Passive Adaptive Solar Shading of Building envelope using Smart Materials

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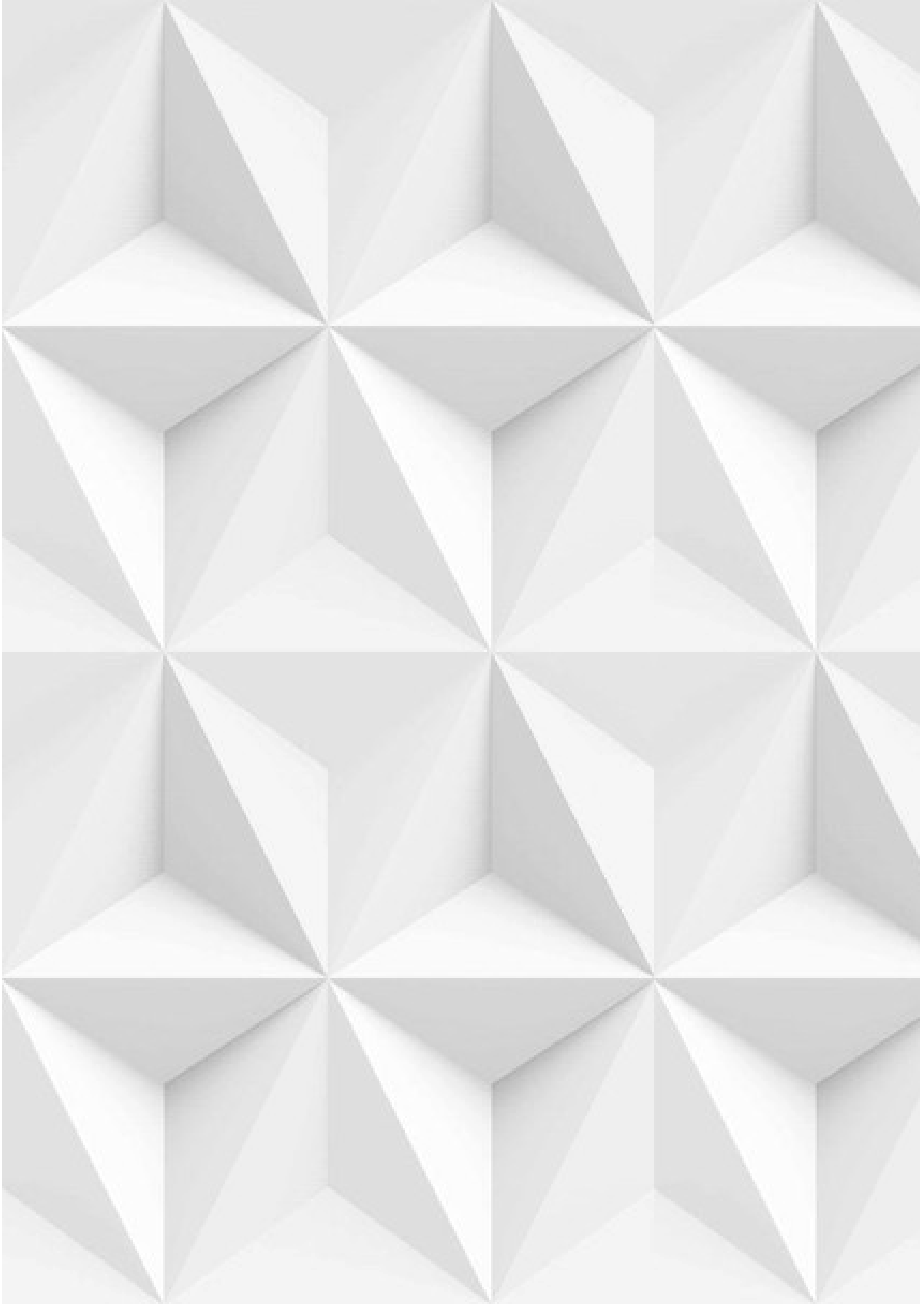

ACKNOWLEDGEMENTS

This thesis, “Passive Adaptive Solar Shading of Building Envelope using Smart Materials”, marks the culmination of an enriching journey of research, exploration, and personal growth. I am profoundly grateful to all those who have guided, encouraged, and supported me throughout this endeavor.

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I extend my sincere thanks to my family members, whose constant support, patience, and motivation have sustained me through the challenges of this research.

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Lastly, I am grateful to the academic community and to the field of urban and architectural innovation itself, which continues to inspire the pursuit of sustainable and thoughtful design solutions for the future.

This thesis is dedicated to all those who believe in the transformative power of research, design, and innovation to shape a more sustainable built environment.

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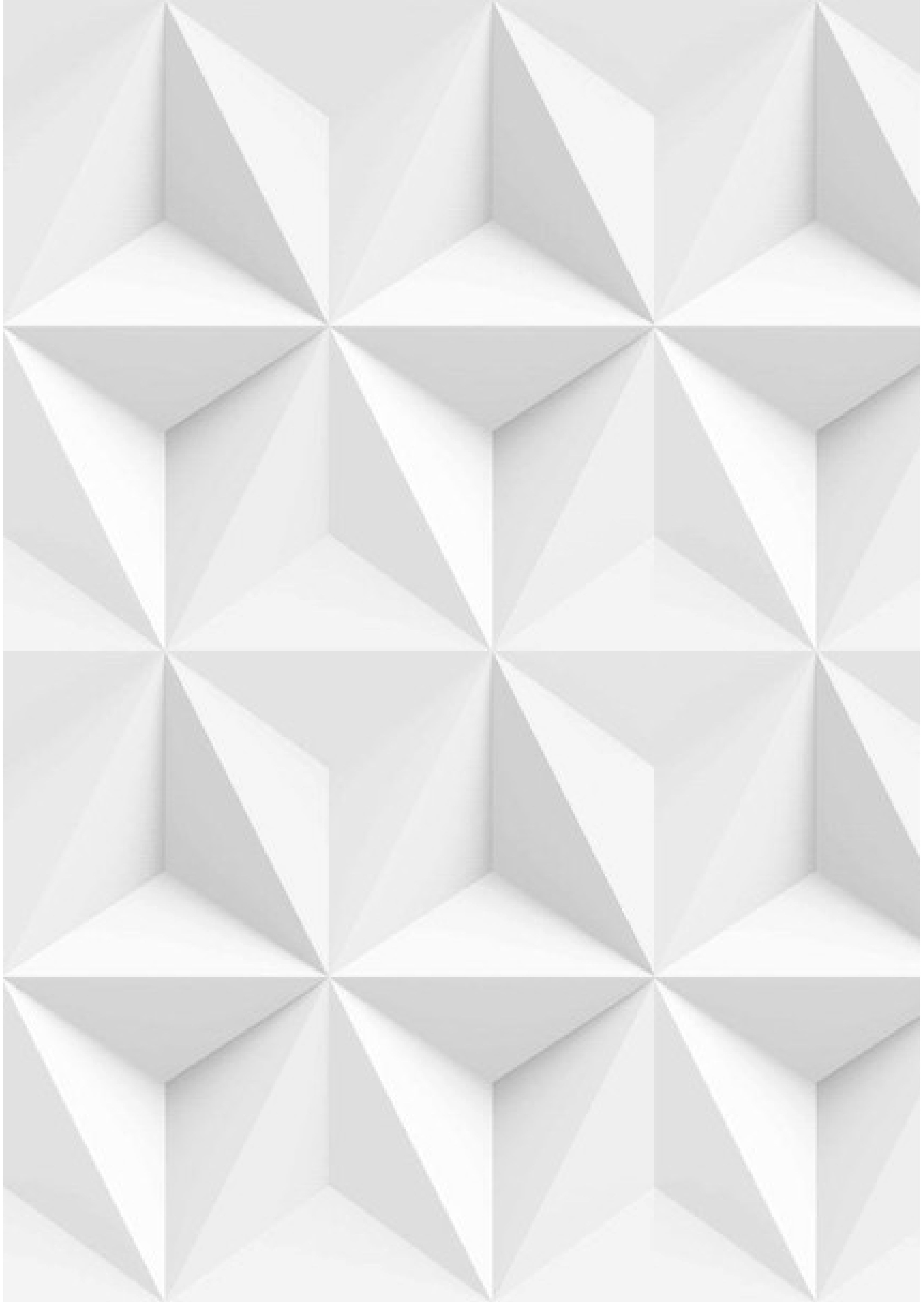


ABSTRACT

Keywords: Shading devce, Smart Materials, Passive Strategy, Thermal transmisison, Visual Comfort, Origami

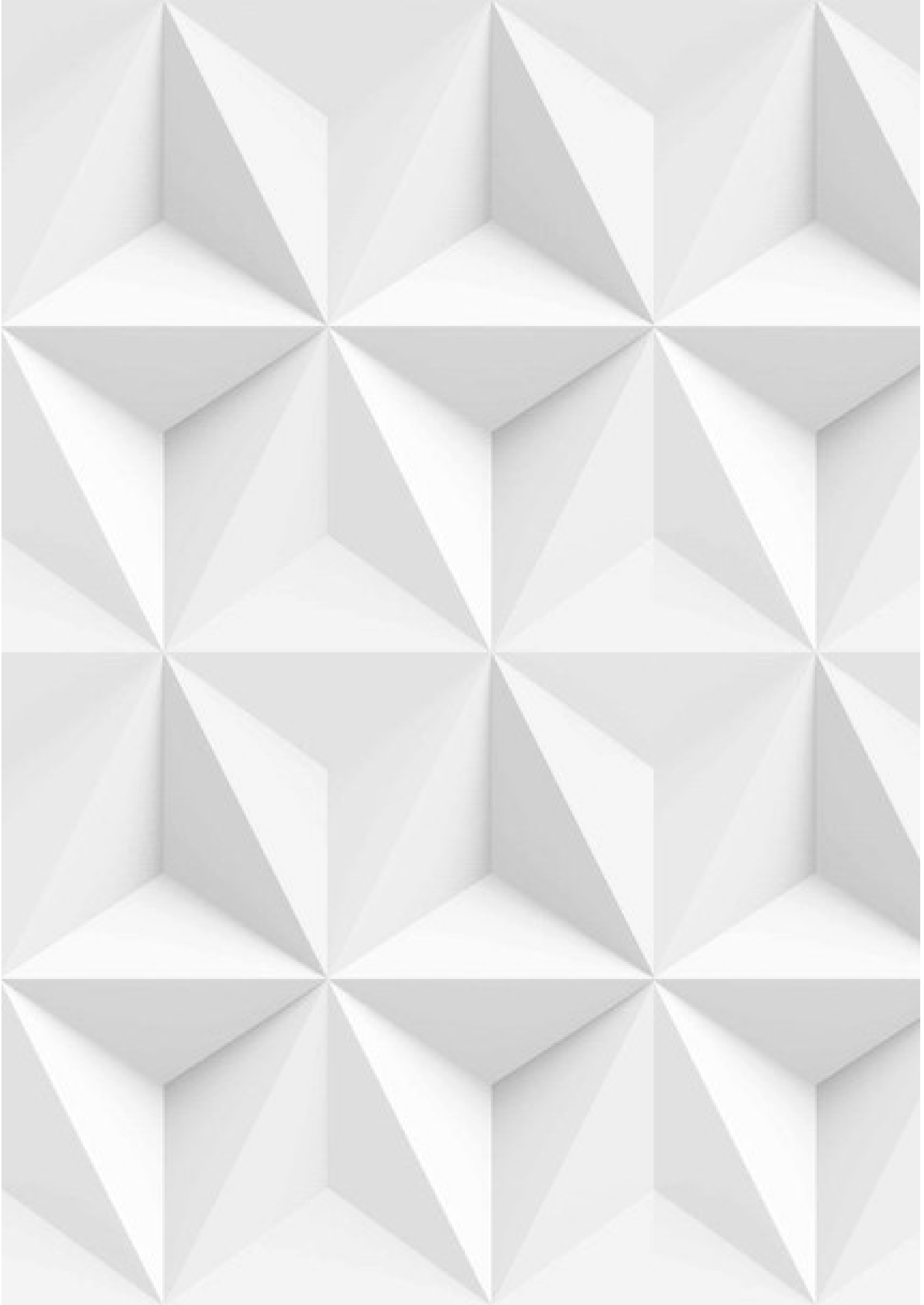
This thesis explores the design and development of a passive adaptive solar shading system aimed at addressing critical challenges in modern glazed commercial facades, including excessive heat gain, glare, and reflection. Since the building envelope plays a pivotal role in determining energy performance, the research focuses on creating shading devices that minimize thermal transmission while enhancing visual comfort, without relying on active mechanical or electrical interventions.

The proposed system harnesses the inherent properties of smart materials to achieve material-driven adaptability, enabling the shading device to respond passively to solar radiation and environmental changes. Unlike conventional shading technologies, the design relies on self-activating mechanisms embedded within the material itself, thereby reducing energy dependency and enhancing sustainability.

The prototype has been tested on a glazed commercial building in Jaipur, India, a representative hot climate, to evaluate its performance in real-world conditions. While validated in this context, the system is conceived as a universally adaptable solution that can be integrated into diverse climatic regions and facade typologies across the globe by adapting the actuation range of the smart materials.

By merging passive design principles, smart material innovation, and adaptive envelope strategies, this thesis contributes to advancing sustainable facade technologies. The outcome demonstrates how building skins can evolve into self-regulating, energy-efficient, and contextually responsive systems, offering a forward-looking approach to mitigating energy consumption while ensuring occupant comfort in the built environment.

Sustainable Development Goals Addressed



METHODOLOGY

This thesis began with an extensive literature review focused on passive strategies in building design and adaptive facades. The research was guided by the PRISMA framework, which was used to systematically identify and select relevant studies from academic databases, journals, and conference proceedings. This systematic approach created a strong foundation for the research and helped define the scope of the thesis.

After understanding the state of the art, identifying the research gap and defining the limitations and research objective, the research work carried out included a thorough analysis of market availability, product specifications, and existing case studies of prototypes developed by universities and researchers worldwide.

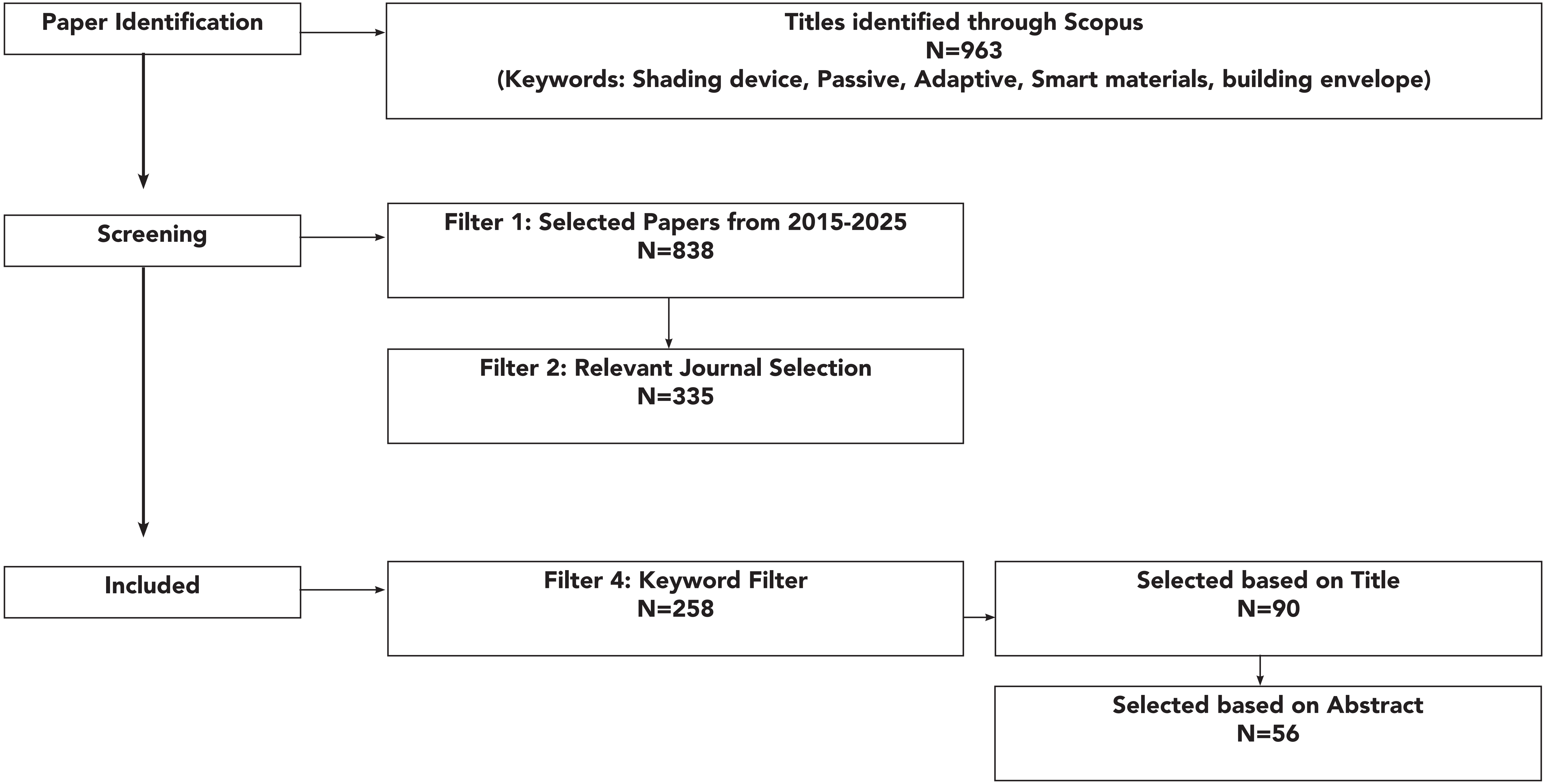
Finally a prototype solution was developed and conceptually implemented on a glazed commercial facade of a building in hot tropical climate.

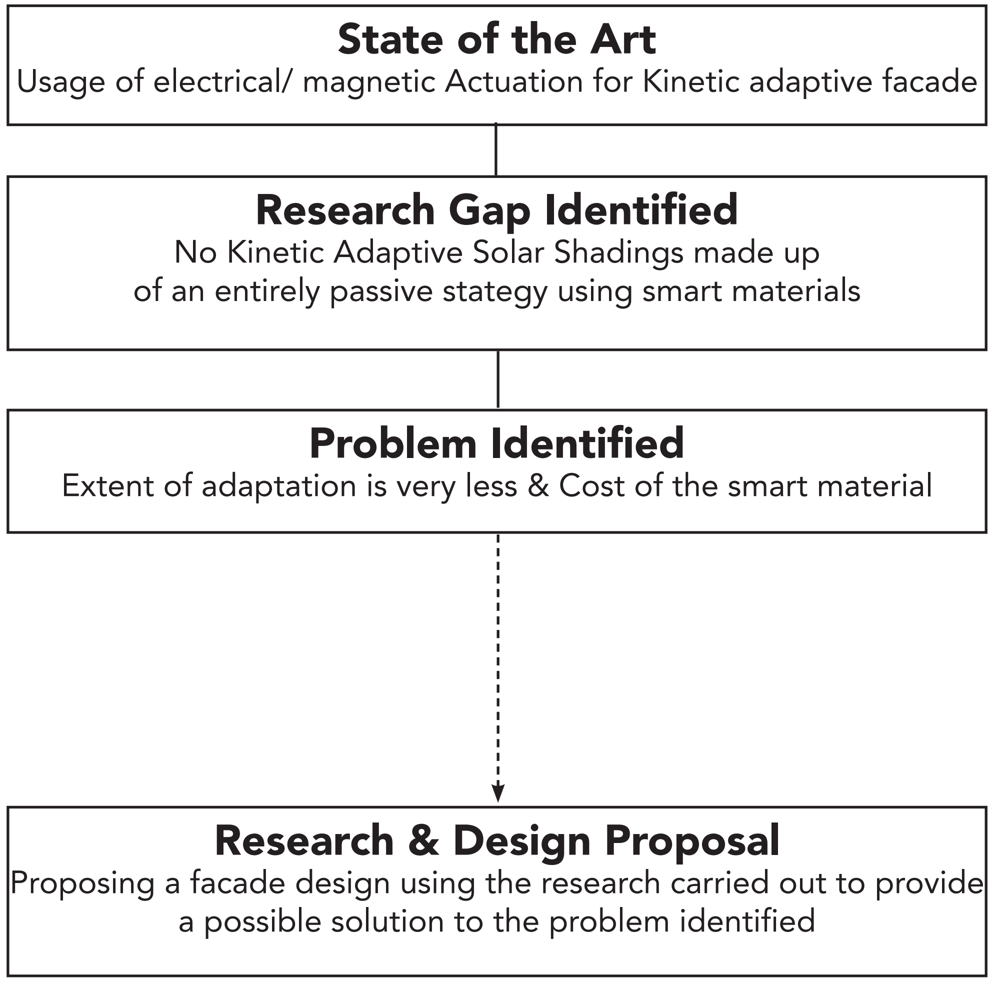
Finally, for the final material selection respecting the context of the site, the 'Technique for Order Preference by Similarity to an Ideal Solution' (TOPSIS) was employed. This multi-criteria decision analysis method was used to evaluate and rank potential facade materials based on key performance indicators found in research articles and technical data. The criteria considered in the TOPSIS analysis were: Cost Profile, Weight, Durability, Thermal Conductivity, Recyclability, and Solar Reflectance. This quantitative ranking provided a clear and defensible rationale for the final material selection.

Overall Development

The development of the thesis was a dynamic process that involved continuous refinement and validation. The work was constantly reviewed by my thesis professor to ensure the methodology and findings remained rigorous. The research was also enhanced by an ongoing engagement with the broader academic community, which included analyzing conferences, papers, research articles, and journals. Insights were gained through collaborative discussions with colleagues and by examining other theses and PhD research on related topics. The study of companies working with smart materials also provided a holistic perspective that strengthened the final thesis.

PRISMA FRAMEWORK





STATE OF THE ART

In terms of the existing innovation in shading of the building envelopes, various kinetic facades, operated through **electrcial or magentic actuation** have been witnessed. Several other experiements and researches are being carried on to achieve these kinetic adaptive facades through passive means by reducing on the energy load of the building. For which the usage of smart materials is being considered as an alternative. While some **prototypes have been demonstrated** in the past using smart materials. No design has yet claimed a ready to be executed real life working of a completely passive kinetic facade.

The problem identified is the **rate and extent of actuation**/ response and the material cost involved with the usage of smart materials for passive kinetic adaptive facade.

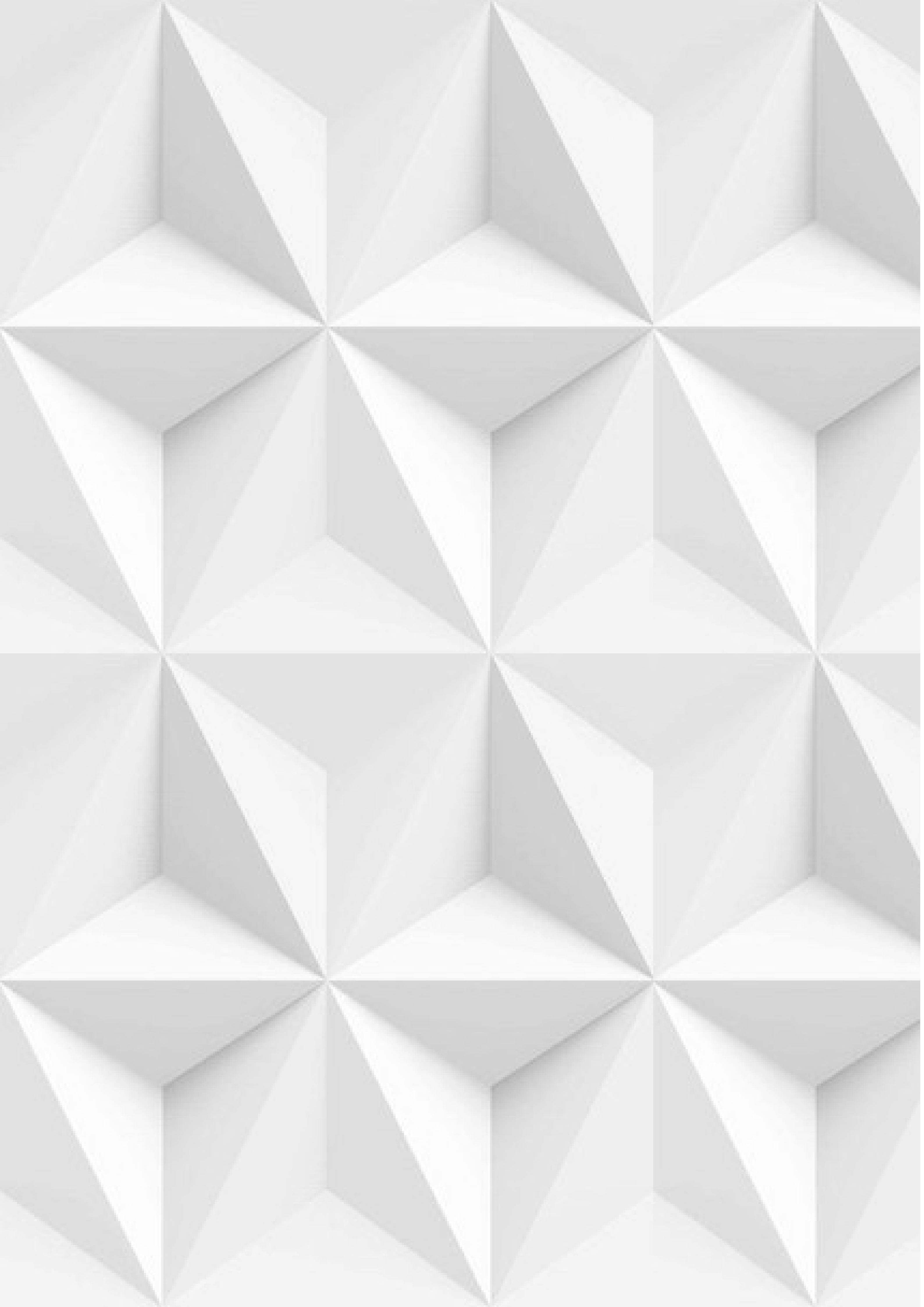
SCOPE AND LIMITATIONS OF THIS RESEARCH

Based on the gap identified, the limitations of the research and design of this thesis are:

1) The scope is limited to designing a conceptual prototype with the use of Smart materials based on the research of the literature available and the market availability of the products in order to define the details and specification needed to design a passive solar shading device for a building envelope and to provide a foundation on the **architecture details** involved with the facade design and working. The extent of real-life execution of the design, however, is left to the precision and expertise of mechanical and material engineers.

2) The conclusion of the research carried out, in terms of its design implementation, is used for developing a facade design for a **specific use-case scenario** and simulating the results for the same to compare the improved energy efficiency with a regular/ existing facade design. However, the same prototype can be altered/ tweaked as per the specific project requirements.

3) The primary objective of using the passive adaptive system is improve upon the thermal transmission, indoor air temperature and lux level of the design and interior space.



PART A
INTRODUCTION TO SMART MATERIALS

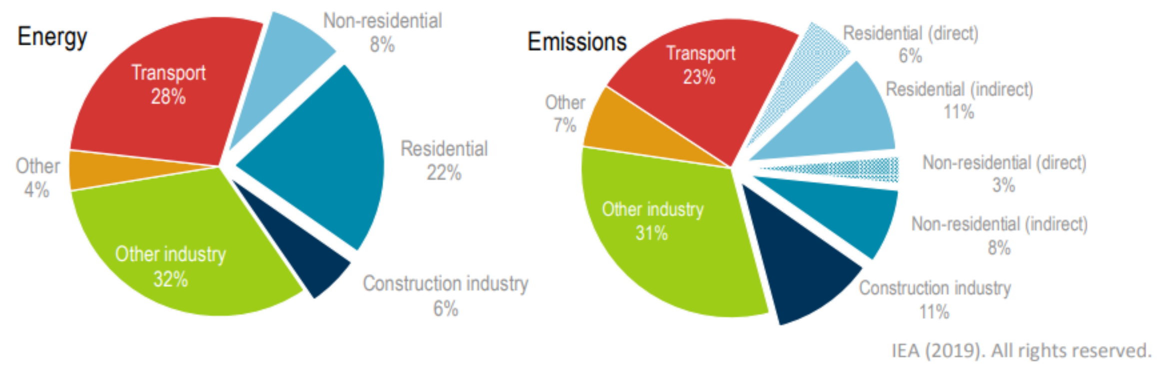


Fig [i] Global Energy Consumption

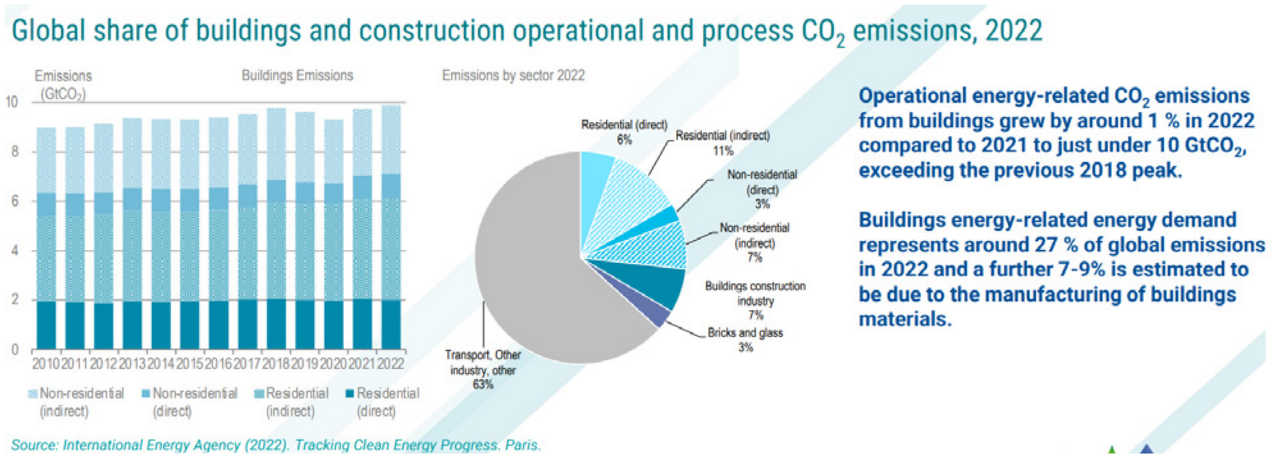


Fig [ii] Global Share of buildings and Construction operational and process C02 emissions

Introduction

The building sector accounts for approximately 36% of global final energy consumption and nearly 39% of energy-related CO2 emissions, according to the International Energy Agency. [1] With rapid urbanization and increasing demand for thermally comfortable indoor environments, energy usage especially for heating, cooling, and lighting continues to rise. Of this energy, up to 30–40% can be attributed to the performance of the building envelope, particularly facades, which act as the interface between interior spaces and the external environment [2] . Hence, improving envelope performance offers a significant opportunity for reducing operational energy demands and associated emissions.

Among various envelope components, solar shading systems play a crucial role in regulating solar heat gain and daylight penetration. Conventional shading systems such as louvers, overhangs, or blinds often rely on static configurations or energy-intensive mechanical systems. These solutions are limited in their adaptability to changing environmental conditions and user needs, leading to inefficiencies in energy performance and occupant comfort [3].

In this context, Passive Adaptive Solar Shading emerges as a transformative approach. Unlike active systems that consume energy to operate, passive adaptive shading solutions are designed to respond autonomously to environmental stimuli (such as solar radiation or temperature), without external energy input. Smart materials particularly thermochromic, photochromic, and shape memory alloys are at the forefront of this innovation, as they can change their optical, thermal, or physical properties in real-time based on ambient conditions [4].

The integration of smart materials into facade design promises to enhance energy efficiency, improve visual and thermal comfort, and reduce the need for mechanical systems. Moreover, such materials support the principles of sustainable and resilient architecture, aligning with global climate goals and green building standards such as LEED, BREEAM, and WELL. However, the deployment of these materials is still in a nascent stage, facing challenges related to cost, scalability, long-term durability, speed of change and architectural integration.

Therefore, this thesis investigates the potential of passive adaptive solar shading systems using smart materials as a viable solution for high-performance building envelopes. The study aims to assess material behavior, design strategies, and performance metrics to propose a framework that can inform future adaptive facade systems.

The research contributes to the broader discourse on climate-responsive architecture, reinforcing the need for innovation at the material interface level of building design.

To dive into the topic, we will first understand the terminologies associated with the topic, starting with adaptive shading systems and then into specifically understanding the world of Smart materials.

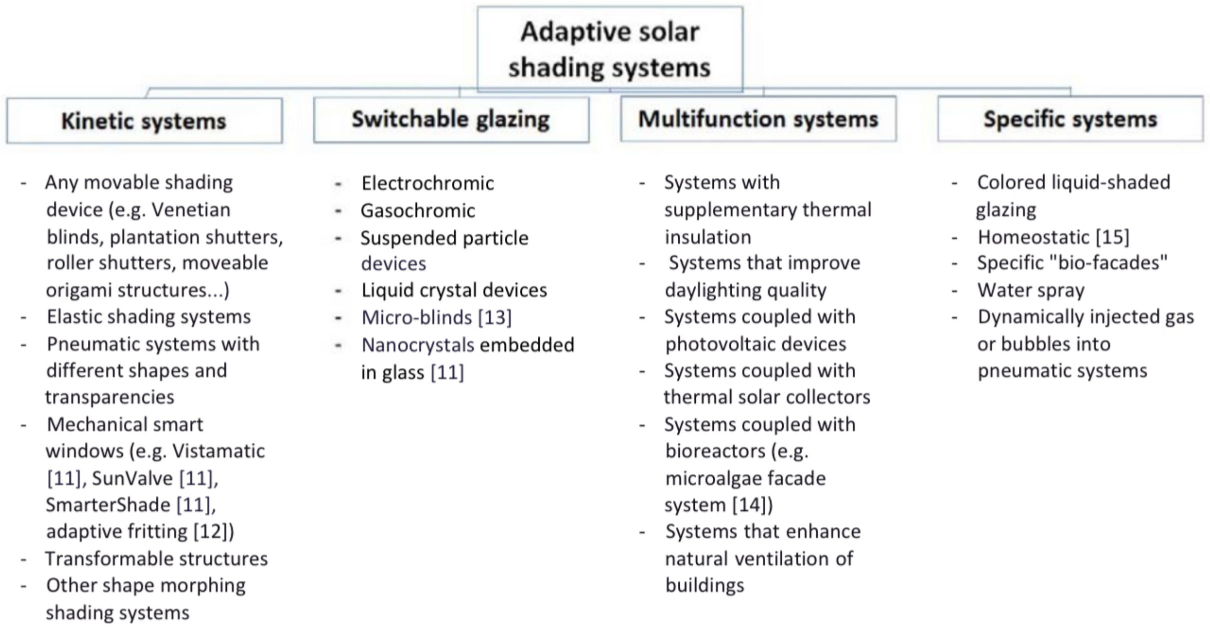


Fig [iii] Types of Adaptive Solar Shading Systems

Adaptive Solar Shading: Categorization

What is adaptive solar shading?
Adaptive shading devices are façade elements that adjust their parameters according to changing weather conditions or indoor preferences, resulting in optimizing different parameters like reduction of thermal transmission, reflectivity, glare, increasing visual comfort, ventilation,etc. [5]
How can we categorize adaptive solar shading?
Adaptive solar shading systems can be categorized by physical/optical processes and systems that provide protection of a building from excessive solar radiation (Fig on the left).

The categories, thus, identified are:

A. Kinetic Systems:
These systems use moving parts to provide shade. They can be any kind of movable shading device, like Venetian blinds, roller shutters, or even systems with movable origami structures. They can also use smart or pneumatic systems with different shapes and transparencies to transform the building's facade.

B. Switchable glazing:
This category involves glass or window materials that can change their properties to control light and heat transmission. This includes technologies like electrochromic, thermochromic, or liquid crystal devices that can be "switched" on or off to adjust their transparency.

C. Multifunctional Systems:
These systems combine shading with other building functions to improve performance. They might be coupled with photovoltaic devices to generate electricity, thermal solar collectors to create hot water, or even with bioreactors (like microalgae facade systems) for a variety of purposes. They can also include systems that improve daylighting quality or enhance natural ventilation.

D. Specific Systems:
This category includes unique or highly specialized systems that don't fit into the other categories. Examples are facades with colored liquid-shaded glazing, homeostatic systems, or systems where gas or bubbles are dynamically injected into pneumatic systems.

The various categories within these typologies are mentioned in the chart on the left (Different types of Adaptable Shading Systems)
For the purpose of designing solar shading devices on the building envelope externally, the ideal category of the adaptive systems to go for is the Kinetic type of system that responds to real-time weather changes.

KINETIC ADAPTIVE SOLAR SHADING

As mentioned adpative systems which are kinetic can be of different types of shading devices like rollers, blinds, panels, etc and their working force/ principle also can be of different types resulting from mechanical actuation, thermo-chemical actuation, elastic deformation, transformable structures, Morphing due to smart materials, etc. For the scope of this thesis we will be exploring how the Kinetic adaptive shading systems can be actuated using smart materials.

What are Smart Materials ?

Smart materials are generally used in smart or adaptive structures where, in response to a stimulus, a change is needed. Commonly, the functions of sensors and actuators are separate: the sensor is able to analyse the variation of an external stimulus and transfer this information to the actuator, which provides the structure with a change in one of its properties. **A smart material combines both sensor and actuator functions, as it is a material that changes one of its properties in response to an external stimulus. [6]**

Characterstics of Smart Materials

Firstly, movement is triggered by an external stimulus
Secondly, motion is carried through volume change (shape) and
Lastly, their anisotropy is derived from an unequal distribution of material in the cells.

For our consideration of the application in solar shading devices, the following selection criteria were used to identify and analyse in detail the most suitable smart materials:

• Corrosion resistance (if exposed to external weather conditions or in chemical aggressive ambient)

• Durability (life cycle of the smart movement/shape memory effect)

• Stimulus responsiveness (solar radiation, outside air temperature, electrical stimulus)

• Workability (how to shape it, process and adaptability)

• Achievable movements

• Impressing force (if used as actuators the released force is necessarily considered)

TYPE OF SMART MATERIALS THAT CAN BE USED IN SOLAR SHADING

1. Thermochromic Materials
Function: Change transparency or color with temperature.
Use in Solar Shading: Automatically darken when exposed to sunlight or heat, reducing glare and heat gain.
Applications: Smart windows, adaptive glass panels.

2. Electrochromic Materials
Function: Change transparency or color with applied voltage.
Use in Solar Shading: Can be manually or automatically controlled to block sunlight as needed.
Applications: Dynamic glazing, switchable glass facades.

3. Photochromic Materials
Function: Change color or opacity with UV light exposure.
Use in Solar Shading: Automatically react to sunlight intensity.
Limitations: May not respond well to heat; performance can degrade over time.
Applications: Glass panels, facade coatings.

4. Shape Morphing Materials (SMMs)
Function: Change shape with temperature.
Use in Solar Shading: Used in mechanical systems (like louvers) that open/close based on heat without motors or electricity.
Applications: Passive kinetic facades.

5. Hydrogels
Function: Expand or contract based on humidity or temperature.
Use in Solar Shading: Can be integrated into adaptive shading skins or screens.
Applications: Bio-inspired facades, responsive surface treatments.

6. Phase Change Materials (PCMs)
Function: Absorb or release heat during phase transition.
Use in Solar Shading: Mainly for thermal buffering, sometimes embedded in panels to moderate solar heat gain.
Applications: Smart glazing with integrated PCM layers.

7. Liquid Crystal Materials (used in PDLC Films)
Function: Electrically switchable from transparent to opaque.
Use in Solar Shading: Privacy glass and light-blocking panels.
Applications: Smart glass partitions, shading panels.

EXISTING SMART MATERIALS, THEIR STIMULI AND THEIR RESPONSE

Intensive research has been carried on smart materials, the stimuli they respond to and how they respond. The table below lists some of these smart materials along with their stimulus (actuators) and the transformation exhibited by them. The entire detail can be extracted from the cited sources [7]

1. A wood bilayer actuator that uses hygroscopic swelling to bend a bistable beam
2. Shape Memory Alloys that trigger the buckling of metal plates
3. Magnetoactive elastomers that actuate bistable laminates
4. Bimetallic actuators that snap bistable beams in the compliant shading project
5. 4DP (4-dimensional printing) material actuators that actuate a bistable disk via hygroscopic expansion.

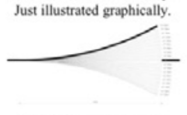
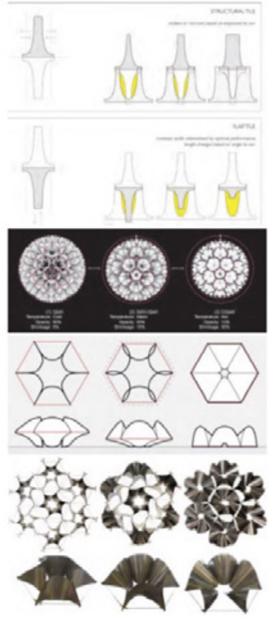
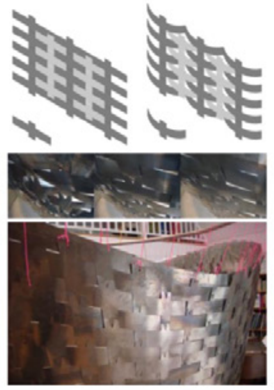
MATERIAL	COMPOSITION	RESPONSIVENESS	GEOMETRY	TRANSFORMATION DATA	STIMULUS	THERMAL CONDUCTIVITY K VALUE (W/m·K)
Copper-polypropylene (3.5 mm)	Copper (0.5 mm) PP (3mm)	Solar Radiation, Temperature	**Length: 300 mm** **Width: 30 mm** 	Fixed from one side. Bending degree: Not mentioned statistically. Just illustrated graphically.  Approximately: up to 19° ------------------------------ "Gradual transformation"	13 °C to 36 °C	Copper: 401 + PP: 0.15
Oak-Polyethylene (1.5 mm)	Oak (0.5 mm) and PE (1 mm)	Solar Radiation "Dynamic bending of the developed composite after approximately **3 mins of direct solar radiation exposure**"	**Length: 300 mm** **Width: 30 mm** 	Fixed from one side. Bending degree: Not mentioned statistically. Just illustrated graphically.  Approximately: up to 20°	The shaded **oak** surface side is warmed to **36** °C through the composite, with the **black PE** surface side measured to **57** °C where the **ambient temperature is approximately 22** °C	Oak: 0.197 + PE: 0.33
TM2: P675R *(Manufactured Shape memory alloy)* **(0.0635 mm)**	72% Manganese 18% Copper 10% Nickel (American Society for Testing and Materials "ASTM" Types)	Solar Radiation, Temperature		"the intended result is a rotation of the surface, almost perpendicular to the original position" Approximately: 100% deformation  ------------------------------ "Gradual transformation"	0 °C to 49 °C	6.00 (P675R)
TM2: P675R *(Manufactured Shape memory alloy)* **(0.25 mm)**	72% Manganese 18% Copper 10% Nickel (American Society for Testing and Materials "ASTM" Types)	Solar Radiation, Temperature	**Length: 304.8 mm** **Width: 50.8 mm** 	Not mentioned statistically. Just illustrated graphically.	38 °C to 49 °C	6.00 (P675R)
TM2: P675R *(Manufactured Shape memory alloy)* **(0.2 mm)**	72% Manganese 18% Copper 10% Nickel (American Society for Testing and Materials "ASTM" Types)	Solar Radiation, Temperature	**Length: 66 mm** **Width: 9.5 mm** 	Not mentioned statically. Just illustrated graphically. Approximately: up to 45 ------------------------------ "Gradual transformation"	38 °C to 49 °C	6.00 (P675R)

Fig [iv] Summary of the various stimulus shape-morphing materials react towards [7]

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pendix A continued

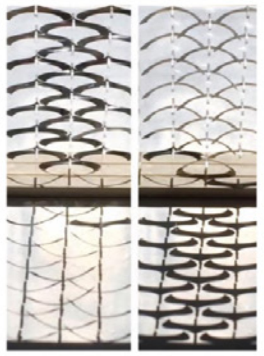
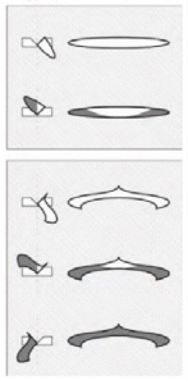
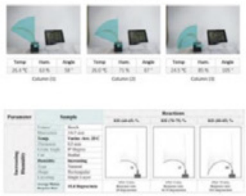
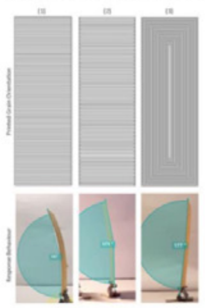
TM2: P675R *(Manufactured Shape memory alloy)* **(Thickness not mentioned)**	72% Manganese 18% Copper 10% Nickel (American Society for Testing and Materials "ASTM" Types)	Solar Radiation, Temperature	Dimensions not mentioned 	Flipping 180° through x axis  ------------------------------ "Sudden transformation"	38 °C "installed in a double-glazed window or double façade system."	6.00 (P675R)
Wood veneer (0.5 mm)	Beech (0.5mm)	Temperature, Humidity	**Length: 14 mm** **Width: 7 mm** 	Fixed from one side. Bending degrees: 14° 15° 19° Respectively ------------------------------ "Gradual transformation"	Temperature variations: 28.3 °C 33.4°C 40 °C Respectively	Beech: 0.185
Wood PLA (0.3mm)	Wood filaments (20% Wood, 80% Plastic PLA)	Humidity	**Length: 120 mm** **Width: 40 mm** First Sample: parallel lines Second Sample: zigzag straight lines Third Sample: concentric straight lines 	Fixed from one side. Bending degrees: 13° 9° 3° Respectively ------------------------------ "Gradual transformation"	"Increase in humidity was applied by means of **spraying water on a single side of the printed samples**"	0.18 (Wood fibers) + 0.13 (PLA)

Fig [iv] Summary of the various stimulus shape-morphing materials react towards [7]

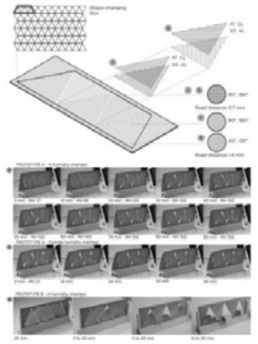
Wood-based filaments (0.35 mm)	Wood filaments (Wood-to-PLA ratio is not mentioned)	Humidity	Isosceles triangles: 55mm 	Bending degrees: Not mentioned statistically. Just illustrated graphically. Prototype A documented on intervals of 20 mints Prototype B documented on intervals of 2 hours ------------------------------ "Gradual transformation"	Relative Humidity variations (in humidity chamber): From 37% (0 mint) to 100% (20 mint)	0.18 (Wood fibers) + 0.13 (PLA)
TPU filaments *(Manufactured Shape memory polymer)* (1.5 mm)	MM3520 filament	Temperature	150mm diameter 	Not mentioned statistically. Just illustrated graphically (open vs closed)	More than 35 °C	6.00 (TPU)

Fig [iv] Summary of the various stimulus shape-morphing materials react towards [7]

CONCLUSION

Based on the research carried out by studying conclusions drawn from the available state of the art technologies and aready in use materials, the optimum category to proceed with, in the context of passive adaptive shading system comes out to be 'Shape-morphing materials' due to the following reasons:

WHY SELECTING SHAPE-MORPHING MATERIALS?

Shape-morphing materials offer a range of advantage over other smart materials that are as follows:

1.Continuous and Adaptive Shading Performance

Shape-morphing materials respond gradually to environmental stimuli such as sunlight, temperature, or humidity, allowing real-time modulation of shading. This ensures more precise and adaptive control over daylight and heat gain throughout the day and across seasons. [8]

2. Passive Operation and Energy Efficiency

These materials can be activated by natural environmental changes without the need for motors or electronic controls. This passive behavior significantly reduces energy consumption and maintenance, aligning well with sustainable building design goals. [9]

3. Design Flexibility and Aesthetic Value

Shape-morphing materials enable fluid, organic movements that open up new possibilities in architectural expression. Their ability to morph elegantly contributes to both functional performance and innovative façade aesthetics. [10]

4. Reversible and Programmable Behavior

They can be programmed to respond predictably to specific stimuli and revert to their original shape, offering a high degree of control over shading performance. This allows facades to adapt dynamically to changing environmental conditions.[11]

5. Compatibility with Smart Systems and AI Integration

Their behavior can be digitally modeled and optimized using data-driven approaches such as AI and machine learning. This opens up opportunities for intelligent, responsive building envelope systems that self-regulate based on environmental inputs.[12]

6. Established Research and Prototyping Support

There is a rich body of existing research, case studies, and experimental projects involving shape-morphing materials. This makes it easier to build upon previous work and access reliable data for simulations and validation.[13]

7. Material Availability and Scalability

Many shape-morphing materials such as thermobimetals, hydrogels, and shape memory polymers are commercially available and feasible to prototype. This supports both small-scale experimental modeling and larger-scale architectural applications. [14]

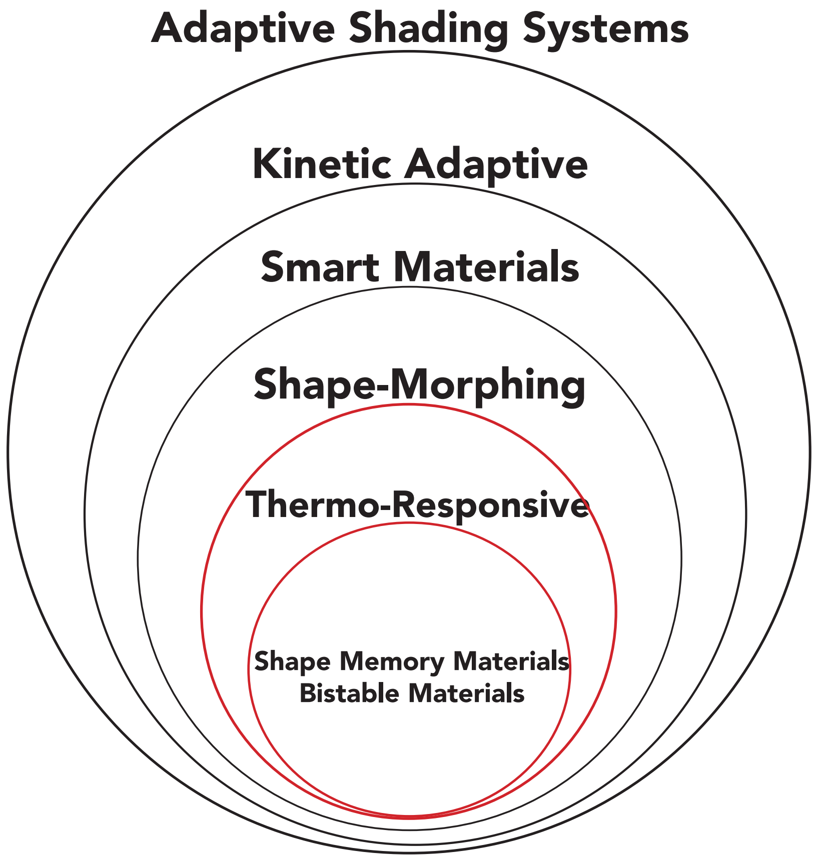
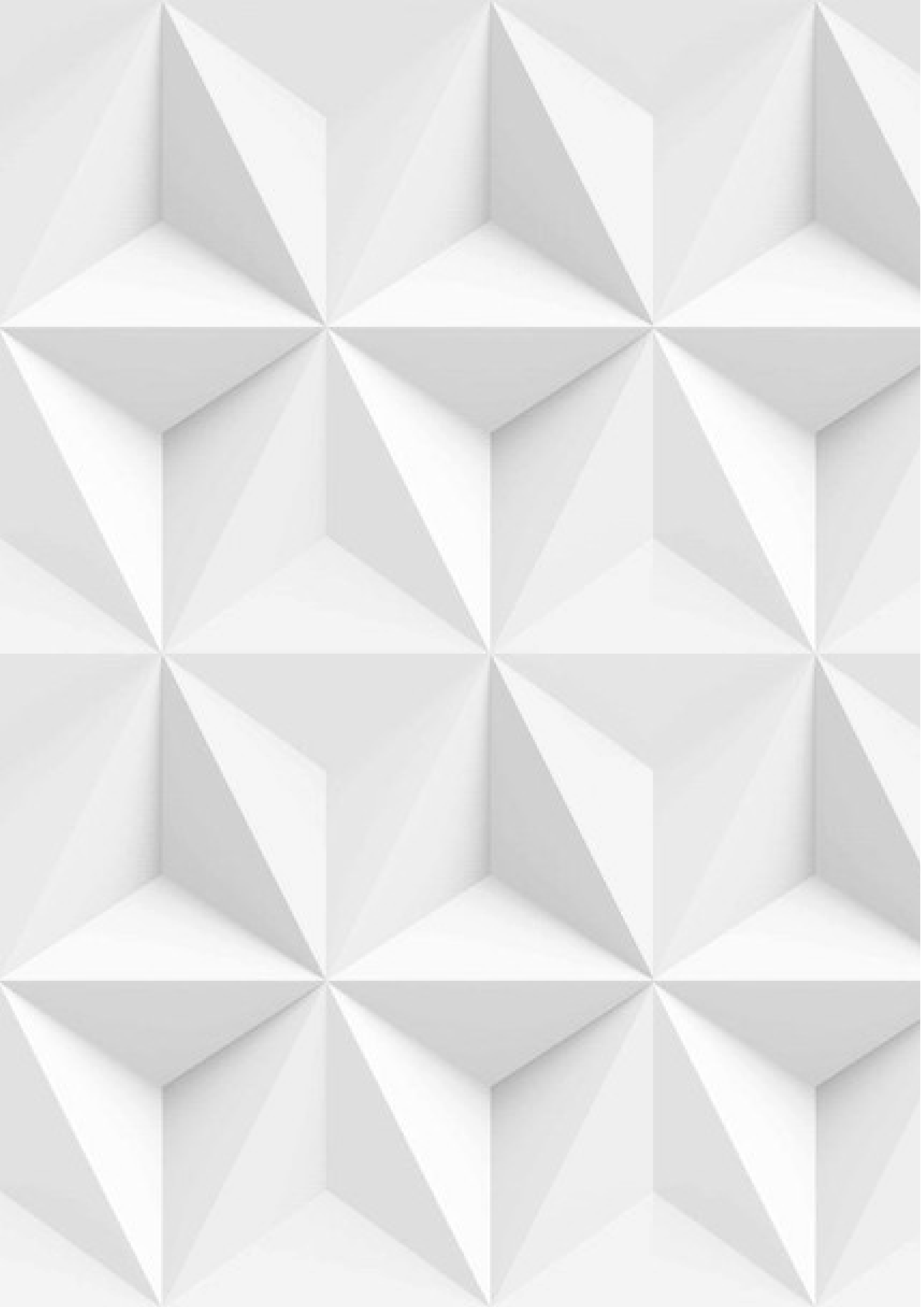


Fig [v] Defining the selection of niche within Adaptive Solar Shading Systems

In conclusion shape-morphing materials offer a versatile, energy-efficient, and responsive approach to solar shading in buildings. Their adaptability, integration potential with smart technologies, and strong design appeal make them an ideal choice for innovative building envelope solutions.

Conclusion
Shape-morphing materials offer a versatile, energy-efficient, and responsive approach to solar shading in buildings. Their adaptability, integration potential with smart technologies, and strong design appeal make them an ideal choice for innovative building envelope solutions.



PART A
INTRODUCTION

PART B
SHAPE-MORPHING MATERIALS

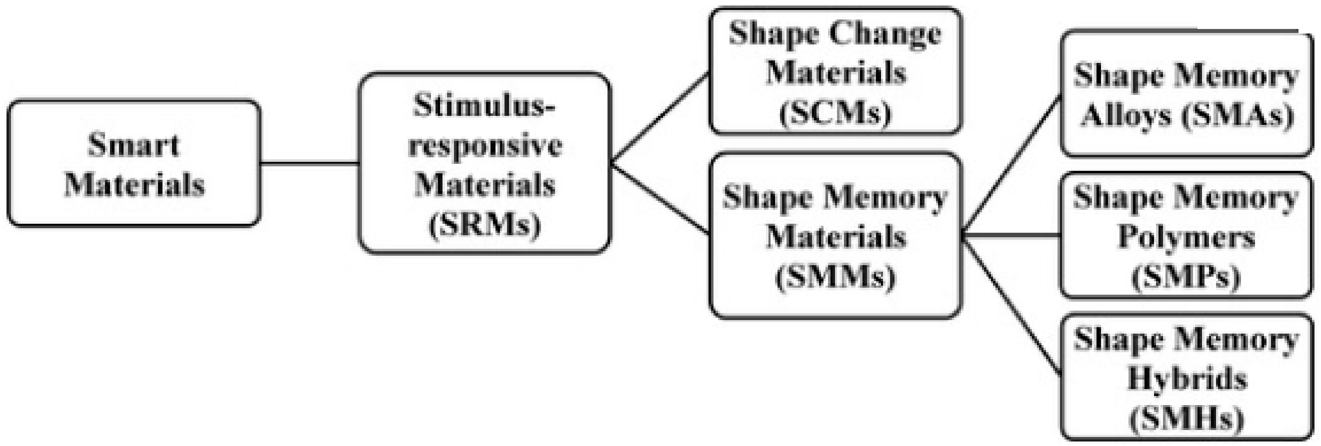


Fig [vi] Smart Material Types

WHAT ARE SHAPE-MORPHING MATERIALS ?

Shape-morphing materials are materials or material systems that are designed to change their shape or geometry in response to external stimuli such as heat, humidity, light, magnetic fields, or mechanical force. The shape change is reversible or programmable, and can be achieved without external mechanical actuators and respond to a natural/ induced stimulus. So let us understand, what are the different types of stimulus that induce reaction/ response in shape morphing materials. The stimulus could be thermal, magnetic, electrical, humidity levels, light sensitivitiy, pH Level change, chemical, ionic change amongst many others. But the ones relevant for application in the building envelope based on natural stimulus could be change in thermal, Light/UV, or Humidity levels. So as a scope for this thesis we will understand them in detail. [15]

Before diving into individual working and detail, it is important to understand the objectives that can be achieved using shape-morphing materials, which are but not limited to the folllowing:

1. Shading – By closing in presence of light

Shape-morphing materials can reduce solar heat gain by automatically bending or folding in response to high light intensity. This passive response helps reduce glare and overheating in interiors, particularly on sun-exposed façades. Materials such as photomechanical films or thermobimetals can perform this function effectively, forming self-shading skins that do not require motors or electronics.

2. Temperature Control – By closing in presence of heat

When ambient or surface temperature rises, certain materials respond by curling or expanding into a closed configuration, reducing heat exchange between inside and outside. Thermally responsive materials like shape memory polymers or bimetallic strips can insulate interiors by blocking unwanted solar radiation or hot airflow, supporting passive thermal comfort.

3. Ventilation – By opening in presence of heat

Some systems are designed to allow ventilation when exposed to heat. Shape-morphing materials open vents, panels, or louvers to enable natural air movement when interior temperatures rise. This promotes passive cooling and reduces dependence on mechanical ventilation systems. Materials such as bistable composites and humidity-activated laminates can be configured for this purpose.

4. Generating Energy – Energy harvesting

When coupled with energy-harvesting technologies, shape-morphing components can convert mechanical movement, heat, or solar energy into electricity. For example, panels that flex or vibrate due to wind or temperature changes can be integrated with piezoelectric or thermoelectric materials to generate small amounts of power. This

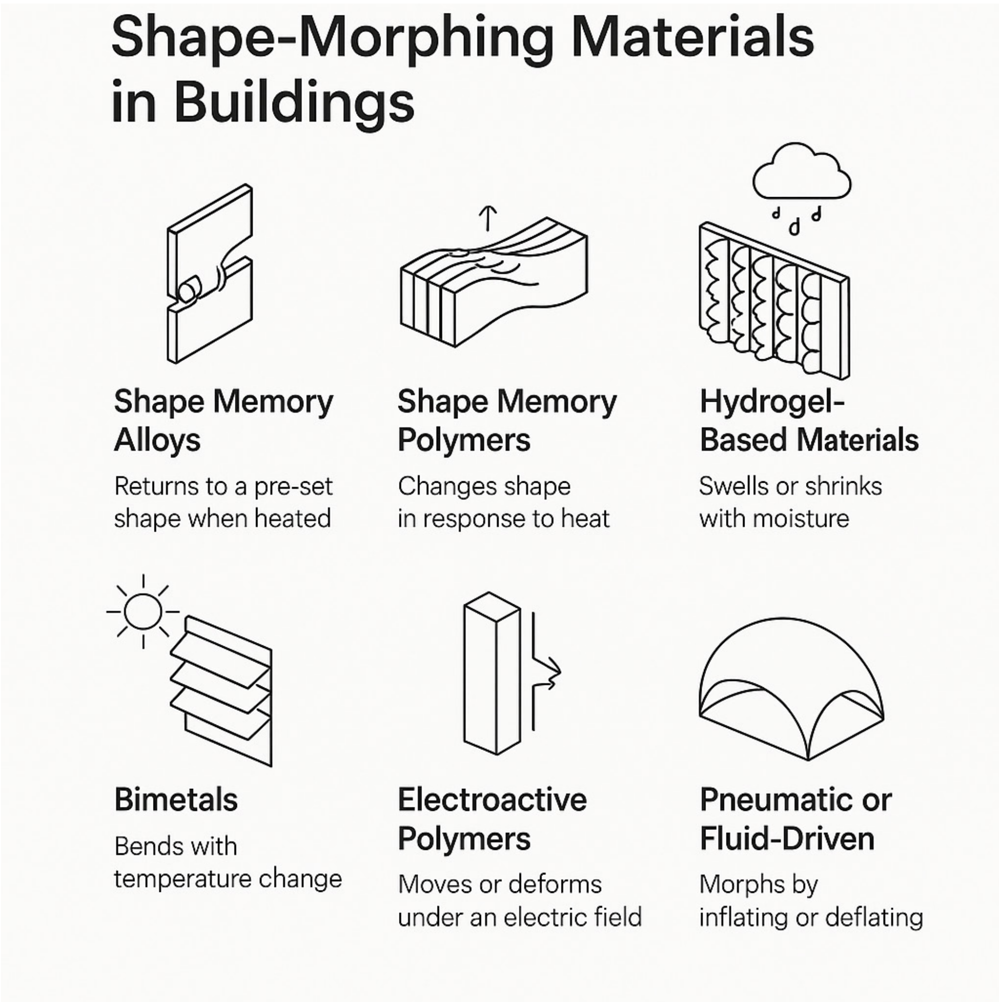


Fig [vii] Different Types of Shape Morphic Materials

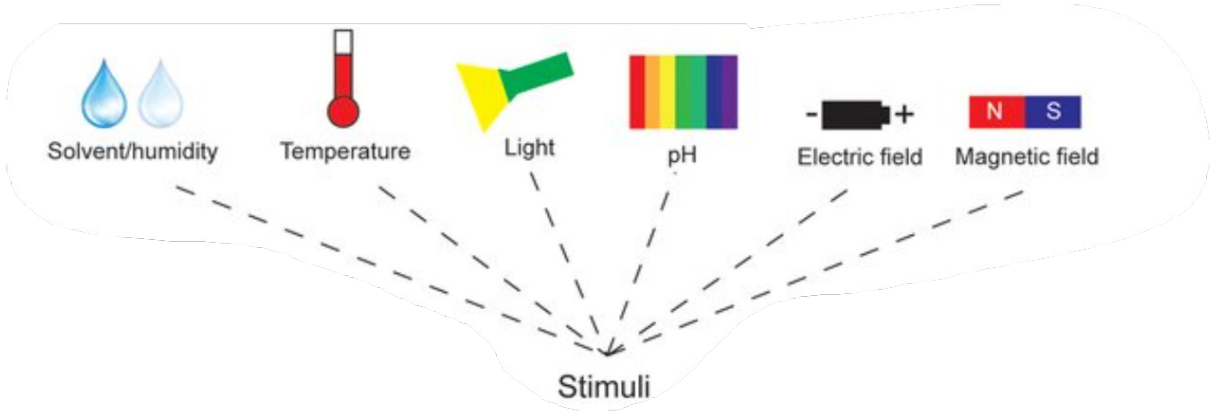


Fig [viii] Stimul that Shape-Morphing Materials respond towards [17]

energy can be used for sensors or feedback systems within a smart façade.

5. Structure

To create self-stable structures without additional support. Some shape-morphing systems can transform into rigid, self-supporting structures once activated. Inspired by biological morphologies and origami geometry, these materials can switch from flat or folded states into curved, load-bearing shapes. Bistable laminates and pre-stressed composite shells are examples of such systems, offering lightweight, deployable architectural solutions without the need for complex supporting frames. [16]

Now, let us understand the types of materials and the stimuli they respond to.

TYPES OF NATURAL STIMULI SHAPE-MORPHING MATERIALS RESPOND TO:

Temperature (Heat / Cold)
Many shape-morphing materials react when the temperature crosses a specific threshold. For example, thermo-bimetals bend because of the different expansion rates of two bonded metal layers when heated. Shape memory alloys (SMAs), like Nitinol, return to a pre-set shape by changing their internal structure through a process called phase transformation. Similarly, shape memory polymers (SMPs) become soft and can return to their original form when exposed to heat. These materials are commonly used in passive shading devices, thermally responsive vents, and kinetic building envelopes that adapt to changes in temperature. [17]

Light (Solar Radiation / UV)
Some materials change their physical or optical properties when exposed to sunlight or ultraviolet (UV) radiation. For instance, photomechanical polymers can bend or twist when illuminated, while thermochromic coatings can adjust their color or transparency depending on sunlight intensity. These materials are often used in smart glazing systems, adaptive louvers, and self-shading façades to improve daylight control and reduce solar gain.

Humidity / Moisture
Certain materials absorb water vapor from the air, causing them to swell, shrink, or deform. Examples include hygromorphic wood composites, which warp when moisture levels change, and hydrogels, which expand or contract when they absorb or release water. These materials are usually applied in responsive screens, breathable façade elements, and systems that promote natural ventilation, especially in humid climates.

Air Flow / Wind
Though not commonly used for precise movements, air flow or wind can activate flexible or bistable components, causing them to shift position or oscillate. For example, kinetic façades with bistable flaps can open or close with wind pressure, while pneumatically actuated textiles inflate or flutter in response to moving air. These systems are often used in wind-driven shading devices and natural ventilation elements in building envelopes.

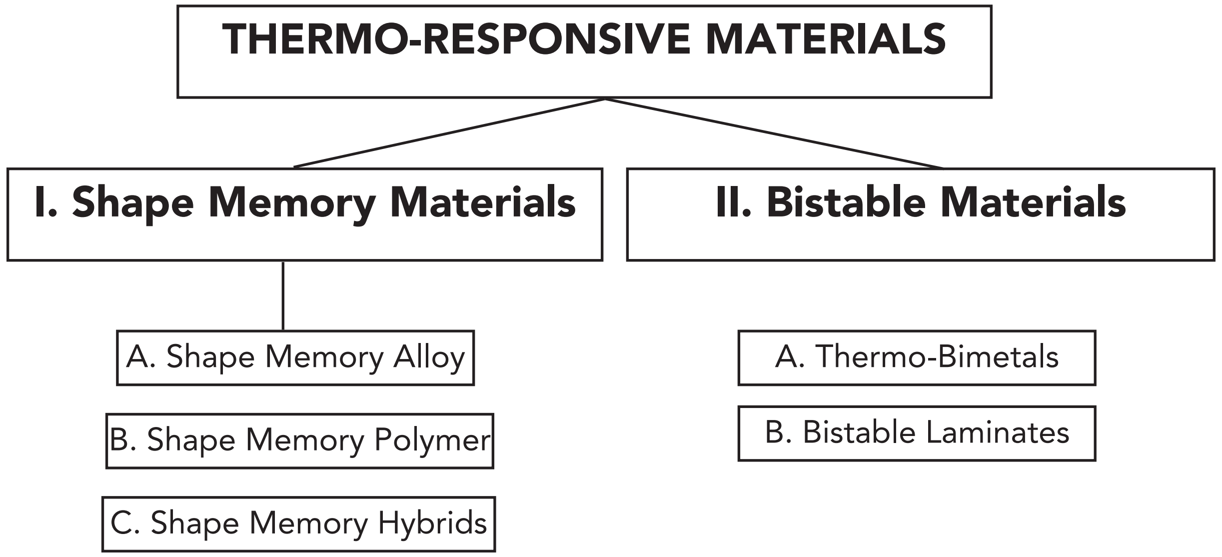


Fig [ix] Thermo-responsive shape morphing materials

Gravity and Structural Load
Some shape-morphing systems respond to their own weight or the forces acting on them. In particular, bistable or folded laminate structures can snap into place and hold their shape using gravity or internal stress. These systems are typically used in deployable roofs, self-forming canopies, or temporary architectural structures that need to be lightweight yet self-supporting.

For the scope of this thesis, we concentrate on the shape-morphing materials that are responsive to heat since the most prominent actuator with diurnal change in the natural climate is sunlight. The category of these type of shape-morphing materials are called thermo-responsive materials.

THERMO-RESPONSIVE MATERIALS

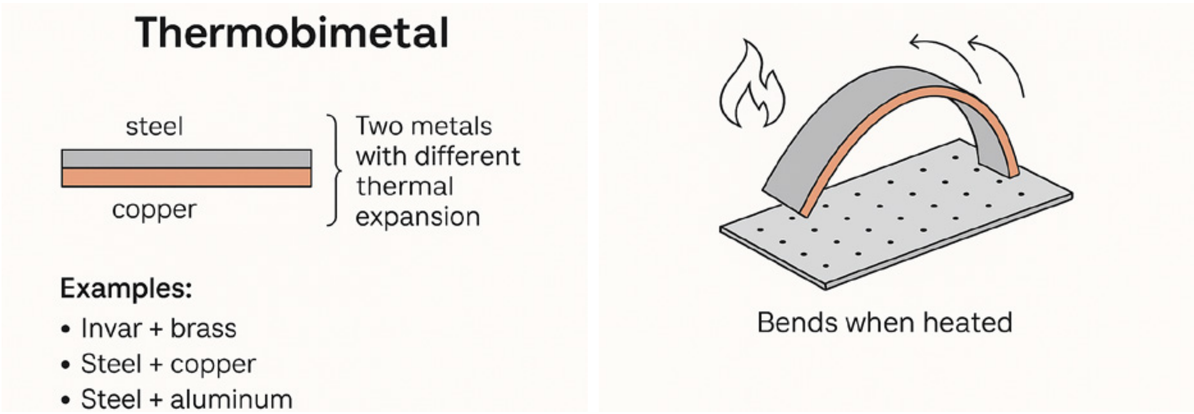
Thermal-responsive materials are a widely explored category in shape-morphing systems, particularly relevant to architecture and building envelopes. These materials react to changes in temperature by altering their shape, structure, or physical properties, enabling passive or active movement without the need for complex mechanical systems. This makes them ideal for creating dynamic façades, shading devices, and climate-adaptive elements that improve building performance and occupant comfort.

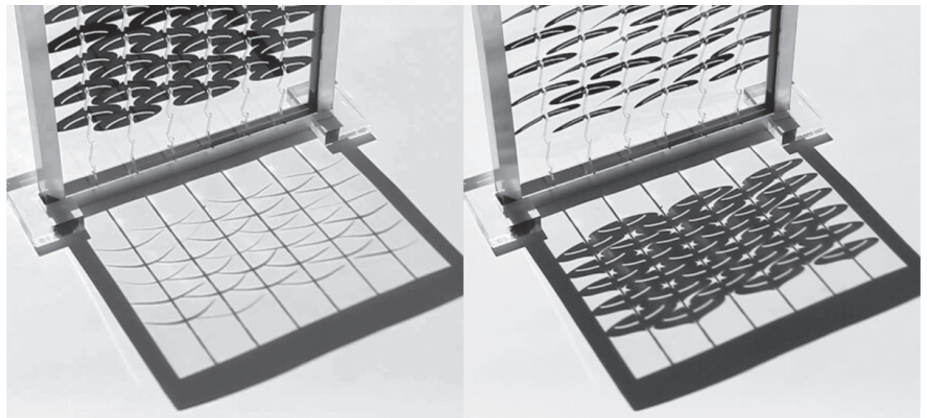
How It Works (Stimulus Mechanism):
Thermal-responsive materials undergo thermal expansion, contraction, or phase transition. When the ambient temperature changes, these materials deform in a programmed way, allowing façades or building components to adapt passively or actively to the environment.

MATERIALS RESPONDING TO THERMAL STIMULI:

I. BISTABLE MATERIALS
Bistable materials are a subset of materials that present two stable equilibrium states where they can remain without the need for an external force. Bistable mechanisms are found in everyday life for example in snap bracelets and are appealing for shape-morphing applications because they present large displacements with low energy requirements. One advantage of bistable systems for kinetic envelopes is that they do not require a constant energy supply; instead, they can remain in their open or closed configurations until a force is applied.

There are different types of bistable materials based on the material type like Bistable Thermo-bimetal (metal based) and Bistable laminates (wood based)





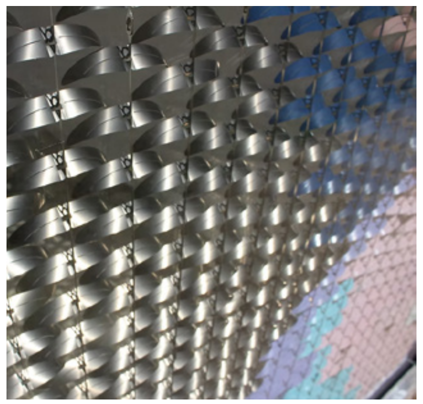


Fig [x] Photograph of the Installed InVert Shading System

I. A. THERMO-BIMETALS

History

The bimetallic property has been used in a range of mechanical and electrical devices, extensively for example for the actuation of on/off switches within early thermostats. The oldest surviving bimetallic strip was created by the clockmaker John Harrison during the mid 18th century. Harrison, who is hence credited as the inventor of bimetals, made it for one of his marine chronometers to compensate for temperature-induced variations in the balance spring. His earliest experiments consisted of two distinct metal strips joined by rivets but later he also invented the method of directly fusing molten brass onto a steel substrate. [18]

Defining the material

A bimetal is a type of smart material that bends in a predictable and repeatable manner when exposed to heat. It consists of at least two different metal layers that are permanently bonded together through lamination. Each metal layer has a distinct coefficient of thermal expansion, and this difference is the key to the material's bending behavior. When the temperature increases, the layer with a higher thermal expansion coefficient (referred to as the active layer) expands more than the layer with a lower coefficient (the passive layer). This mismatch in expansion causes the bimetal to curve, typically bending toward the passive layer. During this process, the active layer experiences compressive stress, while the passive layer undergoes tensile stress. [19]

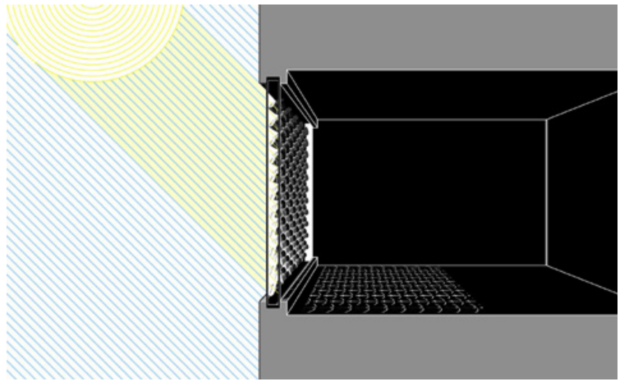
The degree of bending is influenced by several factors. It is directly proportional to the difference in thermal expansion between the two layers and the temperature change on the surface. It is inversely proportional to the overall thickness of the combined layers. Additionally, the modulus of elasticity and the thickness ratio between the two layers further affect the curvature. Other important factors include the ambient air temperature, the total thickness and shape of the bimetal, its fixing axis, and the level of solar radiation it is exposed to.

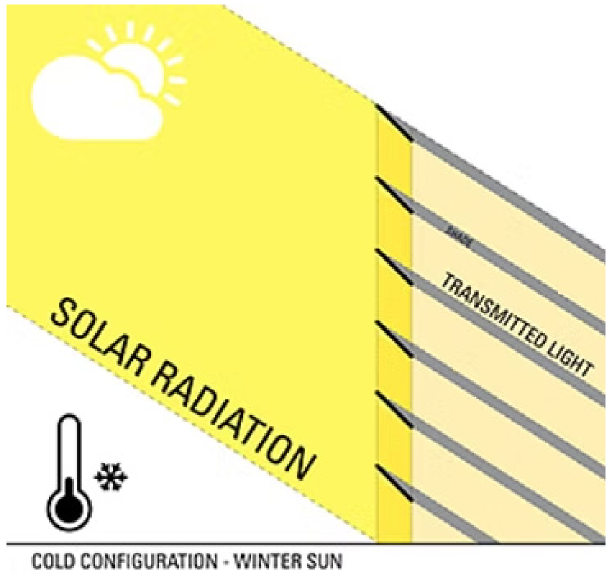
Bimetals can be customized in terms of their composition and geometry to suit different architectural or mechanical applications. A wide variety of engineering laminate configurations already exist, each tailored for specific purposes. In some advanced designs, a third intermediate layer, often copper, is introduced to improve thermal conductivity and enhance corrosion resistance.

Further refinement of bimetal behavior can be achieved through physical manipulation, such as adding creases or folds on the active layer. This technique, inspired by the morphology of leaf veins, allows for directional control over the bending response. Experimental studies have shown that the length and placement of creases significantly influence how the material moves, particularly in determining the ease and extent of curvature. However, it is recommended to avoid excessively short configurations, as the resistance to natural bending increases, reducing the desired performance.

Production Process

Bimetals are commonly produced using the Cold Rolling Method (CRM), a widely adopted technique in industrial manufacturing. In this process, two or more metal layers





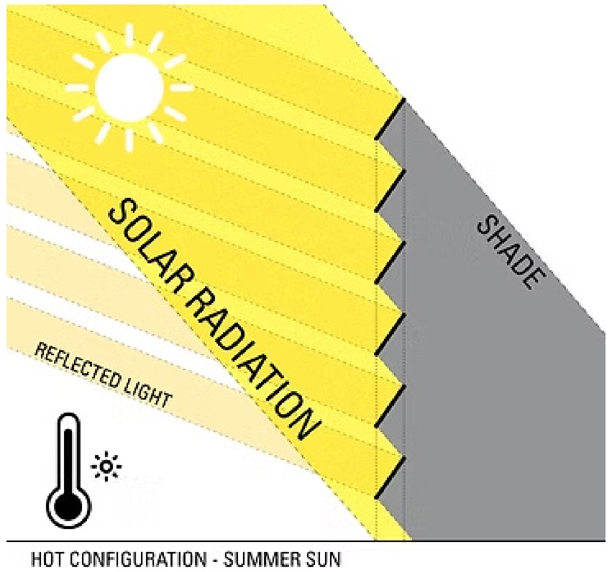


Fig [xi] Position of Transmitting Sun inside [19] *Fig [xii] Position of Reflecting back sun [19]*

are passed through a set of rollers under high pressure. The rolling continues until the desired overall thickness is achieved. Unlike hot rolling, the cold rolling process is carried out at temperatures below the recrystallization point of the metals involved. As a result, the parent metal layers experience significant deformation, which promotes strong adhesion between them. The intense pressure applied by the rollers causes the metals to bond effectively, forming a unified laminated sheet without the need for additional adhesives or heat-based fusion.

Fabrication

The components used for the fabrication of bimetals are chosen first for their temperature characteristics and then for strength, workability, stability, heat conductivity, and electrical properties, depending on the particular requirements. Generally bimetals can be produced to react to temperature changes over any given range by choosing the right components, in particular the low expansion component. Most commonly the layers are welded together into a large bar, which is then rolled in different hot and cold-rolling mills into sheets. Further processing happens according to distinct cold rolling programs. In between the different rolling processes, the sheets are heat-treated in annealing furnaces in a controlled environment. The sequence of annealing and rolling affects the properties of the bimetal. During the final production process the cold-rolled strips are marked according to their quality and the edges are slit and deburred. Marking is usually done on the active layer, which is situated on the convex side of the heated thermostatic bimetal object. The final sheets are cut into strips or bands of 0.1 to 3 mm thickness, which may be fabricated into any of a number of forms, mostly however into rings, coils, or straight strips. [20]

Characterstics of thermo-bimetals

1. The deflection of the bimetal depends on the width it is cut for.
2. The material responds faster to heat exposure than to ambient temperature.
3. On introducing a third layer of Copper inbetween the bimetal, the thermal conductivity and corrosion resistanceis of the material increases.
4. The potential for manipulating the bending direction of bimetals can be achieved by adding creases on its active layer.
5. The length of the crease influences the resistance to natural movement.

Design considerations and conclusion

When using thermo-bimetals in facade design, several considerations and constraints need to be addressed. These include the selection of suitable thermo-bimetal alloys based on the desired thermomechanical properties and compatibility with other facadematerials. The range of temperature variations and the reliability of the shape memory effect overtime should also be considered. Additionally, structural aspects, such as load-bearing capacity, attachment methods, and integration with building systems, need careful attention. Other factors, such as maintenance requirements, cost-effectiveness, and architectural aesthetics, should also be considered during the design process [21]

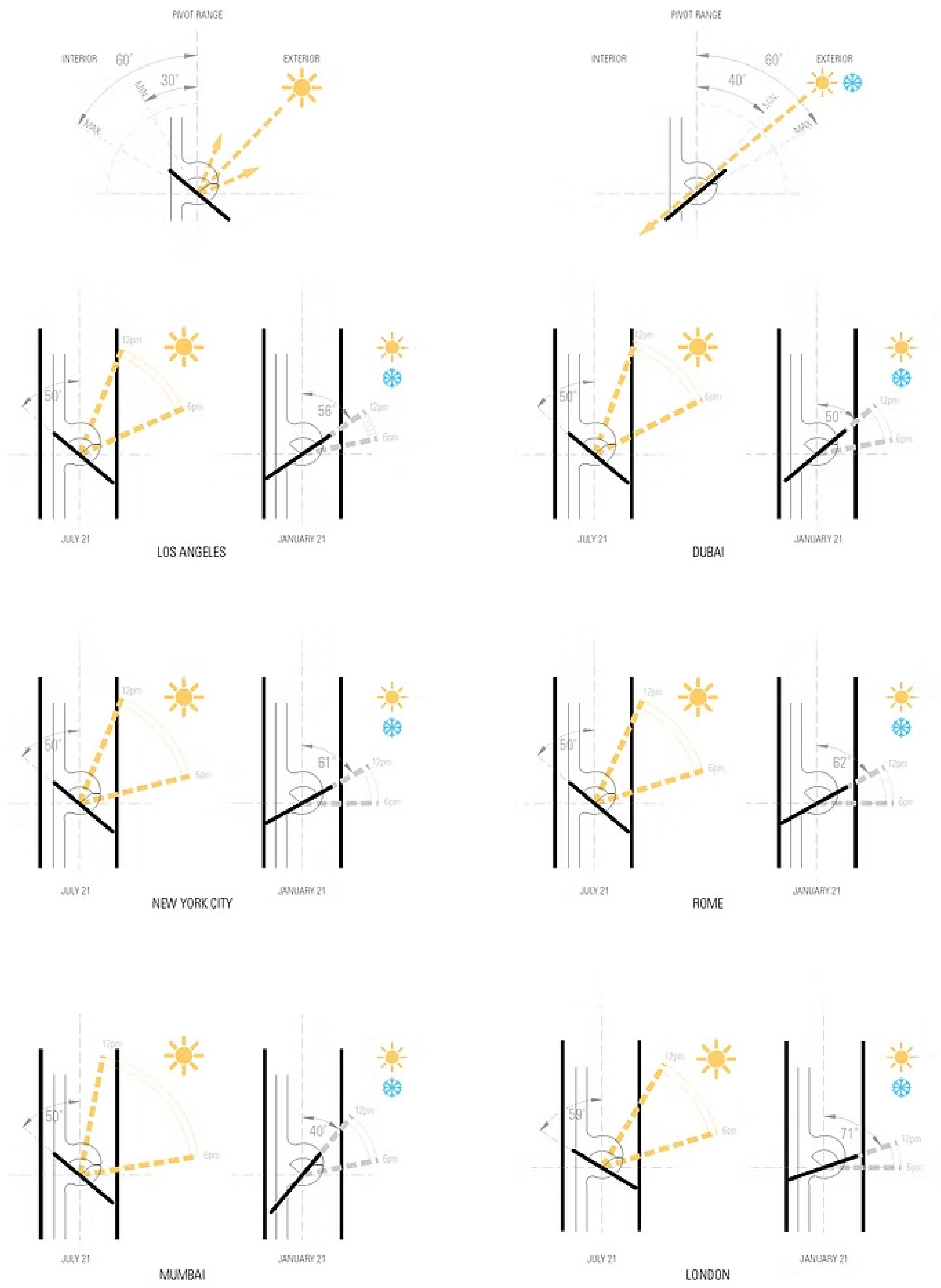


Fig [xiii] Diagram showing difference in design of shading element as per different sun angles in different location of the world [27]

WORKING CONCLUSION
The particular Bimodules tend to close at room temperature of around 18 degree celsius and open at temperature near to 32 degree celsius.
Source: Kinetic module in bimetal: A biomimetic approach adapting the kinetic behavior of bimetal for adaptive Façades)

Case Study 1: Invert Window System by Doris Sung
Over the past two decades, the use of bimetal in architecture has become increasingly significant. Unlike conventional static façades, bimetal systems offer the potential to mediate dynamically between external environmental conditions and internal building performance, allowing the building envelope to behave more like a responsive, adaptive skin than a rigid barrier.

Among the most notable explorations in this field are architectural solutions that investigate the relationship between form, material behavior, and environmental performance. One such innovation is the InVert Auto-Shading Window, a patented and award-winning commercial product that uses bimetal elements to provide passive solar shading.

These systems highlight the ability of bimetal to react directly to solar radiation, which triggers its shape-morphing behavior. As solar exposure increases, the bimetal elements deform in response to heat, adjusting the façade configuration to control light, heat gain, and visibility. Such studies emphasize the material's potential to contribute to the development of passive, climate-responsive design strategies in contemporary architecture. [22]

Eg: "Bloom" Pavilion by Doris Kim Sung which uses thermobimetals to open and close façade flaps in response to solar heat [23]

Video of opening closing of prototype is available at this citation [24]

Invert Windows uses no energy to save energy, It is a system of thermo-bi metals sandwiched inside two double glazed window system which curls and inverts the opposite way to cut the sun, when exposed to sunlight due to the difference in rate of thermal expansion of the alloys that the thermal bimetal material is up made of.
This simple action can save up to 30% of energy used by air conditioning. [25] [26]

Now there might be a problem of functioning of this material because it fails over time due to failure and problem in the adhesive that joins it, but since these these materials are not adhesive bonded but molecularly bonded their perfomace lasts longer but indeed also fades away with time.

Maintenance
Because InVert is sealed inside the air-tight cavity of a standard insulated glass unit, the material and operation of the petals will never tire and no maintenance is needed. The parts remain dust-free and recoating the petals is unnecessary [27].

Fig: Different shapes explored for thermo-bimetal during the process

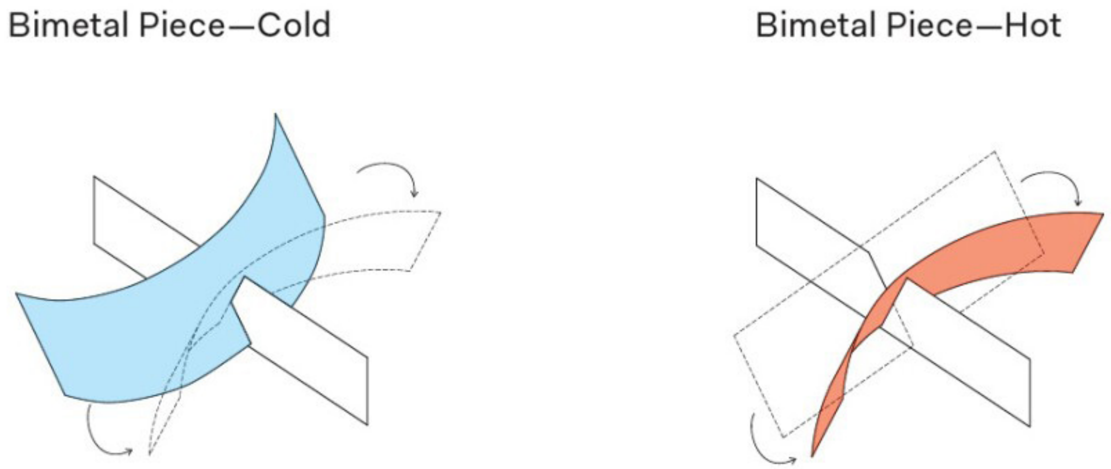


Fig [xiv] Two different position of the thermo-bimetal as per solar radiation [29]

Fig [xv] Detail View of the InVert Panel [34]

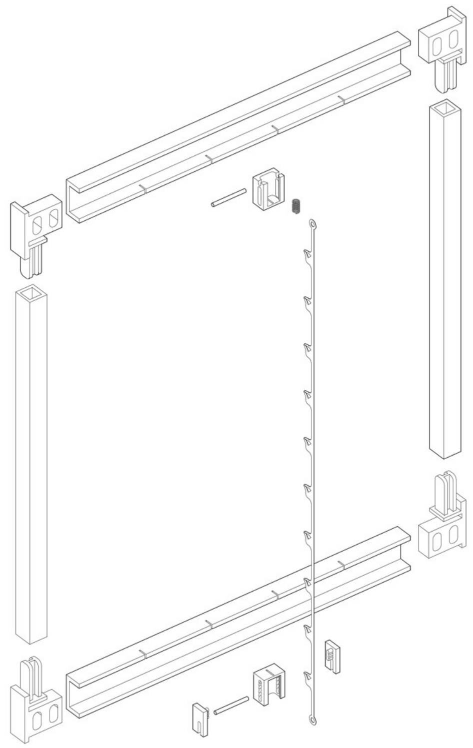


Fig [xvi] Elemental Detail of fixing the panel

After years of study and a reduction of the design to its simplest and geometrically-appealing form, we have found a way to abstract the feeling of butterflies or leaves on a tree fluttering in the wind. The result is a biophilic sensation.

Customization

1. Design Customization: The pixelated system of petals allows the use of multiple colors and a variety of graphic designs. Extensive glass and coating specifications can meet design and performance goals and can include colors, ceramic frit patterns and low-e coatings from PPG, Guardian, Pilkington, Cardinal and St. Gobain. Complexity may affect pricing. [27]

2. Performance customization: Since the individual petals work in response to sun angle, which differs across different climatic zones and latitudes, they should be customized to the area of application.

Market Availability

Thermo-bimetal is available in market in 6" wide rolls [28]

InVert performance is backed by a 10-year warranty by TBM Designs' "InVert™ Performance Certification". Data is certified by independent testing labs and by glazing analysis software, recommended by Lawrence Berkeley National Laboratory, a division of the US Department of Energy. The company will repair or replace its InVert system if it fails in ordinary use from material or manufacturing defects, other than in the case of the failure of the IGU. In connection with the repair or replacement of the product under the conditions of the warranty, TBM Designs will pay, to the extent necessary, the reasonable cost of repair or replacement of an IGU of similar price and quality as the IGU into which the InVert product was first sealed. [27] (Video Link- https://www.youtube.com/live/K3Iyl0xKtI8?si=abD-VBTV17EuJSOp) (Accessed Date: 24th May, 2025)

DIFFERENT TYPE OF BIMETAL	ACTIVE LAYER	PASSIVE LAYER
1. Mangnese- Copper-Nickel and Iron-Nickel	Mangnese- Copper-Nickel	Iron-Nickel
2. Copper and Steel	Copper	SS304
3. Brass and Steel	Brass	Mild Steel
4. Aluminium and Steel	Aluminium	Steel

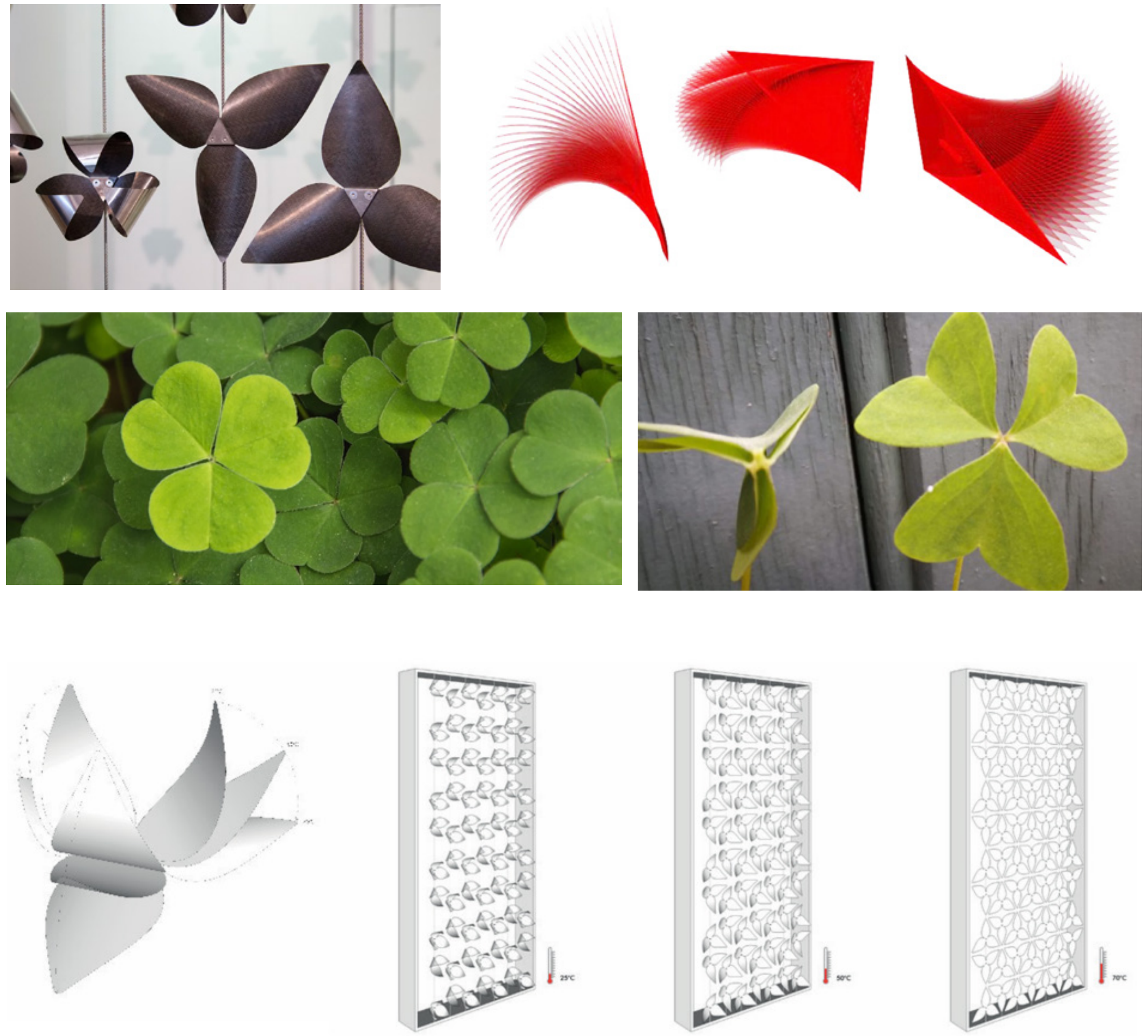


Fig [xvii] The process of taking inspiration of shading device from the plant leaves and its fabrication detail [30]

Case Study 2: Pholiage project [30]

The Pholiage project is an experimental adaptive façade system developed by ArtBuild Architects' innovation lab. It explores climate-responsive solar shading by combining thermo-bimetal and biopolymer materials, creating a façade that moves and adapts passively, without motors or sensors.

Concept

Inspired by the behavior of plant leaves that open and close depending on sunlight and temperature, the Pholiage system mimics this response using shape-morphing materials. The name "Pholiage" is a blend of foliage (leaves) and phos (light in Greek), reflecting its aim to intelligently control sunlight.

How It Works

The façade is made of small shading modules or leaves composed of two materials: Thermo-bimetal and Biopolymer skin. When exposed to sunlight or warm air, the bimetal layer curls, pulling the shading element into a closed position, blocking direct sun and reducing heat gain. When the temperature drops, the bimetal returns to its flat form, and the module reopens, allowing natural light and heat back into the building.This process is completely passive, with no electricity, no electronics, rather the materials themselves do the work.

On warm days, when temperatures soar above 25°C, the "petals" of the device open, creating a vast, protective curtain that shields the building's interior from overheating. As the temperature drops, these petals gently close, permitting natural light to illuminate the indoor spaces.The petal clusters are connected by stainless steel cables to be mounted, on the exterior of the façade. This configuration led to more specific studies on the detailing of attachment components given the need to both hold the TBM petals in place, all the while allowing for their movement when required.

Whats so unique?

The renewable electricity production combined with the dynamic memory-shaped movement of the TBM actuator distinguish this patent pending technology from other existing solutions.

Real-world Application

By the end of 2022, the first real-world application of Pho'liage® graced the new headquarters of the International Agency for Research on Cancer in Lyon, France. This marks a significant milestone, for ArtBuild Paris, and the future of sustainable architecture worldwide.

Two innovative techniques are deployed to provide passive solar protection to the building, both activated and driven solely by the sun's energy. To the courtyard façade, shape memory materials inspired by flower petals open and close according to the sun's movements, whereas to the outer facades, a glazed envelope sequentially reveals organic motifs as integrated thermo-reactive pixels become opaque. The building's bio-inspired architecture is further expressed through the integration of timber elements for which ArtBuild has long been a pioneer and industry leader. [31] [32] [33]

Fig [xviii] View of IARC Lyon made by ArtBuild with solar responsive material in facade [31]

Fig [xix] Application of thermo-bimetal element in IARC Lyon Courtyard facing facade, France

I. B. BISTABLE LAMINATES

Bistable laminates are thin, multilayered composite structures designed to possess two distinct, stable shapes. Once formed, these structures can rest in either shape without continuous energy input. The shape change occurs when a sufficient external force or trigger (like temperature or stress) causes the structure to “snap” from one configuration to the other. [36]

Working of Bistable Laminates

Their ability to switch between two stable shapes comes from residual stresses that develop during the manufacturing process, typically through curing. 1. Asymmetric Layup Bistable behavior begins with the design of the laminate’s layup configuration. In symmetric laminates, internal stresses cancel out, and the laminate remains flat. In asymmetric laminates, the mismatch in fiber orientation causes unbalanced residual stresses during curing. These stresses are “locked in” once the laminate cools or sets.

2. Residual Stress-Induced Curvature After curing, the internal stress causes the laminate to deform into a naturally curved shape. This is its first stable configuration. Due to its mechanical properties, the structure can also be manually deformed (with a click or external force) into a second stable shape usually in the opposite curvature. Both configurations are energetically stable and require no continuous external force to maintain.

3. Snap-Through Instability When an external force is applied beyond a critical threshold, the laminate undergoes a snap-through instability, rapidly switching from one shape to the other. This behavior is similar to a slap bracelet or a bent metal strip that flips sides. The transition is non-linear and sudden, making bistable laminates useful in applications where quick deployment or passive motion is needed.

4. Influencing Factors Several parameters affect the bistable performance of the laminate:

A. Fiber orientation (angle of plies)
B. Thickness of layers
C. Material type (fiber + matrix system)
D. Curing temperature and time
E. Geometric dimensions (length, width, curvature radius)

By precisely controlling these parameters, we can tune the curvature, activation force, and stability of each shape to meet specific application needs. [37]

Case Study of Bistable Laminate Use

Bistable Kinetic Shading System at Penn State

The Bistable Kinetic Shading System developed at Penn State University is an innovative approach to creating adaptive building façades that respond to environmental conditions without continuous energy input. This system utilizes bistable carbon fiber laminates and shape memory alloys (SMAs) to achieve dynamic shading capabilities.

Design and Functionality

The core of the system comprises modular units, each featuring four bistable flaps

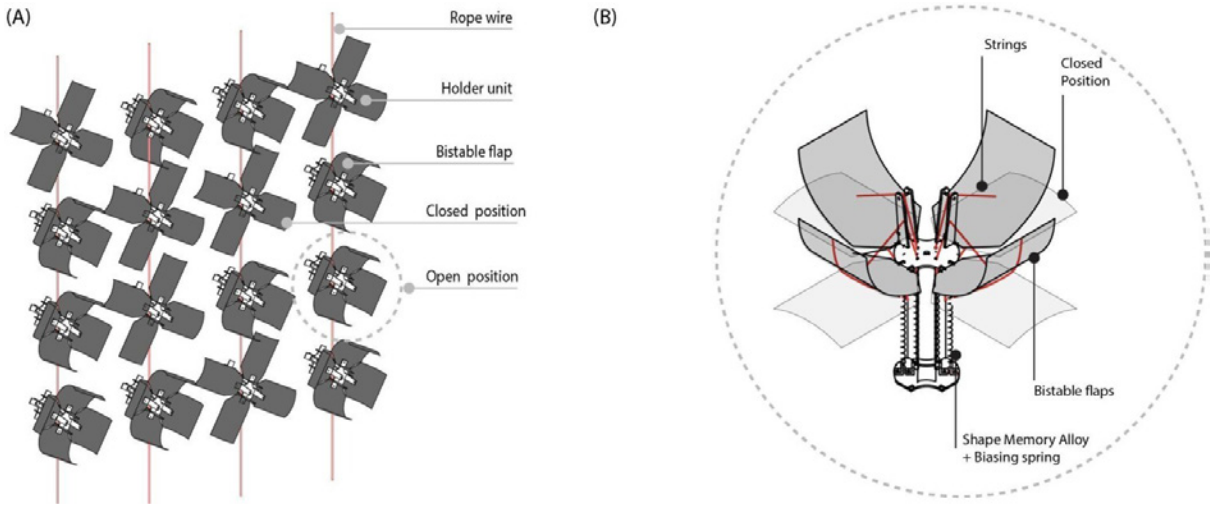


Fig [xx] Details of the Adaptive facade made of SMA and Bistable Laminate at the Penn University [39]

made from carbon fiber laminates. These flaps can maintain two distinct stable position, open and closed, without the need for constant energy, thanks to their bistable nature. Actuation is achieved through linear actuators incorporating SMAs, which, upon thermal activation, induce the flaps to snap between their stable states. This design allows the shading system to adapt to changing environmental conditions, such as sunlight intensity, enhancing indoor comfort and energy efficiency.

How It Works (Actuation Principle)
Shape Memory Alloys (SMAs) are the actuators in the system.SMAs are special materials that can "remember" a pre-set shape (to be discussed in the next section).When heated (by environmental temperature or embedded heating element), they contract or expand, applying force. This force activates the snap-through behavior of the bistable carbon fiber laminates.These lami-nates have two stable shapes (open and closed).Once pushed past a critical point by the SMA, they "snap" into the second shape.No continuous power is needed to keep the shape.Power is only re-quired briefly to trigger the snap Once in place, the bistable laminate holds the position passively.

II. SHAPE MEMORY MATERIALS (SMM)

As implied in the name, these are materials who have a "memory" of their shape. Specifically, they are able to return to their original shape after they have been deformed in some way. They can return to their original shape when a particular stimulus is applied. This stimulus may be heat or light, for example. In the case of shape memory, the property that is affected is their shape, by applying some external stimuli such as temperature, stress, moisture, electric or magnetic field, pH, light or chemical compound. In the following paragraphs, we will study the effects only of temperature change.

This ability is known as the shape memory effect (SME). There are several types of shape memory material and can occur in alloys known as shape memory alloys (SMAs) and in polymers, in shape memory polymers (SMPs), but is also possible in shape memory hybrids (SMHs). [38] [39]

II. A. SHAPE MEMORY ALLOY (SMAs)

Shape Memory Alloys (SMAs) are a class of metal alloys that have the unique ability to "remember" and return to a pre-defined shape when exposed to a specific temperature. There are two phases of SMA's: One low-temperature phase called as martensite, and other high-temperature phase called as austenite.This transformation is enabled by a reversible solid-state phase change between these two phases.

Properties exhibited by Shape Memory Alloys:

1. Shape memory effect (SME): The ability to undergo deformation at one temperature and recover its original shape upon heating.
2. Superelasticity: Exhibits large strains at a constant temperature which are instantly recovered upon unloading.
3. High energy density: Makes SMAs suitable for actuation systems.

Working Mechanism: When cooled, the SMA enters the martensitic phase, where it

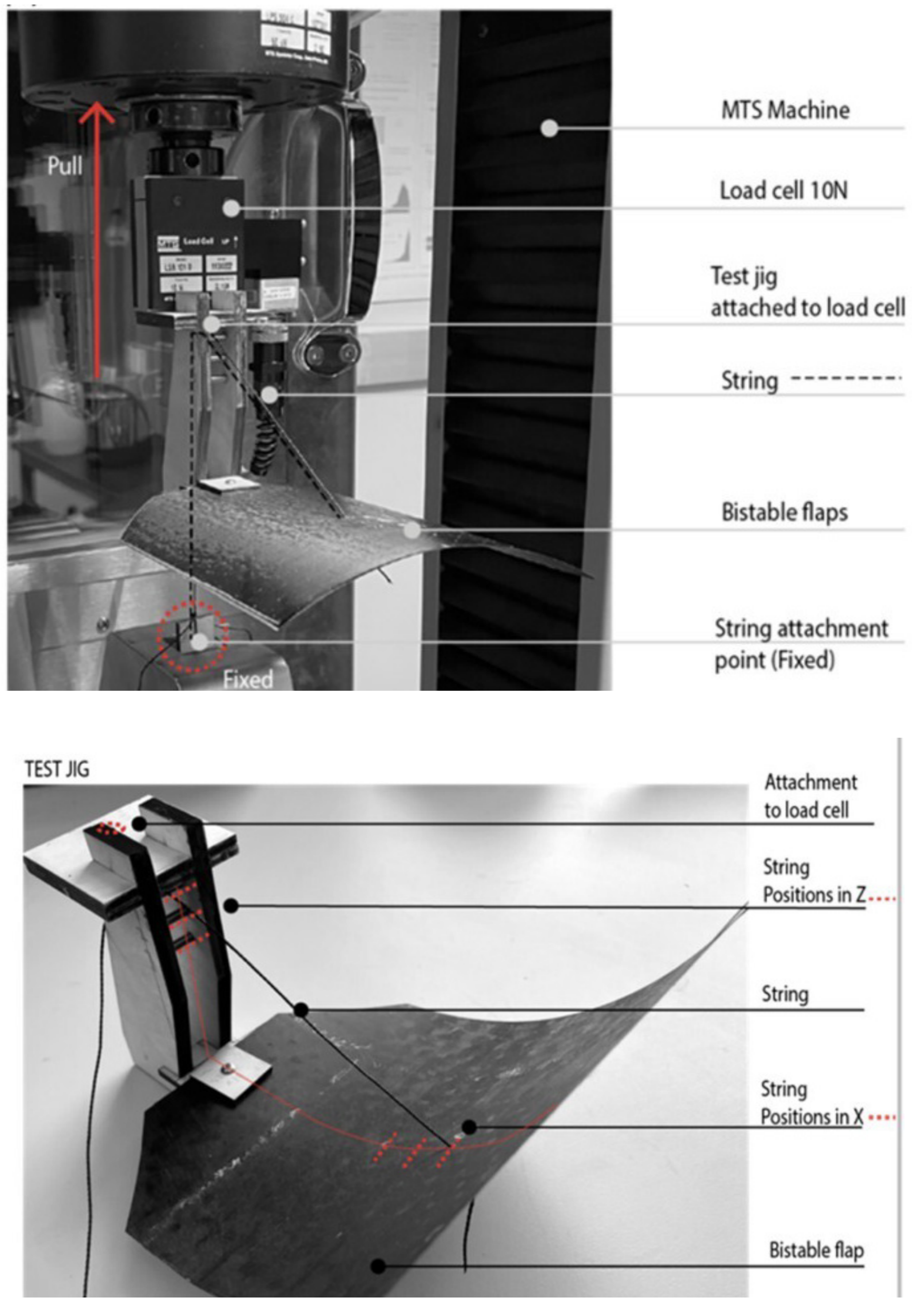


Fig [xx] Details of the Adaptive facade made of SMA and Bistable Laminate at the Penn University [39]

can be easily deformed. Upon heating, it transitions to the austenitic phase, regaining its original shape. This tem-perature-induced transformation can be finely tuned by altering the composition and processing conditions of the alloy.

Applications in Building Envelopes:
1. Adaptive façades that passively respond to temperature by opening or closing louvers or vents.
2. Thermal actuators integrated into kinetic shading systems.
3. Used in low-energy responsive skins to control ventilation, daylight, or thermal gain.
Example: Among SMAs, Nickel-Titanium (NiTi) alloys—commonly known as Nitinol are the most extensively researched due to their large recoverable strain, biocompatibility, and good fatigue re-sistance. [40]

Challenges:
1. Cost of NiTi alloys is relatively high.
2. Durability in outdoor environments still needs more long-term validation.
3. Control precision may require hybrid systems (e.g., SMA + sensors). [41]

II. B. SHAPE MEMORY POLYMER (SMPs)

Shape-memory polymers (SMPs) are polymeric smart materials that have the ability to return from a deformed state (temporary shape) to their original (permanent) shape when induced by an external stimulus (trigger). Most SMPs use heat as their stimulus. These thermally responsive SMPs can be also regarded as thermoplastic elastomers.

How do shape memory polymers work?

Shape memory polymers have a special chemical structure that means they can return to an original state from a deformed state. The external stimulus could be heat, light, electricity or magnetism, and usually these generate heat within the polymer as the mechanism to start the process of changing from the deformed state back to the original state.

Polymers can occur in two states, either a crystalline state where it is organised uniformly and becomes a rigid relatively strong structure, or an amorphous state where the polymer subunits are randomly scattered and relatively soft and flexible, moving around fairly easily. The difference with a shape memory polymer is that is has a semi-crystalline structure. This means both states occur at the same time within a specific temperature, usually room temperature.

There are different ways that this effect of having a 'memory' is achieved, which have different names like "dual-state mechanism", "dual-component mechanism", or "partial transition mechanism". Find out more.

It is useful to explain some of the mechanics that are at play, by looking at the "glass transition temperature":

"Glass transition temperature" Tg, is the temperature at which the polymer changes from one state to the other, so from crystalline (rigid) to amorphous (flexible). Shape

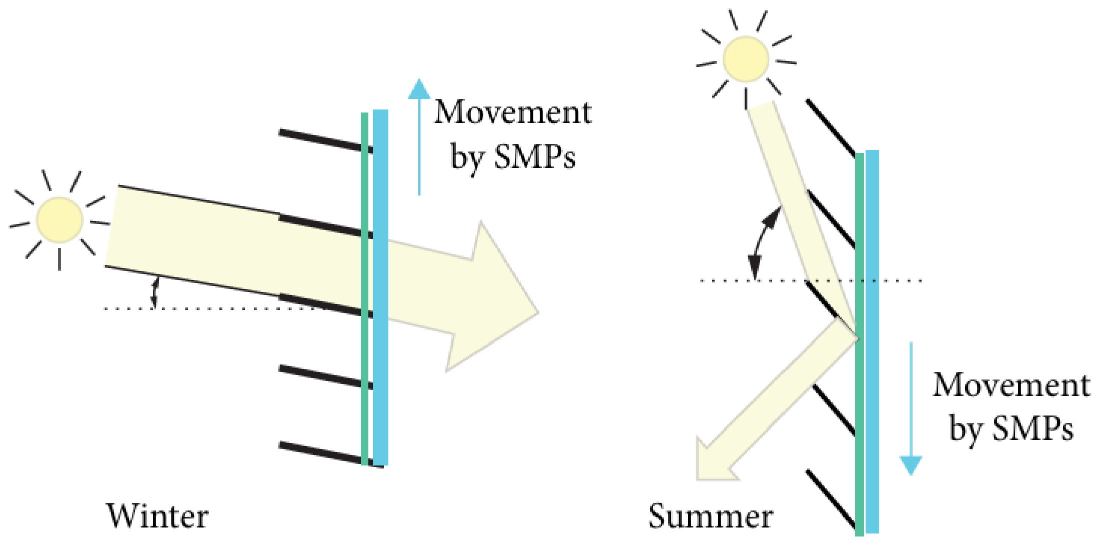


Fig [xxi] Schematic Diagram of thermally resposnsive SMPs in heat controls of window blinds

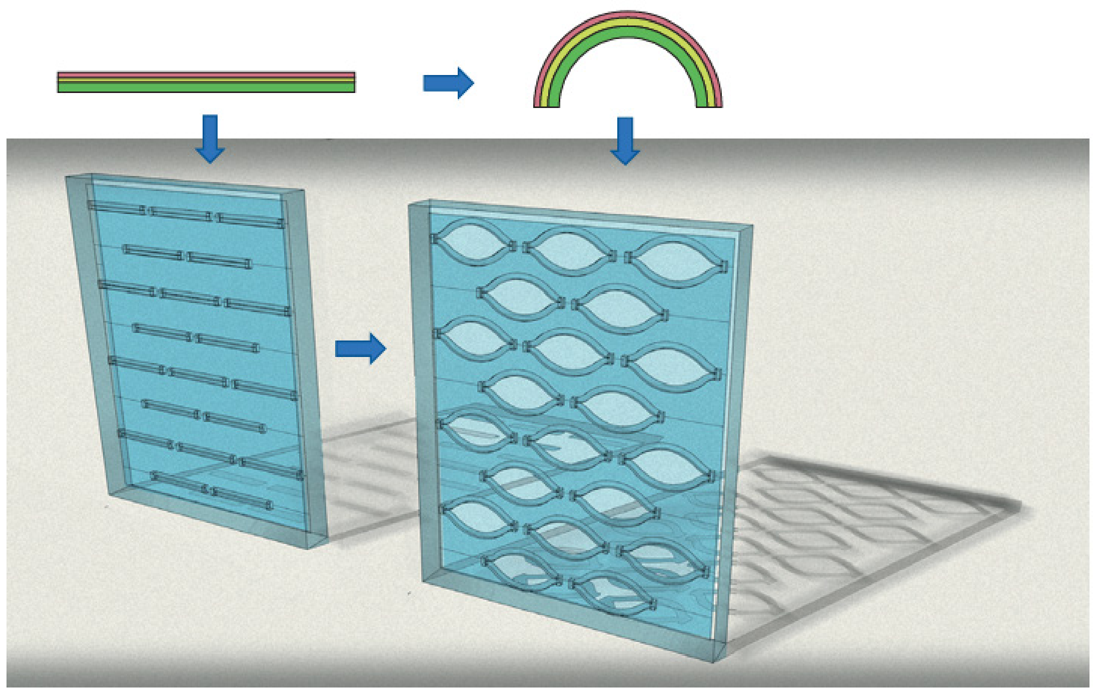


Fig [xxii] Schematic Diagram of composite SMPs in shading controls

memory polymers have two of these temperatures. In the initial crystalline state the movements of the polymer segments are frozen. This is the initial state that it will return to. When these become heated, the state changes. When temperature is increased the rotation around the segment bonds becomes less impeded, and it is transformed into an amorphous state overall.

This is because within the material there are hard segments, crystalline domains of soft-segments, and amorphous domains of soft-segments. These three segment types always exist. Though only two of these segments elongate. The amorphous and crystalline domains of the soft-segments are the parts that elongate, whereas the hard-segments do not.

In their deformed state, the chain segments which have been put under external stress to deform them are prevented from recoiling into their original state. This is achieved by 'reversible netpoints' which act as the molecular switches. These can be formed by physical interactions or covalent bonds.

When the second glass transition temperature is reached, the polymer changes back to its original state. One way of understanding why this happens is that physical systems want to return to a state of most randomness, and less order. So when we add temperature which is an increase the mobility of the chains, it will want to go towards the state of the most disorder. When we stretch it in the first place, goes from a random alignment of the chains, to a slightly less random, because they're stretched. So, when we increase the mobility of the constituent parts at this stage, and due to the interactions within the semi-crystalline structure, it will want to return to the less ordered, original state.

Types of shape memory polymer based on reversibility

Upon the reversibility of shape memory effect (SME), SMPs can also be classified into either one-way or two-way SMPs. "One-way" implies that the shape recovery is irreversible. That is, shape shifting during recovery can only proceed from a temporary to a permanent shape and not the reverse (Figure). "Two-way" means that the shape change is reversible; the initial and temporary shapes can be reversed with the appearance and termination of the stimulus. us, these two-way SMPs can achieve dual or even triple shape changes.

Based on the number of shapes involved in each shape memory cycle, SMPs can be classified as dual, triple, or multi-SMP. A typical SMP is dual (i.e., one temporary shape transformed into a permanent shape). In contrast, tri-ple-SMPs feature two temporary shapes (A and B) in addition to their permanent one (C). First, the temporary shape B must be programmed, followed by the temporary shape A. e appropriate stimulus transforms the second tempo-raryshape into thefirst (A->B). Subsequently, a second trigger initiates the regeneration ofthe permanent shape C. A multi-SMP (shown in Figure 3) is able to memorize more than two temporary shapes and subsequently recover in a highly controllable manner.

Some important part of the thermally responsive SMP are:

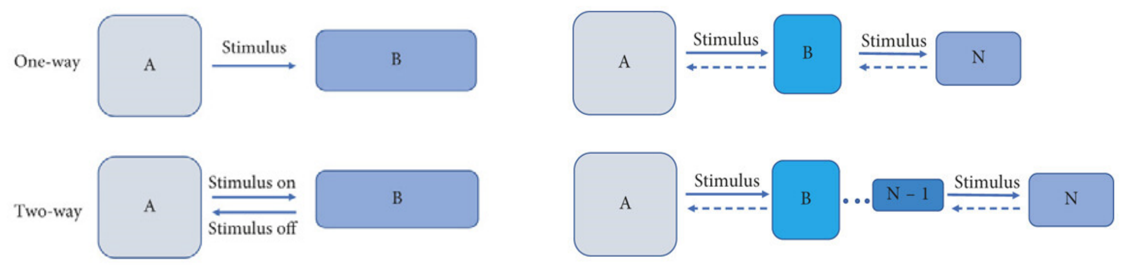


Fig [xxiii] One-way. two-way, three-way and Multi SMP

Shape memory alloys can be divided into two main categories:
1. One-way effect: The shape memory effect is from the cold state to the hot state, meaning that, if the material is deformed in a cold state, can recover its original shape if it is heated.
2. Two-way effect: The material possesses two distinct memories in its hot and cold states and shifts between these two states when is either heated or cooled."

"The shape memory effect can be present at two different types, the one-way and two-way shape memory effects. The one-way type possesses the feature at which the material only remembers its austenite phase's shape and recovers it upon heating. For this purpose, an initial force has to be applied in the spring that would deform it . Despite the one-way effect, the two-way one is comprised of two distinct trained phases and the spring is capable of remembering and transforming to both the Martensite and Austenite phases upon removing and applying the heat, respectively. But it has to be mentioned that the two-way effect generates almost as half as the recovery strain of the one-way. Therefore, a one-way shape memory effect provides a more functional and economical solution. [43]

Actuators	Strain [%]	Stress [MPa]
SMAs	10	200
SMPs	400	4
Ionic gels	40	0.3
DEAs	503	7.7

Fig [xxiv] Actuators Stress Stress Summary [44]

A. Molecular switches and net points are two major molecular-level components of thermally responsive SMPs. Molecular switches are segments with a thermal transition at Tm that fixes the temporary shape by forming physical crosslinks.
B. Net points that link these switching segments and determine the permanent shape of the polymer network can either be physical crosslinks through physical intermolecular interactions or chemical crosslinks through covalent bonds.

Applications in the building Envelope
For instance, when it comes to movable window blinds that respond to a variety of solar angles in different seasons (i.e., winter and summer) to potentially utilize or mitigate solar heat gain, a type of thermally responsive SMP can potentially be used in the hinges of the blind structures. The different external air temperatures in winter and summer would then actuate the shape change in the SMP and adjust the angles of the blind slats (as seen in the schematic figure). Similarly, different SMP layers in a single unit with different Tg values could form various shapes in response to external air temperature changes, which in turn might act as a daylighting control system for potential lighting energy savings (as seen in the schematic figure) . Ideally, these envelope components' changes would be reversible as external stimuli (i.e., temperature, humidity, wind, etc.) are normally periodical. To that end, two-way SMPs show great promise for applications in the fields of dynamic building facades and energy savings. [42]

Different material types of shape memory polymer
There are many different types of shape memory polymer and more are being developed all the time.

Three commonly used engineering polymers that can demonstrate the shape memory effect (SME) include polytetrafluoroethylene (PFTE), polylactide (PLA), and ethylene-vinyl acetate (EVA).

Challenges to Using Two-Way SMPs in DynamicBuilding
For application in the window system, often the tradeoff between extension rate and transparency is seen as a challenge as with increased extension, transparency is compromised but in our case, this is rather benefitial. In architectural shading applications, a decrease in transparency during extension is not a drawback, but can be seen as an advantage if the purpose is to block sunlight. Therefore, when selecting or designing two-way SMPs for shading systems, achieving higher extension and responsive morphing behavior may take priority over maintaining optical clarity. [45]

1. Methods and Designs for Ideal Temperature Ranges
For two-way shape memory polymers (SMPs) to work effectively in buildings, they need to activate and recover their shape within a temperature range of −15°C to 40°C, which reflects typical outdoor conditions. However, this is difficult to achieve in practice. Some methods like UV crosslinking, adding carbon black, or using composite layers have been tried to shift the activation temperature range. These can increase or modify the range slightly, but there's still no precise way to control or predict the temperature window accurately. Also, researchers haven't developed reliable mathematical

Table 9: Summary of shape-morphing solar shading systems. [1] T=Translation, DT = Differential Translation, S=A = Swivel=Axis, S≠A = Swivel ≠ Axis. [2] C = component, SC = Sub-Component, S = System. [3] BU = Bottom-up, TD = Top-Down

Pr. ID	Project name	Ref.	Mov. act. [1]	Mov. Comp. [1]	Degrees freed.	Scale[2]	Stimulus	Smart actuator	Biomimetic approach[3]
A	Flectofin ®	[137]	T	S=A	2	C	External mechanical forces	-	BU
B	Solar Kinetic	[138]	T	S=A	2	SC	Heat source provided through electrical current	SMA	BU
C	Ocean Pavillon	[139]	T	S≠A	2	C	Mechanical force	-	-
D	Blind	[140]	T	S≠A	1	SC	Heat source provided through electrical current	SMA	TD
E	Living glass	[141]	T	S≠A	1	SC	Heat source provided through electrical current	SMA	-
F	Air flow(er)	[142]	T	S≠A	2	C	Heat source provided through electrical current	SMA	TD
G	Homeostatic	[143]	T	S≠A	1	C	Electricity	DEAP	TD
H	Sun shading	[144, 145]	T	S≠A	1	C	Heat source provided through electrical current	SMA/SMP	-
I	Shapeshift	[146]	T	S≠A	1	SC	Electricity	DEAP	-
J	Smart Screen	[143]	T	T	1	S	Heat source provided by solar radiation	SMA	-
K	Piraeous tower	[147]	T	T	1	S	Heat source provided by solar radiation	SMA	TD
L	Lily Mechanism	[148]	DT	S=A	1	C	Heat Source	SMH	BU
M	Curved-line folding	[149]	T	S=A	1	C	Mechanical Force	-	-
N	Kinetic Solar Skin	[150]	T	S≠A	2	C	Heat source provided through electrical current	SMA	-
O	Shape Variable Mashrabiya	[151]	T	T	1	S	Heat source provided by solar radiation	N/A	-

Fig [xxv] Summary of Shape Morphing Solar Shading Systems [48]

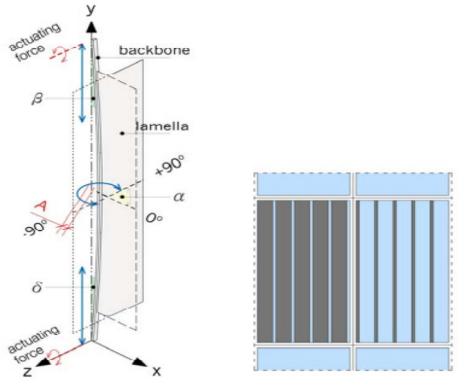


Figure 2: Project (A): Flectofin® [137]. Scheme of operation and example of facade's integration (closed and open configuration).

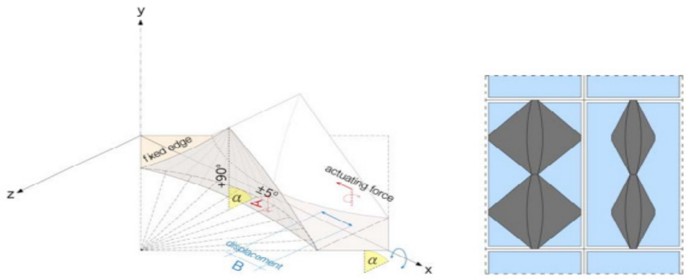


Figure 3: Project (B): Solar Kinetic [138]. Scheme of operation and example of facade's integration (closed and open configuration).

models to show how different factors affect this range.So, while some polymers (like PEU) come close, it's still a major challenge to create SMPs with a perfectly tuned and reliable temperature range suitable for reversible use in real building environments. [46]

2. Fabrication Methods for Microstructure Design

Creating two-way shape memory polymers (SMPs) with the right microstructure for building applications is still a big challenge. While 3D printing (or 4D printing) has made it possible to build complex and responsive SMP structures, most of the successful results so far have only worked in water-based environments, not in air or real building conditions.Although researchers have tried different combinations and materials to create SMPs that can change shape back and forth, the fabrication process for dura-ble, air-responsive, two-way SMPs suitable for buildings is still not fully developed [47]

Some of the common SMP are:

Example 1

Graphene-Enhanced SMPs Material: Shape memory polymers infused with graphene Behavior: Rapid, localized heating when exposed to infrared or direct sunlight; enhanced conductivity and du-rability Use: High-efficiency responsive panels, light-weight façade systemsExample: Light-to-heat driven SMP sheets developed for soft robotics and smart structures

Example 2

4D Origami Structures (Heat-Activated) Material: SMPs or thin laminates with pro-grammed fold lines
Behavior: Complex folding occurs upon heating, forming stable 3D structures from flat sheets
Use: Deployable shading panels, kinetic furniture, emergency shelters
Example: 4D Origami prototypes created using fused deposition modeling (FDM) with programmed heat response

II. C. SHAPE MEMORY HYBRIDS

Shape Memory Hybrids are composite materials made by combining two or more materials (often one active + one passive) to achieve programmable, shape-changing behavior. They aim to enhance or fine-tune the properties of shape memory systems (like SMPs or SMAs). SMHs are composed by well-known materials that have no shape memory properties on their own. Usually, in SMHs there are no chemical interac-tions between matrix and inclusions; therefore the properties of each component are maintained. Both inclusion and basic matrix can vary, as they can be metals, organic materials or inorganic materials, and their shape memory effect can be activated with different stimuli (thermo responsive materials, pressure-responsive materials, and multi-stimulus responsive materials)

Shape memory alloys versus shape memory polymers

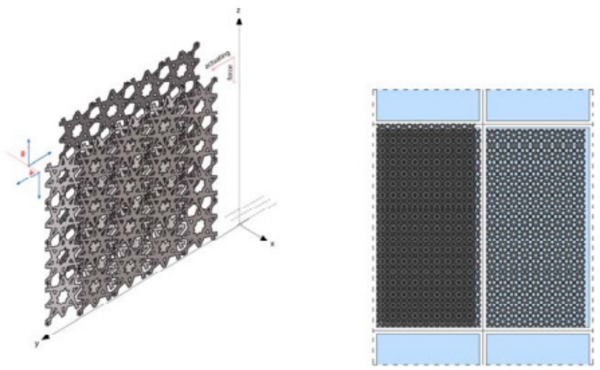


Figure 15: Project (O): Shape Variable Mashrabiya [151]. Scheme of operation and example of facade's integration (closed and open configuration).

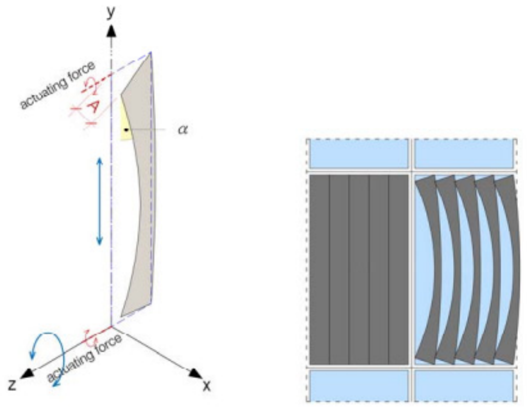


Figure 4: Project (C): Ocean Thematic Pavilion [139]. Scheme of operation and example of facade's integration (closed and open configuration).

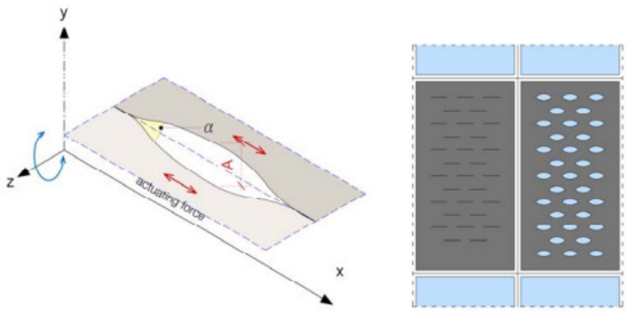


Figure 5: Projects (D): Blind [140] and (E): Living Glass [141]. Scheme of operation and example of facade's integration (closed and open configuration).

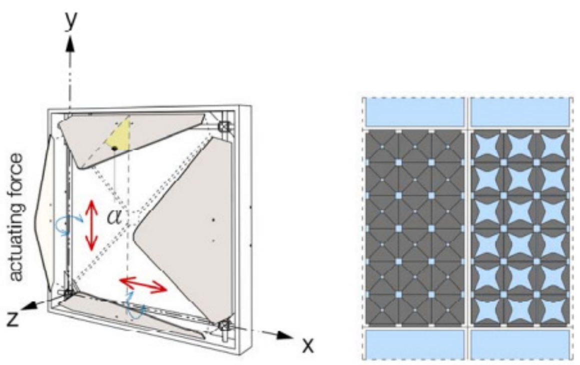


Figure 6: Project (F): Air Flow(Er) [142]. Scheme of operation and example of facade's integration (closed and open configuration).

Fig [xxvi] Summary of Shape Morphing Solar Shading Systems [48]

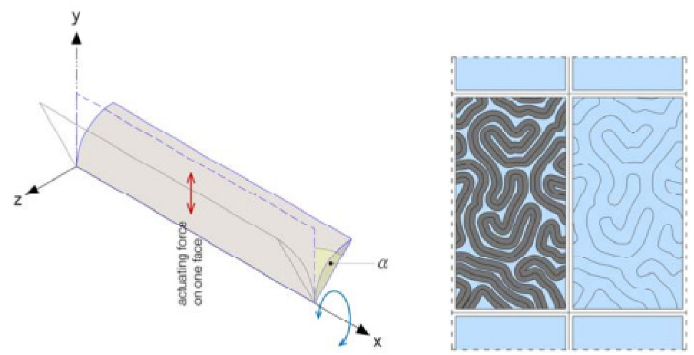


Figure 7: Project (G): Homeostatic [143]. Scheme of operation and example of facade's integration (closed and open configuration)

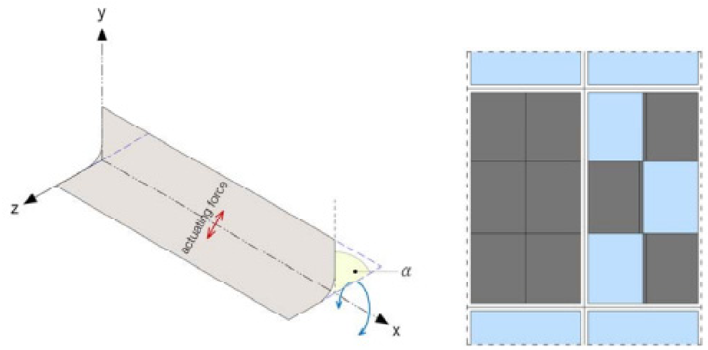


Figure 8: Project (H): Sun Shading [144, 145]. Scheme of operation and example of facade's integration (closed and open configuration).

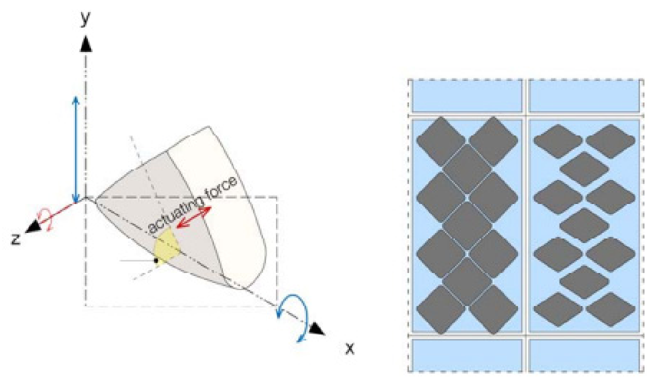


Figure 9: Project (I): Shapeshift [146]. Scheme of operation and example of facade's integration (closed and open configuration).

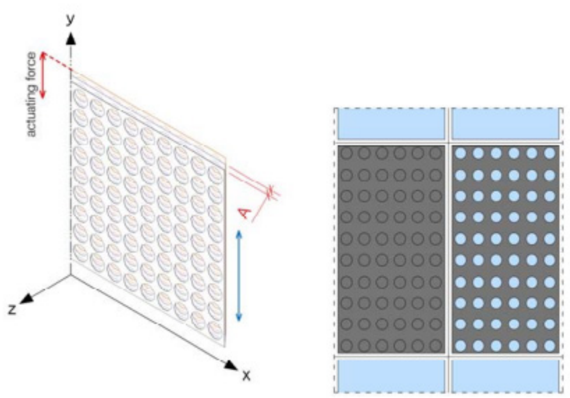


Figure 10: Project (J): Smart Screen [143]. Scheme of operation and example of facade's integration (closed and open configurati

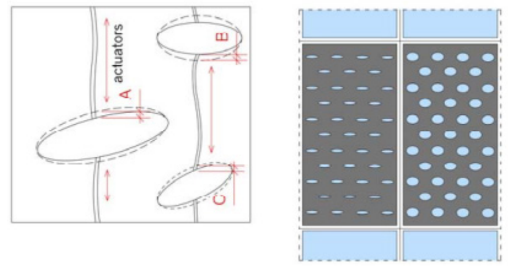


Figure 11: Project (K): Piraeous Tower [147]. Scheme of operation and example of facade's integration (closed and open configuration).

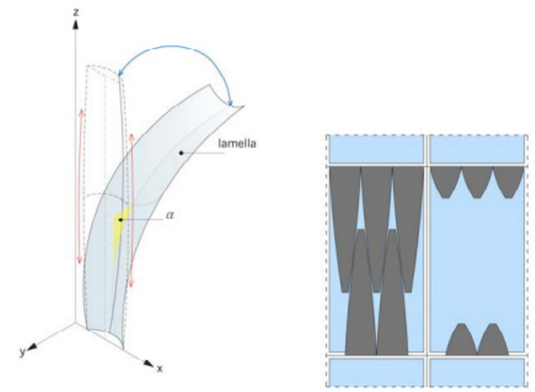


Figure 12: Project (L): Lily Mechanism [148]. Scheme of operation and example of facade's integration (closed and open configuration).

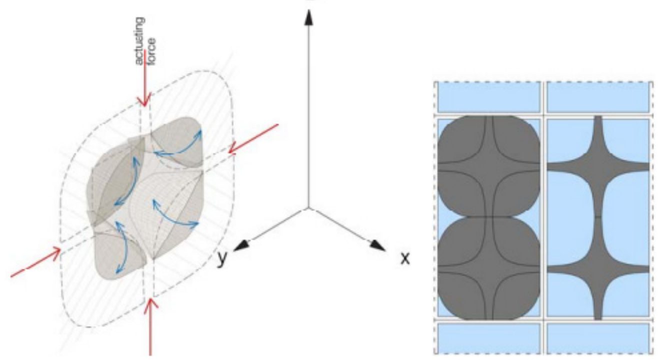


Figure 13: Project (M): Curved-line folding [149]. Scheme of operation and example of facade's integration (closed and open configuration).

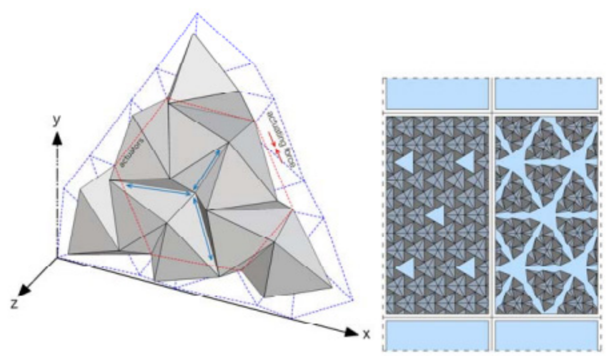


Figure 14: Project (N): Kinetic Solar Skin [150]. Scheme of operation and example of facade's integration (closed and open

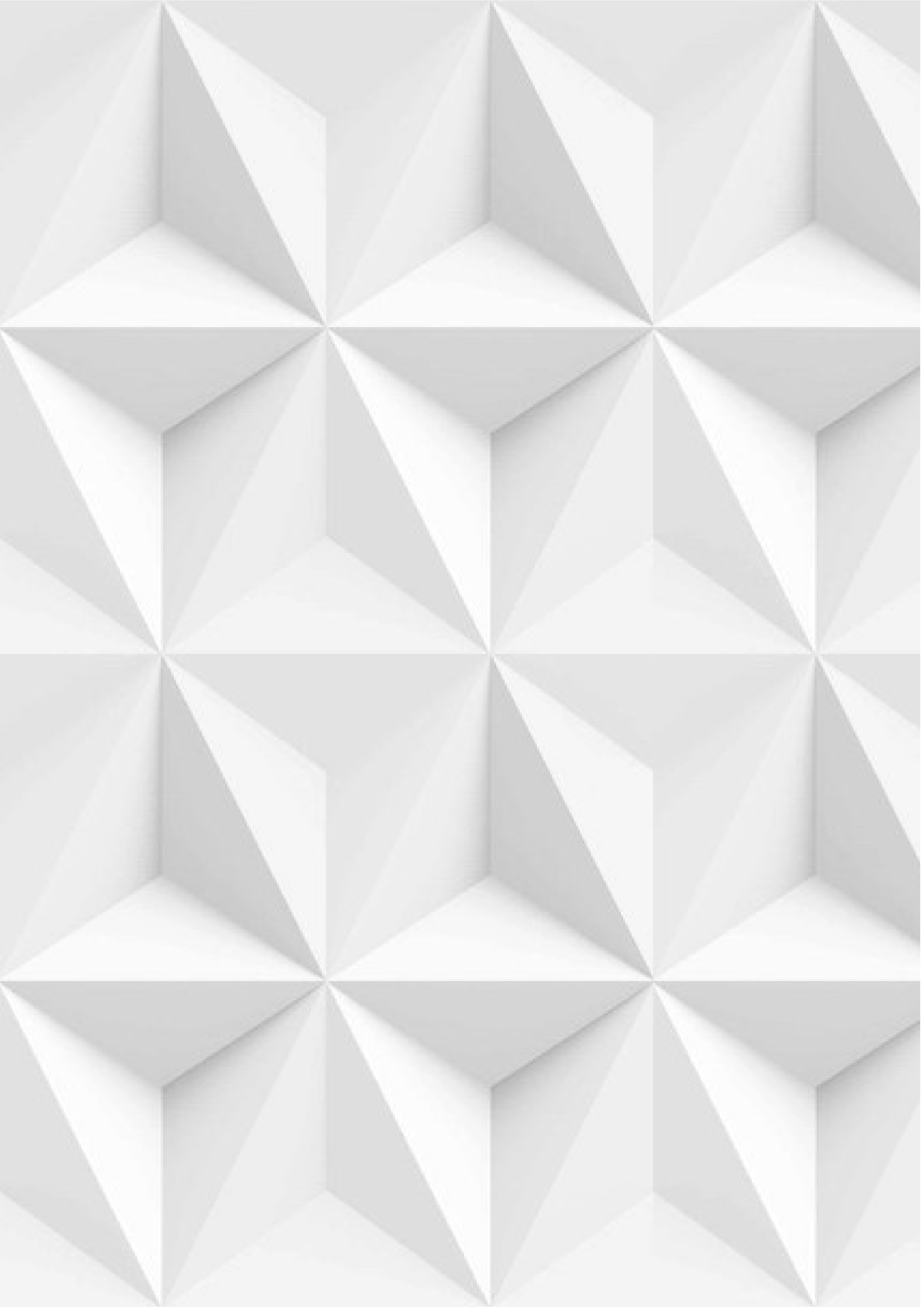
Table 8: Comparison among shape memory materials [90, 98, 134-136].

	SMAs	SMPs	SMHs
Description / Composition	Most diffused are NiTi-based alloys. Classified in Ni-Ti based, Cu-based and Fe-based	More than 20 different types of SMPs. Most common are thermoplastic polyurethanes and epoxy SMPs	Composed of materials with no shape memory effect on their own. They are "custom made". The most studied are Silicon-Wax Hybrids
Movement / Morphing effect	Stress recover and original shape recover. Small contraction (up to 10%) and deformation. A force is required to re-establish the original shape	Stress recover and original shape recover. High deformation (up to 800%). A force is required to re-establish the original shape	Stress recover and original shape recover. Small reversible strain (up to 6-8%). A force is required to re-establish the original shape
Durability issues	More than 200,000 cycles for NiTi alloys. In NiTi alloys high resistance against corrosion and external weather	Up to 200 cycles for SMPU tested. Can be affected by external weather conditions	Currently no experimental data. External weather condition resistance related to composition
Recovery temperature	-10 °C to +200 °C NiTiCu alloys can be tailored for shading devices, A_s ~ 45-60 °C	+25 °C to +200 °C Can be tailored at lower temperatures T_g ~ 60-90 °C	Vary with the components: silicon-wax hybrids have an activating temperature of ~ 45 °C
Density	6000–8000 kg/m^3	900–1100 kg/m^3	Variable
Elastic Modulus E above T_s	70–100 GPa	0.5–4.5 GPa 1.24 GPa (Polystyrene SMP)	Variable
Elastic Modulus E below T_s	28–41 GPa (NiTi SMAs)	2–10 GPa (Polystyrene SMP)	Variable
Transformation strain	6–8%	250–800% 50–100 % (Polystyrene SMP)	~6% (Silicone-Wax)
Actuation stress	150–300 MPa ~100 MPa (NiTi SMAs)	2–10 MPa	Variable
Market availability and shape	Wires (different diameters, already educated in range from few µm to 1 mm) Springs Plates/Sheets	Easily customized shape	Mainly derived from DIY approach User's desired shape

Fig [xxvii] Comparision of SMA, SMP and SMH [49]

Metal alloys such as nitinol were shape memory alloys studied prior to shape memory polymers, but polymers have several advantages over the alloys.
They can increase in size a lot more, for example, doubling in size versus around a 5% increase for nitinol. Such size increase means more complex geometries can be designed for a variety of applications.
The SMPs also have a softer feel, with a rubbery consistency, which could mean they are less likely to damage surrounding tissue when used in biomedical devices, although in such applications it is vital that thorough tests are carried out regards safety.
Shape memory polymers also have a much lower cost, a lower density, and are easy to process than shape memory alloys. In addition they can sometimes exhibit superior mechanical properties when compare to shape memory alloys.

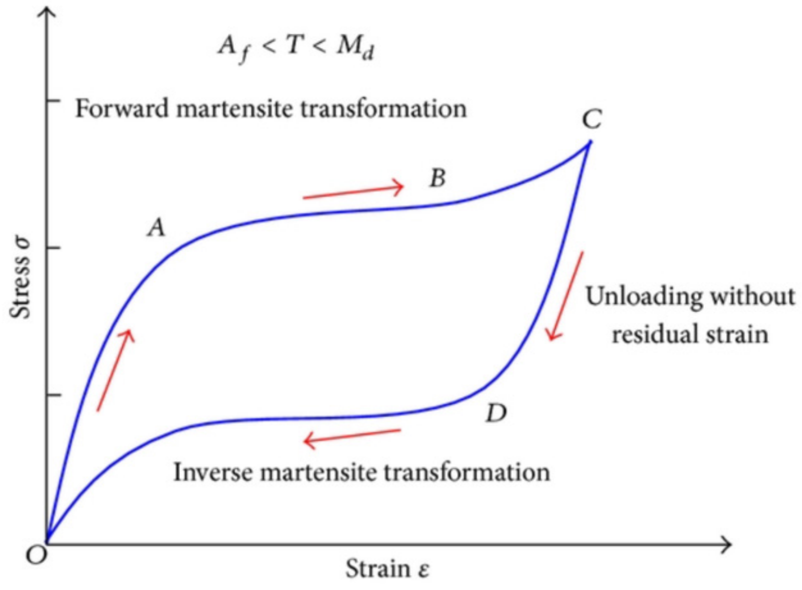
A conclusive comparision of the three types is as shown on the table in the left.



PART A
INTRODUCTION

PART B
SHAPE-MORPHING MATERIALS

PART C
STUDY OF NITINOL



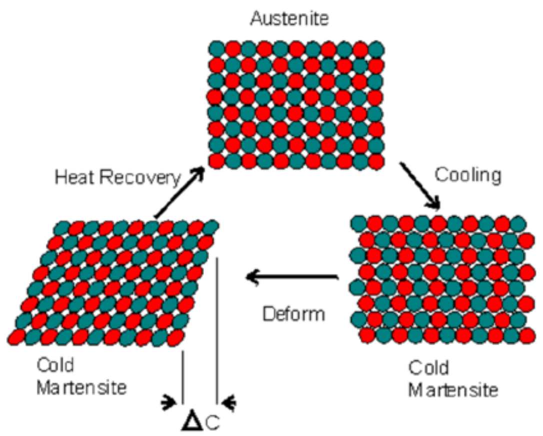


Fig [xxviii] Superelastic behavior of the austenitic to martensitic phase transformation [54]

Fig [xxix] Nitinol Transitions [55]

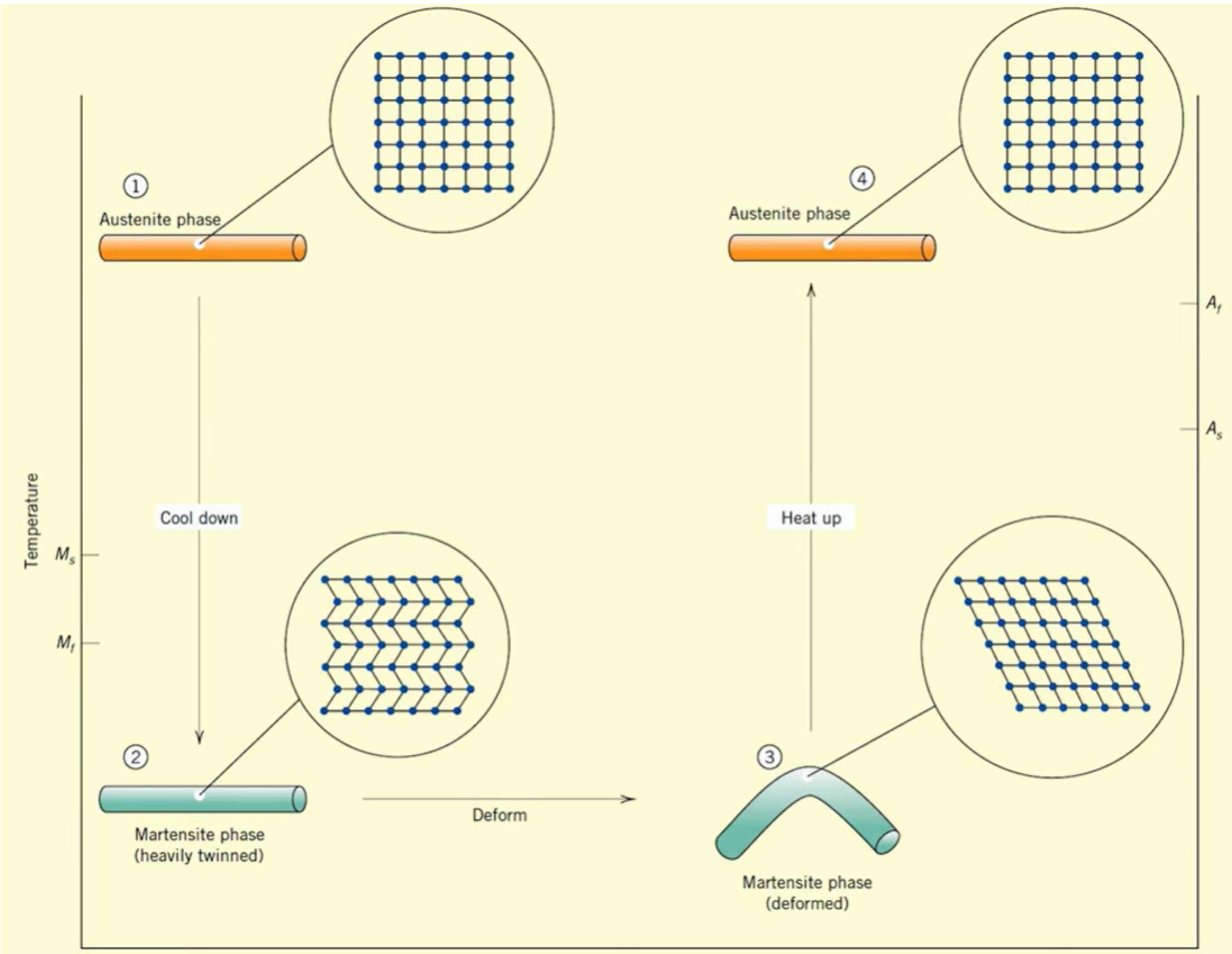


Fig [xxx] Shape memory Behaviour of Nitinol

NITINOL WIRE AND ITS CHARACTERSTICS

As we saw in the previous chapter, Nitinol is a Shape Memory Alloy (SMA). Its name comes from the elements it is made up of, Nickel (Ni) and Titanium (Ti) , and the place of its origin, Naval Ordnance Lab (nol) and it has two unique properties that make it ideal for responsive systems in architecture:

1. Shape Memory Effect (SME) – It can remember a shape and return to it when heated.

2. Superelasticity – It can undergo large strains and recover instantly when unloaded.

The terminologies associated with the Nitinol Temperature ranges are as follows:

Martensite Phase: This is the phase Nitinol is in when it's cool (at or below its transition temperature). In this phase, the metal is soft and can be easily bent or deformed into a new shape. Think of it like a piece of soft wire.
Austenite Phase: This is the phase Nitinol is in when it's warm (above its transition temperature). In this phase, the metal is rigid and very strong. If the Nitinol was previously trained to a specific "memory" shape, it will automatically return to that shape when heated to this phase. Think of it like the soft wire snapping back to its original, rigid form.

The Transition Temperature

The transition temperature is the specific temperature at which Nitinol changes from its cool, soft Martensite phase to its warm, rigid Austenite phase. This temperature is not a single point but a range, and it can be customized during the manufacturing process for different applications. This is why a Nitinol wire can be made to react to anything from body heat to hot water, making it incredibly versatile for use in applications like the kinetic facade. [56] [57] [58]

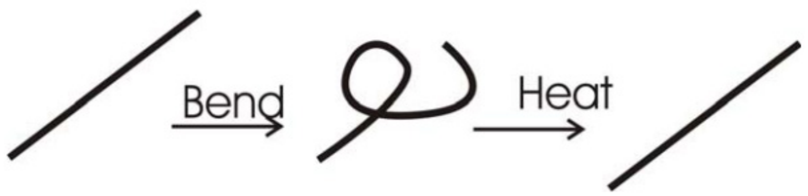
DESIGNING USING NITINOL WIRE

When designing shading or kinetic systems using Nitinol, the following things need to be in consideration:

1. Determine the Actuation Temperature: Choose an alloy with Af (austenite finish) around 30-40°C to activate in hot sun but stay passive in shade.

2. Decide the Actuation Type
Wire: Contracts when heated (used for pulling/rotation)
Spring: Expands or contracts with heat (more flexible)
Sheet/strip: Bends with programmed curvature

3. Nitinol wire contracts by ~4–5% of its length upon heating. For example, a 100 mm wire could shorten by 4–5 mm when heated past Af.
4. Train the Shape Pre-shape the Nitinol (e.g., curved louver form) and heat-treat it. When cooled, you can deform it, and it will return to that pre-trained shape when reheated.
5. Cycle Fatigue Nitinol can handle millions of cycles, but overheating (above ~90°C) or over-straining (>8%) reduc-es lifespan.



Training of the Nitinol Wire

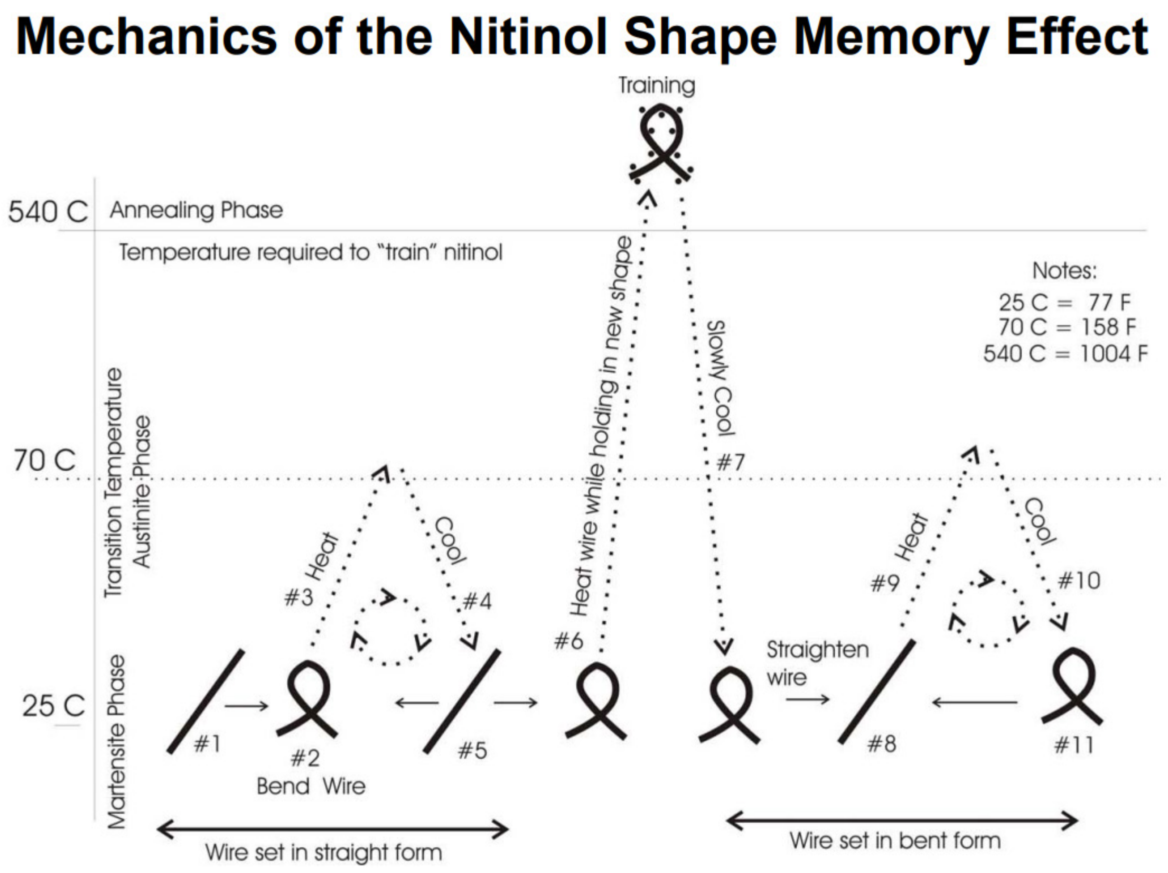


Fig [xxxi]: Mechanics of the Nitnol Shape Mempry Effect

LAB EXPERIMENTS

Testing Nitinol Wire bending and recovering and remembering its initial shape

Step 1
Bend or coil the wire

Step 2

Method 1
Heat the wire with a hair dryer and watch it straighten out as it returns to the preferred higher temperature annealed phase.

To fix the original "parent shape," the alloy must be held in position and heated to about 500 °C (930 °F). This process is usually called shape setting. [59]

Method 2
Alternatively, the bent NiTi wire sample can be dropped into hot water.

Method 3
Still another variation of this demonstration uses resistive heating to change the NiTi wire to its Austenite phase. Simply connect each end of a short sample wire to a 9 volt battery (2 D-Cell batteries in series may be substituted) for a few seconds. As the wire resistively heats , it returns to its Austenite phase.

Setting NiTi Wire into a new shape

Step 1
Place a sample of NiTi wire under tension by bending it and hold so that the wire maintains its bent shape.

Step 2
Holding the wire carefully so as not to burn your fingers, bring the bent end of the NiTi Wire close to a candle or Bunsen burner flame. Heat it slowly until you feel a release of tension. At that point, remove the wire from the vicinity of the flame.
Note do not heat the wire more than is necessary to release the tension.

Step 3
Let cool. The NiTi wire has now been set into a new shape.

Step 4
Repeat experiment #1 to show that heating the wire will now cause it to return to its new bent shape.

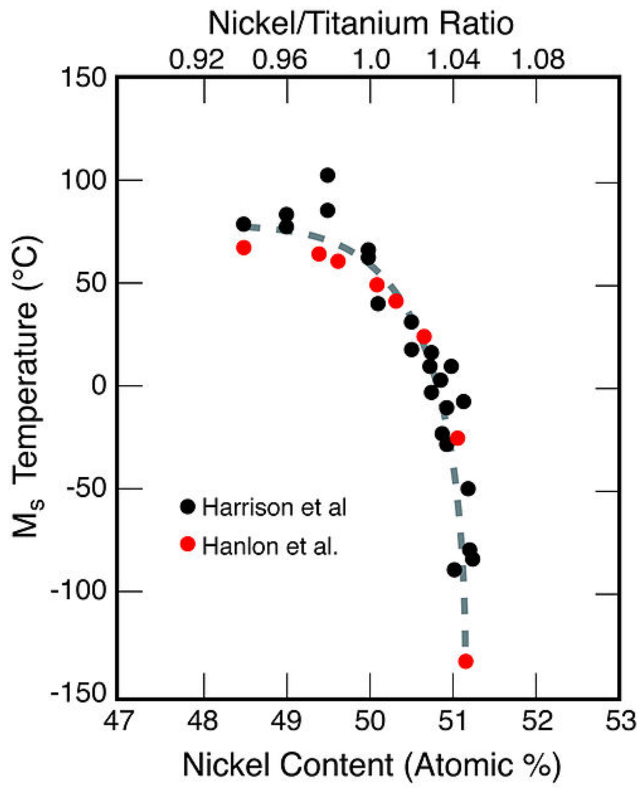


Fig [xxxii]The effect of nitinol composition on the Ms temperature [59]

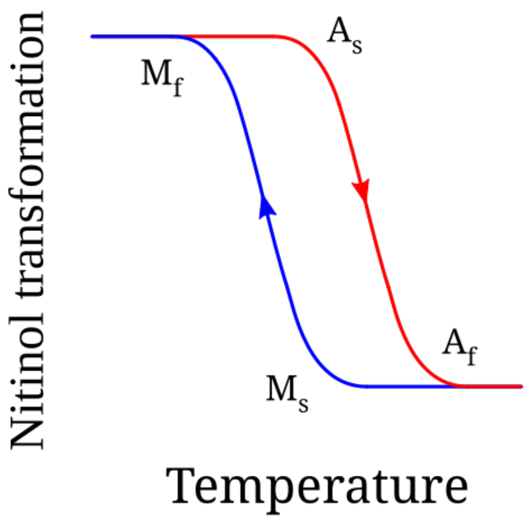


Fig [xxxiii] Thermal hysteresis of nitinol's phase transformation [59]

HYSTERESIS: Studying the behaviour of Nitinol

Thermal hysteresis is the phenomenon where the transition temperatures for a material changing phase are different during heating versus during cooling. Which means that: Nitinol wire needs a certain amount of heat to fully change from its soft state to its rigid state, but it won't change back to its soft state until it has cooled down to a lower temperature. This creates a "lag" or "gap" between the heating and cooling processes. This is called as the thermal Hysterisis.

The hysteresis width depends on the precise nitinol composition and processing. Its typical value is a temperature range spanning about 20–50 °C (36–90 °F) but it can be reduced or amplified by alloying and processing.

SOURCE: Spini, Tatiana Sobottka; Valarelli, Fabrício Pinelli; Cançado, Rodrigo Hermont; Freitas, Karina Maria Salvatore de; Villarinho, Denis Jardim; Spini, Tatiana Sobottka; Valarelli, Fabrício Pinelli; Cançado, Rodrigo Hermont; Freitas, Karina Maria Salvatore de (2014-04-01). "Transition temperature range of thermally activated nickel-titanium archwires". Journal of Applied Oral Science. 22 (2): 109–117. doi:10.1590/1678-775720130133. ISSN 1678-7757. PMC 3956402. PMID 24676581
& Wikipedia (Accessed on 19th August, 2025)

As seen in the graph showcasing Ms temperature changes with changing the nitinol to titanium ratio , we can see a diverse temperature range can be the nitinol can be designed for a diverse temperature set.

Also, as stated by **Kellogs Research Lab**, by altering the metallurgy of the nitinol, they have produced binary nitinol (just nickel and titanium) components with transformation temperatures ranging from -100 C to 120C (-150F to 250F) and by adding additional elements, the range of possible transformation temperatures can be expanded out to -180C to 300C (higher temperatures are feasible, but extremely expensive). So, in short, nitinol can be used across **nearly all temperature profiles** existing on earth.[57] [58] [60]

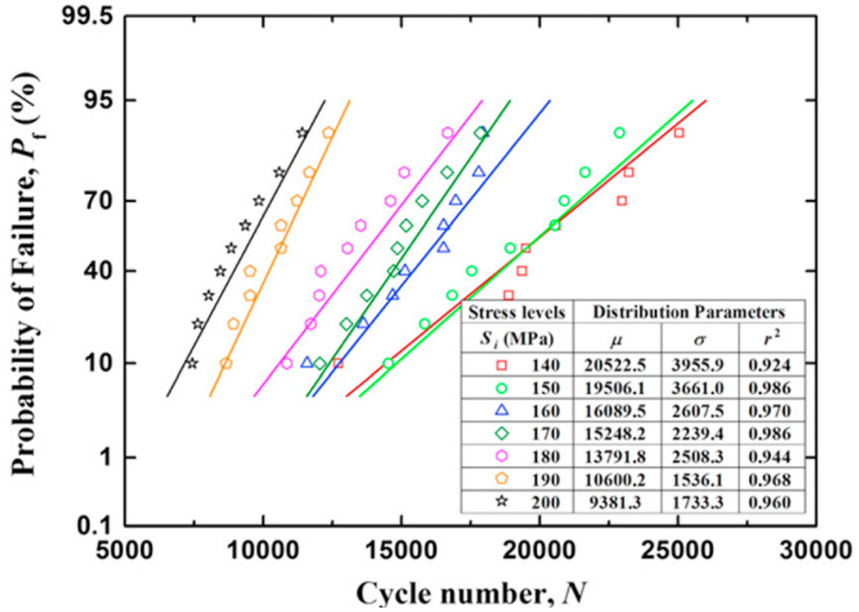


Fig [xxxiv] Fatigue Life of nitinol under various stress levels

Table 1
Selected Nitinol spring parameters.

Spring Parameters	Value
Wire diameter	0.75 (mm)
Spring mean diameter	6 (mm)
Number of active coils	21
Maximum recoverable strain	5%
Final output gear radius	50 (mm)
Austenite start temperature	30 (°C)
Austenite finish temperature	40 (°C)

Fig Nitinol Spring parameters

Table 2
Summarized outputs of the selected Nitinol spring.

Outputs of the spring	Value
Maximum generated force	70 (N)
Recovered stroke	62 (mm)
Maximum generated rotation	60 (degrees)
Start temperature of reaction	30 (°C)
Finish temperature of reaction	40 (°C)

Fig [xxxv] Summarised output of the Nitinol Spring

Nitinol combined with Copper and Iron

NiTiCu is similar to NiTi but a portion of the nickel has been replaced by copper. The primary benefit that people like to take advantage of is the lowered hysteresis (10-20°C). This permits higher cycle rates, lower transition temperatures, and greater efficiency. The fatigue life is excellent (>10 million cycles at 2.5% strain) and fatigue sets in slowly (~5% loss at 50% of fatigue life). The primary drawback is that NiTiCu shouldn't be stressed much beyond 3% NiTiFe is similar to NiTi but a portion of the nickel has been replaced by iron. This results in a very high ultimate tensile strength (UTS), exceeding most titanium alloys for strength. This, coupled with the superelastic effect yields a very durable device that will outlast almost any other material. Most applications of NiTiFe use the superelastic effect rather than shape memory." [61]

Fatigue and long-term behavior of nitinol and mechanical parts

Active mechanical systems, particularly those using shape memory alloys like Nitinol, face a significant risk of failure due to material fatigue. Since these systems are designed to constantly cycle between their cold and hot phases, it is essential to determine a maintenance schedule to prevent failure. By calculating the number of cycles per year and the material's fatigue resistance, a replacement and repair timeframe can be established.

In a typical climate, a single day's temperature changes—rising to a peak at noon and then dropping in the evening—cause each Nitinol spring to undergo one to three cycles. Assuming the system is active for about 80% of the year (roughly 300 days), its total annual usage is approximately 900 cycles. To simplify the estimate, an annual cycle count of 1,000 is used.

This means that over a ten-year lifespan, each spring is expected to undergo approximately 10,000 cycles. Based on research by Zhang on the fatigue behavior of Nitinol, the probability of a spring failing after this ten-year period is estimated to be between 1% and 2%, as the stress levels in the proposed system are typically less than 150 MPa. Therefore, a repair or replacement period of ten years is recommended for the Nitinol helical springs in the proposed mechanical system. [62]

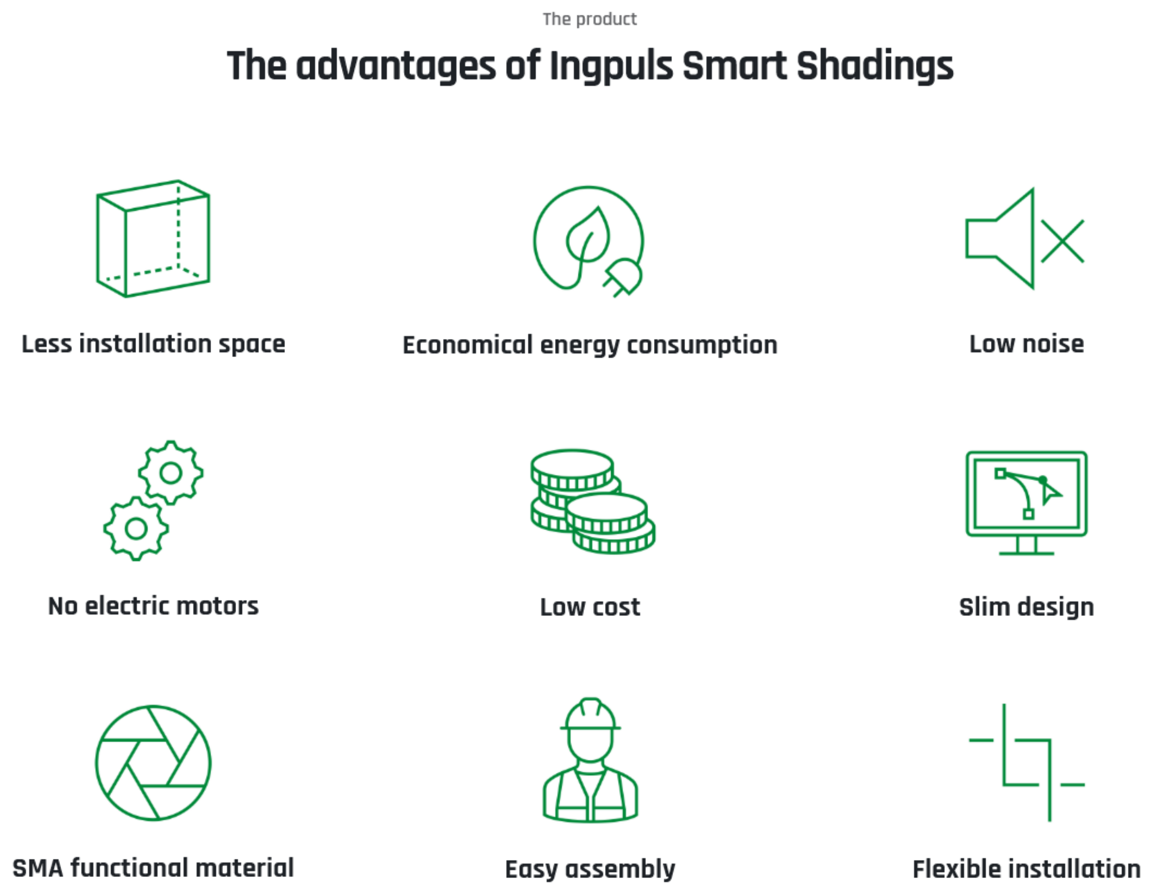


Fig [xxxvi] Advantages of Ingpuls Smart shadings

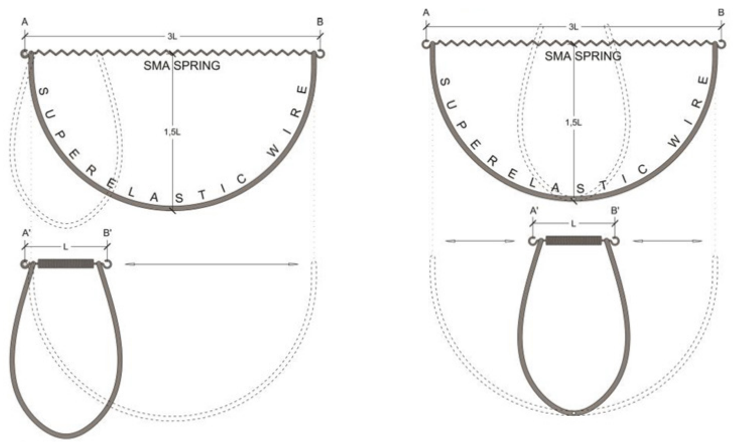


Fig. 1: Actuator Design

ACTUATOR FEATURES	
Heating time	4s
Cooling time	60s
Dimensions (off)	260mm x 180mm
Force delivered	7N
Af (spring)	55ºC
Actuation distance	160mm
SUPERELASTIC WIRE	
Length	500mm
Diameter	2.7mm
Af	0ºC
SMA SPRING	
ø1 spring wire	0.75mm
ø2 outer diam.	6.3mm
ø3 inner diam.	4.8mm
Turns	20

Fig. 2: Actuator Features Table

Fig [xxxvii] Design of the actuator

Market Product Availability of Nitinol for the use case in building facade and Roof Shading

Material Used: Nitinol

Product Used: Ingpuls Shading System

The example shows the design of an actuator that is used to create window shading and patio canopy shading using the similar element design principle

Actuator Design

The actuator is quite straightforward, consisting of only two main elements: a bow and a string (see Fig. 1).The bow is made of a superelastic Nitinol rod, while the string is a Nitinol spring that possesses shape memory properties. The outer surface of this alloy is coated with a polished, oxidized TiO2 layer, which enhances corrosion resistance and makes it suitable for outdoor applications.

As illustrated in the figure, the space between the rod and the spring is filled with an insulating material. This insulation is essential to prevent electricity from spreading across the entire actuator, ensuring that current is directed only through the spring, avoiding unnecessary energy loss. Moreover, both the insulation and the hook-like configuration help secure the system, preventing unwanted sliding.

In its original form, the rod is straight. When bent, it stores elastic energy that can later be released in a controlled manner. The spring governs this release: in its low-temperature (martensitic) state, it restricts the rod from returning to its straight shape, keeping forces balanced. Once the SMA reaches its transformation temperature, it shifts to the austenitic phase, regains its memorized form, and overcomes the rod’s resistance, pulling the bow ends closer. When cooled again, the stronger bow extends the spring back to its maximum length, completing a regular actuation cycle.

This actuator is remarkably simple yet highly durable since it requires no gears, wheels, or complex mechanisms that are prone to failure. Its minimal maintenance needs, combined with the reliable performance of the superelastic rod under repeated loading and unloading, suggest a long service lifespan.

In this particular design, the “string” is not just a wire but a spring, allowing greater linear displacement. The system has been applied in architectural shading devices, such as window shades and patio roof canopies. Here, the actuator’s movement enables dynamic shape changes of the attached elements, producing shading effects as the SMA-driven mechanism cycles between its phases.

CHALLENGE FACED AND RESOLVED

The weather fluctuation in a day does not have a very broad range of change and since the working behind these alloys works with changing betwen the austenite and martensite phase of temperatures, the idea of the shading device working naturally comes out with a challenge. So it was worked out to let the the alloy cool down on its own in the environment temperature, but to efficiently heat it up, some additional elements are required. [50] [51] [52]

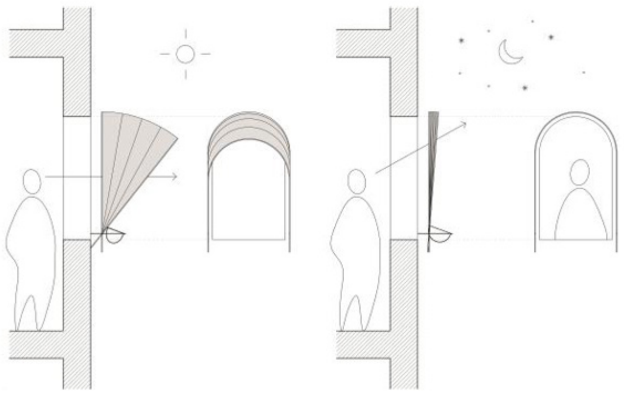


Fig. 3: *Window Canopy*

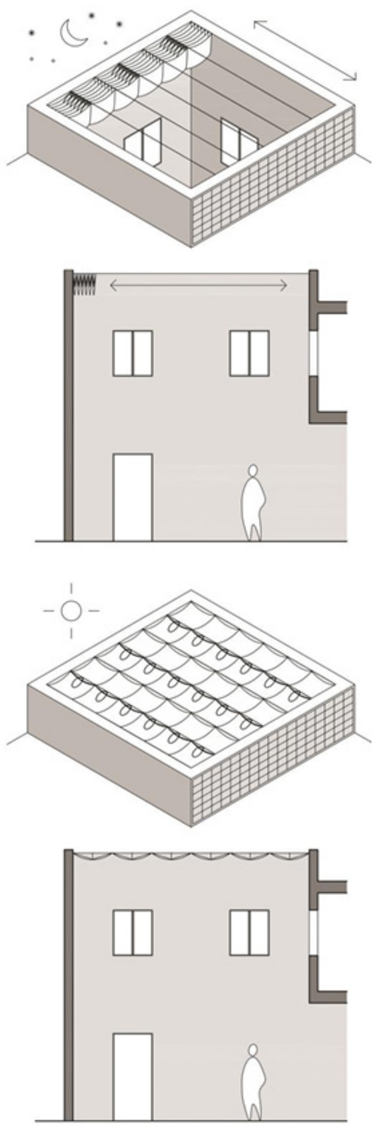


Fig. 5: *Patio Canopy*

Fig [xxxviii] Nitinol Based Actuator for Architectural Technology in Hot Climate Countries

MULTIPLE USABLE METHODS:

As previously said, the system is autonomous but it also can be user controlled and electrcially activated. In the case of Patio canopy shade design, electricity is provided by photovoltaic cells, integrated in the patio south patio wall, which heat the SMA through Joule effect. It can be directly used during the day or stored into batteries in a simple electrical circuit that can also include a switch and a PWM (Pulse Width Modulation) [53] to optimize the electric current supply therefore avoiding overheating the Nitinol. The electric wires needed to provide this electricity to the actuator are inside the hollow articulated bars and also along the guide-wire. If more strength is needed, for example due to the use of a heavier fabric, the actuators can be doubled at each point and/or raise the number of acting lines. Also, as in the window canopy case, it is easy to install and remove from existing canopies. The details of the actuator system when used with electricity is given in the table on the left.

This mechanism was further refined and is being used in production for real life application by the company Ingplus: Smart Shadings.

MARKET AVAILABILITY AND COST of INVERT WINDOW SYSTEMS

The bimetal is typically commercially available with a minimum thickness of 0.1 mm. To optimize the material's responsiveness to temperature variations, we placed a specific order for a thickness of (0.06 mm, based on studies by Sung [12]. We used a PR675r bimetallic strip measuring 0.06 mm in thickness and 10 cm in width. The cost of the 20.45 m coil was 122.37 dollars. The material comprises a passive layer with Ni36 composition and an active layer of MnzsNi15Cu1o. Notably, it lacks an intermediate copper layer. Applying the third layer on small quantities of material is not feasible, as with our acquisition of 1 kg. The chemical composition is detailed in Table 1, while Table 2 outlines the physical-chemical properties.

PARAMETERS THAT AFFECT THE RESULT of INVERT WINDOW SYSTEMS

There is not an isolated and determinant parameter providing result control, but the inter-relational confluence between distinct parameters and characteristics, such as:

a) the direct influence of the module scale on the stamping result

b) the interspersed creasing pattern associated with the absence of creases on the edges that enhance adaptive performance in response to temperature variations

c) continuous and uniform tolerance of 0.25 mm in the flat stamping matrix, and

d) the matrix tooth with a 35° angle, the absence of radius, and a height of 3 mm.

e) the critical role of module height in constraining responsive movement to a single direction facilitating opening upon heating (for dimensions above 6 cm).

f) In contrast, inadequate height may lead the bimetal to overcome the resistance of the crease and initiate closure. As a result, it is recommended for heights exceeding 10 cm. Additionally, we recognize that the biomodule concept transcends the triangular shape showcased in our proof of concept, underscoring the importance of crease creation as a fundamental element for controlling the material's behavior. This principle holds potential applications across a diverse range of formal possibilities In this context, the innovation of the research lies in the relevance of introducing creasing on the

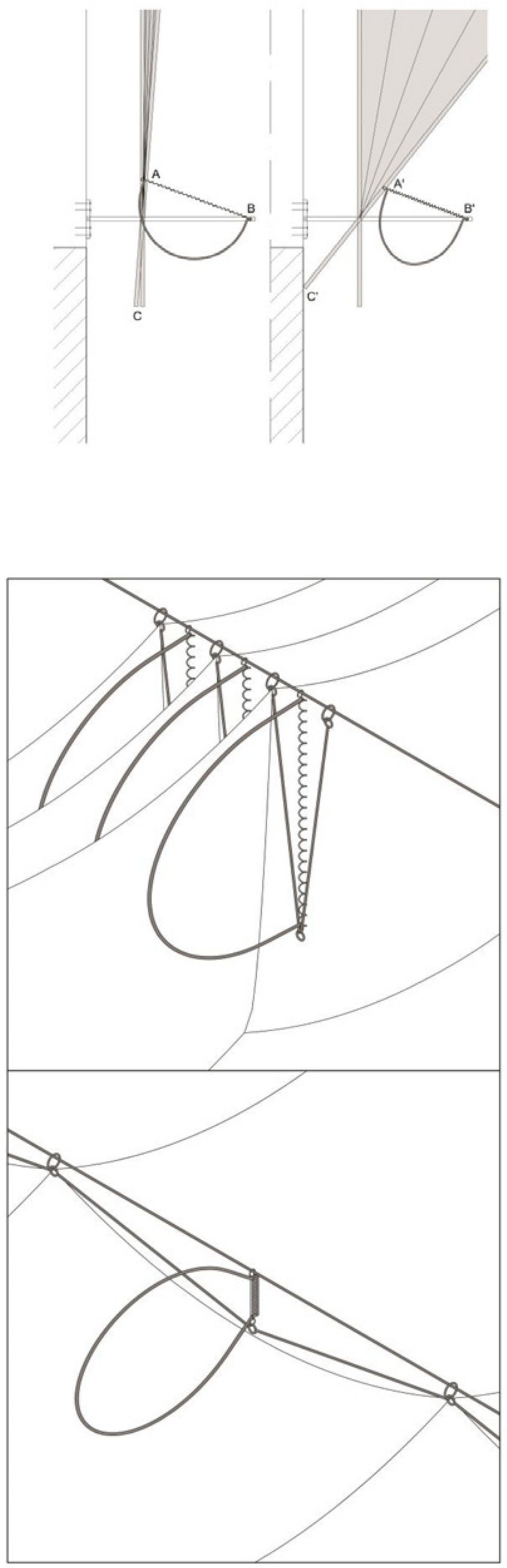


Fig [xxxix] Window Shade and Roof Shade working [65]

bimetal's surface to gain control over its behavior, extending beyond its intrinsic properties. Plastic deformation can impart resistance to the material's innate movement to the extent of reversing its behavior. When the correlation between shape and temperature variation does not exceed the force. [63] [64] [65]

Another example is the Bimetal Façade System, which combines the function of sun-shading with visual transparency, allowing for dynamic light control without sacrificing views. Additionally, the Pho'-liage® prototype demonstrates a hybrid approach, in which bimetal components function as actuators in coordination with biopolymer materials to create a self-adjusting shading surface.

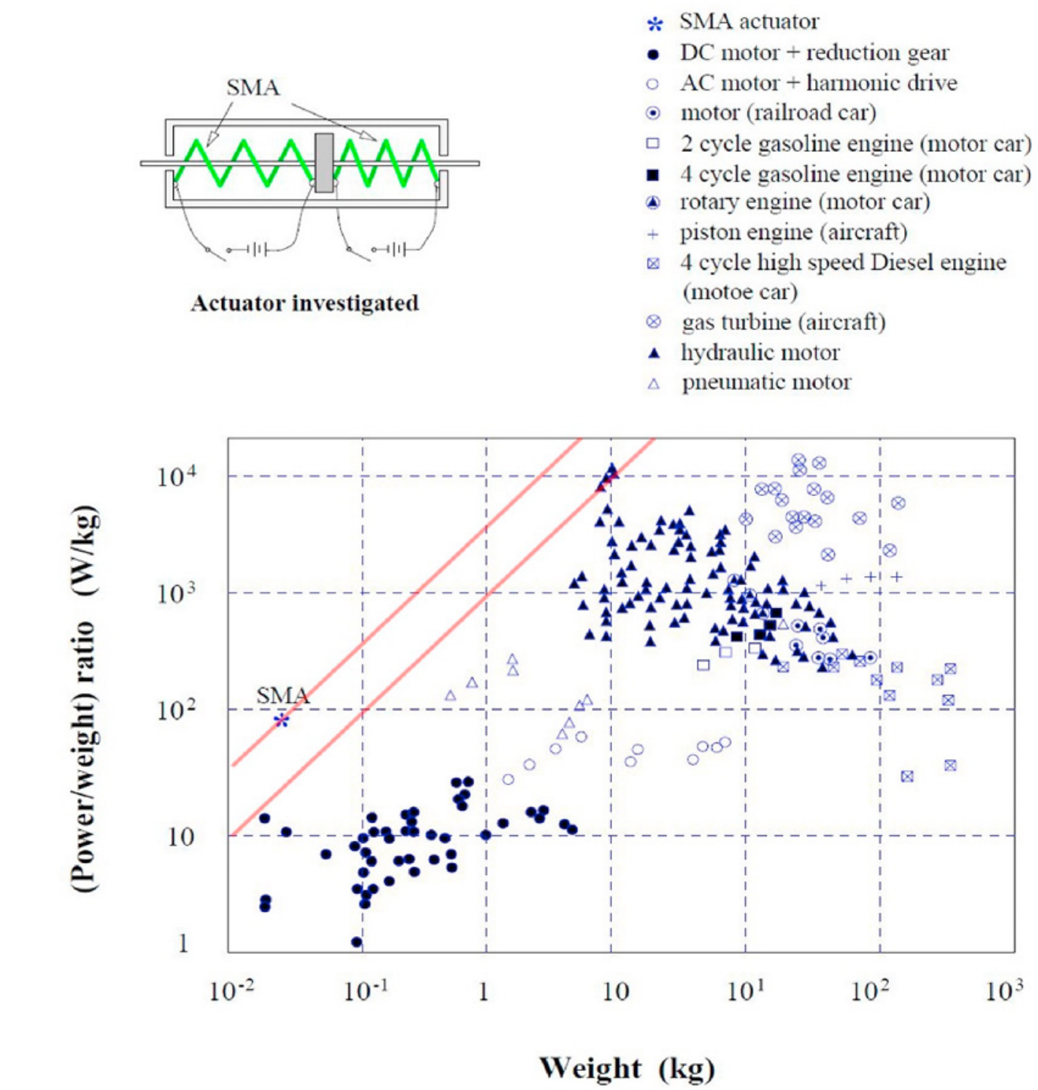


Fig [xL] PowerWeight vs weight diagram.png

COMPARISION OF ACTUATORS FOR FACADE

ADVANTAGES OF SMA

For kinetic and adaptive facade, some kind of actuation mechanism is needed. The graph on the left shows the comparision of power/ weight to weight ratio so that a lightweight material can be chosen for actuation that makes the overall facade weight lighter.

It can explicitly be deduced that the SMAs possess better performance than any other present system, and hence, they can be a novel choice for any system design that includes moving parts, and the kinetic architectural elements are not excluded from them. [66]

CONCLUSION

As we studied the characterstics and working mechanism of different types of thermo-responsive shape-morphing materials available in the market, the case study on SMA Nitinol based technology developed by Ingpuls as shown on the previous page appealed for it simplistic mechanism and easy functionality. Let us now try to design a shading design for a building facade's in a hot dry climate, using similar designing strategy to compare it to conventional building facades shading and energy performance.

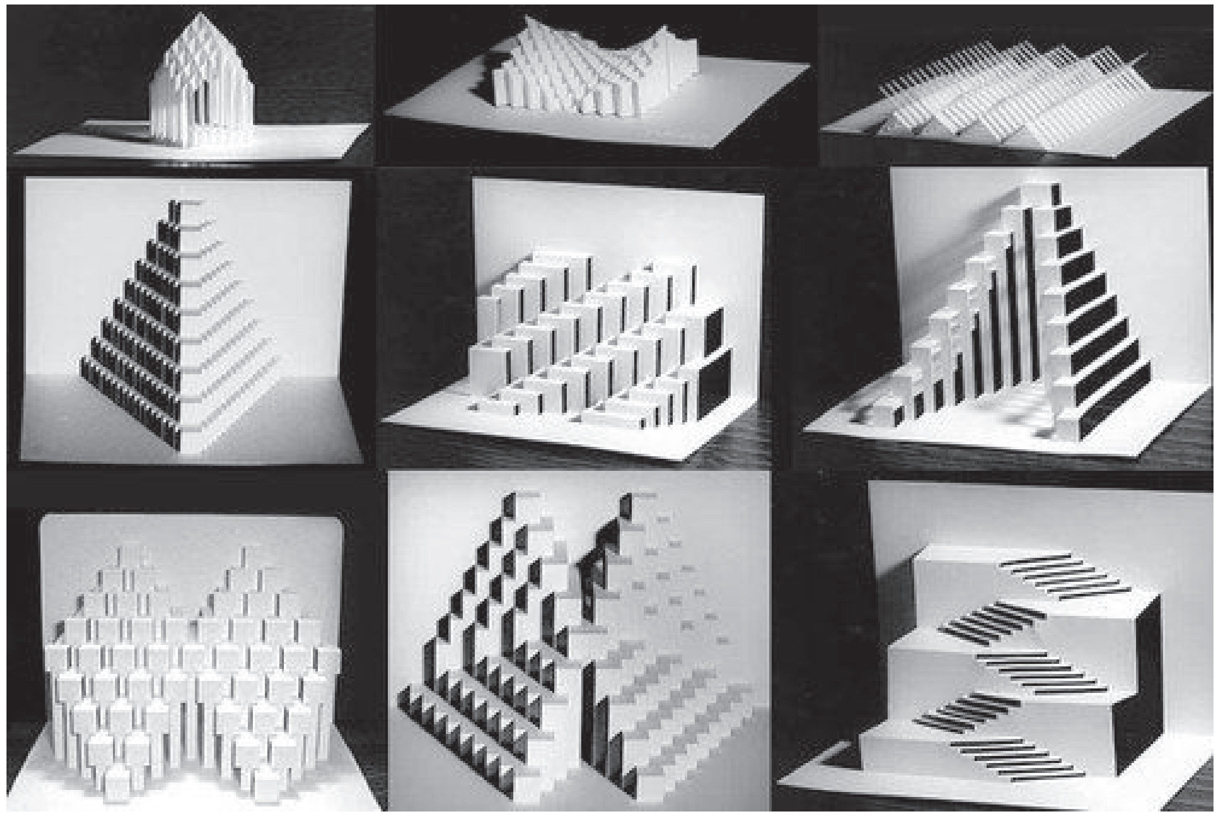
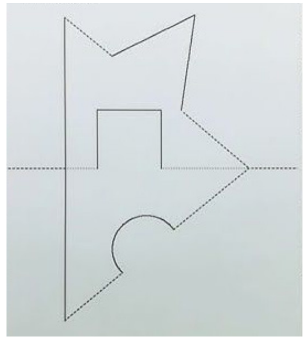


Fig [xLi] Examples of Kirigami, cut and fold technique artworks
Fig Source: https://pin.it/7BQ9cdyh4



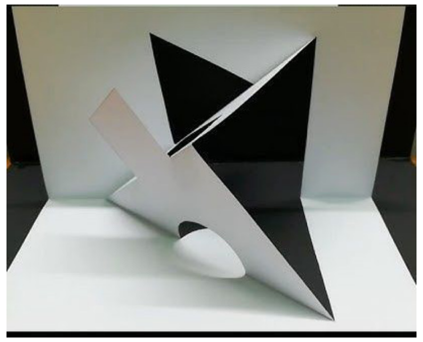


Fig [xLii] (left) Flat cut position and (right) the folded 3D position of the Kirigami artwork
Fig Source: https://pin.it/3kpag3ltT

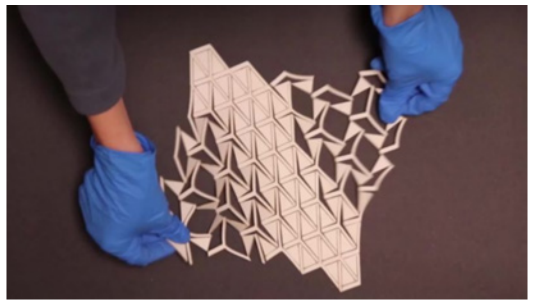


Fig [xLiii] : Manual opening the cuts of Kirigami craft [67]

APPROACHING THE DESIGN

In our search we are looking for geometries or stratregies that have the capacity or opening and closing or bending'/ twisting, for which two concepts proposes a solution, which are:

A. Kirigami
B. Origami

What is Kirigami?

Kirigami is a variation of origami, the Japanese art of folding paper. In kirigami, the paper is cut as well as being folded, resulting in a three-dimensional design that stands away from the page but can also go back to its original flat form when folded or kept open. Kirigami typically does not use glue.

Now, as we see the opening and folding of the Kirigami craft to change its form from flat to 3D requires application of manual force, as an alternative to this manual force, the design intends to use the actuation of the nitinol wires in response to temperature variation as a passive design strategy for shading. For this, let us conclude:

A. The characterstic of the nitinol wire's movement
B. The capacity of shear in kirigami
C. What possible materials can be explored for this buckling induced Kirigami shading device. [67]

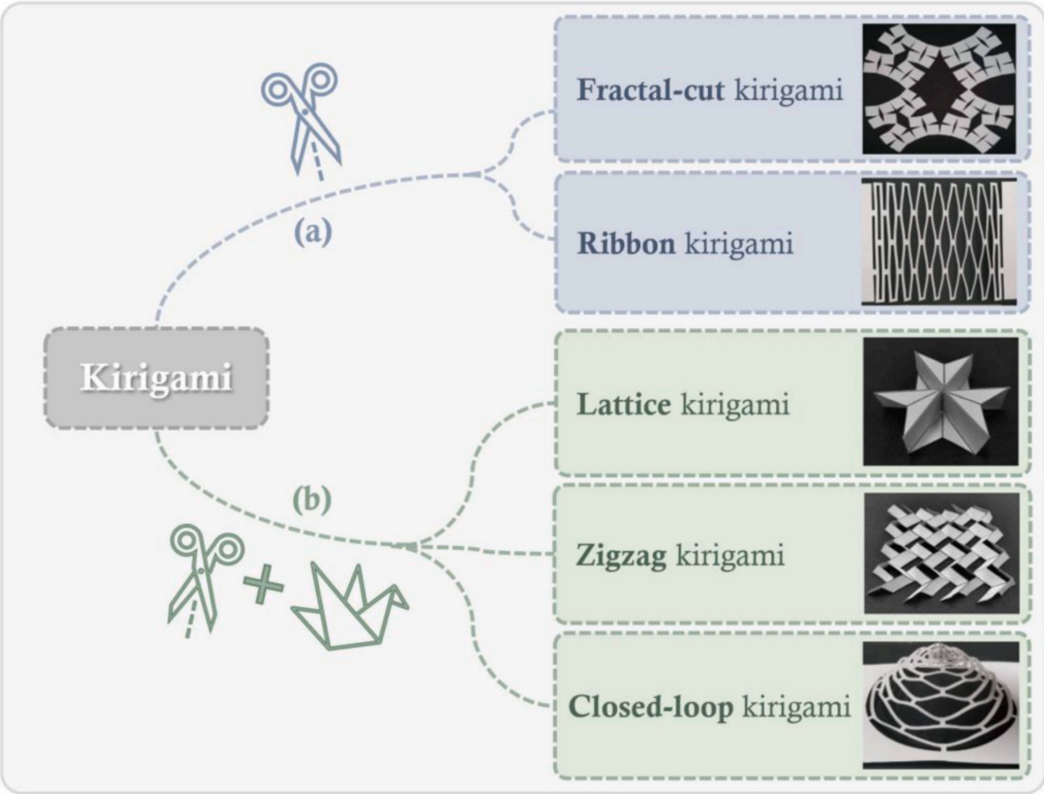


Fig [xLiv] . A general classification of kirigami structures produced by (a) cutting only, and (b) cutting and folding

EXPLORING THE OPTIMUM PATTERN OF KIRIGAMI FOR THE SHADING

Based on the technique of cutting or folding, there are multiple styles of Kirigami, and the tensile properties of kirigami sheets are largely determined by the specific kirigami patterns rather than the tensile properties of the initial material, leading to the development of metamaterials/ metastructures. This also helps in attaining large strains that cannot be attained by the initial material through external tension or compression.The classification of the various types of kirigami based on types of cut and fold looks like this:

1. Fractal-cut Kirigami
Fractal-Cut Kirigami is based on repeating branching patterns, often inspired by nature, such as tree branches or leaf veins. These patterns expand outward in self-similar layers, allowing complex and organic transformation from a compact flat sheet. This type of Kirigami is ideal for biomimetic architectural surfaces, shading trees, or layered kinetic installations that mimic natural growth.

2. Ribbon Kirigami
Ribbon Kirigami features long, narrow, parallel cuts that create thin strips or "ribbons" within the material. These ribbons behave independently and can twist, curl, or bend when stretched or heated.

3. Lattice Kirigami
Lattice Kirigami uses a grid-like cutting pattern to form a net or mesh that can stretch in two directions. When pulled, the surface opens up into diamond or rectangular holes, expanding uniformly across the material.

4. Zig Zag Kirigami
Zig-Zag Kirigami consists of repeating diagonal or wave-shaped cuts that allow the surface to move in a folding, accordion-like motion. The pattern opens or closes predictably along one direction.

5. Closed-loop Kirigami
Closed-Loop Kirigami includes cuts that form enclosed circular or oval shapes. When stretched or activated, these loops rotate or pop outward, creating 3D bulging surfaces.

Each of these Kirigami types provides a unique motion and design strategy. When combined with smart materials like Shape Memory Alloys (SMA) or Shape Memory Polymers (SMP), they can create passive, climate-responsive architectural components that adapt without mechanical systems.

Now let us try to understand which of these kirigami pattern would work best with SMA (Nitinol) actuation.

Out of the five types, Zig-Zag Kirigami is the best fit because:

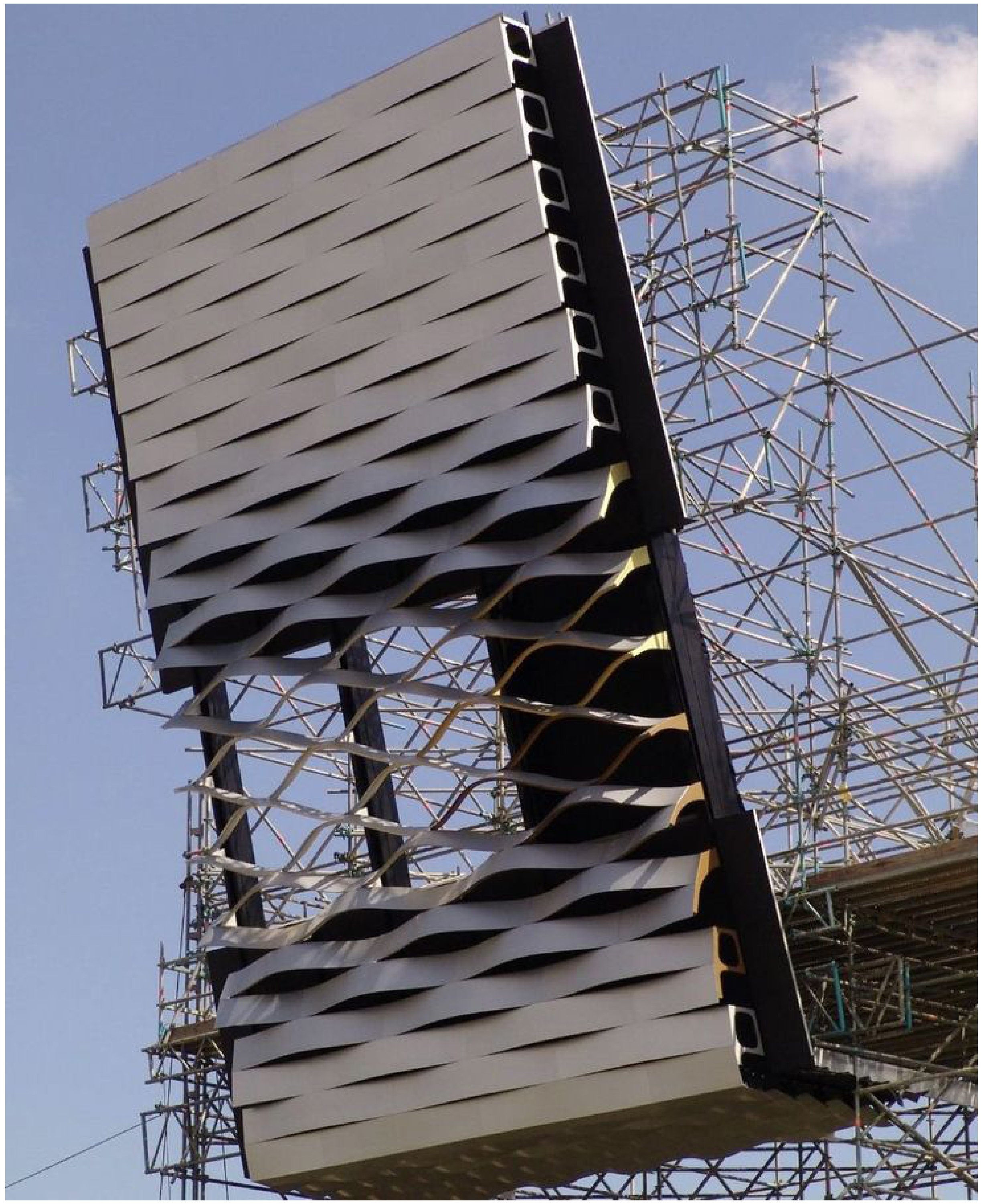


Fig [xLv] The open position of the panel

1. Predictable and Controlled Movement
Zig-zag patterns behave like an accordion: they expand and contract linearly. This movement is smooth, directional, and repeatable and exactly the kind of motion Nitinol wires can easily control by contracting or relaxing along one axis.

2. Simple Actuation Geometry
Nitinol contracts by 4–5% of its length when heated. If placed strategically along the folds, a single wire or a few can control an entire panel by either pulling it open (expand) or relaxing it closed (collapse) without the need for motors or complex linkages, only thermal response

3. Efficient Shading & Ventilation
Zig-zag folds block direct sunlight while still allowing airflow and filtered light. As the fold angle changes, solar exposure can be fine-tuned, depending on sun angle and intensity.

Understanding why other types are less ideal (But perhaps still useful)

Ribbon Kirigami
It produces twisting or curling motion, which is harder to control precisely using Nitinol's linear contraction and it is better suited for wind-activated or soft material responses.

Lattice Kirigami
It expands in two dimensions, requiring complex multi-directional actuation. Nitinol wires contract in only one direction, making it difficult to stretch the lattice evenly.

Closed-Loop Kirigami
It creates 3D bulging or flipping motions that are irregular and volumetric and controlling these with linear wire movement is inefficient and unpredictable.

Fractal-Cut Kirigami
It exhibits complex, layered, and organic growth patterns. The movement is not linear or directly controlled, making it visually dynamic but functionally hard to actuate with a simple Nitinol mechanism.

Conclusion
So we an conclude that among various Kirigami patterns, Zig-Zag Kirigami is best suited for solar shading of building envelopes when actuated by Nitinol. This is because its predictable, linear accordion-like movement aligns well with the contracting behavior of Nitinol wires, which shorten by 4–5% when heated. Its geometric simplicity, combined with directional expansion, makes it the most effective and controllable configuration for responsive, energy-efficient façade systems.

Zigzag-cut patterns allow significant stretching in the planar direction (i.e., along the length of the surface) which allows the panel to open wider in response to force (via Nitinol actuation).This stretching is achieved through out-of-plane deformation (buckling) near the cuts and the more you increase the cut length, the more the panel will stretch but also buckle more. [68]

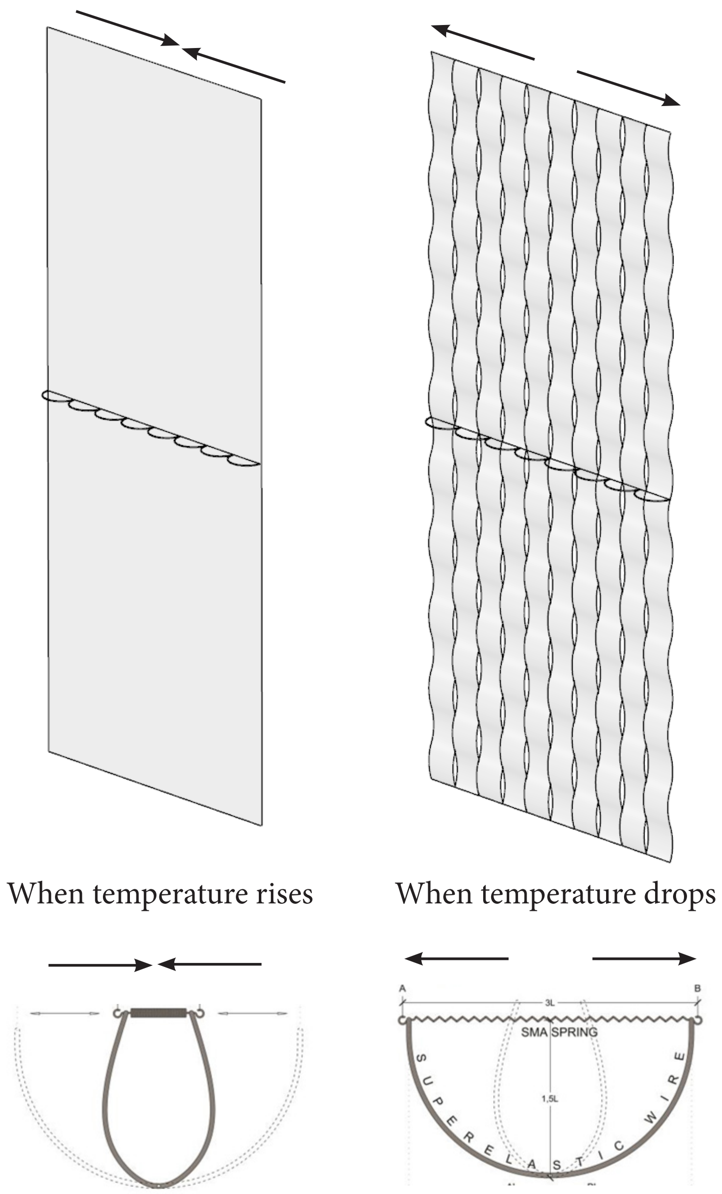


Fig Movement of the passive shading system through Nitinol Actuator

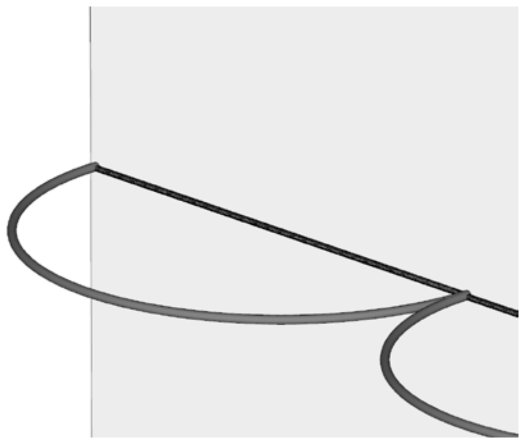


Fig Nitinol Actuator attached in series connection to the panel

DESIGN CONCEPT 1
BASED ON KIRIGAMI

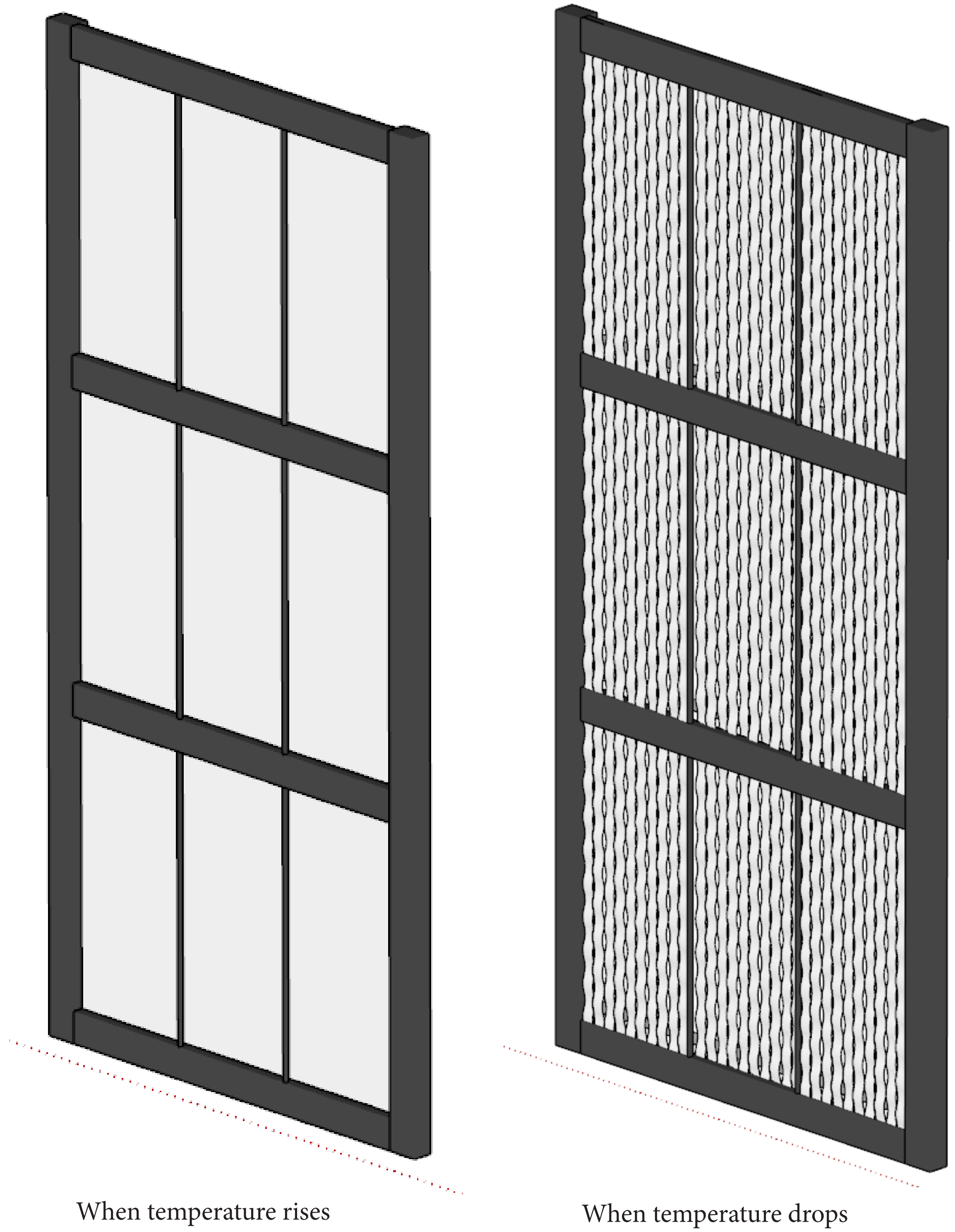


Fig Passive Shading System Kirigami opening and closing under temperature response

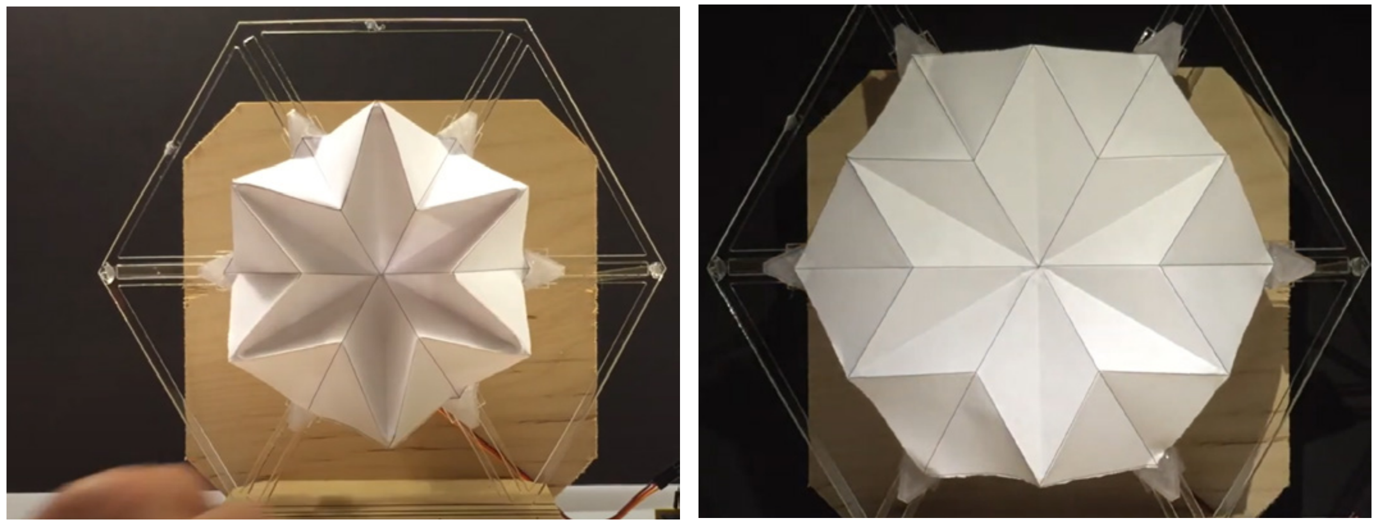


Fig [xLvi] Open State of Facade Element

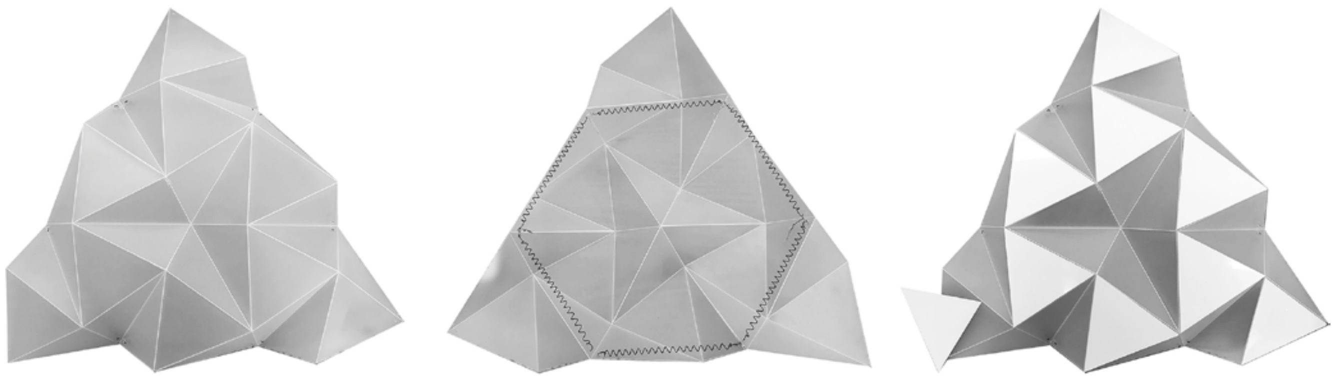


Fig [xLvii] Linear Actuator arrangements on Creases

DESIGN CONCEPT 2
BASED ON ORIGAMI

The other concept that can be explored to achieve the possible opening and closnig of the facade is origami, in which without putting cuts the paper is only folded in various forms to open and close the system.

In order for the shape-memory material. Nitinol springs to work with Kirigami, the linear actuators can be put along the creases as shown in the figure on the left for the overall working of the facade.

COMPARISION OF THE TWO CONCEPTS
When we compare the conepts Kirigami and Origami, we can understand that the force required in Kirigami would be more than the force required in orgiami concepts to perforn the linear actuation and displacement.

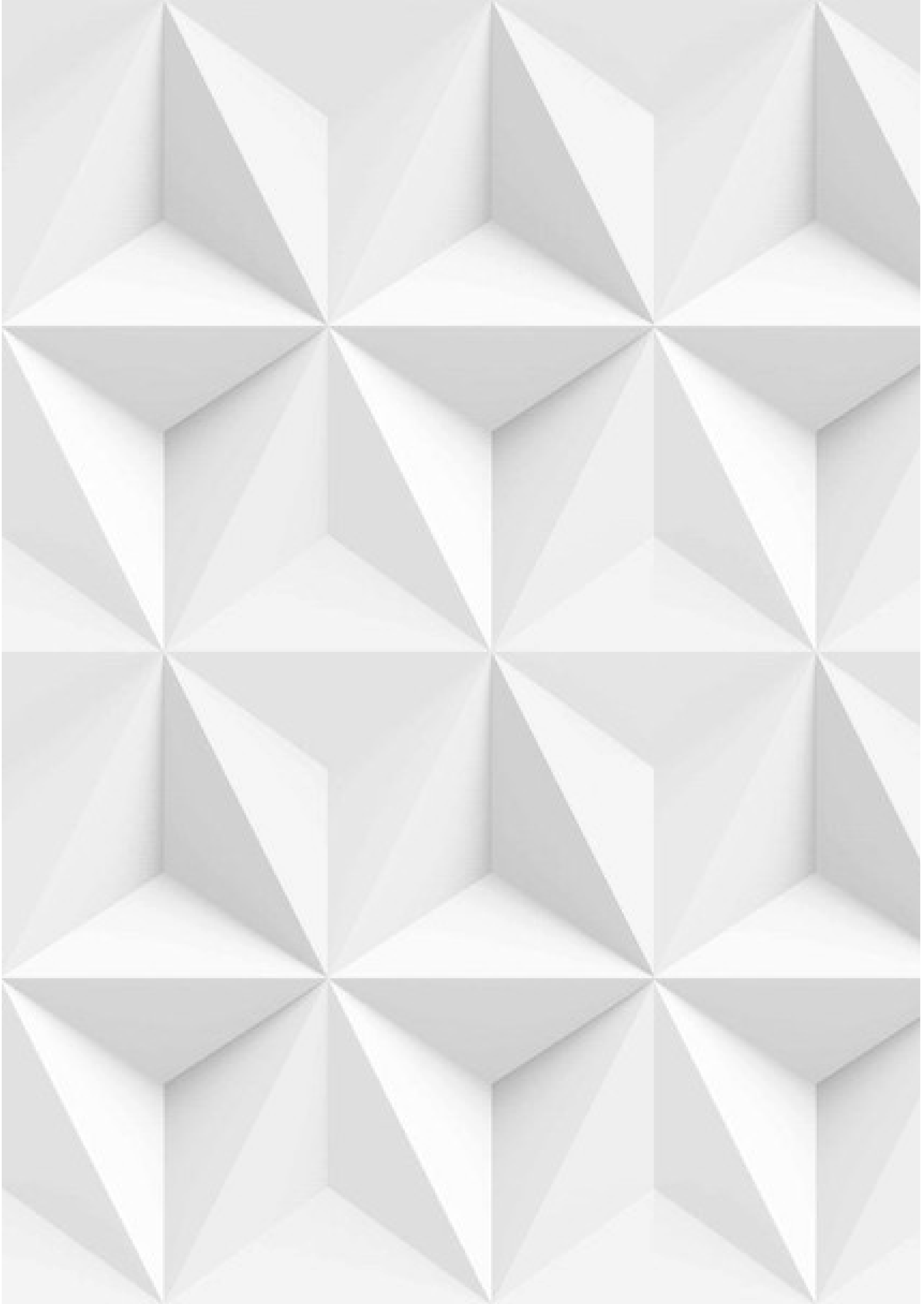
As per our understanding, of the material nitinol spring, from our research carries out so far we can conclude that the lesser the force required to move the solar shading system, the better the nitinol can actuate and displace. So for this use case scenario, **going ahead with Orgami patterns would be a more optimal choice**. So we will develop our design solution based on origami designs.

ADDRESSING THE ISSUE OF COST OF MATERIAL

The thesis began with defining the problem with the state of the art design solutions as to relating it with the cost of the material.

With this example, in mind for origami, we see that the amount of need to not used would be in large quantities. So in order to minimise this cost and quantity, we can use Nithin oil in the activating mechanism than with the shading material in itself, which would reduce the amount of need to not used by a large quantity.

So now, let us explore this above mentioned design option in our origami based solar device design in the final approach. But first, let us understand he basics of shading design and its principle, also establishing the need and use case of kinetic adaptive shading devices.



PART A
INTRODUCTION TO SMART MATERIALS

PART B
SHAPE-MORPHING MATERIALS

PART C
STUDY OF NITINOL

PART D
SHADING DESIGN PRINCIPLES

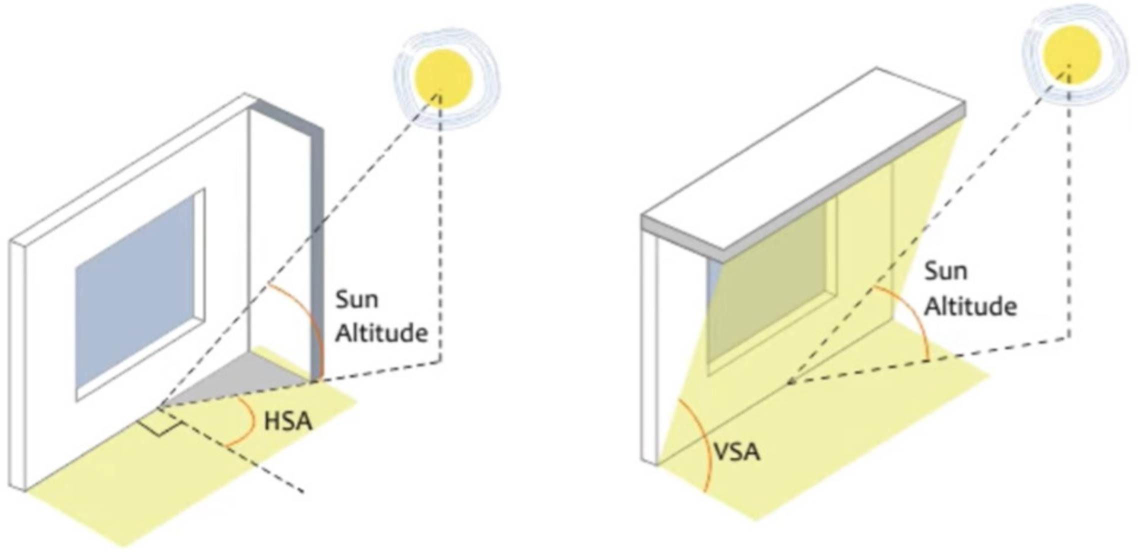


Fig : Defining VSA and HSA

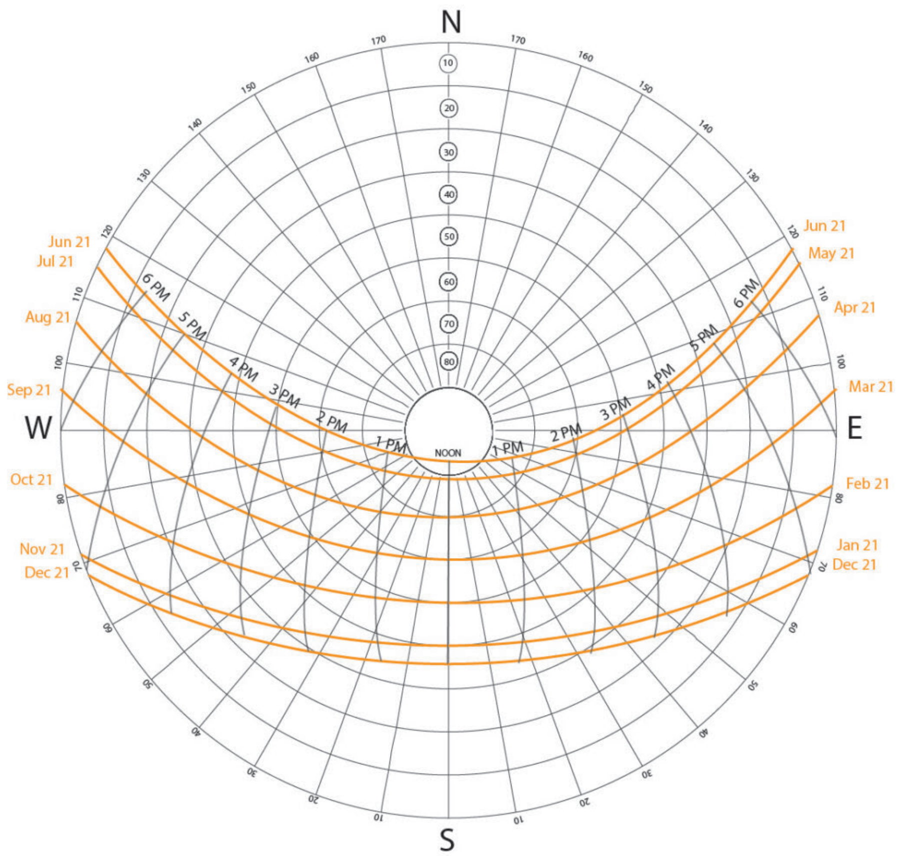


Fig Solar Chart

How is shading designed for a particular time?

A basic shading is designed in two main components, horizontal shading and vertical shading system. We need three main things to determine the shading design for a building:

No. 1: We need a **shading protractor**, which is used in determining horizontal and vertical shading devices

HSA- Horizontal Shadow Angle gives us the shadow angle on a horizontal plane and VSA- Vertical Shadow angle gives us the shadow angle on a vertical plane

HSA helps us determine the size of the fin we need, while VSA helps us with the size of the overhang we need.

No. 2: We need a **2D Polar Equidistant Coordinate Sun Path Chart**

This chart can be obtained for specific locations giving inputs on latitude and longitudes from websites like the Andrew Marsh (https://andrewmarsh.com/) or from the University of Oregon, Solar Radiation Monitoring Laboratory.

No.3 Timetable Plot
This depicts the time during which the temperature ranges are hot, comfortable and cold. This can be accessed from UCLA Climate Website.

We use these three to analyse and intersect what are the time when the building needs to be shaded and how the shading devices are to be designed

Note- We are going to mark above the line for when we are plotting for Winter Chart and below the line for when we are plotting for the Summer Chart, since both summer and winter are marked together in the Sun Chart.

How to read the sun path diagram ad use it to design solar shading length and angle?
A. The orange lines, represents different line of the months
B. The lines connecting the orange lines, represents different time of the day from surise to sunet.
C. By selecting the month and the time of the day, we get an intersection point, by connecting this point from the centre to the outer periphery, we get the value of the Solar Azimuth Angle.
D. The concentric circle on which this point is situated gives us the Sun Altitude Angle.

With all this data available we can then use the formula for calculating the HSA and the VSA. Using which we can then geometrically derive the solar shading length of the overhang and the vertical fin.

HSA helps us determine the size of the fin we need, while VSA helps us with the size of the overhang we need.

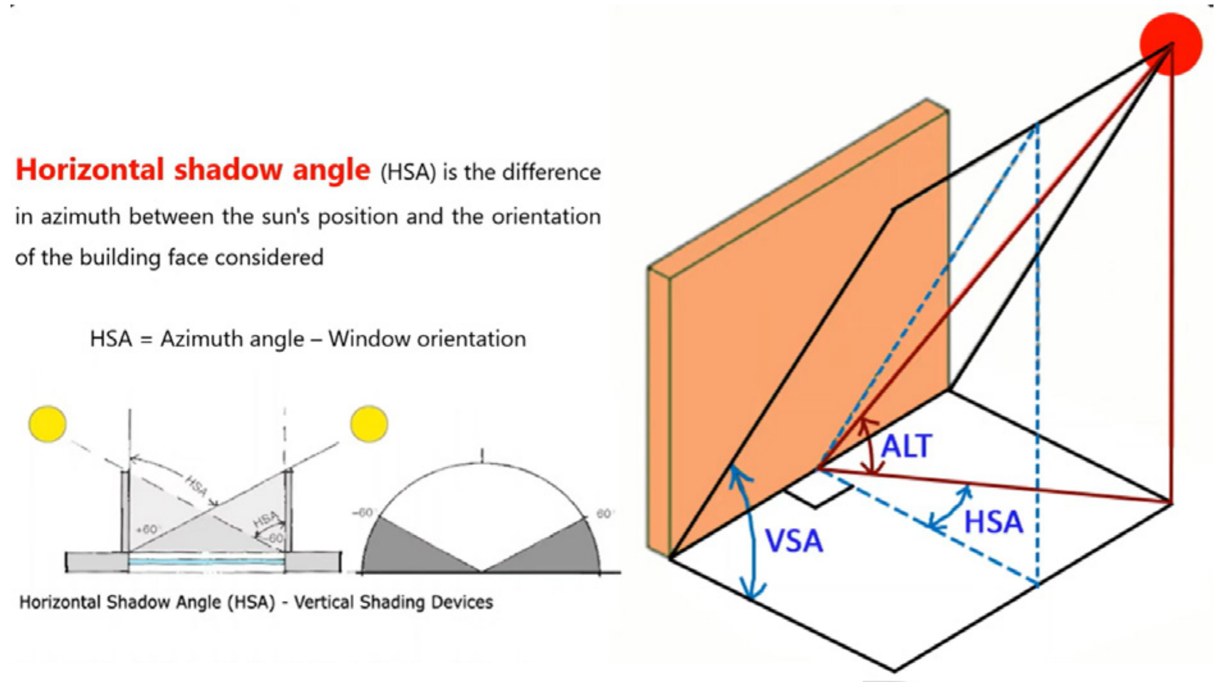


Fig HSA Calculation

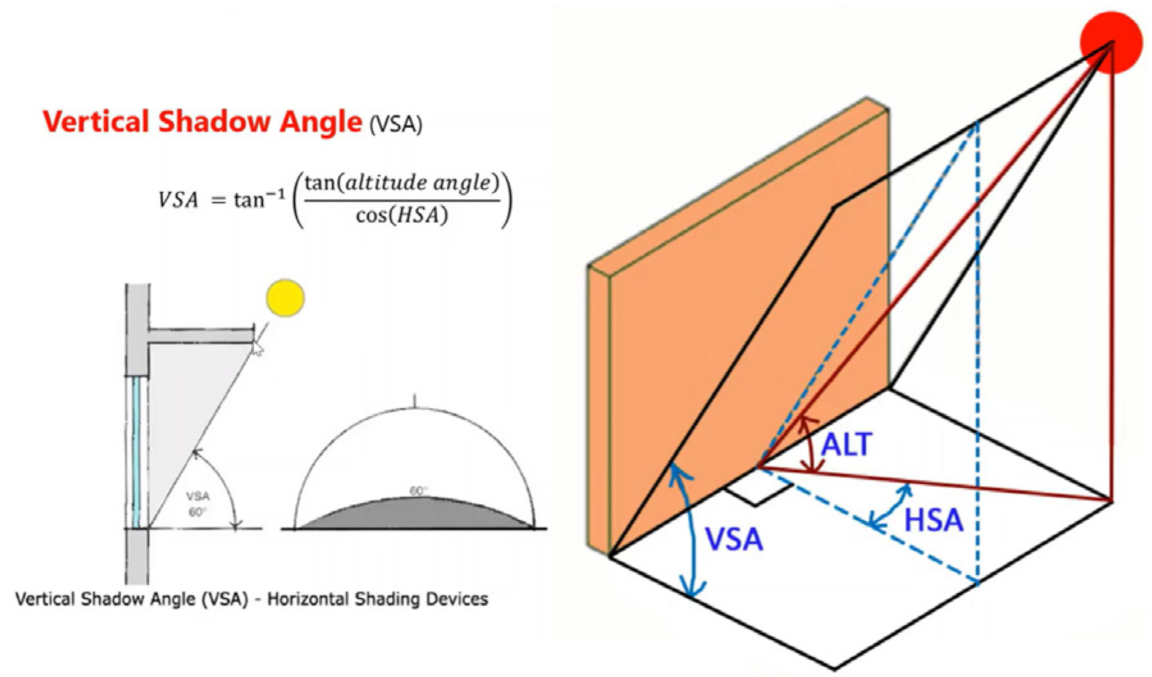


Fig VSA Calculation

CRITERIA & SOFTWARES FOR SIMULATION OF THE DATA

The main criterias to be analysed for the purpose of optimizations can include: Glare Analysis, Daylight Analysis, Energy Analysis, Thermal Comfort, Shading Analysis, PV Production, Energy Harvesting, Indoor Environmental Quality (IEQ) and other subjective criterias like aesthetic impact, visual comfort. The softwares frequently used in the market as of date include EnergyPlus, DIVA for Grasshopper, Ladybug for Grasshopper, Honeybee for Grasshopper, Radiance.

Source: A novel approach to account for shape-morphing and kinetic shading systems in building energy performance simulations

For the scope of our thesis, we will calculate the thermal transmission, indoor air temperature and lux level, for which the software we have used is Rhino+ Grasshopper, for modelling, Ladybug+Honeybee for automated shading calculation and lux level simulation and Design Builder for thermal transmittance and Indoor Air temperature simulation. In the end however, the lux level simulation has also been carried out on design builder for the ease of simulation of the technical aspects of the material taken into consideration.

Rhinoceros + Grasshopper + Plug-ins food4Rhino

DesignBuilder SOFTWARE

Fig: Softwares used for the development of design and simulation

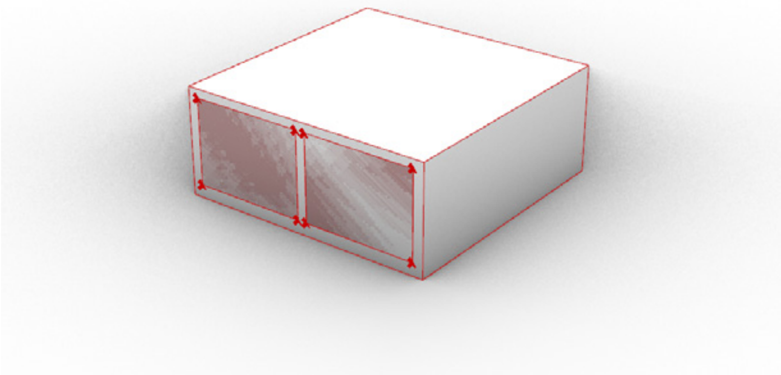


Fig A room without shading device

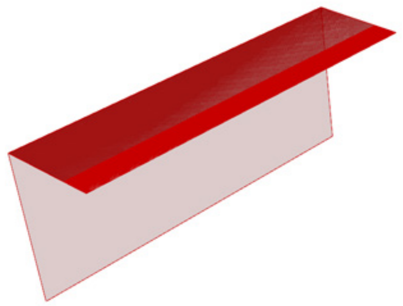


Fig Fixing auotmatic shading onto the room facade

DEVELOPMENT OF A SCRIPT FOR AUTOMATIC OVERHANG SHADING CALCULATION FOR DEVELOPEMENT OF A DESIGN PROTOTYPE

To design automated shading as per window size, the script for overhang shade is given a function of Cotan of the altitude angle, multiplied by the height of the glazed part of window. The altitude angle is extracted from the EPW File of Torino.

Formula Used-
Overhang Depth= Height X Cotan(Altitude Angle)

By only changing the EPW File of the location, automatic overhang shade depth can be obtained.

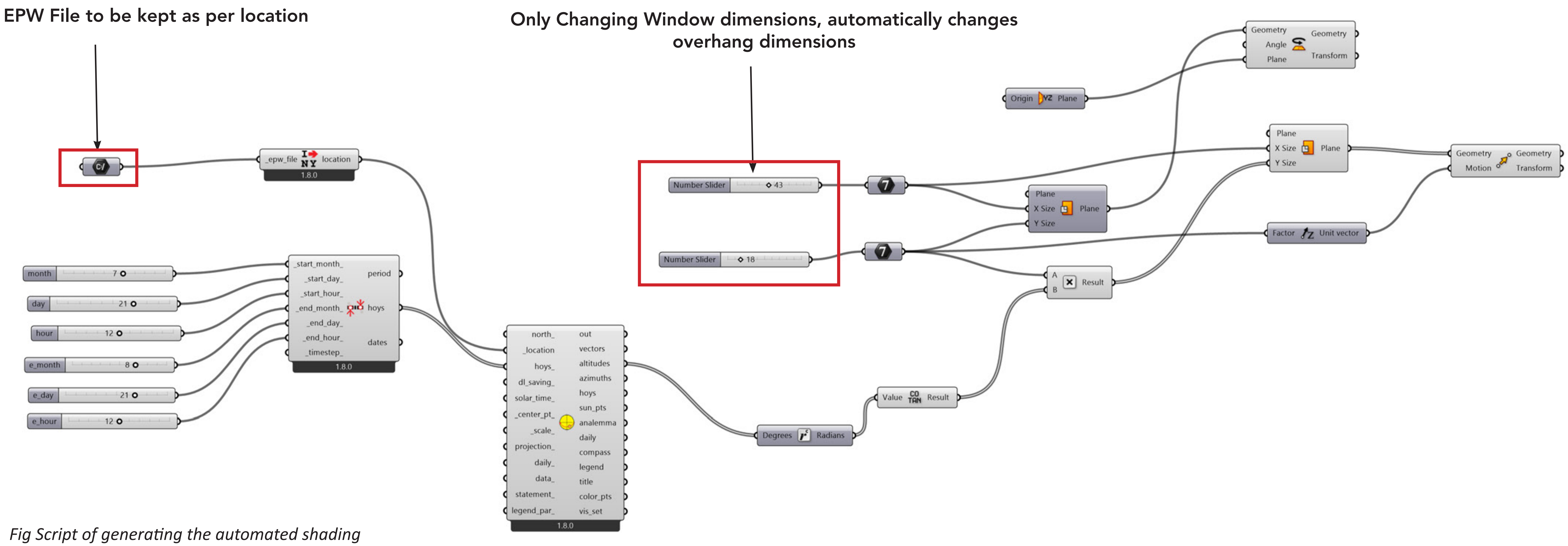


Fig Script of generating the automated shading

ADDITION OF THE HEAT MAP SIMULATION OF LUX LEVEL TO THIS AUTOMATED SCRIPT

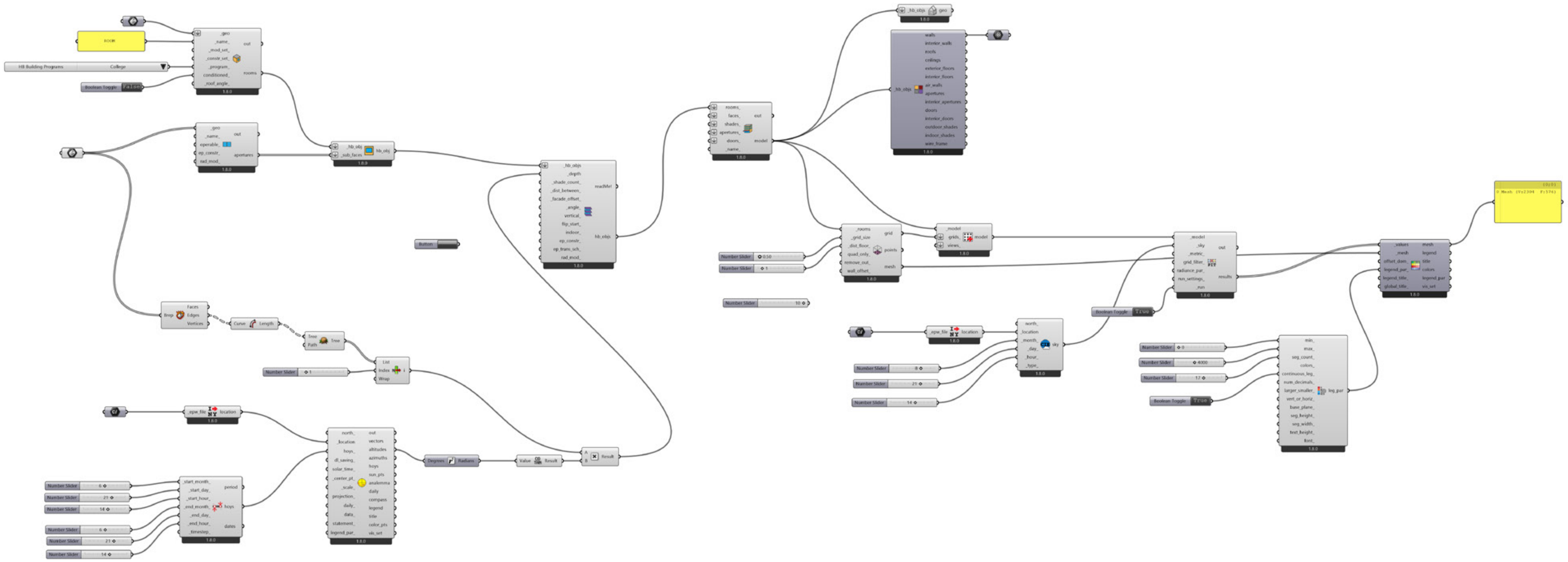


Fig Script of calcualting the lux level through generated automated shading

USING THE LUX LEVEL SIMULATION TO DETERMINE THE NEED OF ADAPTIVE SHADING

STEP 1
Simulation of a Typical existing West facade window in Jaipur (Location of the Site chosen later in thesis)

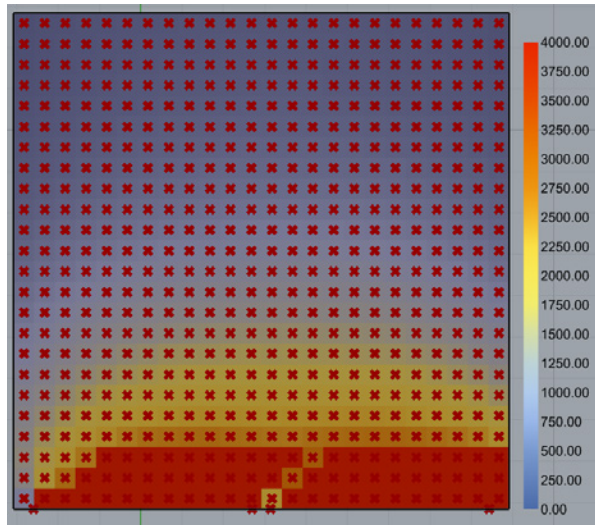
RESULTS
Lux Level is not in a comfortable range of 300-500 lux considered suitable for a commercial building

STEP 2
Using the above generated automated script to determine the optimum overhang length of sun shade and re-perform simulations

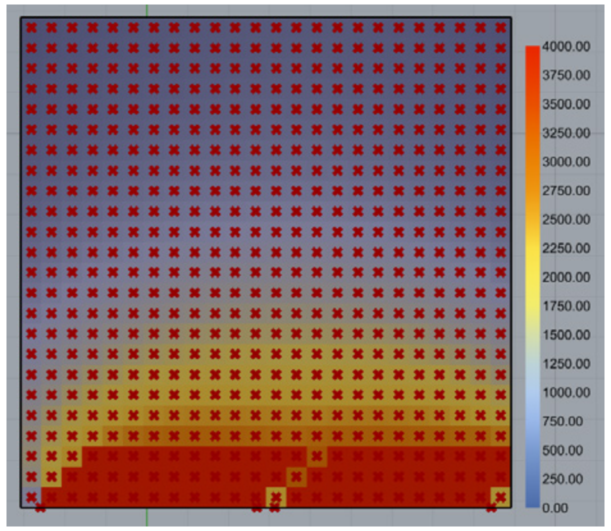
RESULTS
For different months, different shading requirement will get us to an idea shading device range

A need for an Adaptive Shading is established

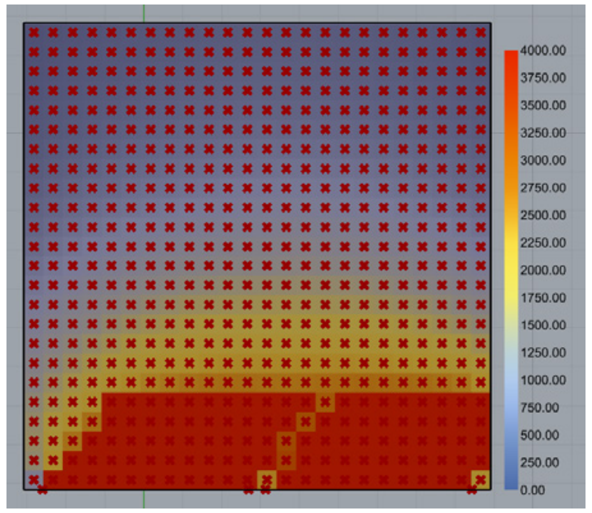
Performing the Simulation as per Step 1 & 2



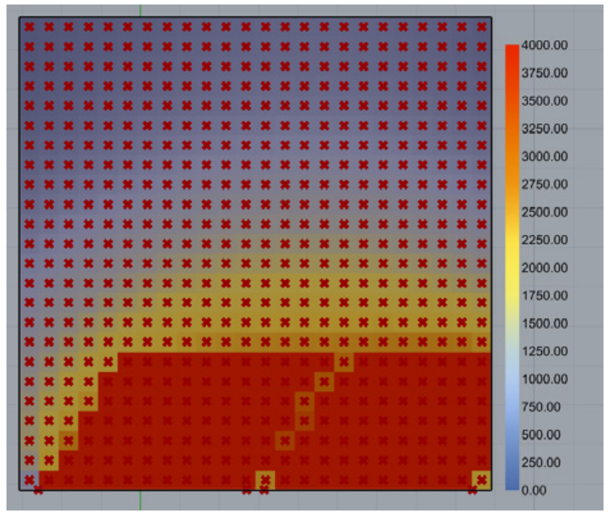
21st June 2pm Without shade



21st July 2pm Without shade



21st August 2pm Without shade



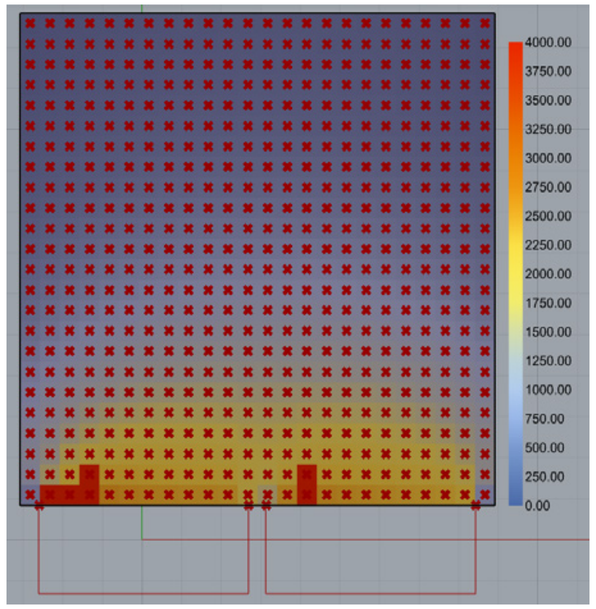
21st Sept 2pm Without shade

Lux Level Simulation of the window during Summer months without Shade

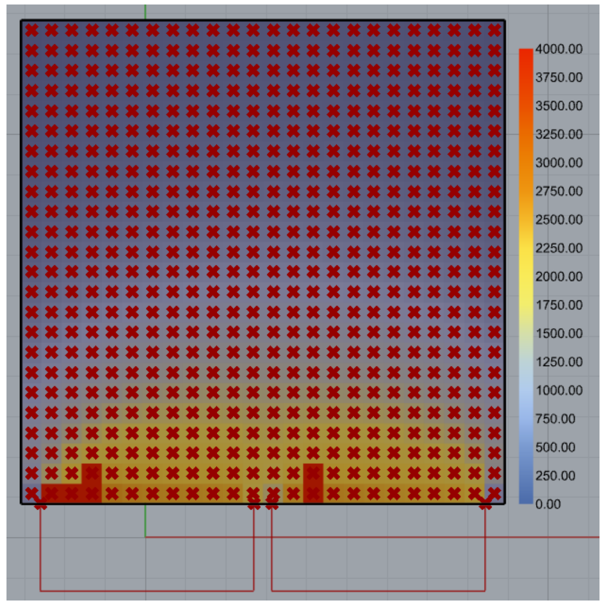
SIMULATION OF THE EXISTING FACADE WITHOUT SOLAR SHADE

We see that a typical room without shade, experiences a lux value of more than 2000 in more than 30% of the room area in leasgt intensity sun day

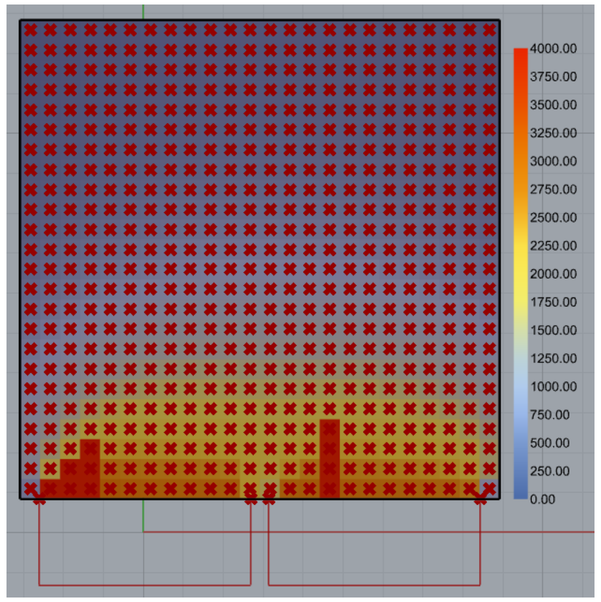
So we need to devise a shading system that shades the window in the summer season for the most heat intensity day, which is 21st JUNE, that marks as the hottest day of summer season.



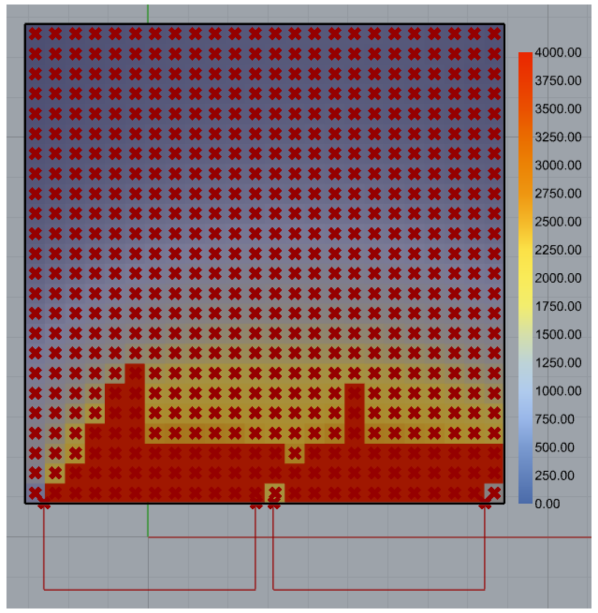
21st June 2pm With shade



21st July 2pm With Shade



21st August 2pm With shade

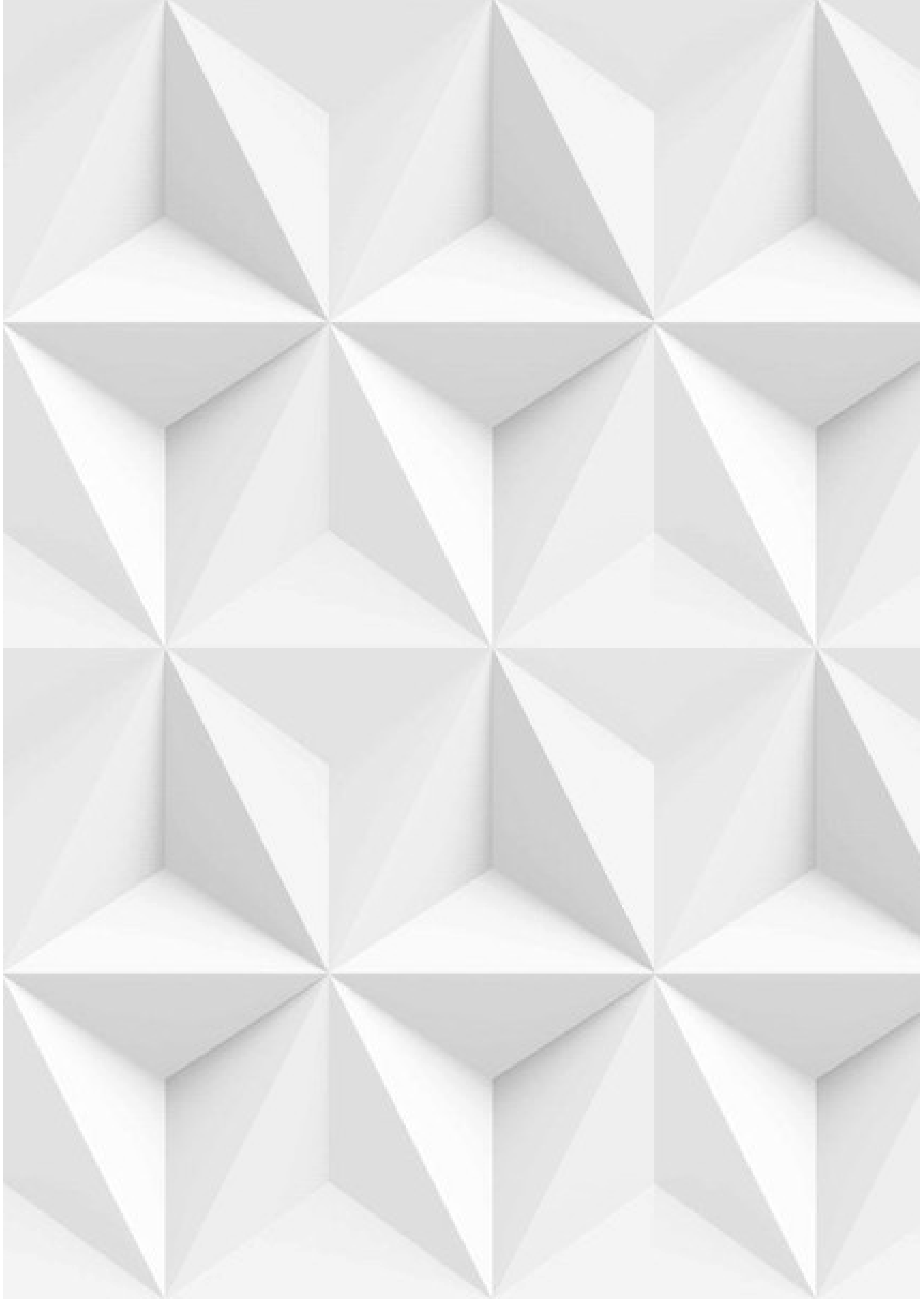


21st Sept 2pm With shade

Lux Level Simulation of the window during Summer months without Shade

SIMULATION OF THE EXISTING FACADE WITH FIXED SOLAR SHADE
If we use the same shading depth throughout the year, the lux level on the other days of season is compromised.

CONCLUSION:
There is a need for adaptive shding system that can adapt as per the summer and winter sun, given the diverse changes throughout the year to reduce glare and direct sunlight on the glass resukting in increased building temperature.



PART A
INTRODUCTION TO SMART MATERIALS

PART B
SHAPE-MORPHING MATERIALS

PART C
STUDY OF NITINOL

PART D
SHADING DESIGN PRINCIPLES

PART E
FACADE DESIGN

SELECTION OF THE BUILDING

Building Selected: **World Trade Park**
Location: **Jaipur, Rajasthan, India**
Typology: **Mixed Use (Shopping Mall, Offices)**
Facade Typology: **Fully Glazed**
Climate Type: **Hot & Dry**
HVAC System: **Completely Close Air Conditioned System**

FIg:
Arial Photograph of the existing World Trade Park in its city's context

Source:
Google Earth Images

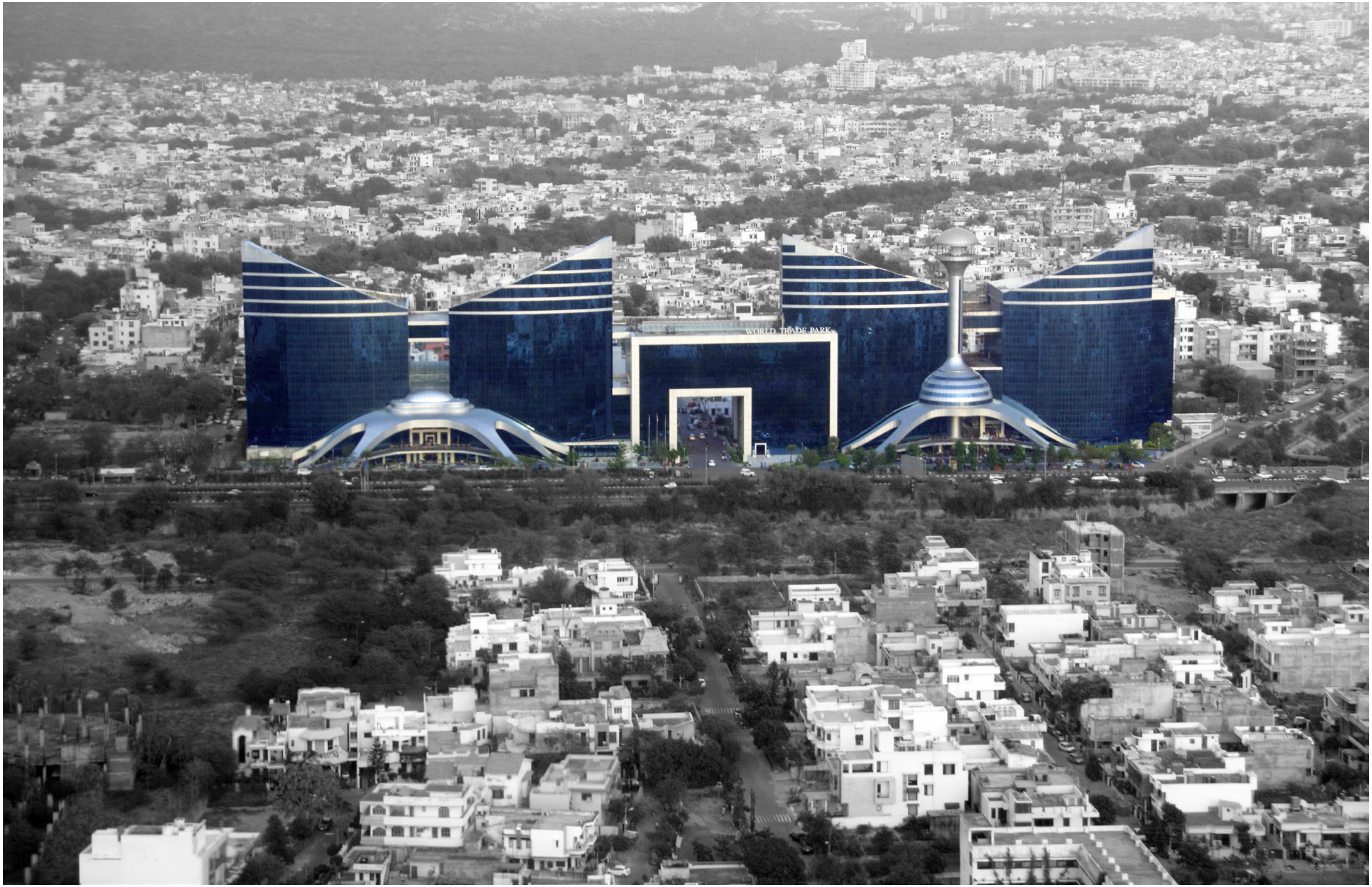


Fig: The above figure is an aerial photograph of the existing World Trade Park building at Jaipur, in which the building is highlighted against the grey backdrop of the surrounding buildings.

Fig: Images showing the reflectivity of the glass facade

IMPLEMENTATION ON A BUILDING

For the verification of this window system, we will test it for a building in tropical climate.

Tropical Climate is defined as places where the major problem is the heat and for greater part of the year buildings need to serve to keep the occupants cool, rather than warm where the annual mean temperature is not less than 20 Degree Celsius.

Comfort Zones for Human Being- Determined as pr Psychromatric Chart

Why this building?

Existing building problems due to facade :

The World Trade Park in Jaipur serves as the ideal case study for this thesis due to its prominent role as an iconic building that embodies the very challenges this research aims to address.

Problematic Thermal Performance:
The building's extensive glass facade, while visually striking, results in significant thermal transmission. This influx of heat directly contributes to a high thermal load on the building, leading to increased energy consumption and operational costs for the HVAC (Heating, Ventilation, and Air Conditioning) system. By selecting this building, the thesis can demonstrate a practical solution to a critical, real-world issue.

Localized Environmental Impact:
Beyond internal energy inefficiencies, the curved shape of the glazed facade creates a tangible external problem. It acts like a large reflector, concentrating solar glare and heat onto the surrounding roads and pedestrian areas. This concentrated reflection causes visual discomfort for both pedestrians and vehicle drivers, highlighting a specific, site-related environmental drawback that an adaptive solar shading system can effectively mitigate.

Justification for Adaptive Solutions:
The World Trade Park illustrates the limitations of static facades that must compromise between aesthetics and environmental performance. This thesis uses the building as a model to show how Passive Adaptive Solar Shading can overcome this trade-off. By proposing a solution that dynamically responds to solar conditions, the research demonstrates how a building's iconic aesthetic can be preserved while simultaneously improving its thermal performance and resolving its negative impact on the local urban environment.

SITE MAP- CONTEXTUAL ISSUES

Fig: Site Plan

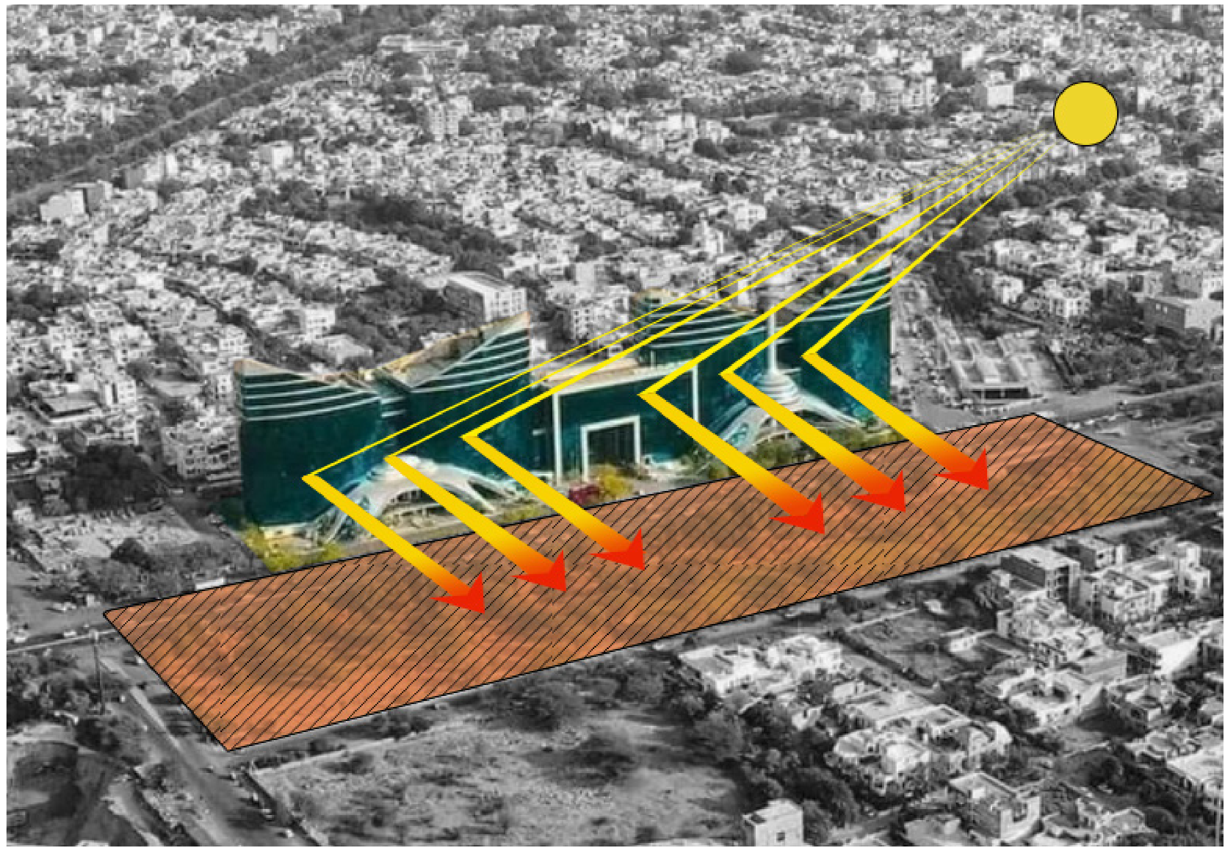


Fig: Showcasing the issue of reflectivity caused in the nearby area

TECHNICAL DETAILS OF THE BUILDING

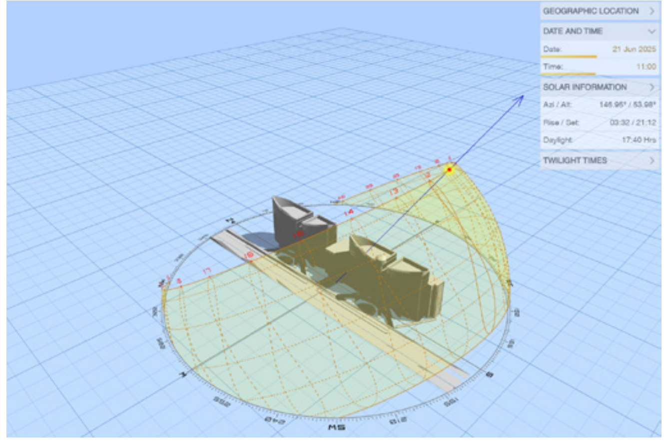
The World trade park jaipur is a mixed use building with shopping complex on the 1st, 2nd and 3rd floor and office on the top floors.

The building although aesthetically pleasing has been criticized by the residents and architects due to its facade material i.e. glass, which is very out of context for a city like Jaipur which has a hot an dry climate.

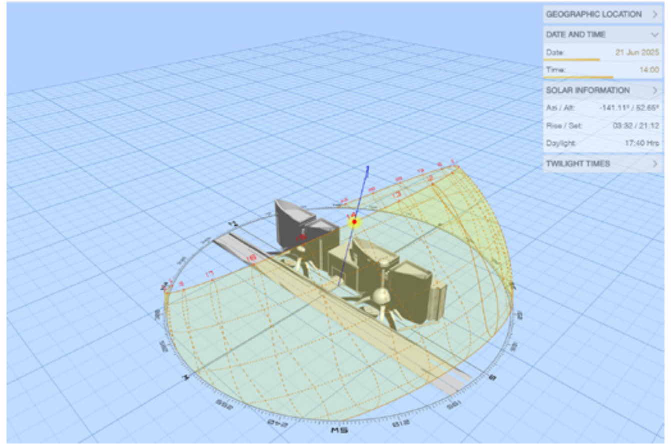
Moreover, even the design language of the building has no contextual relation to the site, but rahter is a landmark building.

From a climatological point of view, it has added significantly to the Urban Heat Island Effect (UHIE) of the surroundings.

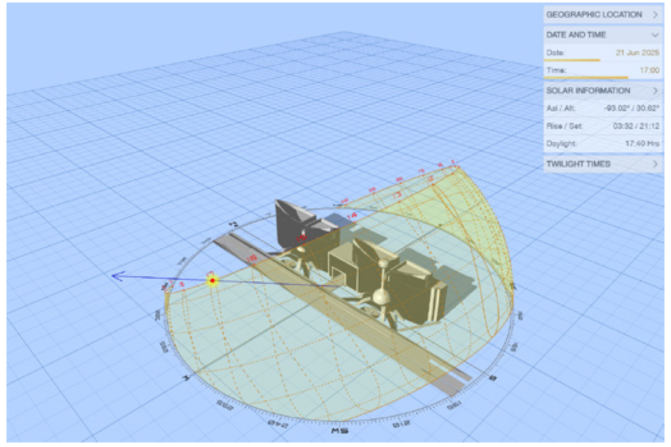
SUN PATH DIAGRAM FOR WORLD TRADE PARK JAIPUR



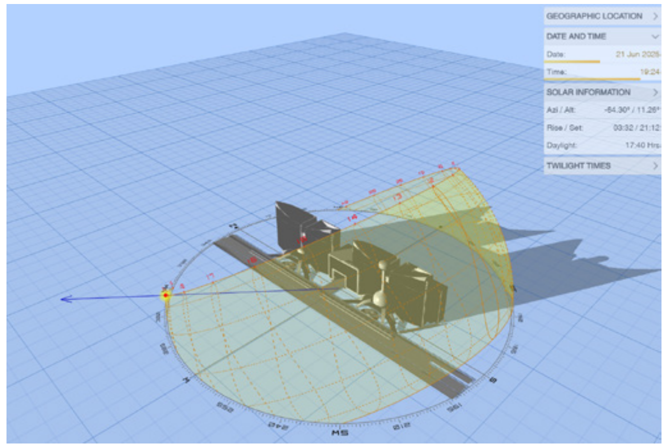
11AM
Building Opening Time



2 PM
The Sun starts to enter



5 PM
Reflectivtity Issue at the peak



7.24 PM
Sunset Time

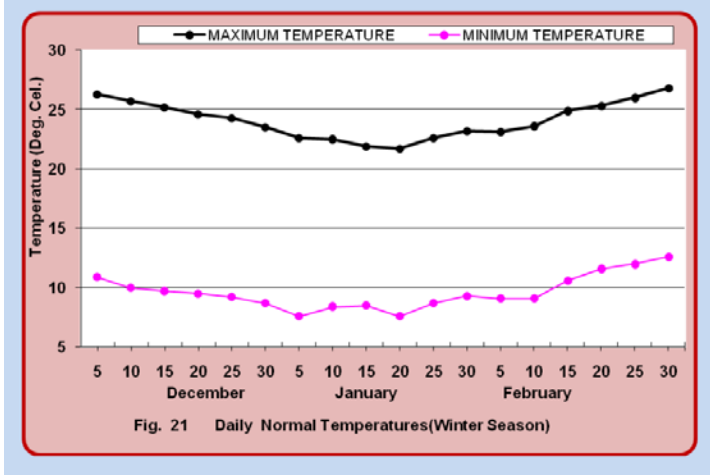


Fig. 21 Daily Normal Temperatures(Winter Season)

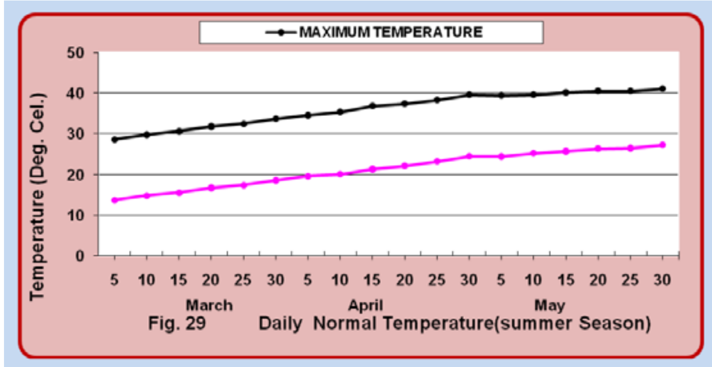


Fig. 29 Daily Normal Temperature(summer Season)

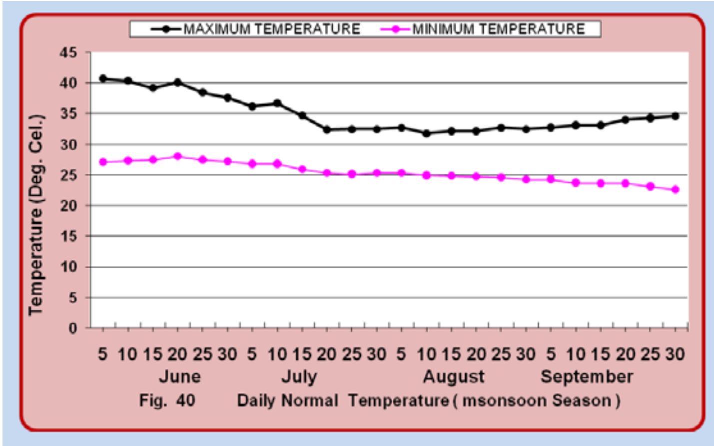


Fig. 40 Daily Normal Temperature (msonsoon Season)

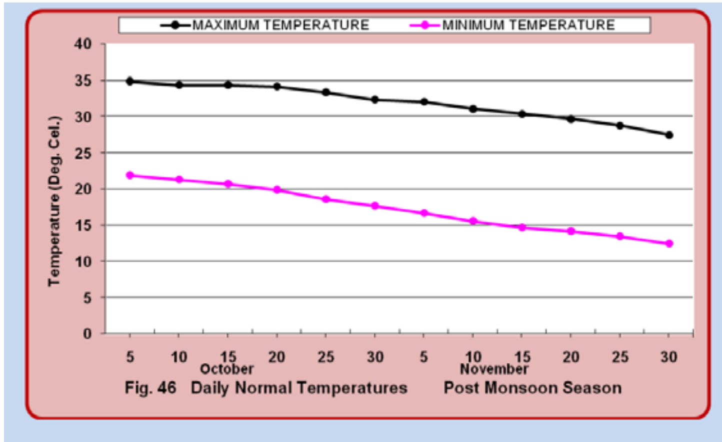


Fig. 46 Daily Normal Temperatures Post Monsoon Season

Climatological Study of City

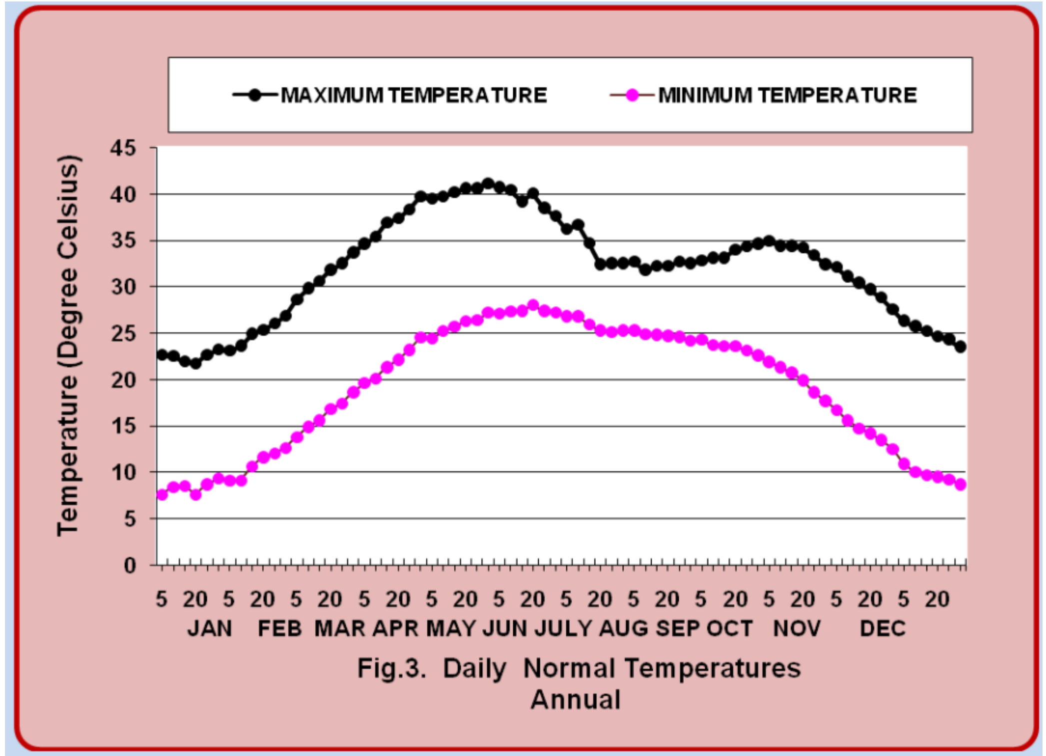
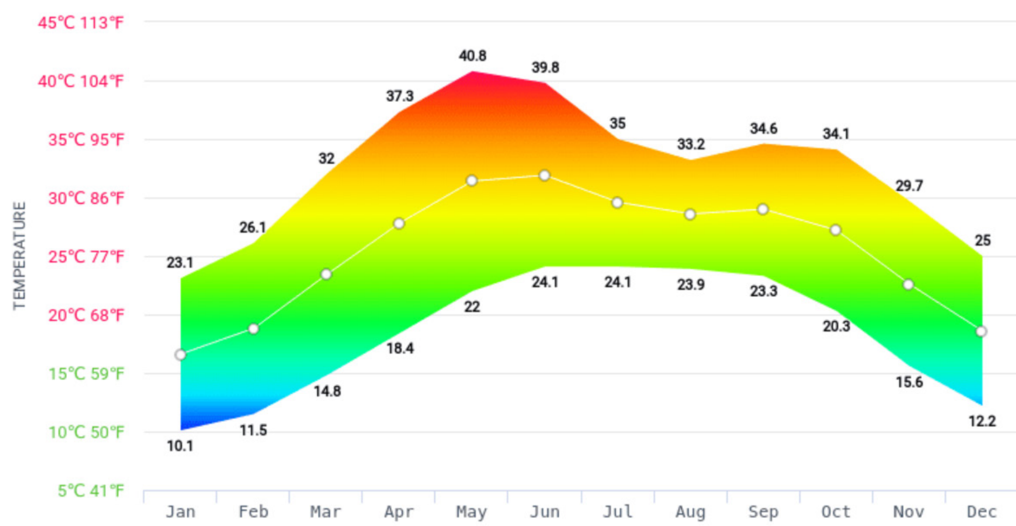


Fig.3. Daily Normal Temperatures Annual



Maximum and Minimum Temperature for Jaipur in different months

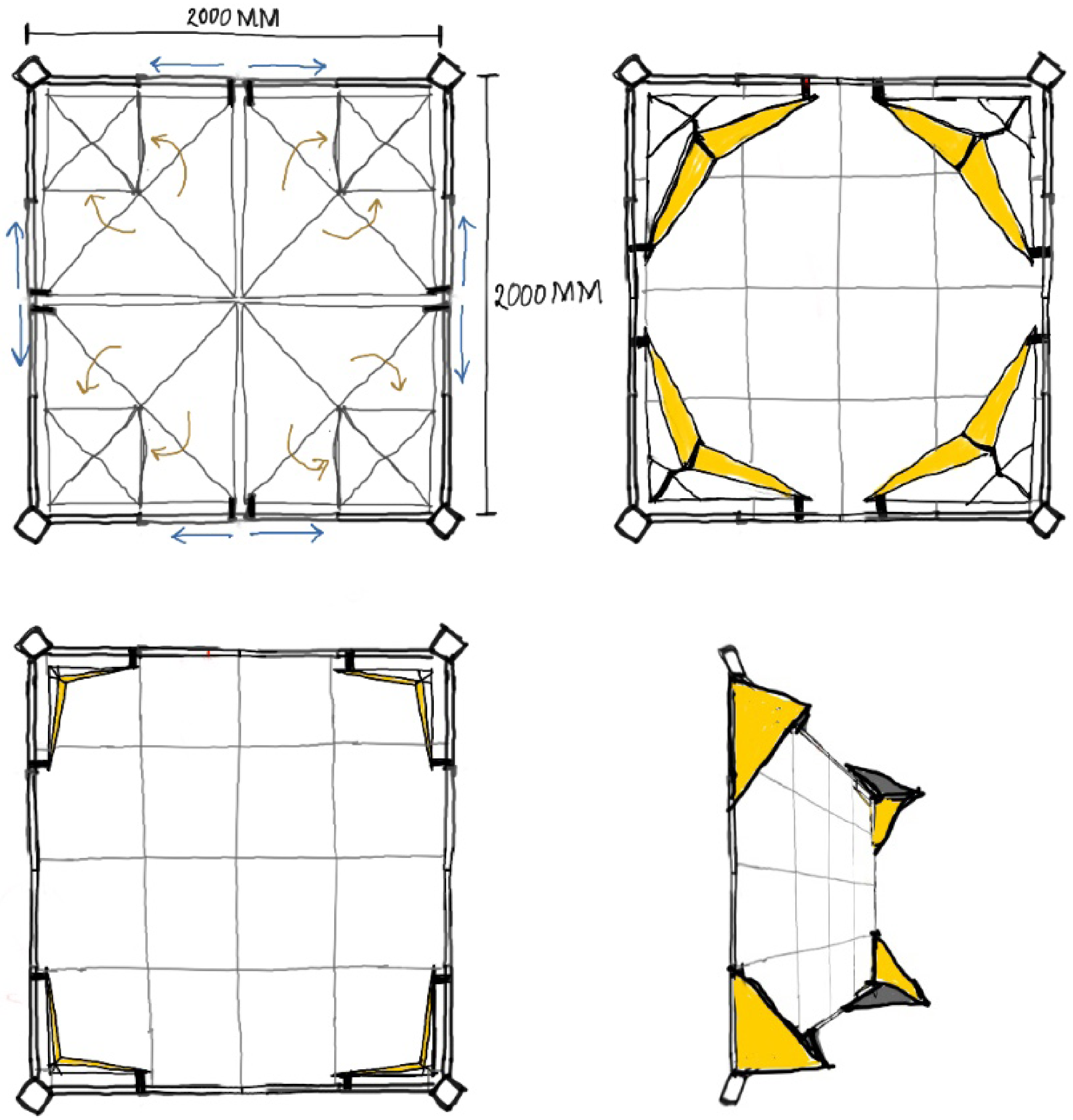


Fig: Folding of the Origami sading

Works as fixed shading when in open position preventing glare within the building

CONEPTUAL DESIGN SKETCHES OF FACADE SHADING SYSTEM USING ORIGAMI

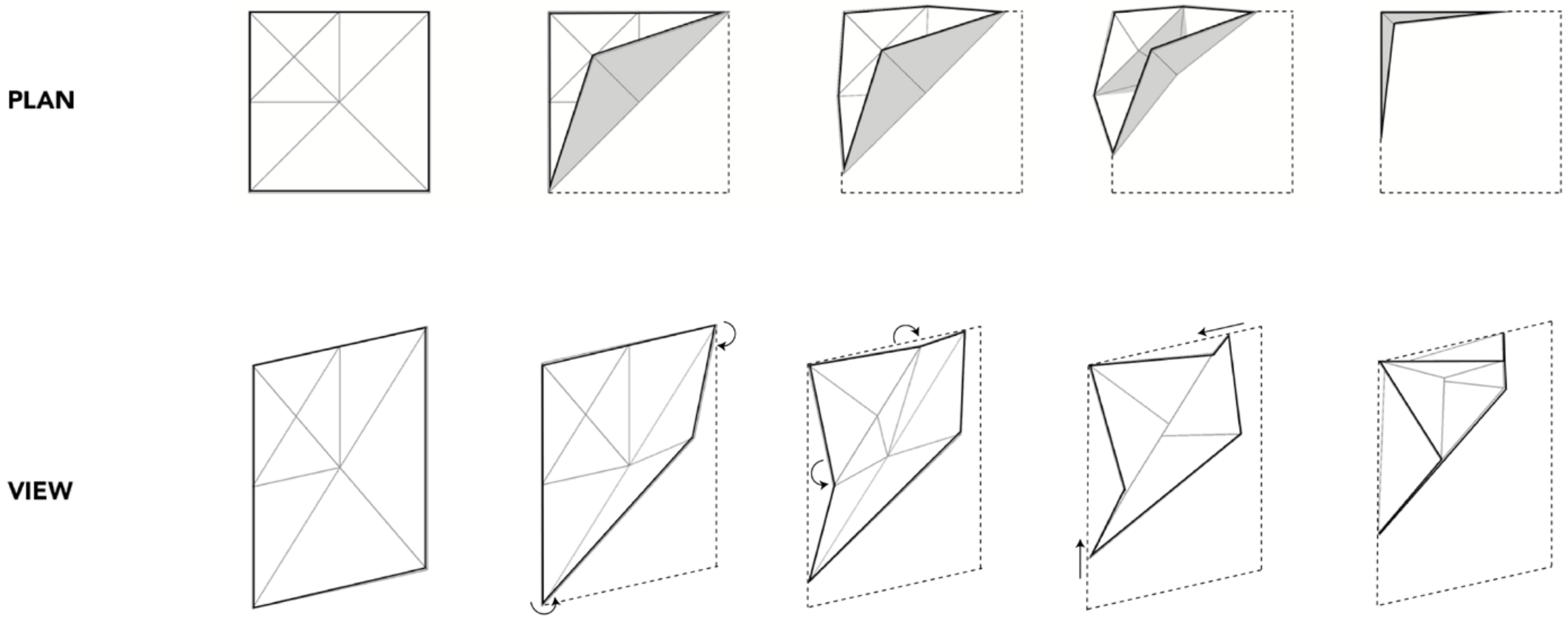
Based on the conclusion from our design concepts research, we had decided to use origami instead of kirigami. This choice was made because origami requires less actuation force, as it does not involve the induced cuts that require additional force to separate endpoints, unlike kirigami.

The design concept is based on a simple origami principle, using a fundamental square or rectangular shape. This shape was chosen for its versatility, as it can be easily adapted and implemented on various building types. The conceptual sketches in the accompanying figure illustrate the initial groundwork for the design's development.

Acting as Fixed Shade :

A key feature of this design is its **dual functionality**. Even in its fully open position, when solar radiation is at its lowest, the panel's components are able to function as an effective passive shading system. This is because the design incorporates both vertical and horizontal shading elements that respond to different angles of solar radiation, a concept derived from the study of Vertical Solar Angle (VSA) and Horizontal Solar Angle (HSA).

DESIGN DEVELOPMENT OF THE SHADE DESIGN



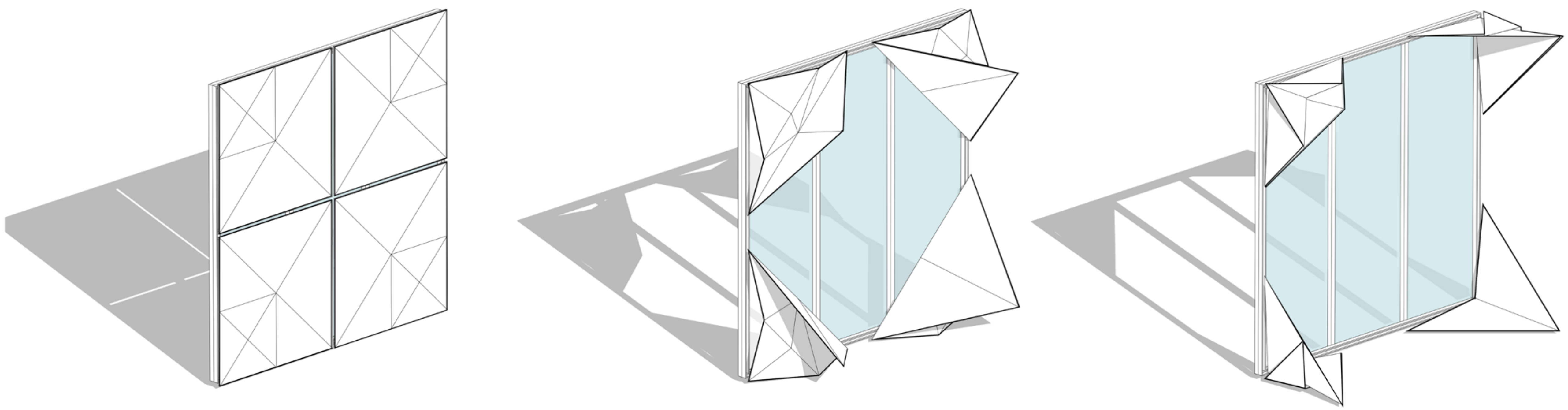
Folding of the shading device

The diagrams on the page show the mechanism of step by step folding of the square shape of the orgiami through the creases.

The figure on the below shows the three different positions the window can be in. The first is the close one, in terms of high solar radiation.

The second image althrough represented statically due to print limitations, is rather a gradual change state, in response ro sun. The transition stage is highlighted for better understanding and linking the flow between the first and the third image.

The third image is of the completely compact position of the shading device, in terms of least solar radiation. The specifications of the lux level, and the selection of the material is now discussed to visualize the design for our use case.



Different Opening Position of the Shading Device

OPTION 1
High Performance Fabric (like Polyester)

Fig High Performance Fabric (Polyester)

Fig High Performance Fabric (Polyester)

OPTION 2
Treated Wood

Fig Wood Panels

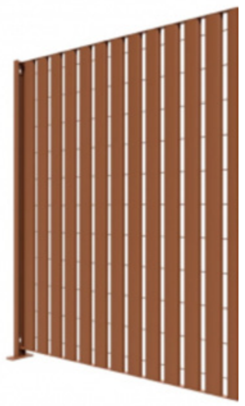


Fig Wood

MATERIAL SELECTION PROCESS FOR THE SHADING DEVICE

Methodology Adopted: TOPSIS ANALYSIS

The full form of TOPSIS is the Technique for Order Preference by Similarity to Ideal Solution. It is a multi-criteria decision-making (MCDM) method that ranks alternatives based on how closely they are to an ideal solution and how far they are from the non-ideal (or anti-ideal) solution.

TOPSIS is used to solve problems where we have multiple alternatives, each with several criteria, and you need to select the best one by considering the relative importance (weights) of each criterion.

Based on the market availability and trends in shading device, these 6 materials were considered for use in our shading device design: Aluminium, High-Performance Fabrics, ETFE, PTFE, Treated Wood and FRP panels.

OPTION 3
PTFE

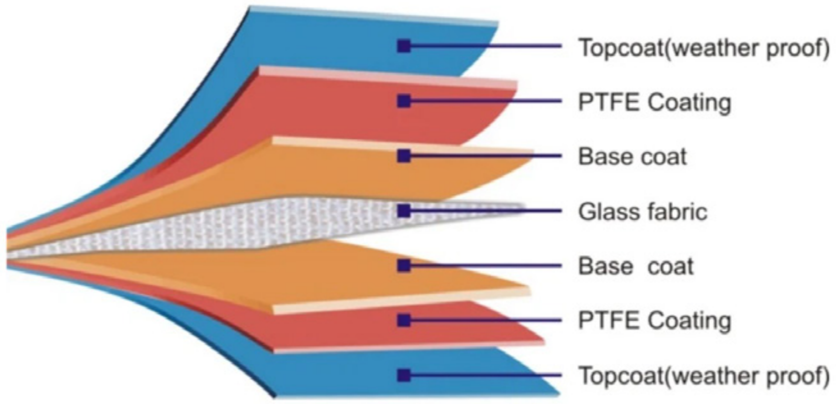


Fig
PTFE Membrane (Polytetrafluoroethylene)

Fig
PTFE Membrane (Polytetrafluoroethylene)

OPTION 3
PTFE

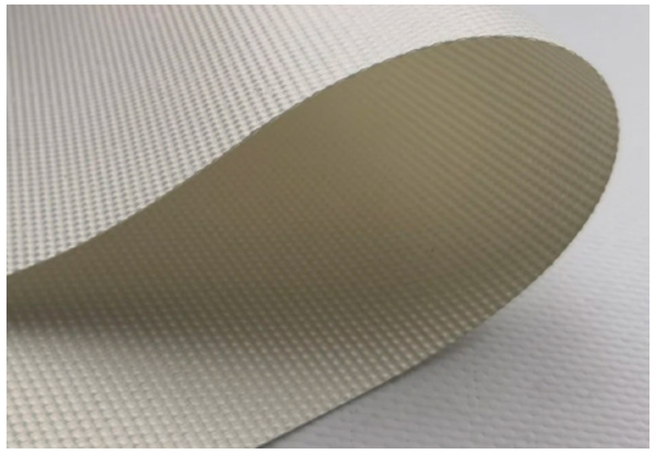


Fig PTFE Membrane (Polytetrafluoroethylene)

OPTION 4
ETFE

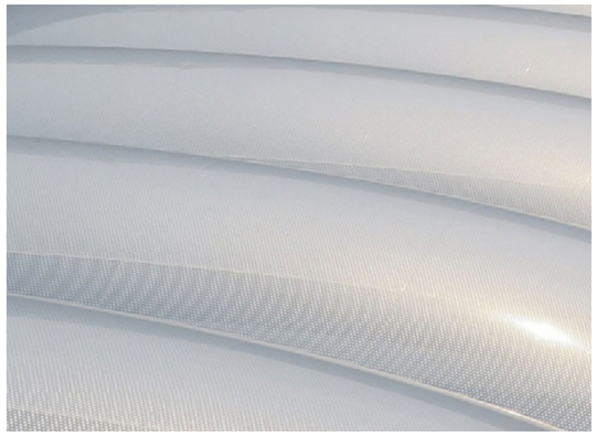


Fig ETFE (Ethylene Tetrafluoroethylene)

OPTION 5
FRP PANELS

Fig FRP Panels (Fibre Glass Panels)

OPTION 6
ACP Panel

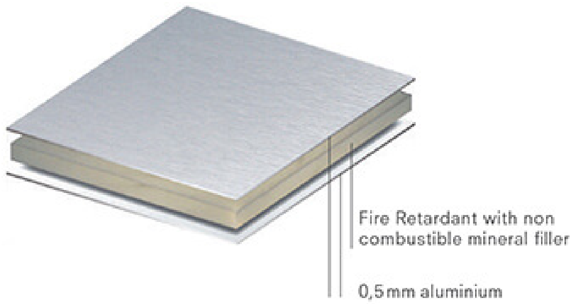


Fig ACP Panel (Aluminium Composite Panels)

COST (C)

Ranking	Material	Initial Cost (Material)	Installed Cost (including fabrication)	Long-Term Maintenance Cost	Overall Cost Profile	Score
1	Aluminum (ACP)	Low	Medium	Low	Low	10/10
2	FRP Panels	Low	Medium	Low	Low	10/10
3	Wood	Medium	Medium	Very High	Medium	7/10
4	High-Performance Fabrics	High	Low	Low	Medium	7/10
5	ETFE	High	Very High	Medium	High	5/10
6	PTFE	High	Very High	Medium	High	5/10

WEIGHT(W)

Rank	Material	Density (g/cm³)	Typical Areal Weight (kg/m²)	Score
1	ETFE	1.7	0.35 - 1.50	10/10
2	High-Performance Fabrics	1.25 - 1.45	0.50 - 2.00	10/10
3	PTFE	2.2	0.80 - 1.20	10/10
4	Aluminum (ACP)	~1.30 - 1.50	3.50 - 5.50	8/10
5	FRP Panels	~1.70 - 1.90	8.50 - 11.00	6/10
6	Wood	0.35 - 1.33	15.00 - 30.00+	4/10

DURABILITY (D)

Ranking	Material	Key Considerations	Relative Durability (1-10)
1	Aluminum	Excellent corrosion resistance; does not rust. Can be prone to denting from impacts.	10/10
2	PTFE	Extremely resistant to UV, heat, and chemical degradation. Very long lifespan.	9/10
3	ETFE	Superior resistance to UV and weathering; very long lifespan, similar to PTFE.	9/10
4	FRP Panels	Highly resistant to weathering and corrosion. Can be susceptible to surface degradation from prolonged UV exposure without proper coatings.	8/10
5	High-Perf. Fabrics	Resistant to UV and mildew, but can be prone to tearing from high winds or abrasion over time.	7/10
6	Wood	Good structural durability, but requires consistent maintenance (sealing, treating) to prevent rot, warping, and insect damage in harsh climates.	5/10

RECYCLABILITY (R)

Ranking	Material	Key Considerations	Score Relative Recyclability
1	Aluminum	Highly recyclable metal panels with established global recycling infrastructure; core materials can vary in recyclability but aluminum sheets are very recyclable	10/10
2	Wood	Natural material, biodegradable and recyclable; can be reclaimed or reused, but treated/finished wood may be less recyclable	9/10
3	High-Perf. Fabrics	Increasingly designed for recyclability; some using polyester/PVC blends with recycling programs; reuse possible; advanced textiles recyclable with proper systems	8/10
4	ETFE	Technically recyclable, but the process is complex and not yet widely available or economically viable for a building's entire facade.	4/10
5	PTFE	Extremely difficult to recycle. Its chemical resistance and high melting point make the process very energy-intensive and not commercially viable.	4/10
6	FRP Panels	Very difficult to recycle. It is a composite of fiberglass and resin, which are permanently bonded together, making it hard to separate and re-use.	2/10

The Fig shows the options, their application and the appearance/ texture of the materials in consideration.

Now based on the market availability and scientific data, we will compare these materials on the following parameters, Weight, Thermal Conductivity, Durability, cost, Solar Reflectance and Recyclability.

The comparision is put out in a summarised way in the tables that follow. After the factual values, a relative integral score is given out of 10 for each criteria, in order to evalulate the materials in a relative way and get the data of all criterias in a similar unit for comparision.

THERMAL CONDUCTIVITY (TC)

Rank	Material	Thermal Conductivity Range (W/m·K)	Key Characteristics	Score
1	High-Performance Fabrics	0.04 - 0.20	Excellent insulator. High-performance polyester or acrylic fabrics trap air within their fibers, creating a good thermal barrier.	10/10
2	Wood	0.12 - 0.30	Very good insulator due to its porous, cellular structure, which traps air. The value varies based on wood density and moisture content.	9/10
3	ETFE	0.23 - 0.25	A poor conductor of heat. Its thermal performance is significantly enhanced in multi-layer "cushion" systems where trapped air acts as the primary insulator.	8/10
4	PTFE	0.20 - 0.30	Low thermal conductivity, making it an effective insulator. Its poor thermal transfer properties can be improved by adding fillers like fiberglass.	8/10
5	FRP Panels	0.30 - 0.40	Good insulator, but its conductivity can vary depending on the ratio of resin to fiberglass content.	7/10
6	Aluminum (ACP)	0.31 - 0.40	While a solid aluminum sheet is a great conductor, ACP has a low thermal conductivity due to its insulating core, making it an effective thermal barrier for facade applications.	7/10

MATERIAL REFLECTANCE (MR)

Rank	Material	Approx. Lowest Reflectance Range	Description	Score
1	Wood	0.10 - 0.20	(Natural material, low reflectance, absorbs heat well, depends on species and finish)	10/10
2	FRP Panels	0.20 - 0.30	(Colored resin panels with matte/dark finishes provide low reflectance)	9/10
3	High-Performance Fabrics	0.25 - 0.40	(Dark-colored or specially coated fabrics absorb solar radiation better)	9/10
4	PTFE	0.40 - 0.50	(Dark or matte finish PTFE films absorb more radiation but higher than fabrics/wood)	7/10
5	ETFE	0.45 - 0.55	(Colored ETFE films typically reflect more solar radiation, less ideal for minimum reflectance)	7/10
6	Aluminum Composite Panels (ACP)	0.50 - 0.60	(Even dark-colored ACPs have higher reflectance due to metallic properties and coatings)	6/10

STEP 1: DECISION MATRIX

OVERALL SUMMARY OF THE SCORE

Serial No.	Material	Cost	Weight	Durability	Solar Reflectance	Thermal Conductivity	Recyclability
1	High-Perf. Fabrics	7	10	7	9	10	8
2	Wood	7	4	5	10	9	9
3	FRP Panels	10	6	8	9	7	2
4	Aluminum (ACP)	10	8	10	6	7	10
5	ETFE	5	10	9	7	8	4
6	PTFE	5	10	9	7	8	4

Yellow weight twice as the blue Columns

STEP 2: NORMALISED DECISION MATRIX

Material	Cost	Weight	Durability	Solar Reflectance	Thermal Conductivity	Recyclability
High-Perf. Fabrics	0.375	0.49	0.35	0.452	0.496	0.477
Wood	0.375	0.196	0.25	0.503	0.446	0.537
FRP Panels	0.536	0.294	0.4	0.452	0.347	0.119
Aluminum (ACP)	0.536	0.392	0.5	0.301	0.347	0.596
ETFE	0.268	0.49	0.45	0.352	0.397	0.239
PTFE	0.268	0.49	0.45	0.352	0.397	0.239

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$$

For example, the normalized score for High-Performance Fabrics on Cost is:

$$r_{11} = \frac{7}{\sqrt{7^2 + 7^2 + 10^2 + 10^2 + 5^2 + 5^2}} = \frac{7}{\sqrt{348}} \approx 0.375$$

STEP 3: WEIGHTED NORMALISED DECISION MATRIX

Material	Cost (1/9)	Weight (2/9)	Durability (1/9)	Solar Reflectance (2/9)	Thermal Conductivity (2/9)	Recyclability (1/9)
High-Perf. Fabrics	0.0416	0.1089	0.0389	0.1004	0.1102	0.053
Wood	0.0416	0.0435	0.0278	0.1118	0.0991	0.0597
FRP Panels	0.0596	0.0652	0.0444	0.1004	0.0771	0.0132
Aluminum (ACP)	0.0596	0.0871	0.0556	0.0669	0.0771	0.0662
ETFE	0.0298	0.1089	0.05	0.0782	0.0882	0.0266
PTFE	0.0298	0.1089	0.05	0.0782	0.0882	0.0266

After analyzing the data related to the 6 criterias as summarised in the tables, we will now do a TOPSIS Analysis

STEP 1: CREATING A DECISION MATRIX TABLE TO SCORE ALL CRITERIA FROM 1-10 SCALE

Weight (W): Materials with a lower weight were given a higher score. For example, “Extremely Low” received a 10, while “Medium” received a 4. This is because a lighter material requires less energy to actuate.

Thermal Conductivity (TC): Materials that are better insulators (have lower thermal conductivity) were given a higher score.

Durability (D): Scores were based directly on the durability from the previous table, where 10/10 is the most durable.

Cost (C): Materials with a lower overall cost profile received a higher score. “Low” received a 10, “Medium” received an 8, “Medium to High” received a 6, and “High” received a 2.

Material Reflectance (MR): The scores were given on the relative comparision of the solar reflectance value of the least reflectance typology of the material present in the market, where 10/10 is the material having least solar reflectance value ensuring maximum visual comfort in the surroundings.

Recyclability (R): The scores were based directly on the recyclability table we established in the previous table, where 10/10 is the most recyclable.

STEP 2: NORMALISED DECISION MATRIX

To normalize the data, each value in a column is divided by the square root of the sum of the squares of that column. This scales all values between 0 and 1.

STEP 3: GIVING WEIGHTS TO THE DIFFERENT CRITERIAS AND OBTAINING WEIGHTED NORMALISED MATRIX

Based on our requirement, the criteria are weighted as follows: Weight, Thermal Conductivity, and Material Reflectance are twice as important as Cost, Durability, and Recyclability.

Weights: W = 2, TC = 2, D = 1, C = 1, MR = 2, R = 1

Total Weight: 2 + 2 + 1 + 1 + 2+ 1 = 9

Normalized Weights: W = 2/9, TC = 2/9, D = 1/9, C = 1/9, MR= 2/9, R = 1/9

Each element vij is calculated by multiplying the normalized score by its corresponding weight (wj).

STEP 5: NORMALISED DATA

$$S_i^+ = \sqrt{\sum_{j=1}^{n}(v_{ij} - A_j^+)^2}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - A_j^-)^2}$$

Material	Distance from Ideal (Si+)	Distance from Anti-Ideal (Si-)
High-Perf. Fabrics	0.0267	0.0954
Wood	0.0747	0.0709
FRP Panels	0.0792	0.0583
Aluminum (ACP)	0.062	0.0784
ETFE	0.0645	0.0722
PTFE	0.0645	0.0722

STEP 6: NORMALISED DATA

Material	Relative Closeness Score
High-Perf. Fabrics	0.781
Aluminum (ACP)	0.558
ETFE	0.528
PTFE	0.528
Wood	0.487
FRP Panels	0.424

STEP 7: FINAL RANKING

CONCLUSION

RANKING	CONCLUSION
1	**High-Performance Fabrics**
2	**Aluminum (ACP)**
3	ETFE
4	PTFE
5	Wood
6	FRP Panels

vij =wj *rij

Step 4: Ideal and Anti-Ideal Solutions
The ideal solution (A +) is the maximum value in each column of the weighted matrix, while the anti-ideal solution (A −) is the minimum value.
A + = [0.0596, 0.1089, 0.0556, 0.1118, 0.1102, 0.0662]

A − = [0.0298, 0.0435, 0.0278, 0.0669, 0.0771, 0.0132]

Step 5: Euclidean Distance to Ideal Solutions
The distance of each material from the ideal (S i+) and anti-ideal (S i−) solutions is calculated using the Euclidean distance formula.

Step 6: Relative Closeness to Ideal Solution
The final score (Ci*) is calculated as

Ci* =Si−/(Si+ + Si−)

A higher score indicates a better material.

Step 7: Final Ranking
The materials are ranked in the descending of their relative closeness score.

Ranking Conclusion

1 **High-Performance Fabrics**

2 **Aluminum (ACP)**

3 **ETFE**

4 **PTFE**

5 **Wood**

6 **FRP Panels**

Now we will simulate the design with the application of the top-2 ranked material, that is, High performance fabric and Aluminium Panels.

Fig: The spider web charts above are plotted for the normalised weighted points (as obtained in step 3) to show the individual material performance in the selected 6 criterias visually.

The largest area covered are by High Performance Fabric and the ACP Panels implying them to be the best preferred options among the rest.

CONCLUSION OF THE TOPSIS ANALYSIS

As per the final ranking recieved which is:

1 High-Performance Fabrics

2 Aluminum (ACP)

3 ETFE

4 PTFE

5 Wood

6 FRP Panels

We can conclude that High Peformance Fabric and the ACP Panela ranked the top preferences, which can also be infered from the radar charts on the left, through which we can visually see the largest blue areas are covered by the same two materials.

The spider web charts above are plotted for the normalised weighted points (as obtained in step 3) to show the individual material performance in the selected 6 criterias visually.

So, we can conclude to select these two material options for our facade application, and now we will simulate our results in detail for thermal transmission and indoor air temperature for these two materials to compare the final result with the existing conditions and to select the final material.

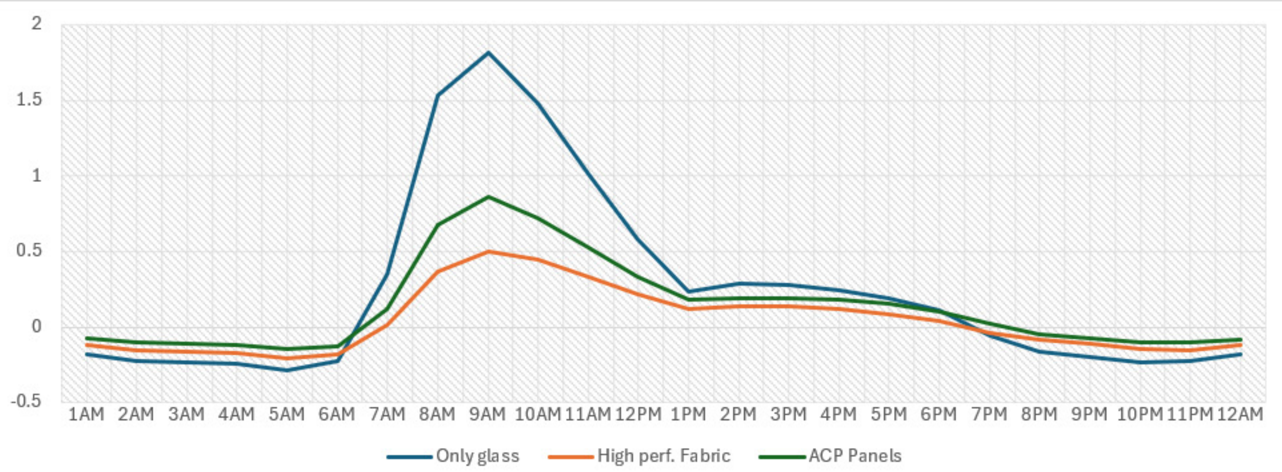


Fig: Thermal Transmission of the Building Envelope with different materials (Results Simulated on Design Builder)

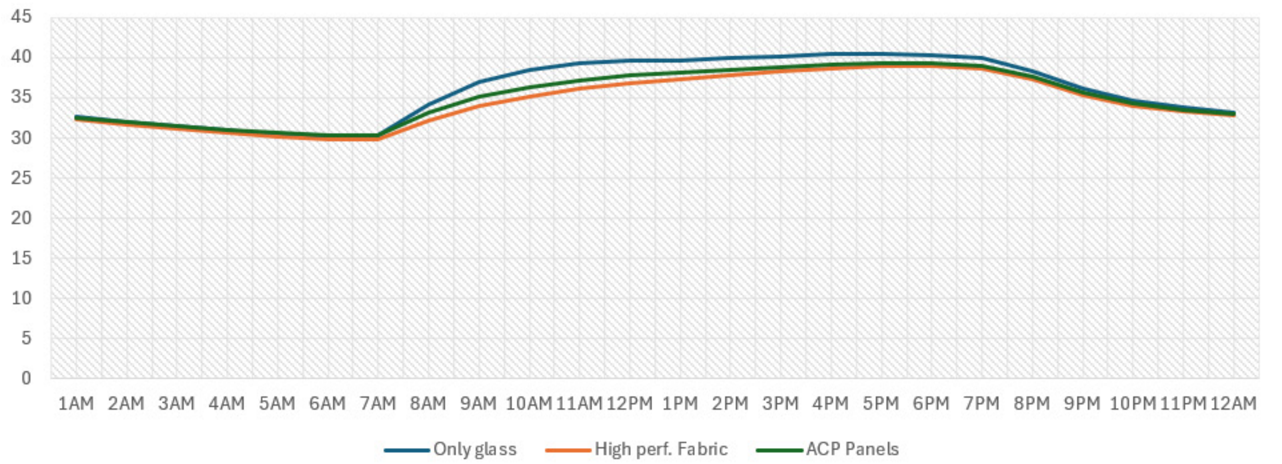


Fig: Internal Air Temperature of the Building with different materials (Results Simulated on Design Builder)

SIMULATION RESULTS

As per the results of the TOPSIS analysis, the first two preference in the material came out to be High Performing Fabric and ACP (Aluminium Composite Sheets) Panels. To analyse them more in detail, a comparitive analysis for the thermal transmission through building envelope and Indoor Air Temperature was simulated against existing glass facade. The graph on the left showcase the results thus obtained. The entire specific values can be accessed through the Annexure-A attached towards the end of the PDF.

The results have been simulated using Design Builder with the following limitations:

1. Only the effect on a single room has been simulated and assumed to be same throughout the building
2. The time of simualtion is considered to be the end of May (3rd-4th week of May), which the typical summer week considered for the climate of Jaipur.
3. The material thickenss for High Performing fabirc was considered to be 1mm, while for the ACP Panel, the to be 3mm.

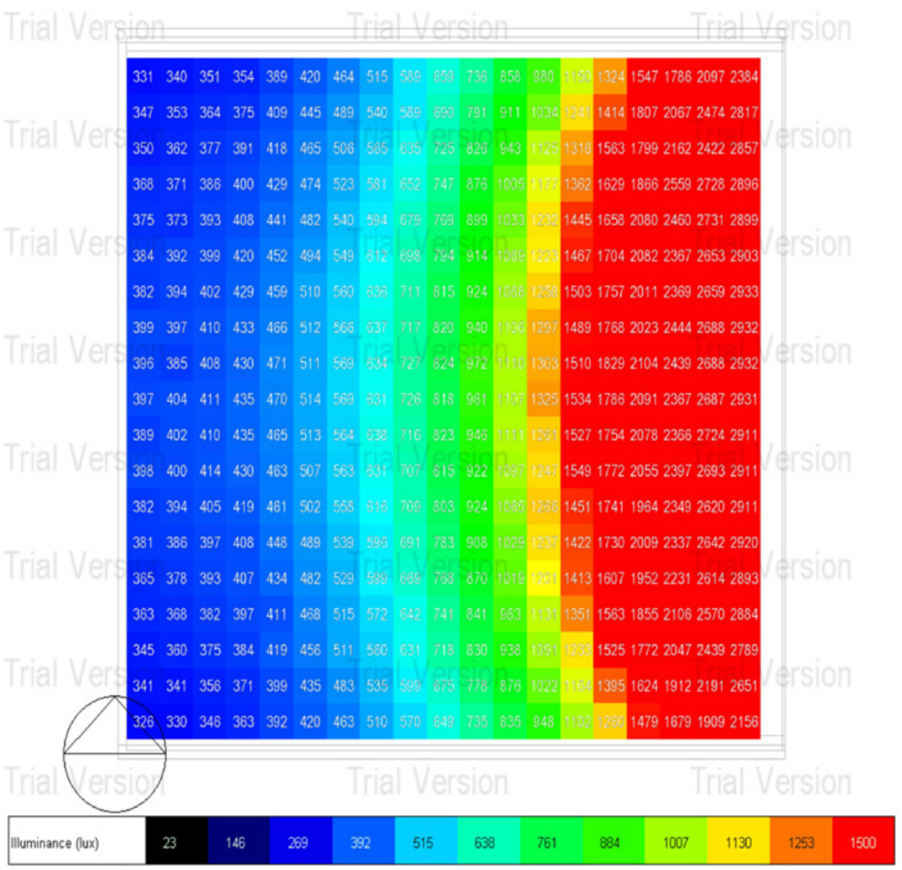
Inference from the Graph:

The first graph shows the thermal transmission through the wall has decreased with the application of ACP Panels and further decreased with High Performance Fabrics, which is a favourable result matching with our TOPSIS Analysis, hence both simulation and Topsis results are verified.

For the period between 6AM-2PM, there is major difference while compared to other time of the day. It should also be noted that during the night this difference decreases and becuase of reverse effect of transmission happening from inside to outside becuase of thermal pressure difference, the materials change their order of transmittance, which is again in our favour since, the thermal transmittance should be more in night to release the inside trapped heat and for both our High Perf. Fabric and ACP, the value is more than glass.

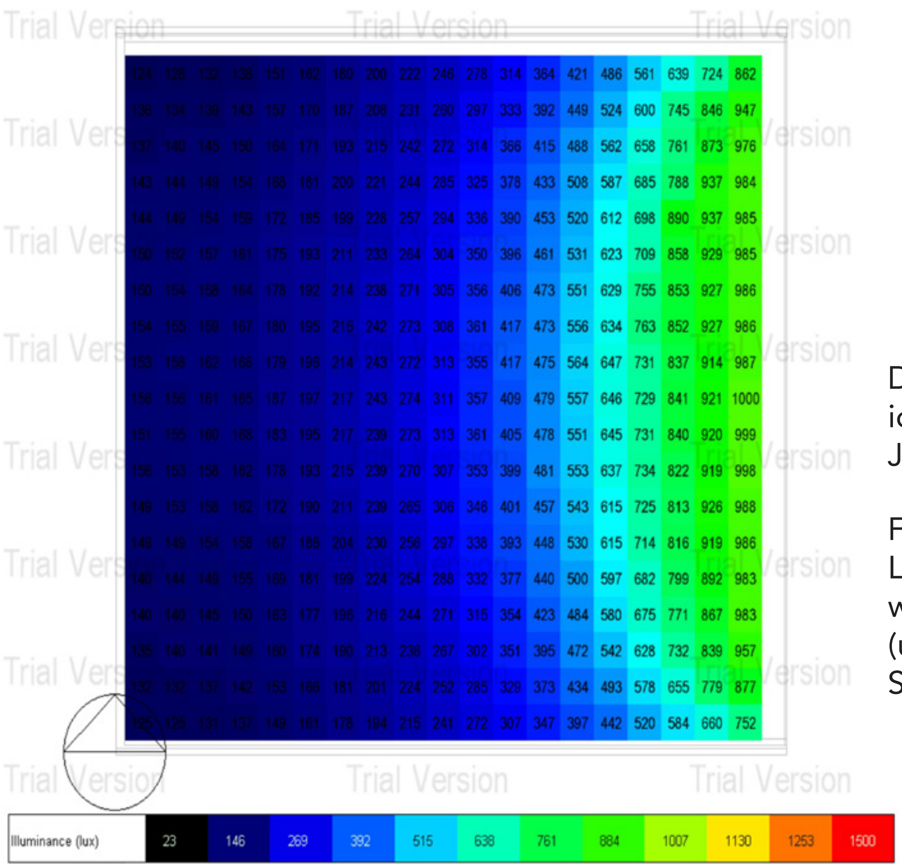
The second graph shows the Indoor Air Temperature which is also favourable justification of our TOPSIS analysis as the temperature decreases with ACP Panel and further decreases with High Performance Fabric.

So, as per the conclusion from our simulation resuls, High Perfomance Fabric is the best option for our application.



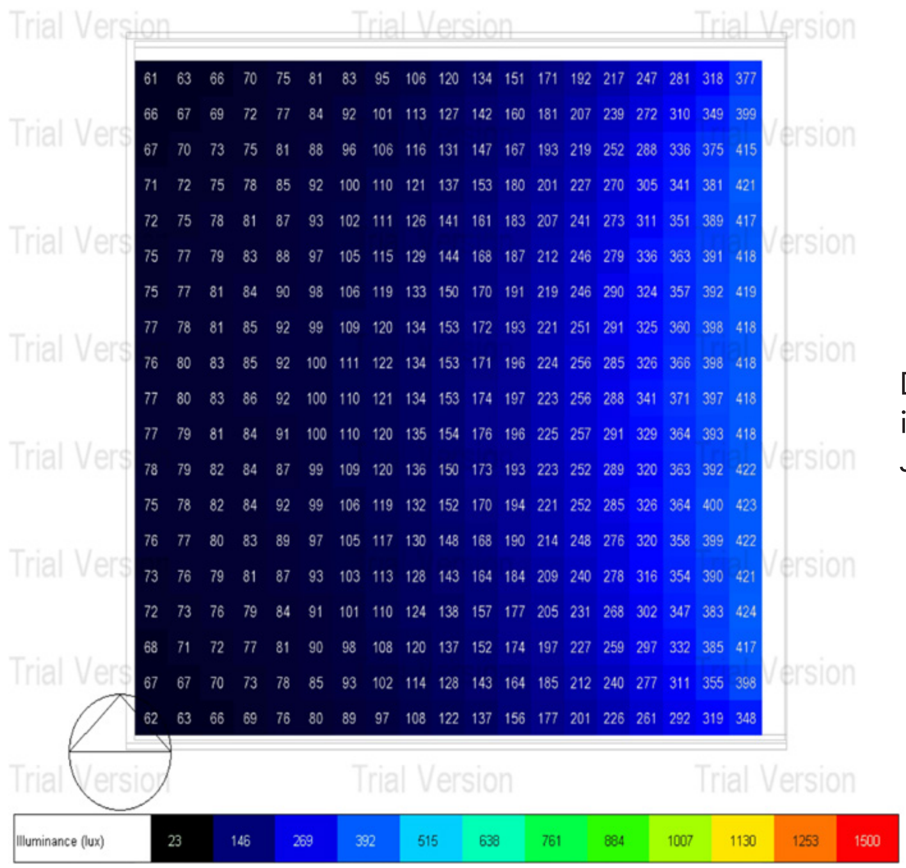
Data Extracted for Typical Summer Week of Jaipur (May 4th Week)

Fig:
Lux Level Simulation without Solar Shading



Data Extracted for Typical Summer Week of Jaipur (May 4th Week)

Fig:
Lux Level Simulation with Completely Open (uncovered) of Solar Shading Device



Data Extracted for Typical Summer Week of Jaipur (May 4th Week)

Fig:
Lux Level Simulation with Completely Close (covered) of Solar Shading Device

Lux Level Simulation Inference

Further, the impact of shading device with **High Performance Fabric**, on internal lux level was also simulated, which is attached on the left. As designed, the lux level simulation are in line with the expectation reduction with an decrease in the percentage opening of the shading device. The comfortable range for the inside of a shopping mall/ commercial building should be 300-500 Lux, which is what we have received with our shading device installed as seen in the third image, the case of completely covered shaging in presence of high solar radiation. The material translucency of the high performance fabric used ensures this optimum range.

Now, as we have verified both the material performance through the simulation results and the shading geometry analysis through the lux level analysis, we will now define how this design can be implemented with the use of smart material, in our case, Nitinol, using it for linear actuation in the mechanism than on the shading device itself to save the material cost and aestheitcs purpose as we had discussed in the earlier sections of

APPLICATION OF NITINOL- WORKING MECHANISM

Structure of Nitinol: Spring Type
Type of Spring: Two-Way Spring
Type of Use: Linear Actuator
System of Use: Mechanism
System Activation Type: Completely Passive using Shape memory Effect

Why Two-Way Spring is selected over One-Way Spring?
While the benefit of one-way springs is that they are lower cost than two-way springs. However, a one-way spring needs to be deformed by an external force when cooled. Since our design does not readily provide this biasing force, additional components may need to be added to the system, increasing cost, size and weight.

Whereas, a two-way spring automatically resets itself when cooled, eliminating the need for a biasing force. This allows actuators to be put into extremely tiny packages. **In short, a two-way spring can exert force in both the directions.** For many applications, the reduction in components offsets the higher cost of the two-way spring as stated by the Kellogs Research Lab.

Why used in mechanism than on the origami crease itself ?
(as seen previously in Design concept 2)
In order to reduce the number of parts used and the supporting mechanism which in turn reduces major chunk of the cost; the superelasticity and shape memory properties of the nitinol have been tried to be directly used in the mechanism of the overall design.

How it Works?
As we know it by now, Nitinol spring is made from Shape Memory Alloy (SMA).
When cooled (martensitic phase), it extends or compresses easily. When heated (to austenitic phase), it contracts back to its memorized length, generating a pulling force.

This contraction acts like a linear actuator to move panels mechanism of the shading system.

Making the system more effective:
In direct actuation, Nitinol spring contracts pulls/rotates the shading element. But when coupled with a Lever/Linkage the spring contraction drives a linkage that rotates louvers or slides panels making the overall system more effective.

Passive Solar Response:
If designed with the right transition temperature, the shading could automatically open/close with sunlight heating the spring (with no electricity required). In summer sun, the spring heats up, contracts and closes the shade. At cooler temps, spring relaxes and the shades reopen.

Design Considerations and Limitations:

1. Force Output:
Nitinol generate decent pulling force but usually only a few Newtons per mm of wire diameter. When a spring is used, it amplifies this effect, but still the linear travel is small you'll need a clever mechanism (e.g., levers, pulleys, or multiple springs).Expertise in mechanical engineering is need to amplify the system of linkages in order to move the shading panels (depending upon on their weight, friction, and wind load).

2. Activation Time:
Passive Activation: For fully passive system, the activation relies on solar heating of the spring which is very elegant, required no wiring, but it has a limitation slower response time.
Active Activation: To increase the efficiency of the overall system and decreasing the activation time needed, it can work with a small electric current through the Nitinol spring to heat and activate it faster, but the idea of passive is lost in that case, since a power supply is needed.

Conclusion:
Nonetheless, the system can work compeltely passively despite these limitations, but with a lower efficiency than a slightly active system. In future, this response time can be engineered to make the overall system even more effective passively.

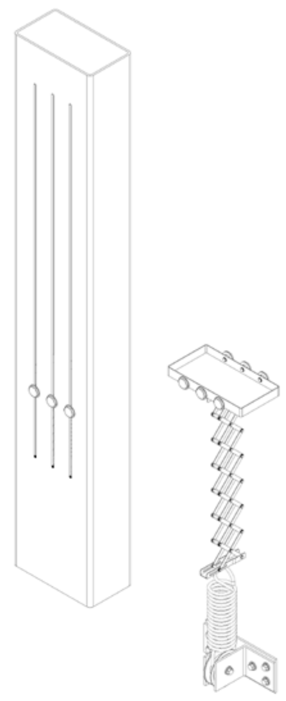


Fig: The detail of the mechanism behind the opening and closing of facade

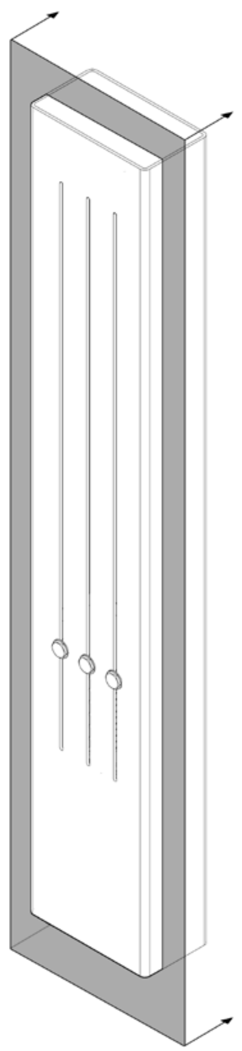


Fig: The grey rectangle shows the section plane where the mechanism box is cut to see inside it in the diagram on the right

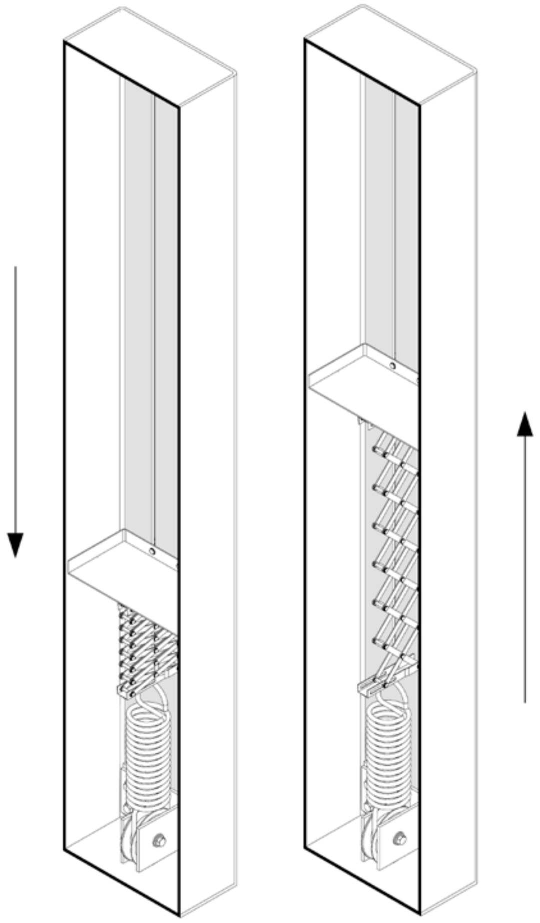


Fig: Contracted position (Left)
Expanded position (Right)

THE MECHANISM

Internal Details of the Mechanism Box

The figure on the left shows the internal section of the mechanical box, in the first section it shows the contracted position of the Nitnol in presence of high solar radiation, and the entire system shrinks.

The second section shows the mechanism of expansion, that as soon as the temperature drops, the nitnol expands back to its natural state, pushing the scissor arm attached to it which inturn pushes the shading panel lever arm to open up.

The diagram on the bottom further shows the detail of this system highlighting the interconnection of these elements that cause the movement.

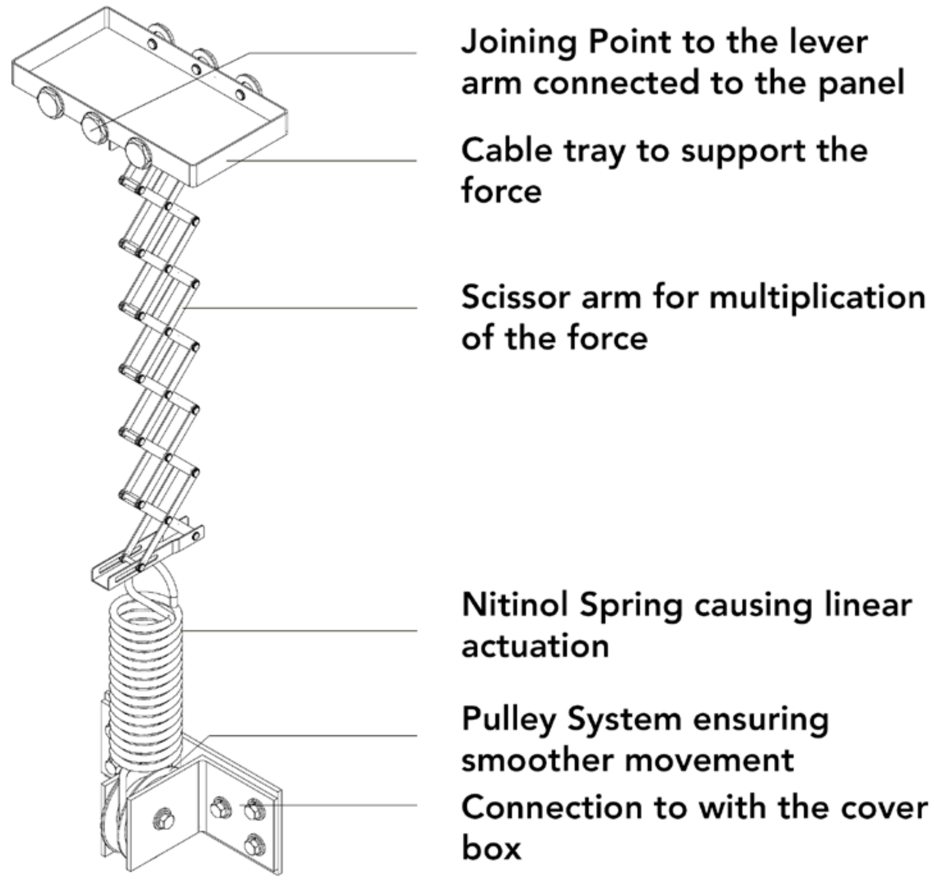
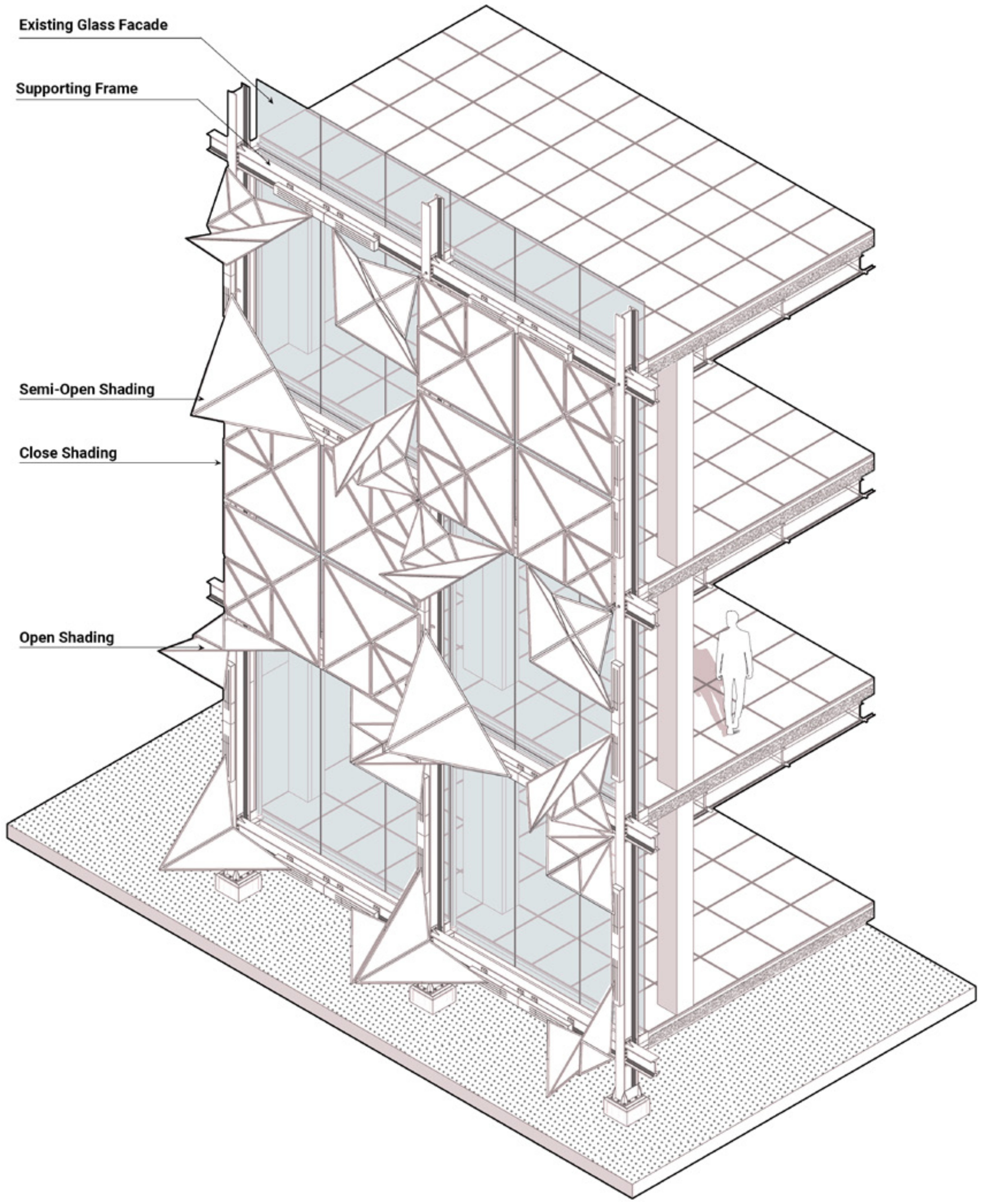
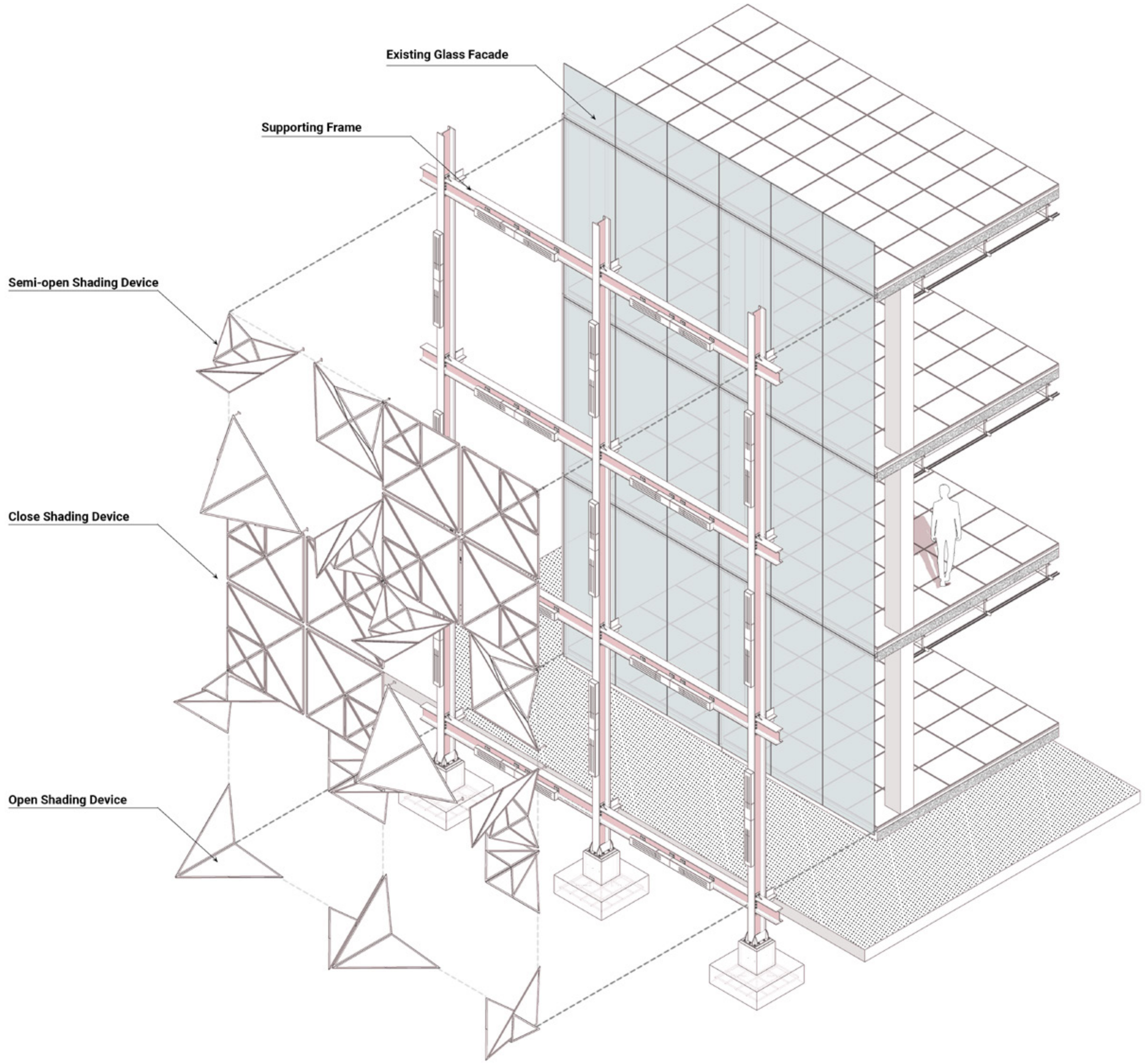


Fig: Internal Mechanism, actuated by Nitnol Helical Spring



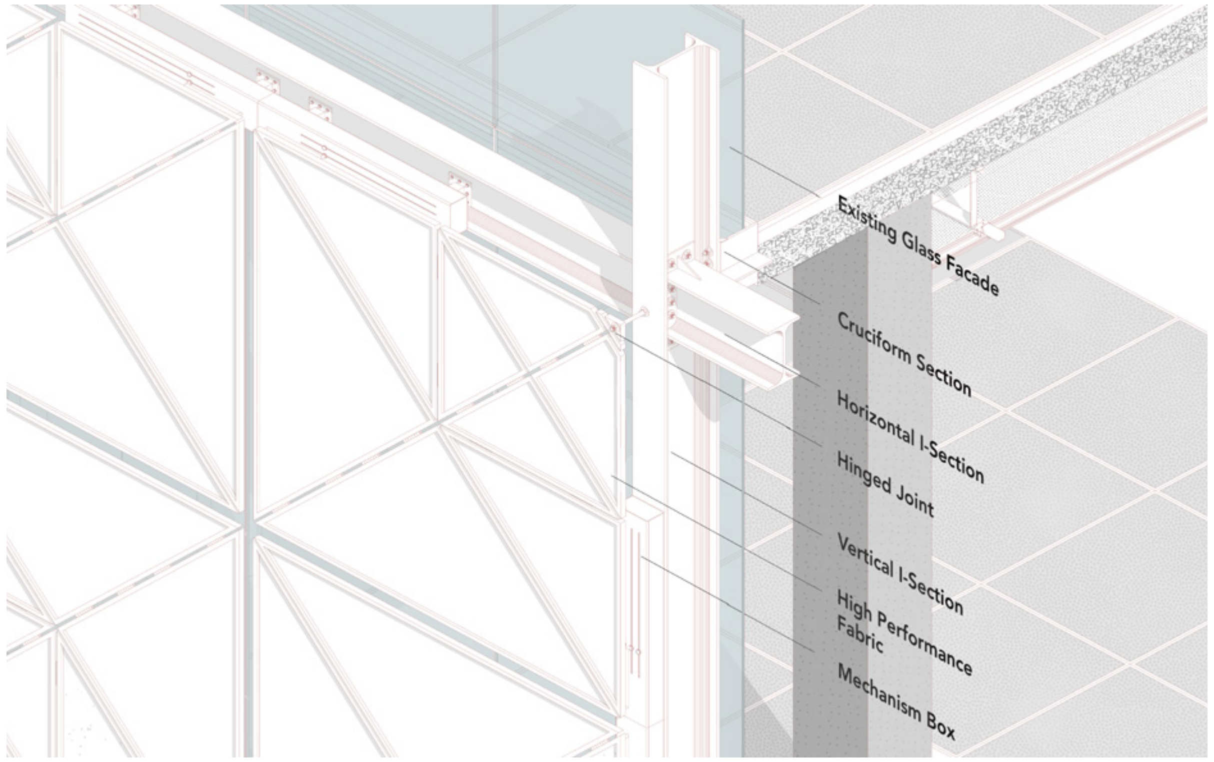


Detailed Axonometric

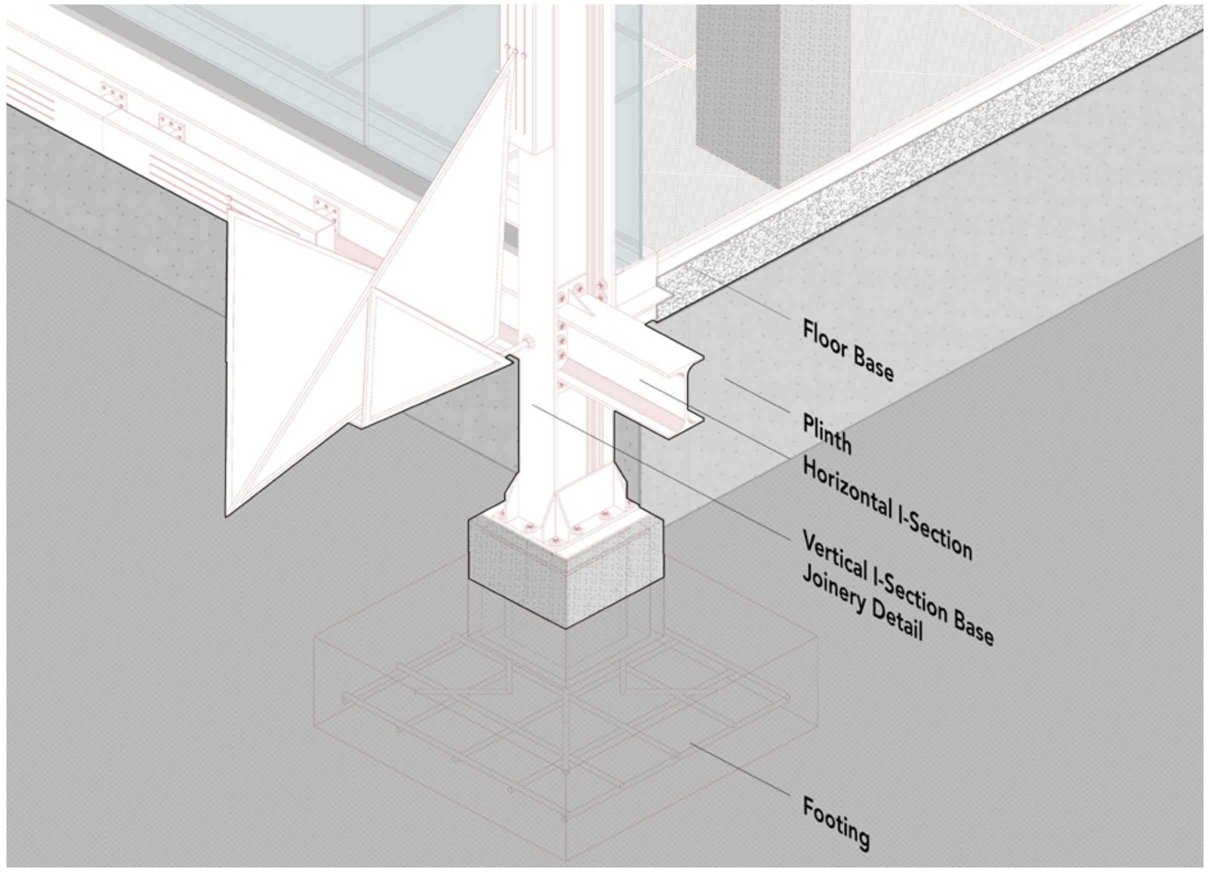
The axonometric view of a typical prototype shows the the three different positions of the panel on the facade, open, semi-open and close as per the sun angle. The diagram is only representaive of the possibilities, not the actual simultion specific working of the facade

Exploded Axonometric

The exploded axono shows the layers of the new shading device facade as a double skin to any existing glazed facade, as a retrofit on the building design. There in an internal structure mad eof I-Sections to support the shading device system installed on top of it.

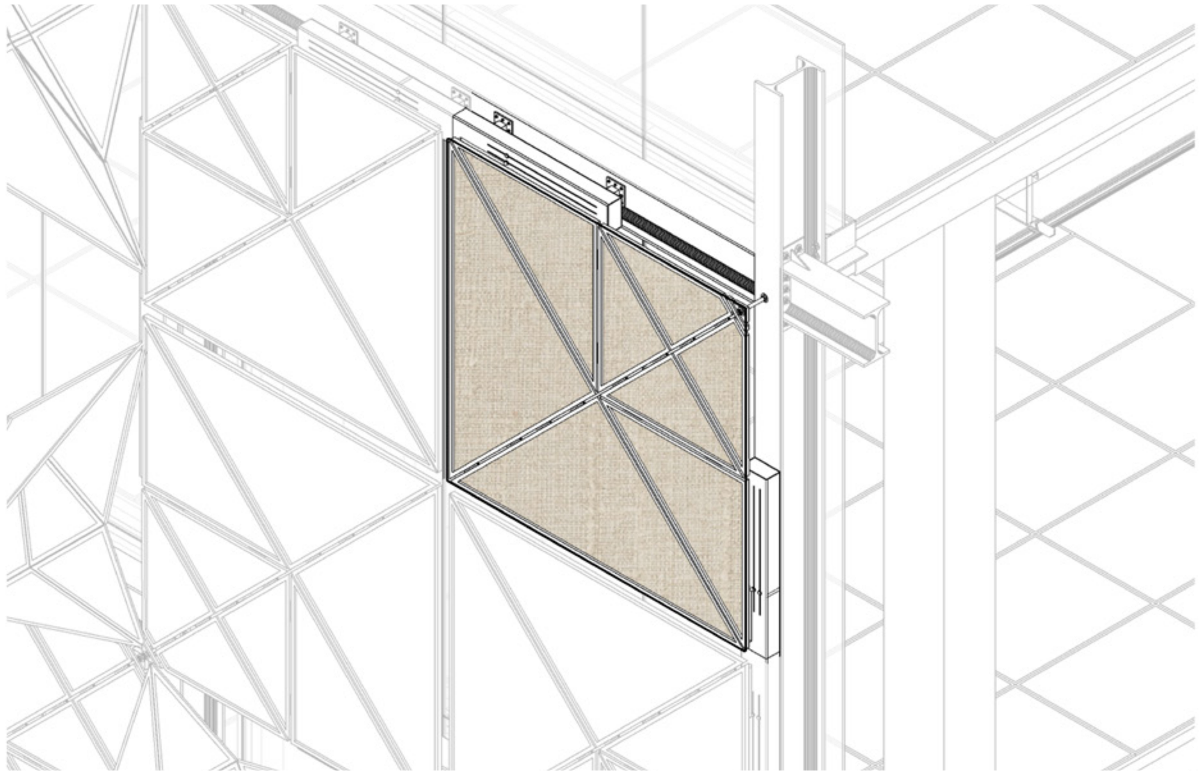


Panel to Facade Joinery Detail

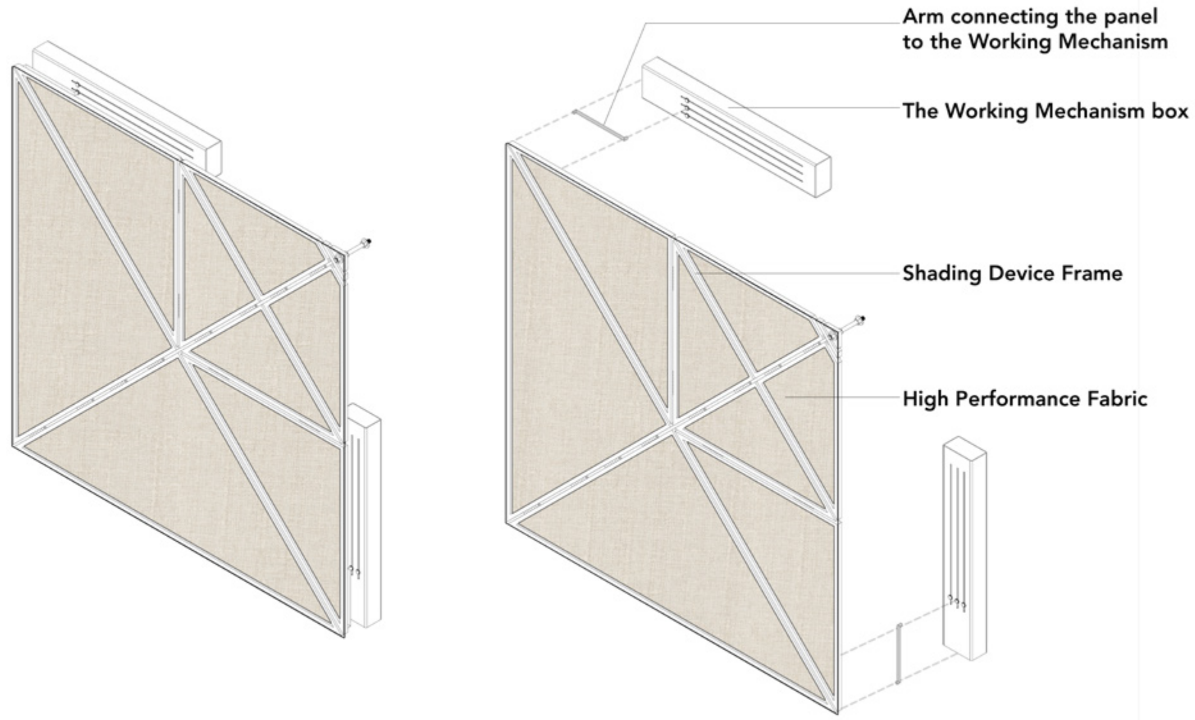


Facade to Ground Joinery Detail

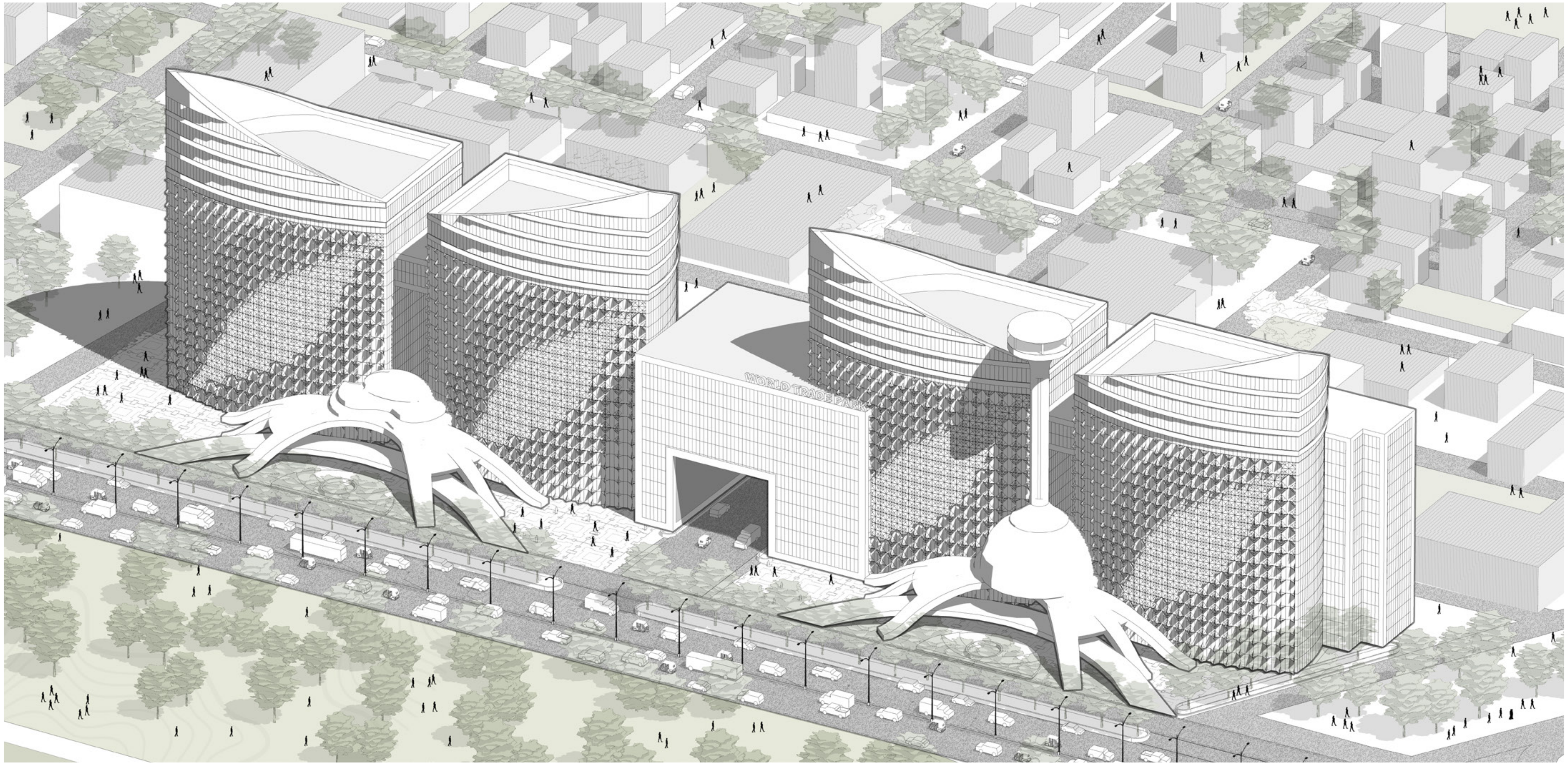
The detail shows the joinery of the existing facade to the new shading device system through cruciform section as shown in the exploded axonometric view before and to the ground through a shalow footing.



Single Panel System to Joinery Detail



This illustration on the top shows a single panel and how it is joimed to the I-Section structure on the back through a steel arm that transfers the actuation initiated by Nitinol to the shading device .The materiality of the high-performance fabric has tried to be shown through the texture addition on the panel.



Axonometric View of the facade with the shading device installed

The axonometric view of the World Trade Park shown above is the final output of the design installation of the shading device onto the facade. The shadow angles for the render is set for 2PM on 22nd May, which is a typical summer day in Jaipur. The facade shows three different opening positions of the shading device as per the solar radiation creating a dynamic look of the facade, also enhancing its beauty and solving the problem of glare and reflection caused to the users of the garden in front, overall increasing the urban design quality of the surrounding area and offering visual comfort to pedestrians with a better energy efficient building for the environment.

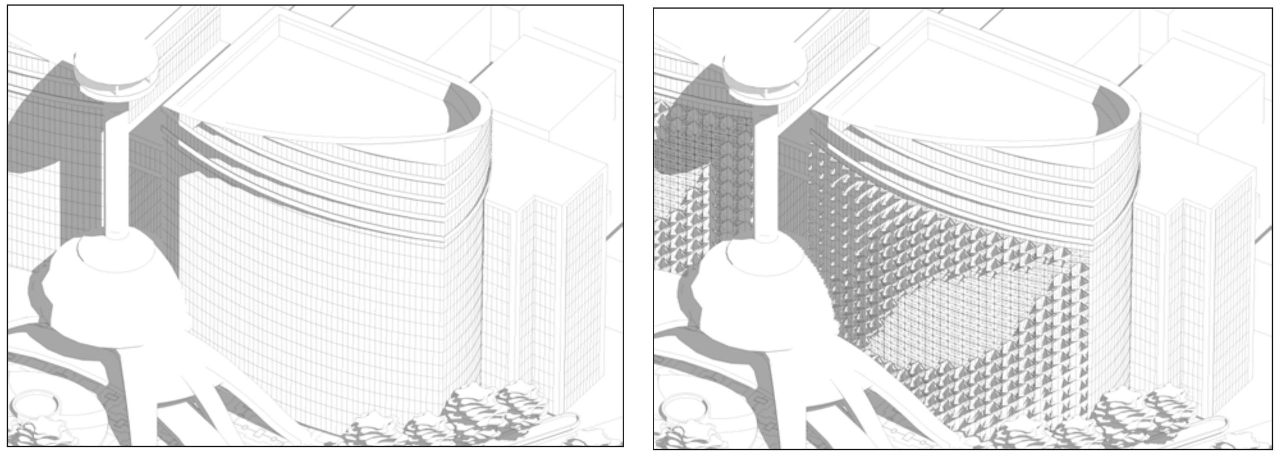
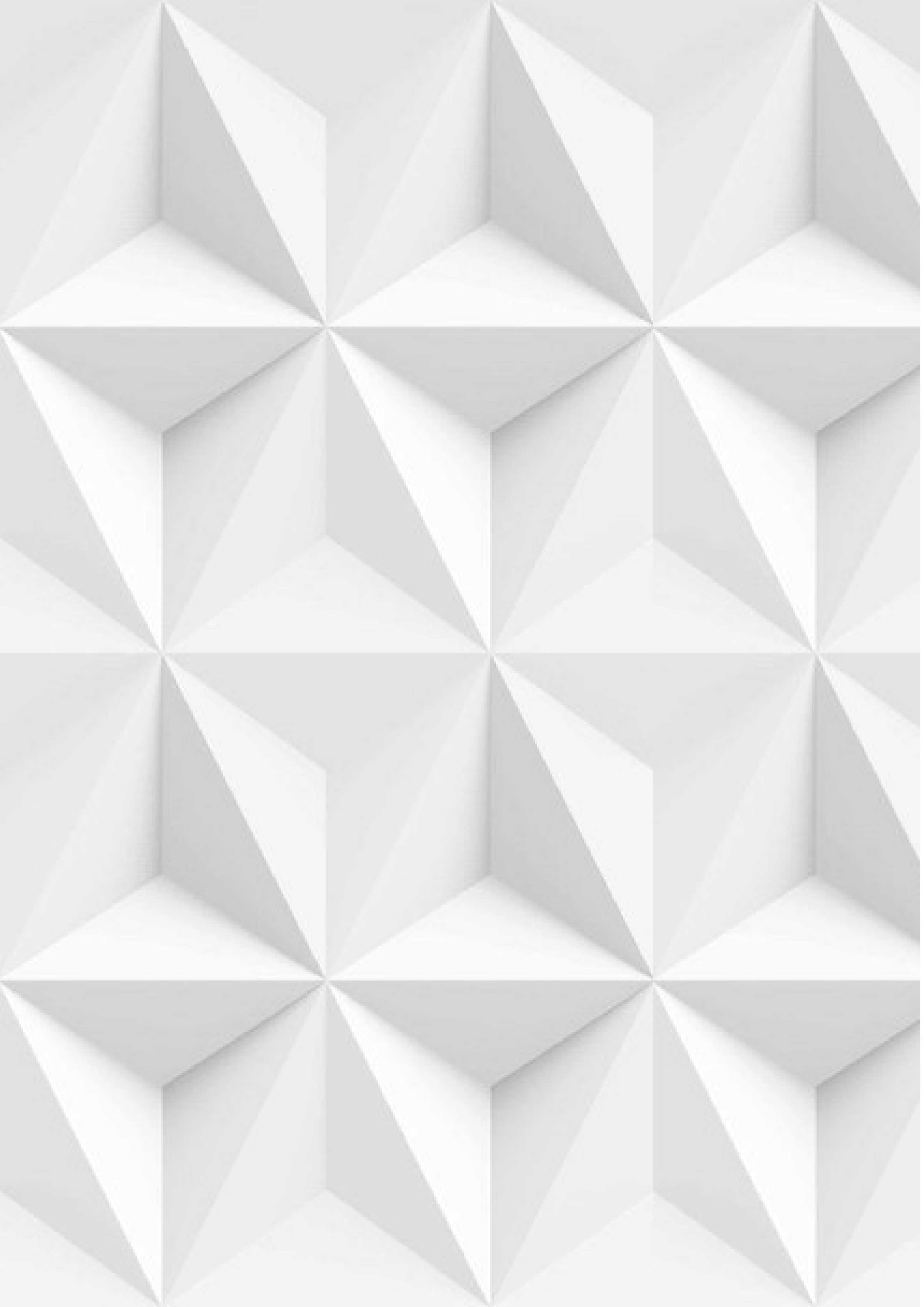


Fig Before (Left), After (Right)



CONCLUSION

From the research and simulation results of the World Trade Park Jaipur, our prototype case application, it can be concluded that, the possibility of having kinetic adaptive system for solar shading of building envelopes which was once heavily depended on mechanics and electrical, magnetic actuation, can be done increasingly passively with the help of smart materials. While this thesis, provided a conceptual prototype for the smart material, Nitinol, being used in actuation process, its real-life execution is subject to efficieny in facade engineering and specific material specifications to be executed with precision. With the ongoing research in companies like the Ingpuls Shading Systems and the Kellogs Research Lab, the market availability of such systems is increasing and becoming more feasible for real- life execution.

The proposed solution tries to decrease actuation time in passive kinetic envelopes by creating amplification mechanisms to increase the kinematic response within a shorter time frame. Additionally, in order to address the problem of cost, Nitinol is used in mechanisms than as a whole for its properties, in combination with the existing design strategies.

FUTURE SCOPE OF STUDY

The current thesis has tried to achieve the best shading of the building envelope to optimize the thermal transmission and glare reduction. An area for future work might considering this completely passive adaptive facade in real-life implementation of a building and can be integrated with solar energy producing skin, like flexibile solar panels or also Helioskin, which is a new tensile fabric, in the market, which works like High Performance Fabric. A future addition could be to do a multi-criteria optimization with all these parameters together.

Futher, the current design could be experiemented and designed with mechanical systems that offer improved efficiency of the existing design with even simpler machinery than the scissor arm to reduce the cost of the overall facade and decrease their actuation time and the difficulty in quickly recovering to their initial state. This may also be possible with the use of Bistable materials, but currently they are not entirely passive and responsive to climatic conditions, so a future research can be carried out in this direction.

Moreover, artificial intelligence and machine learning techniques could also be used to guide and control envelopes' dynamical environment-adapting process, ultimately making envelopes design more active and autonomous to sense the surrounding environmental changes for the most energy saving efficiency and residence comfort.

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Thank you!

ANNEXURE- A SIMULATION DATASHEET

Time Period of Simulation- Average data of the 4th Week of May, which is the Typical Summer Week in Jaipur, India

Thermal Transmission through the envelope			
Time	Only glass	High perf. Fabric	ACP Panels
1AM	-0.18443	-0.11984	-0.079245
2AM	-0.22193	-0.151091	-0.099063
3AM	-0.2307	-0.160013	-0.108867
4AM	-0.2422	-0.169973	-0.116851
5AM	-0.2895	-0.205551	-0.142514
6AM	-0.2227	-0.1824	-0.129689
7AM	0.350789	0.016105	0.117648
8AM	1.53176	0.370934	0.678955
9AM	1.812078	0.500246	0.858044
10AM	1.476126	0.443722	0.723841
11AM	1.012138	0.333836	0.523159
12PM	0.578348	0.220319	0.335327
1PM	0.231575	0.115561	0.177887
2PM	0.285883	0.136526	0.190257
3PM	0.276067	0.136957	0.192531
4PM	0.246028	0.116262	0.178621
5PM	0.188351	0.083222	0.150458
6PM	0.106996	0.037747	0.10344
7PM	-0.05431	-0.037099	0.019901
8PM	-0.16609	-0.083699	-0.047362
9PM	-0.19786	-0.111971	-0.073188
10PM	-0.23538	-0.149479	-0.099522
11PM	-0.22937	-0.150635	-0.102996
12AM	-0.18241	-0.119623	-0.085856

Inside Air Temperature			
Time	Only glass	High perf. Fabric	ACP Panels
1AM	32.67639	32.27743	32.51968
2AM	32.07709	31.73353	32.01681
3AM	31.50545	31.20659	31.52573
4AM	30.96096	30.70255	31.06659
5AM	30.39362	30.18967	30.6202
6AM	29.9941	29.8028	30.28883
7AM	30.37851	29.80692	30.3486
8AM	34.17734	32.26366	33.14881
9AM	36.97674	34.00518	35.13141
10AM	38.56333	35.23066	36.35427
11AM	39.38558	36.1698	37.23
12PM	39.71083	36.90359	37.80872
1PM	39.73055	37.42371	38.19276
2PM	39.95098	37.9079	38.56213
3PM	40.22493	38.36292	38.92554
4PM	40.44288	38.73051	39.22505
5PM	40.55379	38.97495	39.41426
6PM	40.43029	38.99615	39.39209
7PM	39.95817	38.73384	39.09198
8PM	38.38325	37.43344	37.74418
9PM	36.15255	35.43319	35.68892
10PM	34.6595	34.10358	34.35014
11PM	33.8085	33.30922	33.56488
12AM	33.2348	32.78369	33.02555