What is an adaptive façade? Analysis of Recent Terms and definitions from an international perspective

What is an Adaptive Façade? Analysis of Recent Terms and Definitions from an International Perspective

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Abstract
Adaptive façades can improve the building's energy efficiency and economics, through their capability to change their behaviour in real time according to indoor-outdoor parameters, by means of materials, components, and systems. Therefore, adaptive façades can make a significant and viable contribution to meeting the EU´s 2020 targets. Several different types of adaptive façade concepts have already been developed, and an increase in emerging, innovative solutions is expected in the near future. According to recent research, the word 'adaptive' in the context of building façades is often associated in the literature with a long list of similar words. Moreover, there is no consistent definition of façade adaptability, although studies exist in relation to characterisation issues, design parameter, and classification. Even within the discipline of architecture and engineering, words such as 'smart', 'intelligent', 'interactive', 'adaptive', or 'responsive' have been used loosely and interchangeably, creating confusion as to their specific meaning and their conceptual relationship to building performance and design. In response to this, the goal of this paper is to build a provisional lexicon, or descriptive, behavioural, and methodological words, to assist researchers and designers in navigating the field of high-performance façades that incorporate materially innovative and feedback-based systems. It offers a brief overview of current advances in this nascent and rapidly evolving field and articulates a broader conceptual territory for the word 'adaptive', used in many cases to describe the technological systems that interact with the environment and the user by reacting to external influences and adapting their behaviour and functionality. The objective of this paper is to contribute to these developments by presenting the findings. Furthermore, common definitions will be proposed, based on the characterisation design parameters, classification approaches, and real case studies.

Keywords
adaptive façade, energy efficiency, comfort, passive design, intelligent buildings, sustainable architecture

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1 INTRODUCTION

The need to comply with European regulations on the energy efficiency of new and existing buildings has led the construction and scientific research areas, in recent decades, to experiment within the sector of smart and adaptive envelopes: a new generation of vertical closure systems aimed at reducing to zero the net energy consumption of the buildings in which they are integrated, with the aim of improving the comfort and the sustainability of our cities (Davis, 1981; Wigginton & Harris, 2002).

As a matter of fact, over the same period, envelope systems have been transformed from passive technological solutions to active systems that are able to produce energy from renewable sources and, above all, are able to change a building in a dynamic and adaptive system, in terms of spatial configurations and behaviour of its external skin, to improve indoor comfort conditions. Thanks to the presence of smart materials and automated systems with different degrees of complexity, the building thereby becomes a dynamic system that can be compared to a living organism, in which each part reacts to external and internal stimuli, adapting to the surrounding context in order to regulate and optimise the overall energy balance necessary for its functioning.

To the traditional three typologies of building envelopes – conservative, selective, and regenerative – identified by Banham in 1969, a fourth typology has been added: the smart or adaptive envelope. Adaptive envelopes can actively control energy fluxes between indoor and outdoor. Moreover, they can adapt their properties to maximise indoor comfort and reduce energy consumption. Furthermore, several different types of adaptive envelope concepts have already been developed, and an increase in emerging, innovative solutions is expected in the near future. Adaptive façades, in fact, can ensure improvements in building energy efficiency and economics, through their ability to change their performance and behaviour in real time, according to indoor-outdoor parameters, by means of materials, components, and systems. Therefore, they can make a significant and viable contribution to meeting the EU´s 2020 targets.

Today's envelopes are predominantly passive systems and are largely exhausted from an energetic point of view. They can neither adapt to changing environmental conditions related to daily and annual cycles nor to changing user requirements. Multifunctional, adaptive, and dynamic façades can be considered the next big milestone in façade technology. Adaptive building envelopes are able to interact with the environment and the user by reacting to external output and adapting their behaviour and functionality accordingly: the building envelope insulates only when necessary, it produces energy when possible, and it shades or ventilates when the indoor comfort so demands (Aelenei, Brzezicki, Knaack, Luible, Perino, & Wellershoff, 2015).

Moreover, there is no consistent definition of façade adaptability, although studies related to characterisation issues, design parameters, and classification already exist. Even within the discipline of architecture and engineering, terms such as *'smart', 'intelligent', 'interactive', 'adaptive', or 'responsive'* have been used loosely and interchangeably, creating confusion as to their specific meaning and their conceptual relationship to building performance and design. In response to this, the goal of this paper is to build a provisional lexicon, *or descriptive, behavioural, and methodological words*, to assist researchers and designers in navigating the field of high-performance façades that incorporate materially innovative and feedback-based systems. The paper offers a brief overview of current advances in this rapidly evolving field and articulates a broader conceptual territory for the word 'adaptive', used in many cases to describe the technological systems that are able to interact with the environment and the user by reacting to external influences and, in turn, adapting their behaviour and functionality. Finally, the objective of this paper is to contribute to these developments by presenting the findings. Furthermore, common definitions will be proposed, based on the characterisation design parameters, classification approaches, and real case studies.

2 'ADAPTIVE' DEFINITIONS

Most of definitions of a building envelope establish it as an enclosure, a separation between the indoor and outdoor environment that provides the following functions: support, control, finish (aesthetics), and distribution of service. However, we are more interested in the building envelope, without distinction between wall and roof, as an interface and not a separation, between exterior environmental factors and interior demands of the occupants. The building envelope can be considered, in fact, as an environmental moderator (López, Rubio, Martín, & Croxford, 2017).

For years, architects and building scientists have imagined the possibility that future buildings would possess envelopes that replicate our skin's adaptive response to changing environmental conditions. In his 1969 essay, 'A Home is not a House', Banham (1969) introduced minimal environmental solutions such as the tent and the campfire as representations of a building capable of dynamically modifying its boundaries and thermal properties in response to the environment. In 1976, Negroponte explained the concept of a responsive environment, capable of playing an active role, initiating to a greater or lesser degree changes as a result and function of complex or simple computations (Negroponte,1976). In 1981, Mike Davies proposed the idea of 'The polyvalent wall': an envelope system in which several functions are integrated into one layer (Davies, 1981). Another means of categorising responsive architecture is, in terms of rates of change, the approach promoted by Stuart Brand (1995) in his book 'How Buildings Learn'. Brand's 'Shearing layers of change' diagram, with its concentric rings of building components organised according the irrelative rates of change, promoted the idea that building components should be separated according to their rate of change.

However, it is only in recent years that technological research has investigated new experimentation frontiers capable of reaffirming the osmotic quality of a process of exchange concerning energy flows that have been passed and exchanged right through the envelope (Altomonte, 2008). In this regard, there is new research to demonstrate whether the vertical closure surface can be equipped with systems designed to ensure a dynamism that allows them to control the energy flows in the same way as a biological organism does. From the shading device system of the Arab World Institute in Paris by Jean Nouvel to the dynamic screenings of Al Bahar Towers in Abu Dabi by Aedas Architects, the new frontiers of experimentation in architecture are oriented towards proposing new models of living in which the building organism is also able to autonomously ensure the comfort of its users. In this way, the evolution and dissemination of IT (Information Technology) control systems (from home automation to Building Management Systems) to transfer the potential of systems equipped with artificial intelligence to the building scale, have also ensured the regulation of space in the absence of human users and in relation to a whole series of requirements that guarantee an optimisation from the functional and physical perspective of the built space.

However, what does 'adaptive façade' really mean? Is it possible to find a single definition for the complex panorama of smart envelope systems that have characterised the last decade's contemporary architecture?

From the point of view of the biological scientists: 'adaptation' can be defined as the evolutionary process whereby an organism becomes better able to live in its habitat (Dobzhansky, Hecht, & Steere, 1968). According to recent research in the field of architecture, the term 'adaptive' in the context of building façades is often associated in the literature with a long list of similar terms: active (Ochoa & Capeluto, 2008); accommodating; adaptable (Frei, 2015; Möller & Nungesser 2015; De Marco Werner, 2013); adjustable; advanced (Ad, Heiselberg & Perino, 2011); biomimetic (Vermillion, 2002); bio-inspired (Loonen, 2015); controllable (Konstantoglou, Kontadakis, & Tsangrassoulis, 2013); kinetic (Fortmeyer & Linn, 2014; Loonen, 2010; Ramzy & Fayed, 2011; Fox & Yeh, 1999; Wang, Beltrán, & Kim, 2012); intelligent (Knaack & Klein, 2008; Velikov & Thün, 2013; Kroner, 1997; Clements & Croome, 2004; Hayes-Roth, 1995; Wigginton & Harris, 2002; Compagno, 2002; Masri, 2015); interactive (Velikov & Thün, 2013); living; modifying; movable (Schumacher, Schaeffer, & Voght, 2010); polyvalent (Davies, 1981); reactive; reconfigurable; reflexive; resilient; responsive (Velikov & Thün, 2013; Negroponte, 1975; Heiselberg, Inger, & Perino, 2012; Kolodziej & Rak, 2013; Meagher, 2015; Ferguson, Siddiqi, Lewis, & De Weck, 2007); selective; sensitive; sentient; smart (Velikov & Thün, 2013; Fox & Yeh, 1999; Brugnaro, Caini, & Paparella, 2014); switchable (Beevor, 2010); transformable; transient; and passive.

3 REVIEW OF EXISTING DEFINITIONS OF ADAPTIVE FAÇADES

Adaptable architecture is described for the first time by Frei Otto as a system that is able to change of shape, location, utilisation, or spaciousness. By change of location, he wants to indicate that the technological system is mobile, easily transportable, and able to be constructed and deconstructed quickly. The basic principle that is used for the construction of adaptable architecture is the 'Lightweight Principle' that relies on the optimal use of material and built mass (Möller & Nungesser, 2015).

Adaptive façades, in particular, consist of multifunctional, highly adaptive systems, in which the physical separator between the interior and exterior space is able to change its functions, features, or behaviour over time in response to transient performance requirements and boundary conditions, with the aim of improving the overall building performances (Loonen et al. 2015). Furthermore, these types of façade allow energy to be saved by adapting to prevailing weather conditions, and support comfort levels by immediately responding to occupants' needs and preferences (Loonen, Trčka, Cóstola, & Hensen, 2013). Consequently, adaptability can be understood as the ability of a system to deliver intended functionality, considering multiple criteria under variable conditions, through the design variables changing their physical values over time (Ferguson et al., 2007).

In accordance with the above semantic frame, adaptive façades should provide an adequate response to changes in the internal and external environments to ensure or improve the functional requirements of the envelopes in terms of heat, air and water vapour flow, rain penetration, solar radiation, noise, fire, strength and stability, and aesthetics. Therefore, multi-functional adaptive façades should be able to respond repeatedly and reversibly over time to changes in performance requirements and changing boundary conditions. In other words, adaptive façades should be able to provide controllable insulation and thermal mass, radiant heat exchange, ventilation, energy harvesting, daylighting, solar shading, or humidity control (Aelenei, Aelenei, & Pacheco Vieira, 2016).

Moreover, in the context of the smart cities, where the buildings must be interactive in the zero energy frame to provide the operational flexibility needed to avoid or reduce the mismatching, these innovative envelope systems can play a key role (Aelenei et al., 2016). The concept of the smart building is, in fact, closely linked to that of the adaptive façade, as the façade itself is the main element capable of changing its structure to ensure the required performances, emphasising its resemblance to human skin. The envelope thereby becomes a real organic system connected to the building's central control system and to the air conditioning system, which can be compared with the human artery system (Romano, 2011).

For this reason, the adaptive façades built in recent years in many geographical areas are characterised by the complementary nature of the system and building technologies, and by the presence of regulation and control systems that make them a key element in the complex building-plant system.

a b c

FIG. 1 Some pictures of active façades: a) ARTICULATED CLOUD, Pittsburgh (USA), 2004; b) Nordic Embassies in Berlin, Berlin (DE), 1999; c) MEDIA-TIC, Barcelona (SP), 2007

3.1 ACTIVE FAÇADES

Active façades (Figs. 1a), b) and c)) can be definite technological systems which have integrated elements through which envelopes self-adjust to changes initiated by the internal or external building environments, achieving comfort conditions while minimising energy consumptions. These active features should be both automatic and manual and should not need to include sophisticated electronics (Ochoa & Capeluto, 2008).

3.2 ADVANCED FAÇADES

An advanced façade is the outer, weather-protecting layer of a building that can contribute to heating, cooling, ventilation, and lighting requirements and can promote interior comfort through efficient, energy saving measures. The main difference between advanced envelope concepts and other energy efficient envelope concepts is the application of responsive building elements and their integration with building services systems and energy systems in combination with advanced control (Ad et al., 2011).

3.3 BIOMIMETIC OR BIO-INSPIRED FAÇADES

The skins of plants and humans tend to be seen as the most straightforward emulation model and inspiration source for multifunctional and truly sustainable enclosure systems. Functional bio-inspiration can either be direct or indirect. The first approach directly copies the observed functional principle into a building envelope technology that performs the same role. This is an example of phototropism (i.e. changing in response to light) and heliotropism (i.e. changing in response to the sun), applied, for example, in the climate adaptive building shells concepts that enable the active collection or rejection of solar energy (Vermillion, 2002). The indirect approach is loosely based on a selected biological principle but requires an intermediate abstraction step in its translation from biological principle to building envelope technology (Loonen et al., 2015) (Figs. 2a), b) and c)).

a *b* *c*

FIG. 2 Some pictures of bio-inspired façades: a) Hygroscope, Centre Pompidou, Paris (FR), 2012; b) BIPV Adaptive Flakes, Milan (IT), 2017; c) BIQ – The Algaehouse – The Clever Treefrog, Hamburg (DE), 2013

a *b* *c*

FIG. 3 Some pictures of kinetic façades: a) Campus Kolding, Kolding (Denmark), 2014; b) Kiefer Technic Showroom, Bad Gleichenberg (A), 2007; c) ThyssenKrupp Quarter, Essen (DE), 2010

3.4 KINETIC FAÇADES

In 1970, Zuk and Clark defined kinetic architecture as an architectural form that can be inherently displaceable, deformable, expandable, or capable of movement (De Marco Werner, 2013). To elaborate, a kinetic façade is a technological system in which there is a certain kind of motion (Loonen, 2010) and that is able to guarantee variable locations or mobility and/or variable geometry to all or one of its parts. (Fox & Yeh, 1999). The term 'kinetic' also indicates an organism's response to a particular kind of stimulus in biology (Wang et al., 2012) and an ability to modulate energy in its primary forms: visible light and heat. A kinetic façade (Figs. 3a), b) and c)) can respond to the flow energy, both natural and man-made, that primarily affects building performance and the comfort of the people in them (Fortmeyer & Linn, 2014). These types of envelope, in general, need to be efficiently tuned to boundary conditions such as climatic conditions, different locations, varying functional requirements, or emergency situations. In order to guarantee the kinematic, an actuation force is needed that generates the movement.

3.5 INTELLIGENT FAÇADES

Intelligent buildings are those which combine both active and passive intelligence - active features and passive design strategies - to provide maximum occupant comfort using minimum energy (Kroner, 1997). In this context, the definition of 'intelligent' façade introduces the idea of dynamic movement and the 'component' façade in which all building services components are integrated (Knaack & Klein, 2008). Furthermore, the term 'intelligent', when applied to a façade, must indicate the responsive ability of the façade to change according to environmental conditions (Compagno, 2002). The intelligent skin is therefore a composition of elements, which acts as a barrier to the outside environment, yet can respond to climatic changes through the automatic reconfiguration of its systems (Masri, 2015) to produce a pleasant indoor environment (Clements-Croome, 2004). The primary functions that must be performed by intelligent systems were considered: perception, reasoning, and action. This corresponds in robotics to sensors, control processors, and actuators (Hayes-Roth, 1995). For these reasons, an intelligent façade should be able to change itself through 'instinctive autonomic adjustment' (Wigginton & Harris, 2002), optimising the building's systems relative to climate, energy balance, and human comfort, typically based on predictive models. This is often accomplished through building automation and physically adaptive elements such as louvres, sunshades, operable vents, or smart material assemblies (Velikov & Thün, 2013).

3.6 INTERACTIVE FAÇADES

a b c

FIG. 4 Some pictures of interactive façades: a) GreenPix – Zero Energy Media Wall, Beijing (cn), 2018; b) SolPix, New York (US), 2010; c) Cyclebowl, Hannover Expo (DE), 2000

The term 'interactive' is used less frequently with regard to building envelopes than in reference to computer-enabled artworks, installations, and other such environments that encourage active public participation. However, an interactive façade (Figs. 4a), b) and c)) requires human input to initiate a response, and it may also be equipped with sensors and an automated building management system and programmed to optimise energy conservation while simultaneously ensuring the comfort of its inhabitants (Velikov & Thün, 2013).

3.7 MOVABLE FAÇADES

Movable façades can be defined as technological systems that are able to rapidly adapt to the environmental conditions and location, as well as being defined by the opening elements themselves. Furthermore, where individual parts of flexible enclosures are equipped with photovoltaic elements that track and follow the position of the sun, these type of envelope systems can produce renewable energy, thereby reducing the energy consumption of new or existing buildings (Schumacher, Schaeffer, & Voght, 2010).

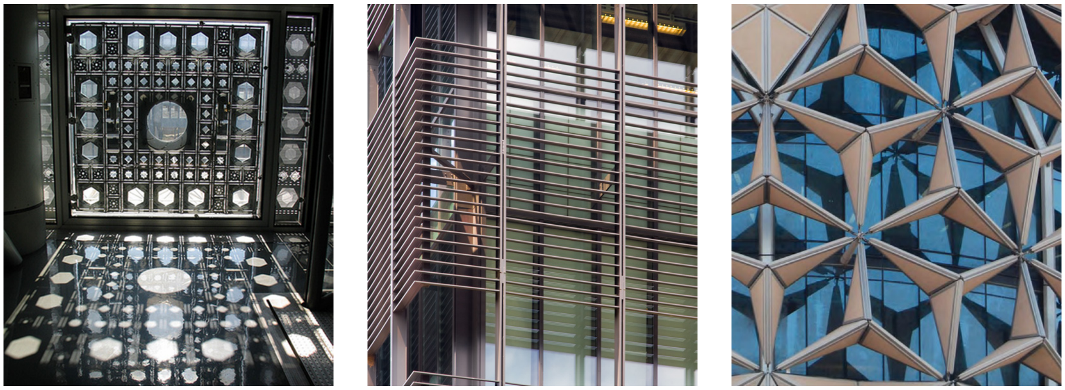
3.8 RESPONSIVE FAÇADES

Functional responsiveness in contemporary architecture can be defined as a system's ability to adapt itself to deliver intended functionality under varying conditions through the design variables that change their physical values (Ferguson et al., 2007). A responsive façade takes an active role, initiating changes, to a greater or lesser degree, as a result and function of complex or simple computations (Negroponte, 1975).

Meagher (2015) defines responsive components as all those elements of the building that adapt to the needs of people as well as to changes in the environment. These components may be high tech systems that employ sensor networks and actuators to monitor the environment and automate control of operable building elements. He also uses this term to refer to the moveable, operable, often manually controlled elements of buildings which allow the adjustment of the building envelope and interior in order to adapt the building's performance to meet everyday needs. Furthermore, these technological systems can be actively used for transfer and storage of heat, light, water, and air. They assist in maintaining an appropriate balance between optimum interior conditions and energy performance by reacting in a controlled and holistic manner to outdoor and indoor environment changes and to occupants' requirements. Responsive building elements can be essential technologies for the exploitation of environmental and renewable energy resources, and in the development of integrated building concepts (Heiselberg et al., 2012).

In other words, responsive building envelopes (Figs. 5a), b) and c)) can be defined as technological systems in which external environmental conditions (e.g. ventilation, humidity, light volume, radiation, and temperature) influence the interior parameters of the building (i.e. thermal and light comfort). The most common solutions are based on several specialised subsystems (such as structural elements, sensors, mechanical actuators, membranes, control devices, etc.) that are responsible for changing the envelope's geometry according to stimulus and programmed performance (Kolodziej & Rak, 2013).

A responsive building skin includes, in fact, functionalities and performance characteristics similar to those of an 'intelligent' building skin, including real-time sensing, kinetic climate-adaptive elements, smart materials, automation, and the ability for user override. However, it also includes interactive characteristics such as computational algorithms that allow the building system to self-adjust and learn over time, as well as the ability for inhabitants to physically manipulate elements of the building envelope to control environmental conditions (Velikov & Thün, 2013).



a b c

FIG. 5 Some pictures of responsive façades: a) Arab World Institute, Paris (FR), 1987; b) Yale Sculpture Building, New Haven Connecticut (USA), 2007; c) Al Bahar Towers, Abu Dhabi (AE), 2012

3.9 SMART FAÇADES

Within the design disciplines, the term 'smart' has most frequently been used in reference to materials and surfaces. Smart surfaces and materials show properties that are changeable and thus responsive to transient needs (Fox & Yeh, 1999); furthermore, they can play a significant role in intelligent, adaptive, and responsive envelopes because of these intrinsic properties. Examples of smart materials used in high-performance building skins include: aerogel – the synthetic low-density translucent material used in window glazing, phase-changing materials such as micro-encapsulated wax, salt hydrates, thermochromic polymer films, and building integrated photovoltaics (Velikov & Thün, 2013). Smart skin systems (Figs. 6a), b) and c)) are able to modify their physical-geometric characteristics to conform to changes in their environment by use of, for example, dynamic solar screenings, placed as a second skin on new and existing multilevel buildings. They also assume a fundamental role in the formal and characteristic aspects of the façade (Brugnaro, Caini, & Paparella, 2014).

3.10 SWITCHABLE FAÇADES

Switchable façades are built as transparent façades in which 'smart glasses' or, more generally, smart adaptive materials, are integrated to regulate light and energy flows through glass façades (Beevor, 2010).

3.11 TRANSFORMABLE FAÇADES

The response of transformable façades needs to be efficiently tuned to boundary conditions such as climatic conditions, different locations, varying functional requirements, or emergency situations. For this response, an actuation force is needed that generates movement. The transformation process goes from a compact to an expanded configuration or vice versa. The transformation phase must consist of controlled, stable movements and results in a rigid and secure structure, once it is locked in place (Chloë, 2016).

a b c

FIG. 6 Some pictures of smart façades: a) InDeWaG, Bayreuth (De), 2015; b) SELFIE Façade, Florence (I), 2017; c) Solar XXI – BIPV/T Systems, LISBON (P), 2006

4 CHARACTERISATION PARAMETERS OF ADAPTIVE FAÇADES (AFS)

As is demonstrated in the previous definitions, adaptive façade systems are notable for the presence of one or more of the following technological features:

- High-performance innovative materials and systems for absorbing and storing solar energy (e.g. smart, biomimetic, or bio-inspired façades, etc.);
- Devices for managing natural ventilation in combination with mechanical ventilation systems (e.g. adaptable, advanced, responsive façades, etc.);
- Mobile screens for controlling solar radiation (e.g., smart, adaptable, responsive, and switchable façades, etc.);
- Technological solutions designed to increase and/or control comfort inside the building (e.g. adaptable, active, kinetic, intelligent, interactive, and switchable façades, etc.);
- Building automation systems for the management of plants and elements of the building skin (e.g. intelligent, responsive façades, etc.).

These adaptive façade systems efficiently contribute to the energy balance of the building, limiting the need to use air conditioning devices, with a consequent reduction in energy consumption.
In many cases, intrinsic dynamic façade systems are used, which delegate the adaptive capacity to the smart materials (e.g. PCM, TIM, ETFE, BIPV, etc.) of which they are composed. This is the case for the façade systems in which the adaptivity does not necessarily involve a change in the spatial configuration but rather concerns the regulation of the thermo-physical properties based on the external climatic conditions (e.g. switchable, smart, and biomimetic façades, etc.). In other cases, adaptivity (e.g. movable, responsive, and active façades, etc.) can be interpreted as the capacity to produce energy in a dynamic way, according to the energy requirement of the building.

In addition, the adaptivity is instead explicit in the façade system's capacity to move all or some of its parts. These are known as kinetic façade systems (Fox & Yeh, 1995; Wang et al. 2012) capable of changing by moving in space and taking on different structures and configurations over time. The long-term changes are achieved through reversible and unique conversions in the context of a flexible structure, while short-term reversible adaptations can be brought about through mechanical solutions.

5 CONCLUSION

The review of the definitions of adaptive façades shows that the architectural research on dynamic envelopes is moving towards innovative solutions. By exploiting the possibility of integrating IT systems, mechanical actuators, and innovative materials, these technological solutions are able to transform the envelope from a static element into a dynamic element capable of rapidly and efficiently changing shape in relation to specific functional, static, and physical requirements. The advanced screen, eco-efficient, and sustainable envelope interacts and regulates energy flows and, in some cases, becomes a plant system, by itself, capable of producing energy, heat, or electricity, and of distributing it at a building or even at an urban scale.

Adaptive architectures can therefore be considered as the last goal of contemporary architectural and technological research and they are always increasingly connected to the wish to propose new dynamic envelope models which – thanks to the presence of sensors, and system components for energy production as well as smart materials – help to reduce the building's energy requirement. These technological solutions, as previously mentioned, can control energy flows by regulating fixed devices that can be characterised by the presence of smart materials, variable structures (e.g. sunshades, opening/closing of windows, ventilation outlets, among others), manual or automatic control, or regulation in relation to the type of user and complexity of the building. This envelope typology is marked by dynamic anisotropy that is the capacity to offer different solutions for the different exposures of the building, where a change in the structure modulates the various environmental flows according to the climatic conditions of the place, including external climatic-environmental conditions. Therefore, it shows all those components that increase its capacity to change the structure in relation to the need to regulate the thermal, light, and sound energy flows passing through it (Banham, 1969).

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