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BIO4EVER PROJECT APPROACH FOR MODELLING OF BIO-BASED BUILDING MATERIALS WEATHERING

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ABSTRACT: The Bio4ever project is a multi-disciplinary research dedicated to fulfilling gaps of lacking knowledge on some fundamental properties of novel bio-based building materials. Investigated bio-materials will be characterized before and during degradation by biotic and a-biotic agents. The experimental data obtained will be used for development of the numerical models simulating the material deterioration in a function of time and exposition. Accurate service life time prediction, service life costing and aesthetical performance models of recently available bio-based building materials are foreseen as the most important deliverables. Dedicated algorithms simulating material modifications by taking into account original material characteristics and degrading process parameters will be developed at the micro, mezzo and macro scale. The appropriate numerical tools, able to capture the multi-scale evolution of damage will be tested under realistic conditions within field trials and surveys on structures in service.

KEYWORDS: bio-materials, service life performance, weathering, multi-sensor characterization

1 INTRODUCTION

Construction marker is one of the major employment sectors across the EU (496 billion € of value added). The sector provides 20 million direct jobs and contributes to about 10 % of the EU's GDP. It represents a large proportion of the consumption of the earth's non-renewable resources in terms of: materials used for construction and energy consumption for operation of buildings.

The trend for rapid deployment of novel/advanced material solutions at reduced-costs through predictive design of materials and innovative production technologies is observed nowadays. Such materials are optimized for specified applications, assuring at the same time expected properties and functionality at elongated life, minimizing the environmental impact and reducing risk of product failure. As a consequence, higher numbers of well performing (also in severe environments) construction materials are available on the market.

Bio-materials, other than wood, defined here as materials derived from organic sources, become also recognized as attractive alternative to many traditional building materials. The expansion of bio-based products availability and its wide utilization in modern buildings is a derivative of the Europe 2020 strategies. According to European Commission in 2010 the European market volume for bio-based products represented € 28 million, it is foreseen that this amount would reach € 57 million in 2020. It is also forecasted that market volume of bio-composites will grow from 372 to 920kt from 2010 to 2020 [1]. Consequently it is estimated that bio-materials will play an increasingly important role in the future, in order to assure the full sustainability of the construction sector.

In Italy 1 on 12 buildings are made of wood and growing tendency is observed nowadays. Bio-based materials are often used for retrofitting of existing structures, upward construction or vertical gardens.
According to Eriksson [2] three development priorities are currently related to the main products:

- structural components; there is a need for developed wood products - Engineered Wood Products, high strength wood, moisture resistant sills, light-weight beams/joists of bio-composites, sandwich panels for exterior walls.
- insulation; there is a need for compactable bats of cellulose insulation, environmentally friendly fire impregnation, high-performance insulation that provides thinner walls, insulation, optimized for soundproofing.
- barrier materials; there is a need for bio-based wind and vapour barrier for moisture-proof

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exterior walls, waterproofing for wet areas, façade and roofing materials with improved durability and serviceability.

Third category is in direct interest of the BIO4ever project.

Bio4ever is a multi-disciplinary research dedicated to fulfilling gaps of lacking knowledge on some fundamental properties of novel bio-based building materials.

The two driving objectives of the project are:

- to promote use of bio-materials in modern construction by understanding/modelling its performance as a function of time and weathering conditions
- to identify most sustainable treatments of bio-material residues at the end of life, improving even more their environmental impact.

A key issue in building construction is durability and performance. Biomaterials used for building purposes allow integration of the structure with surrounding environment. In some cases the aged look of structures is appreciated, in some cases, discoloration affect aesthetical performance. However in extreme cases the structures may become decayed and create risks for users. Natural weathering cannot be avoided, but we may understand this process and predict the appearance changes along time.

Even the most beautiful structure will loosen its attractive outlook along the service life (Figure 1) resulting in possible disappointment of customers. In the modern society, the facade end of life is often not related to the loss of functional performance, but rather to aesthetics.

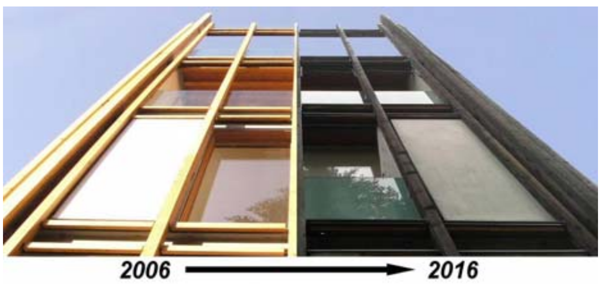


Figure 1: *Appearance change of the unprotected wooden structure in time*

Aesthetical aspects of service life, specific consumer demands and preferences, as well as the functionality of building assemblies are of central focus of the BIO4ever project.

2 MATERIALS AND METHODS

2.1 EXPERIMENTAL SAMPLES

New developments in the field of wood modification offer innovative products with enhanced properties of natural timbers is observed. These include novel bio-based composite materials (fibreboards, particleboards), as well as more effective and environmentally friendly protective treatments, e.g. thermal treatment, densification and chemical modifications (acetylation, furfurylation). Similar revolutionary progress is observed with surface treatments including innovative coatings, impregnations or integration of developments of nanotechnology for wood protection.

The samples investigated within the project represent all above mentioned groups. 25 companies & research organization from 16 countries formed the project consortium and provided samples of bio-materials best performing on the building facades.

The experimental samples include different wood species from various provenances, thermally and chemically modified wood, composite panels, samples finished with silicone and silicate based coatings, nano-coatings, innovative paints and waxes, melamine treated wood, copper treated wood, bamboo cladding, reconstituted slate made with bio-resin and samples prepared according to traditional Japanese technique: shou-sugi-ban. Consequently, nearly one hundred various bio-materials are currently under investigation.

2.2 WEATHERING TESTS

Weathering is the general term used to define the slow degradation of materials exposed to the weather condition. The rate of weathering varies within timber species, function of product, technical/design solution, finishing technology applied but most of all on the specific local conditions.

The process leads to a slow breaking down of surface fibres, their removal, and in consequence to a roughening of the surface and reduction of the glossiness. The formation of discontinuities on the wooden surface can cause penetration of the wood-decaying biological agents into the material structure and influencing mechanical performances of the load-bearing members.

Four different approaches are used for controlled samples degradation:

- Natural weathering of bio-materials on the living laboratory - installed at CNR-IVALSA (San Michele All'Adige, ITALY).

  Experimental samples will be exposed for different weathering doses/periods and characterized in the laboratory with several laboratory instruments.

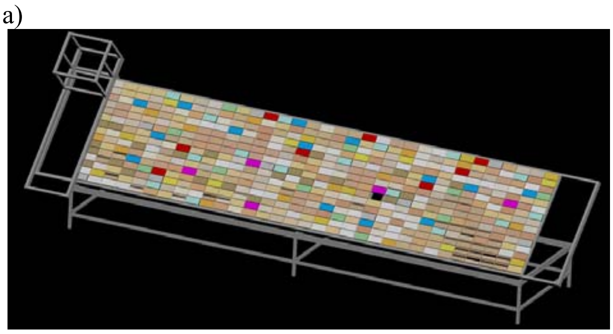
  Two replicates of biomaterial per cycle will be intensively investigated in order to understand kinetic of degradation of various facades materials. The structure before installing samples is presented in Figure 2.

  For all the period of natural weathering the meteorological data will be acquired and directly linked with materials characteristic, as proposed recently by Burud [3]. It will be later used for development of the “dose-response” model.

Figure 2: *Prototype structure used to expose samples of investigated bio-materials to the natural weathering*

- Natural weathering on the robotized stand. The stand will assure exposure to South and variable inclination from 23° to 70° depending on the season – Figure 3. All samples will be automatically characterized weekly with a multi sensor scanner installed on the stand. The robotized stand will host digital camera, VIS and NIR spectrometers as well as a gloss meter.
  Moisture and temperature on the not exposed side of samples will be continuously monitored. Three replicates per bio-material will be installed in order to assure statistical reliability of results.

a)



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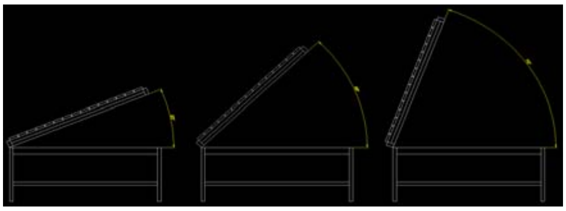

Figure 3: *Robotized stand used for natural weathering of investigated bio-materials (a) with variable inclination (b)*

- Natural weathering of bio-materials on the model structure is planned in order to investigate influence of architectonic details on degradation intensity and rate. Construction solutions are influencing the weathering intensity. Figure 4 presents uneven discoloration of wooden facades. It can be clearly seen that windowsill creates a direct protection for cladding.

Figure 4: *Example of not uniform discoloration of the facades due to natural weathering*

- Artificial weathering tests with SUN-test, QUV according to UNI EN 927-6 standard and custom weathering machine.
  Weathering campaign by using state-of-the-art artificial weathering instruments is foreseen in order to compare performance of investigated materials. In addition, the custom machine, designed exclusively for the purpose of the project, will accelerate weathering simulating varying weather conditions during service life. The prototype machine is composed of two chambers (Figure 5). First is simulating the wet winter season with lights emitting UV-reach radiation. The second chamber simulates a dry and hot summer, having the light sources emitting radiation similar to that of Sun. It is foreseen that cyclic changes of weathering condition will allow highly accelerated degradation of the samples.

Artificial weathering tests are foreseen to include at least three replicates of each investigated bio-material.

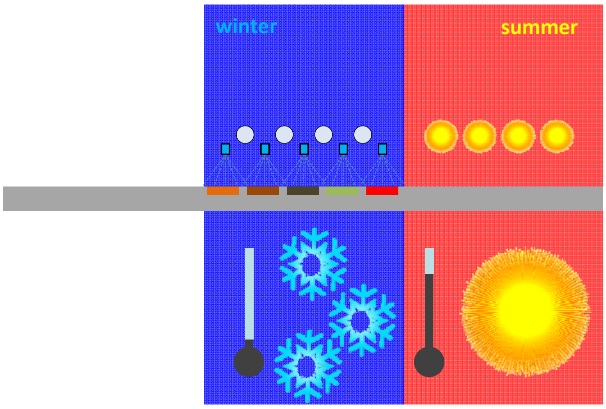

***Figure 5:** Schema of the artificial weathering machine used for samples weathering*

2.3 SAMPLES CHARACTERIZATION

Important issue when evaluating materials performance is to assure as much as possible objective approach. Each sample will be therefore investigated at the initial (brand new) state and at various stages of ageing/degradation.
A multi-sensor measurement chain, including both laboratory and on-site techniques, for the acquisition of properties at different scales (molecular, microscopic, macroscopic) is currently used for data acquisition.

Routine material characterization includes:

- photogrammetry
- moisture and density (by means of x-ray tomography)
- Vis, near and mid infrared spectroscopy and hyperspectral imaging
- IR thermography
- surface characterization (colour, gloss, wettability, roughness)
- X-Ray Fluorescence spectroscopy

It has to be mentioned that beside out-off-the-shelf laboratory equipment series of prototype instruments will be developed for precise characterization of materials surface.

A data base of comprehensive characteristics/material properties at initial stage and their depreciation during long-term service will be scrutinized as a result.

3 MULTI-SCALE MODELLING CONCEPT

3.1 DATA FUSION

The approach of materials/buildings monitoring by using multiple sensors simultaneously has become more frequent due to better representation of the real-life scenarios. In this case fusion of different sources of information is fundamental, which in many cases is a challenging task [4]. It is due to complexity of the optimal sensor selection, measurement strategy, signal processing and interpretations of results [5].
Similar concept as proposed previously by authors [6] will be used for the data fusion within BIO4ever project (Figure 6).

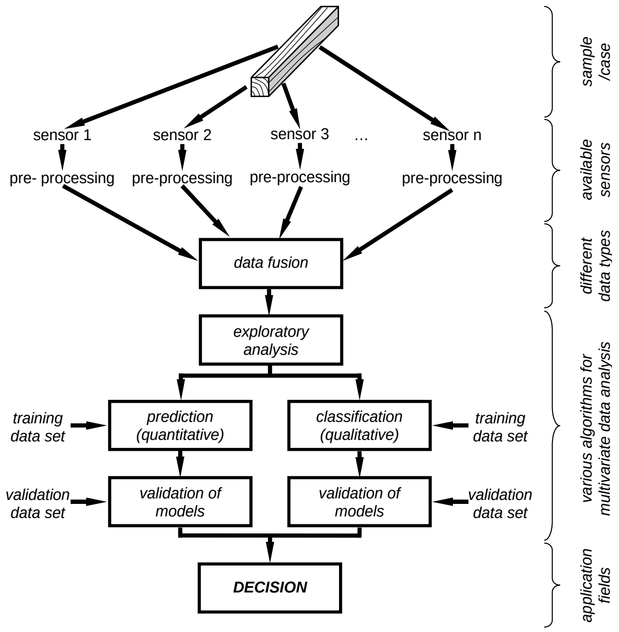

***Figure 6:** Multi sensor approach combined with multivariate analysis for assessment of timber structures [6]*

The high number of data or signals to be managed as a result of measurement with several sensors is often problematic. It is important, therefore, to assure proper pre-processing of the signals from sensors, appropriate data fusion and optimal data analysis. The extensive set of reference data will be used for data mining. Multivariate data analysis (MDA), including chemometrics, will be applied here for processing and generalization of the knowledge.

Following aspects will be explored within the BIO4ever project:

- selection and evaluation of the most suitable signal pre- and post- processing algorithms aimed to the extraction of most useful information from the raw data sets
- elaboration of "Data Fusion" procedures for the integration of the data obtained from different analytical techniques/sensors and from different degradation stages
- multivariate classification/grading of the investigated materials quality/functionality, with a special focus on aesthetical aspect
- development of numerical models simulating changes of bio-materials' properties in function of the weathering doses and construction details

4 PRELIMINARY RESULTS

4.1 WEATHERING COEFICIENT CALCULATION

The concept for calculation of weathering coefficient was previously presented by the authors [5]. The custom algorithm for multi-sensory data fusion and computation of weathering indicator was developed in LabView (National Instruments). The software normalizes the raw data (parameters) p_i as obtained by different sensors i and summarizes these, considering their importance (weight) w_i. The W_{ind} computation algorithm is mathematically expressed in Equation 1:

$$W_{ind} = \frac{\sum w_i \cdot p_i}{\sum w_i} \quad (1)$$

4.2 MODELLING OF SHORT TERM WEATHERING - CASE STUDY

4.2.1 Experimental set-up

First trials regarding multi-sensor data fusion and weathering modelling were performed on experimental samples prepared from Norway spruce wood (*Picea abies* L. Karst.) on the slicing planner (Marunaka). The thickness of samples was ~100μm and the efficient surface exposed to weathering was 30 x 35mm (width x length respectively). Sets of samples were placed for natural exposure at 45º to the horizon, facing the four directions: North, West, East and South in San Michele, Italy (46°11'15"N 11°08'00"E) – Figure 7.

Figure 7: *Experimental set-up for weathering test*

Tests were performed in 2015 for the whole month of July, which according to previous research is considered as a most severe for weathering of wood micro-sections [7]. The simulation of sun path at the beginning of the test is presented in Figure 8. On the figure sun positions at sunrise, specified time and sunset are presented. The thin orange curve is the Sun trajectory at the day of interest, while the yellow area around is the range of sun trajectories variation during the year. The closer a point is to the centre, the higher is the sun position above the horizon.
Samples changed their appearance even after relatively short time (28 days). An image of changes to the sample's appearance during natural weathering is shown in Figure 9.

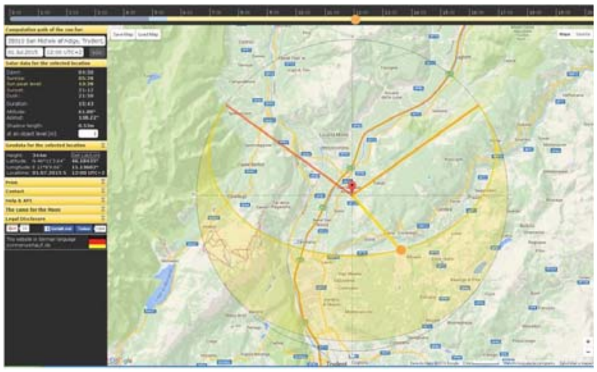

Figure 8: *Computational path for sun at the beginning of the weathering test (http://www.suncalc.org/)*

Figure 9: *Appearance of samples after 1 month weathering test (western exposure)*

4.2.2 Samples measurement

Weathered samples were measured with MicroFlash 200D spectrophotometer (DataColor Int.), equipped with the integration sphere, and entrance of 18mm diameter. The values of colour coordinates (L*, a*, b*) were computed automatically by the instrument on the base of the illuminant D65 and viewer angle 10º.
Both, near infrared (NIR) and mid infrared (MIR) spectroscopy were used for obtaining information about the molecular structure of the weathered wood surfaces. Vector N-22 (Bruker Optics GmbH) Fourier-transform NIR spectrometer equipped with fibre optic probe was used for scanning the spectra in the range from 4000cm^{-1} to 14000cm^{-1}. The spectral resolution was 8cm^{-1} and 32 scans were averaged on each measurement. ALPHA (Bruker Optics GmbH) FT-IR spectrophotometer equipped with the external reflectance module was used for scanning the spectra in range from 400cm^{-1} to 4000cm^{-1}. The spectral resolution was 4cm^{-1} and 64 scans were averaged on each measurement in order to increase signal-to-noise-ratio. The measurement set-up allowed measurement of weathered surfaces in transmittance mode.

OPUS 7.0 (Bruker Optics GmbH) software package was used for instrument control, spectra acquisition, data pre-processing and evaluation.

4.2.3 Data fusion

W_{ind}, is an indicator suitable for presenting the combined effect of the investigated parameters measured with different sensors [8]. An example of the W_{ind} progress during weathering is shown in Figure 10.

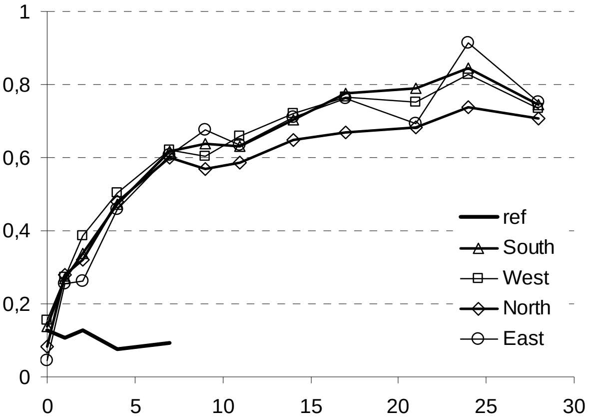

Figure 10: *Progress of the weathering due to exposure duration (horizontal axis, days) and normalized components (vertical axis) used for computation of weathering index* w_{ind}.

The colour parameters: lightness L*, colour-opponent dimensions: a*, b*, NIR absorbance at $5980cm^{-1}$ (band related to first overtone of -CH stretching of lignin), MIR absorbance at $1505cm^{-1}$ (band related to aromatic ring of lignin) and PC1 computed from the NIR and MIR spectra were arbitrary selected for computation of the W_{ind} in all investigated samples. Parameters mentioned above were related to both sample appearance (colour) and chemical composition (selected lignin bands and calculated Principal Components).
The importance of parameters was considered as equal, $w_i = 1$, with exception of parameters related to PC1 of NIR and MIR spectra and CIE b*, where $w_i = 0.5$. The indicator weight assignment was arbitrary choice of the expert person basing on the regularity of the signal.
In presented case even if the weathering period was relatively short the influence of exposure direction seems to have an effect on the degradation intensity.
The measurement campaign is now followed on other set of samples, which were weathered for the period of one year. This approach will be used for evaluation of all investigated bio-materials at various stage of weathering.

4.3 MODELS FOR LONG-TERM ADAPTIVENESS AND PERFORMANCE

In the last decades increasing focus on determination of durability and service life of materials, components, installations, structures and buildings is observed [9]. Service life is defined as the period of time after construction in which a structure maintains or exceeds minimum performance requirements without unforeseen or extraordinary maintenance or repair [10]. Service life of facades depends on many variables, some of which are environmental and, as a result, beyond the control of the designers and owners. In order to minimize decline of general performance of building it is necessary to achieve the optimum balance between functionality, initial and maintenance costs.
It is observed, that architects are choosing the solutions that improve durability and reduce maintenance requirements. Materials suppliers are developing better performing products more resistant to deterioration processes. Owners are more aware of the importance of maintenance. Finally contractors have developed quality control procedures to improve construction practices that consequently will improve durability.
Generally aesthetic requirements are reached before functional lose and reduction of safety level. Figure 11 presents a simulation of the degradation of three bio-materials used for building facades. It can be seen that aesthetical service life of material #1 is much shorter compare to #2 and #3. The acceptance limit for the appearance is reached in this case faster comparing to other materials.
Second scenario is related to simulation of the performance of same material used for building façade in various climatic conditions. It is evident, that the climate #1 seems to be more severe for bio-material of interest; and in consequence such a material solution is not recommended in certain locations. In favourable/mild climate the same material might have acceptable performance and its use may be suggested. It must be also stated that no regular maintenance and material replacement is considered here. Such maintenance action scheduled regularly will allow extension of service life in all presented cases.

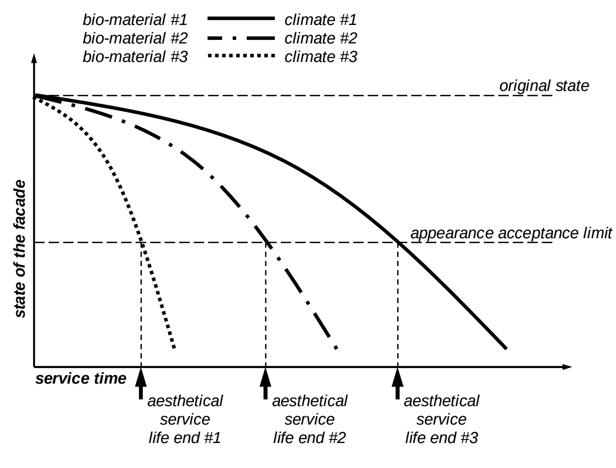

Figure 11: *Models for aesthetical service life performance depending on bio-materials type and climatic loads.*

5 DEVELOPMENT OF DEMONSTRATION TOOLS

Dedicated software simulating bio-materials performance, degradation and end-of-life in severe operating environments is foreseen as a most important deliverable of the project. The concept for the software simulating changes of bio-materials (related to both functional performance and aesthetics) for the whole duration of their service life is presented in Figure 12. Time series of pictures will be acquired during exposure of various facades materials. Those will be subsequently used for interactive simulation of facades appearance. Customers will be able to choose material from project database and see how the building looks at the brand new stage. Moreover time base simulation will allow observing the changes of the appearance depending on time, exposure direction, location and with consideration of architectonical details.

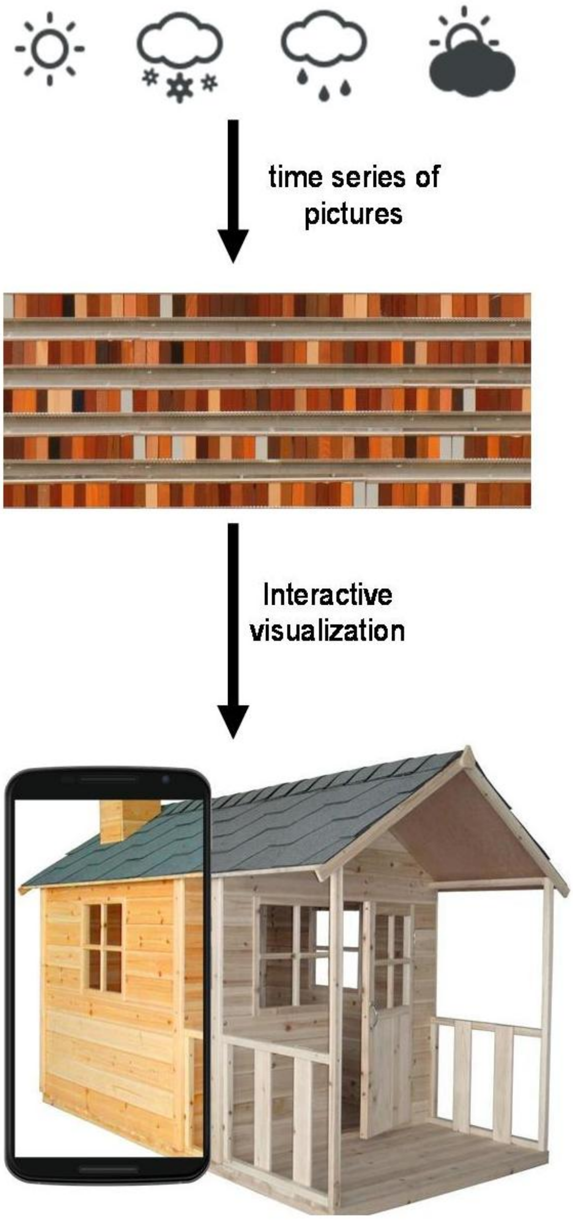

Figure 12: *Concept of enhancing the perception of materials through wood materials simulation over the time*

The software tools for the service life prediction and modelling aesthetical performance will be confronted with the consumer demands and preferences. As a result, definition of the limit state for functional and aesthetical end-of-life and maintenance scheduling will become possible. Additionally, a novel methodology for combining multi-sensor data in to a single indicator related to "beauty" or customer perception will be also developed. It will assist architects/customers to select optimal bio-materials assuring satisfactory performance and high aesthetical valour.

6 CONCLUSIONS

The trend for rapid deployment of novel/advanced material solutions at reduced-costs through predictive design of materials and innovative production technologies is observed nowadays. It is extremely important for the bio-materials production sector to follow this trend and to continuously improve its offer.

The development of really innovative and advanced bio-products relies on the deep understanding of the material properties, structure, assembly, formulation and its performance along the service life.

Comprehensive understanding of the physical/chemical properties and their connection with the material's structure will be obtained as a result of a combination of analytical/experimental methods and numerical modelling.

Results of the BIO4everproject provide technical and scientific knowledge but also contribute to the public awareness, by demonstrating the environmental benefits to be gained from the knowledgeable use of bio-based materials in buildings.

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