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Evaluation of Climate Adaptive Building Skins in the Last Decade

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Abstract
Efficient use of energy and indoor comfort is accepted as the priority of modern architectural design trends, making it obligatory to design building shells in a specific form to provide adequate flexibility for energy flow and thermal comfort. Accordingly, climate-adaptive building shells (CABS) offer opportunities to significantly reduce energy use in buildings and lower CO_2 emissions while serving as a promising alternative for sustainability. This study examines the development of climate-adaptive, high-performance and advanced facade systems through office buildings where energy consumption is higher than other constructions. The research method used in the study is data collection, process tracing, and content analysis from qualitative methods. The study consists of two stages. In the first stage of the study, climate-adaptive facade systems are investigated in detail; facade systems that will form the sub-headings of the CABS term have been determined and explained through the literature. The second stage of the study examines climate-compatible facade systems in energy-efficient design. It considers the factors affecting energy-efficient façade systems following the analysis of the prominent headings in the literature review.

Keywords
climate adaptive facade system, climate control, energy-efficient design

1 Introduction

Today, environmental pollution and deteriorating natural balances threaten the entire world ecosystem. Whether many resources currently owned will exist in the future or not is examined from different perspectives and is a subject of discussion. In this context, the concept of sustainability, which expresses a balance that adapts to human needs without reducing the productivity of health and natural systems, also comes to the fore in architecture.

Architects and urban designers who create the built environment to transform humanity's adverse effects need to consider the conservation of natural resources and local environmental quality criteria in their approach to design as a priority. Globally, buildings are high energy users (35%) (United Nations Environment Programme, 2020). Most of this energy is obtained from fossil resources, the main reason for global warming, confirming that energy-related issues also result in environmental problems. Therefore, one of the most important topics covered by sustainability is energy consumption. In this regard, sustainable housing development can be considered essential to protect natural resources using energy efficiency parameters to minimise energy consumption (Bakar et al., 2010; Ding, 2008; Holton et al., 2010; Van Ree and Hartjes, 2003).

The proposals related to the solutions for environmental disasters caused by the practices on an architectural and urban scale were submitted particularly after the 1970s. As a result of the 1973 oil crisis, energy-conscious building design became an agenda topic in western countries. The green parameters determined from previous studies and the energy-efficient design concept operate at the architectural and structural design stage (heating, cooling and illumination), and include the use of natural energy resources with methods such as passive heating, passive cooling and daylight illumination systems, and the efficient design of mechanical equipment (Ignjatovic and Ignjatovic, 2006; Lechner, 2014; Maliene and Malys, 2009; Oktay, 2002; Seyfang, 2010; Zhang et al., 2011; Zimmermann et al., 2005).

The building shell has a significant role in the broader energy performance of buildings. Pomponi et al. (2015)

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suggested in their study that performing an energy-efficient improvement on a building shell that serves as a thermal barrier between the internal and external environment is one of the effective methods for increasing the energy performance of building stock.

Building shells constitute a border between internal and external spaces and are exposed to varying conditions. Meteorological circumstances that change throughout a day or year also change the comfort-related demands of users. Traditional building shells typically have static characteristics and do not have the capacity of responding to meteorological changes. CABS offers the opportunity to benefit from real-time changes at the optimum level enabling the transition from "manufactured" environment to "mediated" indoor climates (Addington, 2009). Favoino et al. (2014) defined the performance of a building envelope as to how well it protected indoors from the impacts of outdoors. They expanded this strategy through the concept of CABS.

CABS materialises the paradox of connecting the complementary aspects of passive design with active technology, offering the potential for high illumination and reduction of energy demanded by spatial conditions. Moreover, it contributes to indoor air quality and thermal and visual comfort (Loonen et al., 2013).

Adaptive facades, which were first discussed with the active control of the functions performed by the building facade (Wigginton and Harris, 2013), took their place in the literature with the term "adaptive/adaptive facades" in the classification of facade types in the following studies (Knaack et al., 2007). In ongoing research, adaptive/adaptive facades have been described more specifically as "climate-adaptive building shell (CABS)", with a comprehensive review of research, design and development efforts in the field (Loonen et al., 2013). Dynamic performance requirements of CABS, facade design and adaptive facade systems under stochastic boundary conditions, and experiences regarding market needs, evaluation methods, facade performance evaluation, and current trends were discussed with detailed and extensive research (Aelenei et al., 2016; Attia et al., 2015; Attia et al., 2018; Struck et al., 2015).

The literature review resulted in many studies discussing the conceptual assessment of CABS and simulation-based or experimental measurement-based performance assessment estimations.

In the context of energy-efficient design, the study aims to examine how high-performance advanced facade systems have developed thus far. This development process will be examined through the office buildings as one of the spaces where energy consumption is higher compared to other buildings, considering the referential data that "the annual cost for the construction of an office building ranges from 5% to 10% of the total annual costs for 20 years for a business, while the expenses regarding employees vary between 75% and 92%" (Van Ree and Hartjes, 2003; Winch, 2005).

2 Climate Adaptive Building Shell (CABS)

Studies assessing the energy performance of buildings focus on facades serving as the filters between the indoor and outdoor spaces. High and ever-increasing requirements regarding the energy consumption and internal comfort of buildings have been the driving force behind developing more efficient facade constructions.

The performance of a building shell is measured by how well it protects the indoors from outdoor impacts. This strategy has been expanded with the concept of climate-adaptive facade systems (Favoino et al., 2014). Climate-adaptive facade systems dynamically respond to changing conditions and requirements. Utilising climate changes decreases the energy consumed for maintaining a building's indoor climate (Böke et al., 2019), ensuring a more comfortable indoor temperature using less energy and offering better illumination and air quality (parameters affecting energy consumption).

Climate-adaptive facade systems that have developed with the intelligent materials and systems and automation support offered by technology serve as a passive or active climate control instrument for maintaining optimum indoor climate conditions and play an energy-efficient role by consuming a minimum amount of energy.

Researchers and professionals have used various alternatives for the term "climate-adaptive" in the context of facades within the literature. The different approaches and terms reflect the facades defined in line with the most distinct characteristic of building behaviour and adaptation. Terms that are often seen in texts regarding facades include adaptive, intelligent, kinetic, integrated, interactive, convertible, switchable and bio-adaptive (Böke et al., 2019; Hasselaar, 2006; Loonen et al., 2013). These terms support the claim of Perino and Serra (2015) that the adaptability of facades may emerge in different forms, such as the physical change in facade form or the active role of energy flow or energy generation. The common aspect of these concepts with the facades defined as the climate-adaptive facade systems is that they can be adapted to environmental and user factors through different methods and distinctive characteristics.

2.1 Adaptive facade

Climate-adaptive building shells are defined through various terminologies, one of which is adaptive facade systems. Adaptive facades are the shells that can adapt to the changing climate conditions daily, seasonally or annually. Dynamically reacting to climate, these facades improve indoor air quality and increase user comfort and satisfaction while serving as high-performance systems improving the energy efficiency and economic values of new and restored buildings (Attia et al., 2015; Attia et al., 2018; Luible, 2014; Struck et al., 2015) (Fig. 1).

Based on the following schema (Fig. 2), adaptive facades require certain functions or characteristics, such as thermal comfort, energy performance, indoor air quality (IAQ), acoustic performance, visual performance and durability. They control facade requirements such as heat and airflow, water vapour, rain penetration, solar radiation, noise, fire, shape and colour and provide sufficient responses by detecting the changes in indoor and outdoor environments to ensure an acceptable indoor climate. Adaptive facades with multiple functions should repeatedly respond to performance-related requirements and changes in boundary conditions (Aelenei et al., 2016; Attia, 2018; Al Thobaiti, 2014).

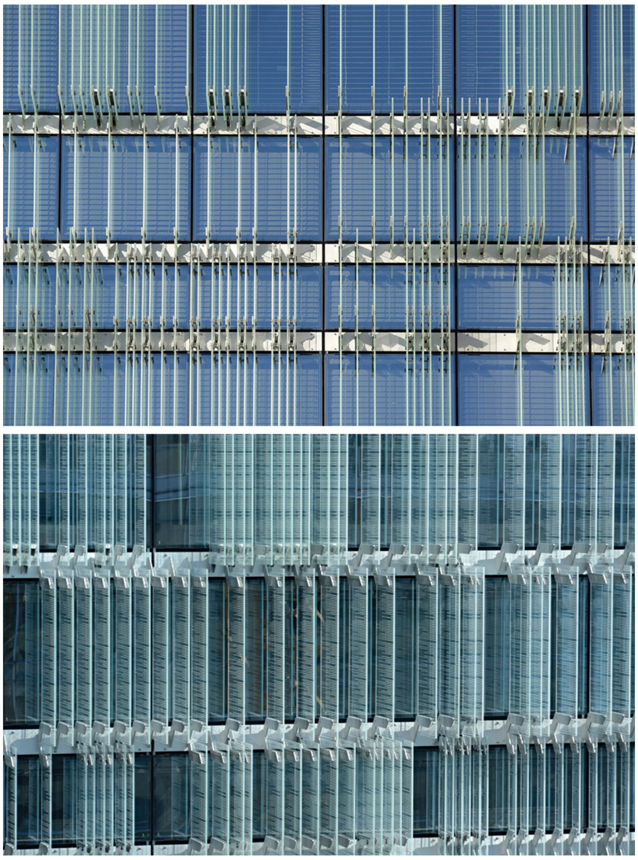

Fig. 1 Solar Control, Swiss Société Privée de Gérance (SPG) (Archilovers, online)

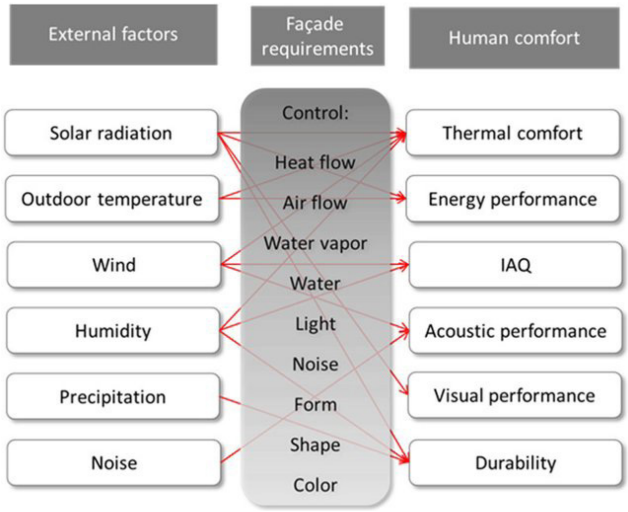

Fig. 2 The role of adaptive facades (Aelenei et al., 2016)

2.2 Intelligent facade

Adaptation to climate is a central ability within the definitions of intelligent facades. Accordingly, it reflects an interface that has the function of making a decision under current conditions (Sala, 1994).

The characteristics of intelligent facades can be understood as the capacity or the ability to respond to conditions and demands in a self-regulating form or through users (Kroner, 1997). Wigginton and Harris (2013) defined intelligent facades as an "active and responsive mediator" between the outdoor and indoor area, indicating an element that ensures optimum indoor comfort by using a minimum amount of energy. A recent definition defines intelligent facades as a result of the personal design process, including adaptation to indoor and outdoor conditions. As a result of this process, components and characteristics make the facades adaptive strategies possible (Capeluto and Ochoa, 2017). Intelligent facades require basic characteristics to be responsive and adaptive, such as being dynamic (change of many parameters over time and at different rates), non-linear (different behaviours according to parameters at different locations) and stochastic (extensive, inestimable/chaotic environmental parameters). In addition, multi-dimensional (a complicated interaction between many different mechanisms) and immeasurable aspects add to the complexity (certain variables are hard to measure and have unknown relationships, thus performing a real-time assessment on these through certain factors such as passenger satisfaction, psychology and future cloud cover is expensive) (Skelly, 2000).

Moloney (2011) defines the intelligence of a building envelope through the main aspects of an "input system", "processing system", and "output system". Capeluto and Ochoa (2016) classified the intelligent building shells as sensor/entrance elements (sensor, user interfaces), control and processing elements (policies, policy management) and activator elements (daylight and shading management, window systems, cooling-heating, ventilation and energy generation); "consideration of time" completes "the ability to learn". Nowadays, there is a technical infrastructure for the application of self-adaptive structures (Schumacher et al., 2010). In addition to the current sensor and actuator technologies, examination and development of intelligent materials result in more technical options (Drossel et al., 2015). Controls are essential as they determine the behaviours of self-adaptive facade systems (Fig. 3).

2.3 Kinetic facade

Designing and developing facades that are interactive and responsive to environmental characteristics is essential for ecological sustainability. Kinetic facades are among the climate-adaptive facade types that can alter their shapes, forms, orientations or gaps to automatically respond to environmental parameters such as temperature, moisture and wind. According to Kensek and Hansanuwat (2011), kinetic facades are dynamic and adaptive in their response to the environment. As an approach to the sustainable development of built environments, they are highly effective for constructing low-energy and finally zero-energy buildings (Fig. 4).

From a historical perspective, use of dynamic-kinetic environments as an environmental instrument has occurred under the control of four main variables: thermal control of sunlight (automatic louvres, adjustable overhangs), control of sunlight (automatic louvres, adjustable overhangs, iris systems, electrochromic windows), ventilation control (double skin facade using variable louvre system or stack effect) and energy generation (building-integrated photovoltaic [B.I.P.V.] systems) (Norberg-Schulz, 1965; Stein and Reynolds, 1992).

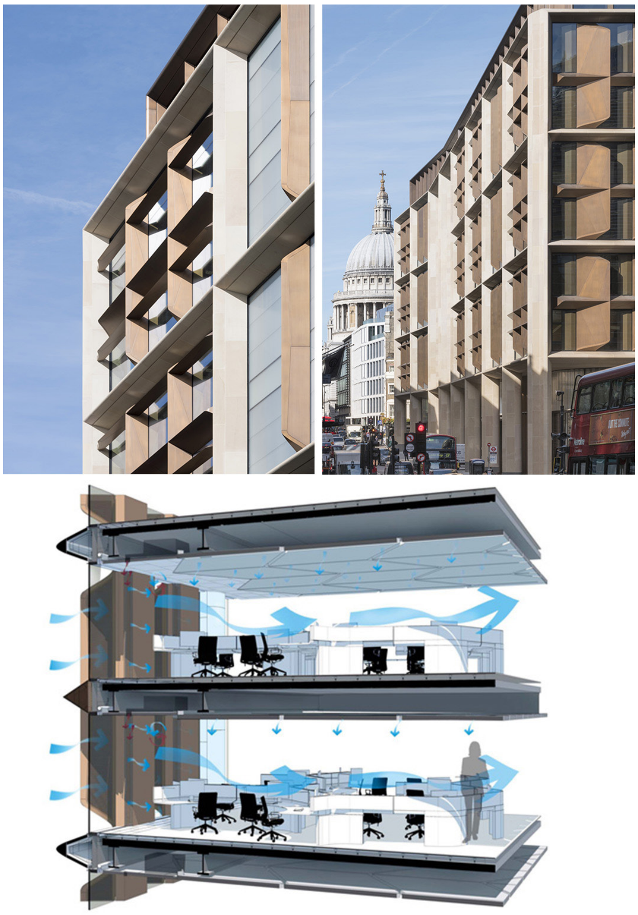

Fig. 3 The bronze wings integrated into Bloomberg's New European Headquarters facade ensure its movement according to environmental conditions with smart automation systems and adapt the building to the ambient conditions (CIBSE Journal, 2017)

2.4 Integrated facade

Integrated Facade Systems (I.F.S.) contain combined technological solutions that increase building performance and reduce environmental impact. Accordingly, technological solutions in this context can be broadly classified under four components (Ibraheem et al., 2017):

- Shading Devices (S.D.),
- Integrated Photovoltaics (IPV),

Fig. 4 CJ Blossom Park provides daylight control with moving panels integrated into the facade (A.I.A. Chicago, online)

- High-Performance Glazing (H.P.G.) and
- Wind turbines, seen less frequently than the other components.

These systems maximise the use of natural light while decreasing the thermal gain from the sun and rate of using air conditioner, ensuring ventilation, shading, and fulfilling certain functions such as energy generation and storage through solar panels (Ibraheem et al., 2017, Knaack et al., 2014).

With the integrated shell systems, future facades will potentially gain more functionality. This approach is an advancement of Mike Davies' "polyvalent wall" approach (Knaack et al., 2007). Adapting to changing climate, user needs, and integrating with the building structure are among the future expectations. Accordingly, adaptive facades can be considered the development steps toward integrated facades (Knaack et al., 2014).

B.I.P.V. offers attractive solutions to strengthen building shells effectively and sustainably. It saves energy and provides indoor comfort while generating energy (Skandalos et al., 2018, Vassiliades et al., 2018). In modern urban areas, most buildings have a broader facade compared to the roof surface. Therefore, in addition to the roof area, building facades in urban areas have been distinctively modified with the P.V. technology. Similarly, the solar radiation received by the facades should also be maximised through design (Yang et al., 2000).

The importance of glass in facades will continue to increase. A series of glass incorporated systems that can be used as a convertible construction material to simultaneously fulfil several functions have recently been developed. Examples of these glass materials include P.C.M. filled glass that acts as a thermal store, thin-film cells - photovoltaic cells positioned as the screens on the glass to generate energy, and solar batteries that generate energy from sunlight. Holographic coatings (films) can provide shading independently from solar radiation (transparent) or energy gained (e.g. radiation received by P.V. modules). Figures can also be printed through laser, and some areas may be left transparent. Also available are electro-chromatic coatings that can be changed by applying a voltage; these are used to adjust daylight and radiation transmission. Heated glass can be used to balance thermal loss and increase surface temperatures (no decrease of comfort due to radiation or cold weather during winter) (Knaack et al., 2014).

Integrated facade systems suggest a vision that will be gradually fulfilled as new components and technologies are developed (Fig. 5).

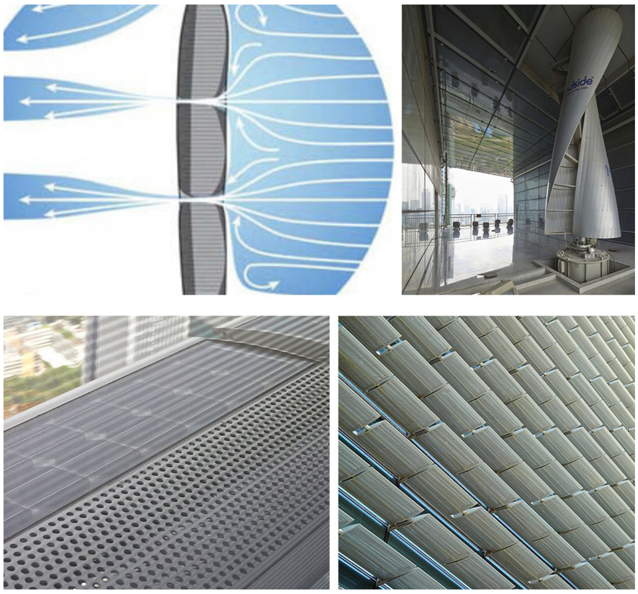

Fig. 5 Use of wind turbines and solar panels in the Integrated Facade, Pearl River Tower (SOM Architecture, online; Arch20, online)

2.5 Interactive facade

Interactive facades are the climate-adaptive facade systems that react to the changes in the external climate and adjust solar energy gain, daylight, heat loss and ventilation according to the changing needs of the occupants and the building (Selkowitz et al., 2003) (Fig. 6).

An interactive facade can take a form based on people's inputs to start adaptation, or it can provide an adaptation that can offer input for the human factor. The pattern here is not fixed; instead, it varies by CO_2 level based on human movement and density, and it is dynamic and interactive. This facade type may also be kinetic, intelligent and rational and have active skills. However, what sets them apart is that they are responsive to and interact with people (Loonen et al., 2013; Velikov and Thün, 2012; Tovarović et al., 2017).

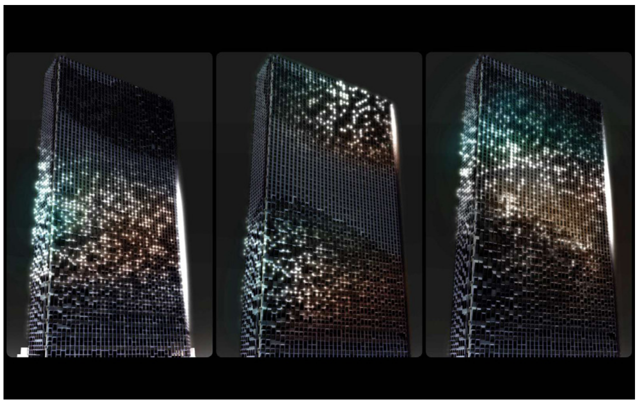

Fig. 6 Interactive Facade, Hanwha Headquarters (Council on Tall Buildings and Urban Habitat, online)

2.6 Convertible facade

Convertibility is considered, with mobility, one of the modes of variability in buildings for adapting to different functions. There are two sorts of convertibility: external convertibility, indicating the building shell, and internal convertibility, related to indoor spaces. These systems were designed based on needs and in a manner to change their forms quickly (Otto and Burkhardt, 1971).

The concept of convertibility for adaptive facades is generally used for buildings with transparent facades. For instance, with intelligent glass technology and climate conditions, changing the opacity settings or physical or chemical structure of the materials in glass systems can contribute to adaptability. Intelligent glass systems serve as a filter between indoor and outdoor spaces. Therefore, solar heat and light transmittance can be changed at any time, and the building can meet users' demands. These glass systems can be controlled automatically or manually. The convertible materials used in transparent facade systems include flexible coatings, pneumatic (swelling) system and thermo-chromic (responsive to heat), electrochromic, liquid-crystal, photo-chromic (responsive to light) and daylight-directing glasses (Beevor, 2010) (Fig. 7).

2.7 Bio-adaptive facade

The inclination to construct sustainable buildings and raise the awareness of the environment revives bio-architecture as an alternative to other construction methods (Sandak et al., 2019). Bio-based materials have a high potential to be used in adaptive facades (Callegari et al., 2015). Bio-based materials are characterised by natural traits that differ according to changes in environmental conditions.

When considering the use of organisms living on the facade, new possibilities arise. Plants' new technologies offer varied possibilities for sustainable construction. Algae, in particular, acts as one of the crucial plant species that successfully integrates into the built environment. Algae has recently been of great interest, especially with regard to energy, as an alternative renewable biomass source and in reducing the amount of embodied carbon (Elmeligy and Elhassan, 2019).

Using live plants introduces numerous applications, including water retention, air filtering, wind gust protection, and heat gain reduction. Those functions are usually accomplished by greenery arranged in different forms in "vertical gardens" that provide the framework for vertical rather than horizontal plant growth. In facades, the greenery layer is typically located at the blind (windowless) sections of walls but may also be deliberately positioned to the front of the window to provide shading and noise protection as well as the light-filtering function (Fig. 8) (Sandak et al., 2019).

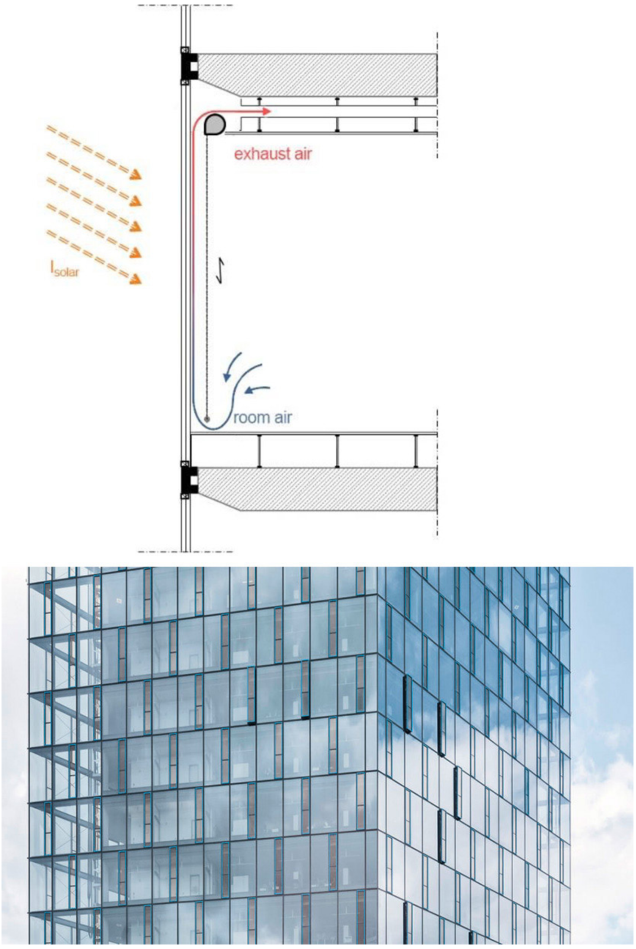

Fig. 7 Electrochromic Glass Facade, Festo Automation Centre (Schlaich Bergermann Partner, online)

3 Case study

As a result of the literature review, adaptive, smart, kinetic, integrated, interactive, convertible, and bio-adaptive advanced facade systems (Aelenei, 2016; Al Thobaiti, 2014; Attia et al., 2018; Ibraheem et al., 2017; Fox, 2009; Fox and Yeh, 1999; Platzer, 2003; Sandak et al., 2019; Sarihi and Derankhshan, 2018; Wigginton and Harris, 2013) were selected and described in subheadings as climate-adaptive facade systems. Conceptual research constitutes the first step of this study. The second step is based on the knowledge that "the most important issue within the scope of sustainability brought about by environmental problems along with energy problems, is energy consumption" (Block and Bokalders, 2009; Hegger et al., 2012; Lechner, 2014; Sayigh, 2020). Consequently,

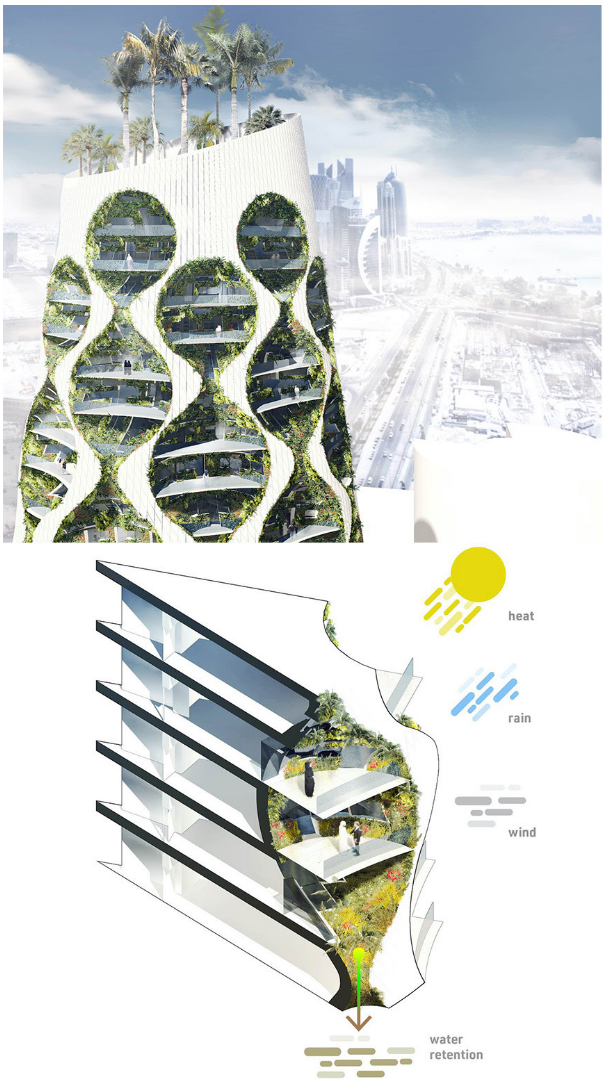

Fig. 8 Vertical Oasis Building Green Facade Design (Poland Architecture News, 2020)

climate-adaptive facade systems were analysed in terms of effectiveness. The factors affecting energy-efficient facade systems are sound, heat, wind, and visual comfort (Knaack et al., 2014). These factors were analysed under the following headings determined to be prominent as a result of the literature review and based on the buildings with climate-adaptive facade systems given in Table 1:

- material,
- daylight control,
- ventilation control,
- mechanical systems,
- integrated systems,
- noise control.

The buildings analysed in Table 1 are office buildings with high energy requirements and consumption due to the intensity of use. The main reason for selecting office buildings is that they closely follow the developments in facade systems and energy-efficient design applications. The building type constitutes one of the limitations of the study.

The primary parameter for evaluating office buildings selected for analysis is the climatic region where the building is located. The measures taken for the selected buildings to adapt to the regional climate will enable them to be evaluated in the context of the factors affecting the energy-efficient facade systems. That office buildings were selected from different climatic zones to evaluate the energy efficiency of different climate-adaptive facade systems constitutes another limitation of the study.

Evaluating the development of climate-adaptive facade systems in terms of measures taken in energy efficiency is essential to predict the performance requirements of soon to be realised zero-energy buildings. Therefore, the selected buildings are those that have been constructed in the last ten years or are under construction.

The analysis of climate-adaptive facade development systems in the last ten years in terms of energy-efficient design was carried out with the data obtained from the literature review in the first phase of the study. Specifically, under the main headings, the office buildings with climate-adaptive facades selected from different climatic zones demonstrate energy-efficient facade systems. The data for the analysis are given in Table 1.

4 Conclusion

Different advanced facade systems combined under the title of climate-adaptive building shells constantly repeat their development with the technology, smart features gained by the material, and the opportunities offered by software and automation systems. The findings and data obtained through this article have enabled the analysis of climate-adaptive facade systems in the context of energy-efficient design. When these data are evaluated in a broad perspective, it can be seen that climate-adaptive facade systems have been developed to prioritise user comfort, energy performance and environmental sensitivity. Another aspect of this development graph is the increased use of living plants and bio-based materials in the building shell. While this trend brings environmentally friendly buildings to the built environment, it is also influential in forming healthy urban environments. Applications such as water retention, air filtration, wind protection, heat recovery, light-filtering, shading and noise control by using bio-based materials in the building shell are carried out with green systems.

Table 1 Investigation of energy efficient design for different climate-compatible facade systems based on examples

							
Project tags							
Project name	Pearl River Tower	Festo Automation Center	CJ Blossom Park	Swiss Société Privée de Gérance (SPG)	Bloomberg's New European Headquarters	Hanwha Headquarters	Vertical Oasis Building
Architect	S.O.M.	Architekturbüro Jaschek, Stuttgart	CannonDesign	Giovanni Vaccarini	Foster + Partners	U.N. Studio	F.A.A.B. studio
Completed year	2013	2015	2016	2016	2017	2019	Project phase
Function	Commercial + office building	Office building	Office building	Office building	Office building	Office building	Commercial + office building
Location	Guangzhou, China	Esslingen, Germany	Suwon-Si, South Korea	Geneva, Switzerland	London, UK	Seoul, South Korea	Saudi Arabia
Climate zone	Warm and moisture climate	Warm and temperate climate	Cold and temperate climate	Marine west coast climate	Marine west coast climate	Cold and warm climate	Harsh dry desert climate
Facade features							
Facade system	Integrated facade	Convertible facade	Kinetic facade	Adaptive facade	Intelligent facade	Interactive facade	Bio-adaptive facade
Facade type	Internally ventilated double skin glass facade (North and South)	Single-skin building envelope Lightweight glass-cable facades	Single-skin building envelope	Double skin glass wall (4 layers of Glass)	Combined curtain wall (movable panel integrated) Explosion protective facade	Single-skin building envelope	Single-skin building envelope
Material	Double skin curtain wall	Electrochromic glass	Perforated aluminium, shading element, Frameless insulated glass Local material	Laminated glass (vertical direction), Glass, Steel, L.E.D. lighting	Bronze facade panel, Insulated metal ceiling, Wood panels	Transparent insulated glass and aluminium frame, P.V. panel, L.E.D. lighting (exterior)	Glasses using clearview power technology, B.I.P.V. active panel, Combination of plants and micro-organisms (facade integrated)
Daylight control	Daylight harvesting system Automatic shutters (daylight sensitive controls)	The use of electrochromic glass helps to reduce light and thermal transmittance while maintaining transparency.	Movable Perforated Solar Panel	Micro-perforated blinds Screen printed vertically oriented glass wings	Automatic shutters (Daylight sensitive controls)	Shading elements (North side), Opaque glass	Facade geometry providing daylight control

Table 1 Investigation of energy efficient design for different climate-compatible facade systems based on examples (continues)

	Facade features						
Ventilation control	Special Outdoor Air System (D.O.A.S.) Double skin facades with internal ventilation	The exhaust air system reduces the need for cooling by removing the hot air coming from the sun-resistant louvres in the cavity (used on two facades).	Atrium design (it effectively spreads the clean air gained by the active cold beam system throughout the building).	Double-skin facade that provides natural ventilation	Integrated movable bronze wings	Responsive facade concept providing indoor climate control	With the plants and micro-organisms integrated into the facade, it is ensured that clean air is taken into the building by reducing carbon emission.
Use of mechanical systems	Automatic shutters (daylight sensitive controls)	Mechanical ventilation (exhaust air) system	Movable perforated solar panel, Active cold beam system using clean air from the facade	–	Using the clean air taken from the façade Chilled ceiling	–	–
Use of integrated systems	Solar panel, Wind turbine, Automatic shutters, Daylight collecting systems	High-performance glazing (electrochromic glass)	Daylight sensor integrated to the facade	–	C.H.P. (Combined Heat and Power) system, Rainwater and gray water recycling, Vacuum drainage system	P.V. Panel (South and Southeast facade)	B.I.P.V. active panel, Rainwater recycling, CO_2 sensors, W.C.C. modular panel, Intelligent automation infrastructure systems
Noise control	3 Glass window	–	Specialty glass system	Double skin facade system	Insulated panel	Acoustic wall panels Insulated glass	Plants used in the facade
References	(SOM Architecture, online; Arch20, online)	(Schlaich Bergermann Partner, online; Stoughton, 2016)	(Medical Expo, online; A.I.A. Chicago, online; Thornton Tomasetti, online)	(Archilovers, online)	(Metal Architect Kikukawa, online; BREEAM, 2017; CIBSE Journal, 2017)	(Council on Tall Buildings and Urban Habitat, online; Designboom, online; Dezeen, 2020)	(Harrouk, 2020; Poland Architecture News, 2020; E-Architect, 2020)

The facade designs of the examples varied according to the climate conditions within their regions, while similar facade designs were present in comparable climate zones. In cold climate zones, transparent surface designs with a higher opaque surface rate, more compact and controlled structure, and facade designs with better thermal performance and insulated shells were present. Controlling sunlight was the priority in hot climate zones, and new material solutions were explored. Kinetic and adaptive facade systems with mixed solutions were utilised in warm climate zones.

One of the most significant factors behind the increased potential of climate-adaptive facade systems in terms of energy efficiency is material technology development. Intelligent materials that develop in line with the flow of technology, store and generate energy, change their optic features based on the environmental conditions, improve air quality, and reduce the maintenance costs owing to self-cleaning features, are critical for energy efficiency. In addition to these intelligent materials, biomaterials that are considered a promising resource for buildings in the 21st century are also important for the building shells to adapt to the environmental conditions thanks to numerous properties such as water retention, air filtering, protection from strong wind and reducing thermal gain.

There is a strong connection between the areas where efforts are made to ensure thermal comfort and daylight control simultaneously. A successful, climate-adaptive facade design should prevent the issue of daylight glare sustain energy-efficient building operation and have the ability to respond to fluctuations in solar radiation. Facade designs varied based on climate, and facade designs that resembled one another were utilised in similar climate zones. Extreme shading elements were exchanged with semi-opaque elements in mild climates, and opaque masses were mainly preferred in cold climates. Another significant parameter in ensuring daylight control is facade components that act according to the conditions, including materials and automation systems. Facade-integrated dynamic solar panels in mild climates offer daylight and ventilation control. Transparency is protected through the use of intelligent materials such as electrochromic glass in hot climates, together with measures to reduce light and thermal transmittance. Transparent insulation material and intelligent materials that feature heat storage and changing phases are used in cold climate regions.

Developments in the last ten years indicate that the cooperation between the automation and materials of buildings that suit the energy-efficient design principles will be highly efficient for managing the triangle of daylight control, thermal comfort and energy efficiency.

Measures regarding ventilation design are more important for buildings in the climate zones such as mild, Mediterranean and tropical or zones with savanna, steppe or desert. The ventilation can be controlled to ensure user comfort, prevent indoor air pollution and air-condition the building. Wind performance is more of an issue on taller buildings' facades. Accordingly, ventilation instruments differ for different heights. The external facade may consist of a series of systems based on thermal effects and the need for ventilation. Accordingly, examples of these systems include "double-wall facades, preferred for the buildings examined in the study, ventilated double-wall facades, adjustable folding instruments that can adapt to changes in wind direction, and ensuring ventilation by reducing carbon emission with the facade-integrated plants and micro-organisms and letting fresh air inside the building".

Additionally, like a mechanical system, the exhaust ventilation system increases indoor air quality. The more effectively the natural ventilation is designed with facade systems, the less mechanical ventilation and air-conditioning are needed, saving both capital costs and energy. The priority regarding the energy efficiency of facades is to fulfil the appropriate comfort conditions through passive systems. If the system is not sufficient, mechanical systems are used for support. The analyses (Table 1) support this result, suggesting that mechanical systems are preferred less.

Facades to be used will gain more functionality with integrated façade systems. The use of daylight reflectors and daylight-responsive controls, automatic shutters and electrochromic glass ensure daylight control, optimum conditions and thermal gains. With the systems used on facades, the need for air conditioning decreases as ventilation can be established. What is more, integrating renewable energy systems such as photovoltaic panels and wind turbines, recycling rainwater, energy generation and storage functions can be collectively fulfilled. The most common system is photovoltaics integrated into the facades, with many academic studies authored in this field.

Double skin facade systems present outstanding acoustic performance against external noise. Multiple-glass (double or triple glass windows) facade systems, glass insulation and acoustic wall panels are used to control noise. Additionally, plants that are often used on green facades within the concepts of ecological design help reduce noise pollution.

In conclusion, designers should consider mixed methods, particularly the passive design approach, for shaping the building they plan to create and designing and planning the shells. In this context, understanding the regional climate conditions that vary by location is the primary parameter for determining the climate-adaptive façade design strategies that establish the interaction between indoors and outdoors. These facade systems will play a key role, optimising themselves according to the climatic conditions gained through environmental inputs via the development of information and communication technologies, as fully integrated systems meeting the performance objectives of zero-energy buildings.

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