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Section 2 **Test methodology and assessment**

Prediction of service life – does aesthetic matter?

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Prediction of service life – does aesthetic matter?

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ABSTRACT

Building structures should be designed in order to satisfy requirements regarding safety, serviceability, durability and aesthetics, assuring proper structure performance along the entire service life. For that reason it is essential to understand overall deterioration mechanism at levels of element, component, façade and entire building. This work focuses specifically on the façade aesthetical properties, identified here as a frequently neglected aspect within the service life prediction. The main goal is to review various processes that influence material appearance changes. The manuscript presents also a review of suitable analytical techniques appropriate for assessment of material look. State-of-the-art as well as alternative methods for service life prediction are compared. Real case examples are provided to illustrate the typical deterioration patterns. Finally, an attempt to define a role of aesthetic aspects in designing building and practical modelling of its aesthetical service life is proposed.

Keywords: service life, aesthetic performance, biomaterials, facades

1. INTRODUCTION

An increasing interest for accurate determination of durability and service life of materials, components, installations, structures and buildings is noticed in the last decades (Hovde 2002). The service life of a structure is defined in standards (ISO 15686-1) as the period of time after construction till a structure maintains or exceeds minimum performance requirements without unforeseen or extraordinary maintenance or repair. The list of factors affecting the length of service life includes appearance, functionality, safety, investment costs and maintenance efforts. It is clear that all the above have to be properly balanced in order to minimize costs and environmental impact of buildings in use.

Aesthetics of building is one of the principal aspects considered in architecture. Appeal of the building covers combined effects of the shape, colour, contrast, type of material, symmetry and simplicity of the repeated patterns used in design. The fundamental elements regarding aesthetics in architecture are related to the mass and space, proportion, symmetry, balance, contrast, pattern and decoration (Mohan 2006). The unique properties and the natural beauty of bio-based materials make these a desired substance for various applications including construction, interior/exterior design or other uses. It is important, however, to guarantee the due aesthetical performance of building elements made of biomaterials along their functional service life. In that case the functional performance is usually not an exclusive issue, but it is extremely important to consider also aesthetical deterioration of surfaces (Sandak *et al*. 2015a). This work focus on the service life prediction of bio-based building materials. Several of novel products are emerging the market, beside of the traditional timber, are of research scope. It includes engineered wood (CLT or glue-lam), wood modified thermally and/or chemically, as well as new composites developed from bio-based alternative resources such as hemp, straw or reed. Their advantage, beside sustainability aspects, is a fact that biomaterials possess wide range of appearances, starting from traditional rustic materials to modern design products. Consequently, it allows use of bio-resources as a retrofitting material for existing structures as well as a material for innovative and ground breaking architectural solution. Moreover, the increased use of bio-based building materials is highly promoted within derivative of the Europe 2020 strategies in order to guarantee the full sustainability of the construction sector in the close future. The goals of this work are therefore; to summarize various processes that influence material appearance, to present available analytical techniques relevant for assessment of material look, and to explain role of aesthetic aspect while modelling of service life.

2. FACTORS INFLUENCING CHANGES OF AESTHETICAL PROPERTIES

2.1 Wood preservation

A range of different treatments has been developed to enhance the durability and service life of timber. Such modification methods were classified by Hill (2006) into active (resulting in changes of the chemical structure of material) and passive (no altering the native chemistry of material). Active modifications include chemical, thermal and enzymatic treatments, while passive methods include impregnation and coating.

Acetylation, belonging to the family of chemical treatments does not considerably change the wood's colour, creating a pale wood which has relatively good colour stability also when exposed to natural weathered.

Furfurylation, as alternative commercialized chemical modification processes, has a greater effect on the resulting colour of the wood bulk. Such wood is considerably darker than acetylated wood and its outlook is similar to that of some tropical hardwood species. This deep mahogany-like colour of furfurylated wood can be maintained along the service life time if properly post-treated. Oppositely, if the furfurylated wood is left untreated, it becomes silver-grey shortly after exposure to the natural weathering (Hill 2006).

Thermal treatments include several alternative processes that differ in terms of process intensity (temperature and duration), treatment atmosphere (vapour/nitrogen/vacuum), use of catalyst, and system configuration (open/close, wet/dry). Darkening of material with varying extend is observed as a result of thermal treatment.

Enzymatic modification is usually performed by means of either lignin activation (mixed with wood particles) or by the direct wood surface treatment.

Various impregnation processes evolved to be effective in non-leachable impregnation. There are several alternative options and configurations, such as resin treatments, impregnation with silicone containing compounds, or other inorganic solutions.

There are also several option while considering wood finishing. Most popular alternatives (dye, oil coating, varnish, stain, wax or paint) are briefly presented in Fig. 1. Depending on the product type and application methodology, some products are certified for external use, including building facades.

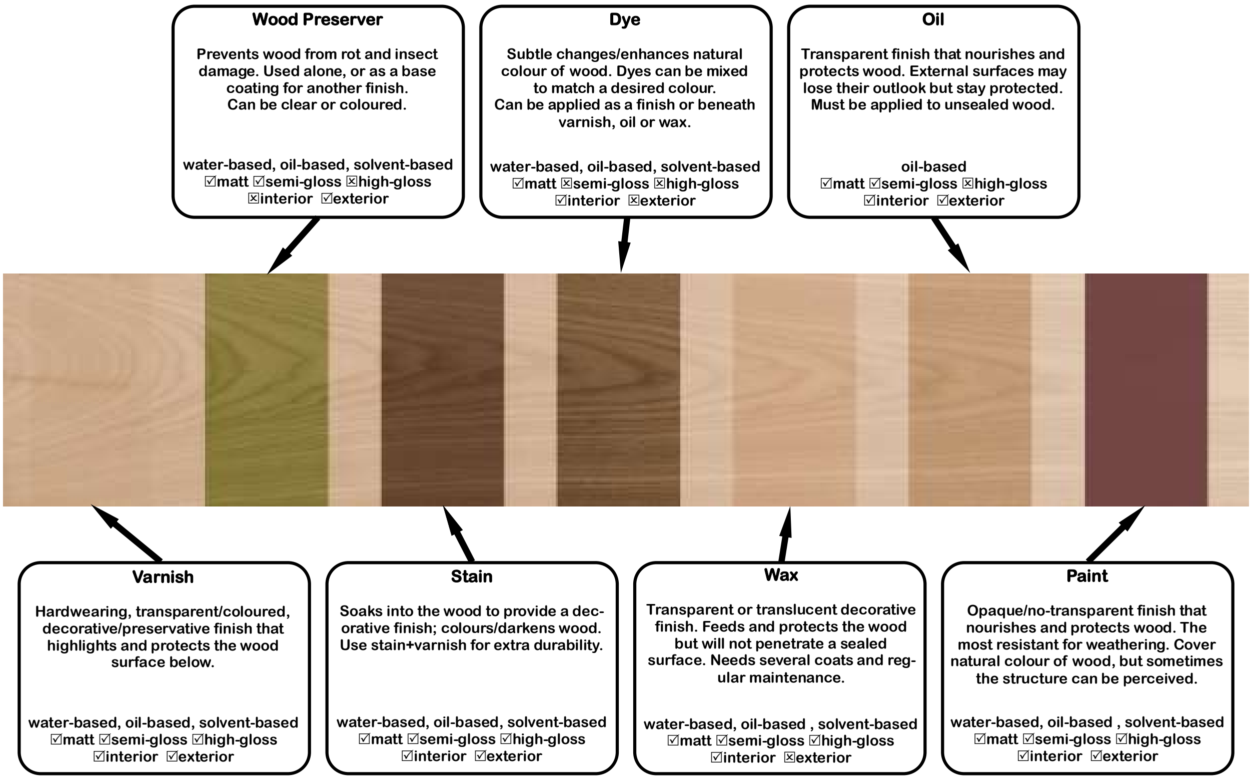


Figure 1: Appearance of wood after different finishing processes

2.2 Wood aging and degradation

Wood and other bio-based materials are exposed during their use to several factors that affect their performance. As any other materials they are a subject of deterioration due to biotic and abiotic agents. The most obvious aspects of degradation are these related to visual appearance, such as changes in colour, roughness, surface checking, dirt uptake and growth of mould (Table 1).

Changes of material appearance, due to several degradation processes, differ in case of their kinetic and/or intensity. Weathering is mainly related to the superficial level and its intensity depends on climatic conditions. Wood exposed to meteorological agents change already after few months. Decay is a process affecting both, materials functionality and aesthetics. The degradation might have different kinetics depending on the fungi type and consequently affects materials' functionality and appearance in diverse way. White-rot and brown-rot fungi are the most destructive microorganisms, but they are active only in presence of oxygen, and when wood possesses a specific moisture content (20-80%) for a sufficiently long period. Soft-rot fungi are the main wood degraders when wood is saturated with water, but when oxygen is still available. Waterlogging is a slow deterioration process in anaerobic conditions due to activity of bacteria. Its intensity depends on temperature, pH, and environmental conditions, e.g. constant saturation with water, immersion conditions: water, peat or soil (Sandak *et al*. 2014). Insects activity might have also significant influences on the bio-materials outlook, as well on material functionality and safety.

There are also several processes that influence building materials appearance, however are hardly to be forecasted during designing phase: acts of vandalisms, fire, flood, storms or earthquake even if not predictable should be considered while designing.

Table 1: Description of degradation processes possible during service life

degradation type	**weathering**	**decay**	**waterlogging**	**insects activity**	**vandalism**	**fire**	**flood**	**earthquake**
process	oxidation hydro-lysis erosion cracks abrasion fracture	deploy-meriza-tion oxidation hydro-lysis reduction	oxidation hydro-lysis swelling shrinkage	deploy-meriza-tion chewing	abrasion, cracking fracture	dehydra-tion oxidation hydro-lysis	swelling shrinkage freezing cracking	fracture cracking
causes								
properties	color gloss roughness cracks mold	color gloss density mech. properties	color gloss density mech. properties	color density mech. properties	color cracks	color gloss density mech. properties	color gloss density mech. properties	mech. properties
aesthetic	✓	✓	✓	✓	✓	✓	✓	✓
function		✓	✓	✓		✓	✓	✓
safety		✓	✓	✓		✓		✓

3. METHODS FOR ASSESSMENT AND MONITORING OF CHANGES TO AESTHETICS APPEARANCE OF BIOMATERIALS ALONG THE SERVICE LIFE

The direct methods for evaluation of the aesthetics appearance of materials base on variations of the visual assessment. Unfortunately, it possesses high degree of subjectivity while performed by a not trained person. The simplest approach to quantify approval is a semantic differential method was proposed by Osgood *et al*. (1957). Examples of bipolar adjectives used for aesthetic assessment of materials according to that approach are presented in Table 2.

Table 2: Representative semantic differential bipolar adjectives related to aesthetic of materials

senses		**emotion**		**evaluation**	
dark	bright	beautiful	ugly	clean	dirty
warm	cold	desired	unwanted	new	old
regular	rare	pleased	annoying	modern	rustic
gloss	mat	interesting	boring	complex	simple
smooth	rough	like	dislike	innovative	conservative

The further advancement of visual assessment methodology is to perform a controlled test according to clearly defined rules (e.g. focus on samples colour, detection of particular defects and other characteristics). This approach is codified in several standards, including prEN 252 2012, EN 330 1993. A wood decay extent grading according to such rating scale is a common example. In this case clearly defined criteria are provided to the assessing person prior material evaluation. The judgment should be performed with samples presented in a random order by the group of equally trained individuals, preferably experts.

Several adaptations of the visual rating, combining different material features and assessing specific degradation phenomena, are present in literature (De Windt *et al*. 2014). An example of the original grading rules defined for the not coated wood samples weathered in natural conditions was also developed by authors (Fig. 2). The detailed definitions of the grading classes/levels and proper rules description are summarized in Table 3.

Figure 2: Weathered samples corresponding to seven levels grading scale

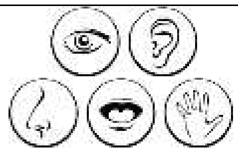
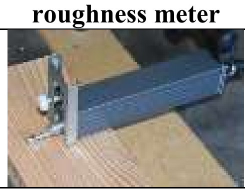
Table 3: Visual rating scale used to evaluate outdoor performance of natural wood

grade	degradation level	characteristics
0	no degradation	no color changes
1	small aesthetical changes	yellow appearance
2	mild aesthetical changes	yellow grey appearance
3	moderate aesthetical changes	light grey color
4	more intense changes	grey color with warm tonality, no visible cracks
5	advanced changes	dark grey color with cold tonality, some raised fibres, surface erosion, no visible open cracks
6	very advanced changes	dark grey, uneven discoloration, surface erosion, presence of cracks, mould, algae

In alternative to the visual assessment, measurement of surface properties/appearance with dedicated sensors provides objective values that might be directly related to the current state of the material in use. Whenever possible, samples can be collected in-field and measured in the laboratory after careful conditioning. Though, recent developments in optics and electronics open new possibilities to perform measurements with portable instruments directly in-situ. Non-destructive techniques, that do not need particular sample preparation are especially useful. The most common sensing techniques useful for assessment of aesthetical properties of weathered surfaces in building facades are presented in Table 4.

Colour meters, gloss meters, spectrophotometers or profilometers are directly mimicking human senses, but are capable of providing numerical quantifiers of the colour (*CIE* $L^*a^*b^*$ colour coordinates, spectrum), gloss (glossiness index) or roughness (R_a, R_z, R_{max}). In most cases, even if above measures provides very valuable and credible results, these include only incomplete information about limited range of aesthetical aspects. Thus, multi-sensor approach is suggested for applied research instead of a single sensor assessment (Sandak *et al*. 2016). The data collected by various sensors are usually expressing complementary physical phenomena what makes the results interpretations more demanding but also reliable. It is a challenge therefore to properly combining the data provided by various sensing techniques and implement proper data mining procedures. The optimal solution when dealing with material performance during service life is a time resolved measurement campaign. When the material state is assessed regularly, such measurement turns into monitoring. Dedicated interfaces are indispensable in order to integrate signals (measurements, images, waves, spectra, etc.) generated by various sensors. For that reason, such data fusions systems are relatively complex and implemented technical solutions are individualized case by case depending on the monitoring objectives and required accuracy (Sandak *et al*. 2015b).

Table 4: Methods for aesthetic evaluation of materials

sensor	human senses	color meter	gloss meter	roughness meter
example				
output data	colour pattern roughness impression	colour parameters (L* a* b*) spectrum	glossiness	roughness parameters (R_a, R_z, R_{max})
objectivity	👎	👍	👍	👍

4. ESTIMATION OF SERVICE LIFE

Biomaterials possess several advantages over traditional/alternative resources. Natural beauty makes them very attractive for several applications providing superior aesthetical impressions, microclimate comfort and environmental friendliness. The performance of biomaterials within house interior is usually not problematic, and its integration with the environment/structure rather simple. However, it is not such straightforward in the case of the exterior use. Natural products may loss visual appeal leading to a perceived need for replacement even if are far from the functional failure. The purpose of regular maintenance is therefore, to maintain the life of the facade element by postponing obsolescence in terms of aesthetic and/or technical requirements. As a consequence, it is critical to re-define the "service life" as not only related to the technical performance of the structure, but also to consider an important factor of aesthetical perception and tolerance for visual depreciation. It may be defined as an "appearance limit", marked in Fig. 3 beside of functionality and safety boundaries. It should be mentioned that elements with higher maintenance requirements are likely to have lower initial costs. Even that, the economic and environmental costs may be significantly higher of refined materials, especially when considering the whole service-life time span.

It is relatively simple to properly define the critical limits when wood is losing its technical characteristics (due to decay, mechanical strength decrease, loss of dimensional tolerances, etc.). It is extremely difficult, however, to define the critical limits as regarding the aesthetics (Sandak *et al*. 2015a, Ruther and Time 2015). In the real cases, the aesthetic requirement limits are reached before functional lose and far before passing the safety limit. The estimated service life end is therefore identified by considering certain constraints, and depends on the critical aspects (including aesthetics, function, safety) disqualifying the structure from the further use.

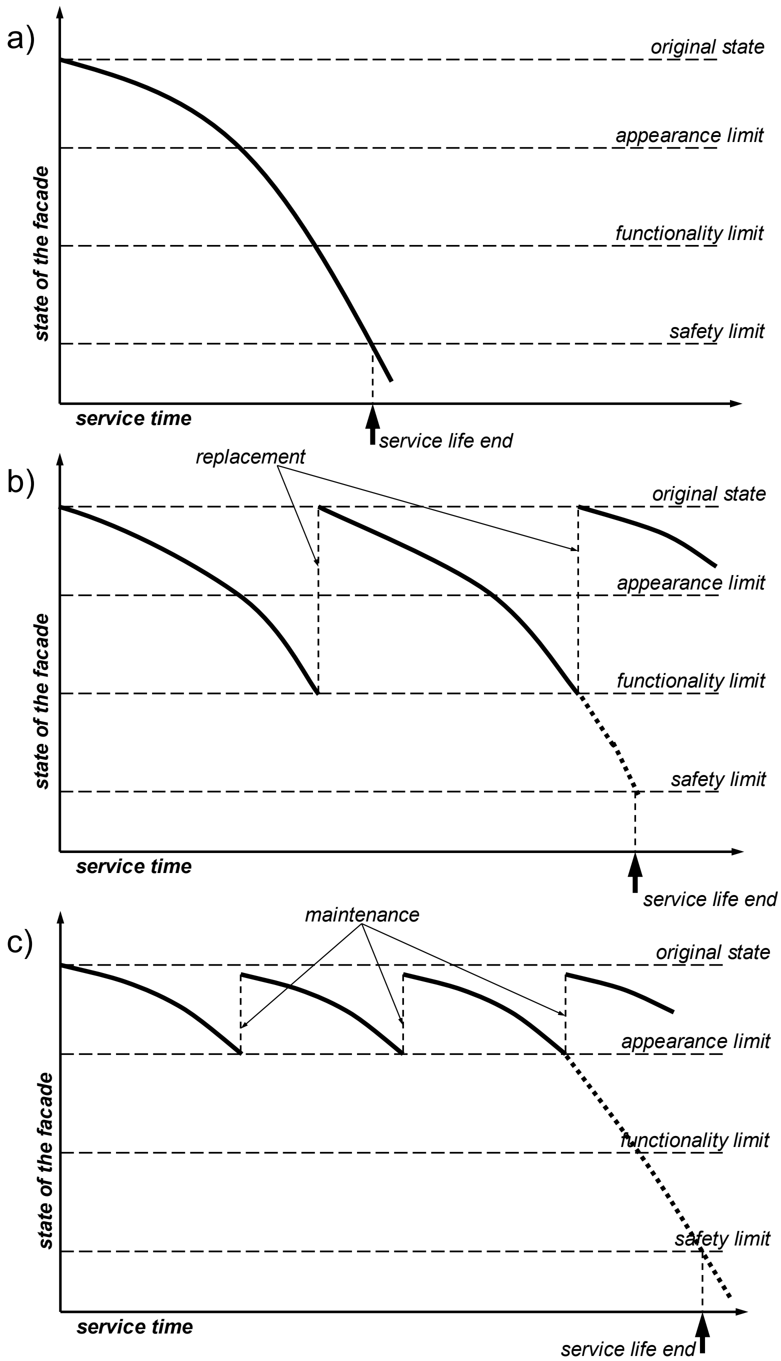


Figure 3: Estimation of the service life time according to different scenarios; no any repairs (a), replacement (b) and frequent maintenance (c)

Fig. 3 illustrates different scenarios of the building façade service life. The shape of presented curves, especially in the time direction, depends on the type/performance of selected material(s). The loss of structure safety is reached relatively fast when no any maintenance and/or replacements are performed (Fig. 3a). The service life can be substantially extended by applying in-time mitigating actions used to protect the façade and/or early repair damages before the further progress of degradation, by replacing damaged parts for example (Fig. 3b). In the best scenario, the regularly scheduled maintenance actions allows highest extension of the expected service life (Fig. 3c). It is challenging, however, to define optimal levels of appearance, functionality and safety limits (states of the façade). In any case it is a compromise between expected functional requirements, performance as well as operational and maintenance costs.

An important aspect that should be considered while designing of building are trends or fashions to use certain type of materials (Ebbert and Knaack 2007). In this case motivation for façade (or other elements) replacements will not be dependent on their in-service performance but will be rather stimulated by personal motivation to follow certain tendencies. Use of modular prefabricated façade modules may be a great advantage, assuring highest aesthetical beauty of the building and minimal cost of the pre-scheduled replacement(s).

5. SERVICE LIFE PLANNING

Reference service life (RSL) is defined as a "service life of a product/component/assembly/system that is known to be expected under a particular set, e.g. a 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). According to the standard and literature references, the factor method is used to describe difference between project-specific and reference in-use conditions. Estimated service life (ESL) can be calculated the by multiplying of RSL by number of factors according to Equation 1:

$$\boldsymbol{ESL = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G} \qquad (1)$$

where; *A* – quality component factor, *B* – design level factor, *C* – work execution level, *D* – indoor environment factor, *E* – outdoor environment factor, *F* – usage conditions factor, *G* – maintenance level factor

Detailed description of different factors was provided by Brischke *et al*. (2006), who also stated that different weightings can be found for different factors. Daniotti *et al*. (2008) proposed classification of factors into three groups: agent related to the inherent quality characteristics (factors *A*, *B* and *C*), environmental agents (*D* and *E*) and those related to operation conditions (*F* and *G*).

The factor method is relatively simple and convenient algorithm, but it still possesses following limitations:

- it neglects the fact that the degradation phenomenon is variable over time;
- it calculates the service life by considering characteristics of the construction element;
- it ignores the specific degradation conditions of the single element;
- small variations in the quantification of the durability factors can lead to a very varying values of the estimated service lives;

- the algorithm leads to an absolute value and does not provide information concerning the dispersion of the results (Silva *et al*. 2016).

In alternative to the factor method, several deterministic, scholastic and computational methods are available for estimation of the service life duration. The deterministic models describe the relationship between the degradation factors and the building condition by means of mathematical and/or statistical formulations. The equation that best fits a set of random data is an output of the deterministic method. Such approach is efficient when applied on large and representative samples sets and high number of reference data (Silva *et al*. 2016). Shohet *et al*. (1999) proposed four deterioration patterns considered as typical effects of the common degradation agents:

- a concave pattern associated with abiotic agents (weathering), whose deterioration develops rapidly at an early stage (first few months), but tends to slow down over time (e.g. weathering index proposed by Sandak *et al*. 2016);

- a convex pattern associated with the physical, chemical or biological phenomena, which act slowly initially but whose action is felt cumulatively (e.g. mould presence after failure of coating)

- an "S"-shaped pattern associated with a degradation phenomenon whose intensity changes over time (e.g. ΔE parameter due to seasonal variation of weathering intensity);

- a linear pattern associated with degradation agents that act permanently (e.g. surface erosion).

Examples of four deterioration patterns with experimental cases illustrating phenomena related to weathering are presented in Fig. 4.

It should be also mentioned that different patterns are often observed while analysing real case data. An example might be change of colour coordinates *CIE* a^* and *CIE* b^* of non-protected wood during first year of weathering. Both chroma parameters increase at the beginning of weathering period and gradually decrease to reach initial level around 2-3 months in case of b^* and 6 months for a^*.

Stochastic models allow establishing an empirical relationship between variables through the estimation of parameters whose statistical robustness can be tested. Those methods model uncertainty and provide information about the risk of failure and the most probable failure time of building elements based on their characteristics. Such information can be used in the definition of maintenance strategies for different parts and elements of the building (Silva *et al*. 2016).

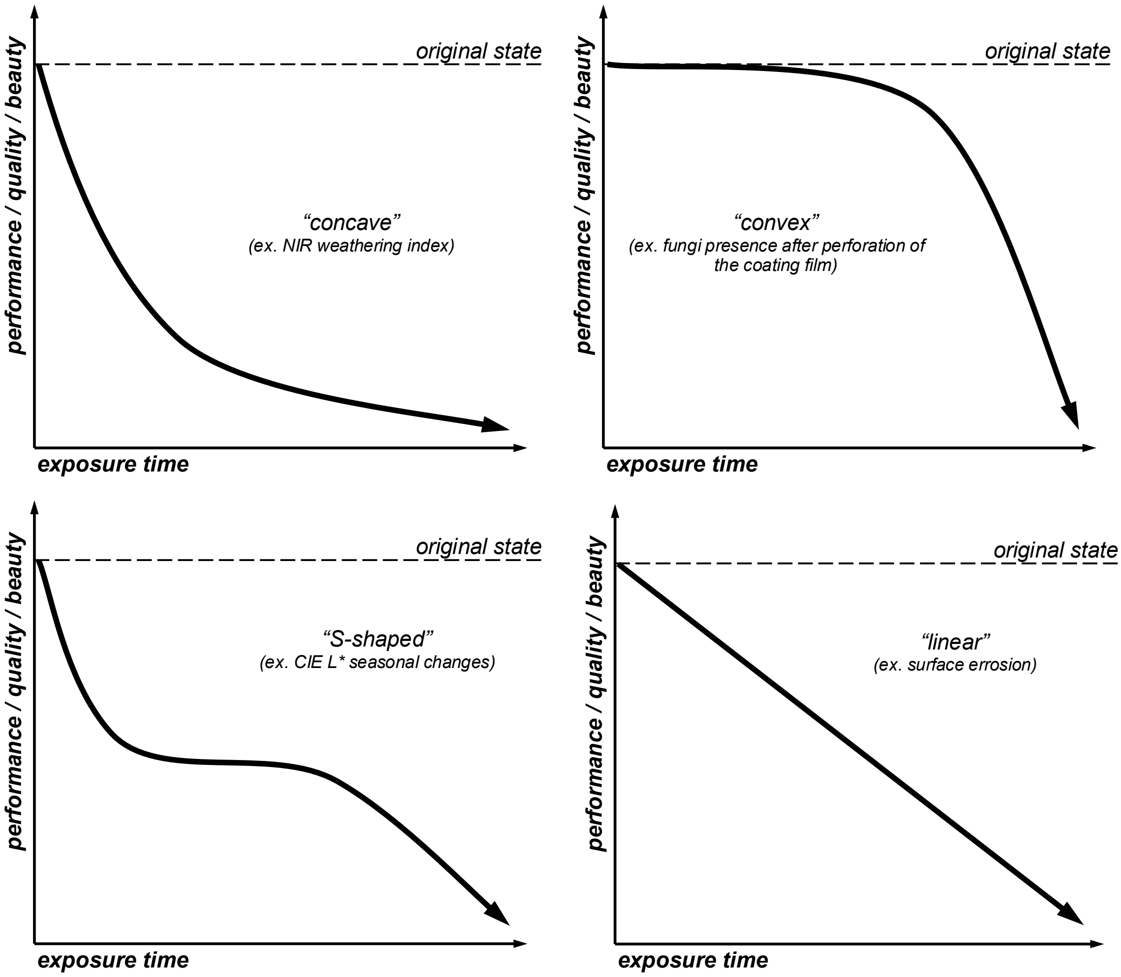


Figure 4: Various deterioration patterns observed in weathering of biomaterials

Computational methods allow obtaining the estimated service life of façades according to the variables considered as explanatory and statistically relevant in the degradation phenomena. Two approaches are used to find the nonlinear function that best fits the dataset to be modelled, using a learning process based on experiences and examples: artificial neural networks (ANNs) and fuzzy systems (fuzzy logic). ANN applies previous knowledge related to the reality that one intends to model, transforming experimental/raw data into weights on neurons within the network. ANN models are very easy to apply, but are difficult to interpret. On the contrary, fuzzy logic-based models are intuitive and closely corresponding to the human interpretation. Fuzzy systems are able to deal with the uncertainty associated with complex phenomena such as degradation of construction elements with higher precision and better performance than conventional linear models. Such methods are particularly useful while dealing with inaccurate data or with sample data sets containing outliers (Silva *et al*. 2016).

All the presented above methods possess unique set of advantages and limitations. Simpler models require less time to be developed, but analyse the problem only in one dimension (determine the loss of the building performance as a function of its age). More complex methods, even if more accurate, needs elongated implementation time since more data are necessary for their generation and validation. In many cases a dedicated software tools and non-standard numerical algorithms are indispensable for the model operation.

6. ROLE OF AESTHETIC IN SERVICE LIFE

The choice of building materials requires considerations of aesthetic appeal, initial and ongoing costs and life cycle assessment issues, especially indigenous material availability, its impact on the environment, ability to reuse, recycle or dispose at the end of its life. Local climate is one of the most important factors to be considered in biomaterial and assembly selection. Materials used in construction must be compatible with the specific local, cultural and aesthetic circumstances. The choice of building materials is culture dependent and it varies with social context. Material selections are also legally limited by the building codes, but also by the type and size of elements.

The hierarchy of performance requirements to be considered when selecting construction materials is presented in Fig. 5. It is clear that even if the safety and the functional reasons are the fundamental selection criteria, only these are insufficient to fulfil the complete list of necessities. The recent survey of Austrian architects and builders revealed that visual appearance become the key product attribute, being followed by the service life span, investment price and foreseen maintenance intervals (Rametsteiner *et al*. 2007). Wood as well as other bio-based building materials are recently classified as perfect for restorative environmental design (RED) due to their sustainability and straight connection to nature (Burnard and Kutnar 2015). Therefore, aesthetic aspects and the human well-being, although not ultimate requirements, should be carefully considered when designing modern constructions.

Nowadays, the reason for façade replacement/renovation is frequently related to changes in architectonic fashion or design trends. Unquestionably, the definition of the service-life end focusing also on aesthetic aspect become even more essential.

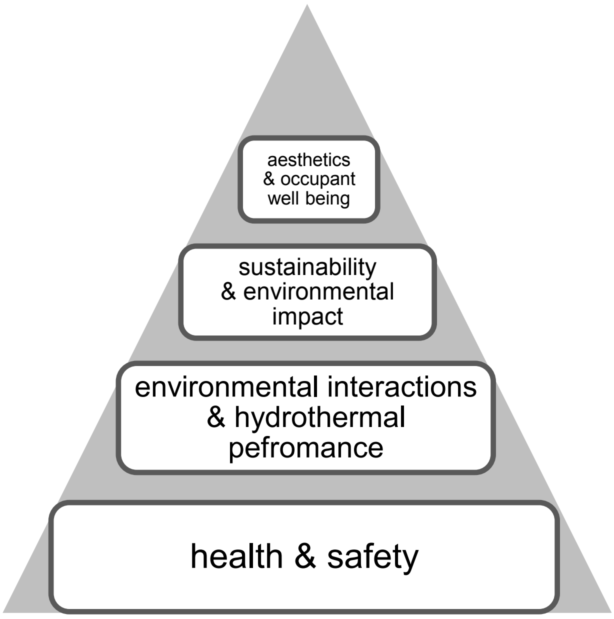


Figure 5. Hierarchy of performance requirements for building sector, source: https://www.wbdg.org/resources/building-science-concepts (modified)

The modern trends in architecture particularly applied to the building's façade, should address both environmental issues as well as aesthetic desire of contemporary architects (Sendi 2014).

The perception of aesthetical quality and related awareness of "beauty" changed over ages and will continue to change in the future. Nevertheless, there are some universal attributes that are perceived as attractive for the built environment, including proper use of natural resources in structures. The bio-based building materials are certainly attractive resources for modern construction sector, however the confidence regarding their proper selection, use and maintenance should rely on profound know-how and best practices. Reliable and validated service life performance models, including aesthetical visualization of buildings in the function of use time are definitely indispensable to convince architects, developers and investors for expansive use of building biomaterials.

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