Chapter 5
Service Life Performance

> *Prediction is very difficult, especially if it's about the future.*
> Niels Bohr

Abstract A special focus of this chapter is directed into assessing the performance of façades along the service life of the building. Influence of biotic and abiotic factors and their effect on materials physical and aesthetical properties are discussed. Principles of protection by design and their role in building performance during use phase are briefly introduced. Various approaches for the prediction of service life performance are supported with real case study data.

Façades directly influence building safety, comfort, and aesthetics. According to Martinez et al. (2015), façades have a role in security, thermal and acoustical insulation, air and water infiltration/mitigation, solar, daylight and glare control as well as in aesthetics. Over time, façade complexity evolved to accommodate a wide range of functionalities. Consequently, proper façade design has become a challenging and demanding task. Flores-Colen and de Brito (2010) listed several difficulties related to the performance of building façades. Those drawbacks are mainly related to poor design of construction details, improper choice or/and application of materials, and inadequate maintenance. To minimize mistakes in façade construction, modern design standards follow current building codes and specifications. However, the choice of proper materials is still challenging. Designers are often not willing to implement novel solutions with improved durability and low maintenance requirements, because they are not confident in their performance. At the same time, regular maintenance of façades is undesired among building owners. Fortunately, biomaterials are continuously improving and becoming more resistant to deterioration. Recent improvements in quality of biomaterials enable contractors to guarantee longer periods without maintenance, as well as to schedule the maintenance in advance. It is commonly accepted that façades require profound maintenance and/or partial renovation/replacement after 20 to 30 years following the construction (Martinez et al. 2015).

By predicting service life, it is possible to calculate lifelong construction costs (Gobakken and Lebow 2010). The deterioration intensity of façades depends on

A. Sandak et al., *Bio-based Building Skin*, Environmental Footprints and Eco-design of Products and Processes, https://doi.org/10.1007/978-981-13-3747-5_5

several variables, including building location, orientation, architectonical details, exposure level, microclimate, and intrinsic properties of materials used in construction. Clearly, all building materials (including concrete, metal, stone, and glass) require periodic cleaning, proper maintenance, and, finally, replacement. However, knowing which materials constitute façades is not enough to reliably predict service life performance of buildings, despite the great effort invested in trying (Fagerlund 1985).

5.1 Service Life Definition

The reference service life (RSL) is defined as a "service life of a product, component, assembly or system that is known to be expected under a particular set (e.g., reference set) of in-use conditions and which may form the basis of estimating the service life under other in-use conditions" (ISO 15686-1 2011). Evidently, service life of façades depends on several variables that are beyond the control of designers, such as local microclimate, environmental factors, or extreme weather events. However, regular inspection, maintenance, repair, or timely replacement of façades can significantly improve both building performance and owners' satisfaction. Proper balance between expected functionality, investment costs, and maintenance efforts enables sustained building performance. To assure optimal building functionality, it is critical to determine durability and service life of various materials, components, installations, and structures (Hovde 2002).

5.1.1 Service Life Categories

Kelly (2007) proposed division of the building service life into three main categories:

- Physical (technical) service life
- Functional service life
- Economic service life.

Physical or technical service life is related to the degradation of building elements due to natural ageing and deterioration factors. Probability of building failure increases systematically with time. This is mainly due to the natural ageing processes and degradation agents. Physical service life ends when the probability of building element failure is larger than the predefined level of acceptable risk.

Functional service life is linked to the expectations and demands of building users. In many cases, people are motivated to replace materials in order to follow recent trends and not because of their degraded technical performance (Rametsteiner et al. 2007). According to the studies conducted by Martinez et al.

(2015), aesthetics is the main motivation for retrofitting façades (accounting for 74% of all responses), followed by energy performance (65%), and remediation (56%). Therefore, trends in material choice should not be neglected when designing the building (Ebbert and Knaack 2007).

Economic service life is defined as the time between the beginning of building utilization and its replacement. Instead of maintaining existing façades, it is often both preferred and more cost effective to introduce new architectural solutions. Accordingly, buildings became economically obsolete with the development of new structural solutions that are more economical, more durable, and requiring less maintenance (Silva et al. 2016).

5.2 Deterioration of Biomaterials

Bio-based materials might provide optimal performance when assuring certain exposure conditions along the service life. Under specific circumstances, biomaterials may deteriorate to a different extent and velocity. Causes of degradation are generally divided into biotic and abiotic factors. Even though degradation mechanisms between these factors differ, both may occur simultaneously and affect degradation kinetics and the extent of the damage.

5.2.1 Biotic Factors

Fungi, insects, moulds, algae, and bacteria are the principal organisms degrading bio-based façade materials. Table 5.1 presents main types of damage caused by biotic agents and boundary climatic conditions stimulating their activity (Brischke et al. 2006; Viitanen et al. 2010). Detailed mechanisms of deterioration processes induced by organisms are described in the following part of the chapter. Severe decay of biomaterials is almost always caused by incorrect design, faulty assembly, or improper maintenance. To avoid deterioration by biotic agents, it is crucial to ensure proper drainage and drying in buildings (Clausen 2010). When it is not possible to maintain dry conditions, it is highly recommended to use either durable wood species or modified wood. Systematic inspection and repairs or replacements of decayed elements should be carried out regularly. Only dry and properly preconditioned elements without signs of fungal and insect infestations should be used as replacements. Obviously, direct causes of the initial decay (such as leakage, water trap, and perforation) should be eliminated to prevent the same problem appearing in the future.

Table 5.1 Key biotic agents causing deterioration of bio-based building materials

Organism	Damage	Environment cond. range	
		RH (%)	Temperature (°C)
Bacteria	Material softening, unpleasant odour, health problems	>97	−5 to 60
Mould	Discolouration, unpleasant odour, health problems	>75	0 to 45
Algae	Discolouration	>95	0 to 40
Decay fungi	Degradation of chemical components depending on the fungi type, material strength loss, unpleasant odour, health problems	>95	0 to 45
Insects	Strength loss (severity depending on insect taxon)	>65	5 to 50

5.2.2 *Abiotic Factors*

Abiotic factors are all inorganic chemical and physical components affecting buildings during their service life. They create boundary conditions for biotic agents. The origins of weathering are known; however, the mechanisms of degradation are only partially understood (Cogulet et al. 2018). Some of the most profound factors influencing the service life of biomaterials in façades are described below.

Water

Water, stemming from various sources (e.g., precipitation, condensation, leakage), is one of the key factors affecting weathering of biomaterials. Water that comes in contact with unprotected biomaterial surfaces is promptly absorbed by the sub-surface bulk, followed by further moisture migration within the cell walls (Feist and Hon 1984). When the relative humidity is increased, water vapour is directly absorbed by the bulk until the equilibrium moisture content is reached. The process of the moisture uptake (up to the level of fibre saturation) leads to material swelling. Due to the moisture gradient between the surface and its inner part, the material swells and shrinks, creating internal tensions and stresses. It may lead to the checking and cracking of biomaterials as well as membranes, when surfaces are coated. Important parameter that merges both climatic conditions and material deterioration is time of wetness (TOW). It indicates the period during which the atmospheric conditions promote the formation of a moisture layer directly wetting the biomaterial surface. TOW highly depends on the façade design, where horizontal surfaces limit the rainwater run-off. In general, TOW decreases with the increase of the exposure angle. TOW depends also on the wood species and modification processes applied (Van Acker et al. 2014; Meyer et al. 2012). In biomaterial surfaces, rain and wind remove residuals of photodegradation and erosion caused by weathering.

Solar Radiation

Biomaterial surfaces exposed to sunlight obtain visible colour alternations. In softwood, surface colours become more yellow or brown at the initial phase of degradation, followed by greying of the surface layer, as illustrated in Fig. 5.1. The colour changes occur to a depth of 0.05–2.5 mm, depending on the species and its specific density (Feist and Hon 1984). Discolouration is related primarily to the lignin decomposition resulting from the photodegradation. Even though discolouration kinetics differ between early and late wood, colour is nearly the same in both after prolonged weathering periods. Different parts of sunlight spectrum—visible, infrared, and UV light—degrade polymers; however, UV is the most damaging among them. Sunlight and water are considered the main factors affecting weathering intensity and kinetics. Interestingly, sunlight can both intensify and alleviate damaging effects of water (Feist and Hon 1984).

Temperature, Its Amplitude, and Gradient

The temperature of building surfaces is influenced by both external climatic conditions and properties of materials used. External factors include surrounding air temperature, solar radiation cumulative energy, relative air humidity, as well as wind direction and speed. Additional factors are the building orientation and its surroundings, presence of other buildings nearby, vegetation, and the proximity of water reservoirs. Material properties that influence temperatures of building surfaces include specific heat capacity, surface emissivity, radiation absorptivity and transmittance, albedo, bulk density, colour, and roughness. Since these properties vary among materials, it is clear that material choice is important in thermal performance of buildings. Materials can either decrease or increase near-surface air temperature, depending on how the bulk surface interacts with the sunlight (i.e., reflection, absorption, transmission). Consequently, façade materials play a major role in controlling ambient microclimates by affecting the temperature on the inside and the outside of buildings as well as inside urban spaces (Al-hafiz et al. 2017).

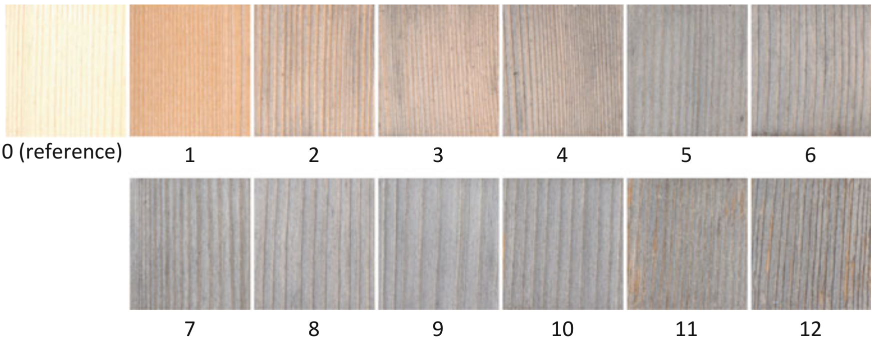

Fig. 5.1 Appearance of samples due to natural weathering (northern exposure) for 1 year in San Michele, Italy (numbers correspond to the months of exposure)

Therefore, in biomaterials that are considered for the use in façades, it is important to assess emissivity since it varies significantly among materials. A simple experimental approach to determine emissivity of biomaterials has been reported by Grossi et al. (2018).

Pollutants

Pollutants may be dispersed in the air as gas molecules, liquid microdrops, or solid particles. Even though most of the air pollution originates from man-made processes (e.g. industrial emissions, agriculture, transport), air is also polluted by natural processes, such as dust forming from rocks, volcanic activities, and soil erosion. According to Kuzmichev and Loboyko (2016), building façades are considerably degraded by dust deriving from polluted air. Especially, the effect of corrosive solid particles, liquid, and/or gaseous contaminants combined with a high humidity of ambient air has a highly negative impact on the external appearance of buildings (Kuzmichev and Loboyko 2016). For this reason, façades made of stone or brick should be regularly cleaned. Paints or coatings containing TiO_2 nanoparticles (or other hydrophobic agents) are recommended façades to sustainably and inexpensively reduce pollution and boost "self-cleaning" of façades (Mansour and Al-Dawery 2017). Moreover, according to recent studies, coating materials containing TiO_2 accelerate natural oxidation process of nitrogen oxides (NO_x) and sulphur oxides (SO_x) due to highly photocatalytic action of TiO_2 (Shukla et al. 2018). Hence, their use might help in reducing pollution and improving air quality in highly urbanized cities.

Physical Damage

Mechanical agents impose physical forces on buildings leading to stress and strain concentrations. The mechanical action can be static and permanent (such as ground pressure), or dynamic. In the second case, it is important to consider the influence of the wind and surface erosion caused by abrasion of suspended particles. The snow load is a static but temporary mechanical action also affecting the stress distribution within the structure. Even though limited mechanical deformations do not affect the structure integrity, they may stimulate generation of microfractures allowing water penetration and intrusion of micro-organisms. Façades, as an external part protecting the building, should be designed to resist such mechanical actions with minimal physical damage.

5.3 Deterioration Processes

By interacting with abovementioned biotic and abiotic factors, biomaterial surface and bulk undergo several changes affecting the original material properties. The mechanism of such changes is rather complex and may result from diverse processes occurring simultaneously or in sequence. The most pronounced processes of biomaterial degradation include ageing, weathering, mould and algae growth, decay, waterlogging, and insect infestation.

5.3.1 Ageing

Biomaterials start ageing immediately after their components, that is, plants, are cut down. The ageing process is highly influenced by environmental conditions (Fengel 1991). In timber, ageing is slow and occurs only in dry exposed wood structures, where the environmental conditions protect the material from fungi growth. Froidevaux and Navi (2013) defined ageing in wood as a slow chemical reaction taking place without the biotic degradation. During natural ageing, chemical reactions occur gradually, and the process may last for centuries. Changes in chemical composition of aged biomaterials depend on the species, environmental exposure, and the temperature–moisture history of the material. Fengel and Wegener (1989) noticed considerable decrements of the hemicellulose content in softwood roof elements aged for more than 300 years. The overall cellulose content in the wood does not change with ageing. However, due to the slow hydrolysis reaction, cellulose chains (microfibrils) were shortened and consequently polymerization degree decreases. Façades rarely age uniformly, since their exposure to environmental factors makes them prone to several degradation factors.

5.3.2 Weathering

Weathering is defined as a degradation process of materials that are exposed to external climatic conditions. In most cases, weathering is caused by abiotic factors and manifests as an alteration of colour, surface cracking, change in glossiness, and increased surface roughness. The intensity and extent of weathering depend on the local microclimate conditions, weather history, material type, function of an element, architectural details, and specific surface properties. The most important factors affecting weathering kinetics are solar radiation and stresses imposed by the cyclic wetting (moisture), together with temperature changes, environmental pollutants, and actions of certain micro-organisms. In general, unprotected raw biomaterials weather fast in the sub-surface, leaving the bulk intact. Differences in discolouration may be very noticeable within the same façade, especially in buildings where water and solar radiation are not spread uniformly across the surface (Fig. 5.2).

Fig. 5.2 Non-uniformly weathered building. Right image courtesy of Lone Ross Gobakken, NIBIO

Fig. 5.3 Weathered building in Stavanger, Norway. Image courtesy of Lone Ross Gobakken, NIBIO

Surface erosion in biomaterials is a side effect of weathering, where certain fibres resulting from the photodegradation of lignin are washed out. As late and early woods differ in their resistance to the erosion, surfaces can become curved, since low-density earlywood is removed faster. In mild climates, middle-density softwood generally erodes slowly, around 6 mm per century (Williams 2005). Often, weathering is a main degradation process affecting both the overall façade performance and the aesthetical perception of the building. However, in some cases weathering highlights building architectonic character and is not considered negative (Figs. 5.3 and 5.4).

Fig. 5.4 Astrup Fearnley Museum by Renzo Piano. Right image courtesy of Lone Ross Gobakken, NIBIO

5.3.3 Moulds and Algae Growth

Although mould does not affect the structural properties of wooden façades, it has a large effect on the aesthetical service life of the cladding. The main factors supporting its growth are water, nutrient source, and suitable temperature. The presence of moulds significantly changes façade appearance (Fig. 5.5). Colour of mould ranges from white, yellow, green, pink, brown to black. Some moulds (e.g., Trichoderma, Aspergillus) can leave a permanent stain or discolouration on the façade surface even after removed. Coatings may prevent mould growth very

Fig. 5.5 Wooden façade with the signs of moulds growth. Images courtesy of Lone Ross Gobakken, NIBIO

Fig. 5.6 Algae growth on the building façade

differently when exposed outdoors depending on the formulation and range of application (Gobakken et al. 2010). Since moulds and their spores are widely present in the environment, appropriate water management, adequate ventilation, and vapour barriers are necessary to protect building envelopes.

In addition to moulds, aerophilic algae frequently grow on building façades. Algae can develop in environments with high moisture levels (up to 100% RH), wide temperature range (0–40 °C), and limited light availability. Most algae can withstand extreme conditions, including severe temperatures and temporary drought. Algae most frequently grow on northern façades, where the direct sunlight illumination is minimal (Lengsfeld and Krus 2004). According to Gobakken and Vestøl (2012), growth of algae and lichen, cracking, flaking, and colour changes may also influence the aesthetical appearance, but usually to a lesser extent than mould and blue stain fungi. Figure 5.6 presents an example of a wooden cladding with algae coverage appearing unexpectedly on the northern façade after only 2 years of service life.

5.3.4 Decay

Fungi degrade wood by decomposing its constitutive polymers. The exact mechanism of this process depends on the specific enzymatic system of fungi. Brown-rot fungi use cellulase enzyme and degrade primarily polysaccharides (cellulose and hemicellulose), while they barely impact the lignin structure. The colour of wood becomes darker (light brown), and multiple cracks appear on the surface. The cracks may not only appear along the fibre direction but also across the grain, creating cubical pattern of discontinuities (Fig. 5.7a). The removal of cellulose results in a drastic decrease of certain mechanical properties of materials, such as modulus of elasticity (MOE) and modulus of rapture (MOR) (Singh 2000).

White-rot fungi are micro-organisms capable of decomposing both carbohydrates and lignin. Selective white-rot fungi degrade lignin in woody plant cell walls relatively to a higher extent than cellulose, while non-selective fungi may degrade all chemical wood components at a similar rate, leading to a uniform decay of the cell wall (Sandak et al. 2013). According to Winandy and Morrell (1993), these fungi do not significantly affect specific gravity, equilibrium moisture content, and bending properties. A visible sign of their presence is a spongy texture of wood without cross-cracks (Fig. 5.7b). Soft-rot fungi are typically active in wet environments, making materials severely low in strength (Singh 2000). The main enzyme of these fungi is cellulase, which easily degrades cellulose. In wood, this weakens the structure of the secondary wall while the middle lamella between cells remains unaffected.

White- and brown-rot fungi negatively impact aesthetical perception of façades and, in extreme cases, affect the structural integrity of buildings (Fig. 5.8). The maintenance of rotten façade parts is highly problematic. Often, the only reasonable strategy is to replace the infected elements.

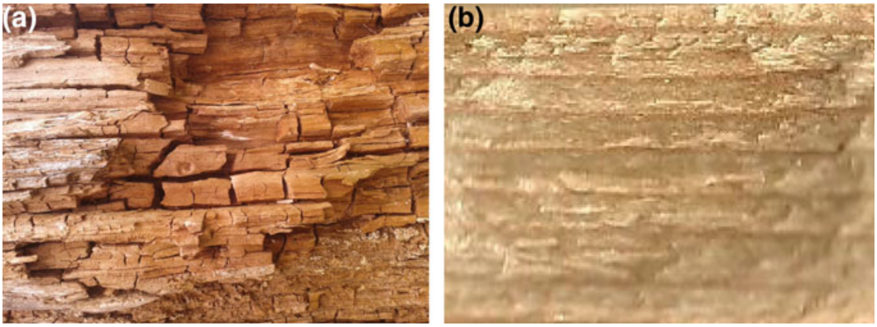

Fig. 5.7 Surface of biomaterial decayed by **a** brown-rot and **b** white-rot fungi

Fig. 5.8 Decay presence on the building façades. Images courtesy of Lone Ross Gobakken, NIBIO

5.3.5 Waterlogging

Waterlogging is typically irrelevant in building façades, unless the structures are erected in places directly affected by the water (including peats and wetlands) or exposed to frequent extreme weather events, such as floods. Most biomaterials slowly decompose in waterlogging conditions as a result of a complex interaction between the damp environment and the chemical constituents of the material. The key factors affecting the process are the presence (or absence) of oxygen, bacteria, fungi, and water temperature and its pH (Babinski et al. 2014; Sandak et al. 2014).

In general, chemical degradations slow down in the absence of oxygen, which can preserve biomaterials from extensive decomposition for millennia. However, certain bacteria are active also in anoxic environments. In this case, bacterial wood degradation is mainly stimulated by the water movement (Klaassen 2008). The most vulnerable part of the structure for degradation is the section that is at times immersed in water and at times exposed to ambient air (Fig. 5.9). In this case, the waterlogging degradation process caused by bacteria is far slower than the deterioration generated by fungi. This is because optimal conditions for fungal growth are just above the water level. Structures in such areas are delicate, and proper selection of construction materials is thus indispensable. It is recommended to use naturally durable wood species, treated/impregnated wood, or frequently replace façade elements at the water–air boundary. It is also important to design a structure in a way that the replacement of elements is simple.

Fig. 5.9 Wooden pier exposed to fluctuations of the water level. Image courtesy of Lone Ross Gobakken, NIBIO

Fig. 5.10 Wooden façade degraded by insects. Images courtesy of Magdalena Kutnik, FCBA

5.3.6 Insects

Most bio-based materials are food, shelter, and breeding environment for insects. Wood-destroying insects lay eggs in wood cracks and generally use wood as their main habitat. In wood, some of the most common insects are beetles (Coleoptera) and termites (Isoptera). Both belong to xylophagus, which means their diet is based on ligno-cellulosic materials (Brischke and Unger 2017). The larvae of beetles consume wood, producing a network of galleries which affect material mechanical properties and ease the access of other decaying micro-organisms. Termites living in large colonies (from 1000 to 2 million) are classified according to their living and feeding habits as dampwood, subterranean, and dry wood termites. Around 30 termite species are identified as causing damage to wooden buildings. It is not known in detail how different termite colonies choose their food. It is possible, however, to identify geographical locations where the termite attack is most probable. The risk of the insect infestation can be substantially reduced by implementing pest-resistant materials or impregnated/modified biomaterials identified as not attractive to xylophagus. An example of a wooden façade damaged by Cerambycidae, Anobiidae, and termites in presented in Fig. 5.10.

Marine borers (including mollusc or crustacean) may also be considered as organisms degrading biomaterials. However, their impact on building façades is minimal, except in waterlogging. In any case, using naturally resistant or impregnated biomaterials should be considered a necessity.

5.4 Potential Hazards and Degrading Agents

Other factors than biotic and abiotic should also be carefully considered when designing, installing, or using biomaterial façades. The most important factors are either anthropogenic or related to natural disasters.

5.4.1 Fire

When exposed to high temperatures, biomaterial properties change due to irreversible chemical reactions and physical changes of their chemical components. The extent of these changes depends on the temperature level and the exposure duration. At temperatures higher than 65 °C, strength and modulus of elasticity can permanently decrease, making the biomaterial more brittle. However, when exposed to high temperatures, biomaterials become a fuel and undertake the pyrolysis reaction when ignited. Following this, biomaterials develop an insulating layer of char that retards further degradation of sufficiently dense biomaterials, such as wood. The temperature in the char layer 6 mm below the burning surface is less than 180 °C due to the low thermal conductivity of wood. Therefore, bio-based structures can continue to carry a load even in the event of fire, assuming that their geometrical dimensions were sufficiently upscaled to assure the presence of uncharred cross sections (Dietenberger and Hasburgh 2016). In façades, knowledgeable design, implementation of proper materials, and careful installation may greatly influence the building performance during a fire. Bio-based materials in building façades can withstand a fire, if the façade geometry design does not permit contact between the fire plume and the cladding. Still, it is recommended to use materials treated with fire retardants and deflector elements able to change flame trajectory (Nguyen et al. 2016).

5.4.2 Flood

Bio-based materials fully immersed in water for prolonged periods will not decay, since the oxygen needed to sustain life of most micro-organisms is in shortage. On the other hand, biomaterials are more prone to biological attack immediately after the extensive wetting or flooding. The elevated risk lasts until the environmental conditions (i.e., air temperature, relative humidity, and biomaterial moisture content) return to non-hazardous levels. It should be considered that biomaterials tend to swell when saturated with water and may interact with other building components through an enormous pressure generated by the swelling. When flooded, bio-based building façade should be cleaned of mud and soil and, if at all possible, quickly dried. The drying process will shrink and further distort materials/structures. The extent of swelling and shrinkage depends on the species of which a biomaterial is derived from, biomaterial type, and the duration of water exposure (MacKenzie 2015).

5.4.3 Earthquake

Earthquakes generate ground motions in three dimensions that vary with time. Seismic movements are classified according to the movement direction. Vertical ground motions (caused by the P waves) generate forces that either add to or subtract from the gravitational force. They cause a fractional decrease of material volume by compressing it. In this case, load-carrying building structures usually help to prevent the damage and façades do not significantly contribute to the building integrity.

The impact of façades, however, may be important in horizontal movement (caused mainly by the S waves) that generates the most damage. Horizontal movements have a relatively large amplitude and cause shear deformations. Therefore, the building strength depends on the strength of the envelope and its connections. A properly designed façade made of biomaterials may help in reducing shear deformations and absorbing the disseminated energy. As a rule of thumb, the base of walls needs to be securely attached to the building foundation, while the roof and the floor must be safely fastened to the walls (Graf and Seligson 2011). Unfortunately, destructive effects of earthquakes can be magnified by the subsequent dangerous events, such as spontaneous fires, floods, soil liquefaction, or avalanches.

5.4.4 Vandalism

In the context of building façades, vandalism is the intentional damage of someone's property without the owner's permission. Damage resulting from vandalism varies in type and extent. Often, it is not necessary to replace damaged elements, since it is possible to clean or repaint the façade surface. In fact, one of the advantages of biomaterial façades is the relatively easy removal of graffiti. In most cases, façade surfaces can be washed, sanded, or repainted. In addition, there are several products able to protect façades with anti-graffiti coatings applied directly on biomaterials.

5.5 Protection by Design

Protection by design is an approach in which the planning process includes careful analysis of both the specific properties of materials used and the tailored building detailing. The overall goal is to eliminate or minimize any negative influences of material natural drawbacks. In bio-based building façades, it is essential to assure a fast water release from the structure after the event of wetting (Lstiburek 2006). This can be achieved in two ways:

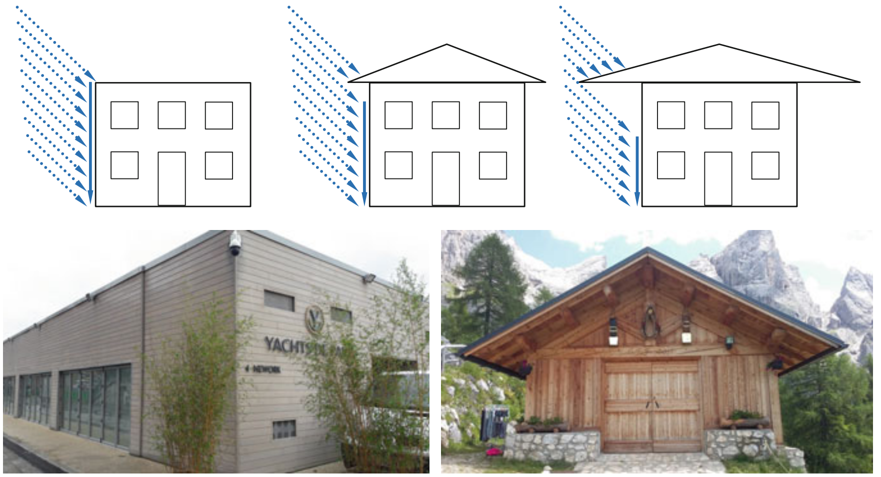

Fig. 5.11 Different strategies for rain deflection. Right image courtesy of Marta Petrillo, CNR-IVALSA

- By implementing large-scale building elements that deflect rain, such as large roof overhangs and eves, protruding slab elements, and cantilevers (Fig. 5.11)
- By careful detailing of the small-scale technical solutions, such as connections, overlaps, and water traps elimination (Fig. 5.12).

Bio-based façades should be designed to avoid water entrapment between elements and to enable unimpeded moisture run-off. For example, tongue and groove connections should be implemented with the grove always on the top or overlapped connections similar to those of roof tiles should be used (Fig. 5.13). In case the water is ever entrapped, the façade design should enforce the air movement to facilitate drying and water evaporation. Open crevices that might create thin slits should be avoided, as they may absorb the water. Desired water migration could be also driven by the pressure differences between the surface of the façade and its interior. In this case, the wind causes higher pressure on the exterior face of the wall. The mitigation action in order to avoid rain penetration might be pressure equalization (Kudder and Erdly 1998). An important part of the protection by design paradigm is the use of flashing over the opening (e.g., windows and doors). Proper flashing includes the layering of water-resistant membranes, where each successive layer moves the water further away from the structure (Magee 2012). An example of the building that was designed by considering the abovementioned rules is presented in Fig. 5.11 (right). Here, the roof is large and protects the façade from the direct rain and snow precipitation. The part of the façade close to the ground is made of stone that avoids rainwater uptake and protects building foundations.

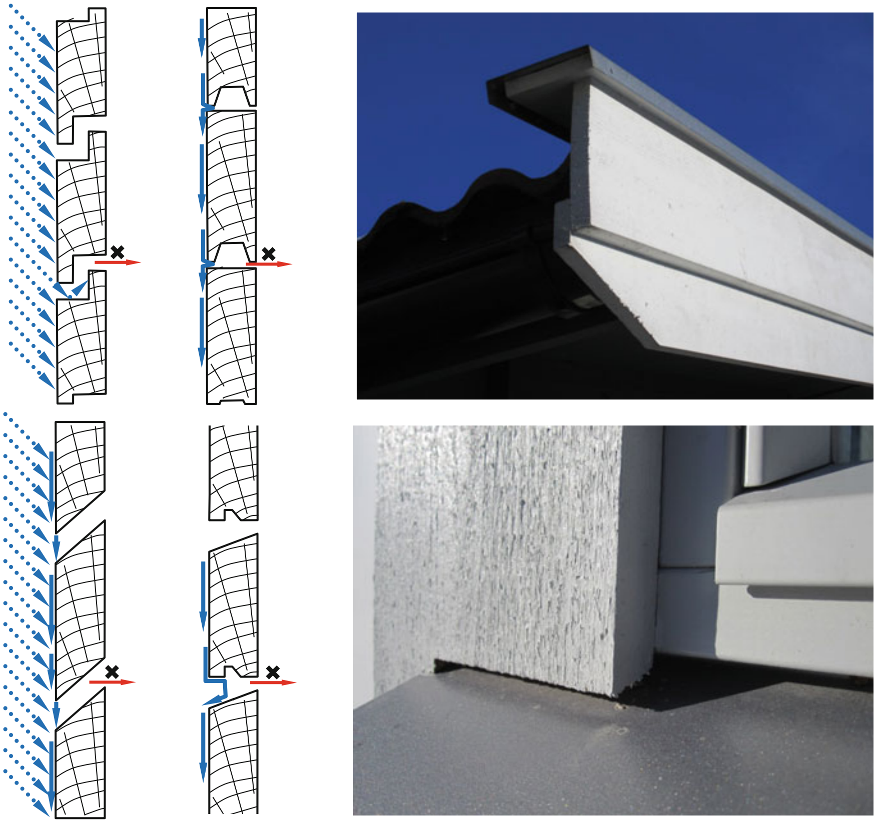

Fig. 5.12 Protection by design details allowing fast water run-off. Image courtesy of Lone Ross Gobakken, NIBIO

Fig. 5.13 Timber cladding with proper spacing between the timber planks and water run-off flashing

It is of utmost importance to foresee the maintenance schemes in different types of bio-based façades. All technical solutions in façades should enable easy dismantle of the modular façade units or at least allow simple replacement of single elements. Modular façades ease maintenance operations, such as sanding (removing the layer of corroded cellulose cells) or repainting/coating.

5.6 Serviceability, Durability, and Performance Over Time

To evaluate the overall building performance, the main criteria to consider are heat and mass transfer, acoustics, light access, fire resistance, costs, sustainability, and service life performance (Hendriks and Hens 2000). While the energy performance during the building use is often accounted for at the design phase simulations, the service life related to the biological, physical, and chemical attacks is often neglected. Service life of the building as a whole is influenced by several façade-related performance indicators, such as its durability (e.g., material quality, decay resistance, lifespan), compliance (e.g., maintenance flexibility, environmental impact), affordability (e.g., maintenance and refurbishment costs), and well-being (e.g., aesthetical appeal, customer satisfaction) (Jin et al. 2014). The estimated service life (ESL) prediction is a method useful in simulating total economic and environmental costs associated with the structure usage. The ESL of a structure ends when it reaches the predefined limit of acceptable imperfections or loses certain functions (Fig. 5.14). Ordinarily, the end of ESL is induced by aesthetical deterioration, long before the structure is deprived of its functions or safety. However, without the proper maintenance, the safety of a structure can be greatly diminished. The service life can be prolonged if the elements are replaced on time. In fact, service life can be substantially extended when maintenance is regularly scheduled and properly implemented. It is challenging, however, to maintain acceptable levels of appearance, functionality, and safety, while satisfying performance requirements and staying within reasonable limits of operational and maintenance costs.

5.7 Methods for Estimating Service Life Duration

Service life duration can be estimated with different methods. They produce different types of information, from absolute values to probabilistic distributions that characterize the estimated service life (Silva et al. 2016). Their advantages, limitations, and the quality of information produced are presented below.

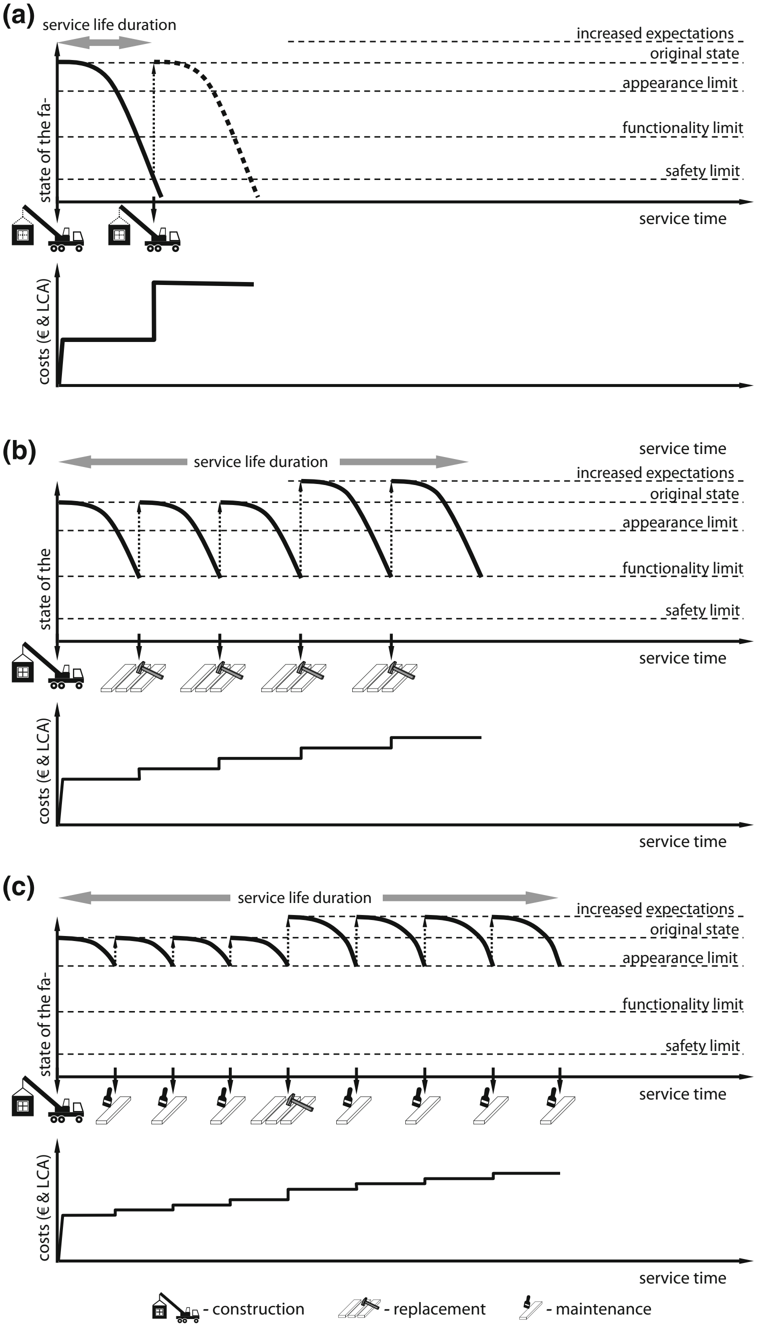

Fig. 5.14 Estimated service life of building façade according to different scenarios; no any repairs (**a**), replacement (**b**), and frequent maintenance (**c**)

5.7.1 Factorial Methods

According to the ISO standard (ISO 15686-1 2011), factorial method is the most frequently used method in recent times. It is based on calculating reference service life with consideration of several factors associated with specific usage conditions (Hovde 2002, 2005). This method considers service life characteristics of constructional elements but neglects degradation conditions. Unfortunately, small miscalculations are enough to significantly affect the service life estimation. Another drawback of the factor method is that it provides a single invariable value without considering possible fluctuations (Silva et al. 2016).

An adaptation of the ISO 15686 standard method used in exterior coated wood was extensively researched within the SERVOWOOD project (www.servowood.eu). There, the key deliverable was a new concept for the service life prediction (SLP) modelling approach using a customized set of "modifying" factors. Each of these factors reflects the effect of certain components on the performance of the wood coating system when compared to the reference coating solution. The weight of correction factors is determined experimentally by conducting long-term natural weathering tests. The SERVOWOOD method is expressed numerically in Eq. 5.1:

$$\mathrm{SLP} = \mathrm{RSL} \times A \times B \times C \times E \times F \times G \tag{5.1}$$

RSL	reference value of service life length (years) estimated based on practical experience or experimental data;
A	coating properties;
B	substrate properties;
C	production quality;
E	exposure dose (outdoor environment);
F	situation of component (usage conditions);
G	inspection/maintenance measures.

5.7.2 Statistical Methods

Deterministic methods use mathematical and/or statistical formulations to describe the relationship between the degradation factors and the building condition. These methods intend to obtain a function that best fits a set of random data. For this, they require sets of large and representative data to be used in numerical/statistical modelling.

Regression can be used to model weathering deterioration progress and, consequently, service life prediction. Here, partial least squared (PLS) regression or multi-way data analysis can be carried out. In example proposed by Sandak et al. (2015a, b), PLS evaluates characteristics of two extreme samples, one not at all exposed to weathering and another that is at the final stage of the weathering deterioration. A non-exposed sample is assigned the degradation index 0, while a completely degraded samples receives the index 1000. PLS incorporates reference data corresponding to both extremes of deterioration levels. The data include objectively assessed characteristics, such as colour, gloss, chemical composition, and roughness. PLS can also incorporate new sets of specific characteristics and thus estimate the progress of weathering in previously unknown samples (Sandak et al. 2015a; b, Sandak et al. 2016). This method can predict the degradation level by placing a sample somewhere in between the brand new and completely degraded. However, the model requires all samples to follow the same degradation mechanism/path and separate PLS models have to be developed for different sample configurations (e.g., material type, coating, exposure conditions).

As an alternative to PLS, multi-way data analysis (MWA) is a method of analysing information sets that can be represented in a multi-dimensional array (Sandak et al. 2017). The dimension may correspond to either measurement duration, location, or methodology/parameter. MWA methods are particularly useful in time series analysis and, consequently, in deterioration/weathering modelling. Variables (sample characteristics) acquired during the weathering in each experimental location are portrayed in a multi-way array. A result of the MWA is a set of loadings and scores for each mode, case, and variable. Loadings can be examined separately to enhance the understanding of the influences of experimental variables (e.g., exposure location, test duration, material properties, surface finishing). Like PLS, the MWA model can predict the weathering of unknown samples. It can also simulate the weathering progress in numerous weathering scenarios.

5.7.3 Experimental Methods

Experimental methods are the alternative approaches to those presented above. These methods typically carry out in situ measurements or accelerated tests in laboratory conditions in order to evaluate effects of specific agents on the deterioration. Empirical methods are usually augmented by in-field survey of degradation factors leading to the determination of the life cycle expectancy (Flores-Colen and de Brito 2010). However, acquiring data in real service life conditions is challenging, since it is often not practical to expose samples to deteriorating conditions for a sufficiently long duration (Galbusera et al. 2014).

Unfortunately, the abovementioned modelling methods do not directly link degradation of samples exposed to natural weathering to the local climate history. Diverse weather factors may cause numerous alterations to the weathered material. Dose–response relationships should be used to explain the biomaterial façade degradation in relation to varying exposure conditions (Petrillo et al. 2019). A procedure in developing a dose–response model typically includes the following steps. First, relevant meteorological data have to be collected and homogenized (Sandak et al. 2015b). These data are used to compute the weather dose separately for each location and time period. Second, the degradation index is computed to characterize the degradation progress at different stages of the weathering test. This process is based on the characteristics of weathered materials measured during the weathering test. The degradation index represents material response to conditions causing deterioration. Both weather doses and corresponding responses are used by the iterative modelling algorithm to develop the numerical model. The model can be used to simulate the façade service life and to determine when in the future will the building lose its aesthetical appeal for future occupants (Sandak et al. 2015b). This information can be crucial in the maintenance planning and in the assessment of environmental and economic costs of the structure during its service life.

Performance of façade materials depends on various factors, whose effects on deterioration, physical–chemical mechanisms, inhibitions, and cross-correlations are often uncertain (Verma et al. 2014). Models based on the probability theory or statistical concepts are suitable for describing such complex processes. Typical steps in such methods are (1) defining failure limit states for the corresponding features, (2) quantifying random variables, and (3) calculating probability levels (Li and Vrouwenvelder 2007).

5.7.4 Stochastic Methods

Stochastic methods provide information related to the risk of failure, where the most probable failure time is predicted by taking into account selected building elements (Silva et al. 2016). The most common examples of stochastic methods are logistic regressions and Markov chains. Logistic regression evaluates the probability of transition between degradation conditions over time, considering specific façades characteristics. It estimates the time when the façade will reach the end of its service life. The Markov chain provides similar results but analyses processes selectively. Markov chain cannot produce context-dependent results, since it does not consider the overall context and the entire range of circumstances. The phases of the deterioration (degradation) process are analysed separately and not sequentially. Stochastic methods provide valuable information, especially for identifying maintenance strategies that should be implemented in façades during their service life.

5.7.5 Computational Methods

Computational methods rely on mathematical models to describe complex systems with computer simulations. These methods use existing data to find the best fitting models. Such approach is particularly useful in predicting the behaviour of building elements, especially when intuitive solutions are not available. Computational methods perform well when dealing with inaccurate data and samples that contain outliers. The most popular techniques are artificial neural networks (ANNs) and fuzzy systems (fuzzy logic). ANN uses existing empirical knowledge to model the reality. Specifically, by applying specific learning algorithms, it transforms raw data into models approximating real-life phenomena. Compared to conventional linear models, fuzzy logic models are better equipped to deal with the uncertainty associated with complex phenomena, such as degradation of construction elements (Silva et al. 2016).

5.7.6 Visualization and Simulation Methods

Aesthetics is highly subjective. To estimate aesthetic service life, specific requirements and accurate prediction of the visual appearance change should be considered (Lie et al. 2018). Numerical modelling can be used not only to anticipate the expected service life but also to schedule the maintenance activities in order to preserve façade aesthetical qualities. The model can simulate changes in façade appearance caused by surface weathering, which is the main process affecting the deterioration of façades (Sandak et al. 2017). The time to the first repair can be estimated in various scenarios while considering a wide array of variables, such as different aesthetical preferences of building owners, diverse architectural solutions, or specific microclimate conditions. When this tool is integrated with the modern building information modelling software, its scope broadens even further. For instance, it can simulate façade appearance (during the entire service life) taking into account the choice of biomaterials. It is an excellent platform to determine aesthetical limit states and environmental impact of façades, both during and after the use phase. It is also an indispensable tool in predicting investment and maintenance costs, considering various scenarios of maintenance and/or replacement. Such modelling tools were developed in BIO4ever project (www.bio4everproject.com) and are currently undergoing extensive testing and validation (Sandak et al. 2018).

5.7.7 ESL Models Update and Validation

The capacity and reliability of a model to represent real-life systems must be confirmed in validation procedures. Ideally, a model should be able not only to describe the variability of the data from the teaching data set, but it should also be applicable to other scenarios. To achieve this, it is important to continuously upgrade numerical models by implementing additional data gradually acquired from newly erected structures. Furthermore, the database of façade materials should be regularly updated, especially by including new bio-based building materials emerging on the market (Brischke and Thelandersson 2014). The most efficient software systems can automatically acquire new data during building service life and incorporate it into the original model. There are different model validation strategies, depending on the extent of the available cases and on the future accessibility to new independent data. However, external validation with independent data is always considered an optimal solution and thus recommended for routine implementation.

5.7.8 *Concluding Remarks*

Existing methods in predicting ESL and modelling long-term degradation and performance of building façades vary in their complexity and reliability. Some of these (e.g., factorial method) tend to oversimplify degradation processes, since they do not always consider (1) the full range of variability of factors involved in the ageing of the structure and (2) the specificity of the modelled component. Other methods, such as stochastic, are too complex to be routinely used, since they describe the service life in too specific conditions and are mostly based on the probability theory (Moser and Edvardsen 2002). Computer-based simulation tools require exceptional skills in using certain software and in building physics. For this reason, most of the available tools are developed and used mainly for research purposes (Vullo et al. 2018). Thus, it is essential to develop simple but reliable modelling tools that integrate all the abovementioned methods. For more details and examples of modelling to predict expected service life, readers are encouraged to refer to the work of Masters (1985), Saunders (2007), Silva et al. (2016), and Jones and Brischke (2017).

References

Al-hafiz B, Musy M, Hasan T (2017) A study on the impact of changes in the materials reflection coefficient for achieving sustainable urban design. Procedia Env Sci 38:562–570

Babiński L, Izdebska-Mucha D, Waliszewska B (2014) Evaluation of the state of preservation of waterlogged archaeological wood based on its physical properties: basic density vs. wood substance density. J Archaeol Sci 46:372–383

Brischke C, Rapp AO, Bayerbach R (2006) Decay influencing factors: a basis for service life prediction of wood and wood-based products. Wood Mat Sci Eng 1:91–107

Brischke C, Thelandersson S (2014) Modelling the outdoor performance of wood products—a review on existing approaches. Constr Build Mater 66:384–397

Brischke C, Unger W (2017) Potential hazards and degrading agents. In: Jones D, Brischke C (eds) Performance of bio-based building materials. Elsevier, pp 188–203

Clausen CA (2010) In: Ross RJ (ed), Biodeterioration of wood in wood handbook—wood as an engineering material. Forest Products Laboratory, Madison

Cogulet A, Blanchet P, Landry V (2018) The multifactorial aspect of wood weathering: a review based on a holistic approach of wood degradation protected by clear coating. BioRes 13 (1):2116–2138

Dietenberger MA, Hasburgh LE (2016) Wood products thermal degradation and fire. In: Reference module in materials science and materials engineering, 8 pp

Ebbert T, Knaack U (2007) A flexible and upgradeable façade concept for refurbishment. In: Bragança L et al (ed) Proceedings of the SB07 Lisbon–sustainable construction, materials and practices: challenge of the industry for the New Millennium, Rotterdam

Fagerlund G (1985) Essential data for service life prediction. In: Problems in service life prediction of building and construction materials. NATO ASI series, 95, pp 113–138

Feist WC, Hon DNS (1984) Chemistry of weathering and protection. In: Rowell RM (ed) Chemistry of solid wood. Advances in Chemistry Series 207, A.C.S., Washington, pp 401–451

Fengel D (1991) Aging and fossilization of wood and its components. Wood Sci Technol 25: 153–177

Fengel D, Wegener G (1989) Wood: chemistry, ultrastructure, reactions. De Gruyter Publications, Berlin

Flores-Colen I, de Brito J (2010) A systematic approach for maintenance budgeting of buildings façades based on predictive and preventive strategies. Constr Build Mater 24(9):1718–1729

Froidevaux J, Navi P (2013) Aging law of spruce wood. Wood Mat Sci Eng 8(1):46–52

Galbusera MM, de Brito J, Silva A (2014) The importance of the quality of sampling in service life prediction. Constr Build Mater 66:19–29

Gobakken LR, Lebow PK (2010) Modelling mould growth on coated modified and unmodified wood substrates exposed outdoors. Wood Sci Technol 44:315–333. https://doi.org/10.1007/s00226-009-0283-0

Gobakken LR, Høibø OA, Solheim H (2010) Mould growth on paints with different surface structures when applied on wooden claddings exposed outdoors. Int Biodeterior Biodegradation 64:339–345

Gobakken LR, Vestøl GI (2012) Surface mould and blue stain fungi on coated Norway spruce cladding. Int Biodeterior Biodegradation 75:181–186

Graf WP, Seligson A (2011) Earthquake damage to wood-framed buildings in the shakeout scenario. Earthquake Spectra 27(2):351–373

Grossi P, Sandak J, Petrillo M et al (2018) Effect of wood modification and weathering progress on the radiation emissivity. In: 9th European Conference on Wood Modification, 17–18 September 2018, Arnhem, Netherlands

Hendriks L, Hens H (2000) Building envelopes in a holistic perspective. Laboratorium Bouwfysica, Amsterdam, Netherlands

Hovde PJ (2002) the factor method for service life prediction from theoretical evaluation to practical implementation. In: Proceedings of the 9DBMC international conference on durability of building materials and components, Brisbane, Australia 10p

Hovde PJ (2005) the factor method—a simple tool to service life estimation. In: 10 DBMC international conferences on durability of building materials and components, Lyon, France

ISO 15686–1 (2011) Buildings and constructed assets—service life planning—part 1: general principles and framework. International Organization for Standardization

Jin Q, Overend M (2014) A prototype whole-life value optimization tool for façade design. J Build Perform Simul 7(3):217–232

Jones D, Brischke C (eds) (2017) Performance of bio-based building materials. Elsevier

Kelly DJ (2007) Design life of buildings—a scoping study. Scottish Building Standards Agency

Klaassen RKWM (2008) Water flow through wooden foundation piles: a preliminary study. Int Biodeterior Biodegrad 61(1):61–68

Kudder RJ, Erdly JL (1998) Water leakage through building facades. ASTM International

Kuzmichev AA, Loboyko VF (2016) Impact of the polluted air on the appearance of buildings and architectural monuments in the area of town planning. Procedia Eng 150:2095–2101

Lengsfeld K, Krus M (2004) Microorganism on façades—reasons, consequences and measures. IEA ANNEX 41 meeting, Glasgow, Scotland

Li Y, Vrouwenvelder T (2007) Service life prediction and repair of concrete structures with spatial variability. Heron 52(4):251–267

Lie SK, Vestøl GI, Høibø O, Gobakken LR (2018) Surface mould growth on wooden claddings—effects of transient wetting, relative humidity, temperature and material properties. Wood Material Science & Engineering. https://doi.org/10.1080/17480272.2018.1424239

Lstiburek J (2006) Understanding basements. Building Science and Corporation

MacKenzie C (2015) Impact and assessment of moisture-affected timber-framed construction. Forest and Wood Products Australia Limited. ISBN 978-1-921763-42-7

Magee M (2012) Wood Protection by Design. Timber Framing 103:21–27

Mansour AMH, Al-Dawery SK (2017) Sustainable self-cleaning treatments for architectural façades in developing countries (in press)

Martinez A, Patterson M, Carlson A et al (2015) Fundamentals in façade retrofit practice. Procedia Eng 118:934–941

Masters LW (ed) (1985) Problems in service life prediction of building and construction materials. Springer, Dordrecht

Meyer L, Brischke C, Pilgård A (2012) Modified timber in various above ground exposures—durability and moisture performance. In: Hill CAS, Militz H, Pohleven F (eds) Proceedings of the 6th european conference on wood modification. Ljubljana, Slovenia

Moser K, Edvardsen C (2002) Engineering design methods for service life prediction. In: 9DBMC international conference on durability of building materials and components, Brisbane, Australia

Nguyen KTQ, Weerasinghe P, Mendis P et al (2016) Performance of modern building façades in fire: a comprehensive review. Electron J Struct Eng 16(1):69–86

Petrillo M, Sandak J, Grossi P et al (2019) Chemical and appearance changes of wood due to artificial weathering—dose-response model. J Near Infrared Spectrosc. https://doi.org/10.1177/0967033518825364

Rametsteiner E, Oberwimmer R, Gschwandtl I (2007) Europeans and wood: what do Europeans think about wood and its uses? A review of consumer and business surveys in Europe. ISBN: 978-83-926647-0-3

Sandak A, Ferrari S, Sandak J et al (2013) Monitoring of wood decay by near infrared spectroscopy. Adv Mater Res 778:802–809

Sandak A, Sandak J, Babinski L et al (2014) Spectral analysis of changes to pine and oak wood natural polymers after short-term waterlogging. Polym Degrad Stab 99:68–79

Sandak J, Sandak A, Riggio M (2015a) Multivariate analysis of multi-sensor data for assessment of timber structures: principles and applications. Constr Build Mater 101(2):1172–1180

Sandak J, Sandak A, Riggio M (2015b) Characterization and monitoring of surface weathering on exposed timber structures with multi-sensor approach. Int J Archit Heritage 9:674–688

Sandak A, Sandak J, Burud I et al (2016) Weathering kinetics of thin wood veneers assessed with NIR. J Near Infrared Spectrosc 24(6):549–553

Sandak J, Sandak A, Burud I (2017) Modelling of weathering. In: Jones D, Brischke C (eds) Performance of bio-based building materials. Elsevier, pp 502–510

Sandak J, Sandak A, Grossi P et al (2018) Simulation and visualization of aesthetic performance of bio-based building skin. In: Proceedings IRG annual meeting. ISSN 2000-8953, IRG/WP 18-20633

Saunders SC (2007) Reliability, life testing and the prediction of service lives. Springer, Dordrecht

Shukla A, Waris RF, Arhab M et al (2018) A review on pollution eating and self-cleaning properties of cementitious materials. Int J Innov Res Sci Eng Technol 7(3):2784–2792

Silva A, de Brito J, Gaspar PL (2016) Methodologies for service life prediction of buildings with a focus on façade claddings. Springer International Publishing, Switzerland

Singh J (2000) Fungal problems in historic buildings. J Archit Conserv 6:17–37

Van Acker J, De Windt I, Li W et al (2014) Time of wetness (ToW) simulation based on testing moisture dynamics of wood. In: COST FP1303: performance and maintenance of bio-based building materials influencing the life cycle and LCA, Kranjska Gora

Verma SK, Bhadauria SS, Akhtar S (2014) Probabilistic evaluation of service life for reinforced concrete. Struct Ch J Eng, Article ID 648438, 8 p

Viitanen H, Vinha J, Salminen K et al (2010) Moisture and bio-deterioration risk of building materials and structures. J Build Phys 33(3):201–224

Vullo P, Passera A, Lollini R et al (2018) Implementation of a multi-criteria and performance-based procurement procedure for energy retrofitting of façades during early design. Sustain Cities Soc 36:363–377

Williams RR (2005) Weathering of wood. In: Handbook of wood chemistry and wood composites edited by Rowell. R. M. CRC Press

Winandy JE, Morrell JJ (1993) Relationship between incipient decay, strength, and chemical composition of Douglas fir heartwood. Wood Fiber Sci 25(3):278–288

www.bio4everproject.com. Accessed on 08 Oct 2018

www.servowood.eu. Accessed on 08 Oct 2018