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The sustainability of adaptive envelopes: developments of kinetic architecture

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Abstract

The paper presents an overview of adaptable envelopes and shading systems applied in contemporary architecture; it offers a study of different design approaches and a brief analysis of exemplifying case studies. The aim of the research is the gathering of built examples relevant to outlining a state of the arts of adaptive façade systems and also understanding their environmental performances. Nowadays two different trends emerge in building development. On the one side the new challenge is given by the possibility to reconfigure the new spaces following environmental changes and users needs, while on the other the focus is on the increase of efficiency and the optimisation of materials for reducing energy consumptions in constructions. The building envelope is the primary subsystem through which external conditions and environmental changes can be regulated and therefore acquires great relevance in the development of new approaches to sustainable building solutions. In this review paper several examples are shown and compared, understanding the search for dynamics applied in architecture and the effectiveness from an environmental sustainability point of view.

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Keywords: adaptability, responsive architecture, kinetic architecture

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1. Introduction

According to the Physical Institute in Maldegem, building façades are responsible for more than 40% of heat loss in winter and for over-heating in summer, which is making the employment of air conditioning systems necessary to guarantee an appropriate internal comfort. For this reason the building sector records the highest amount of energy consumption, even greater than industry and transport. The ES-SO Studies "ESCORP-EU 25" confirms that more than the 40% of the total primary energy consumed in all of Europe occurs in the building construction and building management field. With an accurate design of the façade details and an efficient shading system, office buildings in middle Europe could easily work without high energy-consuming cooling systems. The use of adaptive shading systems could contribute to reduce the energy demand of buildings in 2 ways: thanks to the supplementary thermal resistance in closed position, they may reduce the heating energy demand in wintertime while in summer, they protect the façade from solar heat gain, reducing the need for cooling energy. Following these premises, in Europe, the energy consumption of building construction could potentially be reduced by 10% for oil consumption (approx. 41 million tons) and around 111 millions tons for CO_2 production per year [1]. In 2011 the market related to the façade design and construction has reached a total of 12 billion Euros invested worldwide in the sector, 6% of which are appointed to shading systems. This underlines the potential that lies in the field of innovative façade shading systems.

Current trends in architecture go in the direction of dynamic and adaptive building envelopes, which reconfigure themselves to meet external and internal changes in climate and user behavior. Despite recent developments and some landmark projects, the market is, where applicable, still dominated by traditional blinds and shutters. These systems however fail at high wind speeds and are restricted to planar façades and rectangular grids. However, contemporary high rise architecture shows a trend towards complex curved and triangulated façade systems. This trend is particularly present in the Middle East, where external shading devices would seem essential.

To face these energy problems there are two suitable approaches which may be distinguished. On the one side there are mechanical shading devices, while on the other there are chemical solutions in so-called switchable reflective glazing. In the first case additional mechanical elements are added to the exterior or interior of facade or integrated in the façade complex (double skins) and help to regulate the light reflection and the solar radiation through mechanical movements and controlling procedures (mechanical approach). In the second case innovative types of glasses are used, which change their optical properties in relation to external variables i.e. solar radiation, application of low DC-voltage (electrochromic glass) or by using hydrogen (gasochromic) [2]. Here the adaptation method is based on chemical alteration of a material layer within the glass, allowing the integration of the adaptable system directly in the glazing plane (chemical approach).

As a combination of mechanical and chemical approaches it is possible to point out a third research trend which focuses on material systems, in which adaptive performance is based on material behavior. Most commonly known as shape memory or smart materials those systems react to environmental stimulus changing one or more of their proprieties (chemical, mechanical, electrical, magnetic or thermal). Changes are direct and reversible and do not require an external source of energy to activate the system [2,3]. This is the most significant characteristic of shape memory materials which make their application interesting in the field of sustainable building components. Even if based on different technologies, all approaches pursued the principle of adaptability.

2. Common definitions in adaptive shading

Before introducing the case studies of adaptive façade systems, some definitions are made. To describe the division between architectural exterior and interior there are several expressions. The term façade traditionally describes the vertical plane of the construction, while the term envelope, recently widespread, refers more generally to the total building enclosure. The expression building skin initially underlines the distinction between the cladding and the structural part, but has more recently been associated with conceiving the envelope as an intelligent environmental system [4] able to exchange energy, material and information [5]. To reinforce this tendency Wigginton and Harris in their book Intelligent Skins state "the skin operates as a part of an holistic building metabolism and morphology, and will often be connected to other parts of the building, including sensors, actuators and command wires from the building management system" [6].

Definitions regarding adaptive systems are very broad. There is an apparent tendency of research groups to define their own vocabulary to describe a particular type or approach to adaptive systems. Most commonly the words kinetic, kinematic retractable, convertible or simply adaptive are used to describe the non-stationary nature of the shading devices. In addition terms like performative, responsive and dynamic are used to describe the shading systems functional interaction with its environment.

In order to clarify the use of some of these terms the authors suggest some general definitions.

Kinematics: is the study of motion without considering the mass or external forces that may cause the movement. The study of kinematic systems start with the description of the system geometry and the initial conditions related to the position values. In engineering disciplines kinematics are used to describe the movement laws of systems composed by joined parts and sometimes on refer to it as "the geometry of motion" [7,8,9].

Kinetics: is the study of movement laws considering the forces and masses involved [8]. If the cause of system motion is an elastic deformation the system falls under the category of Elastic Kinetics [9].

Dynamics: is the study of forces acting on an object and that results in a movement [8,9]. The term is often used to identify building systems or envelopes that can move.

Retractable: the term is commonly used in architecture for textile membrane roofs in which the membrane is bunched or folded. As a more simple expression, such systems are also referred to a *movable*.

Convertible: convertibility is considered, with mobility, one of the modes of variability in buildings for adapting to different functions [10]. It possible to identify two types of convertibility: external, i.e. the variability of the external envelope of the building, and the inner convertibility, related to the interior spaces. Convertible systems are designed to change their form in relation to the needs and in a short time [10].

Transformable: Similar to convertible, transformable can be associated to objects or structures which have the intrinsic property of controlled change. Transformable bodies can be foldable, retractable or shape shifting [11].

Performative: is the ability of building skin to mediate between the comfort required by the users and the surrounding environments. Performative envelopes have the capacity to control external factors in relation to pre-defined architectural performances [12].

Adaptive: "means the ability to adjust and adapt to changing circumstances by itself" [13]. Adaptive envelopes have the capability to change their behavior, features or configurations in relation to external variations [14].

Responsive: the term refers to a reactive system, i.e. a system that moves and is opposed to the term manipulate, which means that the system is moved and controlled from outside and refers to passive environments [5]. Nicholas Negroponte defines "responsive means that the environment which has an active role, initiating to a greater or lesser degree changes as a result and function of complex or simple computations" [5, 13, 15].

3. Kinematic approaches to adaptability

The efficiency of sunshading device is related to the solar altitude angle and varies over the course of the day and year. Therefore adaptive systems appear more suitable than fixed ones since they can be adjusted in relation to the changing of solar radiation, allowing individual control, optimal shading and maximization of daylight use [16]. It appears that adaptive shading systems may have a significant influence on the climatic performance of a building although they are not yet widely applied. Modern building facades with their complex geometries, pose geometrical and mechanical limits to the shading systems design [17].

Shading devices like blinds, shutters, and louvers, are usually marketed as standardized components. The mechanics of these elements are based on a modular grid; the system is restricted to planar surfaces with orthogonal axes and right angles. These products are widespread and perform well when applied on planar façades. If applicable at all they offer no standard solution for applications to curved surfaces and free-form envelopes, which are increasingly used in contemporary architecture. Indeed, the increasing use of computational design practices and digital technologies in the manufacturing process offer more freedom in the planning of building structures, resulting in more articulate and complex building systems. Traditional louvers applied on this new generation of buildings seem in most of the cases impossible or ineffective.

In order to solve this issue, new possibilities of shading systems must be developed which achieve a higher degree of adaption and flexibility to adjust to complex geometries. The project Garden by the Bay in Singapore (Fig.

1A) is a successful example of an adaptive shading system applied on large-scale curved structures. Traditional blinds, although responsive and effective, would have been difficult to be applied to the two shell structures of the conservatories and could have hardly been oriented to a correct position for optimal shading [18]. In this project a retractable system has been designed in which canvas shades are positioned externally, allowing light transmission while protecting the façade from over-heating. The sensors installed in the interior spaces control temperature, light and humidity. When the recorded levels increase motors unroll two triangular shadings per element. The key feature of this device may be seen in the fact that the system is laid out on a diagrid. Because of this the two shaded surfaces of one unit are always planar because triangular and therefore may easily be retracted by rolling. As such the system can continuously adapt to the changing double curved surface it is attached to.

"This new generation of façades (or building envelopes) consists of multifunctional and highly adaptive systems, where the physical separator, or part of it, between the interior and exterior environment is able to change its functions, features or behavior over time in response to transient performance requirements and boundary conditions, with the aim of improving the overall building performance" [19]. Besides the optimization of energy use, adaptive shading systems seem a valuable answer to the increasing complexity in contemporary architecture.

Another well-known adaptable façade is the south one of the Q1 building offices, designed for the new Thyssenkrupp headquarter in Essen (Fig. 1B). The façade is shaded by approximately 1280 motorized swivel louvers made from stainless steel and individually controlled by a linear motor drives. Three different configurations are possible: closed (parallel to the facade), following the position of the sun (variable angles) and open (perpendicular to the facade).

A B

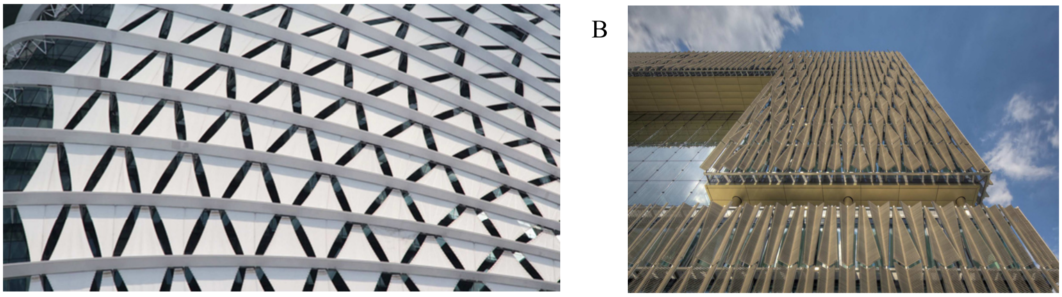

Fig. 1A: Garden by the Bay, Singapore (Serge Ferrari S.A.S); .B: Thyssenkrupp headquarter, Essen (photo by Günter Wett)

A notable and acclaimed example of external adaptive sun-shading is the Al-Bahr Tower in Abu Dhabi (Fig.2.A). The 29-storey building presents an adaptive folding shading system based on ridged link mechanisms inspired to the traditional mashrabiya[2], reinterpreted by means of three-sided umbrellas of translucent PTFE fabric (Fig.2.B). Linear actuators, regulated by a pre-programmed sequence that sends different inputs during the day, activate the elements allowing five different operative configurations, from completely open to totally closed. According to the design estimates, the system should reduce cooling loads by as much as 25% [20].

[2] The mashrabiya is a type of windows protecting system made of curved wood frameworks and used in the traditional Arabic architecture. It offers protection from sun and more privacy inside the building.

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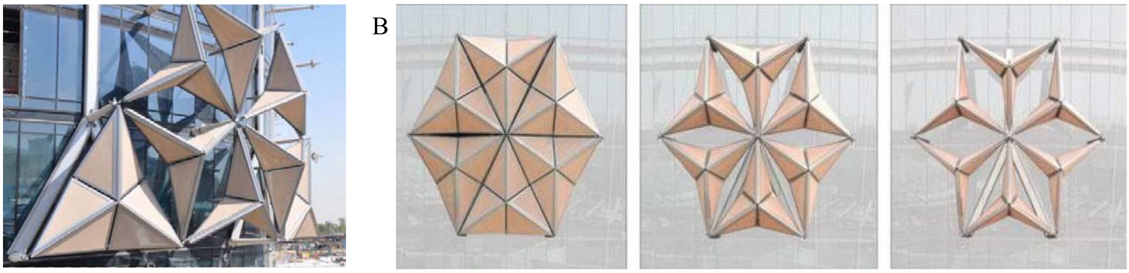

Fig. 2. A: Al-Bahr Tower in Abu Dhabi (Attia, 2015)

B: Different possible configurations of the Al-Bahr façade system (Alotaibi, 2015)

4. Elastic kinetic approaches to façade shading

As a new approach to adaptability without the need of mechanically complex systems elastic kinetics are employed. Here adaption is based on hingeless elastic bending deformation.

Flectofin® is an example of bio-inspired elastic kinetic shading system. The deformation principle is derived through the biological analysis of reversible deformations found in plants movements and then abstracted to a pliable structure which lead to technical construction of a hinge-less shading device. The shading is composed by two lamellas restricted to an actuated beam element [21]. An important value is that the shade can acquire structural stability also in the intermediate configurations, between open and close positions [9].

A similar principle is applied at the building scale with the elastic kinetic façade system for the Thematic Pavilion at the EXPO 2012 in Yeosu (Fig.3a). The Thematic Pavilion is composed by individual lamellas of glass fiber reinforced polymers (GFRP) that control the solar exposure and the light conditions while creating an animated façade pattern. The actuators, spindles driven by an electric servomotor, are located on both the upper and lower edges of lamellas to induce compression forces which trigger the elastic deformation. The activation power is converted into elastic energy stored in the deformed louvers and partially reconverted into electrical power during the closing procedure by using the servomotors as electrical generators [17]. Thanks to this the system can save energy. The opening angle of louvers is related to their length: the longer is the lamella the larger is the illuminated area and the spectacular effect increases [23].

A combination of elastic kinetics and soft textile shadings is presented by the textile façade of the Softhouse (Fig.3B), realized for the international exhibition 'Bauausstellung' IBA 2013 in Hamburg. The textile façade of the 'Softhouse' undergoes two modes of shape adaptation: in a yearly cycle, the GFRP boards on the roof top change their bending curvature and therefore adjust the PV cells to the vertical angle of the sun, while the daily east west sun tracking and daylight harvesting is achieved by twisting the vertical membrane strips in front of the façade. The membrane strips are attached to cantilevering GFRP boards acting as compound springs compensating the change in length of the membrane strip through twisting.

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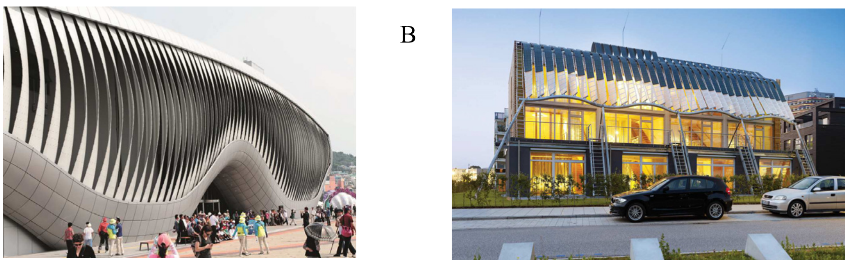

Fig. 3. A: Thematic Pavillion Yeosu Expo 2012 (Knippers, 2012); B: IBA-Softhouse in Hamburg (photo by KVA matX)

5. Sensors and actuators

To make any adaptable system dynamic and responsive it needs to be actuated, i.e. an input of motion has to be transferred to the system so that it can fulfill the performances required [20]. This is generally obtained through control of external loads, internal forces or deformations [23]. Actuators need a control system that translates incoming signals from user interaction or climate change into actuation commands. Sensors are the link between the environmental space and the adaptive system; they record the external changes, they confront them with the desire state (set-point) and transfer the information to the processor, monitoring all the effects on the structure and its reactions. The actuators are the elements that convert the energy into motion and produce a reaction in the system, changing the geometry or main characteristics i.e. size or stiffness, in relation to the stimuli perceived by the sensors and elaborated by the processor. The processor is a controller unit (computer system) where the incoming data are processed and elaborated in an adequate response which respect the initial design requirements [24].

Control systems based on actuators, sensors and processors are identified in the literature as extrinsic control or active systems [14]. Opposed to this there is the intrinsic control or passive systems, or the ability of systems to self-adjusting in response to environmental stimuli like temperature, relative humidity, solar radiation and so forth without the implication of external electrical sources [14]. Smart materials are examples of intrinsic control systems. The following case studies fall in the field of study of elastic kinetic systems and based their design approach on the investigation of material properties and behaviors.

Two interesting pilot projects, which investigate the potential of shape memory form materials in architecture, have been developed in the last years; Bloom, a system designed by Doris Sung (Fig.4A) and Hygroskin (Fig. 4B), the research pavilion developed at the Institute of Computational Design (ICD) of the Stuttgart University. The Bloom system is composed by pieces of laser-cut thermobimetal assembled in stacked panels that form a self-supporting shell structure. Speaking from an environmental point of view, Bloom is a passive system because it automatically opens and closes its lamellas based on the solar heating, without the aid of artificial energy [25].

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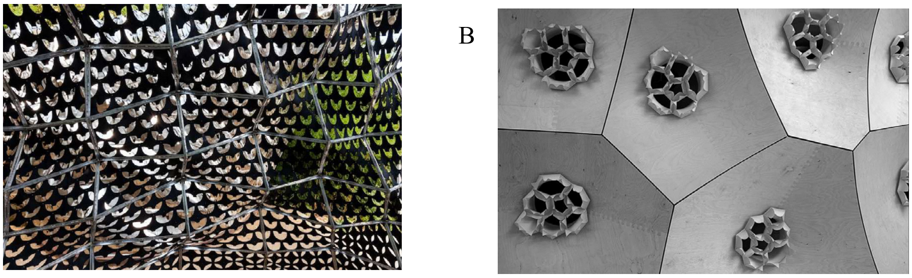

Fig. 4 A: Architectural installation "Bloom", Los Angeles (photo by Doris Sung);
B: Hygroskin Pavilion. Detail of the adaptable climatic system (Correa, 2013)

Based on the same passive approach but related to the hygroscopic behavior of timber, Hygroskin is the result of a research process that aims to deepen intrinsic capacity of wood to reach changes of relative humidity. One of the most traditional construction materials becomes here an innovative climate-responsive element. Wood cones that open when the relative humidity increases and close when the internal moisture decreased compose the adaptable system [26]. Both projects show the possibility to exploit the change of materials intrinsic features for creating "zero-energy" adaptive systems.

If on one side smart materials are suitable solutions from an environmental point of view because self-powering and self-actuating, on the other they have a big limit related to the inability for manual intervention. In fact, in these systems, the individual control from the user side is impractical or restricted. This is why smart materials are so far developed only on prototypical scale with limited applications. Their application is difficult in buildings, except for some public complexes i.e. airports, train stations, museums etc. in which the user does not directly interfere with the internal comfort control system. Several studies have been carried out that the levels of perceived and exercised personal control of living and working environments are important determinants of comfort, well-being and performances. Therefore, user interaction and satisfaction are important factors that cannot be neglected [27].

6. Aspects of building physics and efficiency

It appears clear that the choice of the shading system typology is influenced by different factors: the geometry of the façade (planar or free-form façade), the design conception, the environmental efficiency, the technological performances and so forth. Besides the architectural ambitions, several studies prove that some solutions are more efficient than others. So far it has been tested that external and internal shutters have the same influence on the heating demand during wintertime, while external ones result more effective in summertime, reducing the cooling energy demand [1]. This is due to the fact that internal sunshading elements do not filter the solar radiation on the outside of the façade, which is absorbed and transmitted into the room resulting in additional cooling loads. However, shading systems mounted on the inside of buildings are protected from external wind loads and weathering. They can therefore be built much lighter and need less maintenance.

Looking at the building physics, the most significant differentiation may be seen in differentiating between internally applied systems, externally applied systems and embedded systems (double skins and switchable glazing) (Table 1).

Even if there are fewer popular applications related to internal adaptive shading, some case study results are valuable. The Strata™ system developed by ABI3 (Adaptive Building Initiative) and used as roof shading system in the new campus of the City of Justice in Madrid is an example. The hexagonal sunscreen units move independently by means of servomotors and hide within a single slender when retracted. This system can be customized in relation to the design necessities and can be realized with different materials (metallic, plastic, wood). ABI, in collaboration with Zahner Company, has developed other adaptive façade technologies. An example is Tessellate, a self-contained and framed perforated screen that consists of stacked panels that move and overlap, creating kaleidoscopic patterns, which control light and solar gain, ventilation and airflow, privacy and views. A motor provides the rotational translation of the sheets, resulting in a constantly changing light-diffusion [20]. This system has been applied on the internal façade of the Simons Center for Geometry and Physics (SCGP, Stony Brook University) and combined with external horizontal louvers to guarantee the maximum efficiency [28].

Finally adaptive shading devices can also be embedded in the façade system; this is the case of before introduced switchable glazing and adaptive double skins. Probably the most famous example of kinetic system integrated into glass layers is the Institut du Monde Arabe, designed by Jean Nouvel at the beginning of 90's. This pioneer project is an example of architecture based on change [29]: the southwest façade of the building is composed by series of photo-sensitive metal apertures that open and closed automatically to modulate daylight and solar heat gain to the interior [20]. The squared metal bays that composed the camera shutters system are organized in a grid of 24x10 [4]. Each bay is individual controlled by motors connected to a central computer system, allowing different operative possibilities. Although the system is sandwiched between two glass sheets the delicate mechanisms and controls were left exposed, resulting in the necessity of constant maintenance and mechanical problems [29].

Despite the advantages offered by internal shading systems, external shading elements seem at the moment the most efficient option to prevent undesirable heat gains [16]. Up till now, they are the solution most applied in case of responsive facades, especially concerning high rise building complexes. From the analysis of previously illustrated cases it is apparent that adaptive façade systems applied externally are used often as pretext for designing innovative and unique dynamic facades, becoming outright architectural landmarks more than energy saving systems.

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[3] Adaptive Building Initiative (ABI) is an enterprise that has been founded in 2008 to join the experiences and skills of Büro Happold and Hobermann Associates in the development and design of adaptive building systems.

Table 1. List of case studies and design approaches

Kinematic systems	Externally applied	Internally applied	Integrated in the façade
Institut du Monde Arabe, Paris (1987)			X
Simons Center for Geometry and Physics, SCGP, Stony Brook University (2010)		X	
Thyssenkrupp quartier, Q1 Office Building, Essen (2011)	X		
Al-Bahr tower, Abu Dhabi (2012)	X		
Garden by the Bay, Singapore (2012)	X		
Campus City of Justice, Madrid (2012)		X	

Elastic kinetic systems	Externally applied	Internally applied	Integrated in the façade
Flectofin® (2011)	X		
Thematic Pavilion EXPO 2012, Yeosu (2012)			X
Bloom, Los Angeles (2012)	X		X
IBA Soft House, Hamburg (2013)	X		
Hygroskin, Orléans de la Source (2013)			X

7. Conclusions

At the beginning of the research, the aim was to offer a categorisation method of shading systems based on both their function in the building hierarchy (roofing or envelopes) and their motion characteristics. During the work it became clear that a classification of adaptive envelopes does not lead to any viable scientific or practical conclusions. At the moment there is no common agreement for assessment of adaptive facades. Literature scientifically dealing with façade shading is rare and at the best of times focused on individual projects. In general terms there still is a need in defining what these systems are [30]. As mentioned above, recent architectural trends lead to increasingly complex geometries which entails a revolution in the conception of building system hierarchy; the strict differentiation between roof and façade can often not be made. For this reason terms like envelope or skin are becoming more and more common.

Besides this, the employment of adaptive facades, in particular in the case of big building complexes, ends up in most of the cases with one-of-a-kind systems. This is probably related to the intention of preserving the originality and architectural value of solutions, which are otherwise compromised in case of product applications. Another motivation can be also related to the fact that adaptive systems, in comparison to static façades, are related to the climatic context in which they are applied; a factor that greatly influences their effectiveness.

Due to these facts the analysis of environmental efficiency is complex. There is a limited number of case studies that give information on the operational performances and the state of the arts analysis every adaptive façade is a unique system. Moreover, the criteria to evaluate the performance of adaptive systems values for static façade systems are used, without taking into account the multi-functional and dynamic features of adaptive components.

Some research focuses on the development of new performance calculation methods for adaptive skins [18], but for the moment the indicators developed results which are too specific and prevent the confrontation of parameters. In addition to these, most of the buildings in which adaptive envelopes are employed, use other methods to reduce energy consumptions; therefore the particular efficiency of the façade systems may be difficult to evaluate [31].

Furthermore, the increase of responsiveness goes hand in hand with the increase of system complexity, inflating the costs of construction, installation and maintenance. The singularity and the weakness of components influence the lifespan of systems, causing mechanical problems that reduce the usability.

Last but not least, the adaptive façade systems require a large amount of energy to activate sensors and actuators which should ideally be lower than the energy saving. These aspects will have to be considered to ensure the sustainability of the systems. On the one hand the increase of performance obtained by reducing energy consumptions with the optimization of the building envelope and on the other, minimizing the energy use and raw materials employment (considering the embodied energy of building components).

Most buildings still have adaptive façades with hinged and louvered shutters fixed outside the windows. These devices, which are low-cost and low-energy if manually activated, represent solutions that still have a place in contemporary architecture and provide adaptability in buildings [32]. Ordinary hinge mechanisms, if used in innovative ways, could allow the creation of adaptive environments without complex automatic systems. The Future challenges therefore lie in the development of adaptive shading devices or responsive envelopes which are low-tech in their mechanisms but high-tech in their uses.

One approach to these far reaching questions may be found in elastic kinetics, also known as compliant mechanisms. These hingeless and therefore low maintenance systems have the capacity to store energy when deflected, releasing it later to bring back the mechanism to original position [33]. Therefore, the mechanical response related to the energetic input can be customized in relation to the design requirements, allowing either a maximum displacement or a maximum resulting force [33]. As such elastic kinetic approaches may lead to good solutions for developing adaptive façades that use the energy of motion to activate motors while allowing individual control.

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