Chapter 1
State of the Art in Building Façades

Everything is designed. Few things are designed well.
Brian Reed

Abstract This chapter presents a portfolio of building materials suitable for façades. It describes the relationship between material type, building element, façade, and the entire building structure. Traditional façades based on static components, as well as adaptive concepts able to interact with changing environmental conditions, are briefly described and illustrated with pictures. Climatic design principles, biomimicry, and bioinspiration in architecture are introduced with the purpose of inspiring future developments.

The function of façades in architecture and the big portfolio of protective layers developed by nature (skin, membranes, shells, cuticles) share several similarities. In nature, skin is the largest organ that protects the body from external invaders. Skin is a multitasker performing several functions critical for health and well-being of organisms. Built from several layers, skin protects, regulates, controls, absorbs, maintains, senses, and camouflages. The analogies between functions of the building façades and animal skin are presented in Fig. 1.1. Building façades partly define architectural characteristics of structures and act as a shelter and space for human activity (Gruber and Gosztonyi 2010). They provide UV, moisture, and thermal defence, as well as protection from dirt, micro-organisms, and radiation. Façades communicate by transferring information—they are capable of exchanging and storing energy, heat, and water.

Since the first buildings were constructed, façades have been separating two environments: external and internal. To maintain constant internal climatic conditions, façades had to counteract the influence of various external environments depending on the given climate zone. In hot and humid zones, they provided protection against the sun radiation and allowed for the flow of cooling night breezes. In temperate climates, façades had to adapt to seasonal changes. In harsh north environments, façades were mainly designed to protect against the winter cold. This affected not only the construction material used but also the shape and configuration of windows, building orientation, and the heating strategy.

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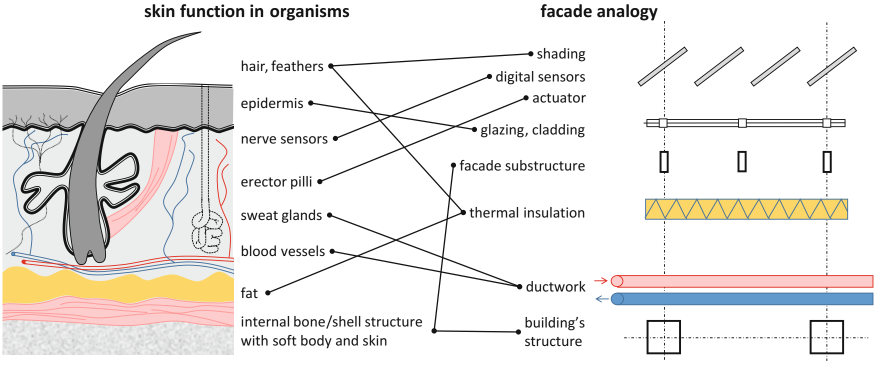


Fig. 1.1 Analogy between animal skin and building façade

In addition to possessing the obvious structural and protective functions, façades also needed to be durable. The most robust materials (e.g., stone) were usually the most expensive and most difficult to acquire. The scarcity of stone led to the development of brick, where the areas abundant in clay were available. Simple adobe brick stemming from dry climates was gradually replaced by the fired brick coming from the north, as this type of treatment provided a long-lasting waterproof layer. However, before the invention of masonry, from the very beginning of architecture, buildings were constructed of wood and other bio-based materials.

1.1 Structure–Façade–Element–Material

A shelter is usually defined as an enclosed space—a space that is somehow delimited from the surrounding environment to enable control over the internal microclimatic conditions. Such a space is the basic spatial element of habitation in many cultures and climate zones. With time, the number of rooms gradually increased, and each space supported a separate activity, such as socializing, sleeping, cooking, storage, animal raising, and cattle breeding. The type of enclosure delimiting the room depends on the exterior climatic conditions, available resources, and lifestyle. In nomadic tribes, light and portable shelters were developed as low-weight fast-to-erect solutions (Fig. 1.2). Those included two clearly separated elements—the load-bearing skeleton and the protecting envelope. With the onset of the static settlements, weight of the shelters was no longer a concern, while their robustness and ability to protect from enemies became a priority. This important change facilitated the invention of the “wall” that could be defined as a multifunctional element providing both the enclosure and load-bearing properties. The following chapter provides a brief overview of the gradually decreasing scale of complexity related to buildings.

Fig. 1.2 Yurts in Kyrgyzstan. Image courtesy of Aleš Oven—InnoRenew CoE

1.1.1 Structure

In human dwellings, two basic principles were developed to construct the envelopes: flexible and less permanent façades represented by tents for mobile use used in arid climates by nomadic tribes, and fixed solid walls designed to last. Walls were generally constructed from locally available materials since the immediate surroundings often provided technical solutions (Knaack et al. 2007). Initially, mud bricks and stone were used. With the spread of humankind further north (continental Europe), new requirements arose for the existing enclosures. Namely, they had to provide an improved insulation from heat and cold as well as better heat conservation properties (air tightness protecting from the heat loss through ventilation). With the scarcity of stone in available form (i.e., fewer available pebbles—more material had to be derived from a quarry), wood became a sensible alternative, as it offered insulation properties surpassing that of stone and proved to be much easier to acquire. This resulted in the widespread development of timber-based wall systems used almost in all climate zones where wood was available.

Timber became a main material in early Medieval cities and was later gradually replaced by stone used in fortifications following the rapid advancement of artillery. Still, timber buildings were not only built within the boundaries of fortified city walls but also on the outside. The latter case illustrates a deliberate strategy, as those buildings could be set on fire just before the enemy invasion.

1.1.2 Façade

The term “façade” generally refers to the external surface of the wall. Sometimes, however, the term is reserved to name only the frontal part of a building (e.g., a theatre overlooking the plaza has just one façade). The term comes from post-classical Latin facia (meaning “human face”). Initially, a façade was simply a by-product of a material type used in wall construction, as external and internal surfaces were no different. Gradually, with the increased significance of aesthetics, the external layer of human shelters acquired refinements that were pleasing to the eye. This lead, together with the development of geometry and mathematics, to the expansion of architecture, which became characterized by different building styles, proportions (e.g., the golden ratio), and classical orders. Façades were also able to advertise the power and prestige of building occupants long before other means of communication, such as writing, were invented. Throughout history, façades functions have been changed and upgraded in response to emerging technologies and materials. They continuously evolve and adapt in order to satisfy the changing demands of occupants (Capeluto and Ochoa 2017).

Humankind developed numerous materials to be used as façade coverings. Some of them originated directly from the wall material (e.g., timber, stone, brick), while others were developed deliberately as covering materials and were intentionally different than materials used in wall construction. Such materials are, for example, plaster, daub, ceramic tiles, and recently developed curtain walls made of steel, aluminium, and glass. The development of these materials was primarily motivated to seal the wall from the air penetration (this holds especially true in the case of plaster that seals the wall but remains vapour permeable) but also to protect a relatively fragile structural material from harsh environmental conditions. This external finish is also intended to either totally block (e.g., curtain wall) or at least control (e.g., in so-called ventilated cladding) potentially hazardous water ingress. Often, the external façade cladding material is less durable than the structural material; thus, occasional refurbishment of façades is foreseen to maintain the overall building durability.

1.1.3 Element

As log houses were probably the first biomaterial-based permanent structures erected by humans, logs represent the first bio-based building elements. Gradually, with the development of tools and building techniques, the framed structures were developed. Those used timber members in different structural components: as beams, posts, columns, bracing elements, rafters, etc. In this type of structure, timber cladding elements (e.g., profiled boards, laths, and wood shingles–shakes) are also considered to be bio-based façade elements. The advent of industrialized production allowed for more efficient timber manufacturing techniques, while the advancement in chemistry provided various man-made binders. This facilitated the production of bio-based materials composed of both full-featured (laminated timber, cross-laminated timber) and previously rejected waste (by-products) materials (chips, sawdust or even stems and leaves). Consequently, a wide variety of elements arose, including block boards, particle boards, oriented strand board (OSB), and—most recently—natural fibre-reinforced polymer composites.

1.1.4 Material

As experience shows, properly handled structural bio-based materials proved to be durable and robust much longer than expected (some timber-framed structures show the astonishing lifespan of a few hundred years). However, bio-based materials used as external cladding face the most severe climatic conditions as they are fully exposed to the outdoor environment. In a temperate climate, the façade is exposed to daily frost and thaw cycles in spring and autumn and to large seasonal fluctuations in UV levels. Considering this, it seems that the protection from the environmental influences is the most important issue in the application of bio-based materials. Controlled ageing of the bio-based materials has thus become a crucial engineering challenge.

Natural Stone

Stone is a natural substance, a solid aggregate of one or more minerals. It is the main building material of the Earth's outer solid layer, the lithosphere. Due to its availability, the stone has been used by both human and prehuman species as a tooling and building material since the advent of civilizations (approximately 12,000 years ago). Stone was initially obtained by collecting and later by mining. In the construction industry, stone can be used in its natural form as a pebble (boulder) or it can be mechanically transformed into a desired form, for instance, a wall element (ashlar). Those basic elements can be either assembled loosely (dry stone wall) or glued using the mortars or plasters.

Stone has a high heat capacity and is generally exceptionally durable, although this varies somewhat depending on the type of rock: for example, while granite is very durable, marble is prone to damage induced by chemical agents. The stone cut in thin slices (approximately 2 cm) is commonly used in buildings and is recognized as a highly durable cladding material. Initial high cost of production is usually justified by low maintenance costs. However, the dramatic increase in deterioration in the built heritage has been observed during the past century due to climate change and increased environmental pollution (Siegesmund and Snethlage 2014).

Concrete

Concrete is a composite material consisting of a fine and coarse aggregate (i.e., sand and gravel mixed in various proportions) bonded together with a fluid cement (i.e., cement mixed with water forming a so-called cement paste). Due to a series of chemical reactions, concrete hardens over time. The Portland cement type is usually used to manufacture concrete, but other binders might also be used, for example, lime-based binders or asphalt. In the production stage, concrete has a form of a slurry that is poured into the formworks typically made of timber or prefabricated elements. As a consequence of certain chemical processes, concrete forms a stone-like material that can differ in strength and other properties depending on the content of the mixture that was used to manufacture the slurry. Concrete is commonly labelled as "artificial stone".

Because of the similar Young modulus in concrete and steel, the steel bars—also called "rebars"—are widely used to reinforce concrete. Concrete is therefore used in the compression zones, while the steel reinforcement is used in the tensile zones to provide tensile strength. Concrete and stone (the aggregate used to manufacture concrete) are similar in weight; however, reinforced concrete is heavier due to the added steel inserts. Concrete has a moderate environmental impact. Bribián et al. (2011) compared the environmental impacts of various building materials, while taking into account the manufacturing, transport, construction, and demolition of buildings. The functional unit applied was 1 kg of the material. The primary energy demand of concrete was calculated to be approximately 1.1–1.7 MJ eq/kg. The higher values are reported for reinforced concrete (Bribián et al. 2011). Cement, on the other hand, has a higher primary energy demand, 4.2 MJ eq/kg, due to the high energy use and generated pollution in the production phase. Although the proportion of cement in the concrete is relatively low, approximately 1/7th of the total mass of the concrete, it considerably contributes to the overall environmental impact of concrete. It should be emphasized that the results could be different if calculated per 1 m^3 of the material, especially when accounting the life cycle assessement (LCA) for materials with different physical properties (Bribián et al. 2011).

Ceramics

A ceramic is a non-metallic solid material comprising inorganic compounds (metal, non-metal, or metalloid atoms). Ceramics can have a crystalline or non-crystalline internal structure (e.g., glass). Building ceramics (e.g., fired bricks) represent a certain range of crystallinity, where the atoms or molecules are arranged in regular periodic microstructures. Ceramics are produced from different types of raw ceramic materials (e.g., clay, ash, different chemical forms of silica) using high temperatures ranging from 1000 to 1600 °C in the process called firing. Ceramic materials are hard, and strong in compression but also brittle, and weak in shearing and tension. As the material is not amenable, it generally has to be shaped during the production stage because of its inherent brittleness.

Ceramics have high heat capacity, yet, due to its porous structure, lower than concrete and stone. Glazed ceramics are very durable and resistant to chemicals. They have been used in buildings since the beginning of the civilization, that is, as soon as firing kilns were invented. In the past, brick was extensively used for the load-bearing construction but is nowadays commonly replaced by concrete and steel (brick is prone to failure in harsh conditions, such as earthquakes). In the present day, ceramic products are commonly used as the building external cladding material and are considered to be safe and durable. However, their environmental impact is relatively high, especially when covered with glaze. For example, the primary energy demand of ceramic tile is approximately 15.6 MJ eq/kg (Bribián et al. 2011).

Glass

Glass is a non-crystalline amorphous solid. It belongs to the group of non-crystalline ceramics being formed from melts. The basic melt contains 75% of silica (SiO_2), lime, and other ingredients (Na_2O, Na_2CO_3) along with several minor additives. In the temperature of approximately 1600 °C, the vitrification process occurs, and silica molecules are positioned randomly without a crystalline structure. After a period of cooling, the transparent glass is formed. Glass, as all ceramics, is brittle, hard, strong in compression but weak in shearing and tension.

Glass should be formed in melt form by casting or blowing. Around the beginning of the previous century, a series of flat glass producing technologies were invented, later topped by the float process developed by Pilkington in 1958. Flat glass can be machined, cut, and ground to the desired form, and it can be hot and cold bent. In the modern building industry, glass is commonly used to glaze windows in the form of insulating glass units (IGU) or employed as a safety glass that holds together when shattered. The typically used interlayers holding the glass in place are polyvinyl butyral (PVB) or ethylene-vinyl acetate (EVA).

Glass is resistant to numerous damaging chemicals. The material is commonly used to manufacture containers for a selection of aggressive chemical substances (acids and alkali). It was initially used solely as a material for window glazing, but after the invention of the curtain wall, it is commonly applied as a whole façade building's cladding for both visual and non-visual (meaning the transparent and opaque) parts of the façade. Since glass requires abundant levels of energy to be produced, it generates a high environmental impact. When calculating the impact from the phase of manufacturing to the time of building demolition (cradle to grave), the primary energy demand of glass is approximately 15.5 MJ eq/kg. The environmental impact, however, would be significantly lower if the calculation would include recycling (cradle to cradle), as glass has a high recycling potential (Bribián et al. 2011).

Metals

Metals are a group of metallic chemical elements, typically lustrous substances, characterized by a high electrical and thermal conductivity. Metals in pure form are rare in Earth's lithosphere; thus, they have to be extracted from the naturally occurring minerals—usually the ores. Metals and their melts were crucial in the technological development of human civilization (Bronze Age, Iron Age) and are currently widely used.

Metals appeared in the building industry in the mid-nineteenth century, following the onset of the Industrial Revolution. They gradually replaced the framed timber structures because of their greater strength and fire resistance. Currently, steel is used both as a structural, load-bearing material and, in the form of the thin sheet, as the façade cladding.

Metals (e.g., steel) are characterized by high compressive and tensile strength but have to be protected to slow down the oxidation process that might eventually destroy metal elements. They are prone to the damage resulting from a wide range of chemical agents, including acids and alkali. Metals are heavy—those used in buildings are approximately 4 times heavier than concrete and stone. The primary energy demand of metals, when considering the LCA calculation production, transport, construction, and demolition, ranges from 24.3 MJ eq/kg for reinforced steel to 136.8 MJ eq/kg for aluminium (Bribián et al. 2011). Due to the relatively high purchase cost, metals are commonly collected at the end of their life cycle and recycled to create new products, which reduces their environmental impact.

Plastics

Plastic is a material consisting of a wide range of synthetic or semi-synthetic organic compounds. Plastics are malleable and can be moulded into solid objects. They are typically organic polymers of high molecular mass and usually contain a variety of substances. Plastics derive from petrochemicals; however, variants that are made from renewable materials are also available.

Plastics were invented at the beginning of the twentieth century and became widely used a few decades later in many fields, including the building industry (e.g., polyvinyl chloride (PVC), polycarbonate (PC), hollow polycarbonate). Plastics are usually characterized by a high water resistance, lightness, and low structural strength; however, those parameters can vary depending on the composition of the polymer matrix. Plastics are combustible, and for the safety reasons, their use in buildings should be restricted (the most resistant plastic polymers can withstand the temperature of maximum 150 °C). Plastics are also prone to the UV radiation, which is considered as the most degrading agent for the majority of plastics manufactured today.

In the building industry, plastics are commonly used in a variety of forms and shapes. They are typically used in the PVC window frames that replaced the timber frames due to their lower cost of maintenance and good heat insulation. Many polymers are used in building industry in the form of thin coatings and paintings. Environmental impacts of plastics are among the highest when compared to other building materials. For example, the primary energy demand of polyvinyl chloride is approximately 73.2 MJ eg/kg. This is due to the high energy demand during the production phase as well as due to the high water consumption (one of the largest among building materials, exceeding 0.5 m^3 for a kg of the finished product) (Bribián et al. 2011).

Coatings and Paintings

Coatings are manufactured from a wide range of materials, usually plastics and metals that are deposited on a base material in a very fine and thin layer. Although the coating layer is thin, it can substantially modify the properties of the base material by changing some of its characteristics. For example, a few nanometres thick layer of a metallic coating applied on glass can substantially modify glass transparency and, consequently, its heat conduction.

In general, paintings and coatings are applied for functional and decorative purposes. Coatings may be used to improve certain physical characteristics, such as fire resistance, sealing, or waterproofing but could also be used to stain the base material (e.g., wood stains). Metals are coated to prevent oxidation and slow down the corrosion.

Application of different materials on building façades is presented in Fig. 1.3.

1.2 Standard Façades Systems

Façades are generally considered as static elements of buildings. This applies to the solid walls that fulfil both the load-bearing and protective function (the external face of those walls becomes the façade). It also applies to the most recent skeleton post and beam structural systems that are clad by lightweight curtain glazed walls. Initially, in all buildings, the internal conditions were maintained via natural means, for example, by ventilation and heat/moisture exchange through the envelope. They were open systems. The control of the environmental conditions was executed manually, simply by adjusting window openings for air exchange or by pulling the curtains for sunshading (Fig. 1.4). The parameters of the façade remained constant (e.g., the wall’s U value or other structural properties) from the moment the façade was erected.

Especially in harsh climatic conditions, the maintenance of internal comfort required a lot of effort; thus gradually, some modifications were done to improve this process. In arid climates, the overhangs and the mass of the building were used to reduce the diurnal changes in interior temperature. In temperate climates, cavity wall and double glazing appeared as one of the best means for reducing the loss of heat. Buildings were temporarily sealed to reduce heat ingress/escape. Night-time cooling was practised in hot climates as a mechanism of seasonal ventilation and temperature lowering. In temperate climates, insulation was added in the winter.

The issues of the façade functions were addressed previously in numerous sources, including the iconic Façade Construction Manual (Herzog et al. 2004) and Timber Construction Manual (Herzog et al. 2012). Both manuals include one of the most comprehensive engineering resources for architects and designers. In 2014, a book titled Modern Construction Envelopes (Watts 2014) was published by Birkhäuser, containing a chapter dedicated to “timber walls”. One of the most recent books titled: Building Envelopes: An Integrated Approach published in 2013 by Princeton Architectural Press provides instruction for designing building envelopes that are both visually appealing and high-functioning (Lovel 2013).

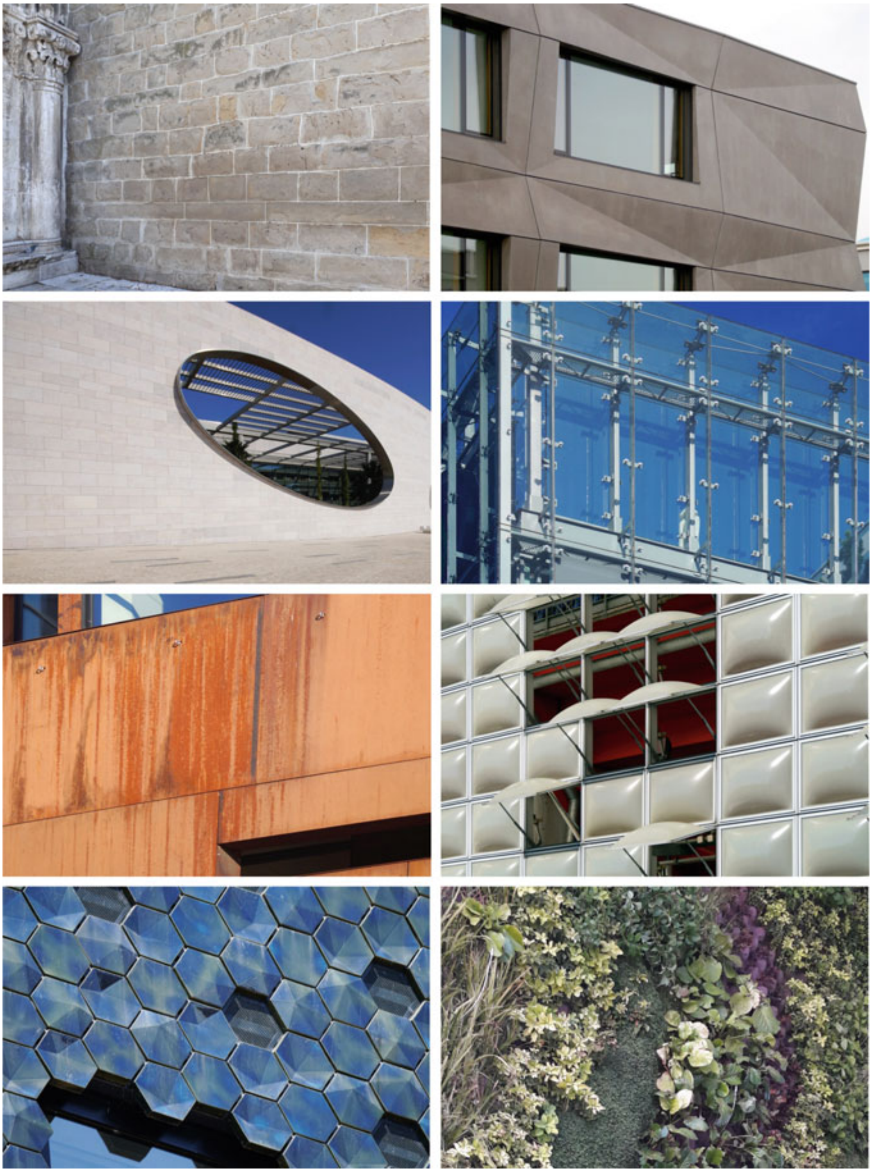


Fig. 1.3 Building façades with different materials: assumption Cathedral, Koper; Büro- und Produktionsgebäude in München/Kurt Tillich, tillicharchitektur, München; Champalimaud Centre for the Unknown/Charles Correa Associates; Skattekvartalet-Tax Administration/Narud Stokke Wiig; European Solidarity Center/FORT—Wojciech Targowski; St. Jakob-Park Basel Stadium/Herzog & De Meuron; Museum der Kulturen/Herzog & De Meuron; Elnos commercial centre, Brescia

Fig. 1.4 Façade with integrated classic windows for direct air exchange (DKV Insurance Company HQ, Cologne, arch. Jan Störmer Architekten, 2005)

1.2.1 Closed and Open Systems

The invention of air conditioning by Willis Haviland Carrier in 1902 and introduction of heating, ventilating, and air-conditioning (HVAC) systems offered several options in microclimate regulation of buildings. Full mechanical microclimate regulation includes temperature, humidity, air circulation, and air cleaning. In buildings, the air exchange is powered by mechanical fans and provided via air ducts. This technology revolutionized the world building industry, starting initially in the USA in 1920. It enabled the manufacture and maintenance of microclimates in high-rise buildings with limited accessibility to windows. This technology is also supposed to facilitate the great migration to the so-called Sunbelt in USA (areas south of the 36th parallel). The technology creates an artificial environment that is maintained by fans, coolers, heaters, and dehumidifiers (generally speaking: compressor systems) channelling air through ducts in full insulation from external conditions. In this system, the façade becomes a tight impermeable barrier separating two environments, since the opening of the windows would disturb the constant indoor air conditions. Initially, HVAC systems seemed to be the solution to maintain certain microclimates in buildings, but eventually numerous drawbacks began to emerge. Filters used in air-conditioned buildings were imperfect, and some mould spores were admitted inside the ducts. As mould does not need the daylight to grow, it flourishes inside the warm and humid ducts producing toxic and dangerous substances subsequently inhaled by the building occupants. Stagnant and kept at the constant temperature, water facilitates the growth of various dangerous germs, such as Legionella pneumophila. On one occasion, dangerous bacteria migrated from the water present in the humidifying system to the air circulating in the ducts and caused the death of 29 elderly men that contracted severe cases of pneumonia (this event is currently labelled “the Legionnaire’s diseases outbreak”) (McDade et al. 1997). The outbreak received significant media coverage, drawing the public’s attention to the issues of the indoor air quality and so-called sick building syndrome. Although the mechanical systems proved to be very effective in maintaining the proper temperature and humidity, the initial system version raised a multitude of questions about the hygiene and health conditions in buildings.

1.2.2 Mixed-Mode Systems

In contrast to isolated environments, open systems are characterized by outside conditions that help maintain occupant comfort and positively influence the interior climate. This is achieved by opening the building façade to the external environment in certain periods of the year. Therefore, contemporary ventilated façades had to work in mixed modes. The first one, an air exchange mode, is achieved by opening the windows (possible even in high-rise building thanks to the use of double-skin façades), while the second is the air-conditioning mode, used in the presence of extreme external conditions (either too hot or too cold). In the latter, the building is sealed, and the air is artificially exchanged by the mechanical system via ducts. The mixed-mode systems (combining both modes) proved very effective and were successfully introduced in numerous buildings. The additional advantage of such systems, apart from the improvement of internal air quality and substantial reduction of energy bills, was the inclusion of the occupants in the process of decision-making by allowing them to open windows, adjust the blinds, and regulate internal temperature to a certain extent. By the first decade of the twenty-first century, previously used fully mechanical systems were overshadowed by new advancements. One example might be the Commerzbank in Frankfurt am Main

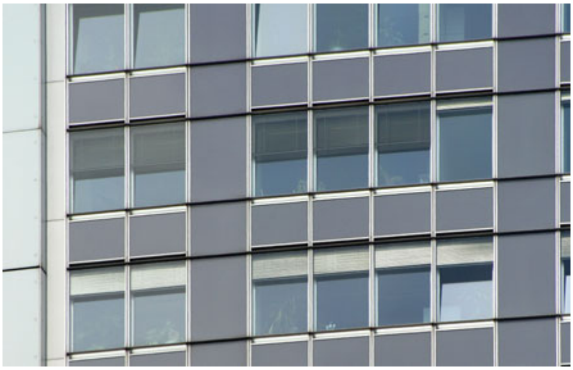


Fig. 1.5 Commerzbank in Frankfurt am main (arch. Foster and Partners, 1997)

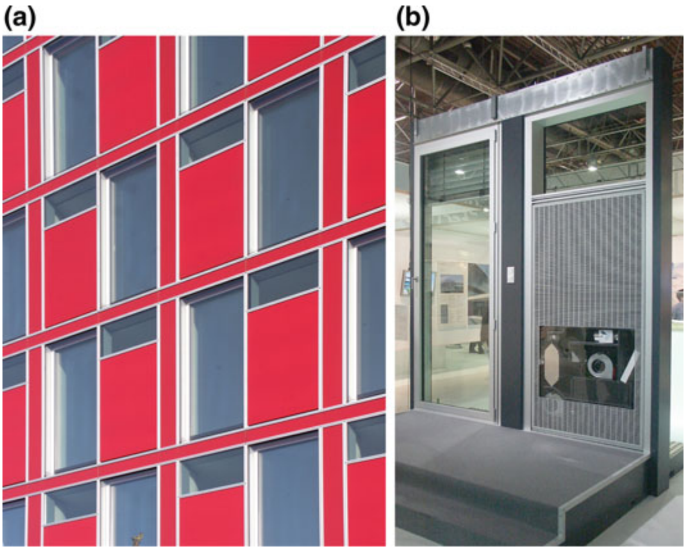


Fig. 1.6 Capricorn Haus Façade (arch. Gatermann & Schossig, 2005). **a** View of the building's façade for the outside, **b** view of the façade module from the inside; see decentralized air-condition system installed in the façade module

(arch. Foster and Partners 1997) that can be naturally ventilated for approximately 60% of the year (Fig. 1.5). The systems have progressed even further towards the decentralized air-condition system in the Capricorn Haus Façade (arch. Gatermann & Schossig 2005), where every façade module is responsible for the climate regulation of an adjacent room (Fig. 1.6) (Brzezicki 2007).

1.3 Climatic Design

Climatic design is a set of design methods and principles used with the purpose of capitalizing on the advantages of climatic conditions surrounding buildings. In the paradigm of "climatic design", buildings try to gain the most from their local environment just like organisms rely on the resources provided by nature. The general rule is to work with the climate and not against it, by using all the available methods to provide comfort in the building with the minimized use of primary energy either for heating or cooling. Since climates are diverse, it is not surprising that specific climates require unique design solutions that could be generally divided into two groups: heat accumulating and heat rejecting techniques. Here, the influences of air humidity have to be taken into the account because, as the psychrometric chart shows, the same air temperature (dry-bulb temperature) proves to be either acceptable or unacceptable depending on the relative air humidity measured by means of a wet-bulb temperature (Lechner 2008).

The effectiveness of certain passive methods of internal climate regulation depends on the climate conditions. Evaporative cooling—the heat rejection technique—is effective only in a relatively dry climate (basically below 40% of humidity, the dryer the better), while the increase of the thermal mass to accumulate heat works in both dry and humid climates (Fig. 1.7a). The latter technique, together with the so-called night cooling/purging, is effective even in high daytime temperatures (up to 42 °C, at approximately 60% of humidity). Natural ventilation effectively lowers the temperature in buildings if, of course, the external air temperature is lower than the desired internal temperature (Fig. 1.7b). When the external air temperature is too high, the ventilation provides the hygienic air exchange but also introduces a lot of heat energy that can increase the interior temperature. In many warm climates, a shading is very effective in preventing the heat build-up in buildings.

Depending on the exact geographical location, wind is also used to lower the temperature and provide the ventilation in buildings, especially in locations where wind direction is constant, and the pressure difference can be used to channel the air through the building. So-called wind towers are used to catch and direct the stream of fresh air, and air tunnels are used to lower the air temperature.

In temperate climates, a different strategy is required as the weather conditions change significantly with seasons. In the hot part of the year, all the warm climate methods can be used, while in the cold season the heat accumulation techniques are more appropriate, including passive solar gains due to the greenhouse effect (e.g., by using glazed atria or conservatories). In cold climates, heat insulation is required to slow down the heat escape during the long and cold winter season.

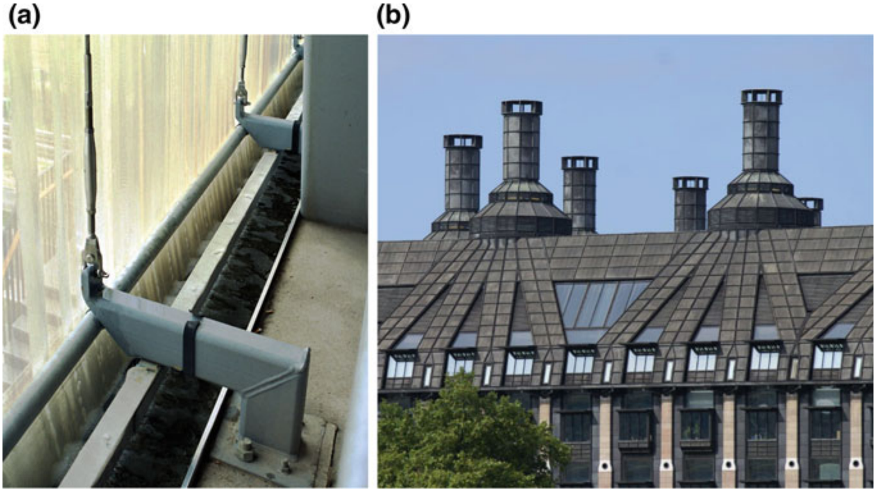


Fig. 1.7 Examples of passive methods of internal climate regulation. **a** Evaporative cooling and **b** natural ventilation

Fig. 1.8 Different buildings architecture all over the world

Different passive techniques were applied in diverse climates by using various building materials, depending on the availability. The use of those materials is usually a part of a local vernacular architecture or building traditions (Fig. 1.8). In vernacular architecture, many typological modifications are present, including the decreased window sizes, installation of an extra glass layer or timber shutters.

In hot and arid climates, building mass usually results from using stone or adobe (sun-dried brick). When those are scarce, dwellings can be “carved” in bedrock or dug into the ground. Tunisian tribes of troglodytes live in the artificial caves that are radially located around the central artificially dug pit. Traditional building methods (e.g., high accumulation mass and night ventilation) are currently also used in the building industry, for example in the Torrent Pharmaceuticals research centre (arch. Abhikram 1994–1999) in Ahmedabad. This building regained all constructional costs from the electrical savings in 13 years of operation, thanks to its passive downdraft evaporative cooling system (PDEC) and minimal air conditioning. In hot and humid climates, nature provides building materials in the form of timber (unmachined timber in a form of palm tree trunks) or plant leaves. These are used to erect lightweight and well-ventilated structures that achieve maximum cross-ventilation and convective air flow. Timber and plant leaves are also used to construct ventilated roofs with the deep eaves to provide shading and rain protection. Building openings (windows and doors) are in this case facing the predominant wind direction (Samuel et al. 2017). In temperate climates, different construction techniques have been developed. Stone is frequently used, but the fired brick becomes an alternative as a robust and water-resistant façade material. Depending on the availability of wood, either solid (in log houses) or framed timber structures are used. Both are easy to erect and relatively long-lasting. In the north, timber is becoming increasingly important due to the insulation potential resulting from its cellular microstructure. Framed timber structures were often filled with the lower-grade material: either with a wattle and daub or by the mix of clay and leaves providing insulation layer protecting against the heat escape in the winter. This vernacular technique evolved with time and is nowadays commonly used together with non-combustible modern insulation materials, such as the mineral or rock wool. In the mid-nineteenth century in northwest Europe, a cavity wall was developed as an effective heat insulation technique. It became widespread in the 1920s, and since the 1970s, it has been used in the wall cavities (e.g., polystyrene). Glass has become an important passive material in climatic design, since it is useful in conserving heat through the greenhouse effect. Glass production techniques, originating from the start of the twentieth century, are able to manufacture large thin glass sheets used to construct building envelopes. Even though metals (e.g., steel and aluminium) are not directly connected to the climate design, they are gaining importance by replacing timber-framed structures. Robustness and water-resistant qualities of metals are especially beneficial to glazed structures.

1.4 Biomimicking and Bioinspiration in Architecture

The systems found in nature are a valuable source of inspiration in many areas. The concepts of biomimicking and bioinspiration are being adopted by scientists and researchers from various fields, including structural engineering, robotics, medicine, and materials science. In the last years, the potential benefit derived from natural solutions has become appealing to the field of sustainable architecture. Biology serves as the initial basis for comparison and understanding of biomimetic principles. Then two approaches might be used to transfer the information: solution based (bottom-up approach) and problem based (top-down approach) (Gruber 2011). For the practice and realization of future urban designs, the architectural and engineering aspects of biomimetics have been far more distinctly developed (Pohl and Nachtigall 2015). In many cases, this approach complies with the general principle of so-called climatic design, which is one of the best approaches to reduce energy consumption in buildings. This analogy is hinting at how to design buildings that are using materials and energy optimally. In fact, the message for architecture that emerges from observing nature is “less materials, more design” (Pawlyn 2016).

1.4.1 Animals Inspiring Design

A paper published by Michael Davies titled “Wall for all seasons” presented a complex multi-layered façade envelope that is regulated electrochemically (Davies 1981). Its structure was analogous to the morphology of organic covering tissues (the skin), and the thermal regulation was comparable to biological mechanisms. Outside temperature and air humidity influence physical parameters of this "polyvalent" wall, that—besides sealing and insulation—provides other functions, such as light transmittance, thermal conductivity, and vapour permeability. The wall's layered structure fulfils different functions: external "weather skin" protects against rain and cold, while two "sensor and control logic" layers gather information about the status of the external environment. Layers equipped with micropores regulate the intensity of gas (vapour and air) infiltration. The presented system included a photovoltaic layer, which enables energy generation. The author also presented an algorithm for the system operation. Even though it was not technically possible to implement this idea, it has become a challenge and inspiration for many modern architects and designers. Most of them intended to create a façade that is "alive and constantly changing like a chameleon skin" (Davies 1981).

Davies's work clearly shows that inspiration from nature can be implemented in (at least) two ways; the bionic innovation could either be inspired by the way the organism functions or it could be modelled on the way that the organism is built, especially at the level of its microstructure. The first method has been widely implemented in systems that are used to maintain stable conditions in buildings (energy conservation and sustainability), while the latter has inspired several innovative material solutions. Observation of animals, especially in extreme weather conditions (e.g., tropical climate or polar zones), provides numerous organic patterns to be used in building systems and components, such as transparent insulation materials (TIM) modelled on the fur of the polar bear. In organisms, the thermal capacity of blood is used in thermoregulation that takes place in the blood vessels. Some animals (e.g., desert animal—fennec fox) take advantage of this mechanism with enhanced emission of excessive heat into their surroundings. Another analogy between the nature and built environment can be seen in the reaction of animal skin on temperature changes and the façade reaction to the solar gain. The use of sunlight for energy production constitutes a technological equivalent of photosynthesis. Many buildings also mimic the natural phenomenon of evaporative cooling. This mechanism is analogous to sweating which takes place in humans and most animals. This process has inspired many technical solutions in modern architecture. After being initially observed in animals and humans, evaporative cooling is effectively used in arid and dry climates to reduce air temperature in buildings (Brzezicki 2002).

The most popular analogy between buildings and nature is the one that compares buildings and warm-blooded organisms. Many similarities could be found between such organisms and the built environment. For example, the process of homeostasis is analogous to the artificial climate regulation in buildings. Another example is the information transfer in the buildings that parallels that found within the nervous system. The maintenance of constant conditions in buildings requires energy and relatively fast reaction times to changing external conditions. Some solutions could be found in nature and directly implemented in some contemporary buildings. Warm-blooded organism analogy contributed to the invention of energy-conserving countercurrent heat exchanger after the similar natural system (veins and arteries

Fig. 1.9 Conceptual façade system modelled on the principle of gaseous exchange in insects. Picture taken during Glasstec Messe 2004, Glass Technology Live Show, Institute of Building Technology and Design, Stuttgart, Prof. S. Behling, Dr. Henning-Braun

intertwined in the limbs) was observed in aquatic birds and mammals. The thermoregulation phenomenon in animals is a continuous inspiration for engineers and architects designing innovative technical solutions and sustainable technologies.

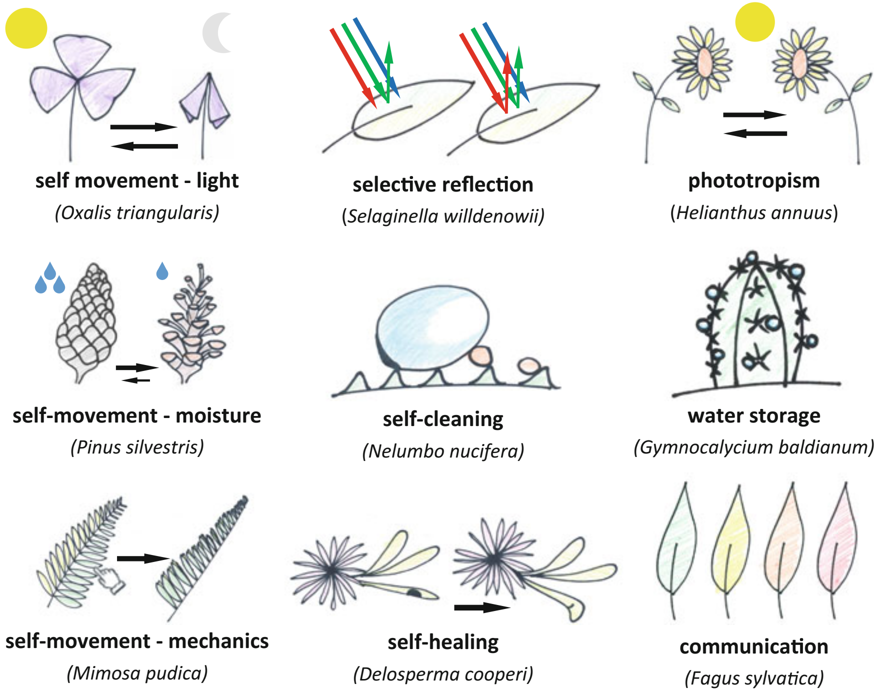
While the condition of the "channelling systems" in an organism is constantly maintained through the biological mechanisms, the same process is difficult and time-consuming in buildings. In this case, the gaseous exchange in insects provided some insights as it is done directly through the exoskeleton through the apertures called spiracles (Fig. 1.9). Further observation of the insect's respiratory systems contributed to the recent invention of decentralized air-condition system that provides direct air exchange with the external conditions, without the use of any channelling systems (Brzezicki 2007). This type of air-conditioning system uses less energy (no energy to pump the air through channels is required) and allows to switch the system on and off depending on the room occupancy. The lack of the channelling permits reducing room storey-height and subsequently the overall height of buildings.

1.4.2 *Plants Inspiring Design*

Plants have been evolving for approximately 460 million years. Due to constant environmental pressures, they have become extremely well adapted to various climatic conditions (Koch and Barthlott 2009). Due to the immobility of individual plants, they are together an excellent biological material for detecting climate phenomena (López et al. 2017). Living organisms use smart, optimized, and elegant solutions to survive, thanks to continuous evolutionary processes (i.e., selection and mutation). Consequently, plants have developed a tissue with barrier properties after facing a number of survival challenges (e.g., water loss, extreme temperatures, UV and solar radiations, and parasites).

One of the most important improvements in existing air exchange solutions in buildings is the introduction of natural ventilation. The gas exchange by stomatal apparatuses is evidently analogous to processes found in plants. Centralized respiratory and circulatory systems are good models of artificial air-conditioning and centralized heating systems. The latter was not mimicking the natural systems from its conception; still, the natural solutions are often used to illustrate the concept of centralized energy and matter exchange.

Figure 1.10 presents several examples representing adaptation of plants to various environmental constraints. These are often identified as straightforward inspirations for the responsive façade materials or solutions. Adaptations are additionally summarized as possible innovations and challenges that may be implemented in specific façade systems (Table 1.1). The description of environments includes a list of abiotic factors that forced specific plants to attain certain



self movement - light
(Oxalis triangularis)

selective reflection
(*Selaginella willdenowii)*

phototropism
(*Helianthus annuus*)

self-movement - moisture
(Pinus silvestris)

self-cleaning
(Nelumbo nucifera)

water storage
(Gymnocalycium baldianum)

self-movement - mechanics
(Mimosa pudica)

self-healing
(Delosperma cooperi)

communication
(Fagus sylvatica)

Fig. 1.10 Adaptations of plants and their possible implementation in façade systems

Table 1.1 Biological adaptations of plants and its possible implementation for façade systems

Climate description	Biological adaptation	Façade biomimetic
Desert—Arid (BW)		
Dry Hot Direct sun Strong wind Extreme temperatures Water loss Drought	Thick, small leaf H_2O storing Reduced transpiration Hair and spines Collecting H_2O Thick layer of wax Low H_2O loss Light reflection Long root system H_2O capturing	Reducing evaporation UV protection Shading system Reflective system Filtering system
Prairie—Arid (BS)		
Hot summers Cold winters Strong wind Uncertain rainfall Common drought	Narrow leaves plant shape H_2O storing Low transpiration Protection against animals Thick bark Fire resistance, high regeneration Seed dispersing system Reproduction	Dynamic Opening–closing system Self-healing materials External protection
Rainforest—Tropical (A)		
Hot Wet Uneven solar radiation Heavy rains	Drip tips High water runoff Wax Protection and hydrophobicity Aerial roots High H_2O, CO_2 uptake Low decay Plant morphology H_2O storing	Self-cleaning Filtering Phytoremediation Self-cleaning surfaces External protection
Tundra—Polar (E)		
Short cool summers Long/severe winters Low rainfall Permafrost Solar light variation	Colour of plant Modulated light reflection Plant movement High absorbance of solar radiation Wax and hairs Protection against freeze	Anti-freezing Energy storage Dynamic shading system Modulation of light Transmission Shading system
Temperate Forest—Temperate (C)		
Hot summers Winter bellow 0 °C No problem with H_2O availability Four seasons	Lightweight leaves High photosynthesis Reaction wood High mechanical resistance Nyctinasty, thigmonasty Different response to light and mechanical stress Thick bark High thermal isolation	Reaction to stress Shading and signalling Dynamic energy storage Insulation, shading Self-healing materials Communication

(continued)

Table 1.1 (continued)

Climate description	Biological adaptation	Façade biomimetic
Water—Everywhere ()		
Continuous wet Stable temperature No direct sun Constant H_2O availability Water current, flood	Flexible stem Floating Hydrophobic surface H_2O protection Thin cuticle High CO_2 uptake Floating seeds Reproduction	H_2O storage Stiffness change Hydrophobic surfaces Self-cleaning surfaces Flexibility

adaptations. The following part presents the mechanisms describing how the chemical composition, anatomy, morphology, and behaviour of plants respond to external environment (i.e., protection against excessive wind, drought, water, cold, heat, and light).

Even though naturally evolved biological tissues are based on a relatively simple set of chemical substances (i.e., containing only carbon, nitrogen, oxygen, and hydrogen), plants created a range of materials with outstanding functional properties. In nature, heterogeneity, anisotropy, and hygroscopicity are utilized as response tools with strategies adapted to diverse climatic constraints. Hierarchical structure of natural materials and various properties at different length scales allowed plants to better meet adaptation requirements. Consequently, simple material elements simultaneously act as sensors, actuators, and regulators. Comprehensive analysis and evaluation of plant adaptation strategies (both static strategies and dynamic mechanisms) to their environment in different climate zones are indispensable for transferring concepts from biology to architecture. Thus, unique adaptation solutions can be implemented in new materials that will be used in building envelopes erected in specific climate zones. Integration of length scales together with biological, chemical, and physical concepts for tailoring properties of materials during their preparation should lead to improved design of future smart materials. This optimization process should promote the development of active biomaterials performing as interfaces between outdoor conditions and internal comfort that are able to regulate humidity, temperature, CO_2, and light and also capture and filter pollutants, self-assemble, self-clean, graft, and self-heal. Such materials could be used as responsive building elements and contribute to an improved performance and energy efficiency of building skins.

1.5 Adaptive and Responsive Façades

Unfortunately, standard static façades require constant human attention to regulate microclimate of buildings. Often, even human effort may be insufficient. For example, opening windows to decrease temperature is pointless when the outside temperature is higher than the desired room temperature. For this reason, a new approach for façade design has been proposed—an adaptive façade. The term "adaptive façade" covers the façade systems capable to change its function, shape, and behaviour in response to the fluctuating external conditions. In buildings, adaptive façade systems (called also "responsive" and "dynamic"), may assure controllable insulation, radiant heat exchange, daylighting, solar shading, humidity control, ventilation, and energy harvesting (Loonen et al. 2015). Façade adaptivity (a self-regulation of certain façade's properties) can be manifested in several manners: by the physical change of the façade shape (so-called kinetic façades), by the active control of the energy flow (e.g., by opening and closing windows, retracting sun shades, or operating fans), or by the energy harvesting (e.g., by solar collectors or photovoltaic panels) (Perino and Serra 2015). The idea of adaptive façade is well integrated with EU idea of near-zero energy building policy, since adaptive façades have a positive impact on the quality of the indoor environment due to significant reductions in building energy use and CO_2 emissions (Loonen et al. 2015).

Mixed-mode systems have been frequently fulfilling comfort needs of occupants, but they have been rarely optimized from the perspective of energy efficiency and carbon emission reduction. This is the reason why adaptive façades systems were first theorized and then implemented into the real buildings. The first concept of an adaptive façade included a multi-layered, multifunctional barrier that would autonomously adapt to changes in the external environment, similar to the human or animal skin (Davies 1981). Throughout the years, this idea has been a constant inspiration for the architects to design new façade systems. Adaptive façade assumes a certain level of façade autonomy. Adaptation takes place automatically, without the need of user attention. This decreases building energy use and simultaneously improves internal microclimatic conditions. Both objectives can be reached while still considering occupant needs, as it is always possible to override system settings manually and thus influence internal microclimatic conditions according to personal preferences.

In general, the idea of façade adaptivity assumes that the systems created would be more energy efficient and environmentally friendly when compared to the system that is static and unable to change any of its properties. It is relatively simple to achieve good energy efficiency in a moderate climate when the outside air temperature is suitable to act as a microclimate regulating medium. In this case, the outer air can effectively cool down the room while taking the heat by the means of simple air exchange, implemented usually as displacement ventilation. Façade systems could provide the energy to the grid by generating, storing, and distributing energy. Such systems can significantly contribute to the global decarbonization goals that foresee 80% reduction of greenhouse gas emissions by the year 2050. However, façade solutions with all the functions listed above currently do not exist. The most up-to-date prototypes can handle a limited number of operations simultaneously (e.g., daylight or/and ventilation control). Fortunately, several innovative solutions are either already emerging in the market or are at the advanced conceptual stage.

1.5.1 Type of Control

In adaptive façades, there are two basic control types: extrinsic and intrinsic. Extrinsic (meaning "directed from outside") type is reflected in three phases of operation: collecting the information about the environment (detecting, sensing); processing the information (computing according to certain algorithms), and taking the physical actions (e.g., actuating, folding, rolling, expanding). These three stages are usually executed by the system based on the propagation of electronic signals (e.g., when a detector senses high levels of illuminance). First, the actuator's displacement is calculated by the integrated computer system, and later, the actuator rotates the louvers to the proper position. This process could be also executed through other means, such as the pneumatic mechanism.

The intrinsic control type relies on the inherent properties of the used components/elements and their self-behaviour/adjustment according to the external conditions. The components/elements change size, shape, volume, phase, or colour when subjected to various environmental triggers and can thus contribute to the improved façade performance by helping with the regulation of certain façade features. This type of control is self-autonomous, as illustrated by, for example, the shape changes of the bimetallic element when under the influence of temperature, which cannot be externally regulated. Bimetallic element returns to its original shape only after the initial influencing factor ceases to act (e.g., the temperature drops after sunset).

1.5.2 Practical Implementation

In practice, integrated façade solutions that would fulfil all the initially postulated features do not yet occur. Selected functionalities are being implemented individually, as pilot sub-systems of larger façade schemes. Daylight regulation was the first automated sub-system. Mechanically or pneumatically controlled blinds, sunshades, or apertures require relatively simple operation schemes, with a photosensor as the light condition detector. The control system is relatively simple and could be intrinsic (meaning autoreactive), as the shading response might be independent of any other functional systems of the building. The shading systems can, however, take various forms: from classic lamellar blinds rotating around their own axis, through rolled shutters, to complex geometrical multifaceted kinetic systems that—like paper origami toys—fold in or unfold when reacting to changes in the daylight level. An Oval Cologne Office in Cologne (arch. Sauerbruch Hutton Architekten, 2010) could be an example of a building aimed to regulate daylight levels in office interiors (Brzezicki 2018)—Fig. 1.11

Daylight regulation can also be executed by systems without any mechanical parts with the advantage of the reliability and low operating costs. Such solutions are based on electrochemical reactions in fine layers of semiconducting materials. This includes

Fig. 1.11 An oval cologne office in cologne (arch. Sauerbruch Hutton Architekten, 2010)

electrochromic coatings that recently gained a lot of attention with many commercialized solutions available under various brand names (e.g., SageGlass). The main obstacles to a wide use of these technologies are relatively high cost and elongated dimming time (7–12 min are necessary to change the material phase). Alternative systems that react immediately and are based on liquid crystals (e.g., from Merck) recently entered the market and are under pilot installations.

The adaptive regulation of other façade parameters causes more technical and practical problems. Materials with variable heat transfer coefficient (so-called regulated insulation) are recently in the prototype phase. In most cases, the insulation action is executed by regulating convection—by creating adjacent air buffers and skilfully controlling the air circulation between them (Pflug et al. 2018). It is also possible to regulate the thermal capacity of the façade so that it can accumulate energy during periods of increased heat load. The latent internal energy for the physical phase change is used. This energy affects the melting/solidification of specific materials without the increase of the insulation layer temperature. At present, certain types of paraffin can accumulate heat during the daytime in a process of melting (phase change from the solid to liquid state) to later return that heat at the cooler night-time by solidification (phase change from the liquid to solid state).

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