Trends and perspectives in the use of timber and derived products in building façades

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Anna Sandak[1,2]*, Marcin Brzezicki*[3] *and Jakub Sandak*[1,4]
[1]InnoRenew CoE, Izola, Slovenia, [2]University of Primorska, Faculty of Mathematics, Natural Sciences and Information Technologies, Koper, Slovenia, [3]Wroclaw University of Science and Technology, Faculty of Architecture, Wroclaw, Poland, [4]University of Primorska, Andrej Marušič Institute, Koper, Slovenia

9.1 Introduction

Wood, being one of the oldest building materials, found a new position in the building sector at the beginning of the millennium due to new developments in its engineering and modification. The current trend for raising sustainable buildings and increasing environmental awareness led to a renaissance of bio-architecture as an alternative to other construction techniques. The use of wood as a viable alternative to steel and concrete is especially relevant due to rising concerns about climate change and carbon dioxide emissions associated with construction. Wood is the only renewable material, called a "carbon sink," due to CO_2 sequestration of trees during their life [1]. In every cubic meter of wood, 0.9 tons (t) of CO_2 is trapped. Moreover, every cubic meter of wood used as a substitute for other building materials reduces CO_2 emissions to the atmosphere by an average of 1−2.5 t CO_2 [2]. Wood can be completely recycled or disposed of in an environmentally compatible manner. Timber products allow cascading use, where priority is given to higher value uses that allow the reuse and recycling of products and raw materials. Use of the products for energy production is permitted when other options are starting to run out. As a consequence, by using timber in the building sector, the need for products that are manufactured from carbon-emitting steel, concrete, or plastic is minimized.

Timber is being used in new combinations with concrete, steel, and glass to maximize structural efficiency. It is integrated into buildings on many levels. The most crucial is using timber and bio-based products as a structural material. Previously, timber was used on a limited scale, mainly in low-rise residential buildings, usually in the form of a timber framework. This type of timber application continues, but massive and laminated timber elements are also used in office, high-rise residential, and government buildings. New developments and fire-proofed bio-based materials allow timber to replace steel and concrete. Therefore, in some cases of application, nonrenewable materials might be replaced by their biobased

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equivalents. Biobased materials could also be integrated into the building as insulation material, both for heat and acoustic insulation. Due to their cellular structure, biobased materials are almost equally as effective as nonrenewable polystyrene-based materials [3]. The third level on which biobased materials could be integrated into the building is cladding. This area of application is the most demanding, as materials of bio-origin are exposed to the influence of the external environment—changes in temperature, humidity, and UV radiation. Therefore proper protection is required along with properly applied building techniques. These include installation procedures that allow for shrinkage and expansion of biobased elements according to changing humidity and insolation. Maintenance and replacement procedures should also be scheduled in case there is failure of individual façade elements [4].

Nowadays, timber is gradually becoming increasingly more important as a building material, especially in the context of a CO_2-neutral economy. Timber is the new concrete, and wood, in its many forms and functions, is experiencing a revival and renaissance [5]. With the introduction of new timber manufacturing technologies such as glulam, cross-laminated timber (CLT), and laminated-veneer lumber (LVL), building with wood has gradually became economically attractive [6]. The current shift from steel and concrete toward massive structural timber elements is evident in a number of mid- and high-rise timber buildings in Europe [7]. The important advantage of using engineered wood products arises from an increasing degree of prefabrication in timber construction and the resulting technical possibilities this offers [8]. Prefabrication increases process efficiency, gives a greater return on investment, and reduces construction time and waste both on- and off-site. It creates better quality products with predictable performance, while generating less waste, dust, and site disruption. This, combined with the use of computers in design and numerically controlled manufacture, offers to architects new possibilities of building design. Timber is an excellent material from this perspective, allowing easy machinability and assembling.

The important concern for every type of construction is fire safety. After a period of tragic fires in timber buildings (e.g., large, tragic whole-district fires) timber was gradually forbidden as a construction material (e.g., London Building Act of 1667; Sweden—1875), especially in dense urban areas. Outdated building regulations inhibited the construction of taller wooden structures in many countries [5]. Recently, novel technologies (laser hole-induced fire-retardant impregnation) allow an increase in the timber structure fire resistance to meet the most demanding building rules [9]. Façade systems involving timber as a material are combustible; therefore their design regarding fire safety should assure no risk of fire spreading over multiple stories. In wooden buildings, fire requirements are usually met by: (1) overdimensioning of timber structure, (2) additional plasterboard cladding, and (3) use of sprinklers. In 2009, the Provincial Government of British Columbia made two pioneering decisions; it permitted timber buildings up to six stories and also passed the Wood First Act. This document decrees that timber should be used in all new buildings erected by the state [6]. This decision facilitated all the following decisions that were taken in other provinces and countries [1988—UK (four-story)]; 2013—Québec; 2010—France; 2009—Finland; 2014—Switzerland]. Recently, timber has been allowed to be used in higher and higher structures. Currently, in Switzerland, timber structures up to 100 m are allowed, so long as full sprinkler protection is provided [10].

Another aspect, which should not be neglected, is the positive effect of natural materials while used in the human environment. There are certain benefits related to human-centered aspects, such as a more healthy and safe work environment, continuity of employment, and lower product operational costs. The use of wood as an exposed material in buildings, allowing humans to interact with it, creates positive psychophysiological effects for building users [11].

The brief overview of recently available biobased materials for building envelopes, as well as perspectives for future development, are described and supported with selected case studies. The objective is to provide an up-to-date summary, containing both advantages and constraints of their use as a façade element, with the overall aim to inspiring future generations of architects and engineers.

9.2 Biobased façade materials

9.2.1 Natural wood

Natural wood as a building material has traditionally been used for different types of load-bearing structures, decking, façade cladding, doors, and windows. Wood and other biobased materials offer a wide range of looks, from traditional rustic materials (wood shingle) to modern design products (wood cladding with several assembly options) (Fig. 9.1). The natural pattern and color of wood can be visible (or even highlighted with certain staining products). The performance of natural wood is influenced by its intrinsic properties. In fact, wood density, mechanical resistance, sorption and permeability, dimensional stability, thermal conductivity, acoustic and electric properties, natural durability, and chemical resistance depend on wood species, its provenance, and silviculture [12]. In the building context, wood mechanical properties are crucial for use in structural applications. From the perspective of the use of wood as a façade material, its density and natural durability are most relevant.

Timber as a cladding material is very versatile; it can be used for the interior and exterior, installed vertically or horizontally with gaps (open wood façade), or without them (closed wood façade). The installation process is quicker than with other materials and it can be easily adjusted on the building site. The profile of the cladding impacts both its installation process and how it will behave and perform. Wood can also be implemented in other external forms of façade, for example, as shingles or large-dimension boards. Each has a specific outlook and esthetic (Fig. 9.2).

Wood-based façade materials can provide optimal performance when certain exposure conditions along the service life are guaranteed. The degradation kinetic and extent of deterioration are usually caused by biotic and abiotic agents. Water, solar radiation, temperature changes, pollutants, as well as fungi, molds, and insects

Figure 9.1 Examples of use of wood in building façades.
Courtesy of Michael Sailer, Xylotrade photo in left, down corner.

Figure 9.2 Plywood and wood shingles implemented on buildings.

lead to a reduction of the esthetic, functional, and safety aspects of building façades [13]). It has to be mentioned, however, that the deterioration process is not only limited to wooden elements. Every façade material needs some maintenance, reparation, and replacement, and its frequency depends not only on the material type but also the climate and architectural details [14]. However, the aging and weathering processes, naturally occurring during building façade service life, can provide authenticity to the building itself. The gray patina that may result from weathering and mold growth can change the façade appearance and, if not presenting uneven discoloration, is often appreciated (Fig. 9.3).

The service life performance of wooden façades can be improved when following protection by design principles. The negative drawbacks of materials can be eliminated (or minimized) by selecting appropriate species or treatments. In the case of biobased materials, fast release of water after a wetting process is particularly essential. Any water traps should be avoided, and potential critical spots should facilitate fast water evaporation. The most vulnerable parts of structural elements should be covered, and a distance of at least 30 cm should be kept above the ground level/terrain level as timber elements in contact with humid ground and soil are especially vulnerable. The above-mentioned minimal distance also protects the timber from splashes of water from the pavement.

9.2.2 Modified wood

Restricted use of toxic preservatives and demand for well-performing materials in service, together with increased environmental concern, has resulted in the development of different methods for wood modification. Modification is implemented to overcome drawbacks of wood that are mainly related to moisture behavior, low dimensional stability, hardness and wear resistance, low durability against fungi, termites, marine borers, and weather conditions [15]. Wood modification processes enhance desired properties by applying chemical, biological, mechanical, or physical agents [16]. Modification of wood includes a wide range of processes, including thermal and chemical treatments, impregnations, specific surface treatments (e.g., densification), coatings, and fusion (e.g., hybrid modifications). New wood modification solutions, implemented to both surface and bulk, improve dimensional stability, esthetics, fire resistance, and biotic and abiotic durability, assuring expected properties and functionality over an elongated service life. Many of these solutions have reached the commercialized stage. Modification methods can be divided into

Figure 9.3 View of a façade with timber façade cladding elements partially replaced. The discoloration and aging are clearly visible.

two main groups: active and passive. In active modification, due to treatment, changes to the chemical nature of the material occurs. This can be achieved by reaction of the reagent with wood polymers, cross-linking, or degradation of the cell wall. In passive modification, material properties are changed without altering the material's chemistry. As a result, the lumen or cell wall is filled with reagent.

Modification of wood by exposure to elevated temperatures (over 160°C) with limited presence of oxygen is called thermal treatment. The exclusion of oxygen can be achieved by different methods, such as steam or nitrogen atmosphere, vacuum conditions, or immersion in hot oil. Thermally modified wood (TMW) possesses superior durability against decay and weathering, enhanced dimensional stability, constant darker color within the bulk, reduced thermal conductivity, lowered equilibrium moisture content, and increased hydrophobicity (Fig. 9.4). However, due to the reduction of mechanical properties (MOE, MOR), TMW is not suitable for load-bearing applications [17]. Thermal modification can be achieved by different processes (with several technologies already commercialized, for example, ThermoWood, Plato, Le Bois Perdure, OHT, Termovuoto, Firmolin) [15,18]. Final properties of wood are process-dependent (duration and temperature); moreover, the dimensions of the treated timber as well as species influence the final results.

Chemical modification leads to change of wood composition by the formation of covalent bonds due to reaction of a chemical agent with wood chemical components and is considered an active modification method [16]. The most developed (commercially available) is acetylation, where acetic anhydride reacts with hydroxyl groups of cell wall polymers by forming ester bonds. The acetic acid formed as a by-product is not toxic but affects the smell of wood, especially shortly after treatment. Acetylated wood possesses improved durability, UV resistance, and reduced surface erosion rate. The process has a negligible impact on the mechanical properties of timber. Acetylated wood is applicable for cladding and decking as well as windows and doors.

Figure 9.4 Façade from thermally modified wood: Castellum Hoge Woerd, De Meern, The Netherland.

Another group of modification processes is called impregnation. This lock chemicals in the wood cell or in cell lumens without creating chemical bonds. In order to ensure effective impregnation, the wood cell wall should be in a swollen state. The critical factor while impregnating wood is leaching, which should be minimal in in-service conditions. Due to several agents used for wood impregnation, the performance of impregnated wood greatly depends on the chemical used and process parameters. An example is the furfurylation process, which is executed by impregnating wood with a mixture of furfuryl alcohol ($C_5H_6O_2$) and catalysts, and then heating it to cause polymerization [15]. The process is conducted in several phases: preparation of chemicals, vacuum pressure impregnation, in situ polymerization and curing, drying, and cleaning [19]. Furfurylated wood is dimensionally stable, weather resistant, and resistant to marine borers and decay (class 1). It is harder but more brittle. Some of the wood modification processes were transferred from different sectors, such as treatment with 1,3-dimethylol-4,5-dihydroxyethyleneurea (DMDHEU), which was first used in the textile industry. This process consists of impregnation of wood with an aqueous solution of DMDHEU in vacuum conditions and slow drying, causing polycondensation of agent molecules [20]. Both processes, furfurylation (Kebony) and DMDHEU treatment (Belmadure), are commercialized and their products are available on the market (Fig. 9.5).

Wood modification processes can also be limited to the surface, including surface enzymatic treatment, plasma modification, densification, or carbonization. The large portfolio of commercial products (coatings, stains, waxes, oils) allows wood protection simultaneously with a change in appearance. Due to their positive UV-blocking function, opaque coatings have been much more frequently used, but the trend to preserve the original wood color and texture is progressing research in the development of clear coatings. Performance of façade elements depends, in this case, on the product type, its quality, and also surface preparation, application procedure, and maintenance schedule. Recent research is directed toward the development of products that require minimal or no maintenance efforts. This is especially relevant in the case of multistory buildings where access to the façade is often limited.

Figure 9.5 Furfurylated wood in service: a boat rental station in Copenhagen.

The new trend to merge benefits of various modification processes (i.e., hybrid modification) allows multiplication of the positive effects of a single process. By merging wood acetylation with surface coating, overall performance of wood cladding will be improved due to reduced shrinkage−swelling of bulk material and, consequently, lower mechanical stresses in the coating film. Another approach to achieve innovative wood modification is implementation of biomimicry toward wood protection. Solutions developed by nature might be a starting point for development of new treatment processes that allow superior performance of façade elements. Since the external layer of the building envelope is exposed to weather conditions, creation of materials capable of handling the influence of different atmospheric agents is particularly relevant. Different strategies for the management of water action at the surface and controlling wettability of materials are present in nature. Examples are self-cleaning, water capture, kinetics of water condensation, and evaporation of biofilm formation [21]. The lotus effect is implemented in different coating systems, allowing fast runoff of rainwater with simultaneous surface cleaning [22]. Another relevant property in the context of building façade and maintenance actions is self-healing and scratch-proof. A commercial example of such technologies is the Xyhlo biofinish, which uses *Aureobasidium* mold as a staining agent on oil-treated wood (Fig. 9.6) [23]. More discussion of the transfer of solutions toward materials and façade design can be found in Section 9.3.1.6.

9.2.3 Engineered wood products

Recent advances in materials research have delivered several solutions for the construction sector. Developments have resulted from the demand for wood components with well-defined properties and larger dimensions. Engineered wood products (EWP) based on sawn timber, such as CLT panels or glued laminated

Figure 9.6 Building façade finished with Xyhlo biofinish technology.
Courtesy of Michael Sailer, Xylotrade.

timber (GLT) beams, allow the design and erection of long-span and multistory buildings. GLT can be produced in many shapes and sizes that, together with its natural look, gives flexibility and esthetic value in architecture [24]. GLT consists of a number of graded timber laminations (25 or 45 mm thick) with their grain parallel to the longitudinal axis of the section. CLT buildings were introduced about 30 years ago, and CLT panel sizes allowed them to be used as a load-bearing element (Fig. 9.7). CLT usually consists of three to seven layers of softwood boards bonded together crosswise. Typically, spruce, but also fir, pine, and larch, are used for CLT manufacturing; however, the feasibility of hardwood species has been recently investigated [25].

Densification of cities is determined by social, environmental, and economic reasons. Use of CLT panels allows prefabrication of elements and a faster construction process. The other advantage of CLT panels is the implementation of the "design for disassembly (DfD)" concept, where materials can be easily reused for other applications. Due to lower weight (total timber building structural weight is around 20% of concrete), CLT allows upwarding and retrofitting of existing structures [26,27]. In many cases, the old roof is removed and a new wooden construction is built to expand the building vertically. In the case of the building presented in Fig. 9.8, the four-story concrete skeleton of a building from 1947 was expanded with a wooden structure and clad with fiber cement cast elements to provide a consistent and urban appearance.

From EWP based on veneers, plywood and laminated-veneer lumber (LVL) are often applied as building materials. Plywood may be used for both exterior and interior use (mainly for roof and floor decking and for wall-sheltering boards). LVL is a structural member manufactured by bonding together thin vertical softwood veneers with their grain parallel to the longitudinal axis of the section under heat and pressure [28]. LVL are often used for high-load applications and in door and window frames. EWP based on strands, chips, particles, and fibers contain large groups of products that are often used in the building sector. The board industry produces a variety of wood-based panel products by gluing different shapes of wood with specific adhesive systems. The most common are oriented strand board, flake board, particleboard,

Figure 9.7 Construction process with CLT panels.
Courtesy of CBD.

Figure 9.8 Implementation of timber for adding stories to existing buildings: Rauti-Huus (Spillmann Echsle Architekten, Zürich, 2015).

hardboard, insulation board, low-, medium-, and high-density fiberboards, cement-bonded board, and wood-plastic composites (WPCs) [28]. These products can be manufactured from different wood species as well as from modified wood. Other materials, such as biobased fibers or inorganic materials (cement, magnesite, gypsum, mica), may be added to improve certain board properties. Even if not all of these composites were some time ago suitable to be used as façade elements, recent developments in modification technologies offer superb treatments dedicated exclusively for biocomposites, allowing their direct implementation as façade elements.

CLT allows construction of multistory buildings, and a worldwide competition to erect the highest, most efficient, and most attractive structures is taking place [29]. In 2015, the 14-story (28 m tall) Treet apartment building in Bergen was erected. In March 2019, the Mjösa Tower [30], presented in Fig. 9.9, became the tallest wooden building in the world (18 floors and 85.4 m tall). The building contains 2600 m^3 of timber structures. The intermediate flooring is made of Kerto LVL. CLT was used for the inner walls, elevator shafts, balconies, and stairs. Large-scale GLT (glulam) was used for the internal columns, beams, and diagonals [Mjosa Tower (Mjøstarnet)]. In Vienna, the 84-meter tall (24-story) HoHo Tower is under construction and approximately 76% of the structure will be made of wood. In London, the world's first supertall building (300 m^+), Oakwood Tower, is planned and will be mainly built from glulam and CLT (around 65,000 m^3 of structural timber). The challenge in this case is responses to wind or seismic excitation and proper transferring of the load at connections [31].

9.2.4 Timber and glass composites

Glass has been considered as a structural component of glass–timber elements; infill glass acts as a stiff plate. Glass is also considered to be a proper material to

Figure 9.9 World's tallest wooden building: Mjösa Tower (Voll Arkitekter, 2019). Courtesy of Igor Gavrić, InnoRenew CoE.

construct glass–timber composites, where glass is adhesively bonded to timber. Such load-bearing timber–glass composite elements are considered as novel developments in the field of structural glass [32]. Glass, as a material of high stiffness, is considered to be capable of taking a portion of the bracing load in timber structures; therefore, timber and glass composites are tested in terms of proving different structural actions, including bracing [33]. In this context, the timber–glass composite is considered mainly as a structural element used for stabilization of the timber-framed façade itself [34]. Structural application of glass includes lamination of timber with fiberglass.

9.2.4.1 Timber-behind-glass

Besides protective treatment that improves timber performance, the implementation of a curtain façade by merging glass and timber can be seen. It is increasingly common in architecture that glass is located in front of the proper façade and serves as a protective layer for the wall behind. This type of external glazing is also used as an envelope for timber façades. It slows down timber decomposition and weathering as it screens out potentially dangerous climatic factors like rain, moisture, and frost. External glazing not only serves as a protective layer for the timber cladding behind but also helps to decrease the amount of chemicals that need to be used to maintain the timber. This emerging architectural trend is tentatively named timber-behind-glass [35].

According to Alexander Smith from Hawkins/Brown Architects, the future of architecture may lie in the development of hybrid technologies, where various building materials with different strong points are combined into a single building system [5]. The combination of timber and glass is expected to simultaneously produce both a very durable (i.e., long service life) and environmentally friendly façade as timber locks CO_2 into its substance. Glass is a homogeneous, nonorganic material that is stable (from the point of view of the material's properties) and recyclable, while the timber is a heterogeneous unstable biological material that changes over the time and weathers but, simultaneously, is sustainable and renewable. Timber also makes a clear contribution to climate protection by CO_2 sequestration —almost 1 ton/m^3 wood [5,36]. Timber-behind-glass has become one of the most promising typologies in façade design from the sustainability perspective. Combination of these two materials with very different lifecycle assessments (LCA) also has a compensation effect because two materials with very different carbon footprints are combined in one solution. That is, timber, a lower LCA material, will compensate for glass, an environmentally higher LCA material.

Typologically, timber-behind-glass morphology could be defined in a straightforward way as "a pane of glass positioned in the front of the timber-clad façade" [35]. Both layers are usually parallel to each other but might also be arranged in deviated geometrical relation. Timber cladding constitutes an internal layer and glass an external layer. The cavity between the cladding and glass envelope is of a different depth, depending on the individual architectural solution. Functionally, the envelope might be sealed or ventilated, allowing for air exchange or not. This has very important consequences on the conditions in which the timber cladding is weathered. In the case of a sealed envelope, timber cladding works in static temperature and humidity conditions, usually the same as those of the internal building microclimate. In the case of a ventilated envelope, the issue is more complicated as timber is basically protected only from the influence of rain and snow, while the changes in humidity and temperature still affect the cladding. In both cases, if transparent glass is used, timber is exposed to the influence of daylight, containing a large portion of UV radiation. Optionally, the use of selective glazing (UV-selective glass) might slow down the destructive process of timber photolysis [37].

Ventilated timber-behind-glass solutions perform better in terms of potentially destructive moisture capture as the circulating air will promote drying of the surfaces. Insulating glass units (IGU) vs. single glazing units are likely to perform similarly, without the serious effect on timber, as a substantial difference of radiation hitting the sample is not expected (this will be proportionally decreased only by the transparency of the glass). A vented façade will be less prone to condensation forming on the internal face of the glass, and, therefore, a lower moisture content will extend the service life of the timber structure or cladding.

The Tamedia building in Zurich (architect: Shigeru Ban, 2013) is an example of a sealed envelope (Fig. 9.10). With the release of fire-rating requirements in Europe, some buildings, especially in Switzerland, do not fully follow EU regulations, and are erected using structural timber. This also applies to buildings up to 100 m, if sprinklers are installed. Tamedia in Zurich is constructed from laminated timber as a structural material and was later clad in a glass envelope—the same type that is used in a standard transom and mullion curtain wall façade. In contrast,

Figure 9.10 Example of a sealed envelope: the Tamedia building in Zurich (architect: Shigeru Ban, 2013).

Figure 9.11 Example of a wood behind glazed curtain wall: the GC Osaka Building (architect: Shigeru Ban, 2000).

in the case of the GC Osaka Building (architect: Shigeru Ban, 2000) the timber is not structural but strictly functional, acting as a fire-rated cladding for the structural steel behind (Fig. 9.11).

Office building Hammer Strasse 19, Düsseldorf (architect: Petzinka Pink Architekten, 2000, Fig. 9.12, left) and Rheinisches Landesmuseum in Bonn (architect: Knut Lohrer, 2003, Fig. 9.12, right) are examples of ventilated envelopes. In the latter, the internal timber façade was erected using mass timber exposed to the outside. The air exchange between the external and intermediate spaces surrounding the building is facilitated by thin vertical slits between the panes of glass [35].

Further investigation of timber-behind-glass façade morphologies will allow knowledge to broaden about the use of timber in a layered combination with glass

Figure 9.12 Example of ventilated envelope: (left) Hammer Strasse 19, Düsseldorf (architect: Petzinka Pink Architekten, 2000) and (right) Rheinisches Landesmuseum in Bonn (architect: Knut Lohrer, 2003).

in façades and identify the most environmentally friendly combination, as well as the most optimal from esthetic, architectural, and maintenance points of view. It is also hypothesized that timber-behind-glass typology has an insulation potential as the thermal buffer created between timber and glass slows down heat exchange and facilitates passive heat capture. A similar mechanism as in double-skin façades is expected, although it has to be taken into consideration that the air exchange rate can influence both moisture management and the buffer's insulation potential. In a broad perspective, timber-behind-glass might substantially influence the discipline of architectural design by building solid ground for the application of novel, previously unused technologies and façade morphologies, reducing carbon emissions and creating an alternative to the old throwaway society.

9.2.5 Green walls and green façades

Many cities suffer from an unnaturally warm environment (heat islands) due to highly engineered infrastructure. Surfaces in urban environments, such as concrete, brick, glass, asphalt, and roofing, collect the sun's heat during the day and reradiate it slowly back into the atmosphere. Green roofs, walls, and façades, by reducing heat gain or loss across the building surface, can reduce cooling and heating costs. Green walls and green façades differ in the way plants are integrated within building walls (Fig. 9.13). Both require regular maintenance and are rather costly solutions.

In green walls, plants are distributed on the entire surface of the building façade; therefore they require support and irrigation systems. This solution is more suitable for plants that have shallow root structures and relatively compact overall

Figure 9.13 Example of green roof and green façade.

shapes (e.g., mosses, ferns, and herbaceous plants). Water can be supplied through containers within the soil matrix, which are usually modular, resistant to weather conditions, but rather heavy. Much lighter solutions are hydroponic systems of water–nutrient mix. In all green wall systems, continuous plant watering and feeding is usually required, and it is typically provided via closed-loop irrigation systems that circulate water and essential plant nutrients [38]. This solution requires higher technology and, in general, is more expensive than green façades; however, it can be created very quickly and is more flexible in terms of plant patterns.

In green façades, containers utilized for plants are located on the base of the building. Selected plants that create an external layer of vegetation should be capable of climbing on the support system. The load-bearing requirements are often considerably reduced compared with green walls. This system can usually be implemented in three different ways. The simplest way is to use self-climbing plants that grow from the ground and fix themselves to an existing wall. The second method requires a frame attached to a supporting wall that supports the plants. The third design uses additional containers or planters located on each floor in a multistory building [38]. This solution is perfect for vines, bushes, and other branching and woody plants, which can spread to fill the façade framework and grow robustly at some distance from their soil source. This concept is cheaper and easier to build than green walls. Since the loads are often lower, it is suitable for retrofitting of existing walls; however, high density of plants is achieved in a longer period and the plant pattern is not easily controllable.

Both solutions are interesting, especially in a city context where natural greenery is often limited by available space. Besides providing natural shadow, these solutions improve air quality, reduce noise and wind, and help maintain constant temperature and relive humidity inside the building. Recently, popular urban farming can also be implemented on building walls instead of the roof. In this case, however, cultivated plants might not be suitable for consumption due to high pollution levels in urban contexts. Green walls and façades, besides having high esthetic value, introduce biodiversity in cities by providing food sources and living habitats for different animals.

9.3 Trends and perspectives

Increasing interest in the implementation of wood and derived products in the building sector observed nowadays is emerging together with other tendencies, which can be divided into two groups: related to façade design and related to façade function and services.

9.3.1 Façade design

9.3.1.1 Digitalization

Digitalization of the building production processes has been recognized as an effective way for optimization of the project phase as well as manufacturing and assembling of building components. Use of computers for designing, engineering, and planning, as well as numerical control machines for producing building elements is, therefore, a common routine in the modern construction industry. It opens unlimited opportunities for experimenting with the form, function, or esthetics of the structure before investor decisions and components manufacturing. Even if several matured software solutions for digital projecting are available for professionals, the field is steadily expanding and novel technologies, tools, algorithms, and programming procedures are elevating architects and designer communities. The integration of computers with the design of building façades allows for precise project decisions, stimulating the optimal form of the structure or using predefined modules to represent the desired outlook of the final building shape. Wood, as well as other biomaterials, is a perfect resource for such experimentation as, if combined with the proper manufacturing technologies, it offers the highest flexibility and adaptability to any façade form envisioned by the architect. The ease of machinability and unique formability of biomaterials permit realization of virtually unlimited façade solutions, which have been extensively tested at the project phase, including esthetic assessment combined with analysis of functionality and simulation of the service life.

Diverse ready-to-use digital solutions are offered nowadays that cover a wide range of activities related to deployment of the timber façade in new or renovated objects. The process starts with a planning phase where computer-aided design (CAD) software is used by an architect to shape the structure and construct façade details (Fig. 9.14).

The feasibility of such a solution can be additionally tested using computer-aided engineering (CAE) software, where optimization of the façade can be performed to assure mechanical and in-service life integrity. If the projecting phase is concluded and approved by the investor, the following production stage can be supported by computer-aided manufacturing (CAM). In this case, all technical drawings of the structure/façade are converted directly into code for CNC machines, simplifying the production process and minimizing errors (Fig. 9.15). In most modern construction industries, all the above software solutions are integrated together with the enterprise resource planning (ERP). This provides numerous advantages,

Figure 9.14 Architectural design and renderings of the InnoRenew CoE building. Courtesy of Eva Prelovšek Niemelä and Aarne Johannes Niemelä, InnoRenew CoE.

Figure 9.15 A computer numerical control machine used for machining of complex wooden elements used in timber structure.

such as cost optimization (and prediction), appropriate scheduling, and also traceability of all the manufactured components together with explicit linkage to the specific part of the erected building [29].

9.3.1.2 Building information modeling (and its new dimensions)

An ultimate level of the state-of-the-art digitalization of design process is its integration with building information modeling (BIM) software solutions. BIM is an advanced design procedure that includes the administration/management of the digital representation of a planned building (structure, installations, and systems), including arrangement, visualization, and management of building façades [39]. BIM is computer technology combining together several aspects of the building within a single software tool that, after some customization, can further extend its usability. It is especially noticeable nowadays where novel BIM functionalities, compared to the original three-dimensional (3D) representation of the building project, are successfully implemented in the regular design process. These functionalities are commonly defined as new BIM "dimensions" and may include integration of construction scheduling four-dimensional (4D), cost management five-dimensional (5D) or maintenance, and operation planning six-dimensional (6D). Other aspects were also identified by the BIM community, including environmental impact assessment, energy consumption, planning the end-of-life scenario (design to demolish), human well-being, occupational health, or building integration with sensors monitoring the structure and air quality (among others). Most commercial software tools allow integration of these new functionalities with custom-made applications by developing plug-ins or apps. As an alternative, exporting data regarding the building developed in BIM software to other applications permits even wider extension of the information use. In this case, the structure's mechanical performance can be simulated with finite element methods (FEMs) or other engineering tools. Eventually, the expanded BIM model corresponds to the "digital tween" concept where a real-life object is fully represented by its numerical or virtual replica. The digital tween links the simulated structure behavior with readings provided by sensors or other Internet of Things (IoT) solutions.

Furthermore, BIM extension includes simulation of the building esthetic appearance along the service life, which is especially important for biobased façades that are more vulnerable to biotic and abiotic deterioration. An example of the material climate simulation and subsequent FEM analysis is shown in Fig. 9.16, where cumulative solar radiation, surface distribution, and raindrop density over the building façade are mapped. This set of data can be converted into "weather dose," highlighting all the surface areas where intensity of deterioration may vary. When the degradation kinetics (or "response") of the façade material is known, it becomes possible to simulate the building appearance changes along time, implementing a dose−response model paradigm. In combination with customer preferences assessment, it may result in detailed planning of maintenance/replacement schedules. Consequently, this knowledge leads to more predicted lifetime costing of the building operation and, consequently, assures satisfaction of the building user.

Even if BIM technology is attracting architects' interest and rapidly widening the users' community, reliable databases regarding biobased building materials are very limited. Several technical characteristics, existing in recent BIM libraries, do not correspond to real material specifications, which is limiting the confidence of

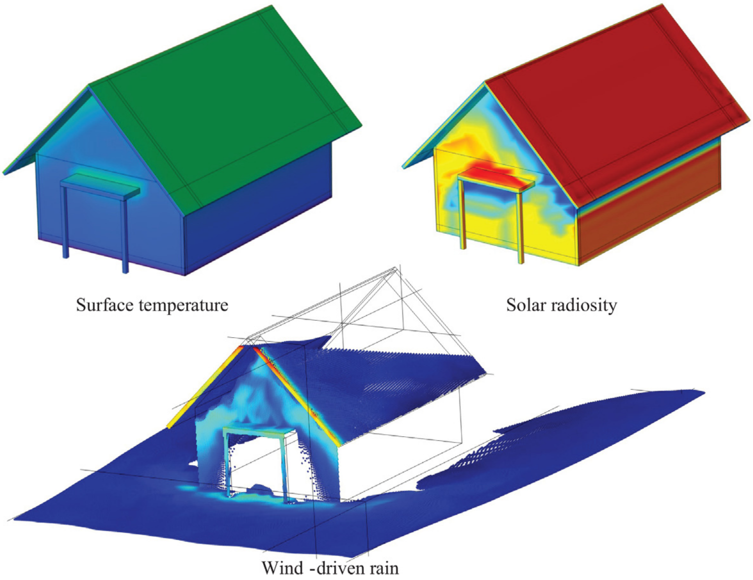

Figure 9.16 Simulation of material climate of the building façade exposed to natural weather conditions corresponding to June 1st, 3 pm in Johannesburg, South Africa.

some architects and engineers to integrate biomaterials into their building designs. Another limitation is the high fragmentation of wood industries supplying components for building façades. In this case, small companies, even if producing superior products, are not taken into consideration by designers if lacking customized BIM libraries. It is a big challenge, therefore, to continuously update the portfolio of biomaterials available in BIM together with continuous extension of software functionalities to assess the environmental impact and esthetic valor of natural façades.

9.3.1.3 Parametric design

The design of a building is a creative work where the artist and engineer at the same time (architect) plan the structure, taking into consideration several factors such as budget, investor requirements, local weather conditions, material properties, specific site characteristics, and manufacturing capacities of contractors, among others. All of these can be considered as numerical model constraints determining design alignment with the expectations of the future user [40]. Revolution of the building design field, as an effect of broad digitization and implementation of BIM philosophy to the process, opened completely new possibilities to conceptualize building function and experiment with its form, rhythm, or composition. The specific tool assisting such an approach is parametric design, where the architect's concept of the building is developed as an iterative process of solving explicit mathematical functions [41]. Parametric design is also called algorithmic thinking, computational design, or associated design, as the creation process translates an idea into a reality/prototype object through changing values of specific variables in equations (parameters). It is a highly flexible design tool capable of coordinating meaningful properties of the design to the framework of the concept, assuring preservation of discrete relationships between composition elements (Fig. 9.17).

Commercially available software assists parametric design by providing several tools for graphical form parametrization, including visual programming. At the same time, it is common practice of architects to develop a custom software code directly enabling changes to the façade design, proportions, and relations by means of varying predefined parameters. The greatest benefit of parametric design is that even minor changes to the parameter set can lead to several output solutions that can be easily visualized by computer-generated rendering. The optimal solution can also be related to fulfilling model constraints defined by investors as well as technical requirements, for example, maximum length of the element, its cross section, or specific geometrical form and type of connectors, among others.

Timber façades or structures are especially suitable for parametric design as it allows long span, low weight, flexible joint, and attractive outlook compositions. An iconic example of parametric design is Metropol Parasol in Spain, designed in 2011 by Jürgen Mayer-Hermann. It is the world's largest wooden structure (150 by 70 and 26 m high) and a popular tourist attraction in Seville. The structure, which has nonrepeating elements, is created out of 8000 birch timber pieces connected using steel and glue. Low-maintenance finishes and materials (polyurethane coating) contributed toward a reduction of the lifecycle costs. Its prefabrication process allowed low-impact construction with minimal dust and noise in the city center. Finally, CAD/CAM software solutions allowed the creation of its complex sculptural-like shapes where no two parts of the Parasol are identical [42].

9.3.1.4 Modular design and prefabrication

Digital solutions for building façades are fully compatible with the modular design paradigm widely accepted in the modern construction industry. There are several

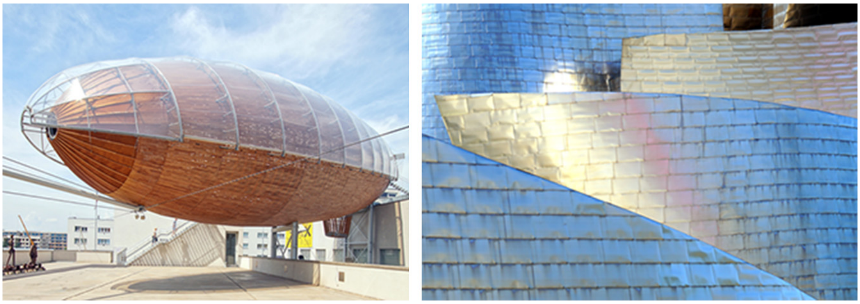

Figure 9.17 Example of parametric design: art installation titled Airship Gulliver (architect: Martin Rajniš, 2016). A galvanized steel structure was clad in timber in the form of a zeppelin and is externally protected by a layer of ETFE foil (left), and Guggenheim Bilbao Museum (architect Frank Gehry, 1991–1997; right).

advantages to implementing a modular design approach, including high reductions of façade cost, simplification of its transport and assembly, very short installation time, and simplicity for imminent façade reparation or replacement [43]. Façade topology may vary depending on architect vision and may include identical modules distributed over the building surface or highly customized units with specific size, geometry, or finishing differing in each module. In the latter case, BIM or parametric models are indispensable as well as faultless coordination of the production of modules and their assembly at the construction site. In a majority of real-world cases, the main part of the assemblage operation takes place in the production plant, which is considered as prefabrication.

The possibility for a high degree of prefabrication in building elements made of timber is one of the most important technical advantages to its broader use. At the same time, using wood allows flexibility in construction of the creative and individualized solutions realized in a very short production time. The quality of prefabricated products/components is usually superior to that developed on-site, thanks to CNC machines used for manufacturing. It is also an advantage of timber façades that, even in the case of production errors or some minor damage to the module, it is usually straightforward to repair or refabricate the wrong component on-site using simple woodworking tools.

Increased interest in prefabricated or modular solutions is especially noticeable for construction/retrofitting of buildings in high-density urban environments. This is related to the limited space available, restriction on heavy traffic, noise emissions associated with construction, and air pollution and dust. Shortened assembly time for timber structures and lightweight building components encourages municipalities to select these technologies. Prefabrication creates better quality products with predictable performance while generating less waste, dust, and site disruption (Fig. 9.18). There are also some benefits related to human-centered aspects, such as more healthy and safe work environments, continuity of employment, and lower product operational costs. Prefabricated building modules usually contain the façade as an integrated part of the unit module.

Figure 9.18 Prefabricated timber façade elements allowing a fast construction process.

9.3.1.5 Climatic design

The advantages of certain climatic conditions can be used for building design in order to exploit the local environment. In general, design should work with the climate, not against it, in order to fully benefit from natural lightning, humidity, wind, and temperature. Design solutions that follow this principle are generally divided into two groups: heat accumulating and heat rejecting. There are several solutions that might be implemented here, such as natural ventilation or shading systems, but what is important to mention is that they are effective only in certain circumstances (e.g., natural ventilation will be efficient only if external temperature is lower than desired internal temperature). In climate, where four seasons are present and weather conditions change significantly, both heat accumulation and heat rejection techniques should be used. In cold climates, heat accumulation is a major requirement, therefore an efficient insulation system preventing heat loss during long and cold winters is most important. Several biobased materials (e.g., fiberboard, flax fibers, hemp fibers, jute fibers, and sheep wool) can be implemented here due to their low thermal conductivity (~ 0.05 W/m/k) and high moisture diffusivity (1.1×10^{-6}–1.2×10^{-5} m^2/s), which make them suitable for use in interior thermal insulation systems without water vapor barrier [44].

The earliest example of a ventilated envelope was dated to the beginning of 20th century in a Steiff Factory in Giengen (1903). One of the examples from the end of the 20th century is the building of Bayerische Vereinsbank in Stuttgart (architect: Behnisch and Sabatke, 1969, 1997, Fig. 9.19). This office building dates back to the 1960s and was reclad in timber and externally protected by nonsealed glass. The double-leafed façade was proposed as part of the building's new climatic

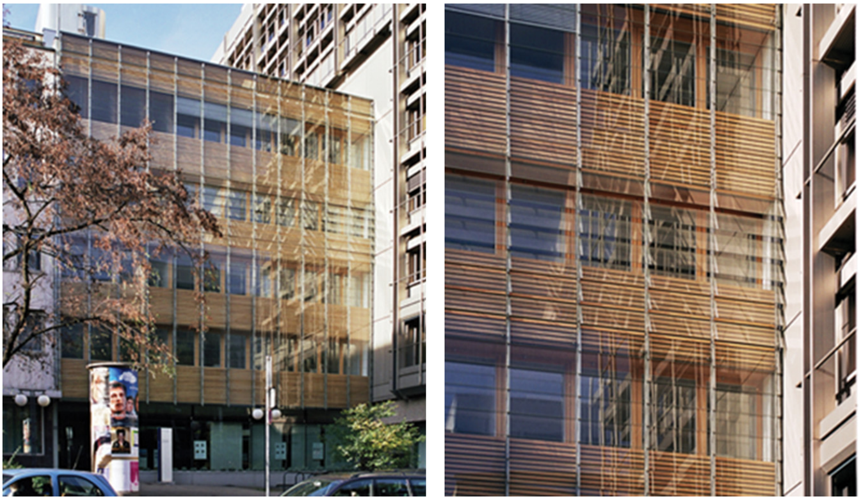

Figure 9.19 Example of a climatic design: Bayerische Vereinsbank in Stuttgart (architect: Behnisch and Sabatke, 1969, 1997).

strategy and different esthetic. The gaps between glass panes promote air exchange; consequently, the building operates in a more environmentally responsible manner.

An interesting example where natural materials are used to maintain the desired indoor climate is the herb cleaning and storage facility in Switzerland (Fig. 9.20). The building, over 100 m in length and around 11 m in height, is made of solid rammed earth. The earth elements were prefabricated in a nearby factory and were made from local resources. The mixture of clay, marl, and soil helps to maintain a cool internal environment, which is indispensable for herb processing.

9.3.1.6 Bioinspiration for façade design

Systems developed by nature have become valuable inspiration for materials scientists, engineers, designers, and architects. Nature, during its 3.8 billion years of development, has created efficient, elegant, and simple solutions allowing full adaptation to the environment. Nature uses a minimum of materials for maximum effect [45]. Efficient structures, such as plant stems, human bones, or feather quills, are built with the approach to provide necessary mechanical resistance in critical places. Examples are bamboo, where nodes provide resistance to structural failure, and trees growing in steep terrain, where reaction wood (compression in conifers and tension in hardwood) is created in order to keep the stem in a normal (vertical) position.

Biomimicry can serve as inspiration for designing the optimal shape of a building; it can also provide certain functionality to building elements. Fig. 9.21 presents Honeycomb Apartments, which was nominated for the Mies van der Rohe award in 2006. The building, built on the Slovenian coast, was inspired by the honeycomb design to provide comfortable outdoor space and shade in the Mediterranean climate. Strong colors inspired by beehives provides additional dynamic to the façade. Each apartment possesses a shady and naturally ventilated veranda partly connected with

Figure 9.20 Rammed earth façade: Ricola storage and herb processing building, Laufen (architect: Herzog de Meuron, 1986–1991; left) and straw wall finish with the clay layer (right).

Figure 9.21 Honeycomb Apartments (OFIS arhitekti, 2006).
Courtesy of Ryszard Sandak.

the interior. A semitransparent textile element fixed on the front of the balconies blocks direct sunlight and accumulates an "air buffer" zone. During summer, perforated side-panels (10 cm holes) allow breeze to ventilate the space. In the winter, warm air stays in the area and provides additional heating to the apartments [46].

The way that nature creates materials often differs from recent manufacturing methods. Around 96% of natural material is made from four elements: carbon, oxygen, hydrogen, and nitrogen. The remaining 4% is constituted by seven elements, with minimal traces of a few more [45]. Nature organizes materials in a hierarchical way, mainly to achieve a given objective (principally stiffness and fracture control) with minimal material quantity. Moreover, the way nature builds is contrary to conventional methods used by humans (subtractive, molding, and forming). Nature uses additive manufacturing methods (similar to 3D printing) and self-assembling methods (similar to 4D printing) in order to use less material but maximize shape. This leads to the creation of smart materials where sensors simultaneously fulfill the role of actuators. In contrast, in conventional systems engineered by humans (described in Section 9.3.2.2), at least three elements are indispensable: sensors, processors, and actuators. Another interesting process related to regeneration is the self-repairing phenomena observed in biology, which is challenging for building materials since they are not alive in the same way as living organisms. However, development of bioconcrete (where limestone-producing bacteria are activated when a crack occurs) and biocoatings (where living *Aureobasidium pullulans* molds are regrooved on the wooden surface after damage) provides the first proof of concept solutions demonstrating novel capacities of materials [23,47].

In building contexts, plants, due to their immobility, can serve as valuable sources of inspiration for architecture. During 460 million years of evolution, they have become extremely well adapted to various climatic conditions: facing water loss or abundance, extreme temperatures, and UV and solar radiations. Plants growing in specific climates, due to exposure to certain conditions, develop biological adaptations allowing them survival and efficient reproduction [48]. Such solutions can serve as inspiration for designing new functional materials as well as for effective façade systems [49]. Brief descriptions of six climatic zones discussed below provide inspiration for transferring biological adaptation to building façade systems.

In deserts, there is evaporation excess over precipitation. This climate is characterized by direct sun, extreme daily temperatures, strong wind, and drought causing water loss. Plants, in order to survive these conditions, have developed a system allowing the collecting and storing of water and lowering its loss. Leaves are thick and small, often possessing hair and pins, and covered by a thick layer of wax for reduction of transpiration. Roots are long, allowing water uptake from deeper parts of the ground. Efficient shading and reflective systems provide a reduction of evaporation, and UV protection can be implemented in building façades, providing an efficient solution against heat in the arid climate. Water capturing and filtering systems integrated with building façades help to solve the problem of water accumulation and supply.

Less severe, but also demanding, is the prairie climate. Rainfall is uncertain, and drought is very common. Seasonal temperatures are extreme; summers are hot but winters cold, additionally strengthened by strong winds. Plants, in order to survive, lower their transpiration by developing a specific plant shape and narrow leaves. In order to protect against animals, thick bark and efficient reproduction systems (seed dispersing, rhizomes) were developed. Plants, due to uncertain rainfall, are efficient at storing water and, due to frequent fires, are capable of quickly regenerating. Solutions developed by plants growing in prairies provide inspiration for the development of materials capable of self-healing and self-regenerating. Seed-realizing systems, sensitive to high temperature, might serve as inspiration for dynamic façade elements capable of opening and closing, assuring efficient ventilation.

Temperate forests usually do not suffer due to limited water availability, however plants there face four seasons and, consequently, temperature changes. Summers are often hot, but temperature during winters drops below 0°C. Trees enter dormancy during winter, saving energy and surviving the winter period thanks to high thermal insulation and thick bark. Plants have developed efficient photosynthesis, which for angiosperms is possible only during the vegetation season. Lower temperature and shorter days initiate an abscission process allowing leaves to fall without leaving an open wound. This phenomenon could be useful in materials that are self-maintaining. Certain triggers (e.g., temperature, UV) might stimulate materials for production of an additional layer and removal of the old one. Simultaneously, at the end of the vegetative season, chlorophyll production is stopped, revealing red and yellow pigments that were masked by green. This phenomenon (e.g., as observed in beech leaves) might be used for communication and signalization actions when, again, certain triggers deactivate/activate pigmentation. Plants in this climate are usually sensitive to different stimuli. Nyctinasty occurs due to the response to temperature and light intensity (such as in *Oxalis*). Thigmonasty is a nastic response of plants to touch (or vibration), observed in mimosa. Other examples of self-movement include *Heliantus* (exhibiting phototropism) or pine cones (opening due to moisture changes). All movement actions might be implemented for the development of façade shading and dynamic energy storage systems.

With lowering temperatures, temperate forests are substituted by tundra growing in the polar zone. There, summers are cold and short and winters are severe and long. Solar radiation might vary, rainfall is low and, additionally, water uptake is limited by permafrost. Plants adapted by developing wax and hair protecting against the freeze. They are capable of efficiently absorbing solar radiation (specific colors) and modulating light reflection (shiny surfaces). These solutions can be implemented for modulation of light transmission in building façades, designing antifreezing surfaces, and developing dynamic shading and self-actuating energy storage systems.

In tropical climates, represented by rainforests, plants do not suffer due to lack of water. On the contrary, they are exposed to heavy rains, uneven solar radiation, high temperatures, and high relative humidity. Overall plant morphology and leaf shape (drip tip) allow high water runoff or, in some cases, water accumulation and storage. Additionally, a wax layer assures protection and hydrophobicity. Aerial roots allow CO_2 uptake. Such mechanisms can be used in the development of self-cleaning surfaces as well as filtering and phytoremediation systems dealing with accumulation and cleaning rainwater.

Finally, plants growing in the water environment possess constant H_2O availability but deal with water current and sporadic floods. There is no direct sun exposure, and temperatures are rather stable. Plants developed flexible stems and floating seeds allowing reproduction. Surfaces are hydrophobic (e.g., lotus leaf) and a thin cuticula layer allows high CO_2 uptake. Such developments are perfect examples for the design of materials and façades with adjusted stiffness/flexibility levels and possessing hydrophobic and self-cleaning surfaces.

The described solutions could be implemented in materials, building elements, or entire façade systems. If successfully implemented, they might improve both the energy efficiency and service life performance of buildings. If these phenomena are realized with renewable building materials, façades will benefit from superior performance and sustainability.

9.3.1.7 Urban mining and design for disassembly

The construction sector represents one of the biggest sources of waste in terms of volume, with approximately 70.5 million tons of wood waste generated annually [50]. Consequently, construction and demolition leftovers are widely recognized as one of the most important sources of waste [51]. Waste can be divided into three categories, according to their source: new construction, renovation, and demolition. Although the quantity of generated waste is significant, only one-third of waste is currently recycled (data related to building wood waste). According to the urban mining concept, building waste could be considered as a huge stock, consisting of many resources with different further uses [52]. In this case, different reuse, recycle, and end-of-life options can be implemented.

Any type of building material is a contributor to greenhouse gas emissions. The high carbon footprint of cement and steel production makes wood an attractive option for the building sector. However, even if CO_2 captured during photosynthesis gives timber a good position over other construction materials, efficient CO_2

management at the end-of-life is still challenging. Choices for the end-of-life scenario (reuse, recycle, upcycle, incineration) are limited by the types of products used for EWP manufacturing and protection (coatings, preservatives, adhesives) [53].

Urban mining is particularly simplified when buildings follow DfD rules. DfD, besides simplifying reparation and upgrading of products, enables components to be reused and recycled. Recovery of materials is intended to minimize the environmental impact and maximize economic value. The degree to which certain products can be disassembled determines the end-of-life option. Some material types and limited fasteners will simplify disassembly. The guide *DfD in the Built Environment* [54] provides 10 key principles to follow, which are summarized as follows:

1. Documents and methods for deconstruction;
2. Use of materials with high quality and feasible for further reuse;
3. Accessible connections;
4. Minimization or elimination of chemical connections (glues, binders, sealers);
5. Use of the standard screwed and nailed connections;
6. Separation of mechanical, electrical, and plumbing systems;
7. Planning and scheduling of separation in order to decrease labor-intense processes;
8. Use of simple structures and forms;
9. Use of modular and standardized solutions;
10. Safe deconstruction.

DfD is an important measure to achieve sustainable building. Several green building rating systems, such as the UK's BREEAM and Germany's DGNB, reward design for deconstruction. Thormark [55] analyzed the motives and benefits of DfD and concluded by summarizing them into three categories: economic, environmental, and social. The economic motives are related to increased costs of waste handling, extraction of resources, value of used resources, and benefits related to environmental labeling. Environmental motives include lack of virgin resources, problems related to waste generation, climate changes, and quality of end products. The social motives comprise demographic changes and faster than planned demolition of buildings.

Environmental aspects related to a circular economy and cascade use are particularly relevant while analyzing tendencies in the building market nowadays. The renovation potential of buildings in the EU is huge—up to 110 million buildings could be in need of renovation [56]. In 2015, renovation accounted for 57% of the total construction market, with residential buildings creating 65%. About 35% of buildings in the EU are over 50 years old. Around 80% of the current building stock will still be present in 2050, indicating a recent and developing demand for renovation [57]. Biobased building materials utilized according to DfD rules fit very well with the general concept of minimizing the amount of waste based on the "reduce–reuse–recycle" paradigm. A favorable weight to load-bearing ratio makes them perfectly suitable for upwarding existing buildings, especially in the urban context where erection of multistory structures is restricted by space limits. Sustainability in this perspective is achieved by using engineered wood products, prefabrication, modular design, and recovery of materials at the end of their service life.

Effective recovery and reuse of components from building demolition requires easily accessible information regarding materials. The idea to create a building passport, where relevant information on materials in the building is easily accessible and comparable, seems to be good solution. Optimally, the Materials Passport Platform should be connected with BIM and other design tools in order to allow information flow through the whole value chain. Data contain information regarding several properties of building materials: physical, chemical, biological, health, as well as information regarding their processing related to manufacturing, transport, construction, use phase, disassembly, and reuse [58].

Recently completed headquarters of the Council of the EU (architect: Samyn and Partners, 2016) is a credible example of urban mining (Fig. 9.22). The centrally located assembly hall is surrounded by a glazed double-leaf façade for the purpose of decreasing traffic noise propagation into the building. The external part of this double-leaf envelope is made of a "harmonized patchwork of reused oak windows" [59] that were "urban mined" on various demolition sites all over the EU. Designers of the building decided to reuse the original, but still efficient, window frames that were replaced by double- and triple-glazed windows according to the EU's new energy-saving policy. The collected window frames were measured and —with the use of computer software—matched to form large-scale façade panels. This is the reason why some were mounted in a rotated position in comparison to the original orientation. Individual frames were fixed to custom-made steel frames to form larger panels. The patchwork of windows is also meant to express the European "diversity of cultures" [59].

Another example that demonstrated how to save building resources is the Circular Pavilion (Fig. 9.23). It was built over 3 months in Paris and was made from 180 wooden doors recovered from an apartment building, used wooden exhibition panels, secondhand insulating board from disassembly of a supermarket roof, discarded furniture from junkyards, and obsolete streetlights. The pavilion was designed by the architects of the Encore Heureux agency, Nicola Delon and Julien Choppin, according to the circular economy philosophy: "one person's waste is someone else's resource."

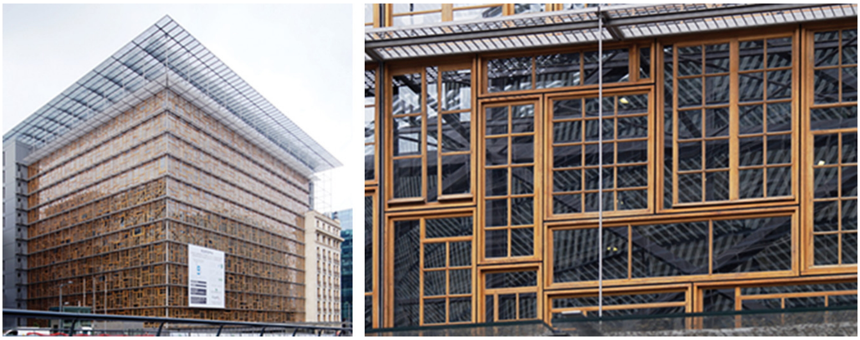

Figure 9.22 Council of the EU headquarters (architect: Samyn and Partners, 2016).

Figure 9.23 Circular Pavilion (Encore Heureux Architects, 2015).

Figure 9.24 Café Fratelli, London.

9.3.1.8 Prestige, symbolism, and individualization

Façades have always been used as a sign of prestige and wealth. They also fulfill an important information function as they communicate the significance of the building and its prestige to the observer. Material choice is an important aspect of the building's overall design. Not only the form of the building but also the material type and its performance characteristics are crucial parts of the process. Solid and durable materials are the first selection if prestige of the building is the focus. Stone and ceramics are used in parliament, juridical, and cultural buildings. They shape the urban scape of a city. However, other materials might also be used to communicate the client's attitude. Glass is frequently used because of its association with an institution's transparency, even if—in many cases—the resulting envelope is not really transparent. The case of biobased materials, which are currently commonly associated with low environmental impact and sustainability, is similar. An example of this is presented in Fig. 9.24, located in central London, merging wood, considered a traditional material, assembled in a modern way—two columns constructed with horizontal layers of thick wooden elements brings dynamics and movement to the building's façade.

Buildings that are made of natural materials are perceived as honest, sincere, and well-integrated with their surroundings [60]. Many construction companies use sustainable building materials due to the green consciousness of their clients and investors. According to Sadalla and Sheets [61], building materials may have both intrinsic and culturally relative meanings that homeowners employ in the process of defining their social identity. Selection of materials is often dictated by certain traditions and lifestyle choices of the individual. It can be expected that persons originating from different regions will have different materials preferences. However, due to globalization, trends in selection of certain materials are related mainly to living places (cities versus rural areas). Høibø et al. [62] analyzed the preferences of over 1700 persons regarding materials choices. In a city context, concrete was the most preferred material, followed by steel. In particular, façades consisting of brick and stone cladding were mainly selected. However, the authors suggested that the focus on wood as a natural and renewable resource may have influenced general attitudes. Additionally, the development of engineered wood products and colors associated with timber architecture may have a positive impact on the acceptance of wooden cladding in an urban context also.

Wood as a versatile material allows the creation of both rustic and modern structures. Additionally, due to relatively simple processing methods, wooden buildings can be tuned to fulfill specific customer requirements. Relatively simple maintenance, possible with a limited number of tools and broad access to DIY products, allows personalization of wooden elements in the façade context also. This is not a new approach, as several buildings in the past were decorated in order to preserve a certain identity of the local culture. In the Slovak village Čičmany, around 200 years ago, people started to paint their homes with lime to preserve damaged wood. Since the image of bright lime pigment on dark wood was prominent, people began elaborating and creating remarkable designs (Fig. 9.25). What is more relevant in this context is the fact that autochthone and rural architecture can be an inspiration for designing of new buildings capable of transforming the local identity in material culture [60].

Figure 9.25 Manually decorated timber houses in Čičmany (northern Slovakia).

9.3.1.9 *Sustainable, restorative, and regenerative aspects*

The implementation of wood as a material and biophilic design creates affinity to the natural environment, which is particularly relevant in an urban context. By including natural materials in interior or architectural design, users are instinctively reconnecting with nature. Surprisingly, even individuals who do not express any appreciation for plants and nature can have a negative effect from a lack of nature [63]. Any natural material perfectly fits into this concept. Using wood as an exposed material in buildings where humans can directly interact with it is known to create positive psychophysiological effects (Fig. 9.26). Research in this area provides evidence of positive health impacts of wood use in the built environment [64]. By directly or indirectly incorporating nature into the built environment, physiological and psychological indicators of stress are reduced, while productivity, creativity, and self-reported levels of well-being are increased [65]. Guidance for the use of natural materials in buildings in order to improve human health is provided by Restorative Environmental and Ergonomic Design (REED) [11]. REED is integrating frameworks aiming at improving occupant and user health, increasing safety, and improving building management. REED aims to design and create ergonomic, accessible, adaptable, and sustainable buildings by using natural materials.

Until now, buildings generally used the environment without having any positive impact, only exploiting natural and nonrenewable resources. Currently, the attitude toward environmental issues is drastically changing. There is a shift toward moving beyond sustainability into a net-positive zone [66]. In this context, sustainable means limiting the damage caused. Restorative and regenerative buildings go beyond traditional building concepts by improving the surrounding environment. Restorative means that social and ecological systems are restored to a healthy state. Regenerative means that the local social and ecological systems are pushed to continuously evolve. Both concepts, restorative and regenerative, are the next stage in green architecture. Buildings not only have to be energy-efficient but they should also give more to the environment during their lifetime than is taken away during

Figure 9.26 Example of restorative design implemented indoors.
Courtesy of Igor Gavrić, InnoRenew CoE.

construction. This principle is the root of the idea of restorative architecture. Buildings should be environmentally friendly and energy-efficient and, in addition, they should improve the surrounding environment. Restorative features go far beyond the building's measured physical parameters. They include farming, creating a friendly environment for fauna and flora (e.g., by placement of beehives), and reusing and collecting rainwater.

Sustainable construction principles require the use of local materials and products. In this perspective, environmentally friendly materials originating from plants or animals are of great interest to architects. An example is the Living Building Challenge certification program and sustainable design framework, which is organized into seven performance areas: place, water, energy, health and happiness, materials, equity, and beauty. Guidance related to materials selection provides rules related to material selection (applicable raw materials include stone and rock, metal, minerals, and timber), defines a list of forbidden materials, requires a certain percentage of building materials to be originated from within a certain distance to the construction site, and requires a materials conservation and management plan in order to reduce environmental burdens [67]. Cuerden Valley Park Visitor Centre is one of the first European examples targeting this concept.

Leadership in Energy and Environmental Design (LEED) is the most widely used green building rating system in the world. Projects pursuing LEED certification earn points across several categories: location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation, and more. Based on the number of points achieved, a project then earns one of four LEED rating levels: Certified, Silver, Gold, or Platinum. The LEED rating system is used in 165 countries and territories and is applicable for any project (new constructions and renovations). Examples of buildings fulfilling LEED certifications are presented in Fig. 9.27.

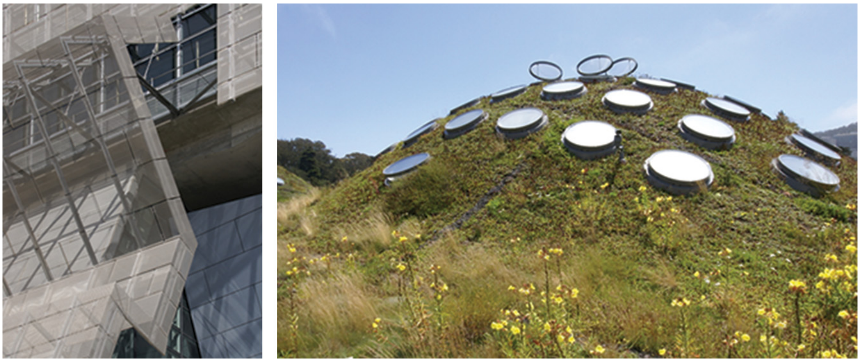

Figure 9.27 Buildings fulfilling LEED certifications: San Francisco Federal Building, the first federal building to be certified under the USGBC's Leadership in Energy and Environmental Design (LEED) criteria, (left), and LEED platinum certification for California Academy of Sciences/Renzo Piano Building Workshop + Stantec Architecture (right).

9.3.2 Façade function

9.3.2.1 Energy efficiency

Buildings all over the world are responsible for 40% of total energy consumption. Because energy production generates a large carbon footprint, buildings are also responsible for 36% of CO_2 emissions globally. This is the reason why so much effort is directed toward improving buildings' energy performance. Regulations limiting energy requirements of buildings are becoming more restrictive. Façades are influencing the energy performance of buildings due to solar gain and heat loss. The performance of the façade defines the energy requirements for heating, cooling, and artificial lighting. In many cases, requirements related to façade functions are contradictory—providing enough natural light and, simultaneously, avoid solar gains during summer months. Therefore, the design of energy-efficient building façades should focus on several aspects and interactions between them.

High energy efficiency of a building can be achieved by implementation of climatic design, high-performing building envelope (efficient insulation, high-performing glazing and windows, air-sealed construction, elimination of thermal bridges), and a well-performing ventilation system, including heat recovery. Climatic design was described in detail in Section 9.3.1.5, but what is important to highlight is that the appropriate orientation of building, openings, shadings, and proper color of façade allow for the achievement of thermal and visual comfort inside the building. Suitable thermal insulation has proven to be effective in terms of energy and cost savings. Every part of the building envelope (ground deck, roof, walls, and façades) should be insulated. Timber and other biobased materials, due to their cellular structure, present low thermal conductivity (~ 0.05 W/m/K). In conjunction with high moisture diffusivity (1.1×10^{-6}–1.2×10^{-5} m^2/s), they might be considered as a proper material to be used in building façades without the application of additional vapor barrier. Biobased materials, due to their characteristics—practically identical to some nonrenewable materials—are the real sustainable option in comparison to nonrenewable alternatives. Besides appropriate insulation, air leakage should be reduced as much as possible in order to create efficient, controllable, comfortable, healthy, and durable buildings. In extreme cases, air leakage might cause structure degradation and a reduction of insulation effectiveness. Another aspect, which should not be omitted, is proper ventilation, assuring controlled ingress and egress of air through buildings. If the ventilation system is not appropriate, buildings will suffer due to high moisture content and, consequently, mold and fungal deterioration.

Demand for low-energy houses in combination with sustainable awareness has resulted in energy-efficient buildings made of natural materials. An example of a passive wooden-straw house, presented in Fig. 9.28, is 90% composed of organic, renewable, and local materials. The building was nominated for the ARCH magazine Award 2013, indicating the progress of sustainable architecture [68].

In Europe, the building sector is the largest consumer of energy; therefore, the EU has agreed to new rules for the energy performance of buildings. National roadmaps to decarbonize buildings should be implemented by 2050. Buildings should

Figure 9.28 Passive wooden-straw family house in Melčice-Lieskové, Slovakia (Oximoron Studio M. Šichman, B. Meluš, 2013).

Figure 9.29 B.O.C. Bonneshof Office Center in Dusseldorf (RKW, Rhode Kellermann Wawrowsky, 2014).

be renovated and more efficiently operated by automation and control systems. Zero-energy buildings (ZEB) were recently defined by EU regulations as structures of very high energy performance, with demand for harvesting a significant amount of energy from on-site or nearby resources. It is planned that all new buildings in the EU will be classified as nearly ZEB by the end of 2020. However, the ZEB concept is both technically very demanding and economically very challenging. This is the reason why high investment cost places the concept of ZEB beyond the reach of many, even institutional, clients. An example of a building combining high energy efficiency (building-integrated photovoltaics) with high-tech façade elements is presented in Fig. 9.29. What is important to mention is the fact that, from an environmental perspective, it is not only the energy consumed by the building that counts. Full LCA analysis shows not only the energy consumed during erection, exploitation, and later, demolishing of the building, but also the environmental impact of built-in materials. This impact might be significantly reduced by structural and nonstructural biobased building materials as they, mostly, naturally degrade in the environment.

9.3.2.2 Adaptability

The major role of building façades is to separate two environments: external and internal. Standard static façades require constant human attention to regulate the microclimate of buildings. The term "adaptive façade" (also called "responsive," "dynamic," "switchable," "smart," or "active") includes systems capable of adapting physical properties in a reversible way as a response and/or adjustment to transient boundary conditions. Adaptive façades are a collection of different systems capable of reacting to external conditions by means of controlling its humidity, daylighting, solar shading, insulation, radiant heat exchange, ventilation, and energy harvesting [69]. In many cases, conventional simulation tools, experimental assessment methods, and key performance indicators cannot be fully adopted in the case of adaptive façades due to their intrinsic complexity. However, their development has recently accelerated with the use of modeling and simulation tools. The impact of different adaptive materials or façade configurations on economic and environmental building performance can be simulated and assist in the optimization of dynamic façade control strategies and material design.

Two forms of façade adaptability can be achieved by extrinsic or intrinsic stimuli. Extrinsic stimuli, such as electromagnetic field or pressure change, are implemented in electrochromic glazing, liquid crystal devices, and vacuum insulation. Those solutions are well-performing but needed to be integrated with controlling devices. Materials that react to intrinsic stimuli in buildings, such as light intensity, temperature, and moisture, are easily integrated within the buildings but are difficult to control precisely. Materials often implemented in adaptive façades are rather nonrenewable (e.g., glass, steel, phase-changing materials), but implementation of biobased materials as active façade elements was recently demonstrated and is under investigation [70]. Use of biobased materials in an adaptable building envelope exploits specific, characteristic features of the material: shrinkage/swelling ratio and directionality of the fiber grain. Inherent heterogeneity of the material, usually considered as a disadvantage, might provide the required changeability, for example, in the case of dimensional distortions. Biomaterial, if properly installed, dynamically reacts on changing environmental and weather conditions by warping, skewing, and bending. This dimensional change could be used to manipulate elements of the adaptable façade. Pine cones open and close according with the change of vapor content in the air; the same principle might be used to open or close vents in a façade, manipulate shading elements or tilt solar cells. Two thin layers of veneer, properly laminated, allow for significant dimensional change that could be used to tilt solar cells toward the sun to optimize solar gain. The same laminated flap is also used as a ventilation device, which controls the opening that is located behind in the project guided by Enrico Sergio Mazzuccheli. Architect Achim Menges used a double-laminated sheet of veneer to create a climate-responsive structure named HygroScope, which is able to respond to changing climate conditions without external steering or control (architect: Achim Menges, 2015). Another approach for the development of biobased materials capable of responding to environmental stimuli is 3D printing [71]. These authors were able to demonstrate shape-changing forms using fused filament fabrication methods. Moreover, by fabrication of custom cellulose composites, desired performance properties were achieved, allowing further control of actuation response.

An example of an adaptive façade is the Research Institute in Cerdanyola del Vallès (architect: Harquitectes + Dataae, 2017), designed to function in the hot and humid climate of Catalonia (Fig. 9.30). With the development of other weather-resistant transparent façade materials, acrylic and polycarbonate are used instead of glass, providing both protection and a better view. The cladding is 16 mm plywood, which is a relatively fragile material when exposed to external conditions, protected by polycarbonate panels. The external façade is adaptive as it can be opened and closed depending on the climatic conditions.

9.3.2.3 Façade leasing

Integration of new materials as well as new functionalities in building façades requires additional knowledge, attention, and maintenance actions. Cost of maintenance and retrofitting of buildings is often high compared to total building costs. In extreme cases, façades with integrated building services can make up over 90% of a project's initial investment [72]. Introduction of new, better-performing materials and systems is therefore usually costly and more demanding.

Application of new materials and façade systems, which are not yet fully validated in service conditions, brings new challenges for investors and contractors. A new business model, called "façade leasing," used as a performance-delivering tool

Figure 9.30 Research Institute in Cerdanyola del Vallès (architect: Harquitectes + Dataae, 2017).

for building façades, has been recently tested in Delft. It is shifting the current business model of "take, make, and dispose" toward a "product-service-systems" model. In the façade leasing concept, clients require energy performance and comfort service delivery instead of the façade itself. Maintenance actions and eventual replacements belong to contractor/investor duties. In this case, materials can be efficiently used and, if necessary, replaced and upgraded. This aspect is particularly relevant since several buildings are soon to reach the end of their service life. In order to make them once again comfortable and functional, energy efficiency of their façades should be substantially improved. Consequently, the façade leasing concept is an ongoing process where building components are constantly replaced by more efficient ones. In this way, materials of high quality and performance are promoted, contributing at the same time to responsible management of materials and resources. This business model is suitable to be implemented in both new constructions and retrofitting of existing buildings. It might accelerate market uptake of new technologies and optimize reuse and recycling of façade elements. This might significantly speed up development of novel solutions and, at the same time, gain clients' acceptance and confidence. Moreover, it might be the solution that mitigates against nonoptimal decisions being taken during a project's planning phase, where a focus on initial investment costs frequently prevents the adoption of more robust or energetically efficient systems [72]. Consequently, the total cost of ownership (TCO) can be lowered.

9.4 Conclusions

All building materials contribute to greenhouse gas emissions. The high carbon footprint of cement and steel production makes wood an attractive option for the building sector. CO_2 captured during photosynthesis gives timber a good position over other construction materials. Most of this captured carbon can be sequestered or result in net-zero carbon emissions, depending on the end-of-life disposal scenario. Nevertheless, choices for the end-of-life scenario (reuse, recycle, upcycle, incineration) are limited by the type of products used for EWP manufacturing and protection (coatings, preservatives, adhesives) [53].

Wood and other biobased materials are becoming increasingly acknowledged in modern architecture due to their esthetic value, improved performance, and sustainability. The façade is an important element of a building, creating a first impression and expressing information about the building function and status. The selection of sustainable materials is often motivated by heightened environmental awareness of clients, contractors, and architects.

The wood industry has witnessed significant growth in the last decade, primarily due to the development of EWPs (CLT, glulam, and LVL) and innovative wood modification processes improving material performance in service. Timber is also implemented in new combinations with concrete, steel, and glass to maximize structural efficiency, service life performance, and building esthetics.

Advanced digital design techniques and CNC processes allow precise prefabrication and, consequently, shorten the construction process and minimize dust pollution and noise. Lighter erection loads lead to reduced craneage; moreover, old buildings can be retrofitted and raised instead of being demolished.

This chapter has described key challenges regarding possible innovations in the biobased building sector from the perspective of development in materials science and design as well as tools and services for improved façade management. Rediscovering wood as a building material, even if challenging, certainly provides comfort and well-being for future users as well as increased sustainability of architecture. Biobased building materials can, therefore, move the traditional building concept toward restorative and regenerative architecture and preserve the environment for future generations.

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