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REVIEW

A Review of Smart and Responsive Building Technologies and their Classifications

Francesco Carlucci

The high impact of the building sector on global greenhouse gases (GHG) emissions, has focused the attention on the energetic behaviour of the built environment. Starting from the second half of 20th century an increasing attention on the insulation of building envelopes has been paid trying to maximize the indoor-outdoor disconnection. Nowadays, one of the main deficiencies of traditional buildings lies in the rivalry between their static behaviour and the dynamic external environment. The increasing awareness that responsive buildings can provide significant improvements in energy efficiency and internal comfort has recently led to a quick spread of innovative technologies, tools, and research topics. The aim of this review is to provide a broad overview of the available and most promising responsive technologies applied to highly performant buildings with a particular focus on building envelopes. Firstly, an introduction of the energy context and of the spread of adaptive technology is presented. Then, an analysis of the existing nomenclature and classification systems is provided to introduce the detailed review of the technologies.

Keywords: Responsive; Adaptive; Envelope; Smart; Dynamic

Introduction

The built environment plays a key role in the reduction of the GHG emissions due to its high impact on the total global energy consumption. With nearly 32% of the total global energy consumption, the building sector affects significantly the global GHG emissions (19%) and the total electric energy consumption (51%) (IPCC 2014); moreover, considering highly developed countries, these figures increases notably reaching nearly the 40% of the total energy consumptions (IEA 2016). In the USA, the energy consumption related to residential and commercial building has registered an increase from 33.7% in 1980 (U.S. Department of Energy 2012) to 40% in 2019 (U.S. EIA 2020); similar values have been registered in the EU where the building sector accounts for nearly 41% of the total energy consumption (Rousselot Marie and Pollier 2018) while in China the percentage is lower – nearly 20% – thanks to the different ratio income-energy prices (Cao, Dai, and Liu 2016). Many studies (Chua et al. 2013) have highlighted that in developed countries nearly half of the total energy consumption of the industrial and residential buildings is related to the Heating Ventilation and Air Conditioning (HVAC) systems whose consumptions are strictly dependant by the envelope losses (Ng, Persily, and Emmerich 2014) and the heat gains (Elsland, Peksen, and Wietschel 2014).

For these reasons, many efforts are being made to improve building technologies and are focused mainly, on the one hand, on the energy generation and transportation and, on the other hand, on the improvement of the building envelope (Feng et al. 2019; Chua et al. 2013). Regarding the envelope, two different strategies have been considered during years to improve the building skin behaviour: the conservative static approach and the adaptive and dynamic approach. Up to the first years of the 21st century, the primary goal of designers was to minimize the thermal losses of the building envelope, maximizing the indoor-outdoor disconnection (Roel C.G.M. Loonen 2018) and pursuing the idea of the energy conservation in buildings. Recently, this strategy has been revised thanks to a new awareness of the dynamism of the external environment; indeed, traditional constructions are static buildings surrounded by changing conditions. Indeed, air temperature, solar radiation, wind, rainfalls, and humidity ratio change continuously during the day with average values that vary throughout the seasons and – considering the climate change – the years; moreover, the occupants' influence varies with time defining, hence, an extremely dynamic context. This new approach is a paradigm shift in the envelope design field as it leads to a wider analysis of the interactions between building and environment; in particular, the envelope is considered as an interface rather than a shield, as a dynamic and responsive element rather than a static boundary, and as multifunctional rather than a single behaviour component (Perino and Serra 2015).

This innovative approach has conducted to a reduction of consumptions and to an increase of the Indoor Environmental Quality (IEQ) as the inflexibility of static

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highly insulated buildings can have drawbacks on the users' comfort such as summer overheating (McLeod, Hopfe, and Kwan 2013) or visual discomfort (Fasi and Budaiwi 2015). The increasing interest regarding the IEQ is confirmed by the soaring number of studies conducted in this field in the last 20 years (Al Horr et al. 2016) and has contributed to move the problem from a strictly energetic point of view to a broader holistic perspective where energy consumptions, natural ventilation (Aflaki et al. 2015), thermal, and visual comfort (Alessandro Cannavale et al. 2013; Hosseini et al. 2019) are considered.

Hence, many researchers have started to dwell on responsive and adaptive technologies, namely, systems that can reversibly modify and adapt their physical properties to external conditions in order to improve the building performance and meet the users' needs (R. C.G.M. Loonen et al. 2013). These systems can, control thermal insulation and storage, solar gains, ventilation, and daylighting to adapt the building to the different external stimuli (Aelenei, Aelenei, and Vieira 2016).

The aim of this review is to provide researchers with an overview of the main available envelope responsive technologies starting from an exhaustive study of the nomenclature and of the existing classification systems.

Nomenclature and classification systems

The quick rise of interest around responsive technologies has led to a rapid spread of different – and sometimes conflicting – nomenclature and classification systems. Despite the rise of smart and responsive technologies is relatively recent, the concept of building adaptability has its roots in previous studies and theorizations. Negroponte stated (1975) that architecture, especially housings, were "unresponsive" to its users' needs, introducing the concept of responsiveness even if from a very theoretical and architectural point of view. A more technical reference can be found in a paper titled "A wall for all seasons" published in 1981 (Davies 1981) in which the author describes a glazed envelope with a single layer that satisfies different functions.

After these first theoretical conceptualizations of responsive buildings, the real spread of the concepts of adaptability, smartness, and responsiveness came in the 21st Century in parallel to the soaring of new materials and innovative technologies experimentations. Nowadays, the most diffuse definitions of envelopes with time-varying properties are adaptive (Attia et al. 2018), responsive (Favoino et al. 2014), dynamic (Konstantoglou and Tsangrassoulis 2016), kinetic (Moloney 2007), smart (Favoino, Giovannini, and Loonen 2017), intelligent (Wigginton 2013), and switchable (Ghosh and Norton 2018); each of those definitions describe similar systems but, generally, with different shades of meanings shortly described below (**Figure 1**).

A definition of the term adaptive is given by Loonen (2018) who considers an adaptive façade – or a Climate Adaptive Building Shells (CABS) – an envelope that can modify its properties or functions repeatedly and reversibly in response to a change in the boundary conditions aiming to IEQ improvements and to the reduction of the energy consumptions. Loonen includes in the CABS also externally controlled systems (e.g. electrochromic glazing) (Roel C.G.M. Loonen 2010); nevertheless, in the writer's opinion, a literary definition of adaptive systems should include only self-triggering devices with an embedded autonomous sensing/actuating system.

A similar concept is expressed by the term responsive proposed in the Annex 44 of the International Energy Agency – Energy Conservation in Buildings and Community Systems Programme (IEA-ECBCS) (Heiselberg 2009). A Responsive Building Element (RBE) is defined as a building element that reacts in a controlled way – managing the transfer and storage of heat, light, water, and air

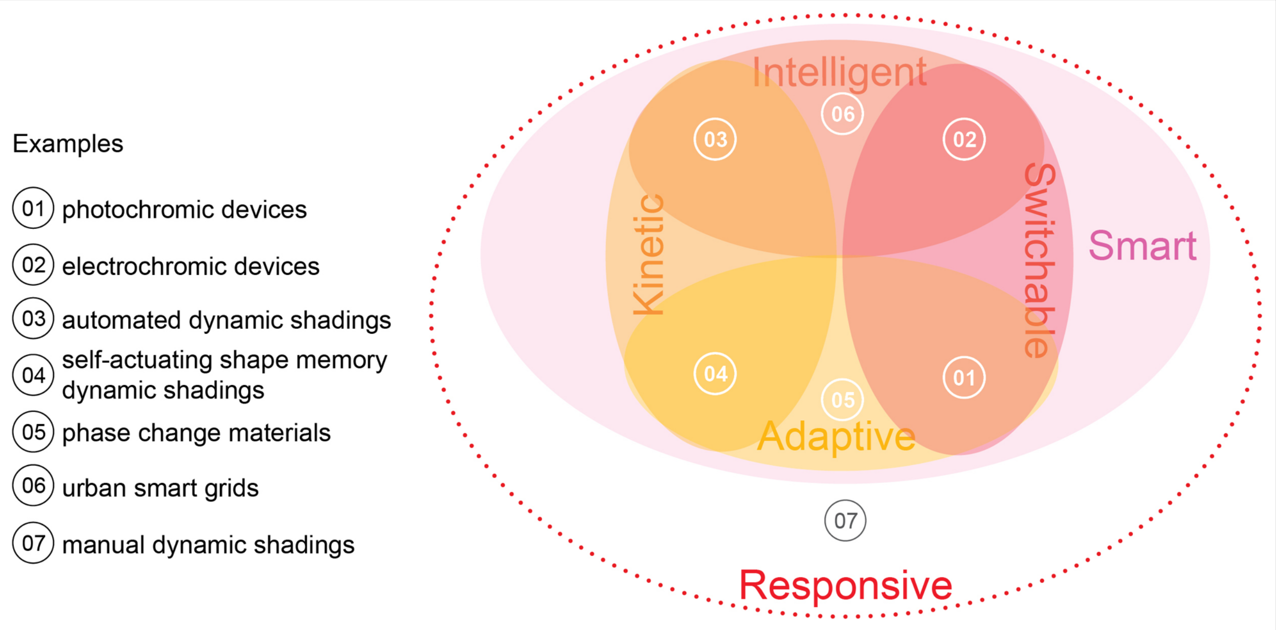

Figure 1: Main adopted nomenclatures, possible overlapping and examples.

(Aa, Heiselberg, and Perino 2011) – in response to external or internal changes and to users' interaction.

A slightly different meaning is usually adopted referring to the kinetic or dynamic envelopes, Wang et al. (2012) define the Acclimated Kinetic Envelope (AKE) as an envelope that reacts to external variations with visible physical changes and not only with microscopic changes. It follows that AKEs focus on macroscopic changes and refers usually to the movement of the building component, while many technologies that work on microscopic variations – such as Phase Change Materials (PCMs) – are not included in this definition.

Intelligent systems are usually considered systems organized in components for perception, cognition, and action to whom correspond sensors, controllers, and actuators (Hayes-Roth 1995) that allow the system – in this case the building – to change itself through autonomous adjustments (Romano et al. 2018).

The term smart is mainly referred to materials, or to technologies that implement smart materials. A smart material modify its characteristics in response to transient conditions and are usually classified in property exchanging and energy exchanging (Addington and L.shock 2005) depending on whether it changes its thermal, mechanical, magnetic, optical or electrical properties (e.g. photochromic), or it converts an input energy in a different form output energy (e.g. photovoltaic). The meaning of smart can change when it is referred to buildings, cities or grids; in these cases, the term represents primarily the availability of advanced control systems that allow for interconnected operability (Lawrence et al. 2016). Therefore, in a broader view, this term can be used to describe both intelligent and adaptive systems (Hasselaar 2006).

The term switchable is mainly referred to glazing and windows and represents all those systems that can switch or modulate their properties in response to external stimuli and that can be actively (e.g. electrochromic) or passively (e.g. thermochromic) controlled (Ghosh and Norton 2018).

The quick spread of these innovative technologies has been followed by the development of new classification systems. One of the most recent classification proposed (Attia, Lioure, and Declaude 2020) refers to the design field and is based on interviews made with façade experts: architects, engineers, manufacturer, contractor, operator. The resulting system considers four major families – dynamic shadings, chromogenic façade, solar active façade, and active ventilative façade – composed, overall, by 11 different technologies. Hence, each technology is provided with a classification of the application-purpose (privacy, insulation, etc.), control type (manual, automated, etc.), building type (residential, etc.), and technology-material (wood, suspended particles, etc.).

Other two exhaustive classification methodologies are proposed by Loonen et al. The first one (Loonen et al. 2013) starts from the relevant physics of the system (thermal, optical, air flow, and electrical) and then identifies its time scale (seconds, minutes, hours, seasons), its scale of adaptation (micro or macro), its control type (intrinsic or extrinsic) and its typology (built, subsystems, full scale or reduced scale prototype). The second one (R. Loonen et al. 2015) revises the first proposal and considers firstly the purpose-goal of the system (thermal comfort, indoor air quality, visual performance, acoustic quality, energy generation, personal control), then the responsive function (e.g. modulate solar gains), the operation (intrinsic or extrinsic), the technologies-materials adopted (e.g. PCM, switchable glazing), the response time, the spatial scale (building material, façade element, wall, fenestration, roof, whole building), the visibility (no, low, high) and finally the degree of adaptability (on/off or gradual).

Wang et al. (2012) propose another classification system specific for the AKE; starting from the relation between façade and climatic source, three different categories – solar responsive, air flow responsive, others – are identified. The next level of classification is based on the main parameters that control the façade system; the solar responsive AKE are hence classified considering solar heat, daylight, and solar electricity. Similarly, the air flow responsive systems are categorized as AKE based on natural ventilation or wind electricity, while AKE based on precipitation or air temperature are included in the "other" class.

Specific classification systems can be found for the kinetic envelopes, one of these (Ramzy and Fayed 2011) proposes four classification criteria: kinematic (limited, medium, major, variable), control technique (direct-responsive, internal or direct, responsive indirect), system configuration (embedded, dynamic), control limit (minor, medium, significant, variable), and cost (small, medium, big, huge). Based on the combination of these criteria, four façade system categories can be identified: skin unit systems, retractable systems, revolving buildings, and biomechanical buildings.

Finally, another broad classification system is proposed by Ochoa and Capeluto (2008) based on three main classes: input elements, control processing elements, actuating elements. Each class is then branched in different subclasses – category, design variable, sub-variable, common values – reaching more than 40 possible combinations.

Responsive technologies applied to building envelopes

This section provides a review of the main promising responsive technologies, organised considering the classification system proposed by Loonen et al. (2015).

Phase change materials

PCMs can be classified as a micro scale adaptive technology and act on the indoor thermal comfort modulating thermal gains and heat fluxes; this technology is intrinsically controlled and is characterized by a gradual degree of adaptability.

PCMs have increased their diffusion thanks to a broad experimentation that have concerned different scientific field (Kuznik et al. 2011) ranging from the design of low energy buildings (Soares et al. 2013), to the space industry (Neri et al., n.d.), and to the waste heat recovery systems (Akeiber et al. 2016). The primary advantage of PCMs is the capability to store great amount of latent heat in low volume elements (De Gracia and Cabeza 2015); this key feature has led to a great interest in this material in the building domain to improve the thermal mass of lightweight construction technologies. The most diffuse building applications of PCMs regard, on the one hand, the reduction of HVAC energy consumptions in active strategies (Berardi and Soudian 2018) and, on the other hand, the improvement of thermal comfort in passive strategies (Fiorito 2014).

Thermal behaviour of materials is characterized by three different kind of storage: Sensible Heat Storage (SHS), Latent Heat Storage (LHS), and Thermochemical Heat Storage (THS). While the THS is not yet applied in building materials (De Gracia and Cabeza 2015), SHS and LHS play a key role in the building thermal interactions.

In general, thermal phenomena are characterized by both SHS and LHS and the heat exchanged depends on the mass (m), on the specific heat of both solid (c_{Sp}) and liquid state (c_{Lp}), on the variation of temperature (T), on the melting temperature (T_m), on the fraction melted (f_m) and on the variation of enthalpy (Δh_m) as described in Eq.1.

$$Q = \int_{T1}^{Tm} mc_{Sp}dT + mf_m\Delta h_m + \int_{Tm}^{T2} mc_{Lp}dT \tag{1}$$

The primary advantage of PCMs is to have a broad range of melting point – depending on their composition and on the type of change of phase – including temperatures within the human comfort range (20°C–30°C). Usually, PCMs used in the building field are characterized by a melting point within human comfort range based on a solid-liquid change of phase (Cabeza et al. 2011). These characteristics allow to store and release heat without increasing surface temperature and to shift temperature peaks improving thermal comfort and HVAC consumptions. Benefits of PCMs are highly variable depending on the building types, location, transition temperature, simulation settings, and applications; however, a reference energy reduction range for envelope applications in offices could be considered 2% – 30% (Carlucci et al. 2021; Berardi and Soudian 2018).

Switchable glazing

Another system that has focused the attention of researchers and manufacturers is undoubtedly the switchable glazing thanks to the wide spread of glazed façades and to their good suitability for retrofitting interventions. Many technologies can be identified in this macro-category and the primary distinction that can be adopted regards the intrinsic/extrinsic control type. In intrinsic or passive technologies, the system can self-adjust its properties simply thanks to an environmental stimulus which directly triggers the envelope responsiveness. In extrinsic or active technologies, the system is externally controlled and is triggered by actuators connected to sensors and processors. This functioning allows a flexible control of the system and allows to develop complex control algorithms that accounts for different environmental aspects. Following paragraphs describe the main switchable glazing technologies adopted in the building domain applied to envelope, excluding only those solutions – such as Liquid Crystal and Suspended Particle Devices – used mainly in other fields or only for aesthetic or privacy applications (Baetens, Jelle, and Gustavsen 2010).

Extrinsic control systems

Electrochromic, plasmonic electrochromic, and nanocrystal in-glass composites

Among the active switchable glazing, the Electrochromic (EC) devices are the most developed technologies. The main advantage of these systems lies in the capability to change their transmittance properties switching between bleached and coloured state thanks to a 5-layers coating applied to the glass panes that allows reversible oxidation or reduction reactions in response to an external electrical stimulus. The coating is constituted by two external transparent conductive layers respectively followed by EC films deposited on each conductor and an intermediate electrolyte layer (Granqvist, Bayrak Pehlivan, and Niklasson 2018; Alessandro Cannavale 2020) as shown in **Figure 2**. The

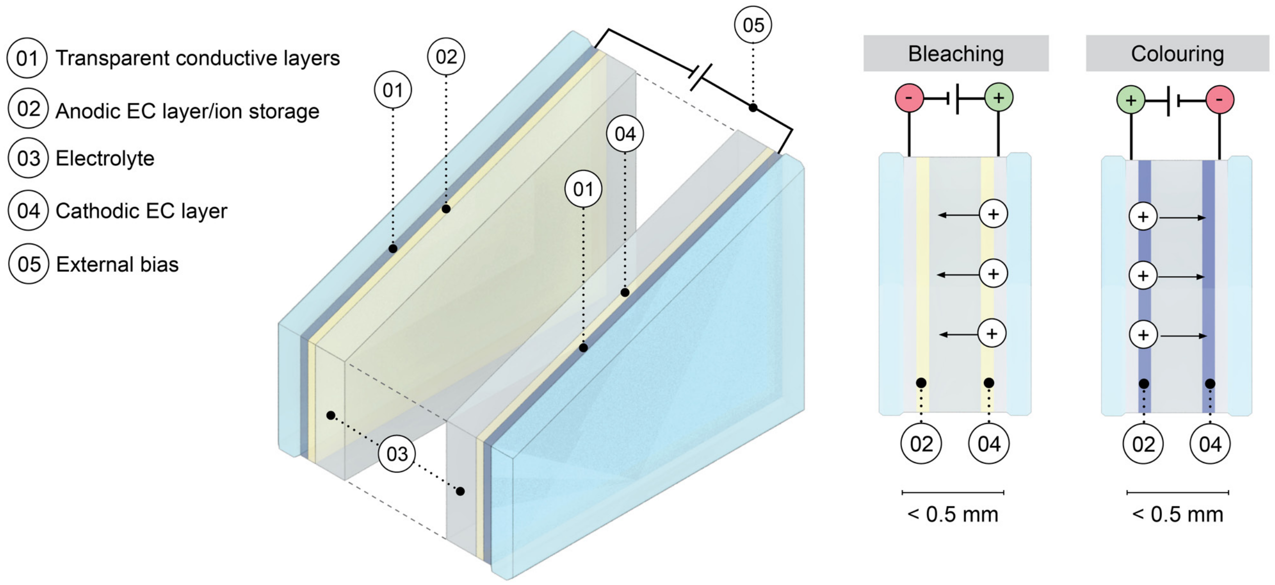

Figure 2: Typical structure and functioning – schematic and not to scale – of EC devices.

system is triggered by a low voltage applied to the transparent conductive layers that allows the displacement of the cations contained in the electrolyte – usually H^+ or Li^+– from the cathodic to the anodic or ion-storage coating. To restore the electrical balance, electrons are extracted or added to the coatings through the electrical conductors changing the transmittance properties of the device.

Depending on the different films used, the EC can be classified as Conventional ElectroChromic (CEC), Near Infrared Radiation switching EC (NEC) and Dual-Band ElectroChromic (DBEC); each device is characterized by a specific capability to act on specific wavelengths. CECs can change their transmittance properties contemporaneously on Near Infrared Radiation (NIR) and on Visible Light (VL) spectra, NECs act only on the NIR spectrum while DBECs can switch between three different states: transparent in both NIR and VL spectra, dark in the NIR spectrum and transparent in the VL spectrum, and dark in both NIR and VL spectra (DeForest et al. 2017).

NECs functioning depends on a plasmonic electrochromic effect that modulates the surface plasmon of doped semiconducting nanocrystals (DeForest et al. 2015), such as the tin doped indium oxide (ITO). The ITO nanocrystals are characterized by a localized surface plasmon resonance (LSPR) in the NIR spectrum and, when activated by an external voltage, show a larger spectral shift thanks to the electrochemical doping effect (Garcia et al. 2013).

A similar functioning can be identified also for the DBECs. The different structure of DBECs has led, in some cases, to a different classification of these systems, defining them as nanocrystal in-glass composites; however, as the functioning criterion is the same of ECs, they can be considered a specific EC application. The main difference relies on the use of the ITO nanocrystals embedded in a niobium oxide (NbO_x) glassy matrix (Llordés et al. 2013) allowing to change optical properties differently in accordance to the voltage applied. When the electric circuit is open at 4 V, both layers are in clear configuration, when the voltage is decreased to 2.3 V the nanocrystal turns to dark configuration blocking only the NIR spectrum and, finally, reaching the 1.5 V voltage both the nanocrystal and the glassy matrix darken acting on both NIR and VL spectra (Llordés et al. 2013). Implementing EC windows allows to reach significant energy savings ranging nearly from 30% to 60% (Alessandro Cannavale et al. 2020).

Colour-temperature-tunable window

One of the main disadvantages of the EC technologies is the aesthetic compromise related to the chromatic change of the façade in the coloured state. To overcome this problem, researchers are developing new technologies capable of controlling not only the quantity of light transmitted – shading behaviour – but also the light colour temperature. To that end, an electrophoretic dispersion of dual-particles of 2 biprimary complementary colours are considered and three properly located electrodes are used to control this dispersion moving the coloured particles. This displacement leads to different states of the window from the neutral clear state to the neutral dark one (Mukherjee et al. 2015).

Gasochromic glazing

Another similar active chromogenic technology is the gasochromic (GC) glazing. While EC devices are triggered by an electric stimulus, GC devices react when exposed to specific chemicals – usually H_2 and O_2 – that trigger a reversible coloration of a gasochromic thin layer deposited on the glass pane (Casini 2018). In this case, the chromogenic capability of the device relies on a single GC porous layer deposited on a glass pane (**Figure 3**) reducing the complexity and cost of the system compared to multi-layers EC films. The GC layer is usually composed by a tungsten oxide (WO_3) film with different textures, morphologies, and compositions; however, molybdenum oxide (MoO_3) – well known as photochromic material – is recently attracting the researchers' attention also for its GC properties (Delalat, Ranjbar, and Salamati 2016).

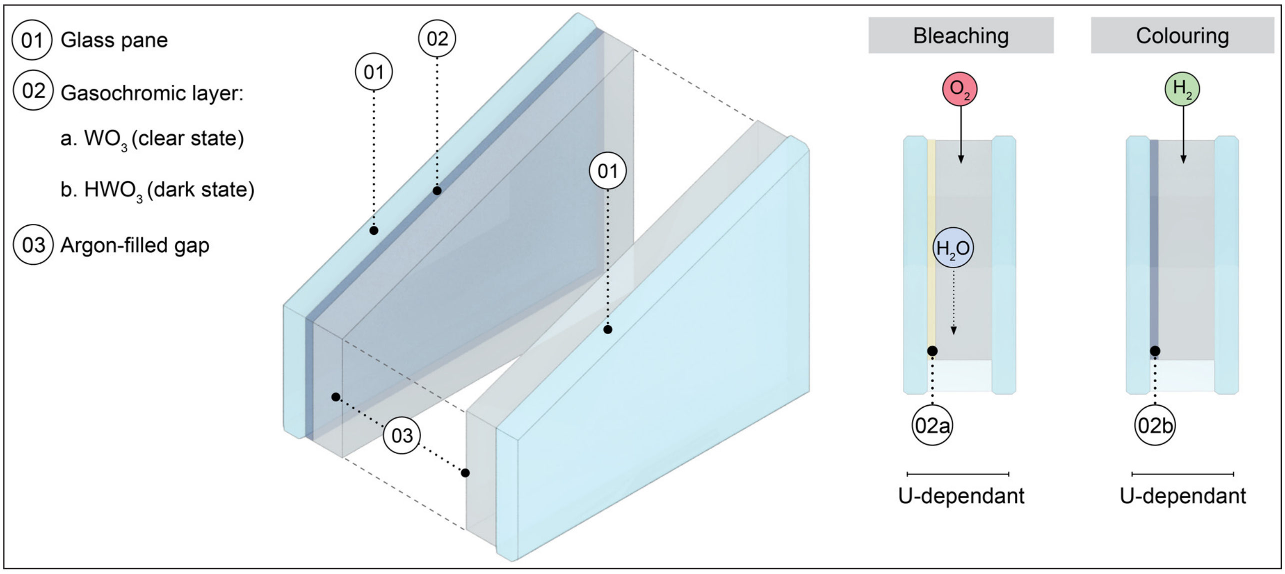

Figure 3: Typical structure and functioning – schematic and not to scale – of WO_3 GC devices.

From a technological point of view, the window cavity is connected to a piping and pumping system that allows to fill the cavity with H_2 – when dark state is required – or O_2 to return to the bleached state (Lampert 2004). The window cavity is usually filled with Argon to both stabilize H_2 and increase the thermal resistance. During the darkening phase, the GC layer – covered with a thin (4–5 nm) platinum (Pt) or palladium (Pd) catalyst – react to the H_2 changing its colour thanks to a chemical reduction. On the contrary, when O_2 is pumped in the cavity, hydrogen binds chemically to O_2, producing H_2O and returning to the clear configuration.

Considering the energy savings related to this technology in an office building located in Shangai, HVAC loads can be reduced by 11.5% when compared with a coloured absorbing double glazing unit (Feng et al. 2016).

Deformation Tunable Device

The Deformation Tunable Device technologies significantly change the functioning comparing to the above-described devices. In this case, the property change is triggered by a deformation of the device rather than a reduction-oxidation reaction of a chromogenic material. Indeed, these technologies act on the surface wrinkling to control the device optical properties thanks to a reversible microscale geometric deformation that can modify the light scattering with a resulting change of the window opacity. As no chemical reactions take place, one of the main advantages of this technology is the colour neutrality of the device in both configurations. The use of surface wrinkling to control the surface topography is a technique that is arising its importance and diffusion in many different fields, from dry adhesives to micro-lens arrays (Lee et al. 2010).

The surface mechanical deformation can be triggered by a voltage applied to silver nanowires embedded in a soft dielectric elastomer. In this case, the applied voltage charges the conducting nanowires that stimulate the elastomers with a resulting microscopic geometry change. This irregular change leads to a different light refraction decreasing the optical transmittance at all wavelengths (Shian and Clarke 2016).

Another triggering solution is to apply a mechanical strain directly on specific device made, for example, of silica particles embedded in a polydimethylsiloxane (PDMS) film (Kim et al. 2018). In this case, the transparency of the system changes with the strain applied that triggers a reversible wrinkling or flattening transformation, in response to the applied stretching or release input.

Currently, no specific studies on building energy consumption are available for this technology.

Intrinsic control systems

Thermochromic windows

Among the switchable glazing systems, ThermoChromic (TC) windows have been widely developed in the last years thanks to their passive and temperature-driven solar modulation. These devices can modulate their transmittance parameters in accordance with their temperature in a self-adapting mechanism that dynamically responds to the external environment. When the temperature is below a certain threshold – defined as critical transition temperature – the material is in its monoclinic state and acts as a semiconductor, less reflective in the NIR spectrum. When this threshold is exceeded, the TC material switches from the monoclinic to the rutile state; with this change, the material behaves like a semi-metal increasing the NIR reflections (Kamalisarvestani et al. 2013). The main advantage of these systems is that the transformation is triggered only by external environmental conditions and does not need any additional control system.

Recently, different TC materials have been applied to smart windows such as the vanadium dioxide (VO_2) (Warwick and Binions 2014), hydrogels, liquid crystals, ionic liquids (Ke et al. 2018), and perovskite (Zhang et al. 2019). VO_2 based nanocrystals, ionic liquids, and perovskite TC windows show a similar behaviour as they act directly on the spectral absorbance, tuning the absorbance intensity or shifting the absorbance peak through the crystal phase transition. On the contrary, hydrogels and liquid crystals act respectively on the phase separation and on the crystal orientation to change the scattering and reflecting properties of the system (Ke et al. 2019).

VO_2 based window is the most studied and developed TC technology and works on reversible crystal phase transition that occurs when the film reaches the critical transition temperature of 68°C. This transition leads to an increase of the absorbance in the NIR spectrum with non-significant changes in the VL and UV wavelengths. It is possible to change this behaviour using different dopants such as the Tungsten, to low the transition temperature, or Magnesium to act on the VL Transmittance. Energy savings related to TC windows ranges between 7% and 46% (Aburas et al. 2021) and, nowadays, researchers are focusing mainly on multifunctional TC windows coupling the TCs with electrochromic, electrothermal or photochromic behaviour (Ke et al. 2019) to further improve these values.

Photochromic glazing

Photochromic (PC) functioning relies on the chromogenic behaviour of materials that can reversibly change colour when exposed to certain solar radiation wavelengths. The PC devices are usually constituted by PC materials embedded in a transparent matrix applied to transparent substrates and, depending on the PC molecules adopted, can be classified as organic or inorganic. In organic PC molecules – such as diarylethene (Timmermans, Saes, and Debije 2019), spiropyran, spirooxazine (Miluski et al. 2017) – the solar radiation triggers a transition between two chemical isomers that leads to a switch between different absorbance spectra. Furthermore, these materials can be classified as thermal reversible – if they switch back to the clear state when heated or irradiated with visible light – or thermal irreversible if they bleach under visible light (Ke et al. 2019). Referring to the building field, attention has been focused mainly on spirooxazine for aesthetic and chromatic reasons as it turns from a colourless to a blue state while other technologies turn in red or purple state.

A different functioning can be identified in the inorganic molecules such as transition metal oxides (WO_3, TiO_2, MoO_3 etc.). Considering the WO_3 (S. Wang et al. 2018) – suitable for building uses thanks to its transparent/blue states – the transformation is triggered by a photon prompted redox reaction as, when the device is irradiated, pairs of electrons and holes are formed on the PC film. Then, the colouring is assured by the reaction between WO_3, hydrogen ions – created by the H_2O and holes reaction – and electrons that forms the H_xWO_3 compound. On the contrary, removing the solar irradiation, the device returns in its transparent state. Few studies involve PC widows performance; however, savings should be lower than other chromogenic technologies due to their narrower modulation range (Alessandro Cannavale 2020).

Photoelectrochromic and Photovoltachromic glazing

The PhotoElectroChromic (PEC) devices are the first attempt to merge the advantage of smart active windows with the use of renewable energy sources. Starting from the EC functioning, PECs can self-produce the energy needed to trigger the redox reaction that leads to the transmittance properties modulation thanks to the coupling with photovoltaic materials, usually the dye sensitized TiO_2. For this reason, they can be used as intrinsically or extrinsically controlled systems. Depending on materials considered, layers structure, and state of aggregation, different technologies can be identified (Cannavale et al. 2016). According to the device structure, two main PEC groups can be identified: separated and combined device. In the former, the EC and PV materials are located on different electrodes while, in the latter, EC and PV materials share the same substrate (Cannavale et al. 2020) (**Figure 4**).

Starting from the PEC technology, Wu et al. (2009) increased the amount of energy produced developing for the first time a PhotoVoltaChromic (PVC) device. In these devices, the amount of energy produced exceed the energy needed for the EC activation and, once the transition process is completed, the extra-power can be used elsewhere in the electrical grid of the building. Therefore, PVC windows can produce energy while improving both visual comfort and energy consumption – with an energy demand reduction ranging from 6% to 32% – (Fiorito, Cannavale, and Santamouris 2020), emerging as one of the most interesting solutions for building integration.

Shading fluid windows

One of the simplest and cheapest switchable glazing passive device was proposed by Fazel et al. (2016) using the shading behaviour of a coloured fluid. The system works moving up and down a thin coloured fluid film according to temperature variation. In the gas-liquid device, a trapped gas expands according to the temperature pushing the coloured fluid in a small cavity changing the optical properties of the device. Instead, in the liquid-liquid device, the temperature variation pushes alternatively a coloured or a transparent fluid in the small cavity thanks to their different thermal expansion coefficients. The savings related to this technology can range between 8% and 33% (Fazel, Izadi, and Azizi 2016).

Dynamic shadings

An easier kinetic system is represented by dynamic shadings; these technologies are the direct evolution of the fixed shading systems typical of vernacular architecture (Al Dakheel and Aoul 2017). In this class, a huge number of technologies can be enumerated (Roel C.G.M. Loonen 2010) and the main distinctions regards the controlling methods and movement type adopted (Al-Masrani and Al-Obaidi 2019).

The first built examples of extrinsically controlled shadings can be found since the end of last century and can be represented by, for example, the Arab World Institute by Jean Nouvel in Paris (1988), continuing with the Burke brise soleil by Santiago Calatrava in Milwaukee (2001),

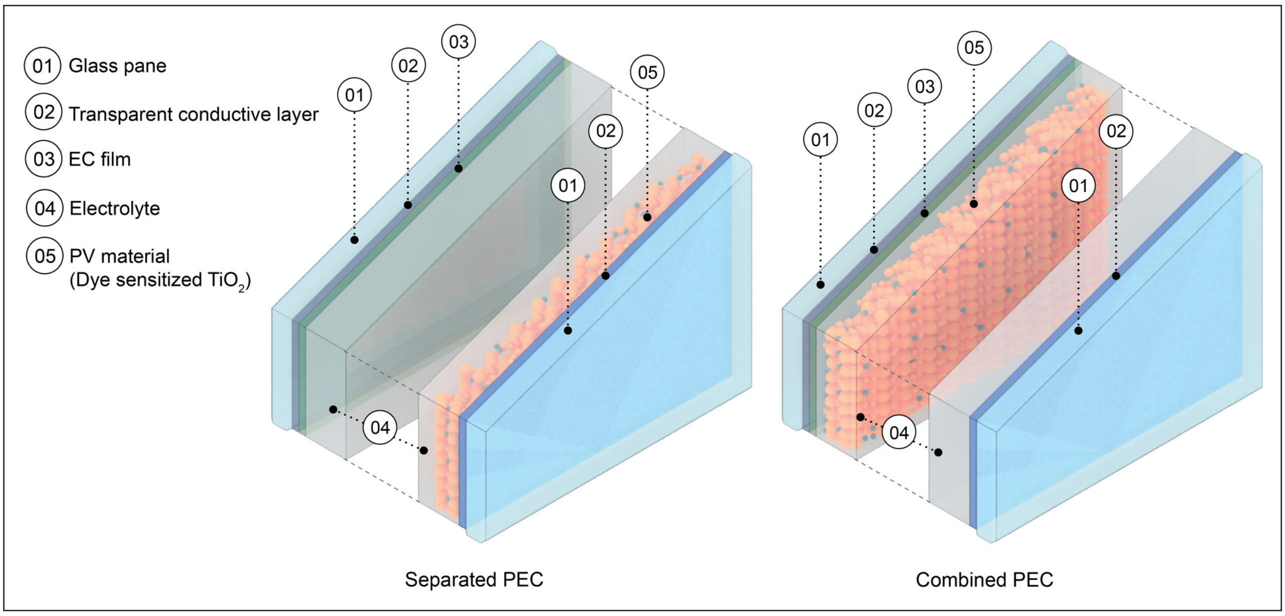

Figure 4: Typical structures – schematic and not to scale – of a TiO_2 PEC device.

up to the Abu Dhabi Al Bahr Towers by Aedas in 2013 (**Figure 5a**). Most of these systems rely on the direct application of external mechanical forces that trigger rotation (swivel, revolving, swing), translation, or their combination (folding, expanding, and contracting) of the shading elements (Fiorito et al. 2016).

Recently, the spread of new technologies combined with biomimetics approaches – especially phytomimetics (Martone et al. 2010) – has led to new more articulated applications. New systems have inherited from nature the capability of driving the movement through a proper distribution and orientation of the material's fibres. Shading devices with a proper anisotropy can be easily treated as responsive systems and – following the biological analogy with nastic structures – can be considered non-autonomous (extrinsic control) or autonomous (intrinsic control) systems, basing on their dependence or independence from external energy source.

Flectofin ® (Lienhard et al. 2011) is an example of an extrinsically controlled plant-inspired shading system based on the anisotropy of Glass Fibre-Reinforced Polymer. The application of mechanical external forces (compression) triggers the buckling of the fin that rotate in the façade-orthogonal plane increasing the fin's shading effect. In this case, the sensing and acting elements are not embedded in the fins but are external.

The development of smart materials such as Shape Memory Alloys (SMAs), Shape Memory Polymers (SMPs), and Shape Memory Hybrids (SMHs) has eased the multifunctionality of shadings, embedding the actuators and – in some cases – the sensors in the shading itself. Depending on their characteristics and on the activation stimulus, the SMAs, SMPs or SMHs can be used as actuators (extrinsic control) or as both sensors and actuators (intrinsic control). The former is triggered by an external energy source – mainly heat provided through electrical current – while the latter is triggered directly by the solar radiation when the device reaches a certain transition temperature. Different examples can be found for shape memory materials applied to dynamic shadings such as the Piraeus Tower (Doumpioti, Greenberg, and Karatzas 2010) – in which the kinematic is activated directly by the solar radiation (**Figure 5b**) – and Tent, Curtain and Blind prototypes (Khoo, Salim, and Burry 2011) in which the activation stimulus is the heat produced by electrical current.

Depending on the technology and activation criteria considered, dynamic shadings can reduce energy consumptions of nearly 20%–34% (Al-Masrani and Al-Obaidi 2019).

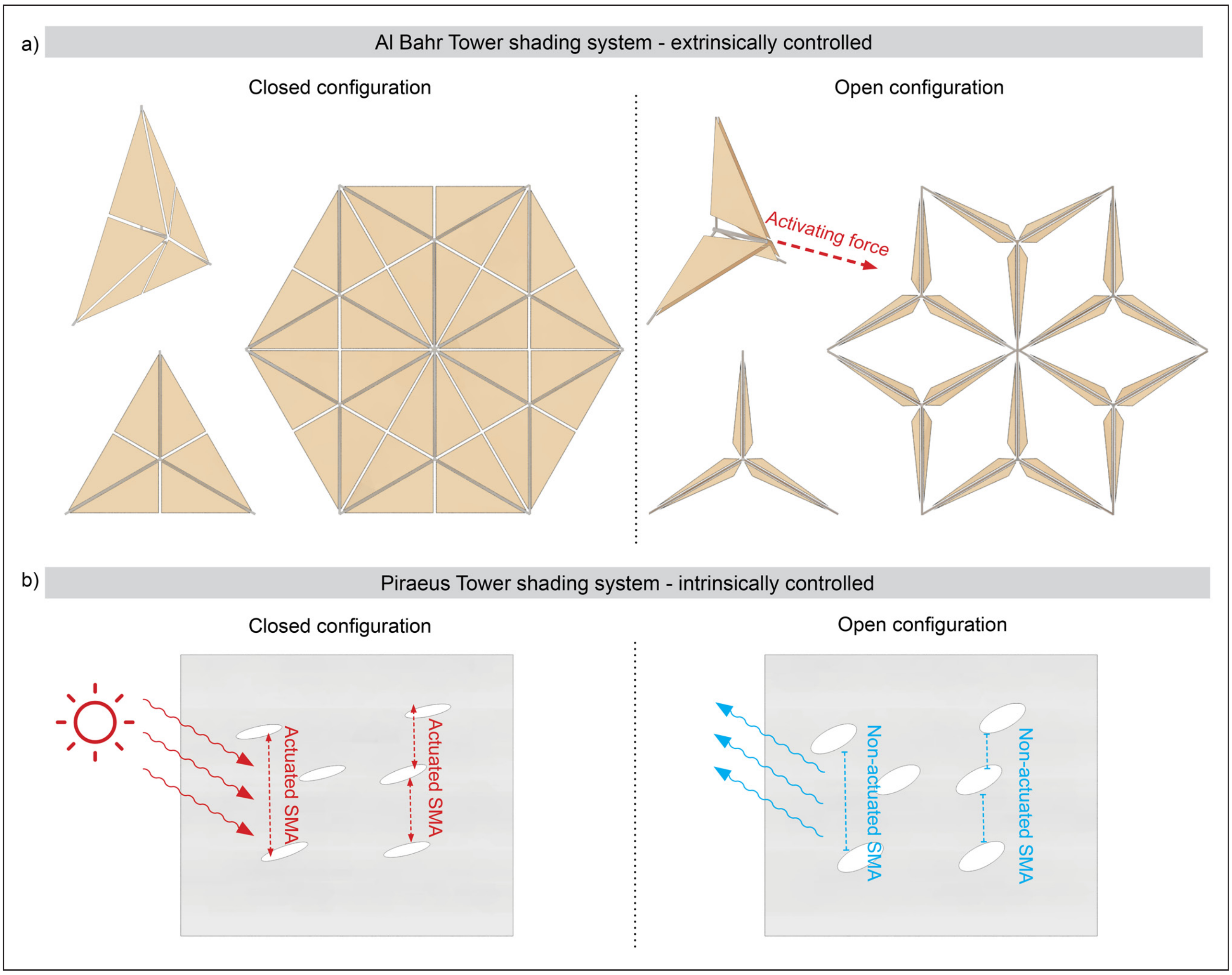

Figure 5: Examples of dynamic shadings: **a)** extrinsically controlled Al Bahr Tower shading system, **b)** intrinsically controlled SMA screen of the Piraeus Tower.

Conclusions

The great attention paid on energy efficiency and indoor comfort has significantly fed the research fields of smart and responsive envelopes. The result is a wide range of technologies and applications that can improve energy efficiency and internal comfort thanks to their responsive behaviour, adapting their characteristics to the changing external environment. This study aims to clarify the current state of the art and provides a synopsis of those technologies considered the most effective and promising for the building sector, through a description of a set of prototypes, built solutions, and research projects ranging from micro to macro scale, from extrinsic to intrinsic controlling systems etc. Each technology with its peculiarities can act on a particular aspect of the building's behaviour, therefore it is fundamental to understand the functioning and the strength of each system to maximize the benefits of responsive envelopes. Finally, it is worth mentioning the strong relationship between these technologies and the environment. Considering their nature, each system can be less or more effective depending on the location – and therefore the climate – considered. Hence, responsive technologies should be always considered in their completeness, analysing both the system and the surrounding environment.

Competing Interests

The author has no competing interests to declare.

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