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Progressive Trend in Adaptive Façade System Technology. A Review

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Abstract:

During the last decades, a great number of innovative building envelope materials, products, and façade systems have been developed. The majority of these progressive technologies promise significant improvements in energy efficiency and occupant's comfort. However, it remains a challenge to assess the performance of such façades, leading to difficulties for efficient design, construction, and maintenance. As a consequence, the market adoption of adaptive façades is not realizing its full potential, resulting in missed opportunities for energy savings and improved occupant satisfaction. In this research, the main trends of adaptive façade development were investigated, with particular emphasis on their performance assessment. The literature review identifies and describes a knowledge gap in the assessment and systematization of adaptive façade systems. Our research methodology combines mixed methods of research involving collecting, analyzing, and integrating quantitative and qualitative research. For the first time, the main types of adaptive façade systems were systematized and ordered. Based on the analysis of consumer properties of these façades, the main trends were revealed. New technologies including adaptive building skins meet changing environmental conditions, host multiple functions and offer decentralized controls for occupants. They serve as strategies for improved comfort and reduced building energy needs. Finally, we can assume that adaptive façades technology is not ready enough to cross barriers today, however, the technology remains a promising technology that can get better in near future.

1 Introduction

In the building sector, developments towards the functionalization of a building's envelope have strongly been pushed [1]. One of the main reasons for this development is the necessary reduction of building's energy consumption. This creates a desire to use the outer surfaces available of a building to improve outdoor environmental conditions, energy efficiency, and the satisfaction of occupants [2].

There is a high variety of different types of façades and building envelopes, as well as there, are many concepts for façades, which contain integrated components for the creation of high-comfort conditions in buildings premises. As a result, there is a great demand for the analysis of the thermal behavior and other indoor quality factors.

The construction of buildings with adaptive façades is a relatively new direction in architecture. Adaptive façades (AF) are building envelopes (often called building skins) that are able to adapt to changing environmental conditions. Such façades have the ability to respond to short-term changes in outside climatic conditions and dynamic occupant requirements and benefit from it [3].

When the façade state transitions are controlled in an optimal way, maximum indoor environmental quality and comfort can be ensured without compromising on energy consumption [4,5]. Moreover, adaptive façades can accomplish step-change progress in energy efficiency and in promoting the use of renewable energy in the built environment [6]. Various AF technologies and

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components are commercially available, including movable shading, electrochromic glazing, phase change materials, naturally ventilated double-skin façade, green façades, and roofs. Scientific publications, documenting the research and development phase of such façade systems, consistently demonstrate significant performance benefits compared to conventional alternatives [7–11]; [12–16]; [17].

However, despite continued technological development of façade solutions, many of which break new ground with respect to innovative dynamic use of façade glazing and fenestration, AF have not yet achieved a significant market share. If buildings with AF do indeed lead to higher occupant satisfaction and reduced environmental impact, then it is of primary importance to investigate and better understand how these buildings perform. By showing how design intent can successfully translate into high operational performance, it is expected that the market adoption of innovative building technologies such as AF can be accelerated [1].

The main barrier relates to difficulties in performance quantification and evaluation of buildings with AF. There is a lack of holistic performance criteria based on testing, assessment, and monitoring of adaptive façade systems. Although there is an ample amount of standards and criteria to assess façades at the material or component level, there are hardly any standards for complete façade assemblies [5,18]. There are no best practices for assessing and documenting the performance of AF systems. Design and construction of buildings with AF tend to transcend multiple engineering disciplines, expecting a high degree of coordination among all the actors involved. This leads to a number of process-related challenges, which take place in a professional environment with procurement mechanisms that in many cases are not streamlined to efficiently accomplish these tasks [3]. There is no evaluation of AF consumer properties. In addition, in the scientific literature, there is practically no data on the systematization of the main types of adaptive façade systems. This knowledge gap is significant and requires being addressed by the scientific community in order to simplify the evaluation of AF based on solid science.

As a contribution to addressing the mentioned barriers, the purpose of this research is to identify the gaps related to systematize the main types of adaptive façade systems and to provide insights into current trends and future challenges in this domain.

2 Materials and Methods

Our research methodology combines mixed methods of research involving collecting, analyzing, and integrating quantitative and qualitative research.

A literature review comprising more than fifty publications was conducted to identify elements found in scientific literature relevant to adaptive façades performance evaluation. In order to elaborate the review, Google Scholar, Scopus, and Web of Science database searches were conducted. The aim here was to collect articles exploring studies that may have performed the evaluation of AF. The literature review identifies and describes a knowledge gap in the assessment and systematization of adaptive façade systems.

The interdependency of relevant physics domains (thermal, mass, optical, acoustic, electrical) and energy fields that impact building skins were analyzed using the simple Venn diagram.

The retrospective data analysis was carried out to identify prototypes and real-world uptake using domestic and foreign construction experience. Based on a detailed analysis of the AF consumer properties, their properties were differentiated.

Two main approaches exist in such design processes: “technology pull” and “biology push” [5]. The International Standard ISO 2015:18458 has provided the following definitions.

The technology pull process is a “biomimetic development process in which an existing functional technical product is provided with new or improved functions through the transfer and application of biological principles”.

The biology push process is a “biomimetic development process in which the knowledge gained from basic research in the field of biology is used as the starting point and is applied to the development of new technical products”.

The generic steps of these processes are presented in Fig. 1.

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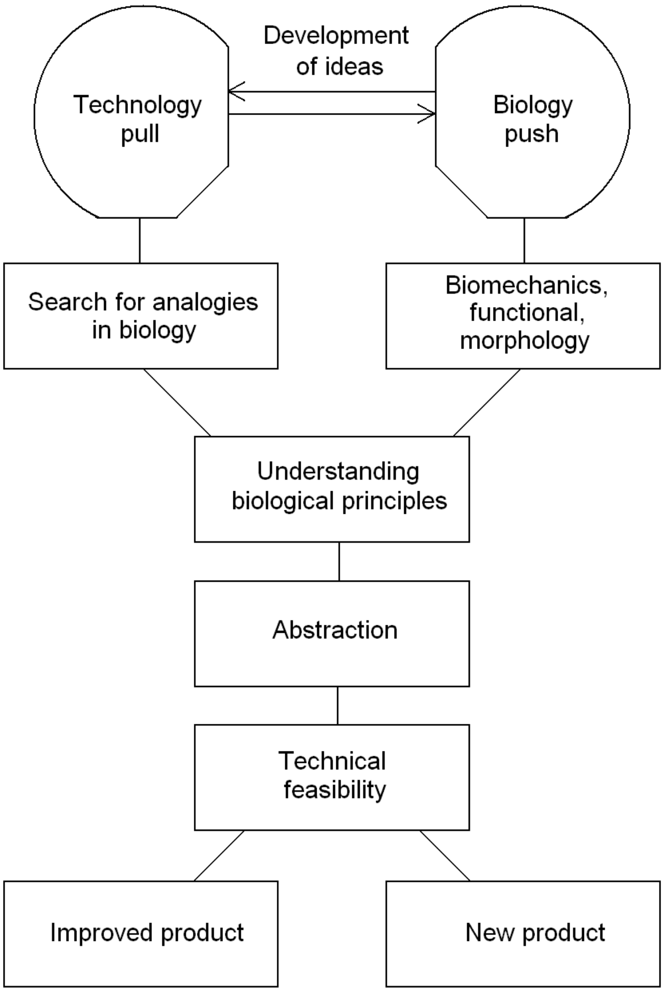

Fig. 1 - "Technology pull" and "biology push" processes

This approach is generic and reflects the most important aspects in the design process of the architectural object.

3 Results and Discussion

3.1 Adaptability: environmental regulation

Building skins form the division between the ambient environment and indoor zones of a building and therefore function as the interface where several physical interactions take place. Every AF influences this multi-physical behavior in its own characteristic way, by for example blocking, filtering, converting, collecting, storing, or passing through the various energy fields [1,19]. In order to characterize the differences and similarities in AF, we distinguish five domains, as listed in Table 1. In fact, most AF influence performance in more than one domain. The interdependencies are visualized via the simple Venn diagram in Fig. 2.

Table 1. List of the physical domains

Thermal	Adaptation causes changes in the energy balance of the building via conduction, convection, radiation, and storage of thermal energy
Mass (air- and moisture flows)	A flow of mass (air or moisture) across the boundary of the façade is present, and adaptive behavior is influenced by the direction and speed of the wind or air relative humidity
Optical	The adaptive behavior influences occupant's visual perception via changes in the transparent surfaces of the building shell
Acoustic	The adaptive behavior influences occupant's acoustic perception
Electrical	Building-integrated energy generation takes place on the façade level, or electricity consumption is an essential part of the adaptation mechanism

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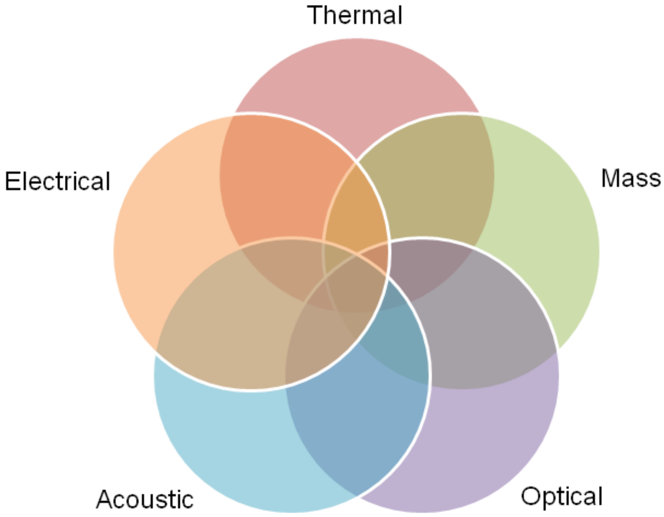

Fig. 2 - Classification of relevant physics: each adaptive façade system can be characterized by one of the combined areas

The five domains and some possible multi-physical overlap together; results of different combinations to represent the relevant physical interactions of AF systems are demonstrated. Some other possible domains, such as moisture (in a mass domain) and sound, were included.

These physical parameters often have a simultaneous effect on a person. Friendly indoor environment conditions are a function of these parameters. However, multifunctional systems only comprise about 10% of the total and are only developed as digital models [4]. Therefore, we can state that multifunctional control and performance of AF systems is a significant research gap in the field, especially, in terms of prototyping and real-world uptake.

3.2 Adaptive architecture: Prototyping and real-world uptake

Adaptive architecture, often called kinetic or dynamic architecture, is a concept through which buildings are designed to allow parts of the structure to move, without reducing overall structural integrity. A building's capability for motion can be used just to: respond to environmental conditions, enhance its aesthetic qualities and perform functions that would be impossible for a static structure. The possibilities for practical implementations of kinetic architecture increased sharply in the late 20th century due to advances in mechanics, electronics, and robotics. Rudimentary forms of kinetic architecture, such as the drawbridge, can be traced back to the Middle Ages or earlier. Yet it was only in the early 20th century that architects began to widely discuss the possibility for movement to be enabled for a significant portion of a structure.

The first prototype of kinetic architecture was the Tatlin's Tower. Tatlin's Tower, or the project for the Monument to the Third International (1919–20), was a grand monumental structure designed by the Russian artist and architect Vladimir Tatlin. Unfortunately, this structure was never built. The tower's main form was a twin helix of 400 m in height. The main framework contained different large suspended geometric structures. These structures had to rotate at different rates.

Another prototype of kinetic architecture was the Monument to Christopher Columbus designed by Konstantin Melnikov in 1929. 80 years before David Fisher, the Russian architect proposed to create a dynamic architecture. In his works, Melnikov put forward many various innovative constructive solutions, including the first projects of kinetic architecture. The design of the monument involved two combined cones. Rotation of the upper cone was to be carried out using wings under the influence of wind. The wings were designed to provide stability to the entire structure. The rotation of the wings, painted in different colors, changed not only the spatial composition but also the color solution of the monument. In the lower motionless cone, a hall was supposed, where a statue of Columbus was placed. This small volume was to be washed by rainwater falling on it from the upper cone, like from a funnel. The water flow could be controlled by the rotation of the wings. They, in a certain position, transferred water to the turbine, which turned the statue at different angles.

Various papers and books included plans and drawings for moving buildings, a notable example being Chernikhov's 101 Architectural Fantasies (1933). For the first few decades of the 20th century kinetic architecture was almost entirely theoretical, but by the 1940s innovators such as Buckminster

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Fuller began experimenting with concrete implementations, though his early efforts in this direction are not regarded as totally successful [4,5,18]. Later, in the book “Architectural Bionics”, Yu. Lebedev showed the connection between nature and architecture and developed the scientific direction of biomimetics. In 1970, engineer and architect William Zuk published the book “Kinetic architecture”, which helped inspire a new generation of architects to design an increasingly wide range of actual working kinetic buildings. Assisted by new concepts such as Fuller’s Tensegrity and by developments in robotics, kinetic buildings have become increasingly common worldwide since the 1980s.

By the early 21st century there are four main directions in dynamic architecture.

The first topic is for functional structures such as bridges which can elevate their midsections to allow tall ships to pass, or stadiums with transformed roofs, for example, the New Wembley Stadium in London.

The second topic is for dynamic structures that can perform changes of shape.

The third topic is for movement to occur on the outer surface of the building (skin adaptive façades). A classic example is the Arab World Institute in Paris. In the façades of this building, there are metal blinds operating on the principle of a diaphragm (the slots expand or narrow depending on sunlight).

In the fourth topic, modern technologies are combined with environmental protection. These kinetic buildings are able to produce energy. The high-rise building clearly demonstrates this combination through the rotation of the floors of the building around its axis; turbines located between the floors must catch the wind, converting its energy into electricity.

3.3 New technologies of adaptive façades

Based on the data available in the scientific literature, we systematized eight key new technologies of adaptive façades:

- Climate adaptive building skins (CABS);
- Smart glazing façade systems (SGFS);
- Biomimetic adaptive building skins (Bio-ABS);
- Vertical greenery systems (VGS);
- Pneumatic building façades (PBFs);
- Kinetic façades (KFs);
- Electrokinetic pixel glazing façade systems (EPGFs);
- Façade augmented HVAC and electrical systems.

The main performances of these façade systems are discussed in more detail below.

3.3.1. Climate adaptive building skins (CABS)

Compared to conventional façades, climate adaptive building skins (CABS) offer potential opportunities for energy savings as well improvement of indoor environmental quality [19]. By combining the complementary beneficial aspects of both active and passive building technologies into the building envelope, CABS can draw upon the concepts of adaptability, multi-ability, and evolvability.

Historically, the façade had the goal of being the primary load-bearing structural element, limited in its functionality and materiality [20]. In the modern era, the façade is often liberated from its load-bearing role providing more flexible spaces to fit in diverse contexts. This has led to describing the enclosure as a building skin with diverse functions. These functions include saving or generating energy, providing thermal properties for comfort, and adaptability to changing conditions [21].

The primary characteristic of CABS is to respond to environmental conditions and users’ needs. This is achieved by changing functions, properties, or behavior over time in response to transient functional requirements and boundary conditions to improve the overall building performance, be it comfort, energy, or otherwise [22].

A classic example is the Arab World Institute in Paris. The southwest façade of this building is a rectangular glass-clad curtain wall. Visible behind the glass wall, a metallic screen unfolds with moving geometric lobes (solar diaphragms). The lobes are actually 240 photo-sensitive motor-controlled apertures that automatically open and close to control the amount of light and heat entering the building from the sun. The adaptive mechanism creates interior spaces with filtered light, an effect often used in Islamic architecture with its climate-oriented strategies (Fig. 3).

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a b

Fig. 3 - Arab World Institute in Paris: a – general view; b – inside view

To realize the cumulative effects of deploying CABS on a regular basis, large-scale production of adaptable materials and components will be needed in the near future. This will require continued cross-disciplinary product development efforts to bring more concepts to the market.

The focus on adaptive building skins is due to their functionalities, which have evolved from load-bearing structures to thermal, acoustic, and visual barriers. New technologies including adaptive building skins meet changing environmental conditions, host multiple functions and offer decentralized controls for occupants. They serve as strategies for improved comfort and reduced building energy needs.

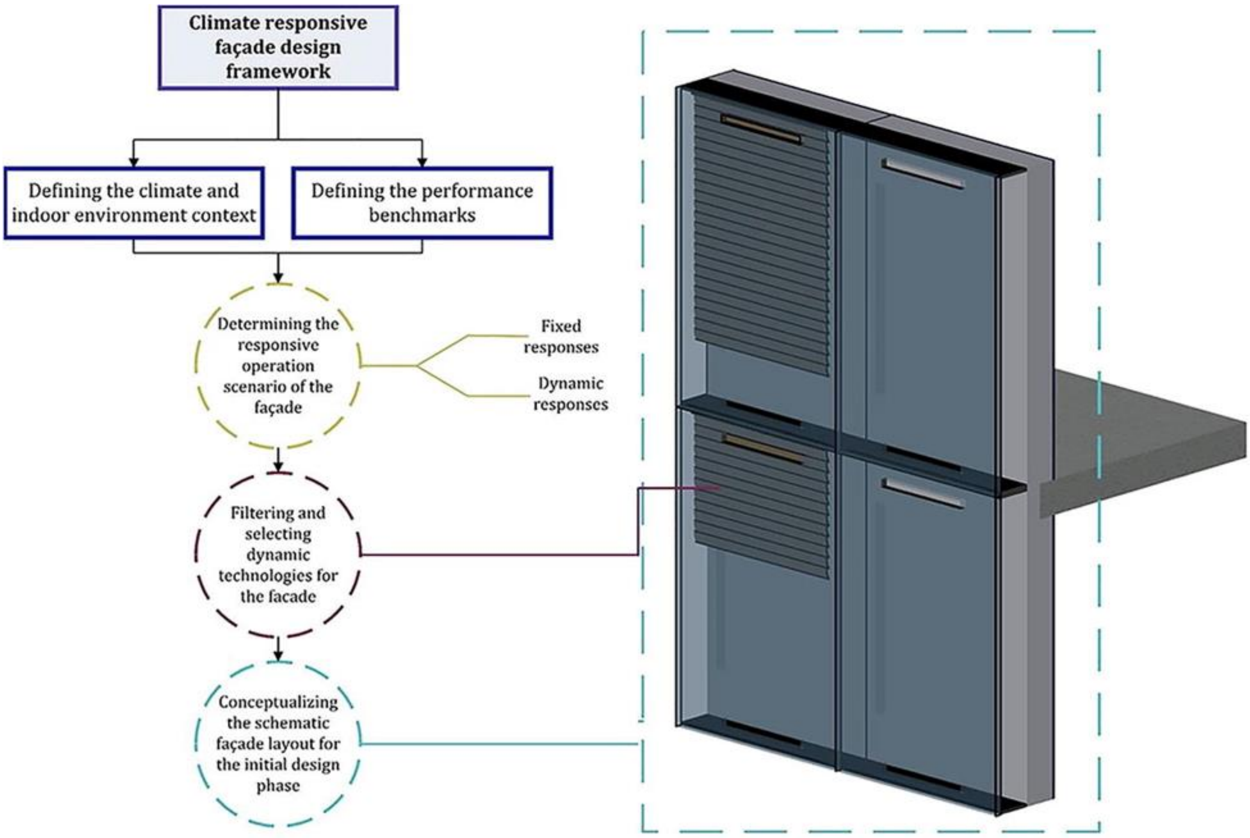

Fig. 4 - CRF design algorithm (Soudian, et al. [23])

The work of Soudian, et al. [23] is focused on the development of a pre-design tool to support the selection of suitable technologies to create multifunctional climate-responsive façades (CRF). The proposed framework includes five steps that lead to a qualitative assessment of the façade requirements based on quantitative metrics. These steps include defining the objectives of a CRF, setting performance constraints based on environmental and building contexts, defining a responsive operation scenario, selecting the most suitable technology, and finally creating a conceptual design of the CRF (Fig. 4).

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The discussion section shows that the specific metrics in the framework and their quantitative ranges are generalizable and can be adjusted to match case-specific architectural, environmental, and technical criteria. The applicability of the framework for the early decision-making stages of façade design is finally discussed, looking at the future steps for better integration of climate-responsive façades.

3.3.2. Smart glazing façade systems (SGFS)

Coating technologies for glazing applications can be static or dynamic [24]. Several static coating technologies with fixed optical properties have been developed, including low-emissivity, electrothermal and photothermal coatings. Low-E coatings are the current industry standard; however, their energy-saving potential has been almost entirely reached due to limitations imposed by their static radiation control properties. Electrothermal coatings, which can convert electricity to heat by the Joule effect, have been developed for cold climates; however, these coatings require a constant power supply. To overcome these issues, photothermal coatings have been recently developed to improve the glazing thermal performance. This is achieved due to photothermal materials' ability to absorb ultra-violet and near-infrared radiations and their efficient conversion to long-wave heat to increase the interior glazing temperature.

On the other hand, dynamic coatings can modulate solar gains by switching between clear and tinted states in response to external stimuli and include thermochromic, photochromic, electrochromic, and gasochromic coatings.

Significant progress has been made in the development of glass with switchable optical properties (smart glazing) to modulate solar transmittance [25]. The smart electrochromic glazing façade technology was implemented in the Swiss School in Dubai, UAE [2]. One hundred ten square meters of electronically tintable glass was installed in both façades with a window-to-wall ratio (WWR) of 85%. Dynamic glass controls sunlight in order to optimize daylight and maintain outdoor views while simultaneously enhance occupant comfort by preventing glare and solar heat. Chromic materials, liquid crystals, and suspended particle devices have been developed over the last few decades, but these solutions remain costly and require high levels of expertise and complicated processes to develop.

Hence, it is believed that integrating static and dynamic technologies would provide an opportunity for the realization of cost-effective next-generation dynamic glazing with enhanced optical, thermal, and long-term performances. In particular, the development of passive dynamic hybrid coatings is very promising. It is expected that the proposed system will significantly improve the glazing thermal performance in cold climates without compromising its optical performance [26]. The proposed coating could also take the form of flexible films fabricated by low-cost roll-to-roll processing techniques, which have an excellent potential for retrofitting existing windows without replacement or interruption to occupancy. Simultaneously, the produced coatings could be made multifunctional by integrating self-cleaning and anti-reflective functions in addition to their solar modulation and self-healing properties. Finally, hydrogel and aerogel-based thin films are also promising for fabricating multifunctional photo-thermochromic adaptive flexible films [27], [24].

3.3.3. Biomimetic adaptive building skins (Bio-ABS)

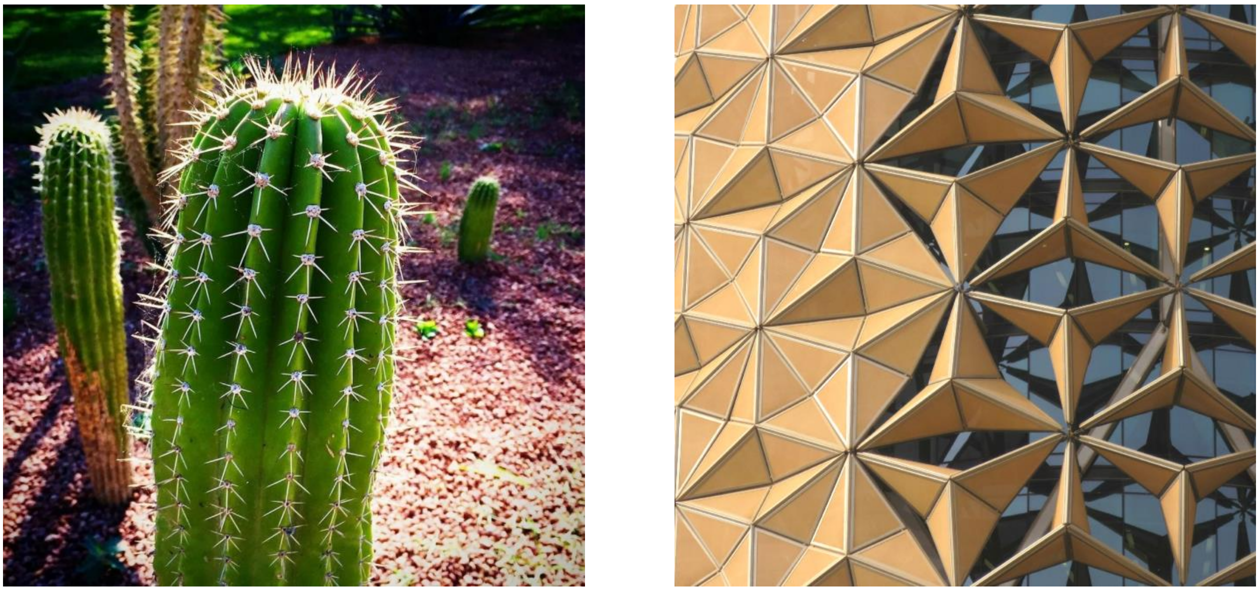
The requirements of modern buildings are often complex, sometimes contradictory, and during their life cycle, need to be adapted. Holistic approaches for new functional and sustainable systems may be expected from a more interdisciplinary field like biomimetic architecture. The overlaps between nature and architecture have inspired many practitioners to adopt biological principles in order to control environmental conditions effectively [28], [29,30], [31], [5].

A biomimetic adaptive building skin (Bio-ABS) is a typology of an adaptive building skin that responds to environmental conditions by changing its morphological or physiological properties or behavior overtime to meet variant functional requirements of a building to improve its overall performance. In this instance, the changing properties and behaviors are translated from biological models that offer environmentally, mechanically, structurally, or material-wise efficient strategies [4].

The Bio-ABS concept is the integration of two topics: biomimetics (Bio) and adaptive building skins (ABS). It refers to ABS that have taken inspiration from nature; therefore, adopting biomimetics as a design generator and ABS as the design product [4] (Fig. 5).

Fig. 5 - Bio-ABS concept break-down [4]

The introduction of computer-aided design supported with digital fabrication and composite materials has allowed designs derived from nature to be practically realized (Fig. 6).



a b

Fig. 6 - Column cactus (a) and adaptive screen system in Al Bahr Towers in Dubai, UAE (b)

It is known that cactuses are known for their frugality and bizarre growth patterns through their optimal adaptation to various niches. The column cactus (Fig. 6, a) can be used as the biomimetic self-shading pattern for the construction of unique buildings, as demonstrated in Fig. 6, b.

Al Bahr Towers in Dubai, UAE has an adaptive screen system. The curtain wall is separated from the kinetic shading system through a substructure by means of movement joints. The dynamic shading system is a screen comprised of triangulating units such as origami umbrellas. The triangular units act as individual shading devices that unfold to various angles in response to the sun's movement in order to obstruct direct solar radiation. The results of the study analysis can be found in the work of Attia [1].

The biomimetic adaptive building skins are functional, durable, and aesthetic. However, there are a limited number of realized or prototyped projects with most studies being at a conceptual stage, lacking quantitative performance analysis. The majority of Bio-ABS are monofunctional, only controlling a single environmental parameter. Multifunctionality in Bio-ABS needs further study to address multiple contradictory functional requirements of buildings regarding energetic and environmental performance.

3.3.4. Vertical greenery systems (VGS)

The construction sector is a large contributor to anthropogenic greenhouse gas emissions and consumes vast natural resources. Improvements in this sector are of fundamental importance for national and global targets to combat climate change. In this context, vertical greenery systems (VGS) in buildings have become popular in urban areas to restore green space in cities and be an adaptation strategy for challenges such as climate change. They are considering to be environmentally beneficial for the building and its surroundings, by improving urban air quality [32], reducing urban heat island effects [33,34]. Green façades can reduce the heat flux through a building envelope; the plants shade the wall and are believed to provide transpiration cooling [35,36]. In addition, green façades are known to improve building energy efficiency by reducing energy used for cooling and heating [37]. The higher

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thermal mass of a green wall also improves the thermal performance of this structure [35,36]. Green walls and façades have high aesthetic preferences.

VGS is composed of the following construction systems (as seen in Fig. 7), such as green walls (GW) and double-skin green façade (GF), in comparison with reference walls.

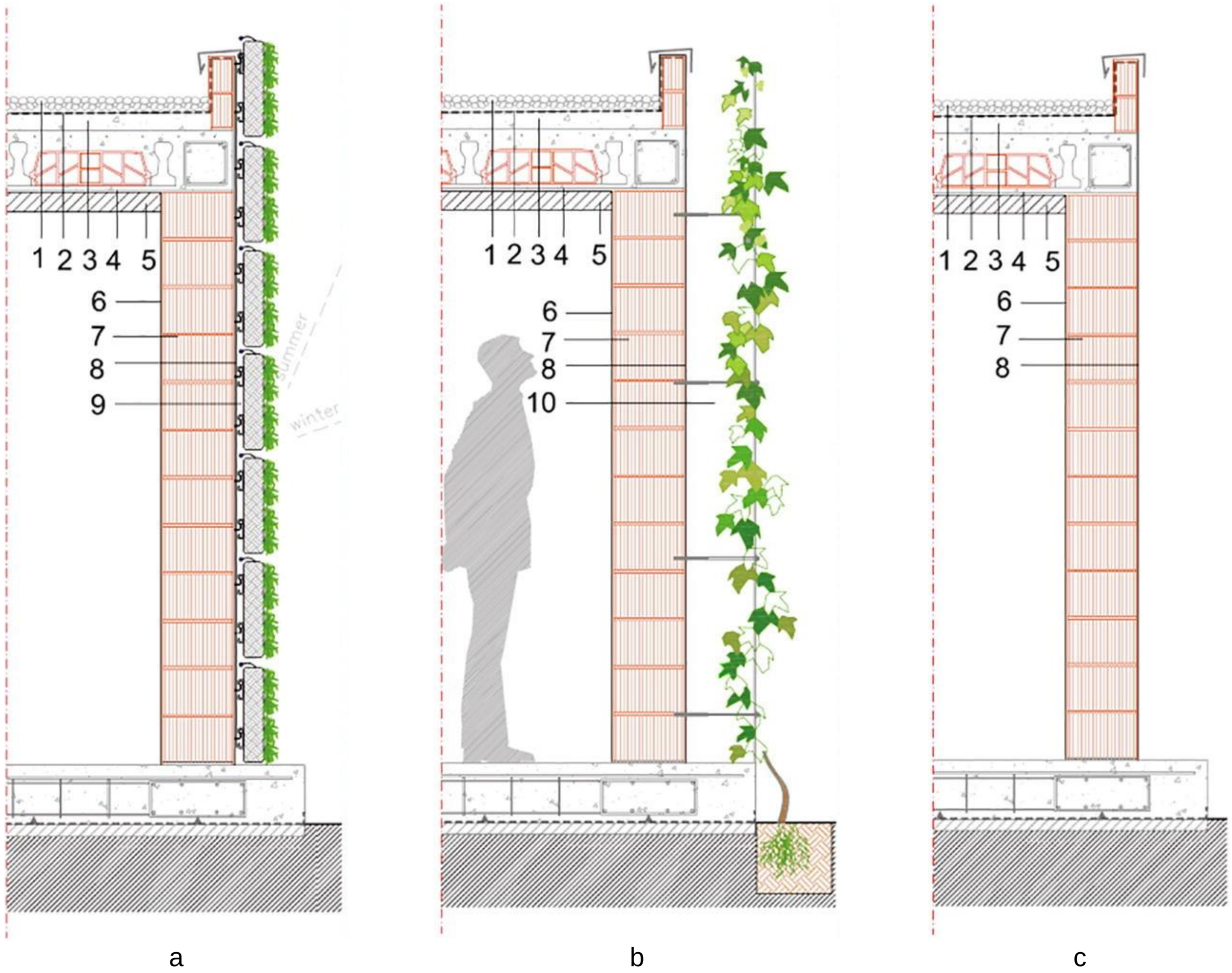

Fig. 7 - Construction section: a – green wall; b – green façade; c – reference wall [36]; 1 – gravel roof; 2 – asphaltic membrane; 3 – cement mortar, flat roof; 4 – concrete precast beams and concrete slab; 5 – insulation; 6 – plaster; 7 – alveolar brick wall; 8 – mortar plastering; 9 – GW; 10 – GF

The description of each VGS system is summarized below.

The green wall is a pre-cultivated modular-based system based on recycled polyethylene modules (Fig. 7, a). The module consists of a closed box that holds them to the supporting structure. The module is filled with a recycled substrate. The support structure consists of stainless steel tubes where the modules are adjusted hanging on the hooks. Each module is designed to have small shrubs.

The green façade is a double-skin that is located usually on the East, South, and West walls. The support is made of a mesh installed on the three walls using metallic screws anchored to the wall. Deciduous plants are suspended from the grid (Fig. 7, b).

The work [35] discusses a comparative life cycle assessment (LCA) between a building with green walls, a building with green façades, and a reference building without any greenery system in the continental Mediterranean climate. This life cycle assessment is carried according to ISO 14040/44 using ReCiPe and GWP indicators. Moreover, the study fills this gap by thoroughly tracking and quantifying all impacts in all phases of the building life cycle related to the manufacturing and construction stage, maintenance, use stage (operational energy use experimentally tested), and final disposal. They adopted a functional unit is the square meter of the façade. Results showed that the operational stage had the highest impact contributing by up to 90% of the total environmental impacts during its 50 years life cycle. Moreover, when considering VGS, there is an annual reduction of about 1% in the environmental burdens. However, in summer, the reduction is almost 50%. Finally, if the use

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stage is excluded, the manufacturing and the maintenance stage are the most significant contributors, especially in the green wall system.

No doubt, the vertical greenery technology is positive and creates friendly psychological comfort. However, this technology is not well investigated under exterior environmental loads and climate changes.

3.3.5. Pneumatic building façades (PBFs)

Thermal regulation of buildings in climates with daily and seasonal weather changes can prove challenging and result in high building energy consumption. While adaptable façades with tunable infrared transmitting properties could modulate solar transmittance through the building envelope and, as such, increase energy efficiency, available technologies to meet these needs are often expensive, relatively complicated, and challenging to implement in a lightweight form factor.

Motivated by these limitations, the work of Tomholt et al. [38] presents a novel tunable light-modulating technology for energy-efficient pneumatic façades in the form of polydimethylsiloxane (PDMS) film with a thin gold surface coating (Fig. 8). Sequential stretching and relaxing of this film results in strain-induced microscale surface cracks that can significantly modulate both visible and near-infrared light transmission, and consequently, the material's solar heat gain coefficient (SHGC).

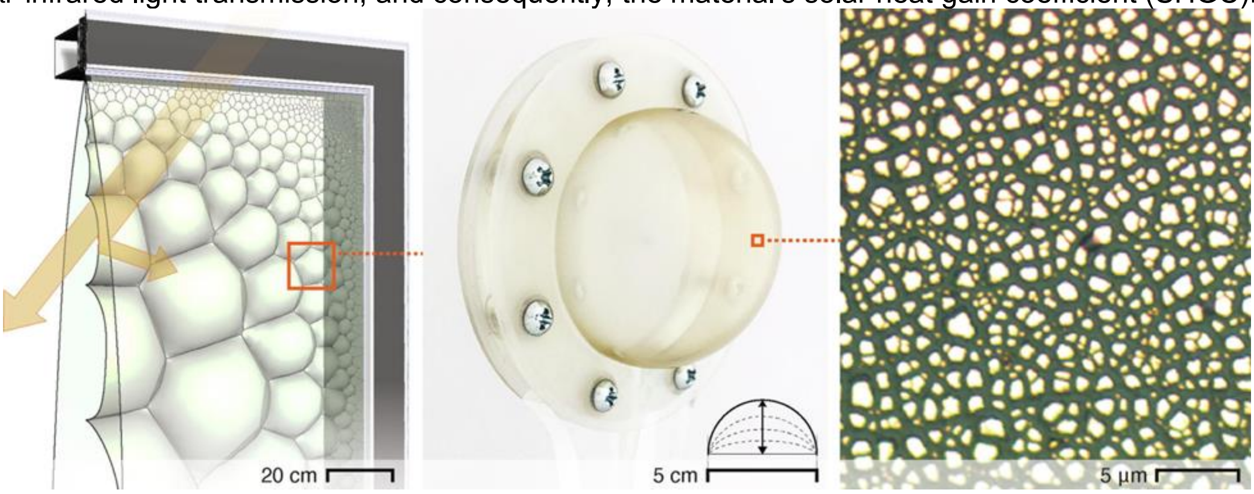

Fig. 8 - Pneumatic building façade (PBFs) fragments [38]

The material's tunability has shown a significant potential to reduce building energy use [18]. The technology offers additional advantages for light modulation in pneumatic façades including real-time operation, ease of implementation and control, and predictable performance. Façade design guidelines for the integration of the infrared-regulating film into ethylene tetrafluoroethylene (ETFE) building envelopes and climate suitability are described, and a critical evaluation of material durability, optical clarity, and material costs are provided [39].

3.3.6. Kinetic façades (KFs)

Kinetic façades (KFs) are based on the principles of maximum adaptation to changing environmental conditions. There are three main types of adaptation: functional, structural and aesthetic [1–3], [40], [41], [42], [43], [44].

In functional adaptation, the main functions of the architectural object change through the transformation of internal building elements (rooms, building structures, engineering equipment) while maintaining the general contour of the building. The process of internal adaptation of an architectural object is considered only within the boundaries of its building envelope. The functional adaptation methods allow to adapt the buildings to existing conditions throughout the life cycle of the building, thereby ensuring the multifunctional nature of the building, improving its performances, and increasing indoor environmental comfort.

Structural adaptation assumes a change in the dimensions of the entire building, as well as its individual structural elements. In this case, complex processes of adaptation of the building occur by transforming its building envelope, which regulates the connection between outdoor environment conditions and controlled indoor parameters. The KFs are aimed at creating optimal thermal, humidity, light, acoustic conditions in the rooms under various climatic impacts (Fig. 9). They are as adapted as possible to these impacts, safe, energy-efficient, environmentally friendly.

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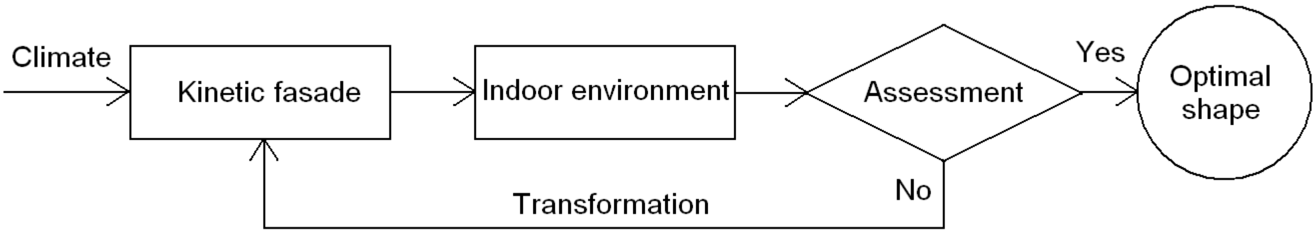

Fig. 9 - Climatic impacts regulation process by KFs

Aesthetic adaptation assumes a change in visual performances. Using modern interactive technologies, it became possible to visually change the spatial characteristics of the environment, creating a qualitatively new perception of the object.

a b

Fig. 10 - AGC Building in Louvain-La-Neuve, Belgium:
a – general view; b – façades fragment

The adaptive glass kinetic façade technology was implemented in the AGC Building in Louvain-La-Neuve, Belgium (Fig. 10). The external façade is fully covered with a double glazing system in combination with thermally insulated glass sunshades printed with a white silkscreen. These louvers respond dynamically and automatically to the angle of the sun which improves the control over energy consumption, solar radiation, and glare with the ability to admit natural light into the building while affording a view over the surrounding countryside. The results of a mapping process and study analysis can be found in the work of Attia and Bashandy [1–3].

Kinetic motorized daylight control systems consisting of multiple interconnected components, such as blinds or adaptive fritting, can also be effective in modulating solar transmission and reducing energy loads, but are typically quite complex, especially when targeting fast response times and require regular maintenance.

3.3.7. Electrokinetic pixel glazing façade systems (EPGFs)

During the evening and night hours, we can observe the majestic urban landscapes. This is largely due to electrokinetic pixel glazing façade systems or media façades [1].

Electrokinetic pixel glazing façade systems (EPGFs) are large area LED screens mounted on the outer surface of the building. LED screens are modular, mesh, rack, and cluster. They are divided into transparent and opaque. Cluster and mesh are lightweight, flexible LED webs that can cover any surface.

The electrokinetic façades actively use bio-inspired technologies. There are many common properties between the butterfly wings and the façade system in Al Bahr Towers in Dubai, UAE (Fig. 11), isn't there?

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a

b

Fig. 11 - *Greta Oto*, often called the "glass" butterfly (a) and screen system in Al Bahr Towers in Dubai, UAE (b)

Media façades of the cluster type are almost transparent (light transmission up to 80%); they can be installed on glazing surfaces. They can provide a well naturally indoor ventilation effect. Electrokinetic pixel glazing façade devices have been developed over the last few decades, but these solutions remain costly and require high levels of complicated processes to develop and maintains.

3.3.8. Façade augmented HVAC and electrical systems

Achieving high energy performance of building requires incorporating energy efficiency measures early in the design process. Such measures include optimizing envelope shape and electricity generation potential by means of integrated PV systems. Integration of PV technologies within the building envelope includes functional, structural, and aesthetic aspects and cooperation with building systems, such as HVAC and electrical systems. This can enhance energy performance and cost savings such as smaller HVAC systems associated with lower peak heating and cooling loads. Façade can be designed so as to provide air circulation behind the panels. This allows cooling of the PV cells and thus increasing the overall efficiency of the system, while also collecting useful heat for space heating and domestic water heating [45], [46], [47,48], [34].

The optimal tilt angle for PV-generated electricity by equatorial facing roof surfaces generally equals the latitude (latitude minus 15° for summer, and latitude plus 15° for winter). This electricity generation potential is reduced by up to 40% for flat façades. Increasing electrical generation and solar potential of multistory buildings can be attained by manipulation of the geometry and other design features of the façades, subject to visual and functional constraints, such as window design and positioning.

The work of Hachem and Elsayed [48] present a study of the impact of the geometrical design of a double-skin façade system on the energy performance of a multistory building. The main objective of the study is to increase the surface area for potential integration of PV and for solar capture of these surfaces without significantly compromising the thermal performance (heating and cooling loads) of the perimeter zone of the building. Additional objectives include the demonstration of the large spectrum of available geometries of varying complexity, and to suggest a methodology for assessing their energy performance (Fig. 12).

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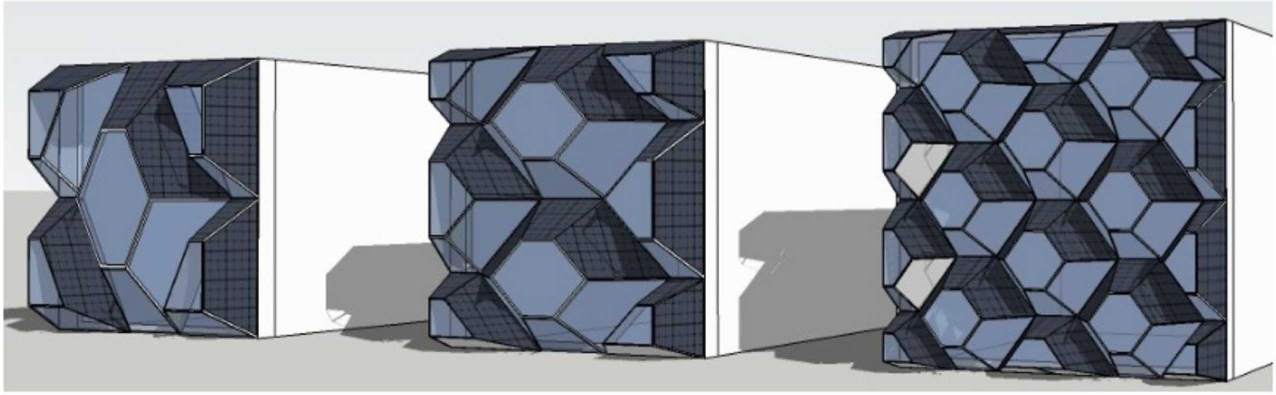

Fig. 12 - A folded-plate units [48]

The results indicate that although deviation from the basic flat façade leads generally to an increase in heating load, this is counterbalanced by a reduction in cooling load, and a considerable increase in energy generation potential from façade integrated photovoltaic systems. The position of the fold and the depth of the cavity has a significant effect on thermal load and energy generation potential. Under the studied climatic conditions (Calgary, Alberta, Canada – 52°N), the total annual electricity generation potential, by the multifold configurations can exceed that of the flat façade by up to 80% [47,48].

Harnessing wind energy in buildings is becoming more important. Amongst other building types, the large exposed body of the high-rise building is subject to significant and unique interaction with the wind kinetic energy. Whilst wind effect for structural engineers is often considered as a negative factor that inflates costs dramatically, to wind engineers, who study its behavior on, inside, and near high-rises, it is a fascinating phenomenon [49] (Fig. 13). As it benefits from the essential potentials of the building type, the use of wind energy in high-rise buildings can be of great advantage, especially when considered as a support to other energy generating system(s), e.g., solar devices.

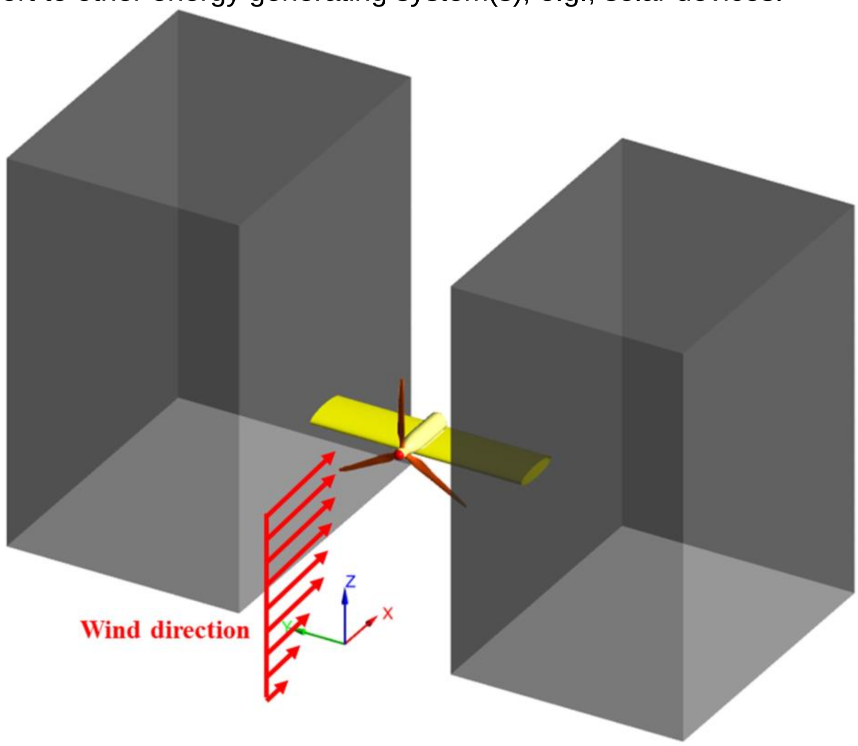

Fig. 13 - Configuration of 110 kW BAWT and buildings with a sky bridge [49]

Building-integrated vertical-axis wind turbines (VAWTs) have been receiving increased attention over recent years due to their remarkable advantages. Compared to horizontal-axis wind turbines (HAWTs) VAWTs function with any wind direction and offer benefits in low wind situations. Besides their safety and easiness to build they can be mounted lower to the ground which enables less complex maintenance as they showed good performance in handling turbulence [50], [51], [52]. However, the

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less efficiency of the VAWT against HAWT that lies around 30% [50] is the main drawback which interestingly provides room for optimization. The enhancement of the building form to drive four embodied VAWT is shown in the recently built Pearl River Tower in China. Analyses have suggested that the façade integration of VAWT is more promising by placing turbines in zones of maximum wind concentration [51].

3.4 Advantages and disadvantages of adaptive façades

Based on the analysis of scientific literary sources, the main advantages and disadvantages of adaptive façades systems were identified, as listed in Table 2.

Table 2. Advantages and disadvantages of AF

Advantages	Provide optimal daylighting, solar control, and natural ventilation based on dynamic operation Increase the energy efficiency of the building by reducing heating energy in winter and cooling energy in summer Nature-inspired AF technology is biopositive and creates friendly psychological comfort Manual indoor climate control over the building management system, leading to higher occupant satisfaction and productivity during operation of the building Enhance the climatic comfort indoors and well-being to increase occupant satisfaction and productivity during the life cycle of building Creation of databases that could be expanded and used in dynamic façade design Various methods to carry out selection and ranking of different alternatives Complex approach for analysis The problem-based approach allows for the connection of natural organisms with responsive behavior to building integrated systems and materials Connecting the building and climate context to façade performance
Disadvantages	High investment costs that may increase the operational cost Complex high-tech systems that require intelligent and flexible automation and predictive control Are not always user friendly and do not empower users through interaction with the façade system and personalized control Climate and indoor context analysis is a challenge Lack a generic and standardized assessment framework, criteria, and delivery process Technology-oriented with limits of application to certain scales and technologies The difficulty of maintenance of façades systems Lack of moisture and acoustic adaptation technologies Limited practical implementation for façade design End up being tailor-made solutions that are time-consuming requiring highly skilled expertise and intensive coordination and collaboration

Based on the analysis of data (see Table 2), it can be concluded that the adaptive façade systems have a high potential. In general, architects and engineers can satisfy their clients and provide a high quality of buildings for users. Further development of adaptive façade technologies can increase their market penetration. The technological advancement of smart buildings and controls can be accelerated in connection with increase satisfaction of users' perception. Biological patterns increase psychological comfort. Bio-inspired buildings have a high potential to create a comfortable energy-efficient environment. The use of new composite materials and smart technology extends the search boundaries of adaptive façade systems.

However, there are several limitations to the use of these façade systems. These façades have a very high cost and are difficult to operate and maintain. The adaptive façade systems can easily turn into fashionable and aesthetical gadgets without the potential for scaling up; they are used sometimes to show economic and political power in countries. Commissioning and operational maintenance can be easily underestimated. Full automation in buildings can exclude personal control if users are not taken into account. The risk of energy use intensity can be increased in relation to traditional buildings.

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These risks can jeopardize the building guarantee during the life cycle. Excessive passion for adaptive façades technology can worsen the architectural pattern of buildings.

4 Conclusions

1. For the first time, the main types of adaptive façade systems were systematized and ordered. Based on the analysis of consumer properties of these façades, the main trends were revealed. New technologies including adaptive building skins meet changing environmental conditions, host multiple functions and offer decentralized controls for occupants. They serve as strategies for improved comfort and reduced building energy needs.
2. Climate adaptive building skins (CABS) offer potential opportunities for energy savings as well improvement of indoor environmental quality. The primary characteristic of CABS is to respond to environmental conditions and users' needs. This is achieved by changing functions, properties, or behavior over time in response to transient functional requirements and boundary conditions to improve the overall building performance, be it comfort, energy, or otherwise. The focus on CABS is due to their functionalities. On the other hand, to realize the cumulative effects of deploying these façade on a regular basis, large-scale production of adaptable materials and components will be needed in the near future.
3. Integrating static and dynamic technologies in the smart glazing façade systems (SGFS) would provide an opportunity for the realization of cost-effective next-generation dynamic glazing with enhanced optical, thermal, and long-term performances.
4. Biomimetic adaptive building skins (Bio-ABS) have high consumer properties; they are functional, durable, and aesthetic. However, Bio-ABSs are a limited number of realized or prototyped projects with most studies being at a conceptual stage, lacking quantitative performance analysis. The majority of Bio-ABS are monofunctional, only controlling a single environmental parameter. Multifunctionality in Bio-ABS needs further study to address multiple contradictory functional requirements of buildings regarding energetic and environmental performance.
5. Vertical greenery systems (VGS) in buildings have become popular in urban areas to restore green space in cities and be an adaptation strategy for challenges such as climate change. No doubt, VGS technology is biopositive and creates friendly psychological comfort. However, this technology is not well investigated under exterior environmental loads and climate changes.
6. A novel tunable light-modulating technology for energy-efficient pneumatic façades (PBFs) in the form of polydimethylsiloxane film with a thin gold surface coating is promising. Sequential stretching and relaxing of this film results in strain-induced microscale surface cracks that can significantly modulate both visible and near-infrared light transmission. The material's tunability has shown a significant potential to reduce building energy use.
7. Kinetic façades (KFs) are based on the principles of maximum adaptation to changing environmental conditions. There are three main types of adaptation: functional, structural, and aesthetic. Kinetic motorized daylight control systems consisting of multiple interconnected components, such as blinds or adaptive fritting, can also be effective in modulating solar transmission and reducing energy loads, but are typically quite complex, especially when targeting fast response times and require regular maintenance.
8. Electrokinetic façades (EPGFs) actively use bio-inspired technologies. Media façades of the cluster type are almost transparent (light transmission up to 80%); they can be installed on glazing surfaces. Also, they can provide a well naturally indoor ventilation effect. Electrokinetic pixel glazing façade devices have been developed over the last few decades, but these solutions remain costly and require high levels of complicated processes to develop and maintains.
9. Significant progress has been made in the development of façade augmented HVAC and electrical systems with integrated photovoltaic panels (PV) and vertical-axis wind turbines (VAWTs). These technologies increase the use of renewable energy in buildings.
10. Finally, we can assume that adaptive façades (AF) technology is not ready enough to cross barriers today, however, AF remains a promising technology that can get better in near future.

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References

1. Attia S. et al. Current trends and future challenges in the performance assessment of adaptive façade systems // Energy Build. 2018. Vol. 179. P. 165–182.
2. Bilir S., Attia S. Performance Evaluation of Adaptive Facades: A case study with electrochromic glazing // Adapt. Facades. 2018. № Luible 2014. P. 315–324.
3. Attia S. Evaluation of adaptive facades: The case study of Al Bahr Towers in the UAE. 2017. № June 2016. P. 95–103.
4. Kuru A. et al. Biomimetic adaptive building skins: Energy and environmental regulation in buildings // Energy Build. 2019. Vol. 205.
5. Cruz E. et al. Design processes and multi-regulation of biomimetic building skins: A comparative analysis // Energy Build. 2021. Vol. 246.
6. Bayoumi M., Fink D., Hausladen G. Extending the feasibility of high-rise façade augmented wind turbines // Energy Build. 2013. Vol. 60. P. 12–19.
7. Korniyenko S. V., Vatin N.I., Gorshkov A.S. Thermophysical field testing of residential buildings made of autoclaved aerated concrete blocks // Mag. Civ. Eng. 2016. Vol. 64, № 4. P. 10–25.
8. Vatin N. et al. Actual thermophysical characteristics of autoclaved aerated concrete // Mag. Civ. Eng. 2020. Vol. 96, № 4. P. 129–137.
9. Korniyenko S. V. Renovation of Residential Buildings of the First Mass Series // IOP Conf. Ser. Mater. Sci. Eng. 2018. Vol. 463, № 2.
10. Korniyenko S. V., Astafurova T.N., Kozlova O.P. Thermal Renovation of Facade Systems in Block Buildings // IOP Conf. Ser. Mater. Sci. Eng. 2020. Vol. 753, № 2.
11. Korniyenko S. V., Astafurova T.N., Kozlova O.P. Energy Efficient Major Overhaul in Residential Buildings of the First Mass Series // IOP Conf. Ser. Mater. Sci. Eng. 2020. Vol. 753, № 4.
12. Sergeev V. V. et al. The building extension with energy efficiency light-weight building walls // Mag. Civ. Eng. 2018. Vol. 84, № 8. P. 67–74.
13. Petrichenko M.R. et al. CFD simulation of the convective flows in the vertical caverns // Mag. Civ. Eng. 2019. Vol. 92, № 8. P. 76–83.
14. Petrichenko M.R. et al. Ventilated facade integrated with the HVAC system for cold climate // Mag. Civ. Eng. 2018. Vol. 77, № 1. P. 47–58.
15. Vieira G.B. et al. Behavior of a hollowed-wood ventilated façade during temperature changes // Mag. Civ. Eng. 2018. Vol. 79, № 3. P. 103–111.
16. Statsenko E.A. et al. Temperature and velocity conditions in vertical channel of ventilated facade // Mag. Civ. Eng. 2018. Vol. 80, № 4. P. 119–127.
17. Nemova D.V., Vasileva I.L., Vatin N.I. Introduction of double-skin facades in the Russian Federation // Constr. Unique Build. Struct. 2019. Vol. 84, № 9. P. 51–62.
18. Flor J.F. et al. Optical aspects and energy performance of switchable ethylene-tetrafluoroethylene (ETFE) foil cushions // Appl. Energy. 2018. Vol. 229, № August. P. 335–351.
19. Loonen R.C.G.M. et al. Climate adaptive building shells: State-of-the-art and future challenges // Renew. Sustain. Energy Rev. 2013. Vol. 25. P. 483–493.
20. Fabrizio E., Corrado V., Filippi M. A model to design and optimize multi-energy systems in buildings at the design concept stage // Renew. Energy. Elsevier Ltd, 2010. Vol. 35, № 3. P. 644–655.
21. Sadineni S.B., Madala S., Boehm R.F. Passive building energy savings: A review of building envelope components // Renew. Sustain. Energy Rev. 2011. Vol. 15, № 8. P. 3617–3631.
22. Pacheco R., Ordóñez J., Martínez G. Energy efficient design of building: A review // Renew. Sustain. Energy Rev. 2012. Vol. 16, № 6. P. 3559–3573.
23. Soudian S., Berardi U. Development of a performance-based design framework for multifunctional climate-responsive façades // Energy Build. 2021. Vol. 231.
24. Khaled K., Berardi U. Current and future coating technologies for architectural glazing applications // Energy Build. 2021. Vol. 244.

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25. Baetens R., Jelle B.P., Gustavsen A. Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review // Sol. Energy Mater. Sol. Cells. Elsevier, 2010. Vol. 94, № 2. P. 87–105.
26. Bogati S. et al. Development of photochromic device with magnetron sputtered titanium dioxide and tungsten trioxide films // Sol. Energy Mater. Sol. Cells. 2017. Vol. 166, № January. P. 204–211.
27. Barile C.J. et al. Dynamic Windows with Neutral Color, High Contrast, and Excellent Durability Using Reversible Metal Electrodeposition // Joule. 2017. Vol. 1, № 1. P. 133–145.
28. Reddi S. et al. Biomimetics of stabilized earth construction: Challenges and opportunities // Energy Build. 2012. Vol. 55. P. 452–458.
29. Zhong S. et al. Urbanization-induced urban heat island and aerosol effects on climate extremes in the Yangtze River Delta region of China // Atmos. Chem. Phys. Copernicus GmbH, 2017. Vol. 17, № 8. P. 5439–5457.
30. Fu S.C. et al. Bio-inspired cooling technologies and the applications in buildings // Energy Build. 2020. Vol. 225.
31. Imani N., Vale B. A framework for finding inspiration in nature: Biomimetic energy efficient building design // Energy Build. 2020. Vol. 225.
32. Ouyang W. et al. The cooling efficiency of variable greenery coverage ratios in different urban densities: A study in a subtropical climate // Build. Environ. 2020. Vol. 174, № December 2019.
33. Serra V. et al. A novel vertical greenery module system for building envelopes: The results and outcomes of a multidisciplinary research project // Energy Build. 2017. Vol. 146. P. 333–352.
34. Goia F. et al. Towards an active, responsive, and solar building envelope // J. Green Build. 2010. Vol. 5, № 4. P. 121–136.
35. Chàfer M. et al. A comparative life cycle assessment between green walls and green facades in the Mediterranean continental climate // Energy Build. 2021. Vol. 249.
36. Chàfer M. et al. Greenery system for cooling down outdoor spaces: Results of an experimental study // Sustain. 2020. Vol. 12, № 15.
37. Sendra-Arranz R. et al. Monitorization and statistical analysis of south and west green walls in a retrofitted building in Madrid // Build. Environ. 2020. Vol. 183, № May.
38. Tomholt L. et al. Tunable infrared transmission for energy-efficient pneumatic building façades // Energy Build. 2020. Vol. 226.
39. Konstantoglou M., Tsangrassoulis A. Dynamic operation of daylighting and shading systems: A literature review // Renew. Sustain. Energy Rev. 2016. Vol. 60. P. 268–283.
40. Andrade Santos R. et al. Auto-responsive technologies for thermal renovation of opaque facades // Energy Build. 2020. Vol. 217.
41. C. O. Souza L., A. Souza H., F. Rodrigues E. Experimental and numerical analysis of a naturally ventilated double-skin façade // Energy Build. 2018. Vol. 165. P. 328–339.
42. Georgakis C., Santamouris M. Experimental investigation of air flow and temperature distribution in deep urban canyons for natural ventilation purposes // Energy Build. 2006. Vol. 38, № 4. P. 367–376.
43. Yang L., Li Y. Thermal conditions and ventilation in an ideal city model of Hong Kong // Energy Build. 2011. Vol. 43, № 5. P. 1139–1148.
44. Iommi M. The mediterranean smart adaptive wall. An experimental design of a smart and adaptive facade module for the mediterranean climate // Energy Build. 2018. Vol. 158. P. 1450–1460.
45. Tripanagnostopoulos Y. et al. HYBRID PHOTOVOLTAIC / THERMAL SOLAR SYSTEMS. 2002. Vol. 72, № 3. P. 217–234.
46. Athienitis A.K. et al. A prototype photovoltaic/thermal system integrated with transpired collector // Sol. Energy. 2011. Vol. 85, № 1. P. 139–153.
47. Hachem C., Athienitis A., Fazio P. Design of curtain wall facades for improved solar potential and daylight distribution // Energy Procedia. 2014. Vol. 57. P. 1815–1824.
48. Hachem C., Elsayed M. Patterns of façade system design for enhanced energy performance of multistory buildings // Energy Build. 2016. Vol. 130. P. 366–377.
49. Heo Y.G. et al. CFD study on aerodynamic power output of a 110 kW building augmented wind turbine // Energy Build. 2016. Vol. 129. P. 162–173.
50. Wang Y.F., Zhan M.S. 3-Dimensional CFD simulation and analysis on performance of a micro-wind turbine resembling lotus in shape // Energy Build. 2013. Vol. 65. P. 66–74.

This publication is licensed under a CC BY-NC 4.0

51. Liu W.Y., Han J.G., Lu X.N. Experiment and performance analysis of the Northwind 100 wind turbine in CASE // Energy Build. 2014. Vol. 68, № PARTA. P. 471–475.
52. Elbakheit A.R. Effect of turbine resistance and positioning on performance of Aerofoil wing building augmented wind energy generation // Energy Build. 2018. Vol. 174. P. 365–371.