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Active materials for adaptive building envelopes: a review

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- ✓ Adaptive buildings,
- ✓ Active materials.

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Abstract

The adaptation of building envelopes is nowadays driven by the transposition of properties from the microscale to the macroscale realized by architects through the hand of the state-of-the-art of material science and engineering to improve building performance. In this way, this decade has seen significant advancements in adaptive and multifunctional facade systems through the incorporation of active materials, which do not need complex electromechanical systems or additional energy supply because they are kinetic systems by itself. This article presents a comprehensive overview of passive and adaptive building envelope systems through novel information focused on the systems which use active materials. Their current progress and incorporation to enhance buildings adaptation to its environment are discussed. The advantages, limitations and future research directions are analyzed as well.

1. Introduction

Architecture has had evolved and developed to satisfy human and city necessities since its origin. Every day new essentials in addition to severe weather changes need to be taken into consideration by designers to ensure the comfort of the building. In the last decade, this process has taken interest by the scientific community and the construction industry due to the complexity of the "modern life" and their impacts on the environment [1]. For those reasons in response to these fluctuating variables, the architecture needs to adapt permanently to satisfy these needs. The buildings adaptation as the relationship between architecture and the environment is through its envelope, the element which limits the inside and the outside [2,3], design to afford comfort and security inside buildings. It's a crucial component that relates the buildings aesthetics with its internal environment. Like the skin is to the human body, an envelope has the responsibility to regulate internal physical conditions [4]. Since the last century, it has become a lightweight and flexible component, instead of robust and heavy system, to improve its performance [5]. These buildings´ systems are being developed together with disciplines such as materials science and engineering achieving every time more interactive and efficient [6,7].

This review article addresses the systems and materials used in the building's adaptation to the environment in concordance with the state of art technology of last decades. Methods, structures, as well as, experimental projects and remarkable examples focused on the facade or the architectural envelope are highlighted. A brief overview of facade development in the last century is introduced, and passive dynamic systems as the most promising research direction are presented. The reported systems are classified, described and analyzed by every variable of control and the physical or chemical principle followed to obtain a dynamic response.

2. Responsive building facades

Until recent times the attention to improving a building's envelope was focused on increasing thermal insulation. Nevertheless, those systems are not enough to solve the efficiency challenges in the nowadays buildings [8] because of the remarkable use of glass and the increasing of additional energetic dependence on heating, ventilation, and air conditioning (HVAC) systems after the modern architecture movement [9,10] including concepts such as the Zero Energy Buildings (ZEB) [11] based-on precise thermal knowledge of the building comfort needs [12] and integration with alternative energies [13] and green technologies [14].

A noticeable change on architectural skins appeared during the second half of the XX century by some postmodern architecture movements [15]. Systems equipped with sensors, processing units, and actuators that can be programmed and have the ability to answer to real-time weather conditions were incorporated into the envelope. These systems allowed the obtention of a new dynamic interface between the building and their surrounding environment [16]. They are based on Data Acquisition Systems (DAS) of a closed loop protocol [17], based on an integrated system where the stimuli are sensed, and their processing is used as a control device.

The versatility of the DAS protocol has been demonstrated in the last decades, as seen in several building active facades [18–22], which enables the development of systems with different kind of actuators (mechanical, pneumatic, and hydraulic). Broad-Spectrum envelope materials and sizes from *brise-soleil* unto laminar structures of some floors have been used. Moreover, multi-layer systems have been used to achieve a real-time response to solar radiation and outdoor temperature firstly [23], because of their influence on thermal and visual comfort.

Nevertheless, all of them requires, firstly an external electric current source to operate [24], and secondly, they are made of mechanical systems with multiple components with high maintenance rate. Both conditions take these active systems to a rapid state of obsolescence [25], for instance, the Arab World Institute, 70´s pioneer building, where the active elements on the envelope were abandoned a few years after the project opened because of the burdensome maintenance. For these reasons, current research developments of building envelopes are focused on more efficient systems exploring flexible and jointless solutions with no electronic components by the hand of other disciplines.

Passive responsive facades

Even when active systems changed the conceptualization of architectural envelopes in the second half of the XX century and continued being used nowadays, the energy supply dependence and obsolescence triggered a new change on the perspective of the building skins development [26]. So that, now to translate properties from nano- to macro-scale is the new challenge to architecture as a discipline to adapt in a passive way [27], by the hand of material science and engineering as an active member of this multidisciplinary development [28], this work has been focused on the research and application of smart materials with a reversible change in shape triggered by external activation, these systems come as a response due to the increase in energy demand in buildings by the use of HVAC systems.

A hierarchical classification of this materials can be seen in Figure 1, [29] proposed a classification of smart materials by their use in architecture and a brief overview was done, but it was not focused on shape memory properties, and a review of the new reports must be done. It is based on the study and application of materials from microscopic to the macroscopic scales, presents kinetic systems that can move without motors, electricity or mechanical parts improving buildings´ performance [30].

In accordance with [31], passive systems of dynamic activation that works with intrinsic properties of materials are perhaps the most promising direction for the development of adaptive building envelopes. Hence, at this moment building envelope can be considered a protective barrier just like the skins is for the human beings, this kind of systems can take buildings to an autonomous homeostatic state without additional energetic sources and be able to adapt to their specific environment.

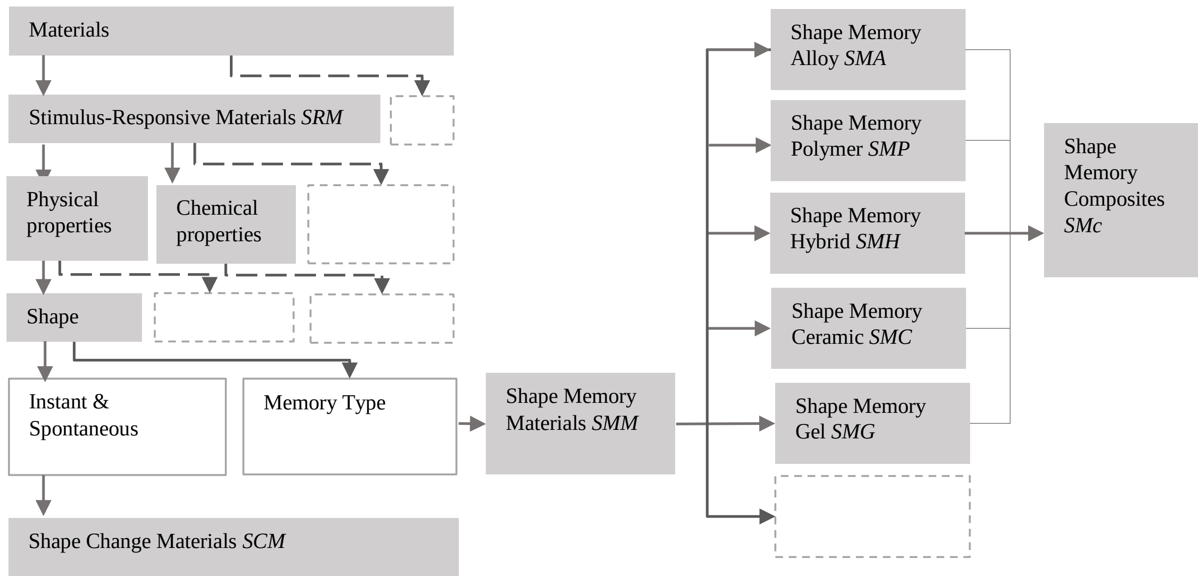


Figure 1: Hierarchical location of stimuli-responsive materials on the materials world. Adapted from [32].

3. Passive responsive activation protocols

Building performance can be improved with the use of passive systems to reduce energy consumption levels, greenhouse gas emissions [33], and new dynamic building interfaces that control outdoor conditions can be done [34]. However, prior to the application in buildings, performance prediction must be made [35], nevertheless this field is in an early stage. New developments must be focused on the integration of design, material selection, operational features [36], and the effect of the human behabior [37] because of the substantial differences between active and passive kinetic systems.

In active systems sensors and actuators are part of an integrative system, but in the case of passive ones they are the system by itself, for this reason, they do not follow a general activation protocol it is relative to the each material´s properties, because from microscopic to macroscopic scale they merge sensing and actuating functions [38].

Nano- and smart-materials application into architecture and building as a new field have been classified by [39–42]. Despite those classifications, in architecture skins these systems are being used to control physical variables, for this reason, the classification of the newest reports is done by control weather variables and the chemical or physical protocol followed by the material proposed to achieve it. As can be seen in Table 1, the passive systems reported are listed and then break down by each protocol of activation.

Physic Variables, protocol, and materials used by passive responsive systems. Current uses and experimental proposals in architecture. It does not mean that other variables which affect building comfort cannot be controlled with this kind of passive responsive systems.

3.1. Humidity passive control systems

3.1.1. Hygroscopic-based protocol

Hygroscopy is the ability of physical systems to absorbed humidity from the environment or gives it back. Systems that attract water such as steam or liquid from their medium are hygroscopic. Wood is a material with that feature through the cellulose as its constituent; it can attract water molecules from the environment when it is dry and give them to the environment when it is wet to be in equilibrium [43]. Hygroscopy properties of different classes of wood were evaluated by [44].

Table 1: Passive control systems reported

Variable	Protocol	Class / effect	Material	Author
Humidity/Rainwater Control/ Airflow Control	Hygroscopy	Shape memory Hybrid	Co-polyester composite with high cellulose content	[45]
			Fagus sylvatica veneer - Polyethylene Terephthalate	[46]
			Lime veneer - nylon - plastic	[47]
			Birch veneer - Epoxy resin-Fiberglass textile	[48]
			Fagus sylvatica, Acer pseudoplatanus, Picea abies veneer - polyurethane HBS309 / HB-S709 Henkel®	[49]
			Picea abies, *Fagus sylvatica* veneer - polyurethane HB-S709, Henkel	[50]
	Hydrophilicity	Shape memory Gel	Sodium Polyacrylate	[51]
			Sodium Polyacrylate 1mm powder, 7mm Crystals, 20 mm Spheres - Clay - Rubber	[52]
			Sodium Polyacrylate - Gelatin - Glycerin - Elastic hydrophobic fabric	[53]
		Shape memory Hybrid	Silicon - Latex - Expanding Hydromorph composite	[54]
Temperature / Air flow control / Heat-gain	Differential Thermal Expansion	Shape memory Hybrid	Thermobimetal strips	[33,55]
	Reversible non-diffusional phase-change	Shape Memory Alloy	Nickel-Titanium NiTi	[56–67]
Sunrays / Heat-gain control	Reversible non-diffusional phase-change	Thermo-chromic effect	Al-doped VO_2	[68]
			VO_2 -ZnO	[69]
			VO_2 Single Crystals	[70]
			W- and F-doped VO_2	[71]
			VO_2/SiO_2 composite	[72]
Sunrays / Heat-gain control	Reversible non-diffusional phase-change	Thermo-chromic effect	VO_2	[73–77]
			W- VO_2	[78]
			Zr-doped VO_2	[79]
			Eu/Tb/W- codoped VO_2	[80]
Sunrays / Heat-gain control	Reversible non-diffusional phase-change	Thermo-chromic effect	Hydroxypropyl cellulose	[81]
			Crosslinked polymer	[81]
			WO_3 - O_2/Ar - H_2/Ar	[82]
			Thermochromic pigments	[83]
Sunrays / Heat-gain	Phase-change		Waxes, Paraffin, Salt hydrates	[84,85]
			Shape-stabilized PCM	[86]

			Paraffin wax/expanded graphite	[86]
			Paraffin wax/polyurethane	
			1-Tetradecanol	
			Hexadecanol	
			Caprylic acid	
			Capric acid	
			Butyl Stearate	
			Capric-stearic acid/White Carbon Black	[87]
			Paraffin	[88,89]
			Paraffin / polymeric matrix	[90]
			$MgCl_2$-$6H_2O$ / $CaCl_2$-$2H_2O$	[91]
			1-Tetradecanol / bisphenol A /Wood	[72]
			Paraffin-wax capsule / Concrete matrix	[92–94]
			Organic paraffin	[95]
			Paraffin MG29	[96]
		Latent heat thermal energy storage	Azobenzene dopant - Paraffin /Wax	[97]
Light / heat-gain control	Attraction-repulsion electrostatic forces	Shape memory Hybryd	Elastomer- Corrugated Silver Electrodes	[98]
			VHB Elastomer / Carbon Black / Silicone - Cooper electrodes	[99–103]
			EAP/PET/ETFE	[104]
	Ion Extraction /insertion	Electrochromic	Alumina	[65]
			W oxide /Ni oxide	[105]
			Sage® Glass	[106]
			WO_3	[107]
	Elongation Induced by thermal transitions	Shape memory polymer	Polyurethane	[108]
			Veritex® SMP	[109,110]
			Polyolefin shrink tape	[111]

This property is usually seen as a disadvantage for building materials, so thermal treatment was elaborated to study its effect on the hygroscopic properties of some wood species to inhibit it to react with moisture [112]. Nevertheless, the cellular structure and the wood fiber orientation allow a dimensional change up to 10% in the grain perpendicular orientation [113]. Expansion and contraction in a specific direction can be obtained by anisotropic deformation controlled by cell wall architecture through cellulose swelling and shrinkage [114]. In this way, changes in the cellulose volume by humidity exchange allows movement, for instance, the pine cone scales hydrated/dried behavior [115] is presented in Figure 2.

Recently by this protocol different authors have reported the application of hygroscopic properties on buildings passive control [116–118]. As remarkable examples, three types of individual laminate pieces systems with specific fibers direction were reported as a principal component to obtain moisture responsive with autonomous movement. On the one hand, architectural skin with closed modules under low humidity conditions and open modules under high humidity conditions as can be seen in Figure 3 was reported [45]. On the other hand, [47] achieved a dynamic architectural surface and a sensor of moisture made of a matrix of tiles elaborated with of lime veneer, nylon, and plastic with hydro-sensitive capabilities because of different porous densities.

Several classes of veneer wood: *Prunus serotinal*, *Acer saccharum*, *Juglans nigra* and *Fagus sylvatica* with specific fiber orientation were evaluated and analyzed to shaped up a bilayer dynamic system with Polyethylene Terephthalate layer as support [46]. This bilayer composite allows the development of a module that can be seen in Figure 4 in a closed and open position; this system can be applied in an envelope system sensible to humidity. Other studies focused on different bilayer veneer made of *Picea abies Karst*, *Fagus sylvatica*, and *Birch* veneer were reported [48,50], and hygroscopic actuated wood elements with simple upscaling shape [49].

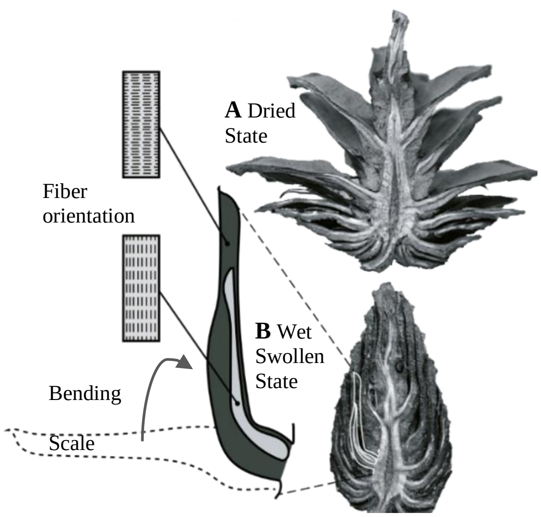


Figure 2

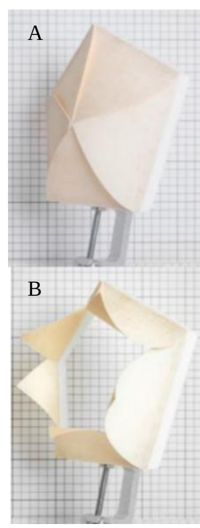


Figure 3

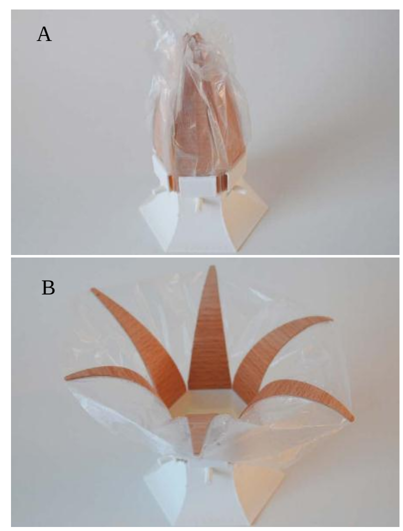


Figure 4

Figure 2: pinecone scales. Axial cut view, dried and swelled state, upper and lower tissue cellulose orientation can be seen on one scale. The first one is located parallel to the scales axis, and the second one found perpendicular. Because both tissues are linked, the system shrinks in the axial direction of each tissue allowing bending when are wet.

Figure 3: 3D printed programmable hygroscopic material, through additive manufacturing of a co-polyester composite thermoplastic with high cellulose content from wood fibers, layers with different orientation and thickness was obtained as well as a multidirectional movement [45] with two positions A low humidity, B high humidity

Figure 4: Motion with Moisture. Responsive biomimetic bilayer module view, A close final module, B completed open final module [46].

3.1.2. Hydrophilic Swelling/shrinkage-based protocol

Synthetic superabsorbent polymers such as hydrogels were introduced in the 70´s in replace of cellulosic fibers, which based their absorption properties in their hygroscopic behavior without significant swelling of their fibers [119]. Hydrogels are water-absorbing polymers that can swell in water, for instance, crosslinked sodium polyacrylate gel is the most used in the pharmaceutical industry and can absorb 10 -1000 % of water above their original weight [120].

The polyacrylic hydrogels are commonly obtained by aqueous polymerization of acrylic acid and crosslinked with vinyl groups. the result is an anionic polyelectrolyte with negative charged carboxylic groups in the main chain [120]. Carboxylic group ionizes with water, and the negative charge makes they

repel each other compelling the polymer net to expand, then polar water molecules are attracted to the negative charged carboxylic groups, and stay caught into the chains between crosslinks as can be seen in Figure **5**, without those crosslinks, the polymer would collapse [119], and dissolution would be obtained. So that, more crosslinks conduce a less water absorption.
This class of environmentally-sensitive polymers [121], were incorporated in dynamic envelope systems with two different approaches based on their properties. The first focused on the capacity of the material to retain large amounts of water, and the second one on the change of volume by swollen. The first approach consist of a multi-cavity system that catches rainwater; it is made of clay and filled with hydrogel spheres [52]. The system is focused on the passive cooling of an envelope module looking for the storage of water in a long-term and their slowly release through the day to improve thermal exchanges between the building and the external as shown in Figure 6.

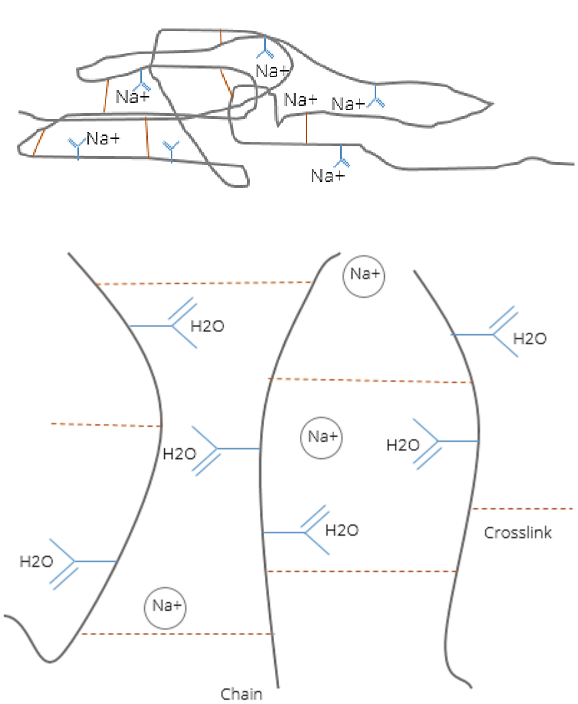


Figure 5

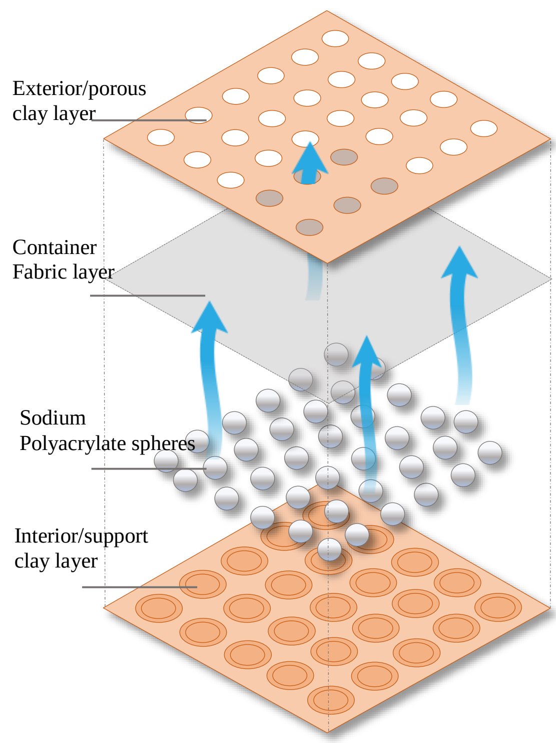


Figure 6

Figure 5: Sodium Polyacrylate Swollen process. A. Polymer chains in coiled chains state (dry). B. Swollen polymer ionized with water molecules caught by carboxylic groups into their crosslinked network (wet)

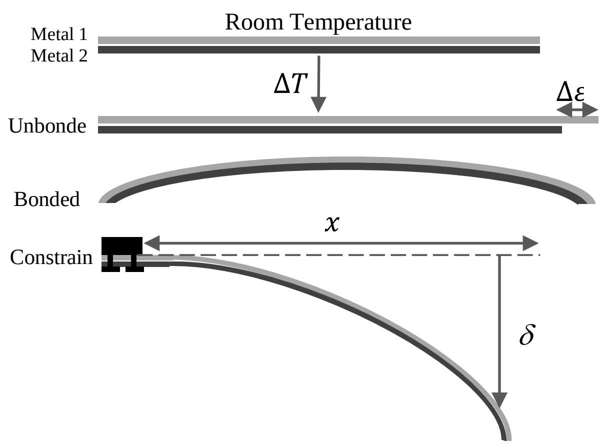
Figure 6: Hydroceramic. Scheme of the components of the cooling systems module, sodium polyacrylate spheres held into clay layers for the slowly water/moisture releasing. Adapted from [52].

The second approach consists of a force generating systems [51,53]. The devices are based on an acrylic piece attached to hydrophobic fabric pockets filled with sodium polyacrylate spheres with a mesh in contact with it. When the humidity goes through the mesh, the change of volume of the pockets is triggered and the systems can allow movement from one side to another or can open to allows air-flow. A different system which uses the generating force of hydrogels was reported [54], a surface made of a matrix of silicone scales fixed by a composite based on polyacrylates was proposed. When the surface is in contact with water or moisture the composites net points swell, and the scales can open and close when it shrinks.

3.2. Temperature passive control systems

3.2.1. Thermal expansion protocol

Hybrid shape memory material is a class of stimulus-responsive component made of two different materials which do not have shape memory independent capabilities [32]. Bi-metallic shape memory strips are made of two metallic pieces with different thermal expansion coefficient bonded by an elastic adhesive. The system operation is based on the asymmetric stress distribution between both surfaces, because of the expansion/contraction of each strip independently by thermal gradient differences. This phenomenon allows shape changes such as bending, as shown in Figure 7, by direct or indirect heating. This principle has been applied to the scope of obtaining architectural surfaces with active thermal features triggered by sun rays as well as weather thermal changes. An early report focused on the behavior of thermo-bimetals in architecture was done by [33], after that, a matrix made of crossing panel pieces of bimetallic strips were applied in an experimental pavilion. The proposed pavilion had a surface were closed modules were achieved when the temperature goes down and porous ones when it rises, as shown in Figure 8, the proposed system enables sun-protect by shading and natural air circulation. Another bimetal application was reported, commercial bimetal flat springs were incorporated into a matrix of intertwined bar elements [55], the system was developed to be a deployable windows system and enable sun-rays protection.



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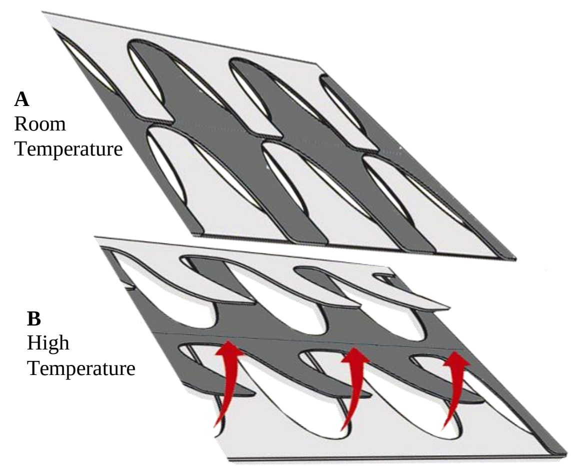

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Figure 7: Bimetal Strip. Two metals bonded together with different expansion coefficients.

Figure 8: Bloom Research Installation Los Angeles. Panel behavior Position A. Room temperature, closed module, Position B. Hight temperature, opened module.

3.2.2. Reversible phase transition protocol

Shape memory Alloys, stress-induced martensite

This protocol bases their operation on the use of Shape Memory Alloys (SMA) a class of SRM as their active component. SMA has several features such as shape memory effect (SME), superelasticity, and high-damping capacity [122]. The first has been used to achieve a bi-directional movement by a martensitic reversible transformation because of warming or cooling. This phenomenon is responsible for the SME. The second has been applied in infrastructure like bridges, and robust behavior was demonstrated under dynamic loads [123].

The process of change of shape starts with a martensitic transformation which takes place in a face-centered cubic unit cell structure, solid state austenite, by cooperative atoms movement without any compositional change. A uniform distorted crystalline network is achieved because atoms are moved within inter-atomic distances, producing a new martensite phase as can be seen in Figure 9, it does not mean that the movement occurs at the same time, but, the transformation spreads through the network [124].

The uses of SMA in architecture either as a dynamic system by itself or as a part of a bigger one has shown an important improvement in performance and energy consumption [125]. Nickel-Titanium alloy (NiTi) is the most reported SMA in responsive envelope systems following the non-diffusional phase transition protocol as an actuator because of its reliable mechanical performance [32]. Several dynamic surfaces, focused on the control of heat and light on buildings reported using NiTi matrix as an actuator. These systems base their operation on prestressed springs or wires which try to recover their original shape because of thermal fluctuations generating mechanical force in the process.

The use of prestressed springs as a bracket in a flexible laminate fabric were reported [56] [63] [58] [59]. In these systems, when the temperature increases up to 45°C, the austenite phase for this composition, the springs return to their original shape allowing changes in the orientation of the laminate of every module as shown in Figure 10. The use of NiTi as wires [60] and springs [61,64–67] were reported and was applied in more stiff and robust panels skins shown in Figure 11, dynamic indirect illumination and heat-gain control by shadowing were obtained because of the mechanical force obtained by NiTi phase transformation. Finally, the relationship between building and users was explored as well using SMA actuators into integrative systems [57].

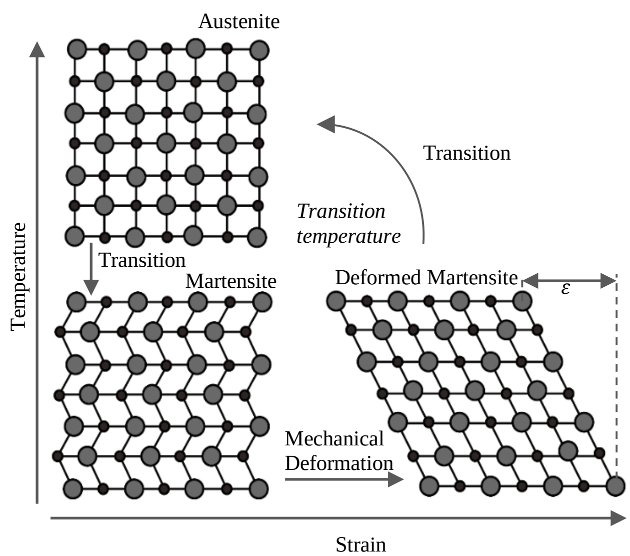

Figure 9

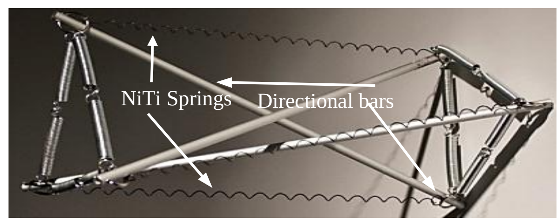

Figure 10

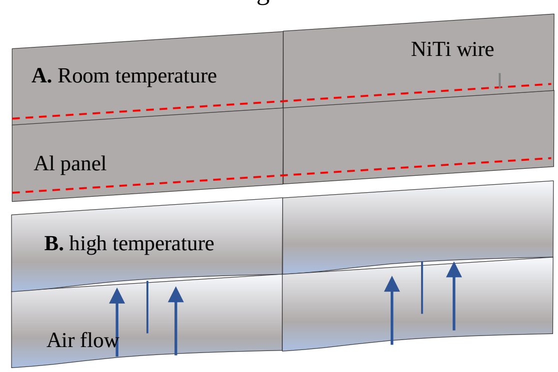

Figure 11

Figure 9: non-diffusional phase change Austenite – Martensite deformed. The system changes shape macroscopically, as the martensite grows or decreases, with a mechanical strain. The evolution of form can be created in a specific direction obtaining deformed martensite; for this reason, the material needs to be deformed previously as training.

Figure 10. Adaptive [Skins]. The dynamic control unit, operated by NiTi springs, Adapted from Cohan, Joe (2013) [126]

Figure 11: kinetic facade actuated by NiTi wires A. close module wire stressed. B. Open module wire contraction.

The thermochromic effect, monoclinic to rutile phase

Inorganic materials can change their optical properties because of temperature variations. Electronic properties of these materials at different temperatures cause the thermochromic effect [127], some of them exhibit a more drastic change of color and variations on their optical properties such as transmittance and reflectance. For instance, vanadium dioxide VO_2 and trioxide VO_3, because of their drastic changes are the most studied inorganic materials with optical temperature-dependent properties [82,128,129].

Vanadium dioxide has a start critical temperature of 68°C for phase change from semiconductor low-temperature monoclinic phase to metallic high-temperature rutile phase shown in Figure 12. Differences in optical properties are achieved because of changes in V-V bonds angles and interatomic distances [130]. In applications where a thermochromic effect is needed such as smart windows, the critic temperature is too high in contrast with room temperature, decisive to ensure the building´s thermal comfort. This is not the only disadvantage of these class of smart coatings, the low transmittance in the semiconducting state and low reflecting rate in the rutile limits their applications on facades of buildings.
For those reasons to enable its use on smart windows, several investigations were focused on the most critic features as transition temperature, light transmittance rate, as well as alternative synthesis methods. The pure VO_2 polymorphous coating cannot achieve those goals, so the general performance has been improved by doping or adding other materials. The incorporation of zinc oxide polycrystalline film as a buffer layer between the glass and VO_2 [69], and sol-gel alternative synthesis process with tungsten doping [71,76,78], has shown thermal transition reduction, higher transmittance rate, and improved hydrophilic properties of the coating. Likewise in the synthesis field, the introduction of impurities in the VO_2 single crystals growth [70] does not have effects on the energy behavior.
Critical transition-phase temperature has been studied through the doping of VO_2 with: Aluminum where a reduction of temperature and higher transmittance rate were found [68], Zirconium ions were the temperature is reduced without modifies the transmittance [79]. Rare-earth and tungsten (Tb/w, Eu/W) codoping has shown temperature reduction and transmittance enhanced in 60% in the visible range as well as the doping with SiO_2 with a 55.6% of transmittance [80,131]. Regardless of these limitations, the incorporation of thermochromic coatings to building glazing can reduce the energy dependence for HVAC [132], through these systems, reduction on the thermal gain can be achieved by blocking sunrays as shown in Figure 13. For these reasons, their application in real buildings was studied through dynamic simulation [73,74] and real scale application [75], they concluded that near-infrared spectrum thermochromic windows are more efficient than visible-light coatings, achieving 20% additional energy savings.

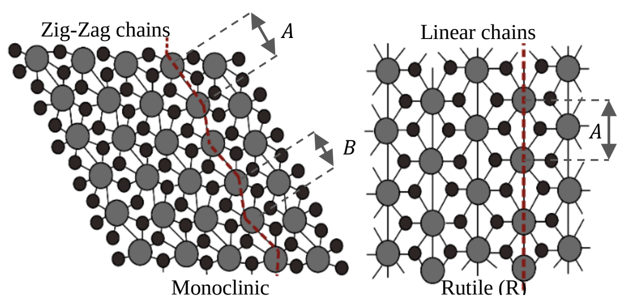

Figure 12

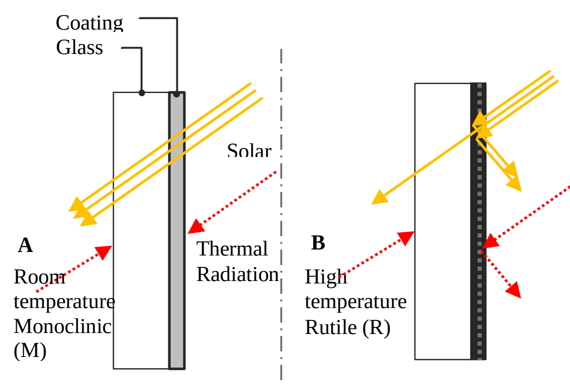

Figure 13

Figure 12: Low-temperature, monoclinic phase (M) zig-zag V-V chains, with two different interatomic distances Insulator/Semiconductor to high-temperature Rutile (R) phase, linear V-V atom chains Metallic

Figure 13: Thermochromic glass coating. A transmittance mode, B reflectance mode

Furthermore, the critic temperature adjustments must look for the temperature of the glass surfaces and not the room temperature, and at least 50% transmittance is needed in the semiconductor state to achieve energetically efficient systems. Otherwise, different projects not based on vanadium dioxide have been developed as an alternative. Thermotropic smart windows based on hydroxypropyl cellulose with 22% of energy savings were reported [81], and thermochromic pigments incorporated into architectural surfaces [83] to display real-time data through the building envelope.

Phase change protocol, liquid-solid.
Phase change materials (PCM) are substances with the ability to have a phase transition at a specific temperature range [133] from which a heat absorption or emission produces latent heat (LH). During the solid-liquid phase transition heat is absorbed and released induced by the weather changes as shown in Figure 14, the LH can be stored, and this process has been classified as the most efficient way to store thermal energy with the highest storage density with small temperature changes [134] the temperature, and amount of LH are unique characteristics of a specific material [86].
Once the efficiency of PCM was determined, this protocol has been used in buildings through the inclusion of PCMs in constructive elements with two different scopes. On the one hand, to store the heat gained through the day and release it during the night and *vice versa*. On the other hand, in the avoidance of direct thermal transfer from the outdoors to the indoors [135], because the heat received for the PCM is used as LH to change of state rather than being transmitted. These developments are focused mainly on envelope elements [87,136].

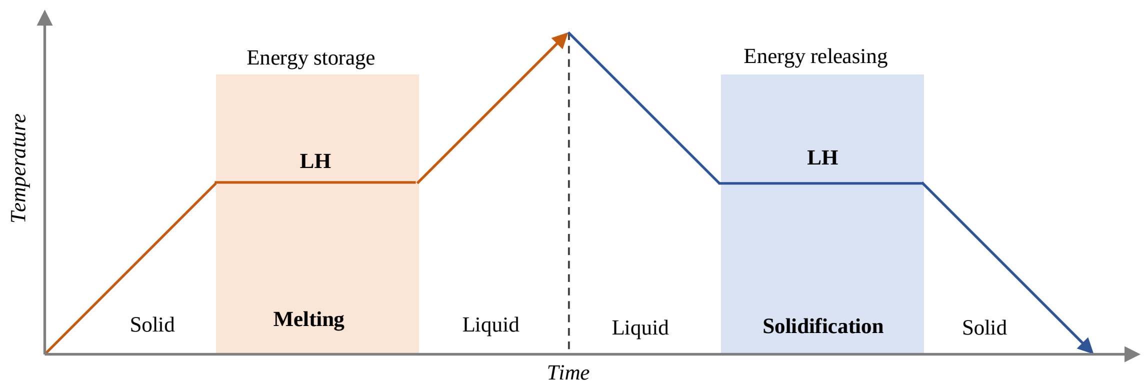

Figure 14: Temperature against time PCM behavior. The Latent Heat is stored and released in function of the temperature of the medium, adapted from © Pazrev, 2014 [137].

The inclusion of PCM on building elements has been assessed in envelopes as follow: window panels [96], Dynamic shading systems [84], opaque building envelope elements [138], Trombe walls [94], lightweight floors [90], concrete blocks [91], and cellulose insulation [89]. Besides, different elements based on wood composite materials were proposed [72], multifunctional concretes [92] doped concretes [93], and mortar based construction materials by Rao et al. [95].
Likewise, simulation and evaluation methods are proposed for passive cooling envelopes based on PCM by Castell & Farid [139], reduced scale evaluation of performance by Young et al. [140], as well as, general optimization of buildings [141]. Detailed studies were carried out in residential and commercial establishments [142], and performance studies in local weather were performed [85]. Finally, the actual state of the art allows the life cycle assessment of PCM inclusions in buildings [143], and the improvement in the synthesis to obtain long-term heat storage systems [97].

3.3. Light passive control systems

3.3.1. Attraction-repulsion electrostatic forces protocol

Following the Coulomb's law, with the use of Electro-Active Polymers (EAP) an elastomer with electric conduction features [144,145] a dielectric system has been obtained. The hybrid is a multilayer system defined by a dielectric elastomeric layer restricted both sides by electrodes. The dynamic behavior is triggered when an electric current, the stimuli, goes through the laminate rising the electrostatic forces generating a contraction of the elastomer. As a result, a dimensional change occurs going from a thick to a flat and thin plate as shown in Figure 15, allowing the development of components that can be deformed in a predicted direction [146]. This protocol is presented as a route to enhanced reactive buildings with the outdoors and users as well [98,147]. With the aim of control sunlight inside a building, a network made of an elastomer coated with silver electrodes limited by glass layers was developed by [98] as shown in Figure 16. A bi-directional movement was produced, in the first position, when sunlight tries to enter the building; the elastomers are compressed blocking and reflecting the light, and in the second one, the elastomer recovers their original shape, allowing the direct contact from the inside to the outside as can be seen in Figure 17.

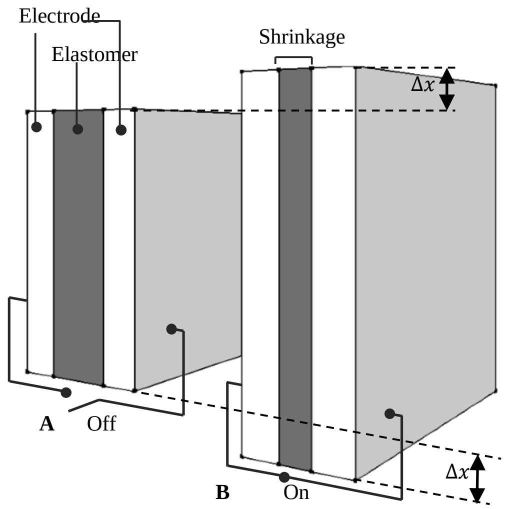

Figure 15

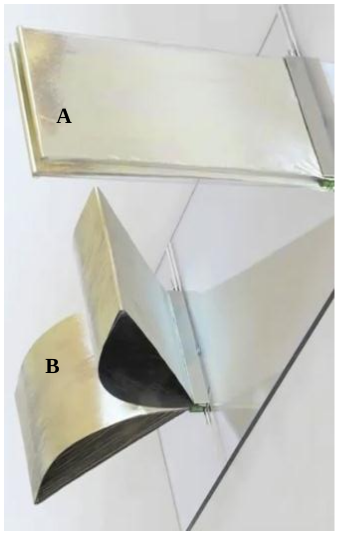

Figure 16

Figure 17

Figure 15: Schematic dielectric electroactive mechanism of actuation. A position. The elastomer has a permanent shape. B position. The elastomer is compressed by electrostatic forces, changing their shape in X and Y direction. The performance of this kind of system can be improved by pre-strain training.

Figure 16: *Homeostatic Facade Prototype* (New York) basic skin unit. Dielectric elastomer coated with silver electrodes. Open and close position view. Reproduced from Decker [98].

Figure 17: *Homeostatic Facade Prototype* (New York). System operation, inside view. *Top.* Permanent shape and path (open position); *Bottom*, temporal shape after stimuli (closed position) reproduced from Decker [98].

Several homeostatic skin projects with the use of electro-responsive elements were developed. A lightweight and semi-translucent actuator film defined by a high elastic elastomeric film, coated with a conductive carbon black powder and insulated by a liquid silicone layer was reported [101–103]. In another approximation, an EAP laminate was joined to water, also used as stimulus, [100] to obtain a hydro-active responsive system. Finally, translucent ETFE cushions actuated by an EAP strip were reported [104], and EAP plates into double glazing facade were simulated [148] showing improvement in the energy performance. The reviewed proposals have one major disadvantage which is a high voltage needed to actuate the systems such that it limits the application and affects the detriment to the overall efficiency.

3.3.2. Electrochromic protocol

The change in optical properties is a characteristic of inorganic materials. The electrochromic effect, for instance, occurs in partially hydrated transition metal oxides [149]. The effect is a reversible electrochemical reaction where oxides are formed by ion extraction and insertion. The process triggers changes in physical properties as, conductivity, IR absorption, and color. To obtain the effect a coating system made of several thin layers as shown in Figure 18 must be done. The system shifts from an oxide insulator state to a quasi-metallic one when an external potential is applied.

The electroactive layers change their optical properties between their oxidized and reduced form because of electron flow in the system. In the case of tungsten oxide WO_3, used in the amorphous state in electrochromic coatings, are the most studied [149], were ions exchange used to be H^+ or Li^+ [150], allowing the change in IR absorption as seen in Figure 19. The system can be customized to obtain different time response as well as absorbing /reflecting rate.

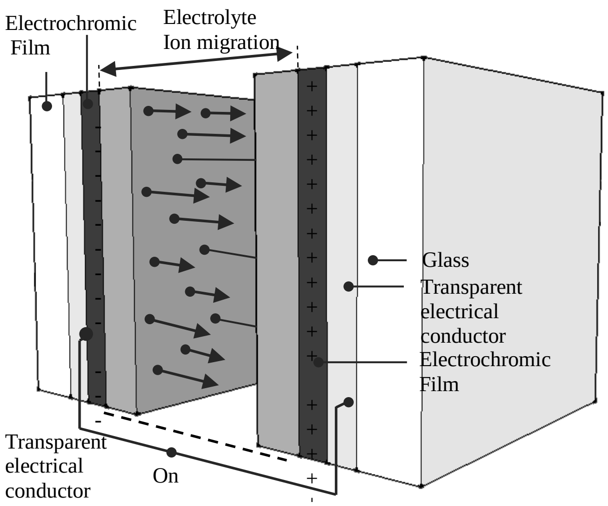

Figure 18

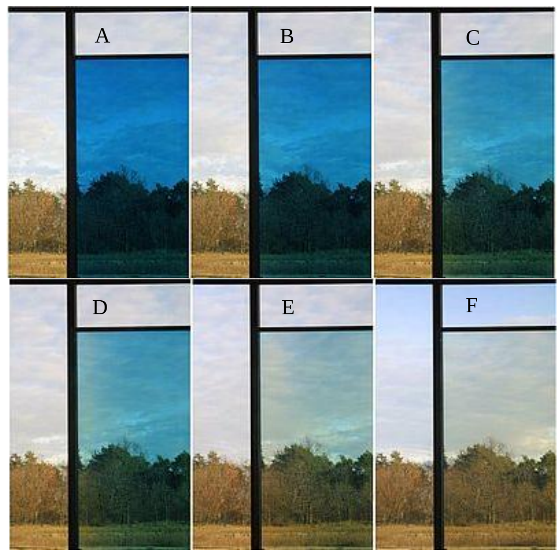

Figure 19

Figure 18: The basis is a glass or plastic covered by a transparent conducting film, on multiple cathodic electroactive layers is affixed. A layer of ion conductor follows these, on its turn followed by an ion-storage film or one (or multiple) complimentary anodic electroactive layers and another transparent conducting film.

Figure 19: Tungsten Oxide Electrochromic coated window, the process of change of conductive and reflecting properties From A (blue) to F (transparent) $M_xWO^3 \leftrightarrow WO_3{}^+xM^+ +xe$

Although, electrochromic thin layers were developed since 1973 [151], their most promising application is electrochromic coated windows (ECW) [152,153] which were designed and commercialized in the last decade. These systems are based on flexible layers that can be inserted into a glass or polymer as a substrate with transparent conductors with high electronic conductivity [105], to allow performance of few volts. The performance of this system was evaluated in comparison to other glazing technologies as fritted glass [154], significantly better performance in ECW was reported because it provides a glare control in the areas of the facade which the sun is in contact with. Meanwhile, other zones remain in the visible mode allowing the entry of diffuse light avoiding the use of artificial light sources.

The use of ECW was evaluated in office buildings located in hot and cold areas [106] achieving 45% of energy savings and from 35% to 50% of carbon emissions reduction using ECW panels in comparison with no-treated glass windows. Moreover, a long-term performance study of tungsten dioxide coating for 20 months period was performed [155] were and 26 ± 15% energy savings was obtained. Meanwhile, efficiency simulations conducted showed a 16% of energy savings [107,156,157]

Despite the use of electric current, this kind of passive system, *Attraction-repulsion electrostatic forces, and electrochromic protocols* differ from active ones, because the electron flow is used plainly as the stimulus, which triggers the change of shape and properties of the system and has shown important energy savings. In the case of active systems based on DAS protocol, electric current is used as an additional continuous resource to ensure the operation of the electronic components.

3.3.3. Elongation induced by thermal transitions.

Shape memory polymers (SMPs) are stable polymer networks with reversible switching transitions triggered by several stimuli as temperature, pH, electricity, magnetic field, light, and ions mainly [145]. There are multiple molecular structures which drive SME in polymers. Nevertheless it is not a property of the material by itself, it is a result of a mix of chemical and processing features. They have been used in several technological areas because of their wide-range stimuli responsiveness.

In the case of thermal-responsive SMPs, are based on a polymer with molecular entanglement, chemical crosslinking, crystallization and interpenetrated network. The reversible switching transitions are crystallization/melting, and vitrification/glass as shown in Figure 20. During this process, a change of shape or mechanical force can be obtained.

Based on these protocols, crystallization/melting, and Vitrification/glass transitions, commercial temperature SMP have been used to realize self-standing structures actuated by dynamic actuators as flexible hinges [108,110] as shown in Figure 21, and a lightweight 2D structure with no structural elements embedded with prestressed SMP [109]. SMP tape was proposed as an actuator of a flexible metamaterial used in indoors for light control [111].

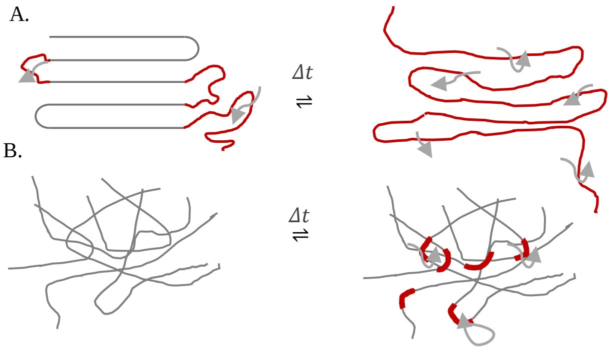

Figure 20

Figure 21

Figure 20: *Polymer Thermal-switching transitions.* A. Crystallization/Melting B. Vitrification/glass. Under appropriate Δt the polymer chains gain mobility allowing a reversible change of shape.

Figure 21: *Translated geometries.* Standing structure actuated by SMP A. open position B. closed position, reproduced from Shambayati (2014) [110].

4. Conclusions

As was seen, passive systems of dynamic control in buildings thus far developed has obtained favorable and promising results. On the one hand, passive systems use responsive materials that cannot be turned off or work just by one-user preferences, limitation to be recognized, likewise thermal, and comfort indexes must be evaluated on those new experimental projects. On the other hand, they have been created or applied in buildings in the last decades, for this reason, most of them are found in an experimental phase. Still, it is necessary to continued proving, verifying and optimizing to tuning and spread of this kind of envelopes systems massively, because nowadays, among others, the systems high costs limits their applications.

The reviewed systems are in different states of the art. On the one hand, PCM, as well as thermochromic and photochromic coated windows were incorporated in building for more than a decade and nowadays are in a stage of evaluation, alternative methods of synthesis are still being developed and studied to enhanced building performance. In addition, hygroscopic systems, shape memory alloys, bi-metallic strips, and shape memory polymers are in an experimental stage were measure systems units, legislation or robust commercial solutions cannot be found. All of them presents interesting and different ways to look at the issue of passive response to micro-environmental fluctuations.

The stimulus-responsive materials evaluated are just a part of the categories presented, reversible phase change protocol and elongation induced by crystallization or vitrification the others are shape memory hybrids, the type of stimulus-responsive systems preferred in architectural envelopes. The use of hybrids can be explained because in the development of these systems a strong background is not needed, it is based on some basic concepts, and are made of easily accessible materials; for these reasons these types of responsive systems are extensively applied. Nevertheless, the other categories of the stimulus-responsive materials presented are still unknown by buildings. Therefore, the possibilities of new developments are broad to improve building efficiency and adaptation from ceramics to polymers.

The interest of the scientific community on the use of shape Memory/responsive Polymers SMP has been growing in terms of research and development because it has some competitive differential features such as low density, wide-spectrum stimuli responsiveness, multiple reaction mechanisms, and programming versatility, among others. These features establish SMP as a group of materials to focus on future responsive building skins research because they can shape up active components independently, as composite materials or be part of hybrid ones. Studies and possibilities are not just for skins but for self-assembly building components (potential 4D printing), change of user interfaces shape or kinetic to electric building energy production.

Finally, the active materials for adaptive building envelopes overall show a very promising field of research and development that could revolutionize the way we do buildings regarding aspects such as circular economy [158] and smart cities [159]. However, large scale solutions, lower costs and durability improvement particularly with shape Memory/responsive Polymers SMP must be further developed. The bigger emerging areas must also be rapidly integrated into these building envelopes in order to make feasible solutions and large solutions: areas such as artificial intelligence, big data, and internet of things are crucial for the optimization of these materials and systems in the cities [159,160].

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