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Adaptive Building Envelopes: Shape-Changing Facades for Temperature Control

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***Abstract*—The building envelope is the boundary between the indoor and outdoor environment and largely decides how much solar heat, daylight and air enters a building. Conventional facades are fixed, whereas sunlight, temperature and wind change continuously through the day and the year. Adaptive building envelopes address this mismatch by changing their shape, position or properties in response to the environment. This paper presents a study of adaptive building envelopes with emphasis on shape-changing (kinetic) facades for temperature control. It explains the need for and concept of adaptive envelopes, classifies them, describes the common types of facade movement and the working principle, and reviews the smart materials used, namely bimetals, shape memory alloys and polymers, electroactive polymers, phase-change materials, and thermochromic and photochromic materials. The heat-transfer and airflow fundamentals behind facade performance are summarised with simple governing equations and illustrative plots. Two passive actuation strategies are then discussed in detail: bimetal-actuated louvers, which open under solar heating to promote natural ventilation, and a *Mimosa pudica*-inspired facade whose "cell-like hinge" uses liquid–vapour phase change to switch between solar-heating and radiative-cooling modes. The FlectoLine facade in Freiburg, Germany, is presented as a case study, and adaptive and conventional facades are compared. Advantages, applications, limitations, challenges and future scope are discussed.**

***Keywords*—Adaptive building envelope, bimetal, kinetic facade, Mimosa pudica, natural ventilation, passive cooling, phase-change, shape-changing facade, smart materials, thermal comfort.**

I. Introduction

A building envelope is the outer part of a building that separates the indoor environment from the outdoor environment. It includes the walls, roof, windows, shading devices and other elements of the facade, and it controls the amount of solar radiation, heat and air that enters the building. The envelope therefore has a direct influence on indoor temperature, daylight, glare, ventilation and the energy needed for heating, cooling and lighting. Buildings are among the largest consumers of energy in the world, and a large part of that energy is used to keep indoor conditions comfortable, so improving the behaviour of the envelope is one of the most effective ways of reducing energy demand and carbon emissions.

Outdoor conditions, however, do not stay constant. Sunlight and temperature change continuously through the day, and the sun's path, the air temperature and the wind pattern all change from season to season. Conventional facades are mostly fixed: their openings, shading and thermal properties are chosen once at the design stage and cannot be changed afterwards. A facade that is ideal for a hot afternoon is wasteful on a cool morning, and a facade that admits useful winter sun may overheat the building in summer. This is the basic limitation of a static envelope.

Adaptive building envelopes are building exteriors that can change their properties or shape in response to environmental conditions. Shape-changing or kinetic facades adjust elements such as louvers, flaps and panels to control solar heat gain, ventilation and indoor thermal comfort. The change can be produced by sensors and mechanical actuators or, more attractively, by smart materials that react directly to temperature or light. Recent research explores bimetal actuators and phase-changing mechanisms that move the facade with little or no external energy.

The objectives of this paper are: (i) to explain why adaptive envelopes are needed and what they are; (ii) to describe the types of facade movement, the working principle and the smart materials used; (iii) to explain the heat-transfer and airflow fundamentals on which their performance depends; (iv) to study bimetal-actuated and *Mimosa pudica*-inspired facades as examples of passive systems; (v) to present a real case study; and (vi) to compare adaptive facades with conventional ones and identify their limitations and future scope. The paper is based on the author's seminar study on the subject.

II. Evolution Of Responsive Facades

The idea that a building should respond to the weather is very old. Vernacular architecture in many regions developed elements that could be adjusted by the occupants: wooden shutters that are opened in the evening and closed at midday, louvered screens that cut the sun but pass the breeze, courtyards and wind catchers that draw air through a house, and removable awnings that are fixed in summer and taken down in winter. The carved timber lattice screens of hot-climate cities, known as mashrabiya, reduce glare and heat while allowing air movement and privacy, and they have inspired modern kinetic screens.

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In the twentieth century, mechanical shading devices such as Venetian blinds, roller blinds and motorised external louvers made it possible to control shading automatically with sensors and timers. Later, double-skin facades with a ventilated cavity and operable blinds were introduced, and they were followed by smart glazing whose transparency changes with an electrical signal or with temperature. In the present century, advances in computation, materials science and digital fabrication have led to kinetic facades in which large numbers of units move in coordinated patterns, and to material-driven systems in which the movement comes from the material itself.

This development can be seen as a progression from *manual* adaptation by occupants, to *mechanical* adaptation by motors and controllers, and to *material* adaptation, where the envelope senses and acts through its own physical properties. Each stage brings more automation and lower demand on the user, and the last promises also lower energy use and maintenance. The facades discussed in this paper belong mainly to the third stage.

III. Need For Adaptive Building Envelopes

Outdoor conditions keep changing throughout the day, especially sunlight and temperature, and a fixed facade cannot adjust itself to these changes. In the middle of the day, strong sunlight falling on glazing or on a thin metal skin can cause excess heat inside the building. This raises indoor temperature, makes occupants uncomfortable, and increases the need for air conditioning and therefore cooling energy. At other times, for example in the early morning, in the evening or in cooler seasons, the same building may need more natural ventilation and more solar heat rather than less.

Glazed buildings show this problem most clearly. Large glass areas bring daylight and views but also admit solar radiation directly, and modern glazed high-rise residential towers (Fig. 1) can therefore suffer from severe overheating when sunlight falls on them for many hours. Fixed shading helps in summer but cuts useful sun in winter; fixed openings supply the same ventilation whether it is needed or not. A facade that can respond to the situation – shading when the sun is strong, opening when air movement is useful, and admitting sun when warmth is needed – solves these conflicts directly.



Fig. 1. Examples of glazed high-rise residential buildings, in which large glass areas expose the interior to solar heat gain (from the author's seminar presentation).

Adaptive envelopes can therefore improve thermal comfort and energy efficiency together. The principal needs they address are summarised below.

- **Limiting unwanted solar heat gain** and glare during hot periods.
- **Admitting solar heat and daylight** when they are beneficial.
- **Enhancing natural ventilation** so that mechanical cooling is used less.
- **Reducing dependence on HVAC** systems and the associated energy use and carbon emission.
- **Improving comfort** by following the changing demands of the occupants through the day and the seasons.

IV. Concept Of Adaptive Building Envelopes

An adaptive building envelope is a building exterior that can respond to changing outdoor conditions. Unlike a conventional fixed facade, it can change its shape, position or properties when the environmental conditions change. The main environmental triggers are solar radiation, temperature, wind and other outdoor conditions such as humidity and rain. The response may be produced using sensors and mechanical actuators or by smart materials that respond automatically to temperature, light or other stimuli.

The concept can be understood as a chain, illustrated in Fig. 2. Changing outdoor conditions are first detected by sensors or by a sensitive material. The response mechanism – an actuator, or the material itself – then produces a facade change: opening or closing, rotating, bending or tilting.

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The facade change controls the amount of solar heat, daylight and airflow entering the building, and the result is an improved indoor environment with better comfort and lower energy use. The envelope may operate in different conditions to give heating, cooling, shading or ventilation as required, and the overall aim is to improve indoor thermal comfort and energy efficiency while reducing dependence on mechanical systems.

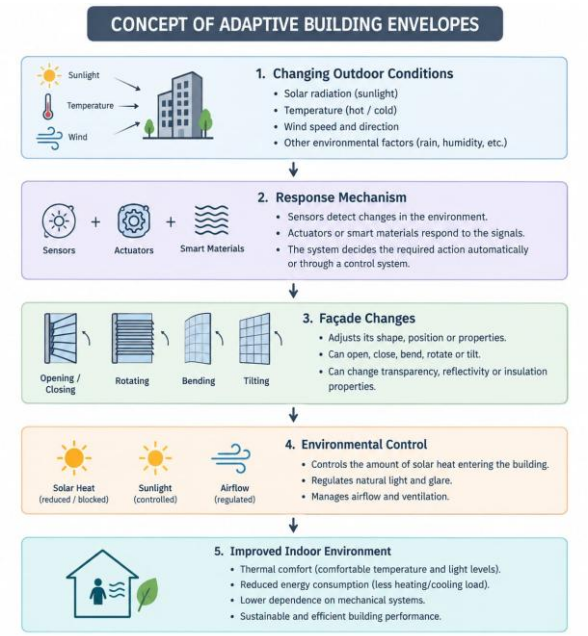


Fig. 2. Concept of adaptive building envelopes: changing outdoor conditions, response mechanism, facade change, environmental control and improved indoor environment (from the author's seminar presentation).

Terminology varies. Adaptive facade, dynamic facade, responsive envelope, climate-adaptive building shell, intelligent facade and kinetic facade are used with slightly different emphasis, but all refer to building envelopes whose behaviour is not fixed. In this paper "adaptive envelope" is used for the general idea and "kinetic" or "shape-changing" facade for those adaptive envelopes that act by physical movement.

V. Climate-Responsive Design Strategies

An adaptive facade should be chosen according to the climate in which it works, because the same movement is useful in one climate and harmful in another. Table I lists the main climate types, the dominant problem and the adaptive strategies that are usually appropriate.

TABLE I
Climate Types and Suitable Adaptive Strategies

Climate	Main problem	Adaptive strategies
Hot–dry	Intense sun, large day–night swing	Shading in the day, ventilation or radiative cooling at night, thermal mass
Warm–humid	Heat and humidity, little night cooling	Strong shading, cross and stack ventilation, light and open construction
Composite	Hot summer, cool winter, monsoon	Seasonal switching between shading and solar gain, ventilation control
Temperate	Moderate swings, cold winters	Admit winter sun, shade summer sun, insulation control
Cold	Heat loss, low sun	Solar heating, insulation, minimise openings

In hot climates the first priority is to keep solar radiation off the building envelope and glazing; in warm–humid climates, where temperatures remain high at night and air movement is the main means of relief, ventilation is equally important and the facade should open to the breeze while still shading. In climates with both hot and cold seasons, a fixed facade is a compromise, and it is here that seasonal adaptation has the greatest benefit. The sun's altitude explains why: as shown in Fig. 3, an overhang or louver at a fixed angle shades a window in summer when the sun is high but lets the low winter sun enter, and a facade that can change its angle can improve on this compromise throughout the year.

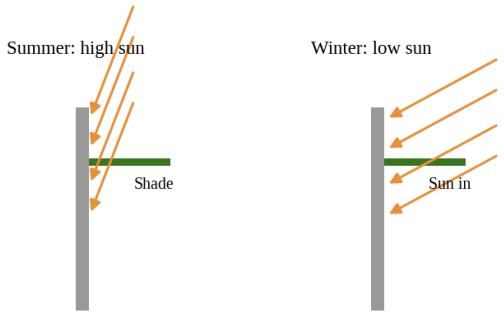


Fig. 3. Effect of sun altitude on a fixed horizontal shading device: summer sun is blocked, winter sun enters.

Orientation also matters. In the northern hemisphere, south-facing facades see high midday sun and are easily shaded by horizontal elements, whereas east- and west-facing facades receive low-angle sun in the morning and evening, which is difficult to shade with horizontal devices and is where movable vertical or inclined louvers are most useful. An adaptive system is therefore best designed separately for each orientation of the building.

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VI. Classification of Adaptive Envelopes

Adaptive envelopes can be classified in several ways (Fig. 4). The most useful distinction for the present study is the way in which the change is produced.

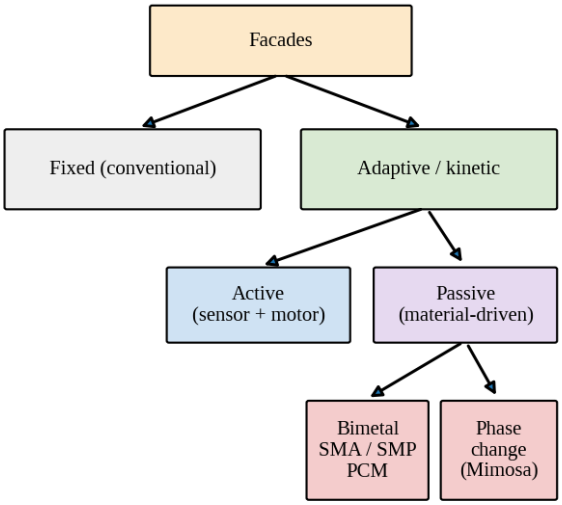


Fig. 4. Simple classification of facades: fixed versus adaptive, and active versus passive adaptive systems.

A. Active (Responsive) Systems

Active or responsive systems use sensors to measure conditions such as solar radiation, temperature, wind speed or occupancy, a controller to decide what the facade should do, and an actuator (for example an electric motor or pneumatic device) to carry out the movement. They give precise and programmable control and can accept input from occupants.

Their disadvantages are cost, complexity, electrical consumption, the need for regular maintenance and the possibility of failure of sensors, wiring or moving parts.

B. Passive (Material-Driven) Systems

In passive systems the sensing and actuation are built into the material or the geometry. Bimetals bend when heated, shape memory alloys recover a stored shape at a certain temperature, phase-change systems expand when a liquid evaporates, and hygroscopic materials swell with humidity. No sensor, controller or external power is needed for the movement, and this makes the facade simple, quiet and potentially long-lasting. The disadvantages are that the response depends on the material properties and local weather, that it cannot be programmed or overridden easily, and that response is not instantaneous.

C. Other Classifications

By transparency, adaptive facades may be transparent (smart glazing), translucent or opaque. By function they may be shading, ventilation, heating/cooling or daylighting systems. By movement they may open, rotate, fold or bend. By material they may use bimetals, shape memory materials, phase-change materials, chromogenic materials or hygroscopic materials. Many practical systems combine more than one of these categories.

VII. Shape-Changing / Kinetic Facades

Kinetic facades are building facades that can move or change their configuration in response to environmental conditions. Their elements – louvers, flaps, panels, fins or membranes – can change position or form so as to change the way the facade handles sunlight, heat and air. Four common types of movement are illustrated in Fig. 5.

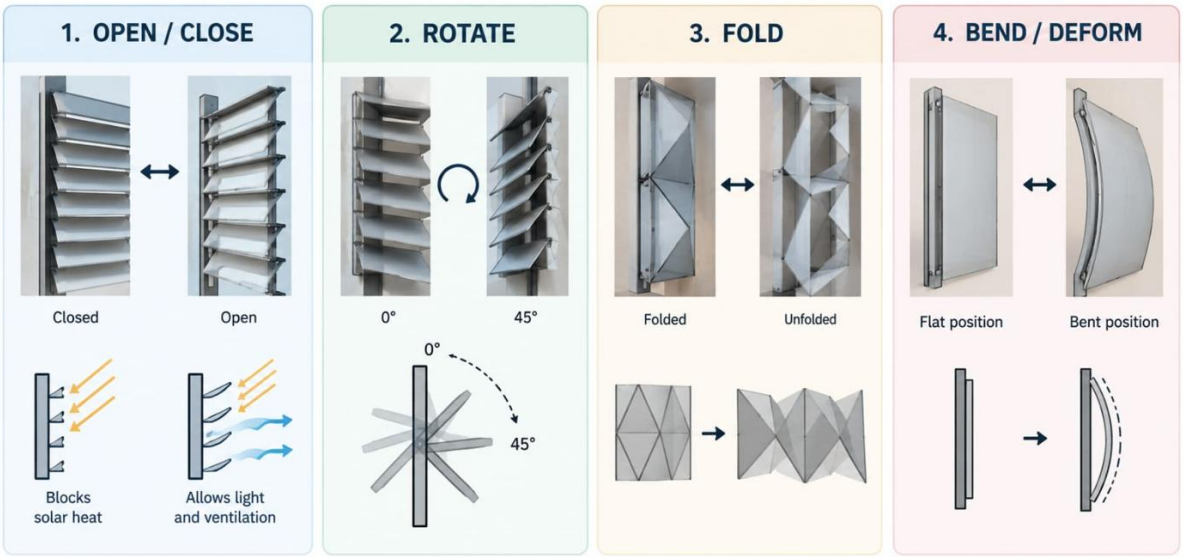


Fig. 5. Types of movement in a facade: opening/closing, rotating, folding and bending/deforming (from the author's seminar presentation).

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- *Opening/closing:* facade panels or louvers open and close to control sunlight and airflow. When closed they block solar heat; when open they allow light and ventilation.
- *Rotating:* louvers rotate about an axis to change their shading angle, so that the same louver can block high summer sun and admit low winter sun.
- *Folding:* panels fold or unfold to change the facade configuration, in the manner of origami or an accordion.
- *Bending/deforming:* flexible elements bend when activated by heat or another stimulus, changing from a flat to a curved position.

The purposes of kinetic movement are to control *solar heat gain*, by reducing the unwanted heat that enters the building; *airflow*, by helping natural ventilation; and *sunlight*, by controlling the amount of daylight and solar radiation. A kinetic facade has the further advantage of visual dynamism: its changing appearance makes the building express its response to the climate.

A. Rigid-Body and Compliant Mechanisms

Traditional kinetic facades use rigid-body mechanisms – hinges, pivots, links, tracks and motors. Well-known examples are the mashrabiya-inspired screens of the Al Bahar Towers in Abu Dhabi, whose many shading units open and close with the sun. Such systems work well, but they contain many parts that wear, need lubrication and can fail.

Compliant mechanisms, in contrast, obtain motion by elastic deformation of flexible members and do not need conventional hinges, so they have fewer parts and less maintenance. Hinge-free bending flaps, bimetal strips and flexible composite fins are examples. The shift from rigid assemblies to deformable, material-driven elements is a major direction in current research.

VIII. Working Principle

An adaptive facade responds to changing solar radiation, temperature and wind. These environmental changes activate sensors and actuators, or smart materials, and the resulting mechanism makes facade elements such as louvers, panels and flaps open, close, rotate, fold or bend. In hot or high-solar conditions, the facade reduces solar heat gain and/or increases natural ventilation. In cooler conditions it changes back so that heat transfer is modified to maintain indoor comfort.

In passive systems, bimetals respond directly to temperature. Solar heating causes differential expansion of the two bonded metals, which makes the bimetal bend and move the facade element. This movement changes the opening area and the airflow path, regulating ventilation and indoor air circulation. The working sequence can be represented as:

Environmental change → Material/actuator response → Facade movement → Heat and airflow regulation → Improved thermal comfort.

Figure 6 shows a typical arrangement of this kind: operable flaps are formed in the facade, each carrying an actuator material, and in the open state an opening appears through which outside air enters the cavity behind the facade.

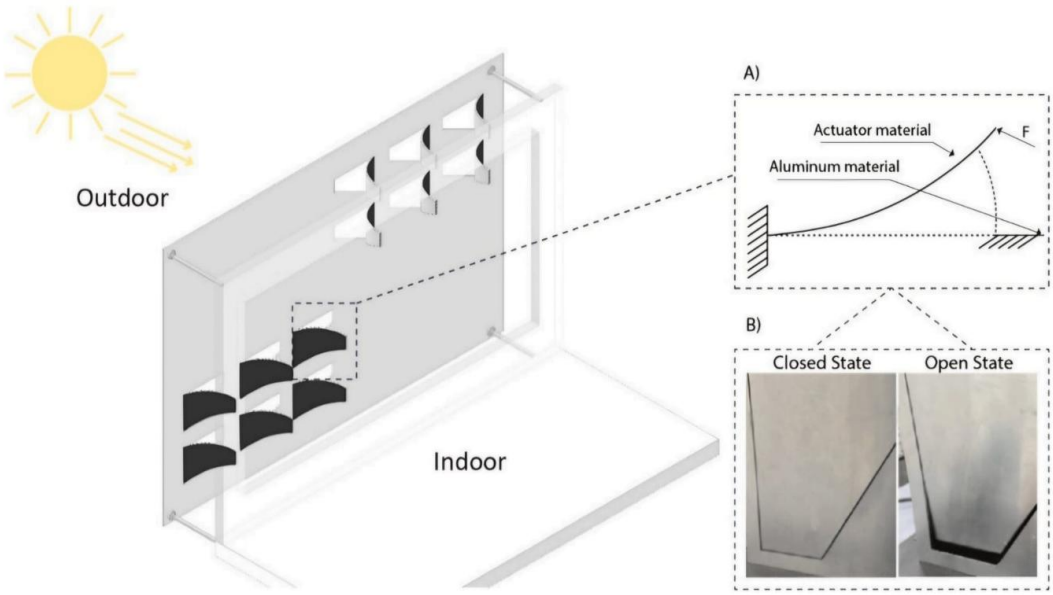


Fig. 6. Working of an adaptive facade: operable flaps with an actuator material on an aluminium skin, shown in closed and open states (from the author's seminar presentation).

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Because the process is continuous, the facade does not simply switch between two states. A bimetal flap, for instance, opens by a small amount when the sun first reaches it and by a larger amount as its temperature rises further, so the opening grows with the demand. When the sun goes in or sets, the flap cools and moves back towards its original closed position. This graded, self-regulating behaviour is one of the strengths of material-driven facades.

IX. Fundamentals Of Heat And Airflow Regulation

To understand how adaptive facades improve comfort it is useful to recall the basic mechanisms by which a facade exchanges heat and air with its surroundings. Only simple, widely used relations are given here; they are illustrative and are not intended as design formulas.

A. Conduction and Solar Gain

Heat flows through opaque and glazed parts of the envelope by conduction according to

$$Q = U A (T_out - T_in) \qquad (1)$$

where U is the thermal transmittance (W/m²K), A is the area and T_out, T_in are the outdoor and indoor temperatures. Solar radiation transmitted through glazing adds

$$Q_sol = SHGC \cdot A \cdot I \qquad (2)$$

where SHGC is the solar heat gain coefficient and I is the incident solar irradiance. A fixed facade has a fixed SHGC; an adaptive facade effectively changes it by changing the shading. Fig. 7 gives an illustrative comparison: the fixed facade passes a constant fraction of the incident radiation, so its heat gain peaks at midday with the sun, whereas the adaptive facade reduces its gain when the irradiance exceeds a threshold, flattening the peak that drives cooling load.

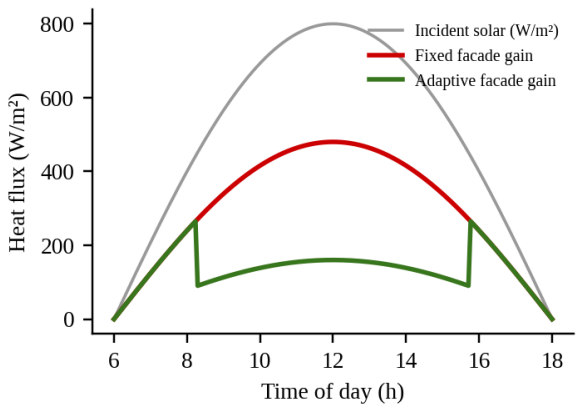


Fig. 7. Illustrative daily profile of incident radiation and solar heat gain through a fixed facade and an adaptive facade (simple model with assumed values).

B. Natural Ventilation

Natural ventilation is driven by wind pressure and by buoyancy (the stack effect). For a pair of openings separated by a height H, with an indoor–outdoor temperature difference ΔT, the buoyancy-driven flow is approximately

$$Q = C_d\, A \sqrt{(2\, g\, H\, \Delta T / T)} \qquad (3)$$

where C_d is a discharge coefficient (about 0.6 for sharp-edged openings), A is the opening area, g is gravity and T is the absolute temperature. The flow therefore increases with the opening area, the height and the temperature difference (Fig. 8). A solar-heated facade cavity increases the temperature difference and so strengthens the chimney effect, and a flap that opens as the facade warms up automatically supplies the larger area when it is needed.

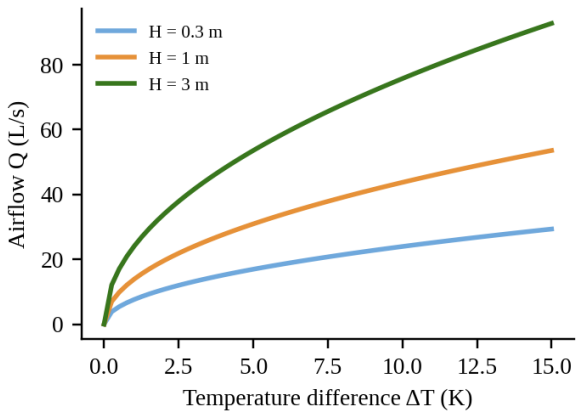


Fig. 8. Illustrative buoyancy-driven airflow through a 0.09 m² opening for different heights between openings (C_d = 0.6).

C. Radiative Exchange

Every surface exchanges thermal radiation with its surroundings. The net radiative loss of a surface of emissivity ε at temperature T facing a sky of effective temperature T_sky is

$$P_rad = \varepsilon\, \sigma\, (T^4 - T_sky^4) \qquad (4)$$

with $\sigma = 5.67 \times 10^{-8}$ W/m²K⁴ (Fig. 9). A clear night sky is much colder than the air, so a surface with high emissivity in the infrared window of the atmosphere (about 8–13 μm) can lose heat to it. This is the principle of radiative cooling. At the same time, a dark surface with high solar absorptivity gains heat strongly from the sun. A facade that can expose either kind of surface on demand can therefore switch between solar heating and radiative cooling – the idea used in the Mimosa-inspired facade described later.

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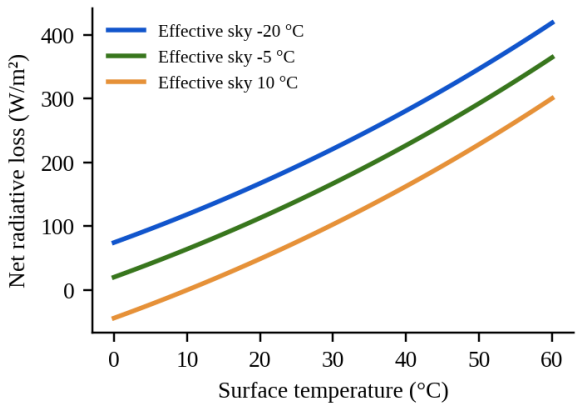


Fig. 9. Illustrative net radiative loss of a surface with emissivity 0.9 for different effective sky temperatures.

X. Smart Materials Used

Smart materials are materials that can change their shape, properties or behaviour when environmental conditions change. They can respond to temperature, sunlight, electricity, moisture or mechanical forces. In adaptive building envelopes, smart materials help the facade move automatically without complex mechanical systems, and they can be used for shading, ventilation, thermal control and energy saving. The common smart materials, their triggers and their facade functions are listed in Table II.

TABLE II
Common Smart Materials Used

Smart material	Trigger	Facade function
Bimetals	Temperature	Bend and move louvers
Shape memory alloys (SMA)	Heat	Return to original shape and operate panels
Shape memory polymers (SMP)	Heat	Change shape for facade movement
Electroactive polymers (EAP)	Electricity	Produce movement in facade components
Phase-change materials (PCM)	Temperature	Store and release thermal energy
Thermochromic materials	Heat	Change colour/transparency to control sunlight
Photochromic materials	Light	Adjust transparency based on sunlight

A. Bimetals

A bimetal is a laminate of two metals with different coefficients of thermal expansion. On heating it bends, and on cooling it returns. It is robust, inexpensive, works for many thousands of cycles and needs no power, but the movement it gives is small, and it is therefore used in a geometry that amplifies it.

B. Shape Memory Alloys and Polymers

Shape memory alloys, for example nickel–titanium, can be deformed at low temperature and recover a remembered shape when heated through a transformation temperature, producing a force and a large movement. They are also superelastic. Shape memory polymers behave similarly but are softer and cheaper, and they can be formed into many shapes. Limitations include the high cost of alloys, the need to confirm long-term cyclic behaviour in outdoor use, and the fact that polymers may need re-programming and are affected by ultraviolet light.

C. Electroactive Polymers

Electroactive polymers change shape under an electric field. They give fast and precise movement and low weight, but they require a power supply and control electronics, so they are active rather than passive and are mainly at a research stage for facades.

D. Phase-Change Materials

Phase-change materials store and release a large amount of heat at a nearly constant temperature as they melt and solidify, which smooths temperature swings in walls and roofs. A different use of phase change is as an actuator: when a liquid evaporates its volume increases enormously and the expansion can be used to move an element, which is the principle of the Mimosa-inspired hinge. Issues with PCMs include cost, leakage, flammability and long-term stability.

E. Thermochromic and Photochromic Materials

Thermochromic materials change colour or transparency with temperature, and photochromic materials do so with light intensity. They can reduce solar gain at high temperature or high light level and admit it otherwise, and they are applied as coatings or in glazing. Their drawbacks are colour degradation under prolonged sunlight, limited range of change and cost.

XI. Thermal Regulation Mechanisms

A. Bimetal-Based Thermal Regulation

A bimetal consists of two different metals with different rates of thermal expansion. When the temperature rises, the unequal expansion causes the bimetal to bend or curve. This movement can operate louvers, flaps or panels and so change the facade opening. Opening the facade increases airflow and natural ventilation. When the temperature falls, the bimetal changes shape back and the facade returns towards its original position. Thus temperature-responsive movement occurs without a conventional motor-driven system.

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B. Phase-Change-Based Thermal Regulation

Phase-change systems use materials that change between solid, liquid or vapour states with temperature. In the Mimosa-inspired facade, a cell-like hinge uses liquid–vapour phase change to produce reversible movement, and the movement changes the facade configuration according to thermal conditions. It enables solar heating and radiative cooling modes: in heating conditions the facade helps to capture solar heat, and in cooling conditions it supports radiative heat release. The reversible movement allows the facade to switch between the two thermal modes as conditions change.

XII. Bimetal-Actuated Facades

Bimetal-actuated facades use two different metals joined together, having different coefficients of thermal expansion.

Temperature changes cause unequal expansion or contraction, producing bending or curvature, and this movement is transferred to louvers, flaps or panels. Under high solar heating the bimetal bends and opens the facade, creating an airflow path and improving natural ventilation. As the temperature decreases it moves back, allowing the facade to return towards its closed position. The system gives automatic, temperature-responsive movement without continuous external electrical power, and the movement can be controlled by changing the metal thickness, the material combination and the bimetal configuration. It thus combines thermal response, controlled movement and natural ventilation in one facade system.

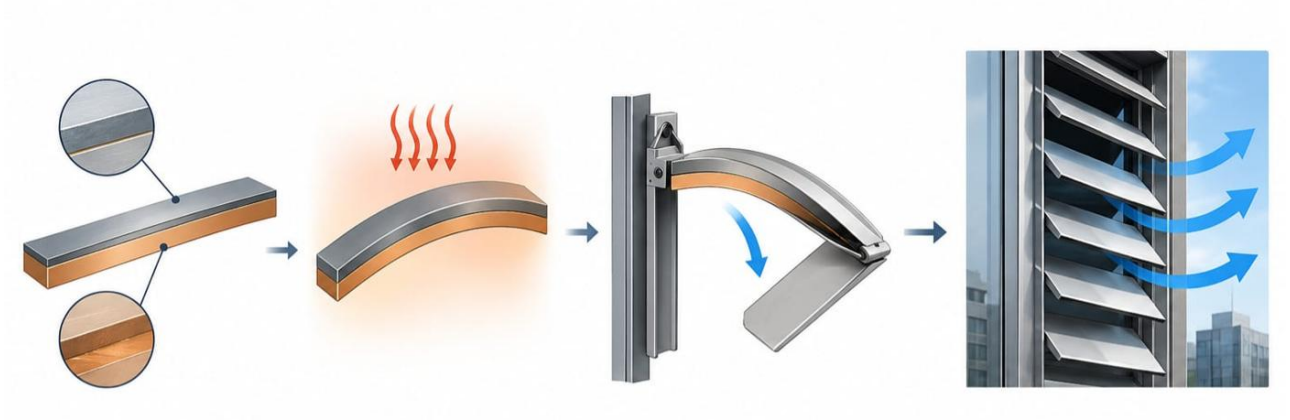


Fig. 10. Operating sequence of a bimetal-actuated facade: bimetal strip, heating and bending, louver movement and increased airflow (from the author's seminar presentation).

A. Bending of a Bimetal

When two strips of equal length but different expansion coefficients are bonded and heated, the strip with the larger coefficient tends to elongate more.

Because they are bonded, the higher-expansion strip is put in compression and the lower-expansion strip in tension, and the resulting moment bends the pair into an arc, as shown in Fig. 11. Placing the higher-expansion metal on the outer side of the bend gives the most effective bending.

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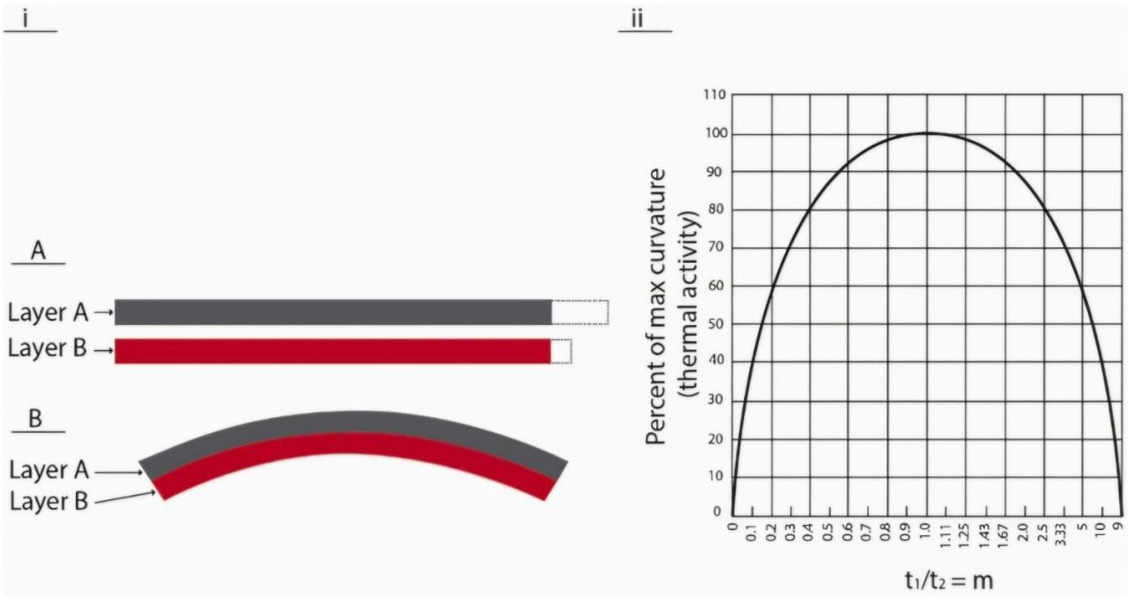


Fig. 11. Thermo-bimetal behaviour: two bonded layers bend on heating (left); the curvature depends on the ratio of layer thicknesses (right) (from the author's seminar presentation).

For two layers of equal elastic modulus and equal thickness t (total thickness h = 2t), the classical result for the curvature κ of a bimetal strip heated by ΔT is

$$\kappa = 3\,(\alpha_2 - \alpha_1)\,\Delta T / (2\,h) \qquad (5)$$

Where α_1 and α_2 are the expansion coefficients. Curvature is therefore directly proportional to the difference in coefficients and to the temperature change, and inversely proportional to the total thickness – a thin strip bends much more than a thick one for the same temperature rise. The thickness ratio t_1/t_2 also matters: when the moduli are equal the curvature is greatest at a ratio of one and falls off on either side, as shown in Fig. 12. If the moduli differ, the optimum ratio moves accordingly. These relationships give the designer three levers – material pair, thickness and thickness ratio – to tune the response.

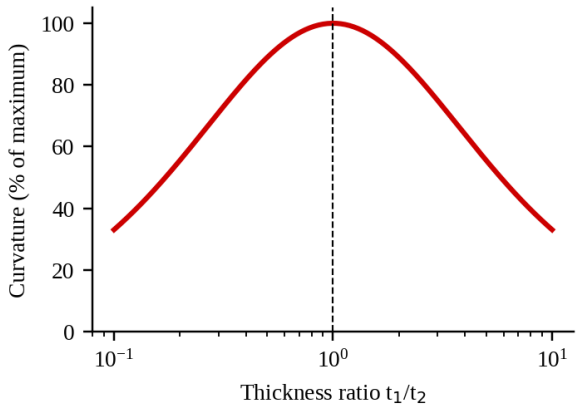


Fig. 12. Relative curvature of a bimetal strip versus thickness ratio for layers of equal elastic modulus (classical beam theory).

B. Integration with a Facade Flap

In a facade flap the bimetal is bonded to a thin metal sheet such as aluminium (Fig. 13). The flap is fixed along one edge and free along the others, so it behaves like a cantilever. When the bimetal bends it exerts a force F and moment on the flap, which bends away from the frame and opens a gap. Aluminium is a suitable base because it is light, formable, corrosion-resistant and widely available. The flap must be thin enough to bend under the actuator force but stiff enough to resist wind, so its thickness is an important parameter. The bond between the bimetal and the flap, commonly an epoxy adhesive, must transfer shear while remaining flexible enough for repeated bending.

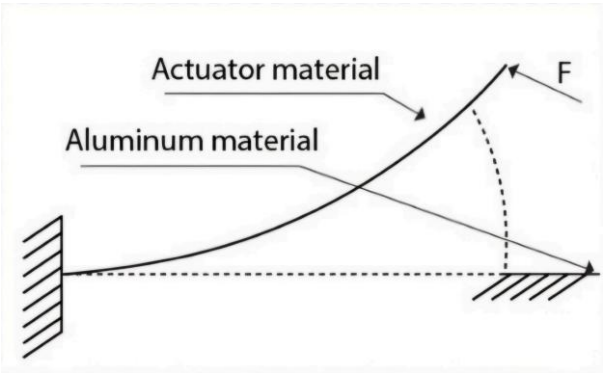


Fig. 13. Actuator material integrated with an aluminium plate acting as a cantilever flap, with force F at the free end (from the author's seminar presentation).

C. Design Parameters

The opening achieved by a bimetal flap depends on the following parameters, which can all be varied by the designer:

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- *Bimetal coverage:* the fraction of the flap area carrying bimetal. Greater coverage gives a greater actuating force and larger displacement but costs more.
- *Number of bimetal layers:* a double layer gives a larger force than a single layer.
- *Base plate thickness:* a thinner plate deflects more easily; a thicker plate is stiffer and safer in wind.
- *Surface absorptivity:* a dark or selective coating of high solar absorptivity heats the bimetal faster in sunlight.
- *Climate:* the solar radiation and air temperature at the site decide how high the surface temperature rises and hence how far the flap opens.

D. Performance and Limits

An open flap allows outside air into the cavity behind the facade and, if connected to the room, into the space. Because the opening increases as the surface warms, the airflow is greatest when the heat load is greatest.

The movement of a bimetal is small, typically millimetres in a module of a few tenths of a metre, so the opening must be designed with this in mind, and the performance in a given climate must be checked. The system works only when the sun is on the facade, so it gives no ventilation at night or on overcast days unless other measures are added. It is nevertheless one of the simplest, cheapest and most reliable passive systems, and it is suitable for retrofitting in front of existing windows.

XIII. Mimosa Pudica-Inspired Facades

Mimosa pudica, known as the "touch-me-not" plant, folds its leaves when touched or exposed to certain stimuli and slowly unfolds them again afterwards. The folding is produced by changes in water pressure (turgor) in specialised cells at the base of the leaves: the cells on one side lose water and shrink while those on the other side stay swollen, so the leaf bends. The motion is reversible and needs no external energy supply. A facade inspired by this behaviour reproduces the folding and unfolding of the leaf using a reversible, phase-change-driven mechanism (Fig. 14).

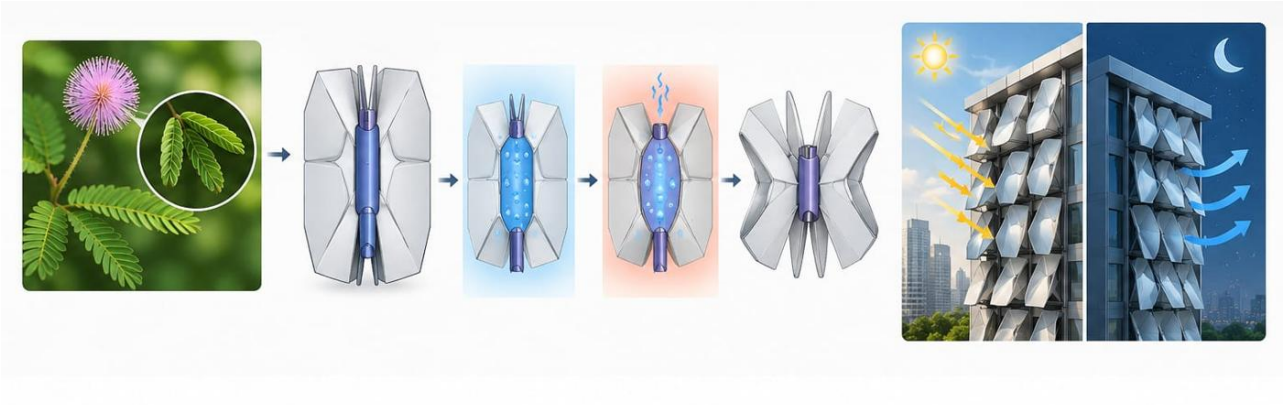


Fig. 14. Mimosa-inspired facade: the plant leaf folds and unfolds, and the facade units change from open to folded configuration to give a da ytime and night-time mode (from the author's seminar presentation).

A. The Cell-Like Hinge

The main component responsible for movement is a *cell-like hinge*. It is a flexible cell, typically made from an elastomer such as silicone, containing a sealed low-boiling-point liquid. When exposed to solar radiation the hinge absorbs heat, and the temperature rise causes the liquid inside to change to vapour. This phase change produces a large volume expansion and internal stress in the hinge, which deforms and moves the facade. When the thermal condition changes – the sun goes in or the day ends – the vapour condenses, the phase change reverses and the facade returns towards its original configuration. The cells play the part of the swelling cells of the plant.

The reason a phase change is so effective as an actuator is that the vapour of a liquid occupies hundreds of times the volume of the liquid, and the vapour pressure rises steeply with temperature.

Fig. 15 shows the vapour pressure curves for two liquids of the kind that could be used, acetone and ethanol, calculated from the Clausius–Clapeyron relation

$$P = P_0 \exp[-(\Delta H_{vap} / R)(1/T - 1/T_b)] \qquad (6)$$

Where P_0 is atmospheric pressure, T_b the normal boiling point, ΔH_{vap} the molar enthalpy of vaporisation and R the gas constant. Acetone boils at 56.5 °C and ethanol at 78.3 °C, so at any temperature acetone has the higher vapour pressure and a cell filled with it begins to swell at a lower temperature and responds faster. The choice of liquid thus sets the working temperature of the facade, which is a clear advantage of the method: the response temperature can be tuned simply by selecting the liquid.

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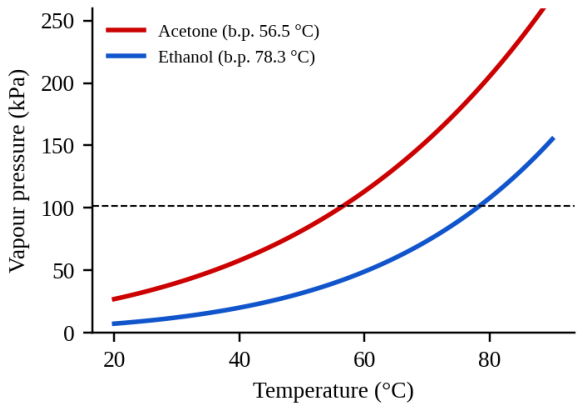


Fig. 15. Vapour pressure of acetone and ethanol versus temperature from the Clausius–Clapeyron relation (illustrative; dashed line is atmospheric pressure).

The response of a hinge also depends on how much sunlight it absorbs. A dark hinge absorbs more radiation and heats up faster than a light one, so the rate of response can be adjusted by the shade or "grayscale" of the hinge material. This gives a second means of tuning the facade, besides the choice of liquid.

B. Heating and Cooling Modes

The reversible movement allows the facade to operate in two different thermal modes. In **heating mode**, the facade configuration promotes solar heat absorption during cold conditions: a dark, heat-absorbing layer is exposed to the sun. In **cooling mode**, the facade changes configuration to support radiative cooling during hot conditions: a highly reflective, infrared-emitting layer is exposed to the sky and rejects heat. The facade therefore has layers with opposite thermal functions, and the hinge movement decides which one faces outwards (Fig. 16).

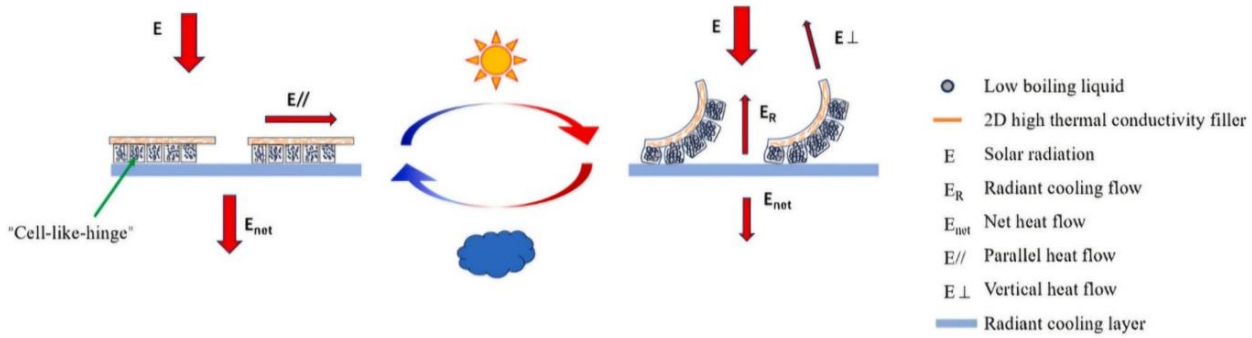


Fig. 16. Principle of the Mimosa-inspired reversible facade: in one state the cell-like hinges are flat and heat flows in-plane; in the other the hinges bend and the cooling layer is exposed, with solar radiation, radiative cooling flow and net heat flow indicated (from the author's seminar presentation).

The system combines *anisotropic thermal conductivity* with radiation-regulating surface layers to direct and control heat transfer. An anisotropic layer conducts heat better in one direction than in another – for example, much better along the plane of the layer than through its thickness. With a layer like this on the outside, heat absorbed from the sun is spread sideways along the surface, which evens out hot spots from uneven sunlight, rather than being driven straight into the building. When the facade moves, the direction of the high-conductivity path changes with respect to the wall, so that heat is led away from the building instead of into it. The radiation-regulating layers set how much solar energy is absorbed and how much infrared is emitted.

C. Advantages and Limits

The principal advantage of the concept is that the facade can adapt automatically to changing thermal conditions without external energy for the switching mechanism, and it addresses both winter heating and summer cooling in one construction, which is rare.

Compared with systems based on shape memory materials it can have a wide, tunable working temperature.

The limitations are those of a new technology: the long-term sealing of the liquid in the elastomer under ultraviolet light and repeated cycling, safety of volatile liquids, response time of minutes rather than seconds, performance in the presence of dust, snow and ageing, and the difficulty of scaling from small units to a building facade.

XIV. Control Strategies for Adaptive Facades

Whether a facade is active or passive, its behaviour is governed by some form of control. In passive systems the control law is built into the material: a bimetal flap opens roughly in proportion to its temperature rise, and a phase-change hinge begins to bend when the liquid reaches its boiling region. The designer chooses this law through the material, geometry and surface properties, and cannot easily change it afterwards.

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In active systems the control is implemented in software. The simplest strategy is rule-based: for example, close the louvers when the measured irradiance exceeds a set value and open them when it falls, or open the vents when the outdoor temperature is lower than the indoor temperature. More advanced strategies use prediction of weather and occupancy to decide in advance, and learning-based controllers adjust their rules from data. Occupant preference must also be considered, as people dislike facades that move at the wrong time or obstruct the view, and a manual override is usually provided.

A hybrid approach is possible and often desirable: a passive material-driven layer takes care of the basic daily response without energy, while a small active system adds override, scheduling or protection against extreme events such as storms. This keeps the system simple in normal use and still gives the control that building owners expect.

XV. Structural, Safety And Durability Aspects

A moving facade is part of the building envelope and must satisfy the same requirements as a fixed one. It must carry its own weight and resist wind pressure and suction, and the moving parts must not be damaged or blown open in a storm. Thin flaps and flexible fins can be very sensitive to wind, so stops, restraints or a design that closes under high wind speed are needed. Fixings and supports must transmit loads to the structure with adequate safety factors, and the effect of the extra load on the structure must be allowed for.

Safety also includes fire, falling objects, and entrapment or injury where people can reach moving parts. Materials should satisfy fire regulations, and polymers and liquids used in actuators should be non-toxic or well sealed. For water and weather protection, the moving elements should not compromise the waterproofing of the facade: they are normally placed in front of a weatherproof wall or window rather than forming the weather barrier themselves.

Durability depends on the repeated movement of the elements over the life of the building. A facade that opens and closes daily goes through several thousand cycles each decade, and each cycle stresses the material. Metals such as aluminium and bimetals are generally good in fatigue at small strains, whereas polymers and elastomers can lose properties through ultraviolet radiation, heat and ozone. Corrosion, dust, bird nests and insects can block small mechanisms. Accessible design, replaceable modules and routine inspection are therefore important.

XVI. Economic And Sustainability Aspects

Adaptive facades usually cost more at the outset than fixed ones. Costs arise from the smart materials, the more complex fabrication, the integration of actuators and sensors, additional structure and, for active systems, the controls and wiring.

Against this are savings in operating energy, possible reduction of the size of cooling plant, and gains in comfort and in the value of the building. Whether the extra cost is justified depends on the climate, the building type and use, and the electricity price, and it should be assessed through a life-cycle cost calculation that includes maintenance and replacement and not only first cost.

Passive systems can improve the economic picture because they remove the need for sensors, wiring and motors and reduce the running cost to nearly zero. Modular add-on units that can be fitted to existing buildings also spread cost and allow gradual upgrading. From the sustainability point of view, the embodied energy and carbon of the facade materials must be counted along with the energy saved in operation. Aluminium and polymers have significant embodied energy, so long life, repairability and recyclability are important. A design for disassembly, in which each module can be removed and its materials separated, supports reuse at the end of life.

In warm and sunny regions, including much of the tropical belt, solar radiation is plentiful and cooling is a major energy use, so passive solar-driven facades are well matched to the conditions. Heavy monsoon rain, high humidity, dust and salt air near the coast, however, are severe for materials and mechanisms, and they must be considered in the choice of metals, coatings and seals.

XVII. Illustrative Calculations

Two short calculations show the order of magnitude of the effects discussed above. The data are assumed for illustration and do not describe a particular product.

A. Bimetal Strip Deflection

Consider a free bimetal strip of total thickness $h = 1$ mm with equal layers and equal moduli, and a difference in expansion coefficients $(\alpha_2 - \alpha_1)$ of 15×10^{-6} per K. If the strip is heated by 30 K above its assembly temperature, Eq. (5) gives a curvature $\kappa = 3 \times 15 \times 10^{-6} \times 30 / (2 \times 10^{-3}) = 0.675\ \mathrm{m}^{-1}$, which is a radius of curvature of about 1.5 m. The tip deflection of a cantilever of length L bent to this uniform curvature is approximately $\delta = \kappa L^2/2$, so a strip of 0.1 m length deflects by about 3.4 mm and a strip of 0.3 m by about 30 mm. The movement grows with the square of the length, which explains why long, thin strips are used when large movement is needed.

When the strip is bonded to a flap, part of its bending moment is used to bend the flap, so the real deflection is smaller than for a free strip, and depends on the relative stiffness of flap and bimetal. A thinner flap or a larger covered area increases the deflection, as noted in the design parameters above. The calculation also shows the sensitivity of the result to the temperature rise: halving ΔT halves the deflection, so the surface coating, orientation and cavity ventilation, which determine ΔT, are as important as the strip itself.

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B. Buoyancy-Driven Airflow

Taking $C_d = 0.6$, an opening of area $A = 0.09$ m² (0.3 m × 0.3 m), a mean temperature of 300 K and a temperature difference $\Delta T = 5$ K, Eq. (3) gives the flows listed in Table III for three heights between the lower and upper openings. The values are of the order of tens of litres per second, and it can be seen that the flow rises with the square root of the height and of the temperature difference.

TABLE III
ILLUSTRATIVE STACK VENTILATION FLOW FOR ΔT = 5 K

Height between openings H (m)	Flow Q (L/s)	Flow Q (m³/h)
0.3	17	61
1.0	31	111
3.0	53	192

For a room of 50 m³ volume, a flow of about 100 m³/h would correspond to two air changes per hour, which is a useful level for summer comfort ventilation. A single small flap cannot supply this alone, but an array of flaps over a facade, opening in step with the sun, can supply a significant part of the ventilation without a fan. The stack flow increases when the flap opens further, so the opening movement and the airflow are naturally linked.

XVIII. Case Study: FlectoLine, Freiburg, Germany

FlectoLine is an adaptive shading system installed as a large-scale outdoor demonstrator at the Botanical Garden in Freiburg, Germany, and its results were reported in May 2025. The demonstrator was tested under real outdoor conditions for two years. It covers an area of 83.5 m² and is a complete exterior responsive facade (Fig. 17). It uses flexible, hingeless facade elements that deform and move, and it includes building-integrated photovoltaics (BIPV). The facade responds to changing environmental conditions and adjusts its configuration.



Fig. 17. The FlectoLine adaptive facade at the Botanical Garden, Freiburg, Germany (from the author's seminar presentation).

The working of each element is summarised in Fig. 18. Compressed air is supplied to a pneumatic actuator; the actuator pushes the flap, and the flexible zone of the flap, which acts as a compliant mechanism in place of a hinge, begins to bend; the bending flap changes its angle; and the solar shading changes accordingly, controlling sunlight, shading and indoor comfort. Because the bending happens in a flexible zone of a fibre-reinforced composite, there are no hinges or bearings to wear.



Fig. 18. Operating sequence of a FlectoLine element: compressed air, pneumatic actuation, flexible flap bends, solar shading changes (from the author's seminar presentation).

The case study is important for three reasons. First, it shows that a hingeless, bending facade can be built at a significant size and operated outdoors for a long period, which most laboratory concepts have not been. Second, it shows the integration of facade movement with electricity generation by BIPV, so that the same surface shades the building and produces power. Third, it demonstrates the compliant-mechanism approach on which many passive concepts, such as bimetal flaps and Mimosa-inspired hinges, also rely. It differs from them in using a pneumatic actuator, so it is responsive rather than fully passive, and it shows how a hybrid of smart and mechanical actuation can be practical.

XIX. Performance And Comparison

Table IV compares a conventional fixed facade with an adaptive building envelope for the main performance parameters. The fixed facade is suitable for relatively stable conditions, whereas the adaptive envelope is better suited to changing environmental conditions.

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TABLE IV
CONVENTIONAL FIXED FACADE VERSUS ADAPTIVE BUILDING ENVELOPE

Performance parameter	Conventional fixed facade	Adaptive building envelope
Solar radiation control	Fixed shading; cannot respond to changing sunlight	Shading elements change position according to solar conditions
Heat control	Same facade behaviour throughout the day	Facade adapts to reduce or allow heat gain as required
Natural ventilation	Fixed openings and airflow paths	Opening can be adjusted to improve airflow
Daylight control	Limited control once the facade is designed	Can regulate the amount of daylight entering
Thermal comfort	Less responsive to outdoor temperature changes	Responds to environmental changes to maintain better indoor conditions
Energy consumption	Greater dependence on mechanical heating/cooling	Can reduce dependence on HVAC through passive strategies
Response to weather	No active change in configuration	Can respond to temperature, sunlight, wind or other conditions
Facade configuration	Permanently fixed	Can open, close, rotate, fold or deform
User/environment adaptability	Low	High
Overall performance	Suitable for relatively stable conditions	Better suited to changing conditions

Table V compares the three kinetic systems discussed in this paper. They differ in how they are actuated, what they regulate and how mature they are.

TABLE V
COMPARISON OF THE KINETIC SYSTEMS DISCUSSED

Feature	Bimetal-actuated	Mimosa-inspired	FlectoLine
Actuation	Differential thermal expansion	Liquid–vapour phase change	Pneumatic actuation of flexible flaps
External energy for movement	None	None for switching	Compressed air
Main function	Natural ventilation, shading	Switching between solar heating and radiative cooling	Solar shading
Mechanism	Compliant bending flap	Cell-like hinge	Hingeless flexible zone
Response	Graded, follows surface temperature	Graded, follows hinge temperature	Controlled
Maturity	Module-scale studies	Small-scale studies	Large demonstrator, 83.5 m²

These comparisons are qualitative. Actual performance depends on the climate, orientation, building type and control strategy, so a facade must always be evaluated for its specific application, normally by simulation followed by prototype testing.

XX. DESIGN CONSIDERATIONS AND EVALUATION

Designing an adaptive facade requires attention to the interaction of structure, materials, building physics and climate. A suggested workflow for developing a passive adaptive facade is shown in Fig. 19. The first step is to define the climate and the function: whether the main need is ventilation, shading or heating/cooling switching, using local data on solar radiation, temperature and wind. The second step is to select the actuator and material to match the response temperature, range and force to the climate. In the third step geometry and fixings are set – which edges are fixed, the size of the module, the depth of the cavity – so that the required motion occurs within the elastic range. The fourth step is to tune the surface optics, choosing absorptivity and emissivity, or the grayscale of the material, to set the trigger temperature and the rate of response. The fifth step is simulation and the sixth is prototype testing and iteration.

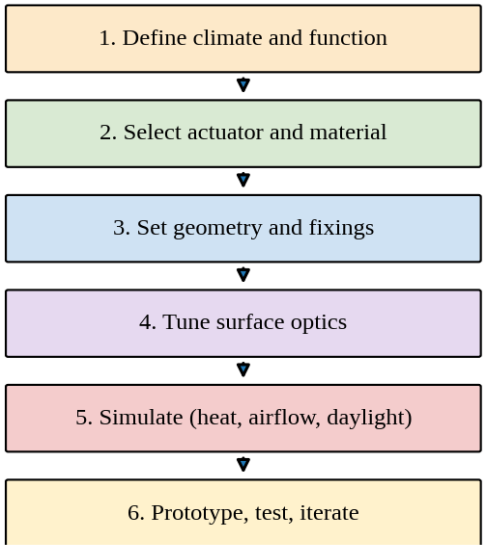


Fig. 19. Suggested design workflow for a passive adaptive facade.

Simulation is essential because the performance of a moving facade cannot be read from a single design condition. Thermal simulation tools predict energy use and temperatures through the year, daylight tools predict illuminance and glare, computational fluid dynamics predicts airflow and air velocity indoors, and finite element analysis predicts the deformation and stresses of flaps and hinges. Comfort criteria such as acceptable indoor air velocity and temperature ranges from standard comfort guidelines are used to judge the results. Laboratory prototypes should be tested under realistic heating, since heating by hot air does not reproduce the short-wave radiation of the sun, and outdoor tests over long periods are needed to confirm durability.

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Evaluation should look at several indicators together: surface and indoor temperatures, heating and cooling energy, air velocity and air change, illuminance and glare, mechanical displacement and fatigue life, cost and maintenance. A facade that improves one indicator at the expense of another – for example reducing solar gain but also reducing daylight – should be judged on the combined result.

XXI. Undefined. Advantages And Applications

A. Advantages

- *Improved thermal comfort:* the facade adapts to changing temperature and sunlight.
- *Better solar control:* excessive heat and glare are reduced.
- *Enhanced natural ventilation:* openings and airflow are controlled.
- *Energy efficiency:* dependence on HVAC systems can be reduced.
- *Dynamic response:* the facade can open, close, rotate, fold or deform.
- *Sustainability:* passive thermal regulation is supported, and renewable-energy integration, such as photovoltaics, is possible.

B. Applications

Adaptive envelopes can be applied to office and commercial buildings, where glazed facades and high internal loads make solar control important; to residential buildings, where comfort and low running cost matter; to high-rise buildings, where wind and solar exposure are severe; to hospitals and educational buildings, where comfort and daylight support well-being and learning; to hot-climate buildings, where cooling dominates; and to smart and sustainable buildings in general. The Al Bahar Towers in Abu Dhabi (Fig. 20), with their sun-responsive screens, are a well-known example of a kinetic facade in a hot climate.



Fig. 20. Al Bahar Towers, Abu Dhabi: a kinetic facade with sun-responsive shading units (from the author's seminar presentation).

For existing buildings, lightweight add-on systems, such as bimetal louver modules mounted in front of windows, are attractive because they do not require alteration of the structure and can be removed when not needed. For new buildings, the adaptive function can be integrated with the structure, shading and energy generation from the beginning.

XXII. Undefined. Limitations And Challenges

A. Limitations

- *High initial cost:* adaptive systems can be more expensive than conventional facades.
- *Complex design:* structural, mechanical and environmental systems must be properly integrated.
- *Maintenance requirement:* moving parts, actuators and smart materials need regular maintenance.

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- *Weather dependency:* performance depends on sunlight, temperature and wind conditions.
- *Limited long-term data:* long-term durability and performance need further investigation.

B. Challenges

- *Material durability:* smart materials must withstand repeated temperature changes and outdoor exposure, including ultraviolet radiation, rain, dust and ageing.
- *Control and reliability:* facade movement must occur at the correct time and position, and passive systems cannot be easily adjusted when the response is not as desired.
- *Structural safety:* moving elements must resist wind and other environmental loads and should fail safely.
- *Scalability:* laboratory concepts must be successfully developed for large building facades.
- *Integration with buildings:* adaptive systems must work effectively with existing structural and HVAC systems.

Beyond the technical challenges there are also practical ones: building codes and warranties seldom cover moving facades, designers and contractors need experience of them, and occupants must accept the changing appearance and, in some cases, the reduced view or daylight when panels are closed.

XXIII. Undefined. Future Scope

- *Advanced smart materials:* develop materials that respond faster and more efficiently to environmental changes.
- *Energy-independent operation:* increase the use of passive systems that require little or no external power.
- *Improved thermal performance:* develop facades with better control of heat gain, heat loss and solar radiation.
- *Better natural ventilation:* optimise movable elements for improved airflow and indoor comfort.
- *Large-scale implementation:* apply adaptive facade concepts to complete buildings and high-rise structures.
- *Improved durability:* develop systems that can withstand long-term outdoor exposure and repeated movement.
- *Renewable-energy integration:* combine adaptive facades with photovoltaic systems for energy generation.
- *Climate-specific design:* develop facade systems specially suited to different climatic conditions.
- *Advanced control systems:* improve sensing and control so facades respond accurately to changing conditions.

Research is also needed on life-cycle assessment of adaptive facades, on their cost–benefit compared with high-performance fixed facades, and on standard test methods so that results from different laboratories can be compared. Machine learning and digital twins may in future allow facades to predict weather and occupant needs and to adjust ahead of time, while passive materials continue to provide a reliable base level of response.

XXIV. Undefined. Typical Operating Day Of An Adaptive Facade

To see how the ideas of this paper work together, consider the behaviour of a sun-facing adaptive facade through a warm day. Table VI summarises the sequence for a bimetal-actuated facade and a Mimosa-inspired facade.

TABLE VI
Typical Daily Behaviour of Passive Adaptive Facades

Time	Bimetal-actuated facade	Mimosa-inspired facade
Early morning	Cool; flaps closed; little ventilation	Hinges flat; heating layer exposed to collect early sun
Mid-morning	Surface warms; flaps begin to open slightly	Hinge liquid warming; movement begins
Midday	Strong sun; flaps widely open; stack flow at maximum	Liquid evaporated; hinges bent; cooling layer exposed; heat rejected
Afternoon	Surface still hot; flaps remain open	Hinges remain bent while sun is strong
Evening	Surface cools; flaps close gradually	Vapour condenses; hinges relax
Night	Flaps closed; envelope sealed	Hinges flat; layers insulate or radiate depending on design

In the early morning the sun is low and the air is cool. The bimetal flaps are closed, so the facade behaves like a conventional wall, and no ventilation is wasted. In the Mimosa-inspired facade the heating layer is facing the sun and collects the early warmth. As the sun climbs, both facades warm up. The bimetal begins to bend and opens the flaps by a small amount, and the hinge liquid approaches its evaporation range.

At midday the radiation is at its peak and the cooling demand is highest. The flaps are most open, so the stack flow is greatest, and the Mimosa-inspired hinges have bent so that the cooling layer is exposed and heat is rejected to the sky. In this way the facade delivers the most help just when it is most needed, which is the principal reason for the interest in material-driven systems. In the evening the surfaces cool, the bimetal returns to its flat state and the vapour in the hinges condenses, so both facades go back to their starting positions without any command, ready for the next day.

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It must be remembered that actual behaviour depends on cloud, wind and season. On an overcast day the surface temperature may never reach the trigger value, and the facade will stay closed, which is appropriate since there is no solar load. On a windy day, convective cooling of the surface reduces its temperature and the opening is smaller. These are natural limits of passive control, and they are the reason that a hybrid approach with simple override is sometimes preferred.

A. Inspection and Maintenance Checklist

- Check flaps, hinges and fixings for cracks, loosening or fatigue marks at regular intervals.
- Confirm that movement is free: remove dust, leaves, nests and debris from cavities and gaps.
- Inspect adhesive bonds and seals, especially at the bimetal–plate joint and around sealed hinge cells.
- Examine coatings for fading or loss of absorptivity, and clean surfaces to maintain optical properties.
- Check protective finishes and fasteners for corrosion, especially in humid or coastal locations.
- Record opening range and response time periodically to detect gradual ageing.

UNDEFINED. RECOMMENDATIONS

From the study the following recommendations can be made for the development and use of adaptive facades:

- Choose the system according to climate and building use: ventilation-oriented flaps for sunny and breezy locations, heating/cooling switching for climates with both hot and cold seasons, and shading systems for glazed buildings.
- Prefer passive, material-driven actuation where simplicity, low maintenance and low energy use are the priorities, and add active control only where precise control or override is required.
- Design for the elastic range and for fatigue: facade elements will be moved thousands of times, so strains should be small and materials should be proven in outdoor conditions.
- Tune the response through surface optics and geometry, so that the facade begins to move at a suitable temperature and at a suitable speed.
- Evaluate by simulation and prototype testing together, using realistic solar loading, and consider comfort, energy, daylight and cost jointly.
- Design for access, replacement and recycling from the start, and consider add-on modules for existing buildings.

XXV. UNDEFINED. CONCLUSION

Adaptive building envelopes are advanced facade systems that can respond to changing outdoor conditions such as temperature, sunlight and wind.

Unlike conventional fixed facades, they can change their shape, position or properties to control heat, sunlight, daylight and airflow. Shape-changing facades can use opening, closing, rotating, folding and bending to achieve the required environmental response.

Smart materials such as bimetals and phase-change systems can provide temperature-responsive movement with reduced dependence on external energy. Bimetal-actuated flaps open under solar heating and promote natural ventilation, and Mimosa-inspired facades use a liquid–vapour phase-change hinge to switch between solar-heating and radiative-cooling modes. These systems can help to improve thermal comfort, natural ventilation and energy efficiency of buildings, and the FlectoLine demonstrator shows that hingeless adaptive facades can operate outdoors at a large scale.

However, challenges such as initial cost, durability, maintenance, structural safety and large-scale implementation still need to be addressed. With further development, adaptive facades have strong potential for creating energy-efficient, sustainable and climate-responsive buildings. A conventional facade separates the building from the environment, while an adaptive facade responds to the environment.

XXVI. UNDEFINED. GLOSSARY OF TERMS

The main technical terms used in this paper are defined in Table VII for ease of reference.

TABLE VII
GLOSSARY OF TERMS

Term	Meaning
Building envelope	Outer part of a building separating indoor and outdoor environments
Adaptive facade	Facade that changes its shape, position or properties in response to the environment
Kinetic facade	Facade whose elements physically move, for example by opening, rotating, folding or bending
Passive system	System in which the response is built into the material and needs no external power for movement
Active system	System using sensors, controllers and actuators to drive the facade
Bimetal	Two bonded metals with different thermal expansion that bend when heated
Compliant mechanism	Mechanism that moves by elastic deformation instead of hinges
Phase change	Change of a substance between solid, liquid and vapour states
Anisotropic conductivity	Different thermal conductivity in different directions
Radiative cooling	Heat loss from a surface to the cold sky by infrared radiation
SHGC	Solar heat gain coefficient: fraction of incident solar radiation admitted as heat
BIPV	Building-integrated photovoltaics

A. Scope of the Present Study

This paper is a descriptive study based on a seminar investigation of adaptive building envelopes. It explains principles, compares systems qualitatively and uses simple illustrative calculations; it does not present new experimental measurements or detailed numerical simulation of any facade. The performance of an actual facade depends on its design, materials, orientation and climate, and must be verified by dedicated analysis and testing before use in a real building.

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