Chapter 3
Designing Building Skins with Biomaterials

We shape our buildings; thereafter they shape us.
Winston Churchill

Abstract This chapter presents several successful examples of biomaterial façade design. It discusses façade function from aesthetical, functional, and safety perspectives. Special focus is directed on novel concepts for adaptation and special functionalities of façades. Analysis of the structure morphologies and aesthetic impressions related to the bio-based building façades is supported with photographs collected by authors in various locations. Finally, particular adaptations and special functionalities of bio-based façades going beyond traditional building envelope concept are supported by selected case studies.

The world population is gradually increasing. In consequence, many new buildings will be erected in the near future to provide housing, services, and recreation. However, it is estimated that buildings are already responsible for 40% of the total energy consumption and 36% of the total CO_2 emissions (Herczeg et al. 2014). It is desired that the renovation and construction of buildings/infrastructure will be highly resource efficient by 2020. Recent trends in advanced material research have focused on the development of solutions optimized for specific applications that assure the expected properties and functionality over elongated service lives with minimized environmental impact and reduced risk of product failure.

Sustainability of bio-based materials is generally highly valued. There are two main groups of environmental benefits associated with the use of bio-based materials. The first group is associated with material production. Carbon dioxide is trapped in organic tissues of biomaterials and, as a result, does not contribute to the greenhouse effect and the climate warming. Processing of bio-based materials, although not always environmentally friendly (e.g., the use of chemical binders, high water use) represents, in general, the best circular economy practice. Namely, even if waste is generated (e.g., chips, sawdust), it becomes a raw material for the subsequent production cycles (e.g., particle board, OSB), as endorsed by the "waste to resources" principle. The second group of advantages is associated with the end-of-life of

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bio-based products. Biodegradability enables environmentally friendly decomposition of products and a return of chemical compounds back to the natural cycles.

3.1 Functions of Biomaterials in Buildings

In buildings, biomaterials perform various functions. Timber elements do not only constitute a load-bearing structure of buildings, but also form its skin that separates external and internal environments. Biomaterials also have an important aesthetic function that is much valued by the building users. While performing various functions, biomaterials must be safe and, wherever possible, adaptable to the needs of inhabitants.

Timber façade introduces many design challenges. Timber is renewable but also biodegradable, which leads to unique obstacles in design. Usually, façades are associated with durability and resistance when facing harsh weather conditions. However, biomaterials used in façades in some cases are less robust than non-bio-based materials. Still, if properly designed, façades constructed from biomaterials could be at least equally resistant as non-bio-based façades. Understanding all façade functions is essential for a successful application of biomaterials in building practices.

3.1.1 Façade as a Barrier and Interface Between the Outside and the Inside

From the energy conservation perspective, façades are barriers between interiors of buildings and the surrounding environment (also labelled as a filtering layer between the outside and the inside). In buildings, the internal environment (microclimate) has to be maintained within the certain limits to provide comfort for the occupants. In a temperate climate, the external environment is variable and changes substantially over the course of the year (four seasons). To conserve energy, it is crucial to minimize the energy transfer between the interior and the exterior of a façade while still maintaining a healthy and pleasant internal microclimate (Lovel 2013). Façades perform many functions in buildings. They provide a shelter for humans, adequate air exchange, light transmission, and a boundary between the public and the private (Herzog et al. 2004). Since they perform a variety of tasks, façades are considered by Boswell (2013) as technically one of the most complex features in architecture.

Functions of façades can be broadly divided into two groups. One group is associated with façade robustness and resilience against the external conditions, while the other relates to the proper maintenance of internal microclimate with minimized use of energy and resources. Building façade is expected to achieve

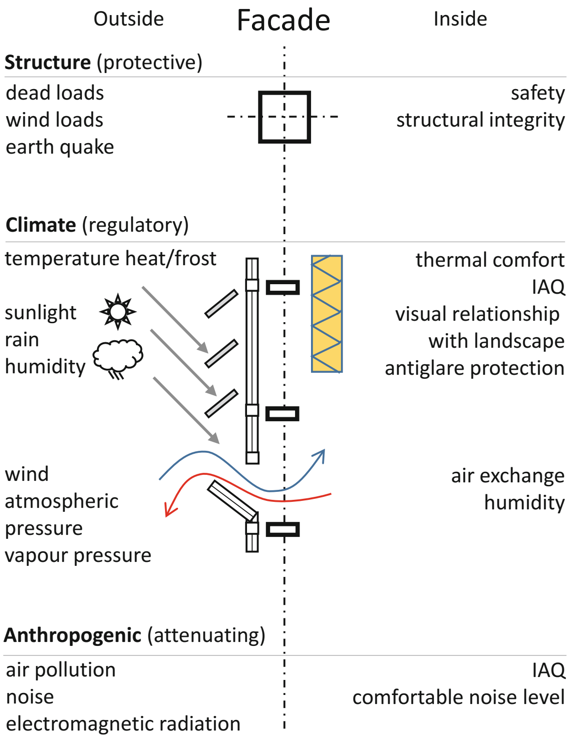

Fig. 3.1 Façade as a border between outside and inside of the building

many objectives: from a building's structural integrity (load bearing) to its proper relationship with the surrounding environment. In some occasions, façades must provide insulation (e.g., protect against heat escape, water ingress, noise), while in others they must ensure permeability (e.g., of air, daylight, view, or vapour). A brief review of factors influencing façade functions is summarized in Fig. 3.1 and presented below.

External Conditions

Façade designers cannot influence external conditions such as climate, pollution, and electromagnetic radiation. Such conditions vary widely depending on the location and orientation of a building. They are, nonetheless, important to consider. Some of them are constant, including orientation, ground-carrying capacity, and water level, while others are variable (diurnally or seasonally), for example temperature, solar radiation, atmospheric pressure, wind speed, and precipitation. It is challenging to design protective measures that are able to withstand such external conditions throughout the building lifetime. Still, impacts of climatic factors should be considered during the design phase of a building. The main factors to take into account include sun radiation and temperature change, rain and air humidity fluctuations, and influence of the wind.

Sun radiation includes infrared, visible, and ultraviolet light. Several parts of the solar spectrum, particularly UV, are contributing to the photodegradation of chemical constituents of materials, which changes the colour of their surface. Direct exposure of biomaterials to light increases their temperature. This is followed by the change in moisture levels that subsequently leads to dimensional distortions. On the other hand, if properly collected, sun radiation may provide ample amounts of energy to buildings. Since direct penetration of light may be irritating for building occupants and can rise the internal temperature, various sun shading systems are implemented (e.g., shutters, blinds, brise-soleil, lamellas).

Typically, normal variations in temperature do not significantly affect bio-based materials as they are accustomed to changing environmental conditions. However, if materials originate from climatic conditions that differ from the building location climate (e.g., when bamboo is used in a temperate climate), materials should be carefully studied to discover all potential incompatibilities (Kim et al. 2016). Water-absorbing elements (if present) can be prone to destruction from frost, as the frozen water—ice—expands. However, it is important to emphasize that the internal flexibility and cellular structure of bio-based materials make them more resistant for repetitive frost and thaw cycles compared to porous rigid materials, such as concrete or stone.

Rain penetration protection includes all measures taken to limit the water ingress into façades. When the ingress is permitted, water should be periodically allowed to evaporate completely. In case of bio-based cladding materials, this includes proper joint detailing that should be either open drained (as in ventilated façades) or overlapped, which is used to direct the water flow towards the façade base (joint transverse to the water flow) (Knaack et al. 2007). It is especially important to consider water ingress in the context of biomaterials, since many of them absorb and store large quantities of water. For that reason, an effective ventilation and air circulation seem to be some of the most important issues in this field. When bio-based materials are exposed to the intense precipitation, it is common to employ an external weatherproofing layer. The design of this layer enables easy renovation after a period of exposure without requiring changes of the underlying façade structure (Herzog et al. 2004). Closely related to precipitation levels are fluctuations in air humidity that can lead to large-dimensional distortions or even the destruction of façades. Bio-based materials absorb large quantities of water from the vapour in the air. Therefore, components in which an alternating moisture content is expected must enable predictable dimensional changes (Herzog et al. 2012). Occupied rooms should be protected from uncontrolled air exchange and draughts, especially if these are resulting from the high wind pressure on the façade. Proper design and subsequent craftsmanship of façades can protect buildings from strong winds. Ordinarily, joints in the external, exposed layer should be designed as overlapped or grooved to assure the proper seal. Airtightness is even more important in passive buildings, where the air exchange is provided by mechanical ventilation with the heat recuperation. In such cases, a leak in the building envelope may influence the building energy performance. The most common solution to this problem, especially in timber-framed buildings, is to wrap the building in a vapour permeable membrane (e.g., Tyvek by DuPont). This barrier must be positioned on the outside of the thermal insulation layers. A proper sealing of the membrane, junction around the corners, and the openings (windows and doors) become issues of major importance.

Internal Comfort Conditions (Including Indoor Air Quality)

Performance of bio-based materials can substantially contribute to the microclimate comfort by managing energy and mass (vapour) transfer. It is important to note, however, that user comfort also depends on the occupant preferences and characteristics, such as clothing, personality, or cultural background. For example, British citizens are comfortable with lower temperatures than citizens of other European countries (Stevenson and Baborska-Narozny 2018). Relevant factors, influencing occupant comfort, are listed below and briefly discussed in the context of bio-based material use.

Temperature

Internal air temperature is a basic factor influencing occupant comfort. It is important to be aware that it could be measured in different ways (i.e., taking the humidity in the account or not) which results in distinct outputs (e.g., dry-bulb temperature, wet-bulb temperature, mean radiant temperature). The most important façade feature related to user thermal comfort is the provision of proper insulation to prevent overheating or/and cooling. Thermal performance of bio-based materials is related to their internal cellular and fibrous structure. Timber acts as a thermal insulator while simultaneously providing a suitable internal surface temperature. Timber also protects from thermal bridges, as it is one of the very few available materials capable of both load bearing and insulation. Wood volumetric change due to heat is minimal; thus, timber is considered to be a good structural material in many circumstances, for example, in solid timber structures, glued arrangements (e.g., glulam or cross-laminated timber (CLT)), or framed solutions (Herzog et al. 2012). Timber, however, possesses a limited potential to act as a thermal building mass in comparison with brick or concrete, since it has a relatively low density and a high heat capacity. Other processed bio-based composites (e.g., wood-based foams or fibrous insulation materials) are more promising for the regulation of the building internal climate, since they are better insulators. Nowadays, insulation materials are manufactured from numerous types of bio-based resources, where some innovative solutions based on plant residuals offer up to 20% higher insulation levels than traditional materials (Sid 2018). A wide variety of innovative resources includes fungal mycelium that is preferably grown (cultivated) than produced (converted) (Fig. 3.2). The new types of bricks are innovative combination of stalk waste and living mushrooms. They are lightweight, low cost, and sustainable. Such material can be decomposed in 60 days and is an interesting alternative to wasteful linear economy. Similar experiments are conducted by several independent research groups aiming to improve growing process and

Fig. 3.2 Bricks made of fungal mycelium. Image courtesy of The Living

thermal performance of the mycelium materials (Attias et al. 2017; Xing et al. 2018). It is estimated that such locally cultivated and processed materials could contribute to the reduction of up to 50% of the building's total embodied energy across the whole life cycle (Sid 2018).

Relative Humidity (RH)

Relative humidity (RH), as well as vapour pressure and migration, is an important component of the indoor air quality. It is important to keep the level of relative humidity within certain limits (usually approximately 30–45% at 20 °C in the office environment) to provide healthy and comfortable living and working conditions. Recommended humidity levels may vary depending on the air temperature. Moisture in the air enables human gaseous exchange system to operate properly, supports the functioning of mucous membranes (either in the eyes' conjunctiva or in the throat), and enhances perception of comfort and well-being. In addition, appropriate level of relative humidity restrains the survival of various viruses (Noti et al. 2013).

Water vapour migrates from the environment with higher vapour pressure to the environment with lower vapour pressure. By being partly moisture permeable, porous façades (also called "breathable") are able to balance this internal/external difference. In general, bio-based materials possess good properties of vapour diffusion that assure microclimatic comfort, and also protect against vapour accumulation in rooms, thus blocking subsequent potentially dangerous condensation. Properties of vapour diffusion through the bio-based materials are inherent properties of the material structure itself. Bio-based materials are generally hygroscopic; that is, they retain water molecules until an equilibrium state of water content related to the RH of the ambient air is reached (ASHRAE 2004). This positively influences internal air quality, as it creates a buffer mechanism that balances rapid changes in relative humidity. Air can absorb water vapour until it reaches its saturation point, which depends on the temperature. The relative humidity has to be always considered in conjunction with room temperature.

Draughtiness

ASHRAE Standard 55-2004 defines draught as an "undesirable local cooling of the body due to air movement" (ASHRAE 2004). Draughts can result from improper installation of an air insulation layer, from mechanical ventilation forcing air into the occupied space at a too high speed, or from natural ventilation resulting from the pressure difference between the wind- and leeward sides of façades. The use of bio-based materials does not substantially affect occupant comfort related to draughts, unless the external bio-based layer installation is faulty or leaks occur.

Toxins and Odours

Many symptoms of the sick building syndrome, such as headache, nausea, drowsiness, dizziness, and nasal congestion may result from the use of materials emitting hazardous substances. In this context, bio-based materials might pose two groups of risks. The first is associated with chemicals used to protect (or aesthetically improve) solid wood products (e.g., protection from dirt or water ingress), including impregnates, coatings, paints, and stains. The second is associated with the use of adhesives in engineered wood products, such as CLT, particle boards, OSB, or plywood. The most frequently used adhesive in wood industry is the urea formaldehyde (UF) resin. Some formaldehyde molecules are not cross-linked with the glue bond, may be released into the room in the form of vapour, and can thus be absorbed by occupants through inhalation. A formaldehyde concentration level exceeding 0.1 ppm may cause coughing, wheezing, vomiting, and skin irritation (Raja and Sultana 2012). More importantly, however, formaldehyde inhalation can cause cancer, according to the International Chemical Safety Card ICSC: 0275 (ICSC 2012). Other commonly used adhesives include melamine formaldehyde (MF), phenol formaldehyde (PF), and methylene diphenyl diisocyanate (MDI). The trend for using bio-based binders led to incorporating cellulose, proteins, lignin, tannins, and fatty oils into various innovative adhesives. The biggest challenges that bio-based adhesives must overcome to compete with synthetic adhesives are related not only to their performance but also to their economic and production requirements (Frihart 2016). Nevertheless, the recent review published by Ikei et al. (2017) shows several positive effects of olfactory stimulation of humans by wood-derived substances.

Amount and Quality of Light (Lighting Environment) and Redirection of Daylight.

Suitable levels of room daylight facilitate occupant comfort. Natural illumination levels depend on numerous factors including the position of the sun, the orientation of the building, the size of the openings, the depth of the reveal, and the colour of internal surfaces. Daylight distribution and redirection is an issue concerning all rooms but especially those that are illuminated on a single side (Herzog et al. 2004). The level of daylight in the room has to be uniform in order to provide comfortable conditions. At the same time, illumination levels that are too high result in glare and visual discomfort. Uncontrolled direct solar illumination also affects the occupant's thermal comfort, since the infrared component of the daylight increases the interior thermal load (Herzog et al. 2004). Different approaches are thus required to redirect, diffuse, or limit penetration of daylight. Prolonged exposure to long-wave components of daylight may also affect surfaces of bio-based materials or interact with applied coating causing discoloration.

Different methods are available to redirect the light at the façade with some of these using bio-based materials. Standard aluminium slats in Venetian blinds could be replaced with wooden ones, having different reflection, absorption, and transmission characteristics. The fibrous structure of many bio-based materials could be used for diffusing the light if the used layer is sufficiently thin for the transmission. In Japan, there is an old tradition of making translucent paper using mulberry bark. The paper is glued to the lattice wooden frame to produce wooden sliding doors called shoji. The doors are commonly used to separate the interior from the exterior and to diffuse the light. Fibrous materials are also used in large-scale glazing, for example, in the factory Wilkhahn designed by Thomas Herzog (Dawson 2016).

Comfortable Sound Level (Acoustic Insulation)

To ensure suitable levels of sound, dwellings or offices must possess proper acoustic qualities which are related to sound transmission, absorption, and reflection. Sound transmission can occur via air (airborne sound transmission) or through a structure (structure-borne sound transmission). Different bio-based materials provide distinct sound propagation/insulation properties that vary with the environmental conditions. Acoustic properties of wood depend on its moisture content and grain direction. Density of timber also highly affects its acoustic properties due to the related differences in the porous/cellular internal structure. The most effective sound insulation in timber structures can be achieved by implementing the multi-skin concept and optimally arrange different wall layers (Herzog et al. 2012).

3.2 Aesthetics

The perception of aesthetical quality and related awareness of "beauty" changed over ages and will continue to change in future. Since it is challenging to study aesthetically pleasant qualities, it is difficult to provide definite guidelines (Eekhout 2008). Nevertheless, some universal attributes that are perceived as attractive for the built environment exist; therefore, it is possible to indicate at least a few important aesthetic guidelines for the application of building materials.

3.2.1 Aesthetical Measures

In general, it is difficult to explain what makes a quality aesthetically pleasing. It does not help that the aesthetical appeal of different qualities varies among individuals and often includes an emotional component. Aesthetics in qualities of façades are associated with prestige and symbolism and are meant to convey power and importance. A set of basic guidelines developed in classical architecture provides the basis for aesthetic assessment of buildings:

Symmetry

Symmetry is a sense of balance, defined as a state of equilibrium of the visual weights in a composition (Leopold 2006). Symmetry (bilateral/linear and radial) and asymmetry are both equally important design tools. Symmetry is usually linked with order, formality, and prestige and is historically associated with public or juridical buildings (Fig. 3.3). The opposite of symmetry is asymmetry, characterized by imbalance and disorder. While symmetry in some cases risks becomes too predictable, asymmetry can include complexity that conveys emotion and might be highly interesting.

Rhythm

Rhythm in design is defined as a regular and harmonious repetition of specific patterns (Leopold 2006). Rhythm could be repetitive or progressive (see Fig. 3.4). In the first case, rhythm is associated with the recurrence of forms (elements, colours), while in the latter rhythm is linked with the change of one characteristic of a motif (e.g., scale, colour).

Hierarchy

An example of rhythmical iteration of balconies on the timber façade hierarchy in design is observed when one element is emphasized more than others (Fig. 3.5). This can be manipulated by changing size, shape, and placement/orientation of building elements. Humans associate size with status; thus, the bigger element is

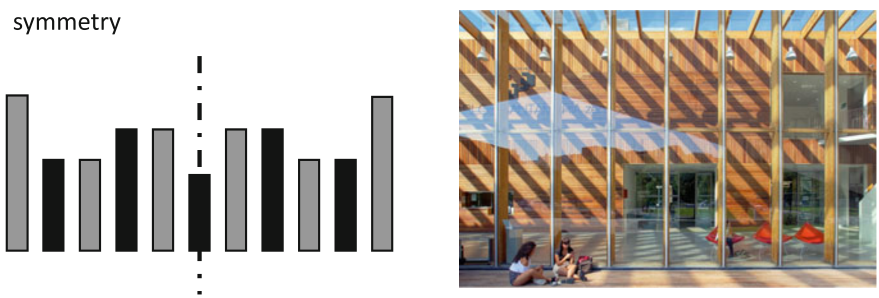

Fig. 3.3 Symmetry in architecture and its implementation

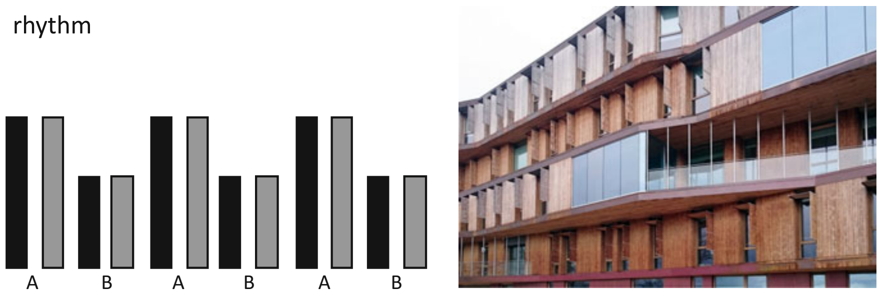

Fig. 3.4 Rhythm in architecture and its implementation. Image courtesy of Iztok Šušteršič—InnoRenew CoE

Fig. 3.5 Hierarchy in architecture and its implementation

perceived as more significant than the smaller one. In a group of identical elements, the one that is different in shape or form from the others will stand out. Similarly, in a group of identical items, the one that is placed in the centre will be perceived as more important even if it is equal to others in size. Hierarchy could also be discussed in the context of accentuation: when the relation of different design elements is described as balanced (almost of equal status), dominant (a case of hierarchical arrangement), or subordinated (when an element is visually less emphasized than others).

Proportion

Proportions are the relations between different dimensional elements of a form: lengths, areas, or volumes (Fig. 3.6). According to Euclid, a ratio refers to the quantitative comparison of two similar things, while proportion refers to the equality of ratios (Leopold 2006). Thus, a proportioning system establishes a consistent set of visual relationships between the parts of a building, as well as between the building elements and entire structure.

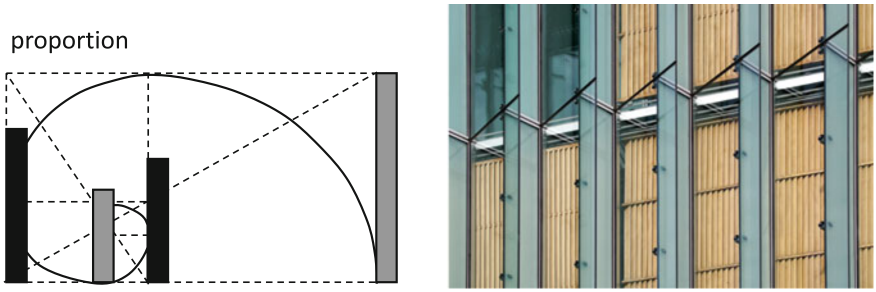

Fig. 3.6 Proportions in architecture and its implementation

Harmony

Harmony includes producing a visually pleasing relation between elements. Those elements usually share a common feature, trait, form, or colour (Fig. 3.7). Harmony in architecture is strongly associated with the compatibility with building surroundings (Salingaros 2017). While harmony is usually associated with the elements of higher order, the contrast is the juxtaposition of opposing elements (different materials, colours, and textures).

3.2.2 Surface Properties

Just like façades created from other building materials, bio-based façades are linked to the general aesthetical principles discussed above. Therefore, it is equally possible to strive towards symmetry or harmony by using timber, stone, or brick. However, there are important differences in surface quality between materials. Due to the specificity of bio-based materials, their surfaces are not uniform but contain diverse patterns. On a larger scale, these are related to the cladding direction (horizontal/vertical and plane/grilled), while on a smaller scale they are associated

Fig. 3.7 Harmony in architecture and its implementation—the Rotho Blaas SRL company, Cortaccia (BZ), Italy. Photograph courtesy of Rotho Blaas SRL

Fig. 3.8 Diagonal cladding on the expo building of Slovenia providing dynamic look. Image courtesy of SoNo arhitekti

with the wood grain direction (in case of timber façades). The pattern direction plays an important role in the visual perception of façades and the entire building. Vertical divisions will increase the perceived building height, while horizontal divisions will “visually” lower it and give the impression of denseness. Diagonal patterns typically imply a dynamic movement, transformation, and freedom (Fig. 3.8). If appropriately used they bring life, add volume, and make space feel larger than it is. However, if applied incorrectly, diagonal lines can increase a sense of confusion and imbalance. The surface heterogeneity and its potential creative use distinguish biofaçades from façades built from other materials.

Colour

In general, bio-based materials are characterized by warm, yellow, and brown hues. Wood-based products include a wide palette of colours commonly found in the nature, including pale yellow, orange, and brown. Cork, depending on the type, can be light yellow, brown, or even light blue. Deep natural-looking blue colouring usually results from the blue stain (sap stain) fungal infection and is considered to be a wood defect (Garau and Bruno 1993).

From an aesthetic perspective, uneven discoloration is a factor most damaging to the façade appearance. Discoloration is a process of gradual loss of the original colour. In bio-based products, it may appear as yellowing, browning, or greying. This process is also called bleaching when the original colours fade to grey. Non-protected wood exposed to UV radiation and moisture will change its colour (hue) depending on the cumulative dose of the weathering. The dose may vary along the façade surface resulting in uneven discoloration. Diverse wood species react to the weathering in different ways. Not only wood, but other bio-based materials also tend to change their colour under the influence of weather conditions. Expanded agglomerated cork, for example, weathers fast and uneven. The surface of the agglomerate becomes lighter, in contrast to the darker brown stains caused by

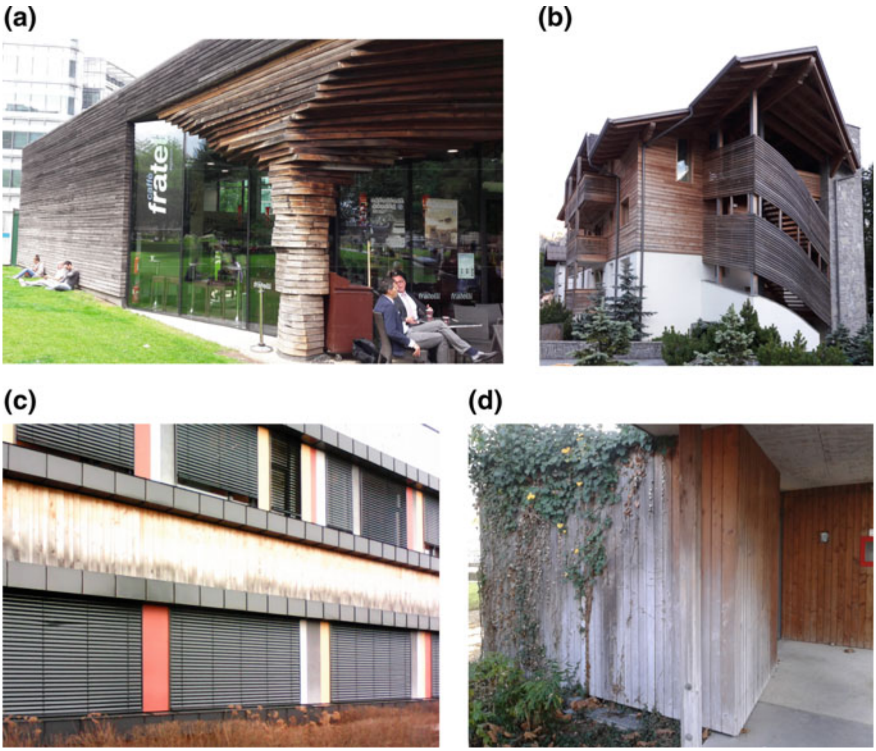

Fig. 3.9 Discolorations of bio-based building façades, with appreciated (**a**, **b**) and undesired (**c**, **d**) appearance

the manufacturing process (Roseta and Santos 2015). The discoloration (greying) of wood is often desired, especially when it is intended to emphasize the age of a structure (Brookes and Meijs 2008). Examples of building façade discoloration that might be perceived as positive and unpleasant are presented in Figs. 3.9a, b and 3.9c, d, respectively.

From a designer's perspective, the use of bio-based materials is always an asset, as bio-based materials are usually perceived as natural and user-friendly. Human mind pleasantly evaluates colours that are typical in biomaterials. Yellow, orange, and brown (especially the dark tones) are associated with the perception of physical comfort, warmth, security, and seriousness. The use of colours in façades can be understood through the colour use theory which is popular in diverse fields, such as visual composition in art (Garau and Bruno 1993). The simplest analogy concerning the colour use is the comparison of the art composition to music. As the colours of bio-based materials are rarely primary (yellow, blue, or red), they usually present a mix of so-called tertiary colours that are composed of the primary and secondary colours (green, violet, and orange). Colour research experts witness two types of reaction caused by colour: tension (leading to connection or separation) and attraction (leading to desirability or antipathy). Tensions originate from the lack of balance, due to maximal contrast or strong demand for chromatic completion, while attractions result from the presence or the absence of the primary colours. These guidelines should be used to optimally design façades and subsequently to select their colour (Garau and Bruno 1993).

Texture/Grain

From the aesthetic perspective, tangible/sensory qualities of biomaterials are generally rated high by users. Timber is appreciated as being warm to the touch thanks to its relatively high specific heat and the cellular structure. Human sense of touch is sensitive enough to detect the texture of the thin veneer itself. It can be easily identified in blind trials when compared to other materials. These qualities are transferred to many industrially processed wood-based products like chipboards (e.g., OSB with palpable texture) and particle boards (palpable only when the raw board is not covered with veneer or laminate). Other bio-based façade products also prove to be very attractive to users, with the cork as an example that is currently developed/researched to be used as an external cladding product. Textural properties of biomaterials are usually utilized in interiors, with multiple options possible regarding wood species and finishing options.

Textural properties of external timber cladding are perceived only in direct contact with the façade. However, it must be pointed out that timber elements are used in cladding at different heights; thus, in some cases, the direct access to them is limited. Exposure of biomaterials to external conditions facilitates natural ageing processes. In consequence, in many bio-based materials, the transformation becomes perceptible not only on a visual level (e.g., as discoloration) but also in others. Initially, flat-planed timber laths warp and split exposing texture of wood. Particularly, spring/winter grains of softwood exposed to weather for a prolonged period deteriorate at a varying speed/rate, thus making the wood texture more apparent. The same process occurs in other biomaterials, such as bamboo. The process of corrosion in biomaterials can be assessed from different perspectives. From the viewpoint of material durability, the surface directly exposed to the weathering is usually corroded the most.

Natural Roughness and Decorative Sculpture

Timber façade cladding can be produced as smooth (planed) but could also be deliberately sculpted. Wood carving is one of the world's oldest decorative techniques present almost in all cultures and regions (Figs. 3.10 and 3.11). This is due to the fact that wood is a relatively soft material that can be easily shaped with metal tools. Softwoods are especially simple to carve but more prone to the weather corrosion, as the water ingress is facilitated by the cross-cut grain. In general, wooden carved elements provide exceptionally tangible qualities, although this varies depending on the relief applied.

Fig. 3.10 Oldest wooden building in Mâcon (France), dated from the late fifteenth to early sixteenth century—La Maison du Bois, Mâcon, France. Image courtesy of Wim Willems—FirmoLin

Fig. 3.11 Sculptured façades of ancient Japanese buildings

3.2.3 Change in Appearance During the Service Life

Environmental factors (e.g., exposure to UV, rain and water condensation, temperature fluctuations, insect ingress) change most aspects of bio-based materials; however, material surfaces tend to be affected the most. Massive elements with smaller external surfaces are robust, while the slender ones are prone to faster degradation due to their relatively large surface area in relation to element's volume and mass. In general, the larger the external surface, the faster the degradation processes will occur. However, in bio-based façade claddings, the progress of ageing does not depend only on the S/V (surface/volume) factor but is also affected by a number of single-element surfaces that are exposed to the environmental conditions. A massive element with a single side exposed will weather/corrode at a lower rate than the slender element exposed to corrosion at all sides (Fig. 3.12). A detailed description of degradation processes during the service life of a building is provided in Chap. 5.

According to the number of sides of bio-based elements that are exposed to the external environmental conditions, façades can be divided into four typologies: not exposure, single-side exposure, double-side exposure, and the whole surface exposure.

Fully covered (unexposed) biomaterials are frequently used in cases where their exposure to external conditions can be severely destructive to the structure of the building's skin. The emerging façade typology in which timber constituting a façade skeleton or cladding is protected externally by a layer of flat glass is gaining acceptance. This solution combines two materials: renewable biodegradable timber and durable recyclable glass with isotropic physical and chemical parameters. This solution was originally introduced to visually enrich the spatial depth of the façade and reduce the heat loss but gradually evolved as a separate engineering solution and has been recently found as beneficial in the context of extending the service life

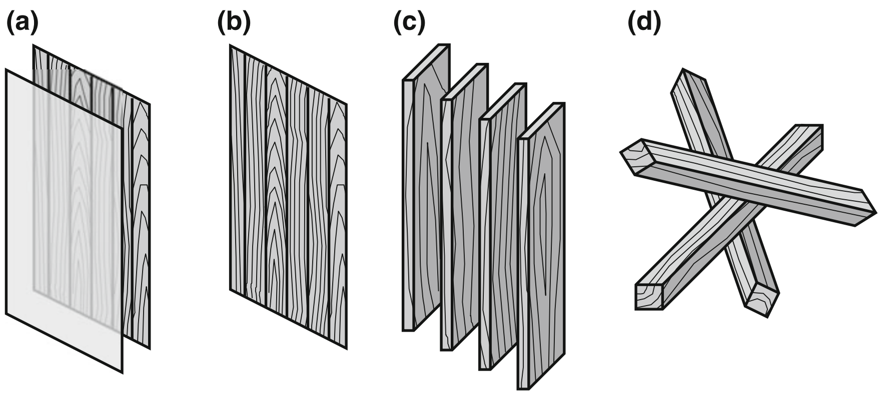

Fig. 3.12 Typology of bio-based building façades in regard to exposure: **a** not exposed, **b** single side, **c** double side, and **d** all surfaces exposed

of bio-based façades. Bio-based façades fully enveloped and sealed by glass are found mostly in structural applications. This typology was introduced in architecture by Japanese architect Shigeru Ban and used for the first time in GC Building in Osaka (arch. Shigeru Ban Architects, 2000), where the laminated timber structure was covered with a glazed façade (Fig. 3.13).

Fig. 3.13 Bio-based façade elements protected by external layer of glass, as implemented in CG Osaka Building (arch. Shigeru Ban Architects, 2000)

In opposition to fully sealed glass façades, a ventilated solution was independently developed in other buildings. Ventilated solutions are expected to perform better in terms of potentially destructive moisture capture, as the circulating air promotes drying of the surfaces. Timber in such façades is not fully protected from the environmental influence (it is susceptible to changes in temperature and humidity) but the rainscreen formed by the glass substantially affects the durability of the façade's cladding, as wetting is prevented. This façade typology is currently developing rapidly, as the issues of sustainable material use are gaining attention of investors and clients. An example of the double-skin façade is the FH 1 building at the campus of Frankfurt University of Applied Sciences (arch. Heribert Gies Architekten, MainzVoigt & Herzig Architekten & Ingenieure, 2007), where the external façade layer protects the timber cladding, while providing the space for the air exchange (Fig. 3.14). The external glass layer was also used in Market Hall in Ghent (arch. Marie-José Van Hee + Robbrecht & Daem, 2012), where the glass cladding protects the timber tiles used on the inclined roof surfaces and on vertical façade (Fig. 3.15).

An alternative approach for the double-skin façade is external layer of decorative wooden elements providing additional shadowing of building interior through the glass wall (Fig. 3.16).

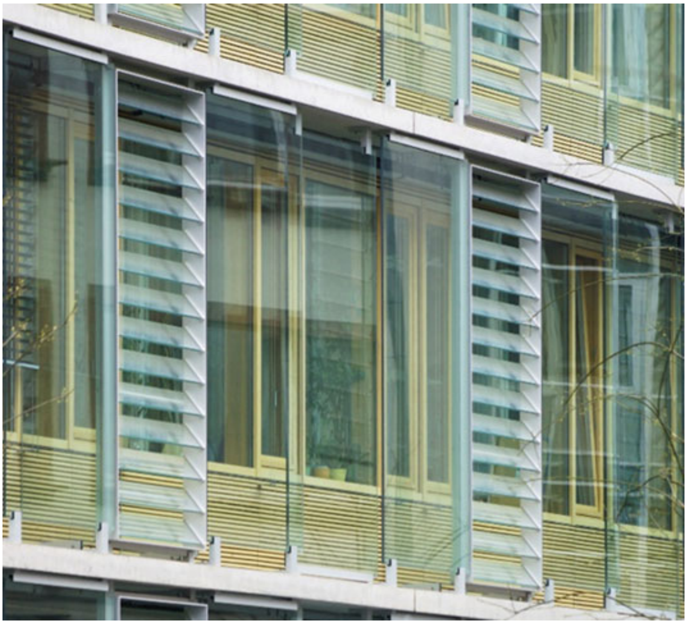

Fig. 3.14 Double-skin façade with bio-based aesthetical components protected by glass and ventilation layers—FH 1 building at the campus of Frankfurt University of Applied Sciences (arch. Heribert Gies Architekten, MainzVoigt & Herzig Architekten & Ingenieure, 2007)

Fig. 3.15 Bio-based façade elements protected by external layer of glass, as implemented in Market Hall in Ghent (arch. Marie-José Van Hee + Robbrecht & Daem, 2012)

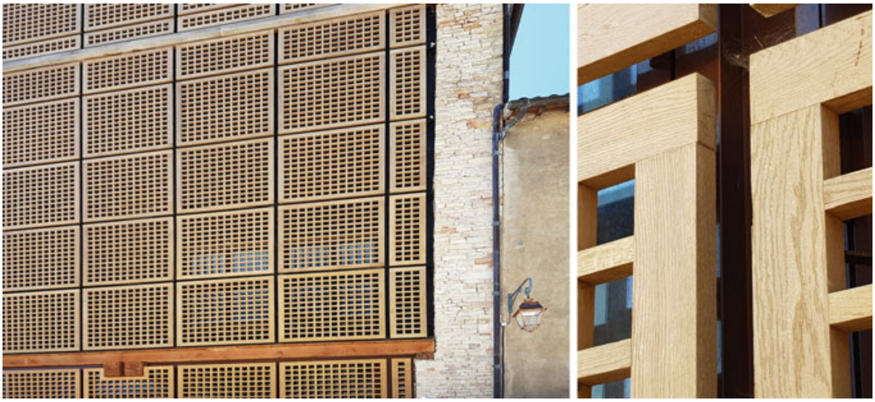

Fig. 3.16 Inversed double-skin façade in Cluny (France). Image courtesy of Wim Willems—FirmoLin

Single-side exposure of bio-based façade elements is widespread, as this type of exposure is typical for cladding. In such an arrangement, timber (or other materials) faces external environment with only one surface. These form large surfaces consisting of bio-based materials, usually containing a combination of smaller elements (boards or planks). Cladding exposed on a single side can be used in various orientations. The most popular is the horizontal orientation, as it enables an easy partial replacement of cladding elements, especially those that are located closer to the ground. The vertical orientation changes the proportion of façade, so the buildings seem to be thicker or longer than they really are. For both types, some extra space for air circulation has to be provided behind the cladding. In Hollainhof

Fig. 3.17 Single-side exposed bio-based façade as implemented in Hollainhof housing development in Ghent (arch. Neutelings Riedijk, 1998)

in Ghent (arch. Neutelings Riedijk, 1998), the horizontal cladding visually emphasizes the elongated building proportions (Fig. 3.17). On the contrary, in Wälderhaus in Hamburg (arch. Studio Andreas Heller GmbH Architects & Designers, 2012), the horizontal cladding orientation influences building perception and makes it visibly less dynamic, despite the overall faceted style.

Vertical cladding orientation is less frequent; however, it possesses an interesting potential in building façades. Such cladding orientations usually make buildings appear higher than they really are. This cladding type requires the horizontal substructure for the assembly process. Usually, this is provided by a system of laths. To ensure proper air circulation, laths must be positioned in a manner to allow air circulating upwards. The Westside Shopping and Leisure Centre in Bern-Brunnen (arch. Daniel Libeskind, 2008) is an example illustrating an optimal approach for implementing vertical bio-based cladding (Fig. 3.18).

Cladding positioned in arbitrary directions is rather rare as it is difficult to design them and to assemble. However, Yokohama Ferry Terminal (arch. Foreign Office Architects, 2003) represents an interesting example of a bio-based cladding used in the form of an undulating polygonized surface that smoothly transforms from the deck to the wall/façade (Fig. 3.19). The use of timber (teak) cladding is often found in ship deck flooring. Although such decks are visually impressive, their construction is technically challenging. Timber serves as a cover only, and the water is channelled in the membrane-covered layer below.

In double-side exposure, two main element surfaces are exposed to the external environment. This includes narrow and slender elements that are arranged perpendicularly to the façade's plane: vertical sun blinds, timber fins, and structural elements. Elements exposed on two sides visually enrich façades and create an impression of spaciousness and depth. In vertical element orientations, two main surfaces are exposed to different degrees which results in uneven ageing processes.

Fig. 3.18 Vertical orientation of cladding in Westside Shopping and Leisure Centre in Bern-Brunnen (arch. Daniel Libeskind, 2008)

Fig. 3.19 Dynamic transformation of the wall façade to the deck—Yokohama Ferry Terminal (arch. Foreign Office Architects, 2003)

Double-side exposure characterizes many finished buildings, especially those with façades containing timber fins or vertical sunshades. An interesting example is Asakusa Culture Tourist Information Center (arch. Kengo Kuma & Associates, 2013) that features vertical timber fins and internal louvers. This rhythmical and

Fig. 3.20 Double-side exposure of bio-based building façade—**a** Asakusa Culture Tourist Information Center (arch. Kengo Kuma & Associates, 2013), **b** coffee shop in Delft

unique appearance leads to a unique building perception depending on the observer's standpoint. If viewed frontally, the façade seems to be made of glass, and if viewed diagonally, the building seems to be made of timber (Fig. 3.20a). Another example is a Sevenhills coffee shop in Delft. The glass façade is surrounded by vertical wooden elements creating external layer on entire façade (including roof) (Fig. 3.20b).

Whole surface exposure refers to elements that are fully exposed to environmental factors. This includes structural elements that are completely uncovered and left to the influence of the outside environment. Several such cases can be found in contemporary cities, also in the form of artistic installations. The example is the Pavilion of Reflections (arch. Studio Tom Emerson, 2016) that was temporarily erected on the Zurich Lake (Fig. 3.21). The large lattice structure is formed to house

Fig. 3.21 Pavilion of Reflections (arch. Studio Tom Emerson, 2016)

Fig. 3.22 Façade of Sunny Hills confectionery shop at Minami-Aoyama in Tokyo (arch. Kengo Kuma & Associates, 2013)

various cultural activities, including the open cinema. Roofs on this structure are supported by the spatial grid made of timber. The elements are fully exposed to the environmental influence. A different approach was adopted in Sunny Hills confectionery shop at Minami-Aoyama in Tokyo (arch. Kengo Kuma & Associates, 2013). A highly irregular grid of timber elements is shaped as a frayed cloud covering the building. Timber laths are positioned diagonally and interlock with each other at unusual angles. The structure gives the impression of being arbitrary and chaotic Fig. 3.22.

3.3 Safety

Façades contribute not only to building aesthetics but also to its technical performance, including its protection from the harsh environmental conditions. There are several safety-related issues associated with risks involved in design, construction, maintenance, repair, and overall performance of façades during their service life. The analysis of façade risks and failures is complex, since there are many materials involved, each with unique performance properties. Risk factors can be related to design, construction quality, or maintenance quality.

Aggressive environments can deteriorate and decrease the integrity and performance of façades. Therefore, façade components and the entire wall system should be primarily focused on protection from the weather. Humidity and water infiltration are the main causes of aesthetic deterioration in façades, since they lead to cracks and corrosion of the joints. The façade integrity can be improved by reducing the number of required joints by maximizing the grid size

Table 3.1 Safety aspects and mitigation action related to façade safety

Safety aspect	Mitigation action
Fire resistance	Using fire-resistant materials or materials treated with fire retardants Proper design that avoids fire spread
VOC emission (particularly regarding odour)	Using materials with particular VOC emissions
Falling façade elements (e.g., during hurricanes)	Proper mounting of façade elements, regular inspection, and maintenance
Resin leakage	Using modified wood or materials treated with coating system preventing resin leakage
Danger of human intrusion	Proper design, avoiding the use of horizontal elements
Dazzle (sunlight reflection)	Using matt elements, reorientation of elements to avoid reflection, external shading, planning of the nearby trees
Leaching of chemicals	Using materials resistant to percolating
Explosion resistance (shingles risks)	Using resistant materials, proper building façade design

(Moghtadernejad and Mirza 2014). Due to significant volume changes related to the shrinkage and swelling, façades from bio-based materials need to be designed with enough extra space allowing for dimensional changes. In addition, it should be taken into consideration that different environmental conditions related to specific building location (e.g., climatic, urban, rural zones) influence façade material deterioration uniquely.

High construction quality, including correct installation, high standards of workmanship, and quality control at the construction site, is necessary for assuring high building performance in future. Using modular structures and prefabrications (both are possible when using bio-based building materials) usually leads to fewer construction errors. During the building erection phase, it is important to consider precise and clear specifications allowing quality control of the construction progress on site. Systematic cleaning and inspections should be performed regularly to assure the desired aesthetic qualities and functional performance. Material selection and construction planning should be carefully carried out at the design phase to minimize future maintenance efforts. Moreover, it should be considered that a difficult access to façades results in costlier and riskier maintenance (Moghtadernejad and Mirza 2014). Other risks that are related to façade safety are summarized in Table 3.1. Some of the safety aspects listed are specifically concerning bio-based façades.

3.3.1 Fire Safety

Fire safety is the most important safety aspect related to the timber use in buildings. Causes of fires are almost never related to the material choice; thus, timber buildings do not ignite more often than buildings made of another material (Herzog et al. 2012). However, when the fire develops, timber behaves differently than other non-combustible materials. Since it can be considered a fuel, it is clear that its rapid oxidation during fire must always be taken into account. This results in large emissions of heat and smoke, both being potentially lethal to humans. Research shows the exposure to dangerous smoke fumes presents a greater threat to the inhabitants than a direct exposure to heat. In 80% of cases, the poisoning by toxic combustion products is the main cause for fire-related fatalities (Aseeva et al. 2014). Clearly, the smouldering of timber is a key factor, as during the process of combustion some of the most dangerous gases are produced (e.g., carbon monoxide).

When timber is used in buildings, it is essential to ensure adequate levels of fire protection. This can be done by preventing the ignition (e.g., by cladding timber in other non-combustible materials or using flame-retardant coatings) or by slowing down the combustion process (e.g., by using massive timber elements). Safety cladding is usually accomplished by using multi-layered gypsum fire-resistant plasterboard (approximately 1.2–1.5 cm thick) that covers the timber element. This method, although effective, has evident disadvantages. First, it requires work precision and is thus labour expensive. Second, it includes covering the timber, which may decrease the aesthetical appeal of buildings. Timber can be coated with fire-retardant chemicals that affect the smoke generation and decrease optical density of smoke during combustion. The chemicals also impede the timber ignition and increase the combustion temperature. Thus, coated timber can withstand in the fire longer since it needs higher temperatures to ignite. Timber coupled with fire retardants is classified as a moderately hazardous material at low heat flow intensity (Aseeva et al. 2014).

In buildings, massive large-sized glulam structural members (columns, beams, arcs, frames, trusses) are frequently used to bear high dead loads. Wood fulfils its structural function even at high temperatures in contrast to aluminium and steel, which lose their strength and rigidity at relatively low temperatures. Depending on the density, wood burns at the rate of approximately 40 mm per hour (Brookes and Meijs 2008). A charred layer appears on the wood surface and acts as a layer of insulation that prevents a temperature rise in the wood underneath, extending the load-bearing capability of timber members (Fig. 3.23). In massive timber structures, it is commonplace to calculate the necessary load-bearing section and then increase the cross section taking into account the intended time of fire resistance (e.g., 0,7 mm of section per minute of fire for softwood glulam) Recently, massive glulam walls and slab elements have become popular as sustainable alternatives to concrete. In massive elements, timber load-bearing capacity in a fire increases with larger dimensions; thus, glulam is hard to ignite and burns slowly (Brandon and Östman 2016).

Bio-based façades pose a unique issue that needs to be considered to fulfil the fire safety requirements. Façade cladding is typically installed in the so-called ventilated façade system. Here, external cladding is not mounted directly on the wall structure, so a layer of an air plenum is present behind the cladding. Air circulates in the plenum to provide the vapour and moisture exchange. The wall

Fig. 3.23 Carbonized surface of the CLT panel after fire test preserving structural integrity of the wall

component beneath (usually insulation) is sealed with vapour permeable membranes. In an event of a fire, air present in the plenum facilitates the development of the fire. When the temperature increases, the chimney effect behind the cladding is observed, which leads to a flame spreading towards the top of the façade (Jeffs et al. 1986). Proper design of horizontal and vertical fire stops, or proper compartmentation of the entire façade's surface may prevent fire distribution. If properly designed, a timber-clad façade can meet the requirements of REI60 (60 min of adequate performance in load-bearing capacity, integrity, and insulation) for a medium fire duration (Lenonn 2008).

3.4 Adaptation and Special Functionalities

Traditional building envelopes act as a barrier between the indoors and the outdoors. The main developments in design focus on structure and energy aspects. The trend for next-generation façades—called adaptive, dynamic, or responsive—is gradually recognized and desired (see Chap. 1 for more details). Key emphases in new façade systems are shifting:

- From the barrier to the interface
- From invariable and static to responsive and dynamic
- From passive and single functional to adaptive and multifunctional
- From conventional to customized.

In consequence, innovative façades are able to modify its structure, function, and behaviour and are responsive to change in harsh environmental conditions. Their overall goal is to improve building performance.

3.4.1 Self-adaptive Biomaterials

Inspiration in novel design strategies is frequently adopted from the field of biology, namely, from the processes of organism adaptation to diverse climate conditions. Bio-based materials have a high potential to be used in adaptive façades, far beyond the use of glass-framed timber elements or the exchange of non-bio-based to bio-based components (Callegaria et al. 2015). Bio-based materials are characterized by inherent properties that change according to variations in the surrounding environmental conditions. Such changes are autonomous and do not require any control mechanisms. To take advantage of these mechanisms, structure design and material engineering must be carried out properly.

Hygroscopic Devices/Energy Control

Cellulose, as the major constituent of most biomaterials, is an example of an adaptive natural material, as it changes its dimensions according to variations in relative humidity and corresponding moisture content equilibrium (Hill and Xie 2012). If shaped properly, cellulose-based elements can be used as actuators facilitating rotating, skewing, or bending façade elements. Such a functionality is so-called passive humidity-driven actuation. Max Planck Institute of Colloids and Interfaces in Potsdam (Germany) manages a long-term research programme on “Biomimetic Actuation and Tissue Growth”. It includes both the distortion of thin layers of biomaterials with different properties and the actuation provided by pressurized anisotropic honeycomb structures (e.g., in D. nakurense seed capsules). Two veneer-laminated wood layers with different properties bend depending on the humidity levels due to the different expansion coefficients and physical properties of wood (related to its grain direction). This absorption mechanism was used in many conceptual designs, and some of them reached a prototype stage. Architect Achim Menges proposed a “Hygroscope”, where dimensional instability of wood is used as an object responsive to climate changes that is capable to react to moisture content without external control (Menges 2012). The triangular flakes that were developed by Menges are constructed from laminated quarter-cut maple veneer. This method of cutting bisects annual growth rings that not only results in a straight grain or ribbon-striped appearance but also facilitates the distortion of the flakes. Similar shape change mechanism could also be employed as a building-integrated photovoltaics (BIPV) orientation device depicted in research done by Mazzucchelli and Doniacovo (2017). In this project, thin-film solar cells were coupled with a thin layer of hydromorphic material capable of responding to changes in environmental humidity by modifying its own curvature (Fig. 3.24).

Bio-based Latent Heat Storage/Energy Conservation

Latent heat storage is one of the most efficient ways of storing thermal energy. As such, it is actively changing the properties of adaptive façades and reducing their energy use. Here, the most common crude oil-based paraffin and salt hydrates are regarded as the optimal solutions. Phase change material (PCM) should be handled

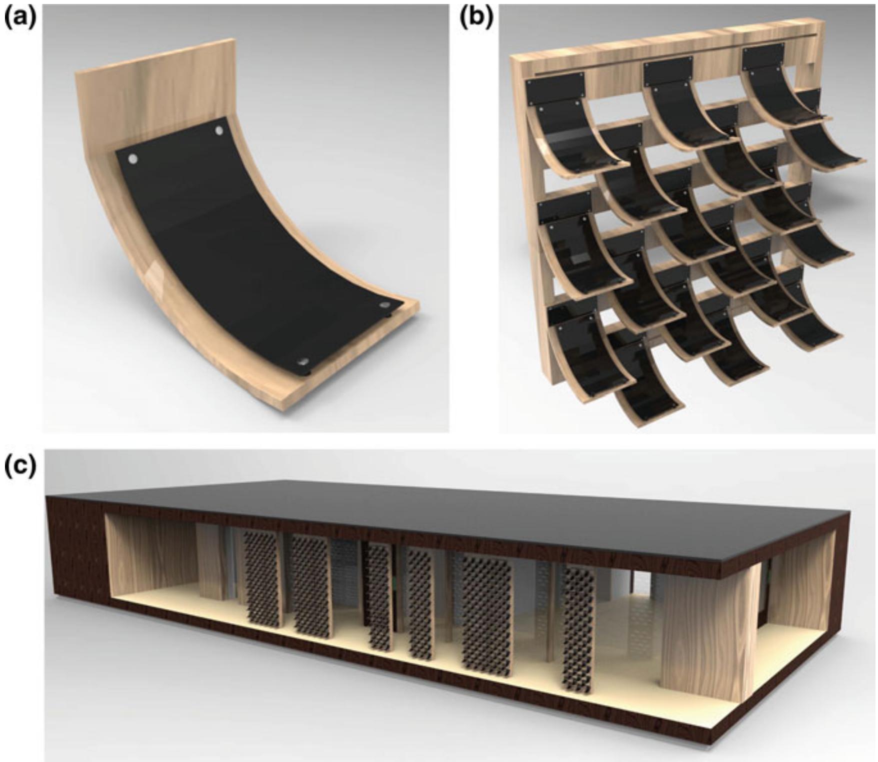

Fig. 3.24 Bio-based materials implemented as building-integrated photovoltaics: **a** single active element, **b** one module of the active façade, **c** integration of the façade with a modern building. Image courtesy of Enrico Sergio Mazzucchelli—Politecnico di Milano

with care, as most of them are highly flammable or/and toxic. One of the ways of reducing potential dangers is to use the method of encapsulation, especially microencapsulation that enables a direct use of PDM (e.g., in concrete). Here, some bio-based materials present many application possibilities and, accordingly, are widely recognized as bio-based phase change materials. Usually, a mix of paraffinic and bio-based compounds or blend of fatty acids is prepared to change from liquid to solid and vice versa at a given temperature (Mathis et al. 2018). One of the most recent solutions is BioPCM™ material marketed in Australia as "room temperature ice" (Ramakrishnan et al. 2017). BioPCM™ absorbs excess heat during the day and releases it back in the evening as buildings cool. The material is designed to be installed in ceilings and upper parts of the walls to stabilize diurnal temperature changes (it starts melting at the temperature of 20 °C and becomes fluid at the temperature of 24 °C). The product uses waste products from the food manufacturing process. Although BioPCM™ is biodegradable, it cannot serve as a food source and is thus not targeted by animals. The material is delivered in the form of a rolled matt with PCM encapsulated in the cells of a flame-retardant poly film. It is installed as an internal layer to act as a heat sink in the extreme Australian climate (Ramakrishnan et al. 2017).

Energy Generation (Biomass)

Although they are deriving from living things, no processes of life are taking place within biomaterials. If life processes happen to appear, they are usually regarded as undesired or even dangerous (e.g., when fungi or moulds develop). Nevertheless, life processes based on energy and substance circulation (e.g., photosynthesis) pose a great potential in energy generation, as the solar energy could be transformed directly to biomass. Apart from being used for energetic purposes, some species, such as willow and poplar, are becoming one of the most widely cultivated plants because of their high fertility and yield as well as their capabilities of phytomining and phytoremediation of soils contaminated with heavy metals (Tlustoš et al. 2007; Sandak et al. 2017).

Prototypes representing innovative and transparent energy-harvesting systems were developed at the IBA Hamburg in 2013 in the BIQ housing building (called also Algae House) (Fig. 3.25). The developed system features a thin glazed tank

Fig. 3.25 BIQ (arch. SPLITTERWERK, Arup GmbH, B+G Engineers, Immosolar, 2013)

called “bioreactor” which creates a biohabitat for algae. The tanks containing a nutrition solution are located on the south-facing façade of the building. A separate water circuit running through the façade continuously supplies the algae with liquid nutrients and carbon dioxide. With the aid of sunlight, algae can photosynthesize and grow. Algae were chosen due to their efficiency in producing biomass. The developer explained that algae produce up to five times as much biomass per hectare than other biomass production systems. Moreover, algae growing in a building in Hamburg contain a high proportion of oils that can be directly used to generate energy (Elrayies 2018).

3.4.2 Special Functionalities of Bio-based Façades

Bio-based materials can be used to perform certain special functions. Microclimate regulation and protection from wind are among the conventional tasks of a building envelope, while some specially shaped bio-based elements can take the role of supplementary tasks and appear in shades, louvers, and shutters. Bio-based materials can be also used for decorative purposes.

Conventional building elements are typically made of timber that no longer contains any life processes. New possibilities arise if the use of living organisms in the façade envelope is considered. Algae can be used to create biomass that is later used in energy production, as previously described. 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 so-called vertical gardens that provide the framework for vertical rather than horizontal plant growth. In façades, the greenery layer is typically located at the blind (windowless) sections of walls (Fig. 3.26) but may be also deliberately positioned to the front of the window to provide shading and noise protection as well as the light-filtering function (Fig. 3.27).

Fig. 3.26 Green façade on blind sections of the wall

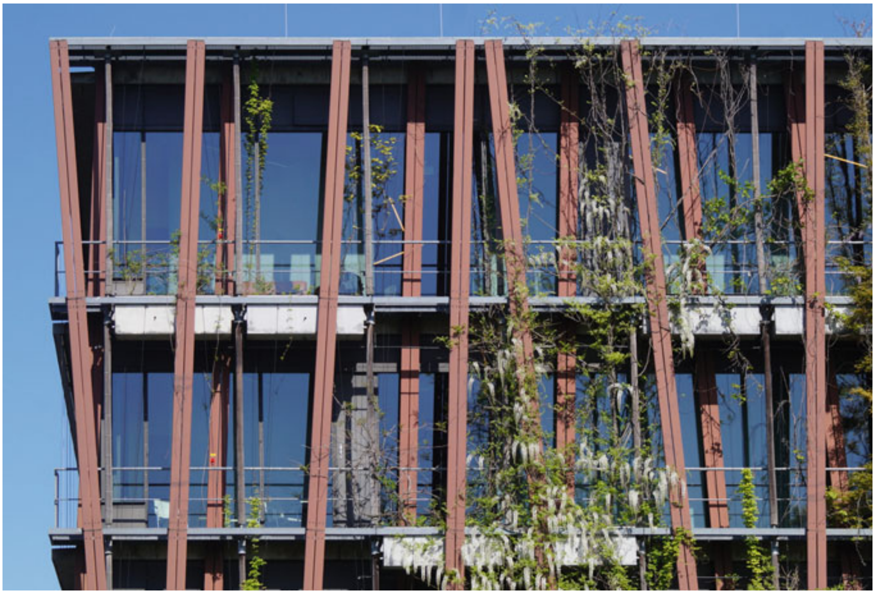

Fig. 3.27 Institute of Physics in Berlin-Adlershof (arch. Augustin Und Frank Architekten, 2003)

Vertical farming presents a particular challenge since plants providing food are typically grown isolated from the external environment, even when the daylight is used. This enables the regulation of heat and moisture flow and reduces the energy use while controlling pests. In many existing examples (a vertical farm in Japan is producing food on the industrial level), food is produced using artificial LED lighting that emits only the radiation wavelengths that are absorbed by plants during their growth (Goldstein 2018).

Urban pollution is another concern that can be mitigated by façade design. A new trend of smog-eating façades aims to improve air quality in highly populated cities. Recently developed façade materials aim to capture CO_2 from the air. One such material—“made of air” or “hexChar”—is composed of biochar (http://www.madeofair.com/). Designers aim to develop carbon-negative building materials, where material production and use phase lower environmental impacts of buildings. Note that this is opposite to the traditional building practice. Alternative approach for sequestering and storage of carbon might be inspired by biomimetic. There are several organisms and processes in nature that are able to store, sequester, or recycle carbon. Understanding mechanism of those processes might lead to the development of technologies suitable for industrial processes and the built environment (Zari 2015).

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