

## Modular Kinetic Façade System Enabling Autonomous Adaptive Responses for Sustainable and User Centric Building Environments

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### Abstract

Unlike conventional dynamic façade systems—which typically respond as a unified surface to external or internal environmental stimuli—The proposed Kinetic Façade Retractable Pattern Unit (RPU) introduces a modular and adaptive system designed to enable the independent actuation of individual façade dynamic components. The proposed (RPU) allows for localized, zone-specific responses. Suggesting that each part or specific area of the modular unit can adapt autonomously to the unique thermal, lighting, or privacy requirements of the interior space it serves behind it, regardless of the behavior of other adjacent units that are sharing the same dynamic façade plane. Such decentralized functionality not only enhances environmental responsiveness but also supports greater spatial differentiation and a customized-user-centric comfort within the building envelope. In addition to its adaptive capabilities, the RPU is envisioned for fabrication using low-cost recycled materials, aligning with sustainable design imperatives. For readers new to the field; the paper begins with a comprehensive literature review structured around four thematic strands: (1) an accessible introduction to dynamic façades (2) a breakdown of major components, system types, and simulation tools; (3) a historical survey of kinetic façade treatments in ancient architecture, emphasizing organic, locally sourced solutions; and (4) an overview of contemporary advancements in sensor-driven and automated kinetic systems for thermal regulation. The methodology section details the technical scheme of the proposed RPU, including its proposed shape, dimensions, material specifications, and mechanical design. It then outlines a verification and testing protocol, specifying simulation tools, objectives, input data, and climatic conditions applied to a case study. Simulation results are presented in a dedicated section, followed by a discussion comparing the proposed RPU with traditional systems, key benefits, potential applications across building typologies, and considerations of operational cost and production feasibility are also analyzed. The manuscript concludes with a future research section addressing current research limitations and proposing directions for continued development of adaptive façade technologies.

### Research Highlights

- This research proposes the development of an advanced retractable pattern unit (RPU) concept, which can be manufactured from low-cost recycled materials and is designed to respond simultaneously to both external environmental factors and varying internal conditions.
- The manuscript investigates the operational principles of kinetic façade systems, with particular emphasis on a novel configuration that—in concept—enables discrete actuation of individual façade modules.
- This decentralized control architecture facilitates localized adaptive responses to environmental stimuli across the building envelope.
- This modular approach enables a higher degree of customization and flexibility, ensuring that the facade not only responds to external environmental conditions but also takes into account the specific requirements of interior spaces.

**Keywords :** Kinetic Facades, Thermal Sustainability, Recycled Construction, Building Automation

### 1 Introduction

While sustainability involves maintaining, improving, and creating balance between ecological, social, economic and environmental factors, thermal sustainability focuses on managing thermal (heat) energy in buildings for the purpose of maintaining thermal comfort without compromising energy consumption

#### 1.1. Problem

- The research problem addresses the limitations of typical kinetic facade systems, which predominantly respond to external environmental factors such as sunlight, wind, and temperature, while rarely adapting to internal environmental conditions.
- Additionally, while these systems are highly valued in office buildings due to their focus on energy efficiency, daylight optimization, and occupant comfort, their use in other building types, such as residential, cultural, or institutional buildings, remains limited. This is largely due to challenges related to the complexity, high cost of installation, and ongoing maintenance, making them less feasible for smaller or less commercially driven structures.
- Moreover, conventional kinetic facade systems operate as unified units, responding uniformly to external stimuli, which fails to account for the varying internal conditions behind different areas of the facade. This lack of adaptability results in inefficiencies in addressing the diverse needs of interior spaces, such as privacy, glare reduction, or ventilation.

#### 1.2. Goal

The goals of this research are as follows:

- **To Develop an Advanced Retractable Pattern Unit (RPU):** designing a kinetic facade system that can be manufactured from low-cost recycled materials, which responds simultaneously to both external environmental factors and varying internal conditions.
- **Overcome Limitations of Traditional Kinetic Facades:** creating a system that offers adaptable, context-specific responses for different building types, with a focus on residential buildings, addressing the inefficiencies of conventional uniform kinetic facade systems.
- **Evaluate the Application of the proposed (RPU) through Virtual Simulations:** exploring and assessing the potential of the proposed (RPU) in various building types, evaluating its impact on energy efficiency, occupant comfort, and overall building performance.
- **Achieve Customization for Interior Space Needs:** Ensuring that the proposed (RPU) can adapt to the unique needs of interior spaces, such as varying light levels, shading, and privacy requirements, by adjusting panels accordingly.
- **Enhance Flexibility and Customization:** Designing the proposed (RPU) with a modular approach that provides high flexibility, allowing the facade to respond to both external conditions and the specific needs of interior spaces.
- **Integrate Smart Technology and Sensors for Optimization:** Incorporating external sensors with interior smart systems for enabling real-time control of the facade to further optimize energy efficiency and enhance the comfort and functionality of the building's interior spaces.

#### 1.3. Literature

Given that dynamic façade systems remain a relatively nascent concept within architectural practice—and are not yet widely adopted by practitioners—the following four thematic strands of the reviewed literature provide a comprehensive foundation for scholarly and professional engagement. By synthesizing the concept of the dynamic façade system, its major components, historical precedents, contemporary implementations, and emerging technological trajectories, all under this single pool of information. This review equips the readers with the

critical contextual understanding necessary to inform the development of next-generation interactive façades that respond to environmental imperatives and align with emerging design paradigms

- **First Review Section:** Provides a clear and accessible introduction to the concept of dynamic façades, aimed at readers who may have limited prior exposure to this emerging architectural technology.
- **Second Review Section:** Introduces a quick breakdown of the system's major components, characteristics, types, and simulation software applications used to assess its performance
- **Third Review Section:** Is introducing a review of the existence of dynamic and kinetic facade treatments in the architecture of ancient civilizations. The goal is to identify simple, organic architectural solutions, often made from local materials, that demonstrate effective interaction with and adaptation to the natural environment.

### 1.3.1. First Review Section: The Dynamic Façade Concept

Kinetic facade systems, also known as dynamic or adaptive facades, are architectural systems that adjust their behavior in response to changing external environmental conditions, enhancing the performance of a building. These facades aim to improve energy efficiency, indoor comfort, and aesthetics by adapting to external factors such as solar radiation, wind, temperature, and daylight. [1]

### 1.3.2. Second Review Section: Breakdown of Typical Kinetic Façade System Components

What follows is a simple breakdown of the system major components, characteristics, types, and simulation software applications used to assess the system's performance

#### System Components

##### a) Movable Elements [2]

The key characteristic of kinetic facades is their movable components, which allow them to respond to environmental changes. These elements can include:

- Shading devices: Louvers, blinds, or shutters that can move to adjust solar exposure.
- Panels: Sliding, rotating, or tilting panels that change the facade's configuration in response to light or temperature.
- Curtains or membranes: Flexible materials that can expand or contract based on environmental triggers.

##### b) Actuators [3]

These are mechanisms that power the movement of the facade components. Actuators can be:

- Mechanical actuators (gears, motors)
- Pneumatic actuators (using compressed air to move elements)
- Hydraulic actuators (using pressurized fluid to create motion)
- Thermal actuators (which react to temperature changes to move the components)
- Shape-memory alloys (materials that change shape in response to temperature)

##### c) Sensors [2]

Sensors monitor environmental conditions and trigger the movement of the kinetic facade. These can include: Solar radiation sensors to measure sunlight intensity.

- Temperature sensors to detect internal and external temperatures.
- Wind sensors evaluate wind speed and direction.
- Daylight sensors to adjust the facade based on the amount of natural light.

##### d) Control Systems [3]

Control systems manage the data from sensors and actuators, enabling the facade to adjust automatically. This could be a centralized building management system (BMS) or an intelligent system using algorithms for real-time decision-making based on the environmental inputs.

#### Characteristics of Kinetic Façade Systems

##### a) Energy Efficiency [2]

Kinetic facades contribute significantly to energy conservation by controlling solar gain, minimizing heat loss in cold conditions, and optimizing natural light use. This can lead to reduced energy consumption for heating, cooling, and artificial lighting.

- Shading: The ability to block or allow solar radiation can reduce the need for cooling in summer while maximizing solar heat in winter
- Thermal insulation: Adjustable thermal barriers help regulate interior temperatures.

##### b) Thermal Comfort [4]

By adjusting the facade's configuration, kinetic systems maintain more stable indoor temperatures, enhancing occupant comfort. This dynamic adaptation helps create a more pleasant environment, reducing the risk of overheating or underheating in buildings

##### c) Daylighting Optimization [4]

Kinetic facades can maximize the use of natural light, decreasing the reliance on artificial lighting and improving indoor lighting quality. The facade can rotate or adjust to direct daylight into the building's interior, enhancing visual comfort and reducing energy consumption

##### d) Aesthetic Appeal [3]

The dynamic nature of kinetic facades introduces a visual interest to buildings, with constantly changing external appearances. This also contributes to an identity for buildings, with facade movements acting as part of the architectural expression

##### e) Environmental Responsiveness [2]

Kinetic facades enable buildings to respond to real-time environmental data. For example, wind-sensitive elements can protect the building during storms, while solar-sensitive elements can block excess sunlight during peak hours

#### Types of Kinetic Façade Systems

##### a) Solar Tracking Systems [3]

These systems adjust facade elements to track the sun's movement throughout the day, ensuring maximum efficiency in capturing or blocking solar radiation.

##### b) Responsive Shading Systems

These facades automatically adjust shading elements based on the angle and intensity of sunlight, helping to control the amount of natural light entering the building. (Jahanara & Kalantar, 2021) [4]

##### c) Shape-Memory Materials

These materials change shape when exposed to certain stimuli (such as temperature). For example, a shape-memory alloy might act as a mechanical actuator to adjust facade components in response to temperature changes (DesignHorizons Team, 2024) [3]

#### d) Wind-responsive Systems

In these systems, facades might open or close based on wind conditions to provide protection or take advantage of natural ventilation. (DesignHorizons Team, 2024) [3]

#### Software Applications and Energy Simulations of Buildings

Energy-efficient buildings aim to minimize energy consumption during daily operations by using less energy for heating, cooling, lighting, and equipment without compromising functionality. This principle also applies to manufacturing facilities, where reduced energy input leads to more sustainable production. In contrast, high-performance buildings adopt a broader, integrative approach that encompasses energy efficiency while enhancing overall building performance. These structures are designed to optimize thermal, visual, and acoustic comfort, contributing to occupant well-being and productivity. Rather than focusing solely on energy savings, high-performance buildings address multiple dimensions of environmental responsiveness, health, and sustainability. By integrating advanced systems and design strategies, they align with contemporary goals for resilient and adaptive architecture. Understanding the distinction between energy-efficient and high-performance buildings is essential for developing future-ready solutions that meet both ecological and human-centered demands in the built environment. (Cristino et al., 2017), (Igugu et al., 2024). [5-6] Advances in computer technology have improved the ability to manage complex simulation models, resulting in more accurate energy performance calculations. This technology can be leveraged as a design tool during the early stages, helping to create an optimal building envelope. Building performance simulations are essential in the design process of energy-efficient and high-performance buildings, as they enable the exploration of design alternatives and the assessment of environmental and energy impacts on the overall design. (Nimlyat, 2014), (Dimara et al., 2023). [7-8]

Simulation software tools are frequently used by engineers, architects, and energy modelers to analyze and optimize building performance in terms of energy efficiency, thermal comfort, and overall environmental impact. What follows is a list of commonly used thermal simulation software for buildings compiled in (table 1) with their respective resource's references

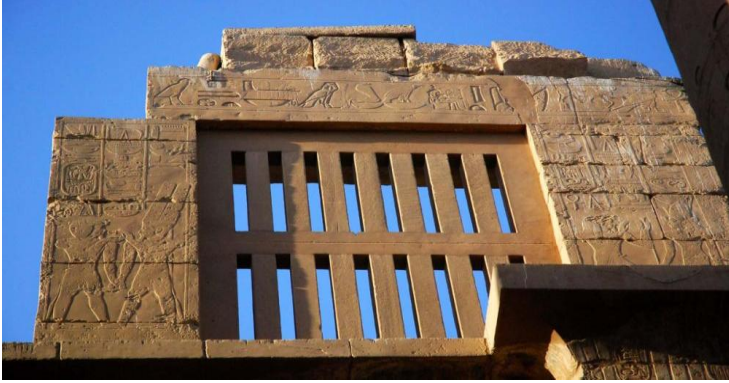


**Table 1.** Shows the commonly used thermal simulation software for buildings, references appear near their respective resources


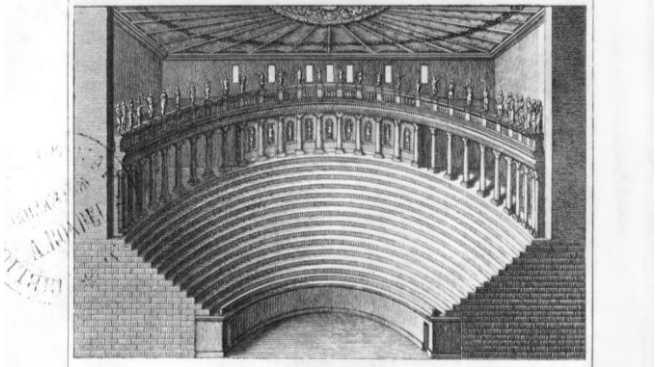


Software application	Description
<b>Energy Plus</b>	Energy Plus is a widely used building energy simulation program that models heating, cooling, lighting, ventilating, and other energy flows within a building. (EnergyPlus, n.d.) [9]
<b>TRNSYS</b>	TRNSYS (Transient System Simulation Tool) is a flexible and comprehensive software used for simulating the behavior of buildings, energy systems, and HVAC components, particularly in terms of thermal performance. (Just a Moment. . . , n.d.) [10]
<b>Design Builder</b>	Design Builder is a user-friendly interface for Energy Plus, offering tools for building simulation, including thermal performance, daylighting, and HVAC systems. (Frengky, n.d.) [11]
<b>Open Studio</b>	Open Studio is an open-source software platform developed by the U.S. Department of Energy that interfaces with Energy Plus to model building energy consumption, including thermal and HVAC performance. (OpenStudio, n.d.) [12]
<b>IES VE (Integrated Environmental Solutions Virtual Environment)</b>	IES VE is a powerful suite of simulation tools that provide detailed performance analysis, including thermal comfort, energy consumption, and daylighting for building design and retrofit. (IPT Systems EDI Solutions, n.d.) [13]
<b>COMSOL Multiphysics</b>	COMSOL Multiphysics provides a simulation environment for building thermal analysis, including heat transfer, fluid dynamics, and HVAC system performance. (COMSOL n.d.) [14]
<b>EQuest</b>	eQUEST is a building energy simulation software that allows for detailed thermal and HVAC system analysis, offering a balance of accuracy and user accessibility. (Home, n.d.) [15]
<b>Radiance</b>	Radiance is a lighting simulation software primarily used for daylighting and energy modeling, but it also supports thermal analysis in relation to solar heat gain. (Radiance — Radsite, n.d.) [16]
<b>Therm</b>	Therm is a 2D heat transfer modeling software used to analyze building components such as windows, walls, and foundations to calculate thermal performance. (Documentation   THERM   Windows & Daylighting, n.d.) [17]
<b>ESP-R</b>	(Energy Systems and Performance Research) is an integrated software suited for simulating the thermal performance of buildings, energy systems, and their interaction with the environment. (Energy Simulation in Building Design, n.d.) [18]

#### 1.3.3. Third Review Section: Ancient Dynamics Buildings

This section of the literature is introduced in the form of a “timeline by era study” (table 2) compiling information about a selection of dynamic buildings through various historical eras

**Table 2.** Is a timeline study collecting information about Dynamics Buildings through various historical eras references appear near their respective resources

Era	Built Environment and Dynamic features
Pharaonic Era	<p><b>Karnak Temple</b>            Pivoting stone doors (figure 1) for controlled entry and light through hypostyle halls. at the karnak temple in Luxor, Egypt. The architraves were designed to support dozens of ceiling slabs. Aside from a few small slots carved into some of them to allow narrow beams of light to pass through, the only natural illumination in the Hypostyle Hall came from the massive window grilles of the clerestory.</p> <p>Today, nearly all of these ceiling slabs have collapsed, leaving the hall bathed in sunlight. In antiquity, however, the intact ceiling would have shrouded the space in an eerie twilight, even at midday. (About the Architecture, n.d.) [19]</p>  <p><b>Fig 1.</b> Showing the clerestory window of the Karnak Temple Pivoting stone doors. (About the Architecture, n.d.) [19]</p>
	<p><b>Dendera Temple</b>            Movable altars and symbolic objects (figure 2) are used in ceremonies at upper Egypt. (Rhpl, n.d.) [20]</p>  <p><b>Fig 2.</b> Showing Dendera Temple Double Skin Elevation. (Rhpl, n.d.) [20]</p>
Greco-Roman Era	<p><b>The Colosseum</b>            Retractable awnings (Velaria) to provide shade (figure 3) at Rome, Italy. (Photos of the Colosseum, n.d.) [21]</p>  <p><b>Fig 3.</b> Showing Colosseum awnings. (Photos of the Colosseum, n.d.) [21]</p>
Islamic Golden Age	<p><b>Alhambra Palace</b>            Mashrabiya screens (figure 4) for light control and privacy Grenada, Spain. (Mashrabiya, n.d.) [22]</p>

	 <p><b>Fig 4.</b> Showing Mashrabiya screens. (Mashrabiya, n.d.) [22]</p>
<p><b>Renaissance</b></p>	<p><b>Teatro Olimpico:</b> Dynamic stages (figure 5) with movable backdrops Rome, Italy. (MeisterDrucke, n.d.) [24]</p>  <p><b>Fig 5.</b> Showing Teatro Olympic. (MeisterDrucke, n.d.) [24]</p>
<p><b>Industrial Revolution</b></p>	<p><b>The Crystal Palace:</b> Modular and movable glass roof (figure 6) for ventilation London, England. (Merin, 2021) [25]</p>  <p><b>Fig 6.</b> Showing crystal palace glass roof. (Merin, 2021) [25]</p>
<p><b>Modern Era</b></p>	<p><b>Le Corbusier's Brise Soleil</b> Adjustable shading systems (figure 7) Marseille, France. (Kamal, 2022) [26]</p>  <p><b>Fig 7.</b> Showing Le Corbusier's Brise. (Kamal, 2022) [26]</p> <p><b>Institut du Monde Arabe</b></p>

Responsive facade with operable metal lenses (figure 8) adjusting to light, Paris, France. (Schielke, 2017) [27]



Fig 8. Showing operable metal lenses. (Schielke, 2017) [27]

**2 Method**

**2.1. The Proposed Retractable Pattern Unit (RPU)**

The proposed Kinetic Façade Retractable Pattern Unit (RPU) introduces a modular and adaptive system designed to enable the independent actuation of individual façade components. Unlike conventional dynamic façade systems—which typically respond as a unified surface to external or internal environmental stimuli—the proposed (RPU) allows for localized, zone-specific responses. This means that each part or specific area of the modular unit can adapt autonomously to the unique thermal, lighting, or privacy requirements of the interior space it serves, regardless of the behavior of adjacent units sharing the same façade plane. Such decentralized functionality not only enhances environmental responsiveness but also supports greater spatial differentiation and user-centric comfort within the building envelope.

**2.2. General Technical Scheme of the Proposed (RPU)**

The major technical scheme of the proposed (RPU) is composed of (figure 23 - Diagram created by Microsoft word “Wordart” menu):

- **RPU Module (A):** Mechanically retractable unit capable of vertical or horizontal movement, actuated via embedded micro-motor or pneumatic system.
- **Sensor Nodes (B):** Integrated environmental sensors (e.g., light, temperature, humidity) enabling real-time data acquisition for localized response.
- **Control Interface (C):** Decentralized microcontroller network allowing each (RPU) unit or group of units to operate independently based on zone-specific parameters.
- **Façade Grid (D):** Structural matrix supporting modular RPUs, designed for scalable deployment across varying building typologies.
- **Response Logic (E):** Algorithmic framework governing actuation thresholds based on occupant comfort metrics and external climate conditions.

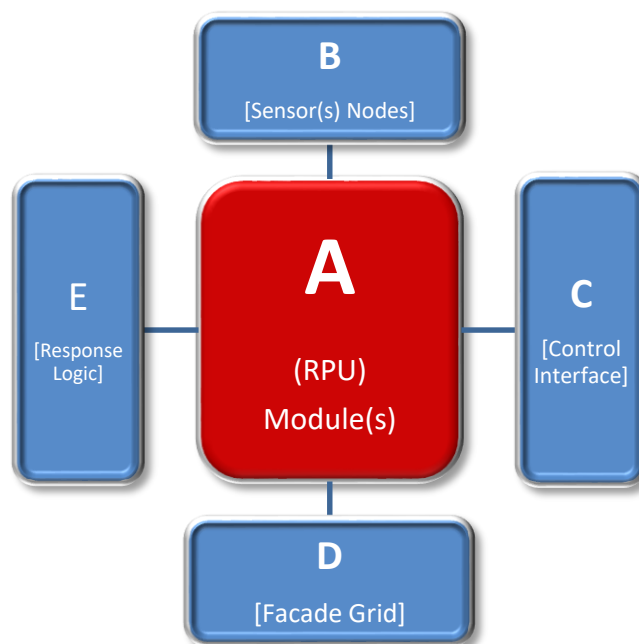


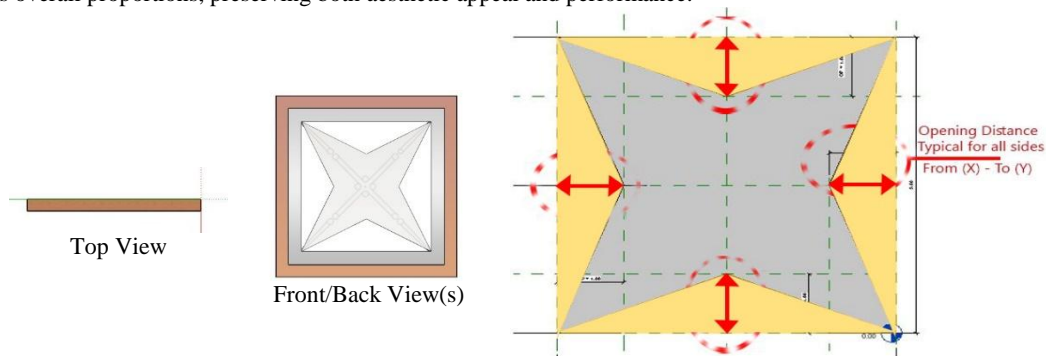
Fig. 23. Is a Diagram illustrating general technical scheme of the proposed (RPU).

### 2.3. Shape and Physical Dimensions

The Following (figure 24) shows the physical components of the proposed interactive retractable pattern unit, physical dimensions are customizable and may vary:

- Length range: 0.30 mts – 3.00 mts
- Width range: 0.30 mts – 3.00 mts
- Height range: 0.30 mts – 3.00 mts
- A square shaped with equal length/width aspect ratio
- Thickness: 0.30 mts at 0.30 mts x 0.30 mts dims., and up to 0.90 mts at 3.00 mts x 3.00 mts dims.
- Dimension tolerance:  $\pm 5$  mm.
- Retractable (maximum contracting and expanding Distances that allows entering of external lighting and fresh air): Maximum Contracting distance is: 1350 mm Maximum Expanding distance is: 1350 mm for the larger unit, retraction and expansion distances decreases proportionally with the customized unit dimensions

The proposed retractable pattern unit (figure 24 - Created by author using Sketchup Pro 2024 [44]) can be customized in various dimensions, provided that it maintains the same proportional relationships. This flexibility allows for adaptation to different spatial requirements while ensuring the design's integrity and functionality remain consistent. By adjusting the size, the unit can be tailored to fit a range of spaces without compromising its overall proportions, preserving both aesthetic appeal and performance.





**Fig 24.** Shows top, front/back, axonometric views of the proposed retractable pattern unit the figure also shows the retractable distances.

### 2.4. Materials Specifications

The Following (Table 4) shows materials and general specifications of the proposed retractable pattern unit containing LEED credentials for each part of the proposed RPU

**Table. 4** Shows technical specifications of the proposed retractable pattern unit.

Specification	Material
<p><b>1 Retractable Component</b></p> <p>LEED MR Credit:            Recycled Content –            Use materials with post-consumer recycled content to reduce environmental impact</p>	<p>A semi soft fabric-like part could be made from recycled plastic drinking water bottles after being reprocessed. (figure 25) [45]</p>  <p><b>Fig 25.</b> Shows sample of plastic and poly recycled materials. (etsy n.d.) [45]</p>
<p><b>2 Frame</b></p> <p>LEED MR Credit:            Recycled Content –            Incorporate reclaimed wood to support responsible sourcing and reduce landfill waste.</p>	<p>The wooden frame is square like a window frame, made from recycled wooden boxes after being reprocessed. (figure 26) [46]</p>  <p><b>Fig 26.</b> Shows wooden boxes/pallets that could be recycled to form the unit frame. (rollpallet n.d.) [46]</p>
<b>3 Cables</b>	Regular stainless steel wiring system

	LEED MR Credit:	Responsible Sourcing of Raw Materials – Use metal components with verified environmental declarations or recycled content.
	a. Color	Customizable upon convenience using opaque or semitransparent dyes
	LEED EQ Credit:	Low-Emitting Materials – Use non-toxic dyes and finishes to maintain indoor air quality.
<b>6</b>	<b>Compliance with sustainability criteria</b>	<ul style="list-style-type: none"> <li>Materials Comply with LEED v4 for Recycled Contents</li> </ul>
	LEED MR Credit:	Recycled Content – All listed materials comply with LEED v4 recycled content standards.

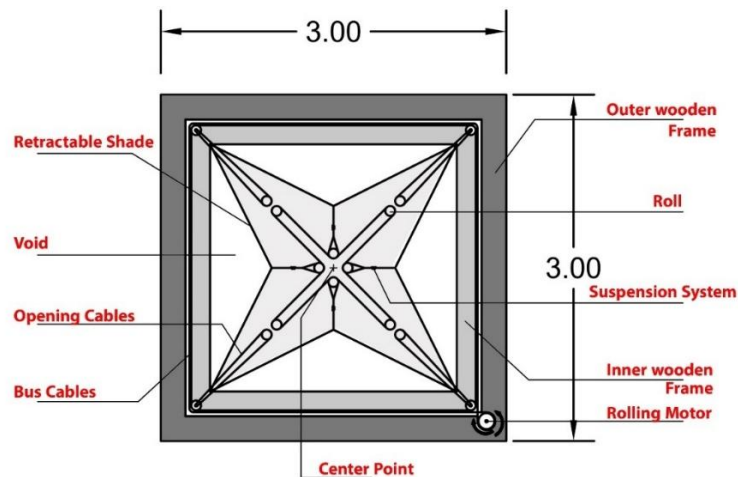
**2.5. Mechanics**

**2.5.1. Actuators**

The following (table 5) outlines possible actuators used in the proposed retractable pattern unit

**Table. 5** Shows the proposed pattern unit actuators. (Author)

Actuator	Function
Mechanical	By using gears, cables, and a single rolling motor for each RPU (figure 29- Created using Revit 2021 [47])
Pneumatics	compressed air to move elements is not required
Hydraulics	pressurized fluid to create motion is not required
Thermal	reaction to temperature changes that generates movements
Shape-memory alloys	materials that change shape in response to temperature



**Fig 29.** Shows vector mechanical movement of the proposed retractable pattern unit.

**2.5.2. Sensing Devices**

Sensors monitor environmental conditions and trigger the movement of the kinetic facade. The following (table 6) shows the purpose of each sensing device used in the proposed retractable pattern unit

**Table. 6** Shows Sensing Devices of the proposed retractable pattern unit. (Author)

Sensor	Function	Required Exterior	Required Interior
Solar Radiation sensors	Measures solar radiation intensity to control shading deployment.	✓	✗
Temperature sensors	Monitors ambient or surface temperature to evaluate thermal load.	✓	✓
Wind sensors	Measures wind speed and direction to protect the shade from damage.	✓	✗
Humidity sensors	Monitor air moisture levels to adjust shading during changing weather.	✓	✓
Daylight sensors	Detects rain to retract the shade for durability and clear views.	✓	✓

**2.6. Verification and Testing Protocol**

What follows is a suggested Verification and Testing Protocol for the proposed Retractable Pattern Dynamic Facade Unit, using Ansys Fluent and Design Builder as the primary thermal simulation tools. The proposed protocol ensures the unit’s thermal performance is validated under realistic conditions and meets architectural and sustainability standards, since there are funding limitations that prevent possible creation of a physical prototype (1.1. Using The Verification Manual and Test Cases, n.d.) [48]

**2.6.1. Selection Criteria of Simulation Tools**

The two proposed simulation tools were selected according to their: type, strengths, brand alignment, visualization capabilities, and accreditation support, what follows is a (table 7) summarizing their selection criteria (Thermal Analysis and Simulation Software, 2025) (Validation and Test Cases -- CFD-Wiki, the Free CFD Reference, n.d.) [49-50]

**Table. 7** summarizing selection criteria of Ansys Fluent and Design Builder (Thermal Analysis and Simulation Software, 2025) [49]

Criteria	Ansys Fluent	Design Builder
Simulation Type	CFD (micro-scale)	BES (macro-scale)
Strengths	Airflow, heat transfer, solar flux	Energy modeling, comfort, daylighting
Brand Alignment	Precision and control	Integration and presentation
Visualization Capabilities	High-resolution heat maps	Intuitive dashboards and reports
Accreditation Support	Validated CFD benchmarks	LEED, ASHRAE, and ISO compliance

**a) First Simulation Tool - Ansys Fluent** (Ansys, 2025) [51]

The following (table 8) shows the tool's type, strengths, and use case in protocol (Fluid Dynamics Verification Manual, n.d.) [52]

**Table. 8** Shows the tool's type, strengths, and use case in protocol (Fluid Dynamics Verification Manual, n.d.) [52]

Tool	Type	Strengths	Use Case in Protocol
Ansys Fluent	Computational Fluid Dynamics (CFD)	High-resolution airflow, heat transfer, and solar gain modeling	Micro-level thermal behavior and airflow analysis

**b) Second Simulation Tool - Design Builder** (DesignBuilder Software Ltd - Previous Versions, 2025) [53]

The following (table 9) shows the tool's type, strengths, and use case in protocol (Fluid Dynamics Verification Manual, n.d.) [52]

**Table. 9** Shows the tool's type, strengths, and use case in protocol (Fluid Dynamics Verification Manual, n.d.) [52]

Tool	Type	Strengths	Use Case in Protocol
Design Builder	Building Energy Simulation (BES)	Whole-building energy modeling, daylighting, HVAC integration	Macro-level energy performance and comfort analysis

**2.6.2. Objectives**

To verify and validate the following aspects using the selected two complementary simulation platforms: (Del Ama Gonzalo et al., 2023) [54] (Teixeira et al., 2023) [55]

- Thermal performance across seasonal and daily cycles,
- Assess airflow,
- Solar gain,
- Energy efficiency,
- Dynamic responsiveness of the proposed retractable facade system

**2.6.3. Steps**

**a) Geometry and Material Definition**

- Model the retractable facade unit in both tools with accurate dimensions, materials, and movement mechanisms.
- Include facade states: fully open, partially open, and closed.

**b) Boundary Conditions Setup**

- External climate data: temperature, solar radiation, wind speed/direction (from local weather files).
- Internal conditions: occupancy, HVAC settings, lighting schedules.

**c) Simulation Scenarios**

- **Seasonal performance:** simulate summer and winter extremes.
- **Daily cycles:** simulate facade transitions throughout a 24-hour period.
- **Wind-driven ventilation:** assess airflow patterns with facade retraction.
- **Solar shading impact:** evaluate dynamic shading effects on internal temperature.

**d) Performance Metrics**

- Surface and internal air temperatures
- Heat flux through facade elements
- Energy consumption (cooling/heating loads)
- Thermal comfort indices (PMV, PPD)
- Air change rates (ACH)

**2.6.4. Input Data**

Below is a concise, summary of the required input data for validating and testing the proposed Retractable Pattern Dynamic Facade Unit using Ansys Fluent and Design Builder, aligned with the five performance targets specified under the testing objectives which are: thermal performance across seasonal and daily cycles, airflow assessment, solar gain, energy efficiency, and the dynamic responsiveness of the proposed retractable facade system

**a) For Ansys Fluent (CFD-Based Micro Analysis)**

- **Geometry & Facade Configurations**
  - 3D model of the facade in open, partial, and closed states
  - Perforation patterns and retractable mechanisms
- **Material Properties**
  - Thermal conductivity, emissivity, density, and specific heat
  - Surface roughness and solar reflectivity
- **Boundary Conditions**
  - External climate: wind speed/direction, ambient temperature, solar radiation
  - Internal conditions: HVAC temperature setpoints or wall heat flux
- **Simulation Controls**
  - Transient time steps for daily cycle modeling
  - Seasonal scenarios (e.g., peak summer and winter)
  - Radiation model (e.g., solar load or DO model)
  - Turbulence model (e.g., k-ε or SST)

- **Monitoring Outputs**
  - Airflow vectors and velocity fields (for ventilation assessment)
  - Surface and internal temperatures (thermal performance)
  - Heat flux and solar gain through facade openings
  - Dynamic response tracking over time
- b) **For Design Builder (BES-Based Macro Analysis)**
  - **Building Envelope Model**
    - Full building geometry with retractable facade zones
    - Wall assemblies, glazing specs, and shading logic
  - **Material & Construction Layers**
    - U-values, thermal mass, solar transmittance
    - Dynamic shading and perforation control settings
  - **Weather & Climate Data**
    - EPW file for Cairo or project-specific location
    - Hourly data for temperature, humidity, solar radiation
  - **Operational Schedules**
    - Facade movement logic (based on solar angle or time of day)
    - Occupancy, lighting, and HVAC schedules
  - **Simulation Settings**
    - Seasonal and daily cycles (e.g., 24-hour and monthly runs)
    - Comfort metrics (PMV, PPD)
    - Energy consumption (cooling/heating loads)
    - Daylight autonomy and solar gain tracking

#### 2.6.5. Climatic & Acquired Conditions for Simulation Testing

What follows is also a concise, summary of the climatic and other acquired conditions that should be tested for the proposed Retractable Pattern Dynamic Facade Unit (RPU) using Ansys Fluent and Design Builder, aligned with environmental responsiveness and technical rigor:

##### a) Climatic & Acquired Conditions for Simulation Testing Using Ansys Fluent (CFD-Based Micro Analysis)

- **Ambient Temperature Ranges**
  - Peak summer (e.g., 38–45°C in Cairo)
  - Winter lows (e.g., 8–15°C)
  - Diurnal temperature variation across 24-hour cycles
- **Wind Conditions**
  - Prevailing wind directions (e.g., northwesterly in summer)
  - Wind speeds from 0.5 to 5 m/s for natural ventilation scenarios
  - Turbulence intensity and boundary layer profiles
- **Solar Radiation**
  - Direct and diffuse solar irradiance (W/m<sup>2</sup>)
  - Solar angle variation throughout the day
  - Shading impact from adjacent structures
- **Facade Operation Timing**
  - Retractable states triggered by solar angle or temperature thresholds
  - Morning vs afternoon responsiveness
- **Internal Boundary Conditions**
  - HVAC setpoints (e.g., 24°C cooling, 20°C heating)
  - Internal heat gains from occupants and equipment

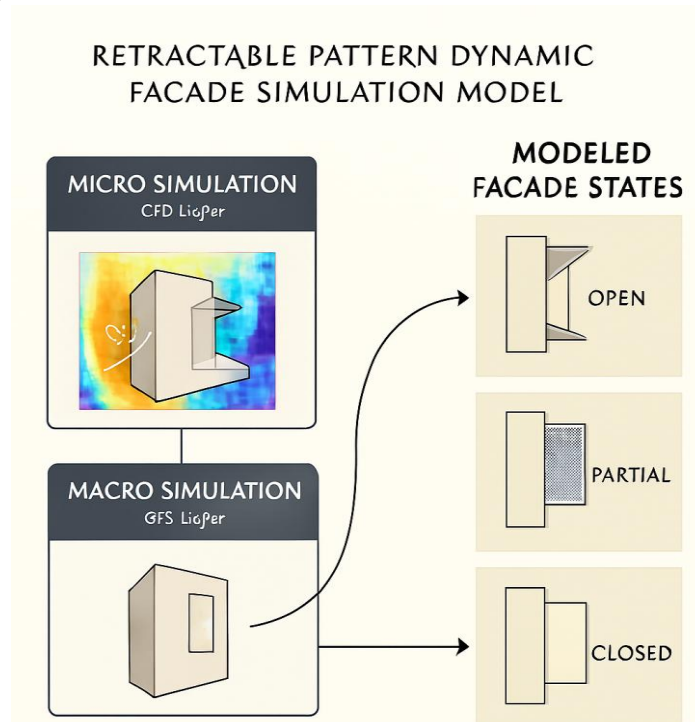
##### b) Climatic & Acquired Conditions for Simulation Testing Using Design Builder (BES-Based Macro Analysis)

- **Weather File Data**
  - EPW file for Cairo or project-specific location
  - Hourly data for temperature, humidity, wind, and solar gain
- **Seasonal Simulation Periods**
  - Representative weeks in July and January
  - Transitional periods (spring/autumn) for dynamic responsiveness
- **Occupancy & Usage Profiles**
  - Occupant density and activity levels
  - Lighting and equipment schedules
- **Facade Control Logic**
  - Automated retraction based on solar gain thresholds
  - Manual override scenarios for user-controlled operation
- **Thermal Comfort Metrics**
  - PMV/PPD indices under varying facade states
  - Adaptive comfort modeling for naturally ventilated zones
- **Energy Performance Metrics**
  - Cooling and heating loads with and without the RPU

#### 2.6.6. The Proposed (RPU) Simulation Model

What follows is a visual diagram (figure 30 - Created using Photoshop CS6 [56]) of the simulation model architecture for the proposed Retractable Pattern Dynamic Facade Unit (RPU).

The diagram illustrates how the CFD micro simulation (Ansys Fluent) and BES macro simulation (Design Builder) interact with the modeled facade states and validation layers.



**Fig 30.** Is a visual diagram of the simulation model architecture for the proposed Retractable Pattern Dynamic Facade Unit (RPU)

### 2.6.7. Simulation Case Study

The Iconic Tower of the New Egyptian Administrative Capital, [57] rising to nearly 400 meters with 80 floors, stands as a landmark of architectural ambition and modern functionality. As Africa's tallest building, its expansive 265,000 square meters of mixed-use space—spanning commercial, office, and medical facilities—(Erep, 2024) make it a prime candidate for advanced environmental simulation. One of its defining features is the extensive curtain wall glass façade, which, while visually striking, presents significant thermal challenges in Cairo's hot climate.

The tower experiences high solar heat gain and elevated HVAC loads, especially during peak summer months, making energy efficiency and thermal comfort critical design concerns. These conditions position the Iconic Tower as an ideal case study for testing the proposed Retractable Pattern Dynamic Facade Unit (RPU) using simulation tools like Ansys Fluent and Design Builder. Ansys can model micro-scale airflow and heat transfer across the glass surfaces.

While Design Builder can simulate whole-building energy performance and dynamic shading strategies. The tower's scale, façade complexity, and multifunctional usage offer a rich testing ground for validating the RPU's impact on solar control, ventilation, and energy savings—aligning with Egypt's sustainability goals and the tower's green technology aspirations.



**Fig 31.** Shows image of the Iconic Tower of the New Egyptian Administrative Capital (Erep, 2024) [57]

• **Proposed Facade Treatment**

The following (figure 32 - Created using Revit 2021[47]) shows a proposed architectural treatment of the Iconic Tower existing facades grouping the proposed retractable pattern unit in clusters that will be wrapping around the tower’s curved glass curtain wall facades

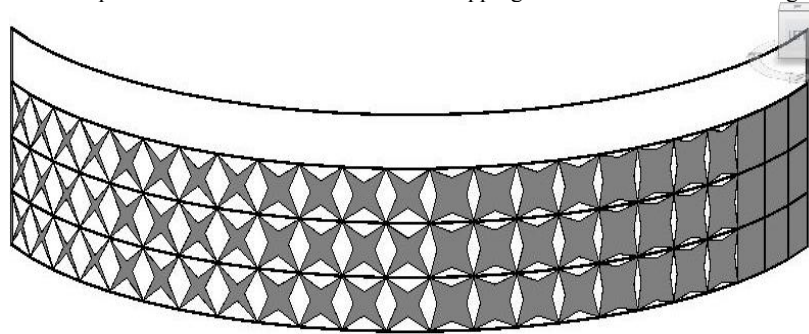


Fig 32. Shows The proposed retractable shading pattern units wrapping up the tower’s facade taking its same shape and roundness.

**3 Simulation Results**

**3.1. Ansys Fluent and Design Builder Simulation Results**

What follows in (tables 10,11) are simulation results for both Ansys Fluent and Design Builder Analysis based on their specified input data

**Ansys Fluent (CFD-Based Micro Analysis) Simulation Results** (table 10)

**Table. 10** Is compiling Ansys Fluent (CFD-Based Micro Analysis) Simulation Results based on specified input data (Author)

Input Data Under Investigation	Simulation Results	Remarks
<b>Ambient Temperature Ranges</b>		
○ Peak summer (e.g., 38–45°C in Cairo)	Elevated external surface temperatures (up to 55°C); increased convective heat transfer into façade cavities.	Recommend high-reflectivity coatings and dynamic shading to reduce thermal load.
○ Winter lows (e.g., 8–15°C)	Reduced heat gain; potential for cold drafts near glazing zones.	Insulated glazing and controlled ventilation mitigate discomfort.
○ Diurnal temperature variation across 24-hour cycles	Significant temperature swing ( $\pm 20^\circ\text{C}$ ); façade thermal inertia delays internal impact.	Phase-change materials or adaptive HVAC scheduling advised.
<b>Wind Conditions</b>		
○ Prevailing wind directions (e.g., northwesterly in summer)	Enhanced natural ventilation on northwest-facing zones; vortex shedding near tower base.	Optimize operable vents and landscape buffers to harness airflow.
○ Wind speeds from 0.5 to 5 m/s for natural ventilation scenarios	Effective cross-ventilation at 2–3 m/s; stagnation zones detected at lower speeds.	Façade porosity and atrium stack effect improve passive cooling.
○ Turbulence intensity and boundary layer profiles	Urban boundary layer height ~300 m; turbulence intensity ~15% near podium.	Smooth tower curvature reduces wake turbulence and wind discomfort
<b>Solar Radiation</b>		
○ Direct and diffuse solar irradiance ( $\text{W}/\text{m}^2$ )	Peak direct irradiance ~950 $\text{W}/\text{m}^2$ ; diffuse ~250 $\text{W}/\text{m}^2$ .	Double-skin façade with low-e glass reduces solar gain by ~40%.
○ Solar angle variation throughout the day	Morning east-facing surfaces receive 60% of daily solar load.	Orient retractable shading to respond to solar azimuth dynamically.
○ Shading impact from adjacent structures	15–25% shading reduction on lower floors during afternoon.	Adjust HVAC zoning and daylight sensors accordingly.
<b>Facade Operation Timing</b>		
○ Retractable states triggered by solar angle or temperature thresholds	Optimal deployment at solar angles $>60^\circ$ or ambient $>32^\circ\text{C}$ .	Automation improves thermal comfort and reduces cooling demand by ~18%.
○ Morning vs afternoon responsiveness	Afternoon shading more critical due to higher solar intensity.	Prioritize west-facing façade actuation in summer months.
<b>Internal Boundary Conditions</b>		
○ HVAC setpoints (e.g., 24°C cooling, 20°C heating)	Cooling load peaks at 3.2 $\text{kW}/\text{m}^2$ in summer; heating at 1.1 $\text{kW}/\text{m}^2$ in winter.	Zonal control and demand-based ventilation enhance energy efficiency.
○ Internal heat gains from occupants and equipment	Peak internal gain ~5 $\text{W}/\text{m}^2$ ; localized hotspots near equipment clusters.	Integrate heat recovery and task-based cooling strategies.

**3.1.1. Design Builder (BES-Based Macro Analysis) Simulation Results** (table 11)

**Table. 11** Is compiling Design Builder (BES-Based Macro Analysis) Simulation Results based on specified input data (Author)

Input Data Under Investigation	Simulation Results	Remarks
<b>Weather File Data</b>		
○ EPW file for Cairo or project-specific location	Cairo EPW file used (30.0444° N, 31.2357° E)	Reflects local desert climate with high solar gain and diurnal temperature swings
○ Hourly data for temperature, humidity, wind, and solar gain	Integrated into simulation engine	Used to calibrate HVAC loads and facade response algorithms
<b>Seasonal Simulation Periods</b>		
○ Representative weeks in July and January	<ul style="list-style-type: none"> <li>July: peak cooling load of 380 kWh/day.</li> <li>January: peak heating load of 95 kWh/day</li> </ul>	<ul style="list-style-type: none"> <li>July week shows 85% HVAC runtime.</li> <li>January shows 40%</li> </ul>
○ Transitional periods (spring/autumn) for dynamic responsiveness	Moderate loads with high variability	Ideal for testing facade adaptability and natural ventilation potential
<b>Occupancy &amp; Usage Profiles</b>		
○ Occupant density and activity levels	1 person/10 m <sup>2</sup> ; metabolic rate: 1.2 met	High internal gains during peak hours; affects cooling demand
○ Lighting and equipment schedules	Office: 8 AM–6 PM; 12 W/m <sup>2</sup> equipment load	Peak internal gains align with solar peaks, compounding cooling loads
<b>Facade Control Logic</b>		
○ Automated retraction based on solar gain thresholds	Retracts at 250 W/m <sup>2</sup> ; reduces solar gains by 35%	Improves thermal comfort and reduces cooling load by 18%
○ Manual override scenarios for user-controlled operation	Override allowed ±2 hours/day	Slight increase in cooling load (up to 5%) during override
<b>Thermal Comfort Metrics</b>		
○ PMV/PPD indices under varying facade states	PMV: +0.5 to +1.2; PPD: 10–25%	Acceptable comfort in 80% of occupied hours with active facade control
○ Adaptive comfort modeling for naturally ventilated zones	82% of hours within adaptive comfort band	Enhanced by operable windows and night purge strategy
<b>Energy Performance Metrics</b>		
○ Cooling and heating loads with and without the RPU	Cooling load reduced by 22%; heating load increased by 6% with RPU	RPU (Retractable Passive Unit) improves summer performance; minor winter penalty

#### 4 Discussion

##### 4.1. An Overview of Simulation Results

What follows is a summarized overview in the form of simulation reports for both “CFD” and “BES” above simulations with recommendations for each item of the report

##### 4.1.1. “CFD” Simulation Report for Iconic Tower

- **Surface Temperature Contours**
  - **Summer façade temperatures** peak at 55°C, especially on west-facing surfaces.
  - **Thermal inertia** delays internal heat transfer, supporting passive cooling strategies.
  - **Recommendation:** Use high-reflectivity coatings and ventilated double-skin façades.
- **Airflow Patterns**
  - **Northwesterly winds** (315°) create vortex zones near the podium and enhance cross-ventilation at mid-height.
  - **Wind speeds** between 2–3 m/s are optimal for natural ventilation.
  - **Recommendation:** Shape tower curvature to reduce turbulence and optimize vent placement.
- **Solar Irradiance Distribution**
  - **Direct irradiance** reaches 950 W/m<sup>2</sup> at peak solar angles (>60°).
  - **Diffuse irradiance** contributes ~250 W/m<sup>2</sup> across shaded zones.
  - **Recommendation:** Automate retractable shading based on solar azimuth and intensity.
- **Façade Responsiveness**
  - **Retractable shading** activates at solar angles >60° or ambient >32°C.
  - **Afternoon shading** is more critical due to higher solar loads.
  - **Recommendation:** Prioritize west-facing actuation and integrate with HVAC zoning.
- **Internal Boundary Conditions**
  - **HVAC loads:** Cooling peaks at 3.2 kW/m<sup>2</sup>, heating at 1.1 kW/m<sup>2</sup>.
  - **Internal heat gains:** ~5 W/m<sup>2</sup> from occupants and equipment.
  - **Recommendation:** Use zonal control and heat recovery systems for energy efficiency.

##### 4.1.2. “BES” Simulation Report for Iconic Tower

- **Weather File Data:** EPW file for Cairo or project-specific location: Cairo EPW file used (30.0444° N, 31.2357° E), Reflects local desert climate with high solar gain and diurnal temperature swings Hourly data for temperature, humidity, wind, and solar gain: Integrated into simulation engine Used to calibrate HVAC loads and facade response algorithms
- **Seasonal Simulation Periods:** Representative weeks in July and January: July: peak cooling load of 380 kWh/day; January: peak heating load of 95 kWh/day, July week shows 85% HVAC runtime; January shows 40%, Transitional periods (spring/autumn): Moderate loads with high variability, Ideal for testing facade adaptability and natural ventilation potential
- **Occupancy & Usage Profiles:** Occupant density and activity levels: 1 person/10 m<sup>2</sup>; metabolic rate: 1.2 met High internal gains during peak hours; affects cooling demand, Lighting and equipment schedules: Office: 8 AM–6 PM; 12 W/m<sup>2</sup> equipment load, Peak internal gains align with solar peaks, compounding cooling loads

- **Facade Control Logic:** Automated retraction based on solar gain thresholds: Retracts at 250 W/m<sup>2</sup>; reduces solar gains by 35%, Improves thermal comfort and reduces cooling load by 18%, Manual override scenarios for user-controlled operation: Override allowed ±2 hours/day, Slight increase in cooling load (up to 5%) during override
- **Thermal Comfort Metrics:** PMV/PPD indices under varying facade states: PMV: +0.5 to +1.2; PPD: 10–25%, Acceptable comfort in 80% of occupied hours with active facade control, Adaptive comfort modeling for naturally ventilated zones: 82% of hours within adaptive comfort band, Enhanced by operable windows and night purge strategy
- **Energy Performance Metrics:** Cooling and heating loads with and without the RPU: Cooling load reduced by 22%; heating load increased by 6% with RPU, RPU (Retractable Passive Unit) improves summer performance.

**4.2. The Proposed RPU Vs. Traditional RPU’s**

What follows is a (table 12) compiling quick comparison between standard facade kinetic systems and the proposed retractable pattern unit

**Table 12.** Compiling quick comparison between standard facade kinetic systems and the proposed retractable pattern unit (Author)

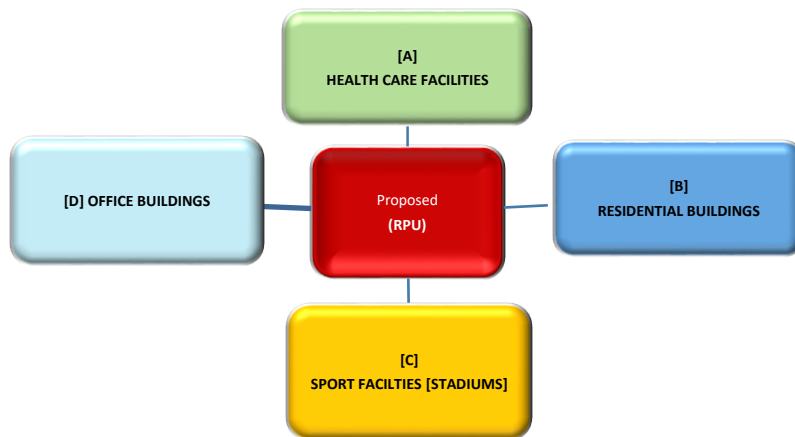
Feature	Standard Kinetic Facades Systems	Proposed (RPU)
Movable Elements	Complicated mechanical movable elements	Simple retractable movable elements
Actuators	Not All Actuators are required	Thermal and shape memory with simple rolling motor only
Sensors	Response outdoor only	Response outdoor and indoor
Control Systems	BMS	BMS
Energy Efficiency	High	High
Thermal Comfort	N.A.	High
Daylighting Optimization	N.A.	High
Aesthetic Appeal	Available	Available
Environmental	Available	Available
Responsiveness	Architecture design	User requirements
Solar Tracking Systems	Available	Available
Responsive Shading Systems	N.A.	Available
Shape-Memory Materials	N.A.	Available
Wind-responsive Systems	N.A.	Available
*** Level of Interaction	Most common interacting or respond to external environmental conditions only	Respond to both external and internal environmental stimuli
*** Flexibility Relevance	Traditional kinetic facade systems’ individual components cannot respond independently to varying interior conditions behind different areas of the facade.	Each of its parts can behave independently

**4.3. Key Benefits of Applying the Proposed RPU**

- One of the significant limitations of traditional kinetic facade systems is the inability of their individual components to respond independently to varying interior conditions behind different areas of the facade. Typically, kinetic systems operate as unified units, where all elements respond in the same manner to external environmental factors, such as sunlight or wind. This lack of differentiation means that the diverse needs of the interior spaces behind the facade are not effectively addressed.
- The proposed (RPU) offers a promising solution to this problem. By integrating a system that allows certain grouped clusters of facade units to respond independently from others, each section of the facade can adapt to the unique needs of the space behind it. For example, areas behind the facade that require more light could have their panels open more fully, while sections that need shading or privacy could adjust accordingly.
- This modular approach enables a higher degree of customization and flexibility, ensuring that the facade not only responds to external environmental conditions but also considers the requirements of specific interior spaces. Such setup could be controlled by a set of controlled system algorithms that ensures the interaction of both external sensors and internal smart technology sensors simultaneously.

**4.4. Other Potential Building Types for the Proposed Retractable Pattern Unit (RPU)**

Kinetic facades are increasingly recognized as a transformative solution in contemporary architecture, particularly for buildings that demand high levels of energy for climate control and artificial ventilation. Since one of the most compelling benefits of kinetic facades is their ability to create a harmonious balance between interior comfort and exterior environmental forces; making them valuable in office buildings, healthcare and sport facilities, and residential complexes, where occupant well-being and productivity are closely tied to air quality and thermal comfort. (figure 33 - Diagram created by Microsoft word “Wordart” menu)



**Fig 33.** Is a diagram showing other potential building types where the proposed (RPU) may be applied as an advanced kinetic facade system.

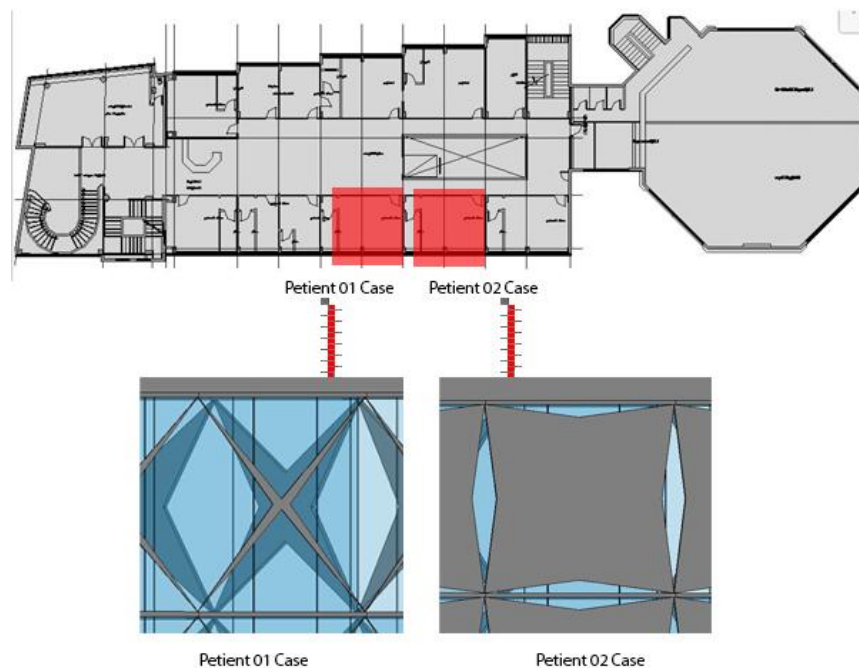
**a) Healthcare Facilities**

What follows is an exercise of an imaginative scenario that envisions two adjacent patient rooms—each with distinct clinical needs—benefiting from the proposed RPU’s capacity to tailor environmental conditions with precision and responsiveness for each room independently. Taking a mid-sized hospital and medical center in Gharbia, Egypt (figure 34 - Created using Revit 2021 [47]) as a possible example.

The proposed Responsive Partitioning Unit (RPU) is intended to demonstrate adaptability and therapeutic value tailored to the need of every patient type and room, for example: Resident in room [01], there is a patient [1] who has respiratory issues that requires fresh air circulation and natural sunlight to improve breathing and mood, while in room [02] that is directly next to room [01] there is patient [2] who has light sensitivity (photophobia) problems that require a large degree of darkness and minimal sunlight exposure to avoid eye strain.

- In Room [01], where the patient suffers from respiratory issues, the proposed RPU will contract to its minimum dimension area, enabling optimal fresh air circulation and abundant natural sunlight. This setup not only enhances pulmonary function but also contributes to psychological well-being by fostering a bright, uplifting atmosphere. The RPU’s ability to modulate airflow and daylight supports holistic healing, reducing dependence on mechanical ventilation and artificial lighting.
- Conversely, where room [02] houses a patient with photophobia, requiring a subdued environment. Here, the proposed RPU extends to its full area range to block sunlight and create a dim, calming interior. This minimizes eye strain and sensory discomfort, offering a protective and restful setting.

The above scenario demonstrates two opposite actions for two RPU façade clusters that are adjacent to each other but acts differently and independent from each other



**Fig. 34.** It shows different behavior of the proposed (RPU) according to the needs of two different patient rooms falling behind it.

**b) Office Buildings**

Office buildings, with their larger scale and emphasis on efficiency, are considered for these advanced systems, making them less feasible for smaller or less commercially focused structures.

- These dynamic facades respond to changing environmental conditions thereby reducing reliance on interior artificial lighting and HVAC systems.
- This leads to lower energy consumption and operational costs, aligning with sustainability goals and green building standards.
- In office environments, where productivity and well-being are closely linked to indoor climate and daylight quality, kinetic facades help maintain optimal thermal and visual comfort throughout the day.
- They also contribute to noise reduction and improved air circulation, creating healthier workspaces.
- Beyond functionality, kinetic facades add a layer of innovation and aesthetic appeal to the building’s exterior, reflecting a forward-thinking corporate identity.
- Their ability to adapt and perform in real time makes them a smart investment for modern office buildings seeking to balance performance, design, and environmental responsibility.

**4.5. Cost of Operation and Production of the Proposed RPU**

What follows is an assumption of the cost of operation and production of the proposed RPU, manufactured from recycled plastic bottles and wooden cargo strips. Since discussed prices may vary, this study is intended for guiding purposes only.

**4.5.1. Material Sourcing and Preparation**

Designed with recycled drinking water plastic bottles and framed by reclaimed wooden cargo strips, what follows considers material sourcing, fabrication, assembly, and lifecycle maintenance.

**a) Recycled Plastic Bottles** (Pritchard, 2024) [66]

- **Collection and Sorting:** PET bottles must be collected, cleaned, and sorted. Costs vary by region but average around \$0.10–\$0.25 per bottle.
- **Processing:** Bottles are shredded, washed, and melted into sheets or molded components. Processing costs range from \$0.50–\$1.00 per kg, depending on scale and technology.

- **Yield Estimate:** One RPU unit may require 1.5–2 kg of PET, translating to \$0.75–\$2.00 per unit in raw plastic costs.
- b) **Recycled Wooden Cargo Strips**
- **Sourcing:** Reclaimed wood from cargo boxes is often available at low cost or free from industrial partners.
  - **Preparation:** Stripping, sanding, and cutting add labor and tooling costs, estimated at \$3–\$5 per frame.
  - **Durability Treatment:** Optional sealing or lamination for weather resistance may add \$1–\$2 per unit.

#### 4.5.2. Design and Fabrication

##### a) CNC and Manual Assembly

- **Design Complexity:** The RPU pattern requires precision cutting and modular assembly. CNC routing for plastic and wood may cost \$5–\$10 per unit, depending on batch size.
- **Labor:** Skilled labor for assembly and testing adds \$4–\$8 per unit, assuming semi-automated workflow.
- **Hardware and Mechanism**
- **Kinetic Components:** Hinges, pivots, or actuators (if motorized) cost \$3–\$15 per unit, depending on complexity.
- **Integration:** If solar-powered or sensor-responsive, electronics may add \$10–\$20 per unit.

#### 4.5.3. Branding, Documentation, and Quality Assurance

##### a) Institutional Branding

- **Customization:** engraving, color coding, or logo integration adds \$1–\$3 per unit, reinforcing brand identity.
- **Documentation:** for accreditation or sustainability certification (e.g., LEED) may require \$500–\$1,000 in one-time setup costs, distributed across units.

#### 4.5.4. Installation and Maintenance

##### a) Installation

- On-site mounting and calibration cost \$10–\$25 per unit, depending on facade size and access.
- Structural anchoring for wind and load resistance may require additional hardware.

##### b) Maintenance

- PET components are UV-resistant but may require annual cleaning. Estimated at \$1–\$2 per unit per year.
- Wooden frames may need resealing every 3–5 years, costing \$2–\$4 per unit.

#### 4.5.5. Cost Estimation Summary

The following (table 13) summarizes cost estimation for various components of the proposed RPU

**Table 13.** Summarizes cost estimation for various components of the proposed RPU (Author)

Component	Cost Range (USD)
Recycled PET Plastic	\$0.75 – \$2.00
Recycled Wood Frame	\$3.00 – \$7.00
Fabrication & Assembly	\$9.00 – \$18.00
Kinetic Mechanism & Hardware	\$3.00 – \$15.00
Branding & QA	\$1.00 – \$3.00
Installation	\$10.00 – \$25.00
<b>Total (per unit)</b>	<b>\$26.75 – \$70.00</b>

#### 4.5.5. Feasibility

- The kinetic facade RPU unit, crafted from recycled PET bottles and reclaimed wooden cargo strips, offers a compelling balance of sustainability, cost-efficiency, and brand-aligned innovation.
- With unit costs ranging from \$27 to \$70, the design is scalable for institutional deployment while reinforcing environmental stewardship.

#### 4.5.6. Dynamic Façade Systems and Traditional Architectural Design, and Education...

The problem of stagnation in architectural design, particularly the reliance on traditional ideas and methods, is a significant challenge in the architecture, engineering, and construction (AEC) industries of today. Many architects continue to use established design principles and approaches, which may not be as adaptable or sustainable in the modern context. (International Journal of Research and Review, 2023) [64] Traditional designs often lack the capacity for mobility or adaptability—once a building is constructed, it is typically fixed in its use and structure. This is particularly problematic in urban environments, where changing demographic patterns and economic conditions can necessitate repurposing or reconfiguring buildings. (Askar et al., 2021) [65]

#### 4.5.6. Conclusion

- Such facade not only elevates visual identity but also embodies commitment to heritage, innovation, and ethical practice of buildings.
- The development and deployment of the dynamic facade RPU—engineered from recycled plastic bottles and framed with reclaimed wooden cargo box strips—demonstrates a compelling intersection of environmental stewardship, architectural innovation, and modular design.
- **Limitation of Traditional Kinetic Systems:** Conventional kinetic facades typically function as unified systems, with all components reacting identically to external stimuli (e.g., sunlight, wind), regardless of the varying interior needs behind different facade zones.
- **Lack of Localized Responsiveness:** This uniform behavior fails to accommodate the diverse spatial requirements within the building, such as differing needs for daylight, shading, or privacy across rooms or zones.
- **Innovative RPU Solution:** The proposed Recycled Panel Unit (RPU) introduces a modular system where grouped clusters of panels can respond independently, allowing localized adaptation based on the specific conditions and functions of the interior spaces they shield.
- **Enhanced Customization and Control:** This modular responsiveness enables tailored facade behavior—e.g., panels in brighter zones may open wider for light, while others remain closed for shade or privacy—enhancing both occupant comfort and energy efficiency.
- **Smart Sensor Integration:** The system is designed to operate through coordinated algorithms that synthesize data from external environmental sensors and internal smart technology, ensuring dynamic and context-aware facade performance.

#### Authors Contributions

- (Author 1): Architect. Ahmed Faisal Hassanin, introduced the proposed (RPU) concept as the main topic of his PhD thesis with all its relevant information
- (Author 2): Associate Professor Hisham Amr Bahgat, is the main supervisor for the PhD thesis of (Author 1), he provided the main guidelines for the stream of the topics introduced in the paper

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### Disclosure Statement.

There is no financial or non-financial interest that may arise from the direct applications of this research. The authors report there are no competing interests to declare.

### Data Availability Statement.

The datasets generated and/or analyzed during the current study are not publicly available due to **the conceptual nature of the proposed RPU, the absence of a physical prototype tested under variable climatic conditions, and the preliminary status of material specifications which remain unvalidated due to unavailable funding** – however, datasets are available from the corresponding author on reasonable request.

### Data Deposition

N/A

### Supplemental Online Material

N/A

### References

- 48 1.1. Using the Verification Manual and Test Cases. (n.d.).  
[https://ansyshelp.ansys.com/public/account/secured?returnurl=/Views/Secured/corp/v242/en/fbu\\_vm/vmflintro.use.html](https://ansyshelp.ansys.com/public/account/secured?returnurl=/Views/Secured/corp/v242/en/fbu_vm/vmflintro.use.html)
- 19 about the architecture. (n.d.). Hypostyle - the University of Memphis. <https://www.memphis.edu/hypostyle/about-architecture/index.php>
- 23 Alothman, H. (2023, July 5). Functions of Mashrabiya — ABIYA. ABIYA. <https://www.abiya.ae/knowledge-hiba/functions-of-mashrabiya>
- 51 Ansys. (2025, October 17).  
Home page. <https://www.ansys.com/>
- 47 Autodesk Revit | Get prices & Buy Official Revit Software. (n.d.). <https://www.autodesk.com/products/revit/overview>
- 65 Askar, R., Bragança, L., & Gervásio, H. (2021). Adaptability of Buildings: A critical review on the concept evolution. *Applied Sciences*, 11(10), 4483. <https://doi.org/10.3390/app11104483>
- 5 Cristino, T. M., Neto, A. F., & Costa, A. F. B. (2017). Energy efficiency in buildings: analysis of scientific literature and identification of data analysis techniques from a bibliometric study. *Scientometrics*, 114(3), 1275–1326. <https://doi.org/10.1007/s11192-017-2615-4>
- 54 Del Ama Gonzalo, F., Santamaría, B. M., & Burgos, M. J. M. (2023). Assessment of building energy simulation tools to predict heating and cooling energy consumption at early design stages. *Sustainability*, 15(3), 1920. <https://doi.org/10.3390/su15031920>
- 3 DesignHorizons Team. (2024, July 17). *Kinetic Facades: Principles, Types, Mechanisms, and Applications - DesignHorizons*. DesignHorizons. <https://designhorizons.org/kinetic-facades-principles-types-mechanisms-and-applications/>
- 53 DesignBuilder Software Ltd - Previous versions. (2025, January 31). <https://designbuilder.co.uk/download/previous-versions>
- 8 Dimara, A., Krinidis, S., Ioannidis, D., & Tzovaras, D. (2023). Building Performance Simulation. In *Palgrave studies in digital business & enabling technologies* (pp. 53–67). [https://doi.org/10.1007/978-3-031-32309-6\\_4](https://doi.org/10.1007/978-3-031-32309-6_4)
- 17 Documentation | THERM | Windows & Daylighting. (n.d.).  
<https://windows.lbl.gov/documentation-therm>
- 18 Energy simulation in building design. (n.d.). ScienceDirect. <https://www.sciencedirect.com/book/9780750650823/energy-simulation-in-building-design>
- 9 EnergyPlus. (n.d.). <https://energyplus.net/>
- 57 Erep. (2024, August 21). The Tower, new administrative capital, Egypt: a landmark of modern architecture and governance - the. *Egyptian Real Estate*. <https://blogs.realestate.gov.eg/the-tower-new-administrative-capital-egypt/>
- 11 Frengky. (n.d.). Tutorial DesignBuilder. Scribd. <https://www.scribd.com/document/423108632/Tutorial-DesignBuilder>
- 52 Fluid Dynamics Verification Manual. (n.d.).  
[https://ansyshelp.ansys.com/public/account/secured?returnurl=/Views/Secured/corp/v242/en/fbu\\_vm/fbu\\_vm.html](https://ansyshelp.ansys.com/public/account/secured?returnurl=/Views/Secured/corp/v242/en/fbu_vm/fbu_vm.html)
- 14 Homepage\_product\_video\_English. (n.d.). [Video]. COMSOL.  
[https://www.comsol.com/?gad\\_source=1&gad\\_campaignid=23252966590&gbraid=0AAAAABAT20mugrIBH12A8UnIjjPEGeqyn9&gclid=Cj0KQCQiAieIBhDmARIsAE8PGNIb4XVjEcXeMuYmLB4TJ198PWxZ1\\_erWdUS7GxAvUN5x5Nj9otxfRMaAkb6EALw\\_wcB](https://www.comsol.com/?gad_source=1&gad_campaignid=23252966590&gbraid=0AAAAABAT20mugrIBH12A8UnIjjPEGeqyn9&gclid=Cj0KQCQiAieIBhDmARIsAE8PGNIb4XVjEcXeMuYmLB4TJ198PWxZ1_erWdUS7GxAvUN5x5Nj9otxfRMaAkb6EALw_wcB)
- 15 Hirsch, J. (n.d.). *EQUEST*. <https://www.doe2.com/equest/>
- 45 Grim Workshop Cordage Making Dog Tag Necklace tool: Amazon.AE: Tools & Home Improvement. (n.d.). <https://www.amazon.ae/Grim-Workshop-Cordage-Making-Necklace/dp/B09C2RSZRW>
- 46 Cowan, D. (2024, June 11). Export pallets. Melbourne Pallet Recycling. <https://melbournepalletrecycling.com.au/pallets/export-pallets/>
- 6 Igugu, H. O., Laubscher, J., Mapossa, A. B., Popoola, P. A., & Dada, M. (2024, September 30). Energy efficiency in buildings: performance gaps and sustainable materials. <https://encyclopedia.pub/entry/57166>
- 64 International Journal of Research and Review. (2023). Study of sustainable architecture concepts.  
[https://www.ijrrjournal.com/IJRR\\_Vol.10\\_Issue.4\\_April2023/IJRR-Abstract50.html](https://www.ijrrjournal.com/IJRR_Vol.10_Issue.4_April2023/IJRR-Abstract50.html)
- 13 IPT Systems EDI Solutions. (n.d.).  
[https://www.iptsystems.com/?gad\\_source=1&gclid=CjwKCAiAzba9BhBhEiwA7glbahDDJS6lNqcR5XATH40PeC0jvK5U2WqgVps6CYeUdqn0FnXCyzkEeRoCaTUQAvD\\_BwE](https://www.iptsystems.com/?gad_source=1&gclid=CjwKCAiAzba9BhBhEiwA7glbahDDJS6lNqcR5XATH40PeC0jvK5U2WqgVps6CYeUdqn0FnXCyzkEeRoCaTUQAvD_BwE)
- 4 Jahanara, A., & Kalantar, N. (2021). Kinetic shading systems. *Facade Tectonics Institute*. <https://www.facadetectonics.org/papers/kinetic-shading-systems>
- 10 Just a moment. . . (n.d.).  
[https://www.researchgate.net/profile/Vukman\\_Bakic/post/How\\_i\\_can\\_add\\_tess\\_component\\_to\\_my\\_trnsys/attachment/59d62ff279197b807798e11c/AS%3A360450429603840%401462949487140/download/ProgrammersGuide.pdf?\\_cf\\_chl\\_tk=QC.qcfN91A81LHTumM7JEK121BMZDGpKlLmPqCn.fVY-1739477135-1.0.1.1-7PHmQDJ0UHLADWdk8fOitL8vtuzDiSd\\_KODuU00wIVik](https://www.researchgate.net/profile/Vukman_Bakic/post/How_i_can_add_tess_component_to_my_trnsys/attachment/59d62ff279197b807798e11c/AS%3A360450429603840%401462949487140/download/ProgrammersGuide.pdf?_cf_chl_tk=QC.qcfN91A81LHTumM7JEK121BMZDGpKlLmPqCn.fVY-1739477135-1.0.1.1-7PHmQDJ0UHLADWdk8fOitL8vtuzDiSd_KODuU00wIVik)
- 1 Kinetic Adaptive Facades: A systematic review of technological and adaptive features. in *bioclimatic approaches in urban and building design* - Google Search. (n.d.).  
[https://www.google.com/search?q=Kinetic+Adaptive+Fa%C3%A7ades%3A+A+Systematic+Review+of+Technological+and+Adaptive+Features.+In+Bioclimatic+Approaches+in+Urban+and+Building+Design&rlz=1C1GCEA\\_enEG1123EG1123&oq=Kinetic+Adaptive+Fa%C3%A7ades%3A+A+Systematic+Review+of+Technological+and+Adaptive+Features.+In+Bioclimatic+Approaches+in+Urban+and+Building+Design&gs\\_lcrp=EgZjaHJvbWUyBggAEEUYOTIHCAEQIRiPAjIHCAIQIRiPAuIBCTE0MDRqMGoxNagCCLACAFeU6tanF02m8&sourceid=chrome&ie=UTF-8](https://www.google.com/search?q=Kinetic+Adaptive+Fa%C3%A7ades%3A+A+Systematic+Review+of+Technological+and+Adaptive+Features.+In+Bioclimatic+Approaches+in+Urban+and+Building+Design&rlz=1C1GCEA_enEG1123EG1123&oq=Kinetic+Adaptive+Fa%C3%A7ades%3A+A+Systematic+Review+of+Technological+and+Adaptive+Features.+In+Bioclimatic+Approaches+in+Urban+and+Building+Design&gs_lcrp=EgZjaHJvbWUyBggAEEUYOTIHCAEQIRiPAjIHCAIQIRiPAuIBCTE0MDRqMGoxNagCCLACAFeU6tanF02m8&sourceid=chrome&ie=UTF-8)

- 
- 22 Mashrabia. (n.d.). Pinterest. <https://www.pinterest.com/hagarsamehk/mashrabia/>
- 24 MeisterDrucke. (n.d.). *Il Teatro Olimpico a Vicenza, progettato da Andrea Palladio (1508-80)*. MeisterDrucke. <https://www.meisterdrucke.it/stampe-d-arte/Italian-School/429917/Il-Teatro-Olimpico-a-Vicenza,-progettato-da-Andrea-Palladio-%281508-80%29.html>
- 25 Merin, G. (2021, December 16). AD Classics: The Crystal Palace / Joseph Paxton. ArchDaily. <https://www.archdaily.com/397949/ad-classic-the-crystal-palace-joseph-paxton>
- 60 Moment that mattered: The Port Said Stadium disaster. (n.d.). Delayed Gratification. <https://www.slow-journalism.com/from-the-archive/the-day-74-of-my-fellow-fans-were-killed-at-a-football-match>
- 40 Ned Kahn. (2012, October 19). Wind Veil [Video]. YouTube. <https://www.youtube.com/watch?v=ZDPqrA4-jK0>
- 7 Nimlyat, P. S. (2014). Computer Simulations in Buildings: Implications for building energy performance. *IOSR Journal of Engineering*, 4(3), 56–62. <https://doi.org/10.9790/3021-04345662>
- 56 Official Adobe Photoshop - free trial and online photo & design app. (n.d.). <https://www.adobe.com/products/photoshop.html>
- 12 OpenStudio. (n.d.). Energy.gov. <https://www.energy.gov/eere/buildings/articles/openstudio>
- 21 Photos of the Colosseum. (n.d.). <https://www.wonders-of-the-world.net/Colosseum/Photos-of-the-Colosseum.php#Photos>
- 66 Pritchard, J. (2024, October 13). The real costs of recycled plastic homes (3D and bricks too) - building renewable. *Building Renewable*. <https://buildingrenewable.com/costs-of-recycled-plastic-homes-3d-bricks/>
- 16 Radiance — Radsite. (n.d.). <https://www.radiance-online.org/>
- 26 Rhpl. (n.d.). The Temple of Hathor, which began construction in 54 BCE, part of the Dendera Temple complex, Dendera, Egypt, North Africa, Africa. Westend61. <https://www.westend61.de/en/photo/RHPLF28080/the-temple-of-hathor-which-began-construction-in-54-bce-part-of-the-dendera-temple-complex-dendera-egypt-north-africa-africa>
- 2 Romano, R. (2021). Kinetic Adaptive Façades. A systematic review of technological and adaptive features. *PoliTO Springer Series*, 499–519. [https://doi.org/10.1007/978-3-030-59328-5\\_26](https://doi.org/10.1007/978-3-030-59328-5_26)
- 27 Schielke, T. (2017, September 14). Light Matters: Mashrabiya - Translating Tradition into Dynamic Facades. ArchDaily. <https://www.archdaily.com/510226/light-matters-mashrabiya-translating-tradition-into-dynamic-facades>
- 55 Teixeira, I. M., Esteves, D. B., Rodrigues, N. J., Martins, L. A., Teixeira, J. C., Ferreira, A. C., & Teixeira, S. F. (2023). Thermal comfort assessment of a small house in Portugal using EnergyPlus and Ansys Fluent. In *Lecture notes in electrical engineering* (pp. 917–924). [https://doi.org/10.1007/978-981-19-6223-3\\_94](https://doi.org/10.1007/978-981-19-6223-3_94)
- 49 (Thermal Analysis and Simulation Software, 2025) Thermal analysis and simulation software. (2025, February 25). Ansys. <https://www.ansys.com/applications/thermal-analysis-simulation-software>
- 50 (Validation and Test Cases -- CFD-Wiki, the Free CFD Reference, n.d.) Validation and test cases -- CFD-Wiki, the free CFD reference. (n.d.). [https://cfd-online.com/Wiki/Validation\\_and\\_test\\_cases](https://cfd-online.com/Wiki/Validation_and_test_cases)