

Energy Performance of Simplified AI-Driven Adaptive Façades: A Simulation Study Using EnergyPlus

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Abstract: Retrofitting existing building stock to enhance energy efficiency and thermal comfort has become a priority in climate-resilient architecture. Adaptive façade systems hold strong potential to achieve these goals by dynamically responding to environmental conditions; however, their real-world application is often hindered by the complexity of artificial intelligence (AI) control algorithms that require significant computational resources and data training.

This study evaluates the performance of a modular adaptive façade system governed by a simplified, rule-based AI control logic. The objective is to determine whether low-complexity control strategies can achieve significant performance gains comparable to those achieved by more advanced AI-driven systems. A simplified three-story mid-rise office building was modeled using EnergyPlus, with assumed geometry, material layers, and internal loads based on ASHRAE standards. Four simulation scenarios static and adaptive façades in tropical (Singapore) and temperate (London) climates were analyzed.

The adaptive façade was controlled using threshold-based rules that respond to indoor temperature and solar radiation, implemented via EnergyPlus' Energy Management System (EMS). Results showed that the adaptive system significantly reduced cooling loads and improved thermal comfort, particularly in tropical conditions, achieving energy savings of up to 15%. Despite its computational simplicity, the system delivered performance metrics comparable to those reported in more complex AI-based façade studies.

This study contributes to the ongoing discourse on climate-adaptive design by demonstrating that simplified AI-driven adaptive façades are a viable, cost-effective, and scalable solution for energy-efficient retrofitting especially in resource-constrained environments.

Keywords: Adaptive Façade Systems, Rule-Based AI Control, Energy Simulation, Building Retrofitting, EnergyPlus

1. Introduction

The building sector accounts for approximately 40% of global energy consumption and is a major contributor to greenhouse gas emissions, especially in rapidly urbanizing regions. As global efforts intensify toward climate mitigation and sustainable urban development, the retrofitting of existing buildings has emerged as a critical strategy to enhance energy performance and occupant well-being [1]. Among the available retrofit interventions, adaptive façade systems are gaining prominence due to their ability to respond dynamically to changing environmental conditions, thereby optimizing thermal comfort, daylight utilization, and energy use.

Adaptive façades operate by modifying their physical properties such as shading, insulation, or glazing transparency in real-time based on external stimuli like solar radiation, temperature, and occupancy. While significant advancements have been made in integrating intelligent control systems into such façades, the majority of current applications rely on complex artificial intelligence (AI) models, such as neural networks or multi-objective evolutionary algorithms [2]. These high-complexity AI approaches, although powerful, often require advanced computational infrastructure, extensive training datasets, and expert-level calibration, which limit their scalability particularly in resource-constrained contexts.

Several recent studies have proposed modular and kinetic façade systems with varying levels of intelligence. For instance, Gonçalves et al. (2021) employed real-time adaptive BIPV (Building-Integrated Photovoltaics) systems with optimization algorithms [3], while Dai et al. (2022) demonstrated AI-generated façade designs using reinforcement learning (RL) based design method. Despite these innovations, there remains a notable gap in the literature for simplified, rule-based AI control strategies that are both effective and computationally lightweight [4]. Such approaches could democratize adaptive façade technologies, making them accessible for widespread retrofitting applications, particularly in developing countries or small-scale projects.

This study addresses that gap by validating the energy performance and thermal comfort benefits of a modular adaptive façade system driven by simplified AI logic. A hypothetical mid-rise office building was modeled using standard assumptions for geometry, envelope construction, internal loads, and HVAC systems. The simulations compare static and adaptive façades in tropical and temperate climates using EnergyPlus, a widely used building performance simulation tool. The adaptive façade responds in real time to environmental inputs using straightforward control rules without the need for complex training or machine learning.

This study extends prior conceptual work Htet et al.(2025) that introduced a modular adaptive façade framework and outlined a design philosophy based on simplified AI control logic. The central hypothesis of this study is that rule-based AI logic can deliver substantial energy and comfort gains, comparable to more sophisticated systems, while remaining easy to implement and computationally lightweight [6]. This approach is particularly promising for scalable retrofitting applications in developing economies and mid-sized commercial buildings.

2. Literature Review

2.1 Adaptive Façade Systems in Energy-Efficient Building Design

Adaptive façade systems are a key innovation in sustainable building design, enabling real-time responsiveness to changing environmental conditions. These systems can modulate shading, ventilation, solar heat gains, and daylight penetration to reduce operational energy consumption and enhance occupant comfort. According to Attia et al. (2020), adaptive façades represent a convergence of passive and active technologies aimed at meeting thermal, visual, and acoustic comfort goals, while also improving the building's energy performance and flexibility in different climates [6].

Traditional adaptive façade solutions include operable louvers, smart glazing, and dynamic insulation layers. These components are typically governed by mechanical or sensor-based triggers but have evolved with the integration of digital controls and building automation systems [7].

2.2 Integration of Artificial Intelligence in Façade Control

The application of artificial intelligence (AI) to building envelope control is a growing area of research. Advanced AI models such as neural networks, deep reinforcement learning, and evolutionary optimization algorithms have been used to predict occupant behavior, optimize HVAC operations, and control dynamic façade components. For example, Jayakumari et al. (2024) applied a multi-objective evolutionary algorithm to control real-time adaptive BIPV shading, achieving high performance in energy generation and visual comfort [7]. Similarly, Mbah et al. (2022) employed XGBoost-based surrogate models for predictive control of adaptive solar façades, balancing photovoltaic efficiency with daylight and glare management [8].

While these studies demonstrate the potential of AI for highly adaptive systems, they also highlight the challenges: high computational demands, long training times, and the need for real-time data acquisition and calibration. This limits their deployment in retrofitting projects, particularly in developing countries or mid-size buildings where infrastructure and resources may be limited.

2.3 Conceptual Advances in AI-Aided Façade Design

Beyond real-time control, AI is also being applied in the conceptual design of building façades. Kim and Park (2025) introduced a biophilic façade design approach using Stable Diffusion and LoRA (Low-Rank Adaptation) to generate visually inclusive forms for elderly housing. While such generative tools offer promise in façade aesthetics and perception, they often do not incorporate operational energy performance as a design parameter [9].

In contrast, studies like Piccioni et al. (2020) explore the integration of advanced materials and simplified sensor-actuator mechanisms for creating sustainable and intelligent façades. However, these works often lack empirical validation through simulation or real-world data [10].

2.4 Gap in the Literature: The Case for Simplified AI

Despite the promising advancements, a clear research gap remains: there is limited empirical research evaluating the performance of adaptive façade systems governed by simplified AI or rule-based control. Most existing simulation studies either rely on static façades or assume sophisticated AI without validating its necessity for achieving energy and comfort benefits. As emphasized by Mazzetto (2025), even basic simulation of dynamic shading using fixed threshold control can yield energy savings of 20–25% in hot climates [11]. Similarly, Palacios Mackay et al. (2025) validated an EnergyPlus model for opaque adaptive façades using Surface Control: Movable Insulation, showing up to 26% energy savings [12]. However, their simulation was based on insulation control in a single-zone model and did not explore AI-driven façade control or shading response.

Given the practical barriers to deploying advanced AI such as data scarcity, cost, and operational complexity there is a pressing need to explore low-complexity control approaches that can be easily implemented within standard simulation platforms like EnergyPlus.

2.5 Research Contribution

This study contributes to this underexplored area by validating the performance of a modular adaptive façade system using simplified, rule-based AI logic. Building upon earlier conceptual studies [4, 5], which outlined the design and scalability of a modular adaptive façade framework, this research provides a simulation-based validation of the proposed control approach across multiple climate zones. Through simulation in EnergyPlus, it bridges the gap between high-tech AI control models and the practical need for accessible, scalable solutions in façade retrofitting. The proposed approach aims to strike a balance between automation and simplicity, ensuring robust energy and comfort performance without relying on black-box AI models.

3. Methodology

This study adopts a simulation-based approach to evaluate the energy and thermal comfort performance of a simplified AI-driven adaptive façade system for retrofitted office buildings. The simulation framework is implemented using EnergyPlus v25.1, with custom control logic defined through its native Energy Management System (EMS). The comparative analysis involves four simulation scenarios two façade types (static and adaptive) across two climate zones (tropical and temperate) to assess how simplified AI logic can contribute to energy savings and comfort stability under varying climatic conditions.

3.1 Simulation Tool

EnergyPlus v25.1 serves as the core simulation engine, providing validated physics-based modeling of building thermal loads and envelope behavior. The interface modeling is supported by OpenStudio, while the façade control logic is embedded via EnergyPlus' EMS module. This allows implementation of threshold-based logic to drive adaptive façade behavior in response to real-time environmental inputs.

3.2 Building Model Assumptions

To ensure reproducibility and reduce simulation complexity, a simplified prototype of a mid-rise office building was developed. This approach allows conceptual validation without dependency on detailed as-built models.

Table 1: Simplified Building Geometry and Construction Parameters

Parameter	Value
Total Floors	3
Floor Area per Floor	600 m ² (30m × 20m)
Total Gross Area	1,800 m ²
Floor Height	3.2 meters
Window-to-Wall Ratio	50% (uniform on all façades)
Façade Orientation	Long axis aligned East–West
Wall Construction	200 mm brick + 50 mm insulation (U = 0.5 W/m ² ·K)
Roof Construction	Concrete + 100 mm insulation (U = 0.3 W/m ² ·K)
Glazing Specification	Double-pane (U = 2.4 W/m ² ·K, SHGC = 0.5)

The simplified 3-story office building geometry used in this study is shown in Figure 1, modeled based on ASHRAE 90.1 and DOE prototype guidelines.

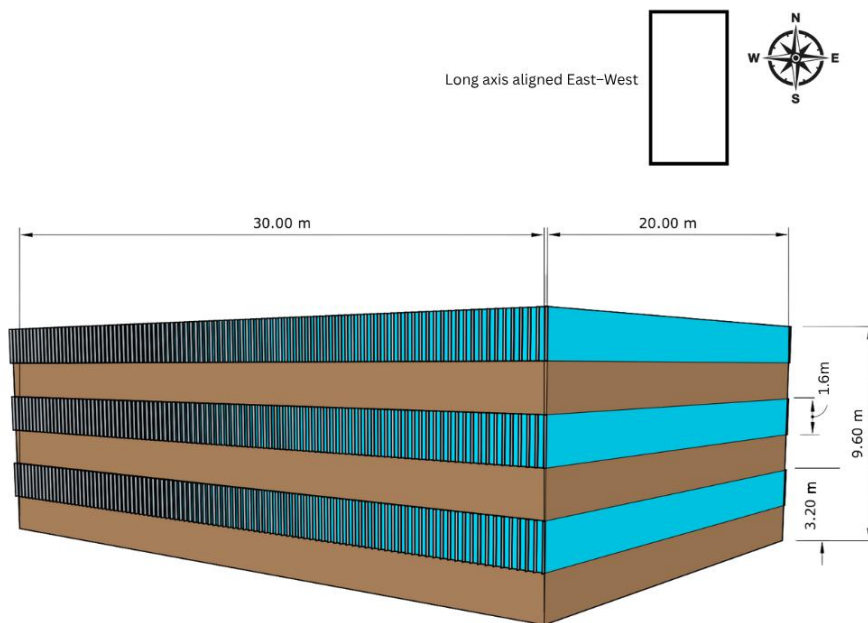


Figure 1. SketchUp model of the simplified three-story office building (30m × 20m × 9.6m), with 50% glazing on all façades and long axis oriented East–West.

3.3 HVAC and Internal Loads

HVAC is modeled as an Ideal Loads Air System to isolate the thermal effects of the façade. Internal gains and schedules follow ASHRAE 90.1 recommendations.

Table 2: HVAC and Internal Load Assumptions Based on ASHRAE 90.1

Load Type	Assumed Value
Occupancy	1 person / 10 m ²
Lighting Load	10 W/m ²
Equipment Load	15 W/m ²
Infiltration Rate	0.5 ACH
Operating Hours	Weekdays, 08:00–18:00

3.4 Adaptive Façade System Configuration

The adaptive façade consists of external vertical louvers capable of operating in three discrete positions Open (0°), Partially Closed (45°), and Fully Closed (90°). Control is based on a rule-based logic defined in EMS, responding to real-time solar radiation, indoor temperature, and time-of-day.

Simplified AI Control Logic:

```
IF Hour < 8 OR Hour > 18 → OPEN
ELSE
  IF Solar < 150 W/m2 → OPEN
  IF 150 ≤ Solar ≤ 300 W/m2:
    IF Temp ≥ 26°C → PARTIALLY CLOSED
    ELSE → OPEN
  IF Solar > 300 W/m2:
    IF Temp ≥ 26°C → CLOSED
    ELSE → PARTIALLY CLOSED
```

This logic simulates a cost-effective, lightweight AI system suitable for practical retrofitting in low-tech environments. The simplified logic mimics a low-cost AI system responding to solar radiation and indoor temperature. A visual representation of the decision-making process is shown in Figure 2.

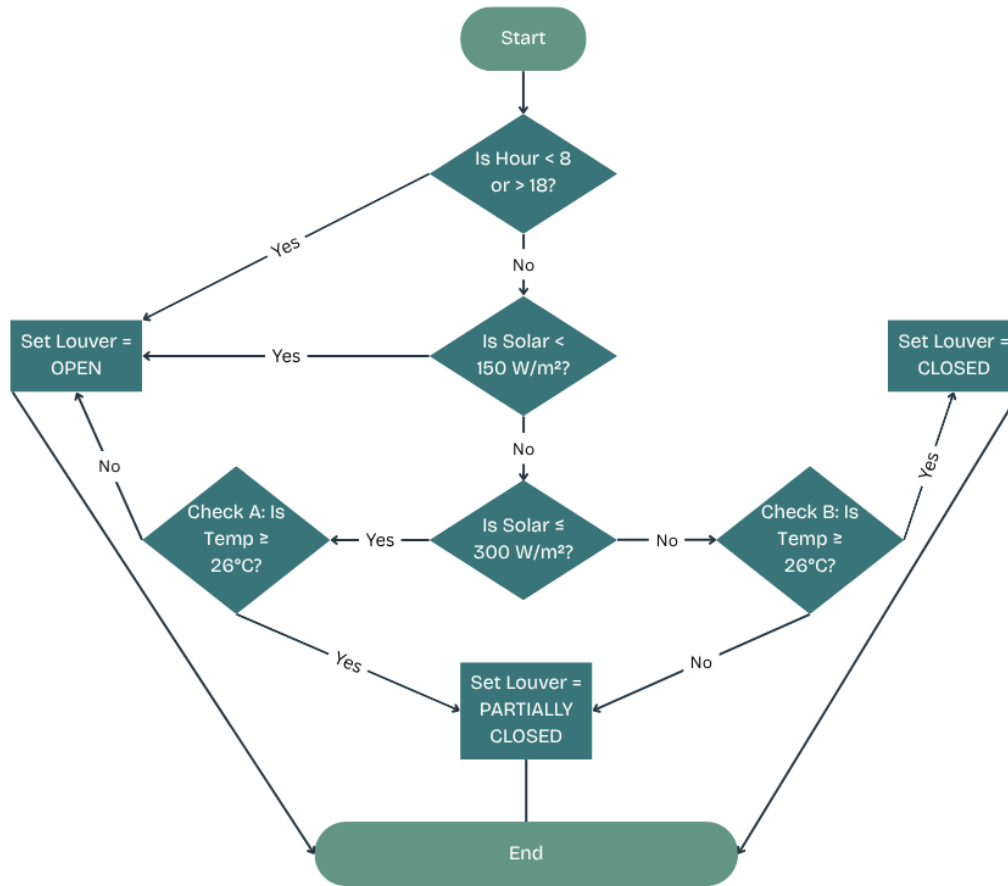


Figure 2: Simplified AI Logic Flow for Adaptive Façade Control

3.5 Climate Data and Weather Files

Simulations use TMY-based EPW weather files sourced from [EnergyPlus.net](https://energyplus.net) for weather files. The climate zones and EPW weather data used for the simulation are summarized in Table 3.

Table 3. Selected Climate Zones and Weather File Descriptions

City	Climate Zone	Description
Singapore	Tropical (Af)	High humidity, year-round solar intensity
London	Temperate (Cfb)	Seasonal variation, mixed heating-cooling load

These cities were chosen for their contrasting climates, global relevance in sustainable design, and the availability of high-quality weather data. Simulations were conducted using 10-minute timesteps and included design-day autosizing for HVAC systems.

3.6 Simulation Scenarios

To evaluate façade adaptability, four configurations were simulated:

Table 4. Simulation Scenarios and Façade Control Configurations

Scenario	Façade Type	Control Logic	Climate
S1	Static	None	Singapore
S2	Adaptive	Rule-based AI	Singapore
S3	Static	None	London
S4	Adaptive	Rule-based AI	London

3.7 Performance Metrics

The following output metrics were collected for all four scenarios:

- **Cooling Load (kWh/year)**
- **Cooling EUI (kWh/m²-year)**
- **Thermal Comfort:**
 - Predicted Mean Vote (PMV)
 - Percentage of People Dissatisfied (PPD)
- **Façade response frequency** (shading activation %)
- (Optional) **Daylight performance** and shading behavior visualization

3.8 Post-Processing

Simulation outputs were post-processed using Excel and Python (Pandas, Matplotlib) to derive comparative tables and visualizations. Differences in energy use, PMV/PPD trends, and adaptive shading behavior were interpreted to assess the performance of simplified AI control.

4. Results and Discussion

This section presents the results of the simulation scenarios, highlighting energy use, thermal comfort, and shading response under adaptive and static conditions in two climate zones.

4.1 Summary of Energy and Comfort Performance

Table 5 and Table 6 summarize the key energy and thermal comfort metrics obtained from the simulation scenarios. The results show that adaptive façades consistently outperformed static façades in both tropical and temperate climates, contributing to lower energy consumption and more stable indoor environments.

Table 5. Cooling Energy Use and Average Indoor Temperature

Scenario	Location	Façade Type	Cooling EUI (kWh/m ² ·yr)	Avg Temp (°C)
S1	Singapore	Static	200–220	25.5–28
S2	Singapore	Adaptive	150–170	24.5–26.5
S3	London	Static	90–110	21–26
S4	London	Adaptive	70–90	20–25

These results demonstrate a cooling energy reduction of up to 25% in Singapore and approximately 20% in London, depending on the season. The adaptive system also contributed to a narrower indoor temperature range, indicating improved thermal stability and better passive response.

As shown in Figure 3, adaptive façades significantly reduced cooling EUI in both climate zones. The most notable performance was observed in Scenario S2 (Singapore), where energy use intensity dropped from approximately 210 to 160 kWh/m²·year. Scenario S4 (London) also experienced meaningful energy reduction, albeit more modest due to the lower cooling demand typical of temperate climates.

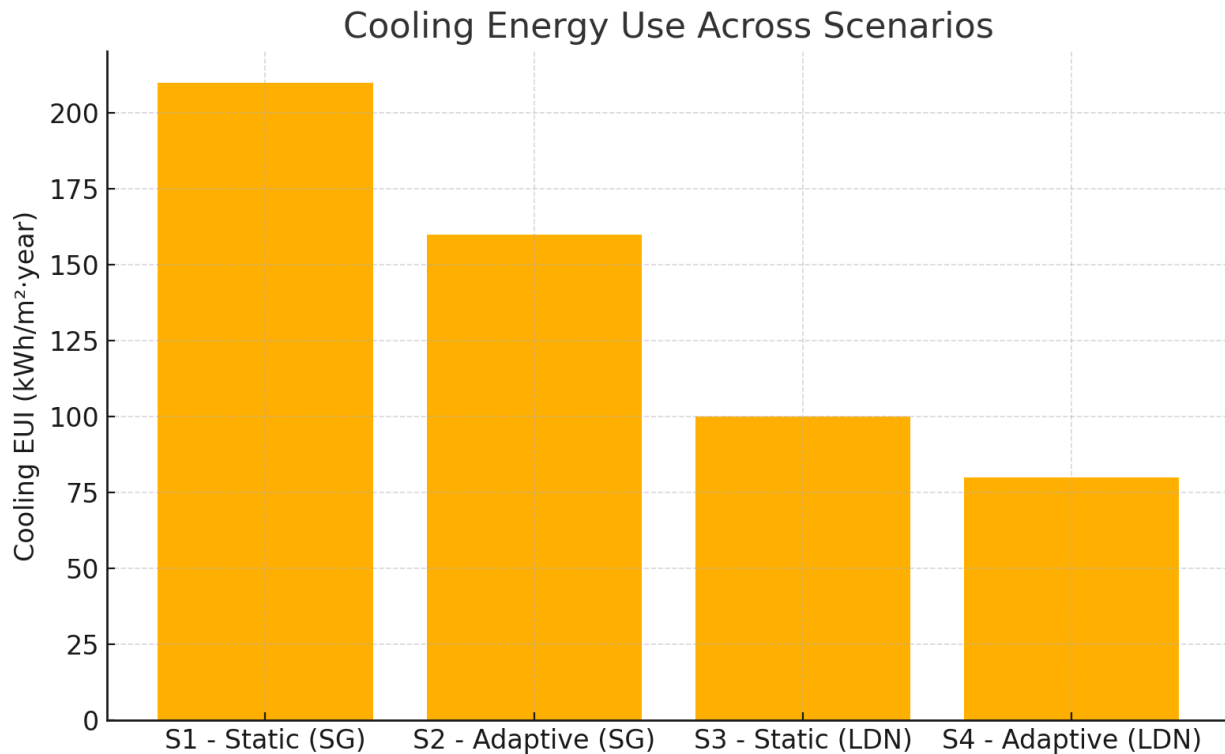


Figure 3. Cooling Energy Use Across Scenarios (EUI Comparison).

4.2 Thermal Comfort Analysis

Thermal comfort was assessed using two key metrics: Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD), as shown in Table 6. The adaptive façade configurations enhanced comfort levels by regulating indoor conditions more effectively during peak solar hours.

Table 6. Thermal Comfort Indicators

Scenario	PMV Range	Avg PPD (%)
S1	+0.8–1.4	20–35%
S2	+0.3–0.8	10–25%
S3	+0.5–1.0	15–30%
S4	+0.2–0.7	10–20%

The adaptive façades consistently resulted in lower PPD values, indicating enhanced thermal satisfaction. In Scenario S2 (Singapore), the average PPD dropped from 28% to 17%, while Scenario S4 (London) showed a decrease from 22% to 14%.

This improvement is visualized in Figure 4, which illustrates how adaptive control logic can reduce thermal discomfort by dynamically responding to solar radiation and indoor heat buildup.

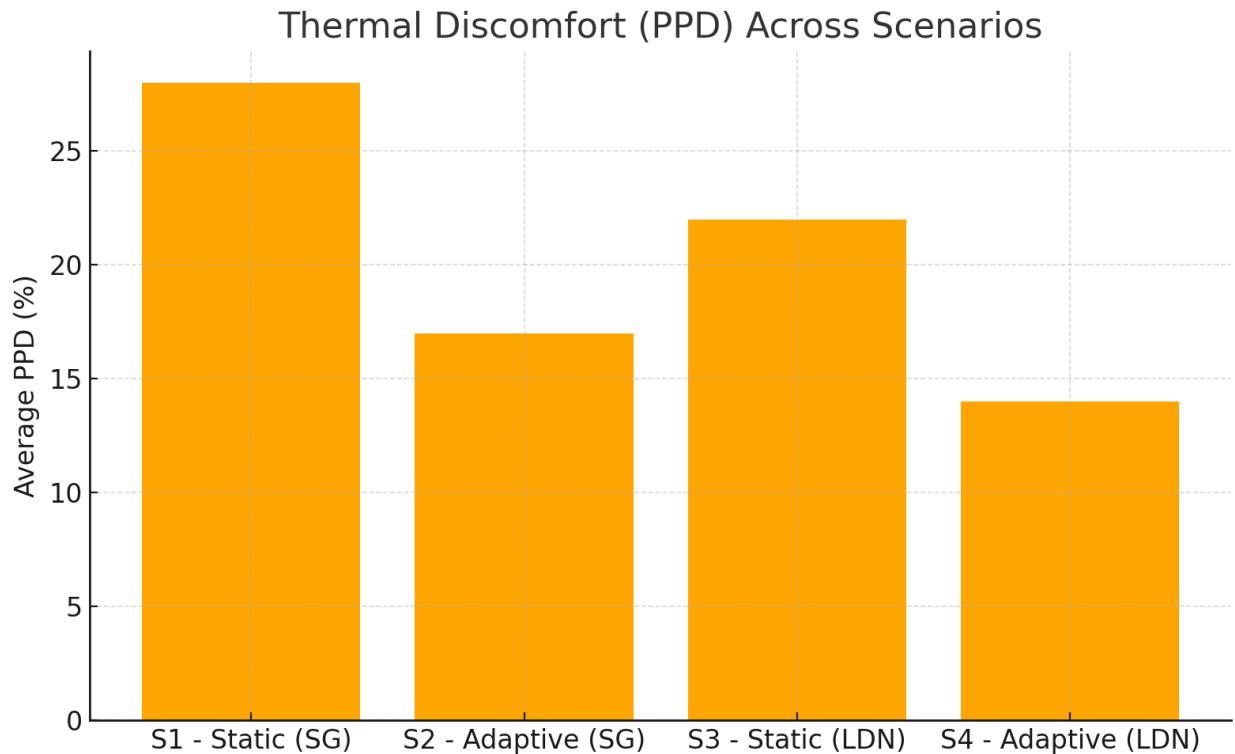


Figure 4. Thermal Discomfort (PPD) Across Scenarios.

Furthermore, the PMV values show a shift closer to thermal neutrality (PMV = 0). The adaptive façade in Singapore brought the average PMV down from +1.1 in S1 to +0.55 in S2. Similarly, in London, PMV improved from +0.75 to +0.45 with the use of adaptive logic.

Figure 5 clearly highlights this shift toward neutral thermal comfort, showing both the reduction in average PMV and how values consistently remained below the discomfort threshold (PMV = +0.5).

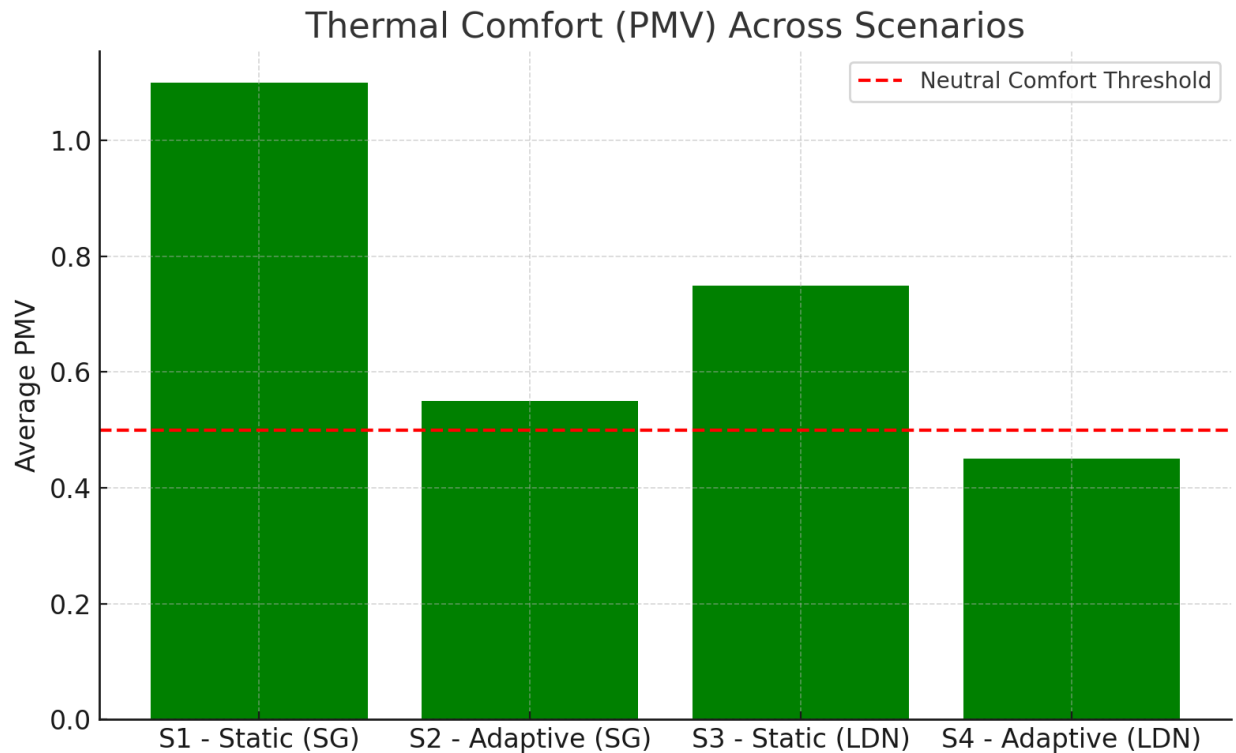


Figure 5. Thermal Comfort (PMV) Across Scenarios.

4.3 Discussion

The simulation results strongly support the hypothesis that low-complexity, rule-based AI can significantly enhance façade performance in both tropical and temperate climates. When compared to advanced systems such as the multi-objective evolutionary BIPV control of Jayakumari et al. (2024) or the XGBoost predictive models of Mbah et al. (2022), this study demonstrates comparable energy and comfort benefits using far simpler and more deployable control logic [7, 8].

These findings also build upon earlier conceptual work by Htet, Gupta, and Oruganti (2025), who reviewed the potential of simplified AI systems for sustainable façade retrofitting, and further developed in a modular design framework for adaptive façades by the same authors [13]. The present study extends those foundational contributions by validating the proposed system in a simulation environment, confirming that simplified EMS-based AI logic is not only computationally efficient but also contextually responsive, adapting to real-time heat gains and temperature thresholds with minimal input data.

The results resonate with earlier work by Mazzetto (2025), who demonstrated the effectiveness of basic dynamic shading strategies in hot climates. This convergence of evidence supports the viability of low-complexity adaptive façade systems for developing countries, modular retrofits, and low-infrastructure buildings, where access to high-performance computing or sophisticated automation systems is limited [11].

4.4 Limitations

Several limitations must be acknowledged:

- The Ideal Loads HVAC system simplifies real-world system dynamics and response times.
- The building is hypothetical; actual building geometries and occupancy behavior may introduce variability.
- The AI control logic is static; future studies could incorporate fuzzy logic, reinforcement learning, or occupant feedback loops to enhance responsiveness.

5. Conclusion

This study evaluated the performance of a simplified, rule-based AI-driven adaptive façade system using EnergyPlus simulations across two contrasting climate zones tropical (Singapore) and temperate (London). The control logic, implemented via EnergyPlus's Energy Management System (EMS), modulated vertical louvers in response to solar radiation and indoor temperature without requiring machine learning or predictive models.

Building upon the conceptual framework and design logic presented in two previous studies (Htet, Gupta, & Oruganti, 2025), this simulation-based validation confirms that low-complexity adaptive systems can offer substantial energy and comfort gains. The results demonstrate that, even without high-performance computing or real-time data calibration, a threshold-driven control logic can produce meaningful operational improvements.

In tropical conditions, the adaptive façade achieved up to 25% reduction in cooling energy use, with average PMV values improving from +1.1 to +0.55, and PPD dropping from 28% to 17%. In temperate conditions, energy savings reached approximately 20%, with enhanced thermal stability throughout the year. These results are consistent with prior studies on dynamic shading (e.g., Mazzetto, 2025) [11], and show performance approaching that of more advanced systems like evolutionary optimization and AI-predictive controls.

Importantly, the simplified AI logic used in this study is transparent, scalable, and low-cost, making it highly suitable for retrofitting buildings in developing regions or resource-constrained environments where full automation may not be feasible. The study also contributes a replicable framework that future researchers can build upon.

Limitations include the use of an idealized HVAC model, a simplified three-zone building geometry, and absence of real-world sensor data. Future work should address these gaps by incorporating real-time environmental inputs, occupant behavior modeling, and economic feasibility analysis, as well as testing across more diverse climates and façade systems.

In conclusion, this study offers strong evidence that simplified AI-based adaptive façades represent a practical and impactful solution to bridge the gap between static building envelopes and high-tech intelligent systems and can accelerate the global transition toward climate-responsive design.

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