu, A. Abdou, M. Asif, Dynamic facades for sustainable buildings: a review of classification, applications, prospects and challenges, Energy Rep. 11 (2024) 5999–6014. https://doi.org/10.1016/J.EGYR.2024.05.047
[101] H. Alkhatib, P. Lemarchand, B. Norton, D.T.J. O'Sullivan, Deployment and control of adaptive building facades for energy generation, thermal insulation, ventilation and daylighting: a review, Appl. Thermal Eng. 185 (2021) 116331. https://doi.org/10.1016/j.applthermaleng.2020.116331
[102] ISO 52016-3:2023 - energy performance of buildings - energy needs for heating and cooling, internal temperatures and sensible and latent heat loads - part 3: calculation procedures regarding adaptive building envelope elements. https://www.iso.org/standard/75395.html.
[103] S. Stevens, Intelligent facades: occupant control and satisfaction, /10.1080/01425910108914369 21 (2-3) (2007) 147–160. https://doi.org/10.1080/01425910108914369
[104] W. O'Brien, A. Wagner, M. Schweiker, A. Mahdavi, J. Day, M.B. Kjærgaard, S. Carlucci, B. Dong, F. Tahmasebi, D. Yan, T. Hong, H.B. Gunay, Z. Nagy, C. Miller, C. Berger, Introducing IEA EBC annex 79: key challenges and opportunities in the field of occupant-centric building design and operation, Build. Environ. 178 (2020) 106738. https://doi.org/10.1016/j.buildenv.2020.106738
[105] O. Straeter, Human and automation: system design and research issues: Thomas B. Sheridan (Ed.); Wiley, New York, 2002, Reliab. Eng. Syst. Saf. 81 (1) (2003) 111–114. https://doi.org/10.1016/S0951-8320(03)00081-4
[106] A.K. Frison, Y. Forster, P. Wintersberger, V. Geisel, A. Riener, Where we come from and where we are going: a systematic review of human factors research in driving automation, Appl. Sci. 10 (24) (2020) 8914. https://doi.org/10.3390/APP10248914
[107] K. Goddard, A. Roudsari, J.C. Wyatt, Automation bias: a systematic review of frequency, effect mediators, and mitigators, J. Am. Med. Inform. Assoc. 19 (1) (2012) 121–127. https://doi.org/10.1136/AMIAJNL-2011-000089