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A SYSTEMATIC REVIEW OF THE EVOLUTION OF BUILDING FAÇADES AND THEIR ROLE IN IMPROVING THERMAL COMFORT

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Abstract

Façades (the outer "skins" of buildings) have transformed from passive static envelopes into intelligent, adaptive systems that regulate indoor–outdoor environments. With the growing use of façades in built space, façades are no longer the defining element of a building in terms of looks but also play an integral role in thermal performance of buildings as well as comfort of the occupants inside1. Architectural changes in durable materials and gadgets have led architects to move beyond conventional brute walls and immovable fenestration to versatile designs. In contrast, for instance, ventilated double-skin façades, moveable shading elements and smart glazing systems allow façades to adapt to the environmental conditions rather than resist 1. These high-performance façades are capable of modulating solar gain and natural ventilation to lower heating and cooling loads. Deploying such adaptive façades has been shown to reduce building energy use by up to ~50% and results in considerably better thermal comfort over static façades [3]. In principle, modern façades combine insulation, daylight control and even energy generation (for example, photovoltaic glazing) to enable buildings to come as close to Net-Zero Energy targets as possible [4,3].

Introduction

Facades have evolved in the field of thermal comfort based on indoor behavior. An appropriate envelope minimizes heat transfer and peak indoor temperatures, and can utilize natural ventilation and shading to provide comfort without excessive air-conditioning [2, 3] Abstract: This review analyzes façade technologies evolution between 2020 and 2025 and applications in thermal comfort in a range of climates. We do so by systematically organizing façade types (static, dynamic, passive, active, smart, etc.) and assessing the trends, challenges and future opportunities in façade design by climate zone from a review of current literature in comfort and energy efficiency.

Methodology (PRISMA)

This review follows a structured PRISMA-based approach to identify and analyses relevant literature[5]. We searched Google Scholar and allied databases (2020–2025) using combinations of keywords such as “building façade”, “thermal comfort”, “energy-efficient façade”, “dynamic façade”, and “climate-responsive envelope”. The initial search yielded several hundred records, which were screened by title and abstract. Inclusion criteria required peer-reviewed comparative or analytical studies of building façades that explicitly addressed thermal comfort or energy performance; regional climate context was noted. Excluded were papers before 2020, non-English publications, opinion pieces, and studies without quantitative facade or comfort analysis. After duplicate removal, preliminary screening, and full-text review, approximately 180 articles remained for synthesis (Figure not shown)[6]. This set covers all major climate regions (tropical, arid, temperate, cold, etc.) and façade types (e.g. traditional vs. dynamic, passive vs. active systems). Key data (façade type, climate context, comfort findings) were extracted into a matrix for comparative analysis.

Classification of Studies and Façade Types

Façade systems can be classified by their mechanism and function (see Table 1). Static conventional façades (heavy insulated walls, fixed glazing) rely on thermal mass and insulation to limit heat flow; they often include fixed overhangs or louvers for shading. Ventilated façades (such as double-skin or multi-layer walls) introduce an air cavity between layers. This cavity (ventilated naturally or mechanically) adds insulation and allows controllable shading (via internal blinds) to buffer solar gain[2]. Adaptive shading systems (movable louvers, kinetic panels) actively redirect sunlight. These elements may be manually or sensor-controlled to optimize light and heat gains in real time. Smart-material façades use advanced glazing or wall materials (electrochromic glass, thermochromic panels, or Phase-Change Materials) that automatically change their optical or thermal properties in response to stimuli. Lastly, energy-generating façades integrate photovoltaics or thermoelectric into the envelope, so the façade itself produces electricity or heat[3][4].

Combined with passive design strategies (proper insulation, natural ventilation), these technologies represent a continuum from low-tech to high-tech facades. Table 1 exemplifies major categories with their features and thermal-comfort roles. A given building may incorporate multiple strategies (e.g. a ventilated wall with automated shading and PV glazing). In all cases, the objective is to modulate heat transfer and airflow to keep indoor temperatures in a comfortable range under varying outdoor conditions[2][3].

Table 1: Classification of building façade technologies and their thermal comfort functions. Passive strategies (left) rely on materials and fixed designs, whereas active/smart strategies (right) dynamically adjust envelope performance

Façade Type	Features	Thermal Comfort Role
Conventional Static Envelope	Solid insulated walls, fixed glazing, no active control	Provides thermal mass and insulation; passive shading elements (e.g. fixed overhangs) limit peak heat gain. Overheating risk if not combined with sufficient shading.
Ventilated Façade (Double Skin)	Two glazing layers separated by air cavity (natural or forced ventilation); may include operable blinds/louvres	Cavity acts as buffer, improving insulation in winter and providing controlled ventilation in summer. Dynamic airing of cavity can flush out heat, reducing cooling load[2].
Automated Shading / Kinetic Façade	Motorized louvers, shutters or panels; sensors and actuators adjust orientation or opacity	Actively blocks or admits solar radiation to maintain target interior temperature and daylight levels. Responds to sun path, reducing overheating and glare.
Smart Glazing (Electro-/Thermo-chromic)	Glass panels change tint/transmittance with voltage or temperature; may incorporate PCM in glazing units	Automatically modulates solar heat gain and visible light in real time. PCM elements store and release heat to damp temperature swings, improving comfort stability.
Photovoltaic-Integrated Façade	Semi-transparent PV modules or thin-film solar integrated in panels/glazing	Generates electricity from sunlight; also serves as shading by absorbing solar energy. Reduces net energy demand for cooling, contributing indirectly to comfort[4][3].

Analysis by Climate Zones

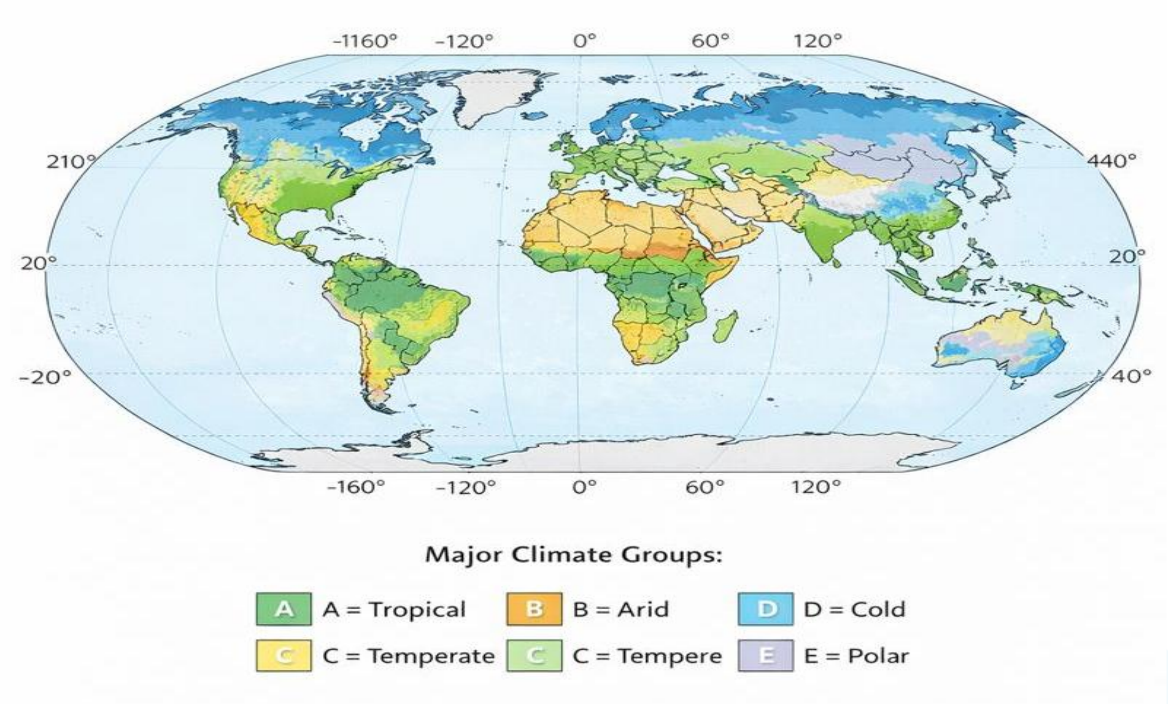

Figure 1: Köppen–Geiger climate zone map (1991–2020) used to contextualize façade strategies. Major climate groups (A = tropical, B = arid, C = temperate, D = cold) influence façade design priorities.

At the same time, the demands that climate environments place on façade are different. In hot-humid zones (A) focus on solar heat blocking & reducing ventilation. In tropical climates, this may mean façades with heavy overhangs and/or high albedo (Reflective) finishes, as well as operable walls or windows for night-time cooling. Hot-arid regions (B) incorporates thermally embracing (thick walls with a high thermal mass) an adequate level of insulation to cut back on the solar-induced heat gain and small window sizes with horizontal and vertical shading elements to reduce direct solar gain. Façades in temperate climates (C) play a dual role, balancing insulation with daylighting: moderate ratio of glazing to wall area, insulated walls, and adjustable shading in the form of blinds or louvers provide a balance between summer cooling and winter solar gain. The envelope in the cold/continental (D/E) climatic zones stresses euhymenium insulation and airtightness, large south facing glazed areas can be used to harvest the winter sun (passive solar gain).

The literature reflects these trends. As an example, several façade investigations for hot/humid environments stress shading elements and passive double-skin configurations to decrease maximum cooling load [7]. In contrast, cold climate literature often includes high-performance glazing and thermal breaks to limit heat loss. Importantly, climate Responsive façade systems (e.g., dynamic louver system or phase change material) are designed; one review found that adaptive façades "reduce thermal losses in cold climate and block excessive solar gains in warm climates" [2]. In conclusion, a familiarity with regional Köppen zones (see Fig. Locally appropriate guidelines for facade technologies to inform the heating and cooling needs of the place resistencia and maintain thermal comfort.

Table 2: Example façade strategies by climate zone. Each climate calls for different envelope features and control (e.g. high insulation vs. flexible shading) to maintain thermal comfort

Climate Zone	Envelope Strategy	Shading/Ventilation
Tropical Humid (A)	Light, insulated walls; high reflectivity	Deep fixed overhangs; openable walls/windows for cross-ventilation
Hot-Arid (B)	Heavy insulation and thermal mass; minimal glazing	Solar control with shutters/fins; night cooling ventilation
Temperate (C)	Moderate insulation; well-sealed fenestration	Adjustable louvers/blinds for seasonal control; operable windows
Cold Continental (D/E)	Very high insulation (triple-glazed windows, low-U walls)	South-facing glazed areas for passive solar gain; limited winter shading

Comparison of Techniques (Passive vs Active; Traditional vs Smart)

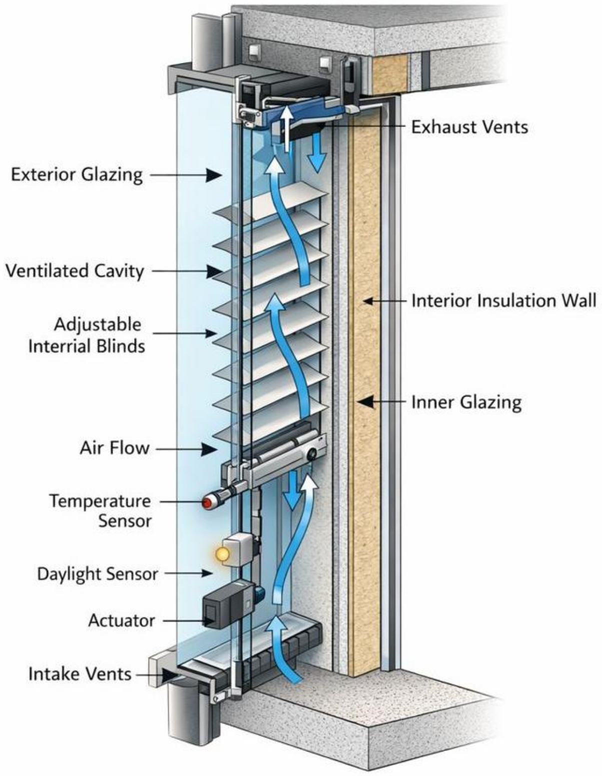

Figure 2: Section detail of a ventilated double-skin façade. Layers include exterior glazing, a cavity with shading, and interior insulating wall. Advanced façades may integrate sensors, controls and multi-functional materials to enhance thermal comfort.

Façade strategies can also be contrasted by control and energy use. Passive designs rely purely on geometry and materials (insulation, thermal mass, fixed shading) without moving parts or power. Active or smart façades use sensors, actuators or phase-changing materials to adapt to conditions.

Table 3 highlights key differences:

Aspect	Passive Techniques	Active/Smart Techniques
Solar control	Fixed overhangs, light shelves, reflective coatings	Automated blinds/louvres; electrochromic (tinting) glass
Thermal storage	Thick walls, high thermal mass, passive PCM panels	Controlled-phase-change materials; integrated radiant panels
Ventilation	Natural ventilation (open windows, stack effects)	Mechanical ventilation ducts; smart vents with climate control
Control	No sensors; design optimized for expected conditions	Sensors (temp/light), controllers modulate openings and tint
Energy use	No external energy (beyond day-to-day lighting/cooling)	Requires power for motors/glass; may harvest energy (PV façades)
Maintenance	Simple, durable (fewer moving parts)	Higher complexity (periodic maintenance of motors/electronics)
Example materials	Concrete, brick, insulation foam, conventional glass	Smart glass (electrochromic), PV cells, embedded microcontrollers

While Passive façades may be inherently low-cost and reliable and thus simply less flexible. While passive façades are typically non-active (and limited by their materials), smart façades (like sensor-driven shading or thermoelectric panels) can adapt to changing conditions and provide major comfort enhancements3. As an example, recent work on thermoelectric façades demonstrates active prototype panels that provide heat and/or cooling to perimeter spaces based on the indoor and outdoor temperature difference, which could serve to approach near-elimination of certain HVAC loads [8]. Electrochromic glazing performs a similar function, automatically tinting in bright sun and lowering glare and solar heat gain without human input. In practice, hybrid solutions mix both: for instance, a double-skin façade (passive insulating buffer) plus motorized blinds inside and sensors that automatically ventilate the cavity when needed.

Thermal comfort results arising from these approaches are summarized in Table 3. Contrasts between control complexity with better comfort regulation Dynamic façades can provide improved comfort regulation as they dampen the indoor climate fluctuations compared to static façades, but they come at a greater cost and are more complex to control. In contrast, passive façades that do not take this variability into account sometimes under-perform (e.g. a fixed-shade design can lead to overheating if there is an anomalously sunny day). Promisingly, and contagiously, the trend is towards intelligent/adaptive systems: international research is moving towards "short response" (seconds/minutes) adaptive envelopes that either learn or predict environmental changes9.

Table 3: Contrast between passive and active façade features. Active (smart) façades provide dynamic control for comfort, whereas passive façades use fixed design strategies.

Aspect	Passive Façade	Active/Smart Façade
Energy source	Relies on natural phenomena (sun path, wind)	Uses grid power or harvested energy (PV, TE)
Cost/Complexity	Generally lower cost, simpler design	Higher initial cost, requires sensors/control
Comfort adaptability	Fixed; comfort depends on design fit for locale	Adaptable; can maintain comfort in variable conditions
Example	Thick insulated wall with fixed shade	Smart window + automated vent + PV facade

Trends, Challenges and Opportunities

There is an increasing trend of research related adaptive façade technology in literature. Interest in responsive building design is also evident in the yearly increase of scholarly publications on adaptive building envelopes, as noted by a recent review [11]. Recent studies taking the approach of combining comfort and energy metrics: dynamic façades are often assessed on basis of energy savings, but also on the basis of the improvement of the Indoor environmental quality (IEQ), and most prominently, thermal comfort. This net Zero Energy Buildings transition only spurs on the need for façade innovation9.

However, challenges remain. Smart façades usually can cost a lot more expensive for installation and maintenance. Integration problems also abound: the moment you start adding moving parts or electronics to the building skin, you need to properly design these (necessary sealing, durability, user interface, etc.) The cost vs benefit trade-off is something that researchers often highlight – e.g. do the energy and comfort gains outweigh the additional cost and complexity2? The absence of standard metrics is another challenge: thermal comfort involves quite subjective aspects (people perception bottleneck, clothes, etc.), this is not always the case with façade studies. In addition, previous studies are almost all case-specific or simulation-based and we lack long-term, real-world performance data.

Opportunities are abundant. Smart materials (e.g., phase-change composites or transparent photovoltaics) are becoming increasingly sophisticated, allowing façades to perform multiple functions. Combining the IoT and AI, façades that adapt to behaviour patterns of the occupants and climate predictions are looming on the immediate horizon. Now, the move towards sustainability: LCA (life-cycle analysis) of façades is an emerging new research need, which needs to take care of embodied energy or recyclability of high-tech façades too. Lastly, adaptive façades fit very well with resiliency goals — in the case of cities with extreme heat event, a controllable façade can achieve local outdoor and indoor comfort at the same time. Despite the higher first cost to dynamic façades, one review notes that their "compelling performance gains" make these technologies a promising solution in our path toward buildings that priorities health and performance [9].

Conclusions and Future Recommendations

This systematic review has surveyed the latest advances in building façade design (2020–2025) across climate zones and technology types, focusing on thermal comfort outcomes. We find that façades are no longer simple static walls but have evolved into dynamic environmental interfaces. Modern envelopes employ a mix of passive and active strategies – from high-performance insulation and shading (passive) to automated shading, smart glazing, and renewable-integrated skins (active) – all aimed at improving occupant comfort while lowering energy demand[2][3].

Key conclusions are:
(1) Diversity of solutions – No single façade type dominates; designs are tailored to climate and building use. Arid regions favor high insulation, tropical zones rely on ventilation and shading, while temperate zones use hybrid approaches.
(2) Prominence of adaptive systems – A growing number of studies emphasize dynamic façades (e.g. louvers, smart glass) that can adapt in real time. These systems consistently improve thermal comfort compared to fixed façades, especially under variable conditions.
(3) Integration with sustainability goals – Façade research is increasingly linked with net-zero and resilient design. Systems that combine thermal regulation with daylight optimization and on-site energy generation are highlighted as future benchmarks.
For future work, we recommend: Longitudinal field studies to validate predicted comfort gains of smart façades in real buildings; standardization of comfort metrics in facade research; and economic analysis of façade innovations (including life-cycle costs). Additionally, exploration of hybrid solutions – e.g. combining natural ventilation with smart controls – can yield robust designs for changing climates. Finally, policy and design guidelines (such as building codes and smart readiness indicators) should evolve to encourage use of adaptive façades where beneficial. Overall, the evolution of façades toward intelligent, climate-responsive systems holds great promise for creating buildings that keep people comfortable while saving energy[9][4].

Acknowledgement: This review is based solely on available literature and does not present new experimental data.

Citations: Key sources include recent systematic reviews and research articles on façade technology [1][2][3][5][11], which document the advances, performance, and challenges of façade designs.

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