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Shape Morphing Solar Shadings: a review

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Abstract

This paper provides an overview of available innovative shape morphing building skins and their design principles. In particular, the proposed review deals with comfort-related issues associated with dynamic solar shading devices, building integration of smart materials, and morphological analyses related to the most recent shape morphing solar skins.

In the first part of the paper, an introduction to the typologies of movement in architecture, its concept and application are presented. An explanation of biomimetic principles together with an overview of user's response to dynamic shading devices is also provided. This is followed by the description of the design principles for shape morphing solar shadings with particular focus on energy and comfort aspects, smart materials and biomimetic principles for efficient movements.

A review of most recent developments on the topics of comfort, users' response and control of dynamic shading devices, is presented and summarized in a comparison table. The main technical and mechanical properties of the most diffused smart materials (Shape Memory Alloys, Shape Memory Polymers and Shape Memory Hybrids) that can be used for innovative shape morphing solar skins are illustrated in detail and compared. Biomimetic principles for efficient movements complete this part of the work.

The principles illustrated in the previous part of this paper are then used to critically analyse the most recent examples of building integrated shape morphing shadings.

Keywords

Shape Morphing, Solar Shadings, Shape Memory Materials, User's response, Biomimetics, Daylighting, Comfort, Adaptive, BiPV

Nomenclature

Acronyms of materials

CPU	Copolyester-Urethane
DEAP	Dielectric ElectroActive Polymer
EOC	Ethylene-1-octene copolymers
EOET	Ethylene oxide – ethylene terephthalate
GFRP	Glass Fibre Reinforced Polymer
MMA-co-PEGDMA	Methyl methacrylate copolymerized with poly(ethylene glycol) dimethacrylate
PCL	Poly(ε-caprolactone)
PCLU	Poly(ε-caprolactone) polyurethanes
PEG-SMPU	Polyethylene-glycol shape memory polyurethanes
PMMA	Poly(methyl methacrylate)
PMMA-LPEG	Poly(methyl methacrylate) – linear poly(ethylene glycol)
PMMA-SPEG	Poly(methyl methacrylate) – star poly(ethylene glycol)
PPS	Poly(polyol sebacate) (polyester based)
PU	Polyurethane
ZDA	zinc diacrylate

Materials' properties

A_f	'Austenite' finish temperature upon heating of a Shape Memory Alloy
A_s	'Austenite' start temperature upon heating of a Shape Memory Alloy
E	Elastic modulus of the material
E'	Polymer's Storage modulus (through dynamic mechanical analysis)
M_f	'Martensite' finish temperature upon cooling of a Shape Memory Alloy
M_s	'Martensite' start temperature upon cooling of a Shape Memory Alloy
R_r	Strain recovery ratio of shape memory polymers
T	Temperature
$\dot{T}$	Time derivate of temperature
T_c	Temperature of crystallization of a semicrystalline Shape Memory Polymer
T_d	Deformation temperature of a Shape Memory Polymer
T_g	Glass transition temperature of a Shape Memory Polymer
T_m	Melting Temperature of a Shape Memory Polymer
T_s	Setting/Fixing temperature of a Shape Memory Polymer
T_{trans}	Transformation/Switching temperature of a Shape Memory Polymer
α	Thermal expansion coefficient
ε	Strain

$\dot{\varepsilon}$	Time derivate of strain
ε_c	Creep strain of a Shape Memory Polymer
ε_s	Irrecovery strain of a Shape Memory Polymer
ε^e	Elastic strain of a Shape Memory Alloy
ε^t	Transformation strain of a Shape Memory Alloy
ε^T	Thermal strain of a Shape Memory Alloy
ε_{pr}	Programming strain of Shape Memory Polymers
$\varepsilon_{rec,m}$	Remaining strain after the programming of Shape Memory Polymers
λ	Retardation time
μ	Viscosity of the material
σ	Stress
$\dot{\sigma}$	Time derivate of stress
ξ	Fraction of transformation of a Shape Memory Alloy

1. Introduction

In the current trend towards the use of high performance buildings and in the future scenario of Nearly Zero Energy Buildings (NZEB), a specific role is played by natural light control strategies. Future facades should interact with external environments as well as with occupants' behaviour, combining energy efficiency requirements and comfort needs. This paper presents a critical review of the most recent developments in the field of facade engineering, with particular attention devoted to smart morphing shadings activated by solar radiation. The specific focus on solar shadings depends on the high impact that they have both on total building energy consumptions and on daylight performance of internal spaces [1, 2]. This has been demonstrated by several studies involving static [3, 4] or dynamic window's shading systems [5-10].

Current designs of facades and even kinetic facade systems focus on energy saving issues at their conceptual stage, usually adopting layered facades, such as double skin, corridors and boxed types, where each layer performs a specific function and where their combination can be described by a very complex system. At the current state of development, this additive approach can hardly yield any further technical development, and therefore a new hybrid and integrated system approach should be established for the development of future facades [11]. In addition, there are also maintenance issues, especially in mechanical actuators of kinetic facade systems, which make them prone to failure [12].

Biomimetics offers a new way to approach technical problems identifying analogies in the natural world, where these technical issues already have a solution. Plant are recognized examples of systems that perform mobility with minimal energy use, due to the fibre elasticity composition, and integrating sensing and actuating capabilities into their system [13, 14].

On the other hand, smart materials are able to perform reversible shape variations triggered by various stimuli, such as heat and electricity. As a consequence, sensing and actuating functions could be integrated into a single element, offering a feasible way to achieve the idea to the future facade sought by Knaack et al. [11].

In this paper, the review of the current trend of shape morphing facades is complemented by an overview of possible future developments. The aim has been achieved by analysing the morphological, comfort and materials' aspects as well as integrating them in a critical discussion presented in the following sections.

1.1. Climate adaptive building skins

Adaptive building skins play a new role in high performance buildings' design. Nowadays, the external envelope has become highly important because capable of improving buildings' energy performances. The use of passive solutions derived from traditional technologies is reliable and easy to implement, making this new idea of skin relatively cost-effective. In addition, no moving parts characterize passive strategies. So, the need of complex control systems is limited and no energy is spent for facilitating adaptive behaviour.

Berge [15] highlights three ways to control the energy consumption which consist of consuming more efficiently, consuming differently and consuming less.

Currently, adaptive building skins are described using different definitions, often related to how the envelope reacts to users' needs and weather conditions. A summary of definitions currently available in the literature is included in Table 1. Loonen [12, 16] defined the Climate Adaptive Building Shell (CABS) as a building skin able to adapt itself as a function of the buildings' users' needs and the variable climatic conditions to which the shell is exposed. The adaptive behaviour of CABS aims to reduce the overall energy demand. Moreover, Loonen compared passive building envelopes with CABS, regarding the latter as an evolution of the earlier system. In particular, he stated that the 'active' and 'passive' systems do not exclude each other and, on the contrary, can enhance each other.

Wang et al. [17] described the Acclimated Kinetic Envelope (AKE) as an envelope with the aptitude to adapt itself through changes in reversible, incremental and mobile ways.

The mobility and deformation of adaptive (and kinetic) facades requires specific control issues that depend on various inputs and on technical/mechanical solutions adopted. Ramzy et al. [18] considered the use of robotics, mechanics and electronics as essential to redefine the traditional envelope applications. They discussed the different types of machines' sophistications, classifying these systems according to degrees of freedom, system configuration, control technique, control limit and cost.

Hasselaar [19] gave a definition of adaptive skin "*as something that becomes adjusted to new conditions*", distinguishing adaptable solutions, able to adjust themselves by external interference, from the adaptive ones, able to adjust and adapt themselves to changing situations. Loonen [12] defined two ways of control, i.e. closed-loop and open-loop control. The words 'automated' and 'automatic' define the distinction between these two automatic control concepts, where only the first type is automated, i.e. adjusted by the user. Wigginton and Harris [20] further developed the concept of intelligent skins, as part of an Intelligent Building Program, identifying responsiveness, not only to environmental changes, as their main property.

In the FACET Project, de Boer et al. [21] performed a research for the ideal building envelope based on adaptive and variable properties. The main feature of the FACET project was the use of the 'inverse modelling approach'. This approach starts from the definition of the desired output and consequently calculates which building shell's properties are able to define that output using the smallest amount of energy. A similar approach has been recently used by Kasinalis et al. [22] and by Favoino et al. [23, 24] to assess the performance potential of respectively seasonally and daily adaptable facades.

Pan and Jeng [25] explained that "*the logic underlying interactive architecture is that buildings with interactive systems use less energy, provide more occupant smartness, and feature better overall space flexibility than static buildings*". Nguyen and Aiello [26] highlighted the needs to perform automated adaptations in a way to optimize energy consumptions and to realize truly adaptable buildings. Berge [15] focused his attention on the acceptance of building automatic systems. Analysing the results of a study on occupants in low-energy homes in Sweden, Berge found a positive response by the use of automatic temperature controls from the dwellers. However, after a deep evaluation of the data, it turned out that almost none of them knew how they should have been connected and operated and so only a small part used the automatic control system. Moreover, some of the users exhibited a lack of interest in controls' capabilities. Most of people, stated Berge, suffer of *"techno stress"* because of the lack of accessing the possible management of the adopted technology. For example, the concept of "Smart Home" can be seen *"as impenetrable as black boxes"* and attention should be devoted to better enhance the system implementations to develop reliable tools to produce enhanced confidence and comfort for the users.

Table 1: Climate adaptive building skins: definitions and properties

Definition	Properties	Reference
Climate Adaptive Building Shell (CABS)	Able to adapt itself in function of building's users' needs and variable climatic conditions	[12, 16]
Acclimated Kinetic Envelope (AKE)	Able to adapt itself through changes. AKE's changes have to be reversible, incremental and mobile	[17]
Climate Adaptive Skin (CAS)	Able to adjust and adapt itself to changing situation	[19]
Intelligent Building Skins (IBS)	Responsiveness, not only to environmental changes	[20]

1.2. Daylight and visual comfort: physiological and psychological effect of natural light

Comfort is a complex perception based on the interactions between physical stimuli and cognitive/emotional processes leading to consider that as a result of the overall appraisal perceived through human senses.

Rybczynski [27] associated the idea of comfort to *"an onion with overlapping layers"*. As the concept of comfort evolves in time, a new layer is added to the previous one.

For Brager and de Dear [28] it is not enough to explain comfort using a single definition because they highlighted that comfort must be considered by the physiological and psychological point of view as a part of the processes used by people to improve the fit between needs and environmental conditions. Brager and de Dear reintroduced the concept of comfort connected to the occupants' satisfaction through an adaptation to the surrounding environment. In this way, they identified the following three categories of adaptation: behavioural adjustment, physiological adaptation and psychological adaptation.

A review of comfort literature suggests that, among the adaptive behaviours of buildings' users, the control of shading devices is one of the main actions adopted to change the perception of discomfort. Thus, the shade's movement can be predicted as a function of physical conditions of the environment producing a discomfort feeling [28].

The presence and operational strategies of windows' shading systems can affect the indoor comfort not only from the thermal point of view (thermal comfort), but also for its visual implications. The relationship between thermal and visual comfort should be investigated and related to the function of window's shades [29].

Light should be seen not only as necessary for vision, but also as a powerful modulator of non-visual functions, like the improvement of alertness and performances on cognitive tasks. Windows provide better health conditions and high indoor environmental quality by influencing physiological responses, such as the regulation of the diurnal cycle of body activity. Several studies provide links between daylight and physiological or psychological benefits on humans. A summary of these studies is included in Table 2.

Ulrich [30] investigated the importance of view through windows in a way to generate positive physiological effects on people while Küller et al. [31] showed how classrooms with windows have a better feedback on children's physical and psychological conditions. Boyce et al. [32] demonstrated for the first time the link between lighting conditions and sensation of health and well-being. They showed that people exposed to daylight were finding the space more attractive, highlighting a more pleasant mood and showing a better well-being at the end of the day. Leslie [33] argued that the strongest economic argument in terms of daylighting could be the better worker's productivity and the improvement of job satisfaction.

Aries et al. [34] carried out a survey on users in office buildings in the Netherlands. The individual factors in this study were gender, age and seasons' mood. Architectural factors included the view type and the related quality, the distance from windows and the density in the office space. The results showed that the window view is an important factor to improve satisfaction but being close to the window can cause glare problems. However, Tuaycharoen & Tregenza [35] found that glare discomfort, which is one of the environment variable in the Aries' model, decreased as the interest of view increased.

Boyce et al. [32] gave an overview of the lighting impact on human performances, demonstrating how melatonin is more efficiently suppressed by lights with higher energy intensity in the shorter wavelengths. Consequently, daylight has the right quantity and quality amount of solar radiation able to trigger the circadian rhythm.

In humans, circadian rhythms influence numerous factors like executive functions, alertness, memory and other cognitive process. Arendt [36] explained the importance of the melatonin as a marker of the circadian rhythm. This hormone is usually produced during the dark phase of the day. The lighting conditions have been found to have a high impact on the synchronization and phase-shifting of the circadian clock.

In the work carried out by Cajochen [37], several studies have been summarized with the aim of defining and quantifying illuminance levels, timing, exposure duration and wavelength of light sources required to arouse physiological responses in human. For Cajochen, all the beneficial properties of light – such as the circadian stabilization, the acute alerting and the performance enhancing effects – are important factors in the definition of the indoor lighting standards. In Cajochen's study [37], compared to people who worked under right levels of vertical illuminance, people who worked under low vertical illuminance levels are subjected to more fatigue and worse sleep quality. Considering the adjustment factors such as gender, age, eye correction, and seasonal sensitivity, these conclusions have been confirmed.

Webb [38] found that the non-visual effects of light could be singularly analysed considering the different wavelengths of light's spectrum. For instance, the mood seems to be most responsive to blue light, while skin is affected by UV radiation.

Similarly, Bellia et al. [39] analysed different types of electric lighting, verifying the circadian effect in term of efficiency and calculating the circadian action factors. The authors reported the correlation between the circadian efficiency and the non-visual parameters, like the dominating wavelength and the wavelength peak.

All these studies demonstrated how natural light is important to reach a satisfying level of comfort. Solar shadings, acting as a selector of direct and diffuse natural light could contribute in enhancing the benefits of natural light and reducing the detriments.

Table 2: Psychological and physiological effects of natural light.

Factor	Effect	Reference
View through windows	Positive physiological effect on people recovering from surgery	[30]
	Better feedback on children's physiological and psychological conditions in classrooms	[31]
	Improved satisfaction of workers' in office buildings	[34]
	Higher ability to tolerate glare discomfort if the interest of view increases	[35]
Exposure to daylight	Influence on the perception of the space and on the mood	[32, 38]
	Better worker's productivity	[33]
	Capacity to suppress melatonin	[32, 37]
	Better circadian efficiency	[32, 37, 39]
	Less fatigue and better sleep quality	[37]

2. Principles for designing shape morphing solar shadings

2.1. User's response to shading devices

The use of shading devices in buildings is linked to occupants' behaviour. In fact, the actions that users take, such as moving shades, significantly affect the building performance. The review takes into account three types of shading devices, i.e. manual, automatic and automatic with override, in order to understand the advantages and disadvantages of the different systems. Compared to fixed shades, the automatic ones provide a better adaptation to the indoor environment with a consequently higher users' satisfaction. Shades' operational strategies are prescribed mainly from visual and thermal comfort. Considering the massive use of Heating, Ventilation and Air Conditioning (HVAC) systems, that provide and maintain the indoor thermal comfort, the main cause that acts as a trigger is related to the visual comfort. Thus, the review investigates the role of daylight in office buildings, highlighting physical, physiological and psychological effects. The application of user behaviour models with high resolution and complexity is here analysed starting from factors that could act as a trigger for blinds' movements.

Several projects of commercial buildings demonstrated that adding blinds irregularly controlled by occupants don't change significantly the building performance. This remark points out that, starting from the design phase of a kinetic shading device, an accurate knowledge of occupants' blind use is necessary to achieve a reduction of building energy demand.

2.1.1. Manual and automatic control

In buildings, the energy demand used to reach a good level of comfort is significantly influenced by the facade, as a large amount of energy exchanged between indoor and outdoor space comes from windows. As a consequence, solar shading devices play a central role in the buildings energy optimization. Especially where automatic controls are present, it is important to correlate the activation of solar shading devices to occupants' response to direct solar gains and changes in visual comfort conditions.

Several studies have already focussed on these topics, highlighting the connections between users' comfort and solar shading operation.

Frontczak et al. [40] carried out a survey investigating the factors that influence occupants' comfort in Danish residential buildings. The results showed that the majority of the users preferred manual control instead of automatic control, especially for artificial light, windows opening and solar shading. 70% of respondents indicated that they had a low awareness about their impact on the energy use and indoor environmental quality, and 5% of respondents knew nothing or almost nothing about it. Because of this, the authors analysed the possibility to have an automatic system able to ensure at least the minimum requirements for an acceptable indoor quality, with the possibility of manual override by the occupants.

Inoue et al. [41] interviewed about 800 building occupants in two high-rise commercial buildings located in Japan. All the windows were provided with an automatic blind controller based on orientation and season, which could also be manually adjusted by the users. The authors reported that about 60% of the occupants thought that automatic blinds were a good addition to reach a positive indoor quality with only 10% being against it.

Sutter et al. [42] observed that the major part of the users set their blinds fully raised or lowered. They analysed the position of remotely controlled blinds in eight individual offices for 30 weeks every 15 minutes. In parallel, they registered the position of manually controlled blinds made by fabric in other seven offices, with pictures taken by webcam every 15 minutes. The experiment showed that remotely controlled blinds were used three times more often than manually controlled ones.

Moreover, they reported a 'hysteresis phenomenon' in the use of blinds, as most of the users tended to keep the blinds down until very low illuminance levels.

Haldi et al. [43] developed a model for the prediction of operating strategies on shading devices, based on 6 years of continuous measurements. Analysing in detail the parameters that influence the use of these systems, such as occupancy, thermal and visual comfort, they predicted the real usage of the shading devices in the office building. They studied also the individual use of shading devices and suggested how this diversity could be accounted in the model. Albeit the data resulting from their analyses was related to a specific building design, group of occupants and shading systems, the results could be applied to a wider class of buildings.

Selkowitz and Lee [44] conducted a research on fixed shading devices to explain the use of integrated facade systems. In buildings with many occupants and an operating design strategy, the authors argued that the control by users should be replaced with a more reliable control system that includes automatic features.

Wienold [45] analysed and compared different shadings' control strategies, aiming to design and assess a shading system based on real user behaviours. When a manual control is provided especially during summer, said Wienold, the shading device is rarely activated.

Reinhart and Voss [46] performed a simulation-based study using a stochastic method for lighting and shades control. Three blind controls were studied: automated, dynamic manual, and static manual. The savings on lighting consumptions were in the range between 0% and 60% depending on the blind control type, and the highest energy savings are observed in automatic control strategies. Guillemin and Molteni [47] developed and tested adaptive fuzzy controllers for blinds, electric lighting and heating. The aim of their research was to develop an energy-efficient fuzzy controller in order to enhance the users' acceptability. The controller was trained by means of genetic algorithms with users' preferences of blinds' position, and the data were filtered using energy efficiency criteria. Results showed that the automatic control rejection percentage was reduced using the adaptive system [48].

Bakker et al. [49] carried out an experimental research using human subjects in a controlled environment and found that users experienced a moderately positive experience when an automated dynamic facade was implemented. The authors also found that discrete transitions were perceived much better by users than highly frequent and smooth ones.

2.1.2. Factors influencing blinds' operation

Van Den Wymelenberg [50] suggested that blinds' use is prescribed by the visual and thermal comfort demand. Besides, privacy, view quality and social dynamics are other possible factors. Inkarojrit [29] organized these factors into four categories:

(i) physical factors (such as orientation, time of the day, time of the year, weather conditions, latitude, workstation position within the room, and lighting characteristic), (ii) physiological factors (such as individual sensitivity to brightness), (iii) psychological factors (such as a desire for privacy or view), and (iv) social factors (such as sense of blind ownership and organization policy).

A recent critical review made by O'Brien et al. [51] collected published observational studies used to identify the factors that motivate the operations on shading device in buildings. Several studies acknowledged the impact of weather conditions on shading controls. Starting from that, the review highlight that the occupants tend to control their shades according to long-term conditions so, the use of local weather station could be considered adequate for an occupant behavioural model.

Zhang and Barrett [52] found that blinds movement rates increased by 200-300% at peak horizontal radiation relative to low irradiance levels and Mahdavi et al. [53, 54] indicated that the global solar radiation on shading activation patterns should be considered for the facade orientation, as the global solar horizontal irradiance is not necessarily indicative in a way to consider the solar gains through windows. On the opposite, Foster and Oreszczyn [55] reported that shade operating movements are independent of solar conditions. They quantified the intensity of solar radiation using a "sunshine index" as a function of the horizontal global radiation and the time of the day. Reinhart and Voss [46] and Inoue et al. [41] stated that another predictor that must be considered is the solar penetration depth, considered more reliable than the solar irradiance on facade's plane.

About half of the studies collected by O'Brien et al. [51] measured indoor air temperature and relative humidity envisioning these as valuable parameters. However, they found that these factors are not significant contributors to occupant's shade changes. Instead, the importance of skin temperature gradient, affected by direct radiation and absorbed by the body, should be recognized as a factor that can trigger the movement of shades to restore comfort.

Some of the analysed studies are based on occupant surveys as a complement of the quantitative shades data. The typical questions involved the motivation to open and close shades and the importance of daylight and views.

Haldi and Robinson [43, 56] found that in private offices (i.e. single-occupancy offices) shading device operations were more linked to changing in indoor illuminance levels if compared with double-occupancy offices. Rubin et al. [57] hypothesized that the social factors associated with offices with more than one occupant could impact on shade movement. While solar phenomena were found to be the major variable affecting shades control many of the studies found that the type of shades control, the lighting controls, the air treatment system and the relation between people affected the use of shade [51].

All the factors that act as a trigger for the movement of shades are summarized in Table 3.

Table 3: Factors acting as a trigger for the movement of shades by occupants, adapted from [50] and [51]

Category	Factor	Shades pattern	Reference
Physical factors	Orientation	Shades exposed only to indirect solar radiation (north exposure in northern hemisphere) are fully closed for less than 1% of the time and fully open for more than 83% of the time.	[58]
	Peak horizontal solar radiation	Mean Shade Occlusion (MSO) [51] increases of 35% when the horizontal irradiance is more than 500 W/m^2.	[53, 54]
		Shade Movement Rate (SMR) [51] increases by two to three time at peak horizontal radiation than the lower radiation levels.	[52]
	Global horizontal solar radiation	MSO increases of about 20% between the lowest and the highest value of global solar horizontal radiation detected.	[53]

		The 'sunshine index' (function of global horizontal solar radiation) and the 'occlusion index' (function of shades' operation) are not directly related to manually operated devices.	[55]
		When the intensity of direct solar radiation is lower than 11-58 W/m^2 the users kept the blinds open.	[41]
	Solar irradiance on human body	The fastest rate of change corresponds to a value of solar irradiance on human body of 233 W/m^2	[59]
	Weather conditions	The 67% of shades kept open on cloudy day decrease to 43% on a sunny day. 50% of the occupants move their blinds once or more per day on sunny day while half of them move shades on cloudy day.	[29]
		The overall Mean Shade Occlusion is 59% with tested sky conditions. The MSO on a clear day is 63% while it's up to 55% on a cloudy day.	[60]
		The south façade have a range of 50-.60% of shades closed on overcast days. The occlusion is about 0-10% on east façade with overcast afternoon and on west façade with clear mornings.	[61]
		The Mean Shade Occlusion is about doubled during sunny days.	[62]
	Solar Penetration depth	The solar penetration depth is independent of the other radiation data and façade features, such as the glazing type.	[41]
	Workplace illuminance	The greatest number of operations on shades occurs when the workplane illuminance has a value of 200 lx (open) and 1200 lx (close)	[56]
	Vertical illuminance	Occupants override the blinds when the exterior vertical illuminance has a value of 25,000 lx (open) and 50,000 lx (close).	[46]
	Window's luminance	Users keep the window's luminance up to 1,800 cd/m^2 for the 75% of the day.	[42]
	Time of the day	Actions on blinds are five times higher when the users reach the office than during the rest of the day.	[56]
		Occupants close shades on east façade when they arrive on the building but then are gradually opened during the day. The opposite occurs on the west façade.	[41]
	Conditioning	The MSO for air-conditioned offices is 30%, while it is 49% for those non-artificially conditioned.	[29]
		There is significantly more occlusion in naturally ventilated building (mean occlusion value of 41%) if compared to air-conditioned buildings (mean occlusion value of 30%)	[63]
Physiological factors	Individual sensitivity to brightness	Shades' patterns for single-occupancy offices are more sensitive to changing of indoor illuminance levels if compared to the ones of double-occupancy offices.	[56]
		43% of the surveyed occupants prefer to close their shades to reduce the direct light, while 37% of occupants close them to reduce glare.	[58]
	Solar radiation	Higher Mean Radiant Temperature (MRT) decreases the mean tolerable threshold of window luminance by a factor of ten (from 10,000 cd/m^2 to 1,000 cd/m^2).	[29]
		The 50% of shades are closed at 10,000 lx of external illuminance when indoor temperature is lower than 26 °C. When the indoor air temperature is higher than 26 °C external shades tend to be closed at a lower external illuminance (3,000 lx)	[42]
	View	The level of obstruction of view from trees is correlated with the shade use.	[57]

		Lower façade shades are in a closed position four times less frequently than the upper façade ones. This suggests that this may be an effort to maintain views of the outside.	[56]
Psychological factors	Privacy	The presence of a proximate building could influence occupant's control of shades to allow for privacy.	[56]
		3 out of 25 interviewed occupants closed their blinds for visual privacy.	[29]
		90% of the users close shades for privacy for less than 4% of the day.	[46]
Social factors	Different people	In offices with more than one occupant the shades are less used (not tested)	[57]
	Space use	Shades' movement is affected by space use. MSO is 20% higher for office spaces than non-office spaces (i.e. hallways and waiting areas).	[52]

2.2. Integration of renewable energy systems in shading devices

Shading devices are one of the building envelope components suitable for the integration of renewable energy systems. For example, integrated photovoltaic (PV) shadings could be used to provide energy required for activating and/or controlling shape morphing mechanisms.

Several studies on PV-integrated solar shadings can be found in literature, with main focus devoted to the maximization of PV performance by providing shadings with an optimized configuration [64-68].

A prototype of an innovative PV-integrated shading device based on venetian blinds, was built and monitored as the result of a project funded by the European Community [69]. Each blind was composed of a glazed static concentrator and of a crystalline silicon bifacial solar cells. The system exhibited good performance with a theoretical efficiency of PV cells of 85%. For this solution, the total weight of the shading was estimated to remain under 20 kg/m^2, i.e. within the range of suitability for facades' applications.

Of interest to the scope of the current review are the research projects aimed at finding a point of balance between visual and/or thermal performance requirements of indoor spaces and maximization of PV production.

Khedari et al. [70] compared the visual and thermal performances of transparent and PV-integrated slat windows. The authors found that a PV-integrated system with slat angles between 60° and 68° could provide good thermal and visual performance if integrated in residential buildings in hot humid climatic regions.

Kim et al. [71] investigated the influence of visual comfort requirements on the efficiency of automated PV integrated shading devices. They identified two sets of different strategies for the movement of shading devices based on the presence of cloudy or clear sky.

Sun et al. [72, 73] carried out a parametric analysis of the effects of the variation of shading's tilt angle and orientation on the electric production and on the potential cooling load reduction in Hong Kong. The authors found that optimum tilt angles of fixed shadings vary between 30° and 50° and that the most cost-effective solutions are the ones involving small wall utilization fractions.

Mandalaki et al. [74-76] worked on a similar topic, involving the optimization of fixed PV-integrated shading devices. The authors developed a method for a qualitative and quantitative comparison between benefits of different typologies of fixed PV-integrated shading systems. They concentrated on both thermal and visual comfort.

Priatman et al. [77] developed a solar-powered automatic shading device. A prototype was built and tested in a physical testing chamber. The researchers used an illumination-based control in order to reach and maintain in the chamber a target illuminance of

300 lx while they were monitoring solar gains and, thus, indoor air temperature. They found a reduction of indoor air temperature of about 3°C due to the control of incoming solar radiation.

Kim et al. [78] proposed a new PV-integrated adjustable shading device combined with a daylight responsive dimming system. The authors conducted a series of experiments during different seasons to identify the impact of two control strategies: optimization of PV production and optimization of indoor daylight levels. They found that in the first case, an increase of 32% of power generation was possible, while in the second case a reduction of 35% of energy consumed by lighting systems was achieved.

From the analysis of existing literature it can be concluded that integration of renewable energy systems in external shadings can help in meeting two requirements for new and existing buildings, i.e. the improvement of indoor comfort conditions and the generation of clean energy. Control strategies are needed in order to define the most appropriate geometric pattern of shading devices. In this context, shape morphing and adaptive solar shadings could provide the envelope with the required movement for the optimization of PV production and indoor comfort conditions.

Some of the limitations related to the adoption of rigid PV cells and panels can be overcome with the adoption of innovative flexible and lightweight products [79].

2.3. Biomimetic approach for efficient movement

Schumacher et al. [14] categorized 'good movement' in architecture in analogy to the numerous existing canons to assess static architecture's quality. Generally, these principles are mainly addressed to visual perception, in terms of sensing movement through human eyes. The following key concepts are essential for movement appreciation: *Analogue or Digital movement*: whether movement is fast (the transition is not relevant but the change of state is) or slow (movement itself becomes relevant and of design potential); *speed*: how our senses are able to determine the source, magnitude and speed of movement, including optical effects; *acceleration; serial repetition*: how simple movements can be set into patterns to create a more appealing movement and/or independent movements from each of the serial components; *complexity*: as a result of mixing other parameters of movement; *weight*: how movement modifies the perception of the weight of a body; *balance; mystery; and interaction.*

Both rigid and elastic bodies are able to perform mechanical movements, which can be categorised into two types, i.e. translation and rotation. Each category of movement has degrees of freedom related to geometrical constraints according to one, two or three coordinate axes. Based on this, combining the two categories of translational and rotational movements, a maximum of six degrees of freedom can be achieved. As a function of the number of degrees of freedom involved for each category of movement, different typologies of movement can be defined. In this context, rotation can be broken down into three typologies: swivel (constrained rotation), revolving (free rotation) and swing (off-centre rotation, flap). Combining rotation and translation, a different set of movements can be defined, such as folding, expanding and contracting [14]. Several possible simple and complex movements are summarized in Table 4.

Table 4: Typologies of movement breakdown

Characteristic	Typology	Structural response
Rotation	Swivel	Bending
	Revolving (rotation)	
	Swing (flap, lever)	Bending
Translation	Slide	
Combined	Slide + Swing	Fold, expand and contract
	Swing x ("n" cycles)	Gather and roll up

	Swing + Swivel	Fold, Buckling

In order to enhance the efficiency of movement of shape morphing solar shadings, principles of biomimetics can be applied. Biomimetics is a term coined by Otto Schmitt in 1969 [80]. It is known as the science that studies the replication in humans' design of natural methods and processes. Jeronimidis and Atkins defined also biomimetics as "*the abstraction of good design from nature*" [81]. The final aim of this discipline is to improve human life with solutions derived from natural world, which are efficient, as they have overcome survival and evolution. In this field of study, nature is considered more an inspiration than a model to be completely replicated. This is the case because human technologies capabilities are, in general, not able to completely reproduce the complex systems found in nature [82]. Although the field of biomimetics is relatively new, as it has been developed only in the last few decades, people have tried to find in nature source of inspiration for millennia [83].

The applications of biomimetics in research follow two different approaches: "*bottom-up*" and "*top-down*". Both of them acknowledge biomimetics as a multidisciplinary approach [84, 85].

In a bottom-up process, research starts from biology and then it is transferred to other disciplines like engineering. Research studies give a range of possible solutions, which could be used in different practical applications. Commonly, the bottom-up approach is slower if compared to the top-down one, as it takes a long time to develop a technical solution. However, the process could potentially lead towards highly innovative solutions.

On the contrary, in a top-down approach, research starts from the engineering side of disciplines, where technical problems are accurately defined prior to finding a solution. Nature is considered as a source of possible solutions to be replicated to obtain the technical solution. The top-down process is faster if compared to the bottom-up one as the time for the implementation of technical solutions is much shorter. However, the innovativeness of solutions is limited as it is mostly only applicable to the investigated technical problem.

According to Stahlberg and Taya [86] the classical approach of deriving mechanisms of man-made design from mechanisms of biological design – classical bottom-up process – can be defined as *biomimetics*. On the contrary, the opposite process of understanding biological principles behind human-made design can be called *bioconvergence*. This second approach, generalizing the top-down principle of design, allows including some inventions derived from natural principles but with the unconscious awareness of a natural precedent [86].

Knippers and Speck [87], classifying natural systems for architectural applications, identified four main principles:

- *Heterogeneity*: characterized by different geometries for different elements and local adaptation of structures properties. The authors established a link with functionally gradient materials (FGM), which are not already applied in the building industry.
- *Anisotropy*: nature shows the use of composite fibre reinforced materials, where the orientation of fibres and their spatial distribution are key factors.
- *Hierarchy*. In natural systems, hierarchy is multi-levelled and present at different scales (opposite to static hierarchy principles adopted in civil structures). This principle has not been already fully explored in architecture and engineering fields.

- *Multifunctionality*: characterised by integration of functions into a single element.

Focusing on the design of shape morphing solar shadings, the principles of anisotropy and multifunctionality are of great relevance, if the design is approached following the principles of biomimetics. Anisotropy would define how deformation, and therefore movement, can be achieved through the distribution and orientation of material's fibres. Multifunctionality is then related to the capacity of embedding different functions into one single element (as sensing and actuating functions of smart materials).

For these scopes, the most interesting branch of biomimetics is the *phytomimetics* [82], related to the study of plants' structure. Plants do not rely on metabolism to produce motion and are able to produce movement without muscles, because motors are integrated in their structure [88].

To illustrate this condition Yoseph Bar-Cohen compares human movements with plant movements [82]. While in humans, motors (muscles) and moving parts (bones) are separated systems where muscles utilise energy, plants trigger movement by modulating water pressure in their cell structure, making them flexible. Consequently, flexibility constitutes a key lesson from natural models to reduce complexity of moving parts in buildings [87].

From the range of motion types performed by plants, reversible movements are the ones of highest interest in deployable structures in architecture. These motion patterns are found and almost are a particularity of nastic structures. Furthermore, nastic structures are very promising as natural actuators, working with very high actuation densities (about 100 kJ/m^3) [89].

Nastic structures present three important characteristics interrelated with kinetic building systems, which are also present in 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.

Nastic movements respond to an external stimulus regardless the direction of the stimuli inducing movement and predominantly reversible, for instance: the folding/unfolding and raising motion of leaves.

Nastic structures can be divided into two groups [82]:

- Autonomous structures, with an embedded motor and;
- Non-autonomous structures, depending on external energy sources to produce movement. An example of external source of movement can be found in the flowers pollination mechanism.

According to Stahlberg & Taya [86] and Bar-Cohen [82], three major hydration mechanisms can be found in nature: osmotic, colloidal and fibrous motors. In osmotic movement, hydrostatic pressure difference can be reached by means of added solutes into the cells. Colloidal motors provide movement by the presence of micro-hygroscope particles, while the adhesiveness of parallel capillary walls (like cellulose) is the main driving agent of fibrous motors.

Nastic movements are also determined by the anisotropic nature of plant cell distribution, as in timber, thus changes in shape are addressed by the direction of fibre distribution [13]. Table 5 includes a summary of typologies and mechanisms of movement that can be found in nastic structures.

Table 5: mechanisms of movement in nastic structures

Typology	Mechanism	Motor	Reference
Non-autonomous structures	Pollination	External agent	[82]
Autonomous structures	Osmotic	Hydrostatic pressure	[86]
	Colloidal	Micro-hygroscope particles	[86]

Fibrous	Capillarity	[86]
	Anisotropy of fibre distribution	[13]

2.4. 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 [90, 91].

In consideration of the application in shape morphing 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)

Currently, due to the material properties and costs, there are no solar shading devices made entirely of smart materials; in most of the projects, smart materials are still used either as sensors or as actuators.

When requiring a combined system of sensor and actuator, inducing an activating stimulus and a response in the movement, stimulus-responsive materials (SRMs) are the most suitable ones for shape morphing solar skins. SRMs are materials able to respond to an external stimulus through a change of their physical or chemical properties [92]. Focusing on the physical phenomenon of the shape change, these materials can be grouped in two main categories: shape change materials (SCMs) and shape memory materials (SMMs).

SCMs are able to change their shape at the presence of the right stimulus (commonly a potential difference). Some relevant examples are the electro-active polymers EAPs and piezo-electrical material PZTs [92, 93]. In the second category (SMMs) are included all the materials that are able to held the modified shape until the appropriate stimulus is applied to activate the shape recovery cycle [92, 94]. Commonly, those materials are activated by a difference in temperature. This characteristic makes them as the most appropriate choice for activating smart morphing solar shadings with the thermal effect of incident solar radiation.

Many Shape Memory Materials have been studied during the years, with the Shape Memory Alloys (SMAs) and the Shape Memory Polymers (SMPs) [95] being the most diffused and used. The newest types of SMMs are the Shape Memory Hybrids (SMHs) that are made combining at least two different components, which in their original state do not have any shape memory behaviour [92, 96].

In the following sections the three most diffused SMMs are analysed in detail, synthesizing the main aspects related to their potential use in architecture as sensors or actuators for solar shading devices.

2.4.1. Shape Memory Alloys (SMAs)

After their first discovery in 1951 in an Au-47.5% Cd alloy, SMAs have been widely studied and many patents have been released. Their large-scale diffusion started in the 70's of last century, from the initial application in the Grumman F-14 aircraft [90]. Thanks to their biocompatibility, high corrosion resistance, and high electrical resistance SMAs have been applied in different sectors, with an extensive use in clinical applications [90, 94, 97]. In addition to their shape memory effect, SMAs have also the characteristic to be super-elastic, which enabled its use for applications requiring super elastic behaviours, e.g. reinforcing wire in the heel of a shoe, eyeglass frame, structural reinforcements [90].

According to the type of stimulus SMAs can be categorized into two groups: thermo-responsive and magneto-responsive. The first type is activated by a thermal stimulus, both direct and indirect (e.g. joule heating), while the second type is activated essentially by a magnetic field [92]. In this paper, the attention is focussed on thermo-responsive alloys, especially activated by heat produced by the absorption of direct solar radiation.

The mechanism behind the shape memory effect of a SMA is the reversible martensitic transformation. At lower temperature, the martensitic phase exists and the alloy is relatively soft and easily deforming, whereas austenite is a stronger phase that occurs at higher temperatures. Below the transition temperature (T_s), the alloy is in the martensitic phase and still conserves its shape memory effect. After re-heating the material above the transition temperature, the original shape is recovered, i.e. from the deformed martensitic transformation the sample reaches its cubic austenite phase [90, 92, 98-100].

Starting from a parent phase at high temperature, the SMA can be cooled down till a critical temperature, called Martensitic phase Start (M_s), is reached and the structure of the alloy changes into martensite (lower temperature phase with lower symmetry). Since the parent phase has a higher symmetry, there can be more variants (or domains) of martensite due to the same structure with different orientations. The martensitic transformations can be thermoelastic and non-thermoelastic; the shape-memory and super-elasticity effects are characteristics of a thermoelastic transformation [101].

Main characteristics temperature parameters of a thermally activated SMA are:

- M_s: martensite start temperature upon cooling;
- M_f: martensite finish temperature upon cooling;
- A_s: reverse-transformation (Austenite) start temperature upon heating;
- A_f: reverse-transformation (Austenite) finish temperature upon heating;

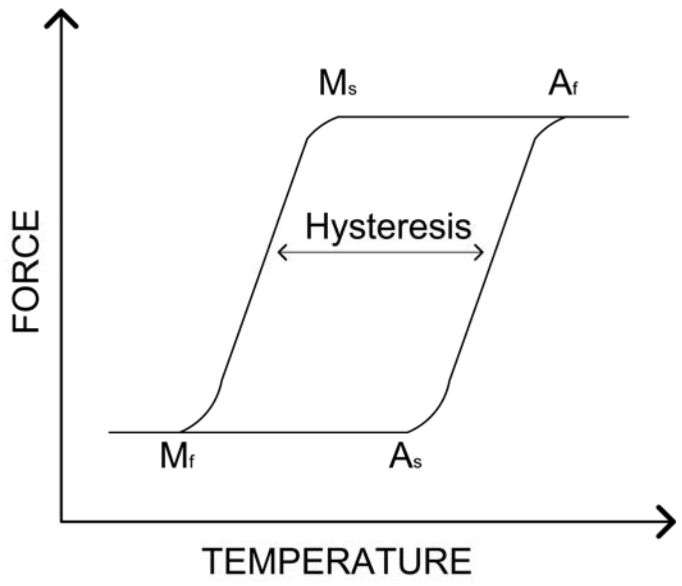

Figure 1: Example of SMA chart and terminology

If a sample if stressed at a temperature above A_f, the alloy behaves as a super-elastic material with a recoverable strain exceeding 10% [101]. Since the martensitic transformation occurs with a shear-like mechanism, it is possible to induce it even above M_s with a stress applied. At the same time, it is possible to induce martensite phase even above A_f with a stress-induced approach, even if in this case the martensite is completely unstable [101]. Super-elasticity and shape memory effect can both occur in a SMA depending on the specimen's test temperature.

The process described above shows the typical one-way effect because only the shape of the parent phase is remembered. However, in particular circumstances a SMA can present a two-ways shape memory effect, where both the martensite and the parent shape are remembered. These circumstances include the thermal treatment of the alloy, a high deformation at the martensite phase, the addition in the alloy of a precipitation, or a specific process of training.

SMAs are divided in three different categories according to their base alloy: NiTi based, Cu-based and Fe-based. Their main characteristics have been synthesised in Table 8, including a summary on smart materials [92, 102].

Although the higher costs, NiTi-based alloys have higher recoverable strain, generated force and corrosion resistance than Cu-based and Fe-based alloys.

The most diffuse SMAs are the NiTi alloys, thanks to their relatively high recoverable strain (around 7%), high actuation stress (up to 500 MPa) and high corrosion resistance added to high bio-compatibility [92].

The difficulties in working with SMAs are related to their different behaviour and characteristics due to many different possible martensitic configurations. There is no international standard for the characterization of the material and each supplier develops its own product according to its specifications [92]. Therefore, when a specific behaviour of the material is needed or when a new alloy is used, a proper characterization is needed.

Many constitutive models have been developed to explain the behaviour of a SMA. W.M. Huang et al. [92, 99] group the constitutive models as follow:

- *"Phenomenological models based on the uni-axial stress-strain temperature data;"*
- *"Theory of non-equilibrium thermostatics that describes the thermodynamic paths of SMA;"*

- *"Models based on the interaction of the different sets of atoms in the alloy;"*
- *"Models derived from a special free energy formulation;"*
- *"Models based on thermodynamic laws;"*
- *"Constitutive laws based on a model for hysteresis;"*
- *"Model based on nonlinear thermo-plasticity theory, general plasticity, or visco-plastic theory;"*
- *"Mathematical models for the dynamics of phase boundary motion;"*
- *"Models derived from the deformation of crystal structure during phase transformation;"*
- *"Constitutive laws that allows for micro-structural deformation during phase transformation and the free energy concept using an energy dissipation or energy balance approach;"*

According to reference [92], the most practical approach for modelling engineering applications is based on phenomenological models. These latter models are based on one-dimensional constitutive representations and, considering a SMA specimen subjected to a uni-axial tension, the total strain can be expressed as:

$$\varepsilon = \varepsilon^{e} + \varepsilon^{t} + \varepsilon^{T} \tag{1}$$

where ε^{e} is the elastic strain, ε^{t} the transformation strain, and ε^{T} is the thermal strain.

Following a first order simplification, the Young's modulus (E) and the thermal expansion coefficient (α) can be considered as constant and, consequently, the terms included in previous equation (1) can be expressed as:

$$\varepsilon^{e} = \frac{\sigma}{E} \tag{2}$$

$$\varepsilon^{t} = \varepsilon^{t}_{max}\xi \tag{3}$$

$$\varepsilon^{T} = \alpha \times \Delta T \tag{4}$$

Where σ is the tensile stress, ε^{t}_{max} is the maximum transformation strain that can be determined experimentally with stretching/heating tests. For a NiTi alloy, the maximum transformation strain is around 6.7%, ξ is the fraction of transformation, which is a function of σ and T, and is thermo-mechanical history-dependent. Many transformation functions are proposed in references [92, 99, 103-106], and ΔT is the gradient of temperature from the reference one.

In normal temperature range transformation, ε^{T} is very small (about 0.2%) and it can be ignored.

To extend the one-dimensional model to a three-dimensional one, it is necessary to define a yield surface. Experimental results show a significant difference in tension and compression for many SMAs [92], so it is not possible to apply the traditional criteria (e.g. Von Mises or Tresca) to describe a transformation start stress. Many models have been developed to describe the yield surface [92], most of them are based on experimental results. In most cases, these representations are not defined in terms of closed-form solutions and are evaluated from numerical solutions.

In order to design thermally activated SMAs, it is primarily necessary to define the desired transformation temperature, the force or the motion requirements and the cyclic requirements. The required transformation temperature dictates the composition of the alloy to be used. The temperature amplitude is the difference between A_f and M_f, and the hysteresis is the width of the hysteresis loop at one half of the obtainable force or motion. Hysteresis can be defined as the difference between the forward and the reverse transformation paths. In addition, it is always necessary to fix a maximum and minimum service temperature (above A_f and below

M_f), which should include a temperature tolerance according to commercial alloys. When activated by electricity, it is necessary to control that the M_f temperature is above the maximum expected ambient temperature as, otherwise, the reverse transformation would not occur [107].

2.4.2. Shape Memory Polymers

Shape memory polymers have been widely used over the last years due to their lower density, lower costs (compared to SMA), and high biocompatibility. Polymers are constituted by chemically bonded molecular chains of monomers. In certain polymers, the fundamental molecular units are not the same monomer, but they are two or more similar molecules, in which case the polymer is referred to as a copolymer [90]. Due to the nature of their chemical links, shape memory polymers have different behaviours and classifications.

There are many actuation methods of SMPs, such as heat, electricity, light magnetism, and moisture. Their actuating stimulus directly depends on their composites and fillers [98] and, in this paper, the attention is focused on thermally activated polymers.

The original shape of SMPs is fixed during the production process, and their temporary shape can be set during a fixing phase. For thermally activated SMPs, the fixing cycle can be summarized as follow. Once the transition temperature is reached, SMP becomes relative soft and, through the application of an external force, it can be deformed to the desired temporary shape. If the material is then cooled by keeping the applied deformation, its shape becomes fixed until the specimen is heated again above its transformation temperature. At this temperature, the specimen releases the acquired stress and reaches its original shape [90, 98].

Currently, there are more than 20 different types of Shape Memory Polymers [98, 108, 109]. Depending on their chemical architecture, SMPs can be classified as follow [98, 108-110]: chemically cross-linked glassy thermosets, chemically cross-linked semicrystalline rubbers, physically cross-linked amorphous thermoplastics, and physically cross-linked semicrystalline block copolymers.

Transformation/Switching temperature (T_{trans}) is the most important parameter for describing thermally induced SMPs. T_{trans} can be defined as the temperature at which the SMP recovers its permanent shape. This temperature is commonly called glass transition temperature (T_g) if the network chains of the SMP are amorphous, or melting temperature (T_m) if network chains are crystalline. SMPs based on glass transition are chemically cross-linked glassy thermosets and physical cross-linked amorphous thermoplastics, while the SMPs based on melting transition are chemically cross-linked semicrystalline rubbers and physically cross-linked semicrystalline block copolymers [109].

Another parameter used for describing the shape memory behaviour of polymers is the strain recovery ratio (R_r). According to [111], it can be expressed as:

$$R_r = \frac{\varepsilon_{pr} - \varepsilon_{rec,m}}{\varepsilon_{pr}} \quad (5)$$

where ε_{pr} is the strain produced by stretching in the polymer's programming phase, while $\varepsilon_{rec,m}$ is the remaining strain after the programming phase has been completed.

The main characteristics of a selected number of SMPs potentially suitable for application in shape morphing solar skins is included in Table 6. SMPs have been subdivided in two categories: polymers based on melting transition and polymers based on glass transition. For each typology of material, main shape memory (T_{trans} and R_r) and mechanical (E or E') properties have been collected from existing literature.

Table 6: Main characteristics of SMPs, adapted from [109].

Category	Material	T_{trans} [°C]	R_r [%]	Mechanical properties	Comments	Ref.
Melting transition based	EOC	60-100	> 95	-	Opportunity of tailoring T_{trans} by a variation of chemical composition	[111]
	Natural Rubber	0-45	-	E(20°C) = 6-16 MPa	Stress-induced shape memory effect	[112]
	Natural Rubber	75	88-95	-	Commercial rubber band swollen in molten stearic acid	[112, 113]
	EOET	45-55	84-85	-	-	[113, 114]
	PEG-SMPU	40-50	82-98	-	-	[114, 115]
	PU	60	80-100	E' (-75°C) = 2000-2800 MPa E' (45°C) = 50-385 MPa E' (75°C) = 15-165 MPa	-	[116]
	PMMA-SPEG	46-52	> 98	E' (0°C) = 682-2740 MPa	-	[117]
	PMMA-LPEG	50-53	75-93	E' (0°C) = 958-1465 MPa	-	[117]
	PCLU	45-60	94-100		Properties could be adjusted	[118]
	Radiation crosslinked PCL	54-56	99-100	-	-	[119]
	PCL methacrylate	30-50	92-97	E (25°C) = 2.4-72 MPa E (70°C) = 0.7-6 MPa	-	[120]
Glass transition based	ZDA Epoxidized natural rubber	20-46	> 90	E (25°C) = 1.5-21.1 MPa	-	[121]
	Epoxy	31-93	~ 100	E' ($T=T_s$) = 1751-3017 MPa E' ($T=T_d$) = 4.5-18.9MPa	-	[122]
	CPU networks	48-66	> 99	E (25°C) = 330-600 MPa E (70°C) = 0.77-5.85 MPa	biodegradable	[123]
	PPS	15-45	~ 100	E (20°C) = 1.8-130 MPa	-	[124]
	Hybrid hydrogels	45	~ 100	E (23°C) = 0.06-0.2 MPa	-	[125]
	MMA-co-PEGDMA	56-92	-	E ($T=T_g$) = 9.3-23 MPa	Biocompatible materials	[126]

Other characteristic temperatures are the Setting/Fixing temperature (T_s) and the deformation temperature (T_d). T_s is the temperature at which the temporary shape can be fixed, while T_d is the temperature at which the specimen becomes soft and can be easily deformed. For amorphous polymers, T_d and T_s can be expressed as:

$$T_d = (T_{trans} + \Delta T) \quad (6)$$

$$T_s = (T_{trans} - \Delta T) \quad (7)$$

where ΔT is usually equal to 20 °C.

For semicrystalline polymers, the deformation temperature T_d is defined as for the amorphous polymers as the transition temperature (T_{trans}) increased of the temperature gradient ΔT, while the setting temperature T_s is defined as the temperature of crystallization (T_c):

$$T_s = T_c = (T_{trans} - \Delta T) \quad (8)$$

where ΔT is usually assumed to be 40 °C [110].

The transition temperatures of the most diffused SMP are summarized in Table 7.

Table 7: Market diffused SMP, transition temperatures, adapted from [98]

Base Material SMP	T_{trans} [°C]	Company/Producer
Styrene butadiene	60-90	Asahi company

Styrene-based (Veriflex®)	60-70	Cornerstone research group
One part epoxy	90	Cornerstone research group
Two parts epoxy	104	Cornerstone research group
Cyanate ester	135-230	Cornerstone research group
Thermosetting epoxy	113	Composite technology development
Thermoplastic polyurethane	40-55	Mitsubishi heavy industry

There are many constitutive models of SMPs available in the literature. Although SMPs undergo large three-dimensional deformation, Leng et al. [98] commented that current understanding of the thermomechanical behaviour of SMPs is limited to one-dimensional deformation. The most common models are based on viscoelasticity and phase transition.

Linear viscoelasticity models are used to describe the behaviour of SMPs at a macroscopic level [98, 127]. A typical linear constitutive model based on viscoelasticity has been developed by Tobushi et al. [98, 128], where the stress-strain-temperature relationship is expressed as follows:

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\mu} - \frac{\varepsilon - \varepsilon_s}{\lambda} + \alpha\dot{T} \qquad (9)$$

where σ, ε and T are respectively stress, strain and temperature (the dot point represents the time derivate of each of the three properties), while ε_c is the creep strain of the polymer. If the temperature of the polymer reaches a value higher than T_g, the creep strain is recovered, while if the temperature is lower than T_g, an irrecovery strain remains (ε_s).

The increase of ε_s is proportional to the increase of ε_c, and their relationship can be expressed as [128]:

$$\varepsilon_s = C(\varepsilon_c - \varepsilon_l) \qquad (10)$$

where C and ε_l are related to the process of shape fixity and they can be expressed by the same function of temperature.

In 2001, Tobushi et al. [129] have developed a non-linear constitutive model based on equation (9) previously cited [98].

Another constitutive model is based on phase transition. In 2006, Liu et al. developed a model under uniaxial loading conditions of SMP [98, 130, 131], according to which two kind of extreme phases, i.e. a frozen phase and an active one, exist in a SMP at an arbitrary temperature.

Many other properties of Shape Memory Polymers are currently under study. Because of this, only the most important parameters relevant to the design of a smart facade have been considered in this paper.

2.4.3. Shape Memory Hybrids

Shape Memory Hybrids (SMHs) are regarded as more recent materials when compared to SMAs and SMPs. Although more research needs to be carried out to better understand their thermo-mechanical properties, they are attractive since they can be designed also by not professional experts in material science [92], [94]. SMHs are composed by well-known materials that have no shape memory properties on their own. Usually, in SMHs there are no chemical interactions between matrix and inclusions; therefore the properties of each component are maintained [92].

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) [92, 96, 132].

For the purpose of this paper and concentrating on solar responsive facade, the most promising SMHs are the thermo-responsive ones. An example of these materials is represented by a silicon and wax hybrid. When a silicon/wax hybrid is heated, the wax becomes soft and can be deformed to a temporary shape. In this specific case, the wax works as the transition inclusion, while silicon keeps the elasticity of the material. After cooling, the wax will store its temporary shape while an elastic energy will be stored in the elastic matrix. When the SMH is re-heated the elastic energy stored is released and the original shape is restored. Recent developments are studying the possibility to integrate shape memory alloys with SMH to develop self-healing Shape Memory Composites [133]. The shape memory effect of SMHs is similar to SMPs' one. Due to the different composition of SMHs, their modelling requires a specific applied study, even if SMHs can be modelled in similar ways to SMPs [92].

2.4.4. Comparative properties of SMAs, SMPs and SMHs

A comparison between SMAs, SMPs and SMHs is presented in terms of their main properties affecting their use as sensors/actuators in shape morphing solar shadings [90, 98, 134-136].

The morphing effect of SMPs is the most promising one if compared with SMAs and SMHs, as their global deformation is sensibly higher (800%) than the one achievable with SMAs (up to 10%) and SMHs (up to 6-8%). However, for all the three classes of materials, a force is required to recover the initial shape.

SMAs are currently the most durable shape memory materials. In fact, while SMAs are able to exceed 200,000 cycles, SMPs have been tested only up to 200 cycles and SMHs have not already undergone fatigues tests. Furthermore, SMPs and SMHs, depending on their composition, can be affected by external weather conditions.

Recovery temperatures of all the three material classes are comparable and compatible with predictable temperatures of solar shadings, while physical and mechanical properties (density, elastic module, transformation stress) vary as a function of the properties of basic components. These are summarized in Table 8.

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

3. Application in buildings of shape morphing solar shadings

The current research on shading devices is aiming at the development of solutions that do not require mechanical systems (e.g. hingeless solutions). Responsiveness to variable external conditions and ability to minimise energy required to perform adaptation are additional characteristics of innovative solar shadings. These objectives have been observed to be applied to the shading component development either by using a biomimetic approach and/or by specifying smart materials. Table 9 summarizes the projects reviewed, where a letter relates each project to its reference enabling a more comprehensive analysis of the work carried out to date. Figures 2 to 15 depict some detailed schemes of operation of the projects considered in the following.

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	-

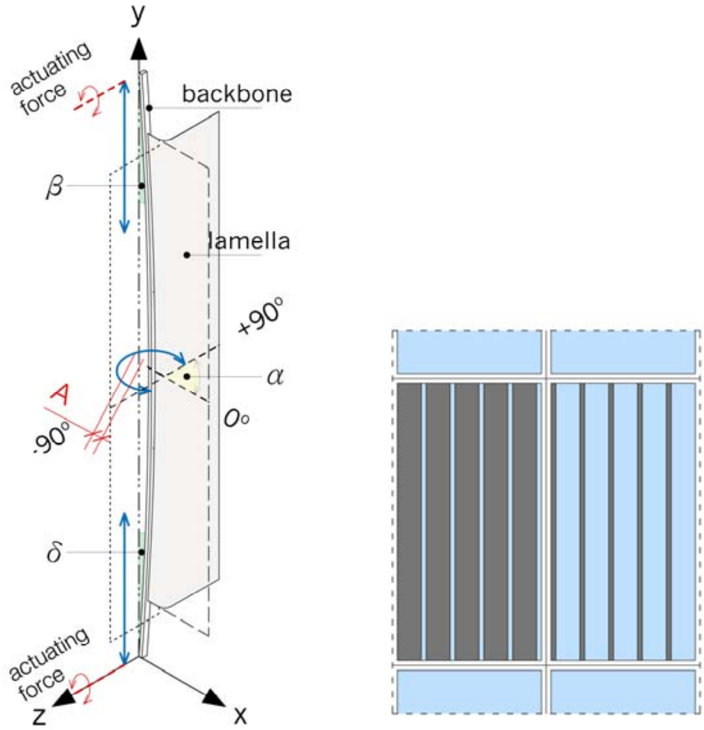

Figure 2: Project (A): Flectofin® [137]. Scheme of operation and example of facade's integration (closed and open configuration).

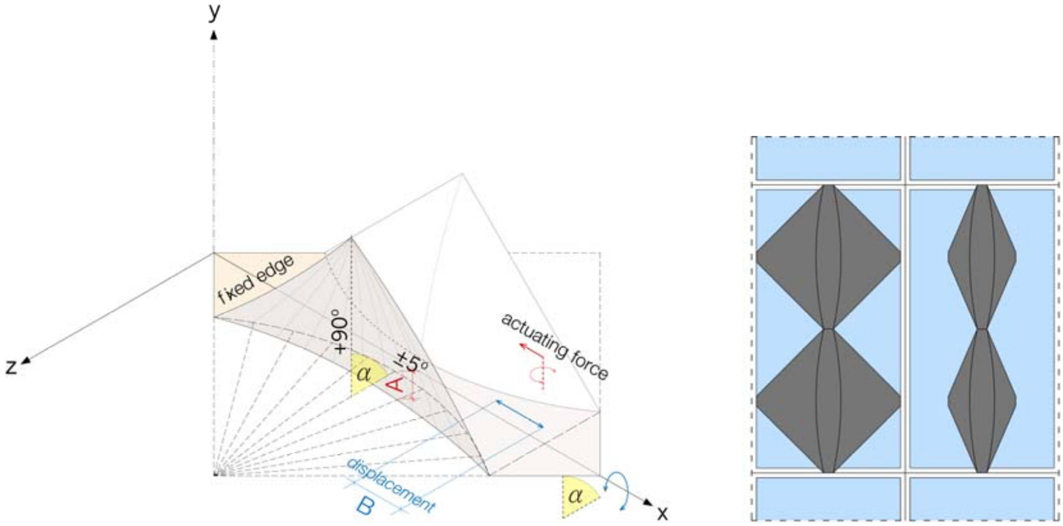

Figure 3: Project (B): Solar Kinetic [138]. Scheme of operation and example of facade's integration (closed and open configuration).

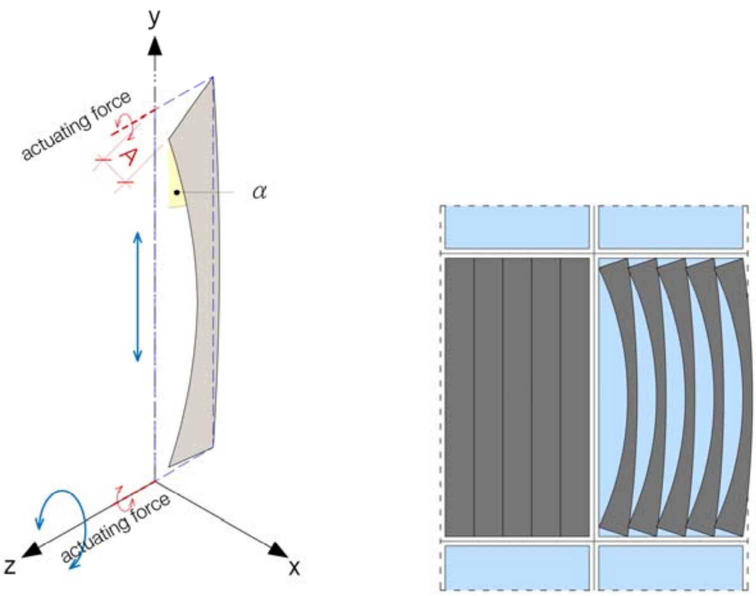

Figure 4: Project (C): Ocean Thematic Pavilion [139]. Scheme of operation and example of facade's integration (closed and open configuration).

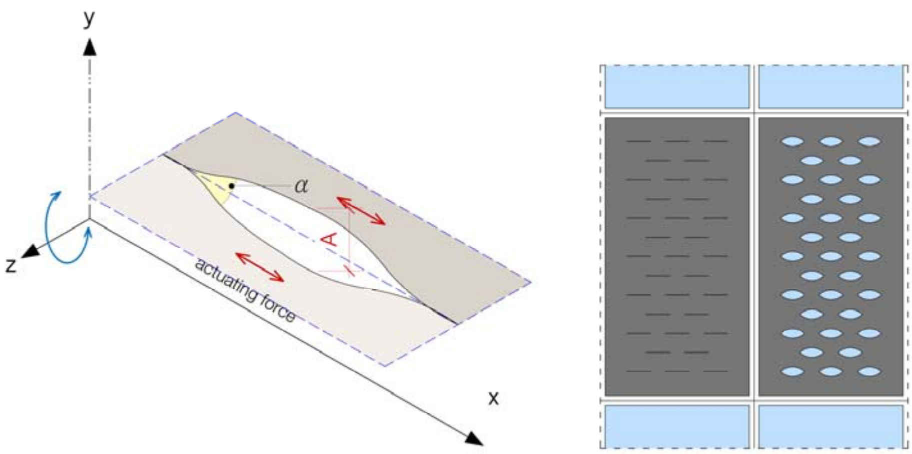

Figure 5: Projects (D): Blind [140] and (E): Living Glass [141]. Scheme of operation and example of facade's integration (closed and open configuration).

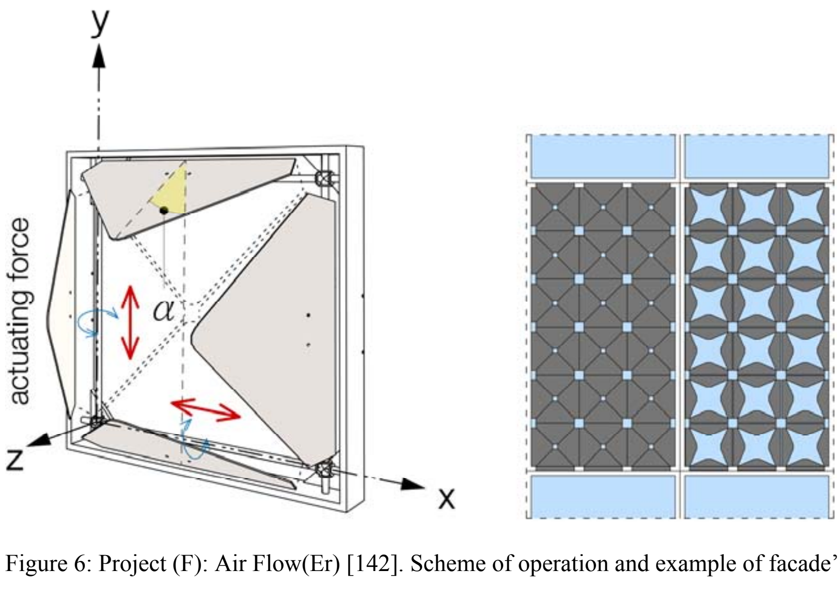

Figure 6: Project (F): Air Flow(Er) [142]. Scheme of operation and example of facade's integration (closed and open configuration).

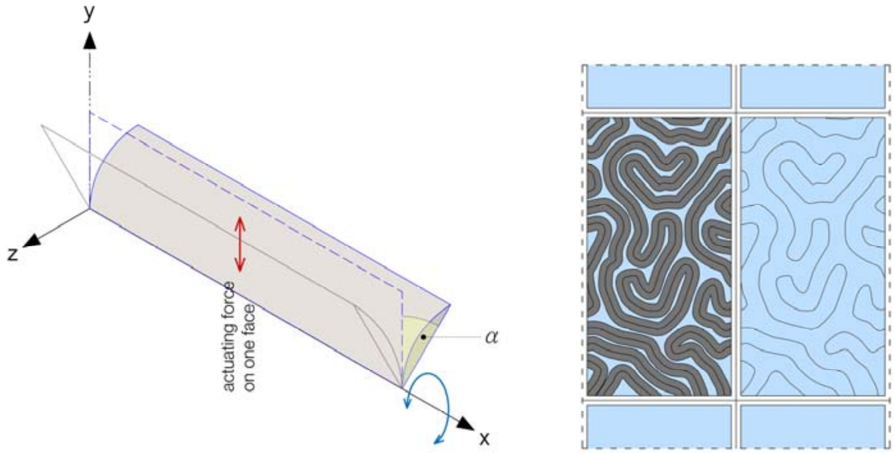

Figure 7: Project (G): Homeostatic [143]. Scheme of operation and example of facade's integration (closed and open configuration).

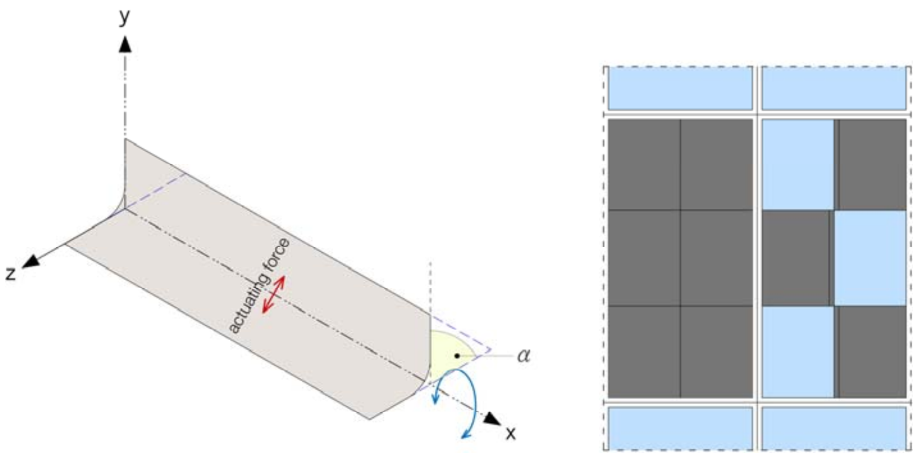

Figure 8: Project (H): Sun Shading [144, 145]. Scheme of operation and example of facade's integration (closed and open configuration).

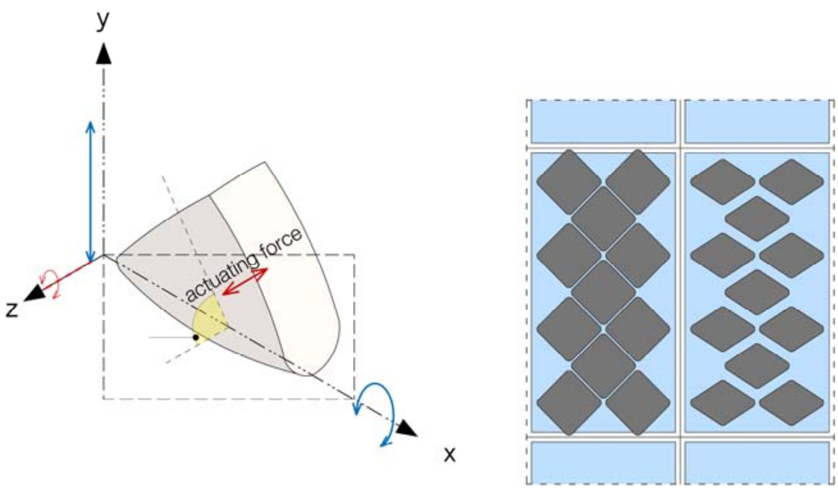

Figure 9: Project (I): Shapeshift [146]. Scheme of operation and example of facade's integration (closed and open configuration).

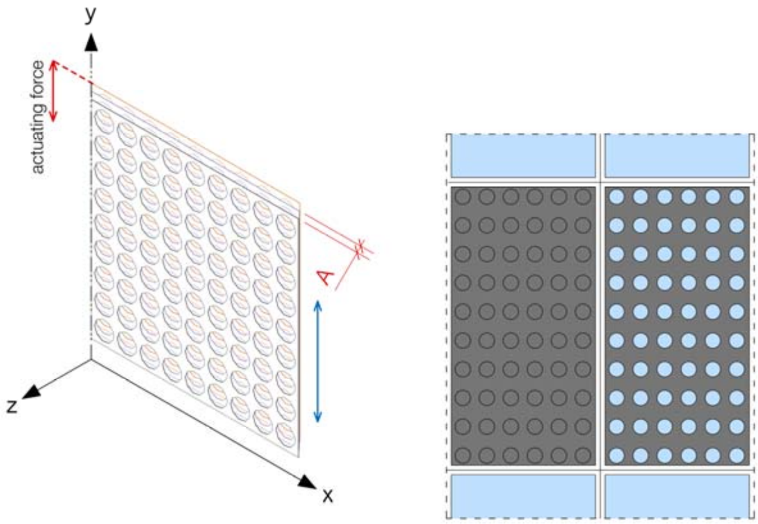

Figure 10: Project (J): Smart Screen [143]. Scheme of operation and example of facade's integration (closed and open configuration).

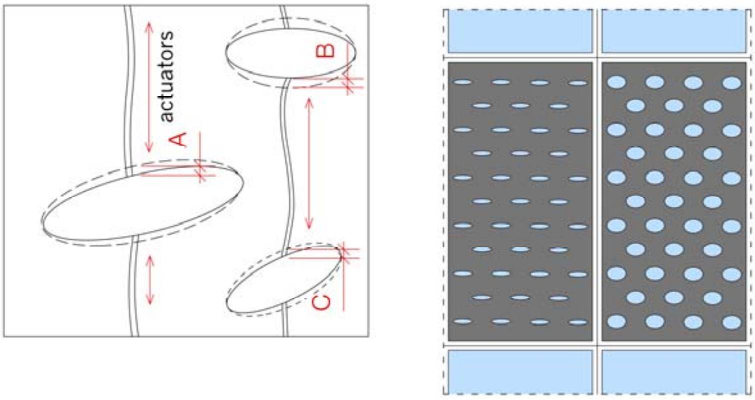

Figure 11: Project (K): Piraeous Tower [147]. Scheme of operation and example of facade's integration (closed and open configuration).

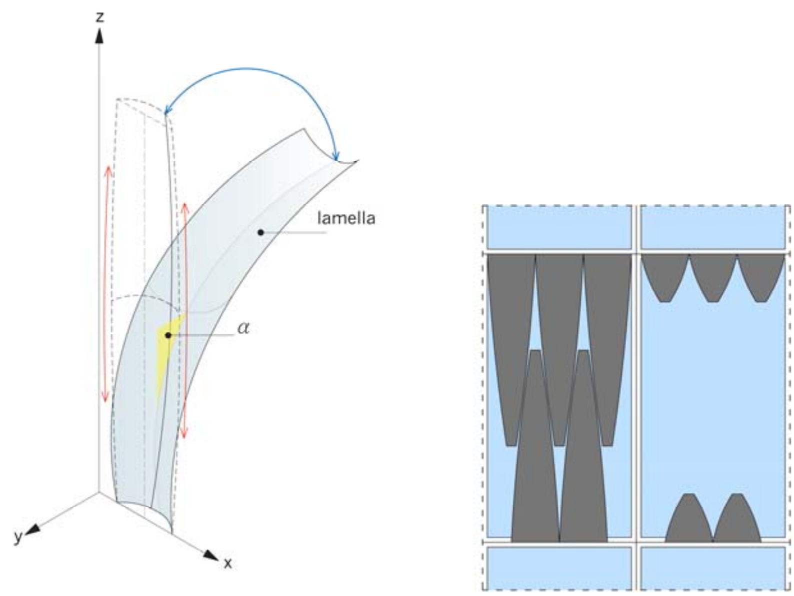

Figure 12: Project (L): Lily Mechanism [148]. Scheme of operation and example of facade's integration (closed and open configuration).

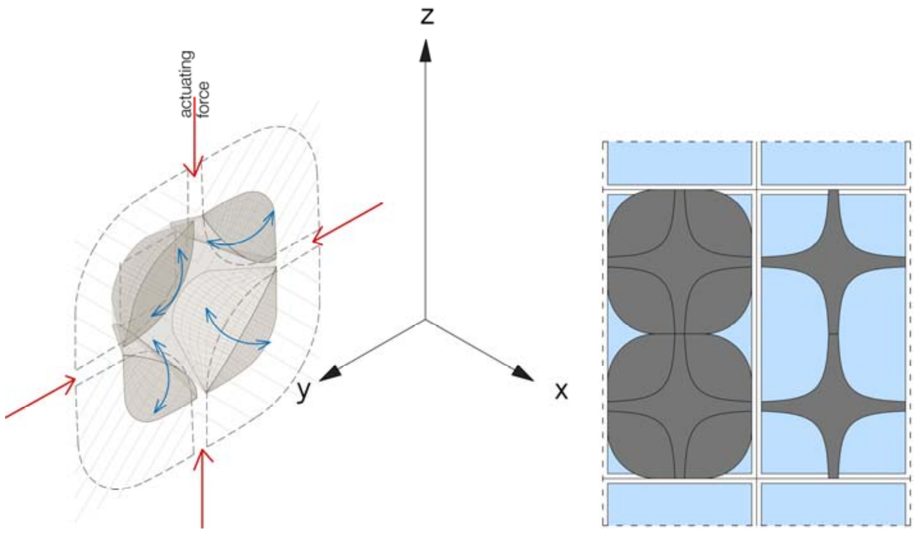

Figure 13: Project (M): Curved-line folding [149]. Scheme of operation and example of facade's integration (closed and open configuration).

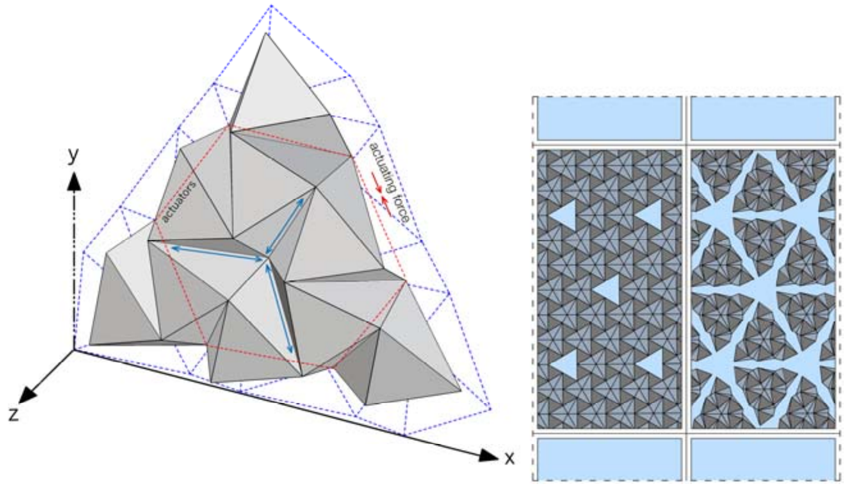

Figure 14: Project (N): Kinetic Solar Skin [150]. Scheme of operation and example of facade's integration (closed and open configuration).

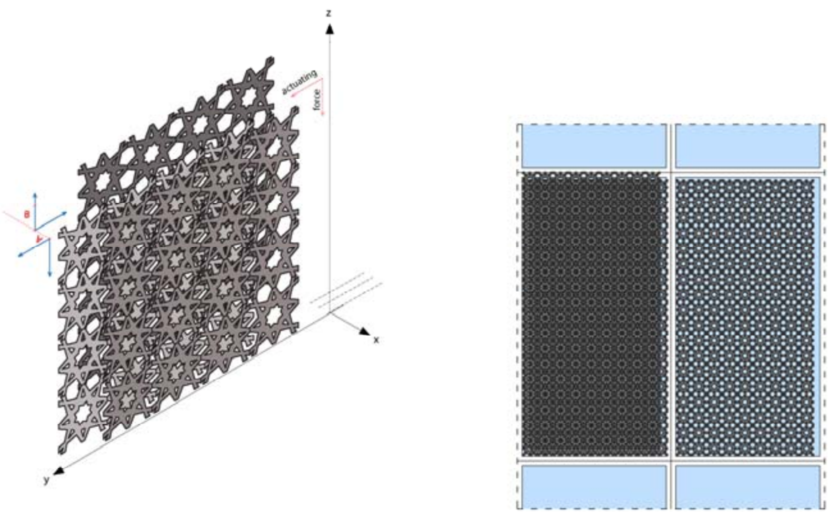

Figure 15: Project (O): Shape Variable Mashrabiya [151]. Scheme of operation and example of facade's integration (closed and open configuration).

3.1. Movement of actuators and shadings

Movement of shadings can be grouped according to the typology, differentiating between translational movements (able to perform a bi-dimensional change of shape) and rotational movements (characterized by a tri-dimensional change of shape).

Both typologies require an actuator, which can be completely embedded into the device or strategically located to trigger a specific action.

An external stimulus in the actuator causes a variation in its volume, which turns into a translational motion producing movement.

Bi-dimensional movement (projects J, K and O) is linear and allows adjusting permeability levels of the experimented building-skins by size-opening variation (K) [147] and by overlapping layers (J, O) [12, 143, 151].

On the other hand, three-dimensional movement can be described as a swivel motion, both in the same axis (projects A, B, L, M) [137, 138, 148, 149], and/or around a different axis (projects C, D, E, G, I, N) [139-141, 143, 146, 150].

All the selected projects present one or two degrees of freedom in the desired movement, varying between two extreme positions, open and closed modes, with continuous transition between the two positions. Where movement is three-dimensional, a constrained swivel motion produced by bending and buckling of elastic materials characterizes rotation. An exception is case (F), in which hinges are used to rotate stiff wings [142].

If the systems aim to be responsive to external conditions, modulation would need to be taken into consideration. Simple rotation and/or translation movements define opening ratios at component scale according to the different shapes proposed for each project.

For all the selected projects, the shading ratio varies from generally about 100% in closed mode, to a variety of opaqueness percentages (from 5% to 50%) determined by the shape of each component in open mode.

The majority of the selected projects performing three-dimensional movements have been developed either at component or sub-component scale, due to the discrete sizes and capabilities of smart materials as actuators. On the contrary, translational movements are more suitable for larger scale projects (movement at sub-system or system scale).

Scale of projects and selection and sizing of smart actuators strictly depend on the weight of the developed facade systems. Prototype of projects (A) was developed using a very lightweight Glass Fibre-Reinforced Polymer (GFPR) profile. Thicknesses were defined according to the length of the fin, in the range between 2 and 8 mm (for fins long respectively up to 2 m and up to 14 m). This resulted in an overall lightweight profile (ranging between 3.8 kg/m^2 and 15.2 kg/m^2) [137]. The same lightweight material is used in project (B), with thicknesses variable from 5 to 10 mm, resulting in an average aerial weight of the facade component of about 15 kg/m^2 [138].

Projects (D), (E), and (K) concentrate on the production of flexible lightweight components, usually composed of a curtain of silicon rubber [140] or thermoplastic resin [147] supported by a structural skeleton. In this case, the overall aerial weight of the system can be reduced to less than 3 kg/m^2 and small scale sensors, like SMA wires can be more profitably adopted.

Project (L) uses a combination of two materials (GFRP and PMMA) with different thermal expansion coefficients and thicknesses (respectively 2 mm and 13 mm) [148]. In this case, the overall aerial weight is about 20 kg/m^2 for a 2 m long fin. The system is self-actuated by temperature change and the increase of weight has no significant effect on the ability of the system to change shape.

Projects (M) and (N) have been developed using cardboard (less than 1 kg/m^2 of weight) for producing small mock-ups as a proof of concept [149, 150]. Also in this case, the key point for the optimization of the movement will be the selection of a thin lightweight profile.

3.2. Biomimetic approach in the selection of shapes and materials

A selection of properties and design approaches inspired by nature would make hingeless movements feasible. Anisotropy and multifunctionality are therefore the most efficient strategies.

Considering the described biomimetic approaches illustrated in paragraph 2.3, anisotropy can be classified as a bottom-up approach aimed at taking into abstraction reversible and repeatable movements found in nastic structures, by means of materials properties and distribution within the component, like in projects A, B, and L. Movement is produced from the material elasticity and from the fibres' arrangements while minimising stress when movement is produced, just like the plants used in bio-inspiration.

Research carried out using a biomimetic bottom-up approach are characterized by the use of an iterative process, starting from the reproduction of movement, and followed by the optimisation of shape and by the selection of materials.

Flectofin® (A), Solar Kinetic (B) and Lily Mechanism (L) projects were inspired by existing studies in plant movement, selected from previous investigations on nastic properties of Strelitzia Reginae flower [137] and Aldrovanda Vesiculosa carnivorous plant [138], and Lilium Casablanca flower [148] respectively.

The three examples can perform fast actions and are, therefore, suitable for applications responsive to the continuous changing position of the sun. The bottom-up approach used in the projects (A), (B), and (L) is composed of three main steps. Firstly, properties of plants allowing reversible movements were identified and transferred into basic models, either analogue (A) or digital (B) and (L), testing their feasibility of being reproduced. Afterwards, researchers carried out an optimisation of movement, by means of further studies on how plants show anisotropic arrangement of material and fibres to reduce material stresses. This last task was carried out either with the aid of computer simulations or using prototypes. Finally, configuration and array of sub-components were tested, to explore ways of covering the entire facade with the proposed shadings.

Although there are projects inspired by natural principles different from those classified as nastic structures, such as homeostasis [152] and collaborative work of insects [147], movement in these cases is still produced using elastic properties of materials working at high strain. These projects are inspired by nature using a top-down approach, in which case the aim is to replicate integrated and multifunctional characteristics found in nature.

A top-down approach can be identified in projects D, F, G and K using analogies from various natural sources, but not related to movement in all cases. However, multifunctionality is considered a predominant feature in all projects, mainly incorporating smart materials for sensing and actuating the systems.

All the selected projects experiment the use of polymers as constituent materials for their components. The main reason is for exploiting the elastic properties in tension and low stiffness in bending, enabling the desired movement to be achieved. Formed and amorphous polymers were used, with layered compositions to reproduce anisotropy of plants. A second material can be found either as protective layer or as actuator. In all the analysed case studies, materials like glass fibre reinforced polymers (GFRP), silicones and elastomers, were used with thicknesses of no more than 10 mm.

3.3. Integration of smart materials

There are several applications using smart materials and extensive research has already been carried out in morphing wings for space and aircraft applications, biomedical devices, textiles (smart clothing) and structural repairs for buildings [153]. In the field of architecture, smart materials have been mainly experimented for the operation of shading devices. Some prototypes have already been experimented. However no practical application on existing building has still been implemented.

The most commonly used materials are SMMs, in particular SMAs (in form of wires and springs embedded into other materials or as stand-alone actuators) and SMPs.

Nespoli et al. [154] reviewed several strategies for integrating SMAs in more sophisticated mechanical components, emphasizing their potentialities as "mini-actuators". These characteristics can be transferred to the fields of civil engineering and architecture, mainly embedding smart materials as continuous layers – like in the project (I) [146] – or as discrete actuators, like in the projects (H) and (N) [144, 150].

The central role of Shape Memory Materials in the analysed project depends also on stimuli used to trigger the movement.

Thermal triggering has been discovered as the most widely researched and developed method for changing shape of solar shadings. In fact, a temperature gradient can be directly provided by direct sunlight exposure. Different activation temperatures have been tested in the analysed projects. For instance in project (K) action would occur between 35ºC and 40ºC [147], whereas in (H) SMAs would move when reaching more than 90ºC [144, 145]. In project (L), researchers have planned to use a Shape Memory Hybrid combining two materials with different thermal expansion behaviours, like GFRP and PMMA, capable to trigger the movement when materials' temperature exceeds 70°C [148].

It should be noted that variable external conditions could limit the efficiency of any system intended to produce movement by means of heat and solar exposure. In fact, not always a univocal relationship between devices' temperature and solar irradiance can be established.

In projects like (B) and (H), heat was, instead, generated indirectly from electricity produced by a photovoltaic converter. Other examples, like (D) and (P), are directly activated by electricity, but no relationship with solar power was sought.

The generation of heat through electricity would add a component to the system, and integration strategies are not completely clear. Finally, control is generally considered to be automated and responsive to outdoor conditions, and this does not require any central brain to control the whole facade system. Despite this, occupants' control is highlighted to be potentially available, mainly for ventilation purposes [147], even if no practical application has been yet proposed.

4. Conclusions

The attention to building energy performance in the last decades has led to new types of building envelopes to be interactive and responsive using natural energies like solar radiation, daylight, and seasonal wind.

New approach in responsive, adaptable facade systems by using hingeless, integrated and bio-inspired systems has not been extensively developed. Therefore, this can be considered as an emergent and new research topic.

Based on the analysis of the case studies considered in this paper, it can be concluded that movement suitable for sun-control purposes can be produced at component scale through lightweight and elastic materials. The adoption of these materials allows fabrication of components with an anisotropic composition, like differentiated thicknesses and a predominant fibre distribution in a desired direction. The optimisation of movement, through a reduction of material's stress and the use of new low energy triggering methods such as smart materials actuators are other unquestionable benefits.

Biomimetics, having nature as an inspirational source to look for proved and optimised technical solutions, appears as a discipline, which addresses new research work. Nastic structures and their reversible movements represent a recurrent model to be mimicked, presenting solutions to be abstracted. Elastic reversible movements, integration of systems and optimised distribution of materials are common issues that can be solved through this approach.

The comparison of selected projects has enabled the recognition of efficiency associated with several working principles. Projects following a biomimetic approach are able to develop more accurate and efficient systems.

Smart materials, e.g. alloys and polymers, have been shown to possess the characteristics to work as actuators, either separated or integrated into shading components. Through their memory shape effect and speed of actuation, these actuators are able to produce ranges of movement and responsiveness suitable to be applied in dynamic shading facade systems.

Although there are a few examples of applied use of smart materials in shape morphing solar skins [94], many researchers are working in this direction addressing the development of future building skins toward environmental responsive façades. Further studies need to be carried out on the use of shape memory actuators in building sector, especially for their solar activation, life cycles and resistance to external weather conditions. As in the last decades, Shape Memory Alloys have been extensively tested and used, and these can be currently considered as the most suitable materials for shading applications. Despite this, Shape Memory Hybrids, together with thermo bi-metals, can present future interesting opportunities, due to their user-friendly customization.

The review of studies, surveys and analyses related to the prevision of use of shading devices by occupants highlight the importance in understanding the level of users' consciousness of smart materials' adoption. Based on this, the interface of smart materials with intelligent shading components should be further investigated.

Literature has shown that users' behaviour is an important aspect of the overall process, because the lack of interaction between system and occupants brings to an inefficient use of the building. Occupants have demonstrated a low tolerance for outer changes despite the advantages in using automated shading control. This brings users to override the automatic settings. Future studies must be set on the quantification of thermal and comfort indexes, collecting data coming from records of user's override (in terms of occlusion, rate of change, and physical measures). The aim should be the definition of threshold comfort levels that prompt shade movement.

Thus, future smart solar skins should be designed to minimize glare phenomena and it will be fundamental to design the next generation of facades relying on the occupant shade use patterns.

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