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Section 2 **Test Methodology and Assessment**

Simulation and visualization of aesthetic performance of bio-based building skin

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Simulation and visualization of aesthetic performance of bio-based building skin

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ABSTRACT

Performance of 120 selected façade materials provided by over 30 industrial and academic partners is under evaluation. The experimental data, acquired during BIO4ever project duration are used for development of the numerical models simulating the material degradation in a function of time and exposure. The weather data calculated according to the ASHRAE 2013 database allows numerical simulation of cumulative radiation and temperature on building facades, situated in 6000 locations all over the world. Dedicated algorithms simulating material deterioration by taking into account specific material characteristics, kinetic and intensity of weathering process as well as specific architectonic details are extensively tested and validated. Accurate service life prediction, service life costing and aesthetical performance models of evaluated bio-based building materials are foreseen as the most important deliverables. Software visualizing bio-materials’ performance will be dedicated for investors, architects, construction engineers, professional builders, suppliers and other relevant parties, including also final customers. It will assist architects/customers to select optimal bio-materials assuring satisfactory performance and high aesthetical valour.

Keywords: service life prediction, modelling, visualization, aesthetics, facades

1. INTRODUCTION

The trend for raising sustainable buildings and increasing environmental awareness observed nowadays leads to the reactivation of the bio-architecture as an alternative to other construction techniques. Recent advances in biomaterials research have delivered several solutions for the construction sector. Biomaterials, defined here as materials derived from organic sources, have become recognized as an attractive alternative to several traditional building solutions, and are often called “building materials of the 21st century”. Currently industrialized engineered wood products, such as glued laminated timber beams (glulam), cross-laminated timber panels (X-lam or CLT), or Laminated Veneer Lumber (LVL) allow using wood for erecting long-span and/or multi-story buildings. New developments in the field of wood modification offer innovative products with enhanced properties of natural timber. These include novel bio-based composite materials, as well as more effective and environmentally friendly protective treatments. The same revolutionary progress is observed with surface treatments including innovative coatings, impregnations or integration of nanotechnology developments for wood protection.

The development of innovative (in terms of embedded functionality and performance) bio-products relies on the deep understanding of the material properties, structure, assembly, formulation and its performance along the service life.

The ISO meaning of reference service life, 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), applied for estimation of aesthetic limits is challenging. Building façade is the first protective layer from environmental degradation agents of the wall and the structure, therefore has a fundamental role in the performance of entire building (Silva *et al*. 2016). Very often designers and architects base their decision regarding to the cladding selection on commercial documents, referring to "brand new state" of materials. The interaction between time and the elements that constitute the cladding system, the interaction between the materials applied in the cladding and the environmental exposure conditions, and the potential effects of changes in material's performance in the overall performance of the assembly is rarely taken into account (Fagerlund 1985). However, there is close inter-relation between material, component and building façade (Fig. 1). The functional improvements to materials is shifted to components, and, in turn, the entire building façade. The failure of material itself has an effect on the appearance and function of façade.

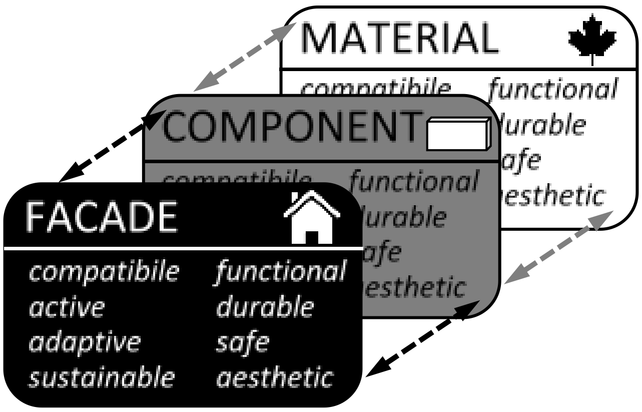

Figure 1: Hierarchical interrelations between functionalities and properties at different scales

Buildings are composed of various subsystems, which degrade at different rates. In consequence deterioration of buildings does not occur uniformly. According to Silva *et al*. (2016) several aspects should be considered for an effective selection, use and maintenance of a façade's cladding system. Those includes:

- the façade's expected service life;
- the forecasted degradation mechanisms (e.g. chemical, physical and mechanical);
- the properties of materials applied on the façade and their execution conditions;
- the compatibility between the cladding system and the structure;
- the effects of environmental exposure conditions and of the use of the building.

Today's bio-based building materials, even if well characterized from the technical point of view, often lack reliable models describing performance during their service life. The BIO4ever project is merging several disciplines: wood science, architecture, building physics, chemistry and mathematics, as well as psychology and customer preferences in order to deliver validated solutions closer to user-defined expectation. The overall goal of the project is to contribute to public awareness, by demonstrating the environmental benefits to be gained from the knowledge-based use of bio-based materials in buildings. The main project output is an interactive software simulating bio-materials aesthetic performance integrated with LCA interactive calculation. The tool, dedicated for investors, architects, construction engineers, professional builders, suppliers and other relevant parties, including also final customers is now under extensive validation and integration with the BIM software.

2. EXPERIMENTAL METHODS

2.1 Experimental samples

Hundred twenty samples investigated within the project were provided by over 30 industrial and academic partners from 17 countries. 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, nanocoatings, 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 焼杉板 (http://shousugiban.com/) The treatments were classified in seven categories and are presented in Fig. 2.

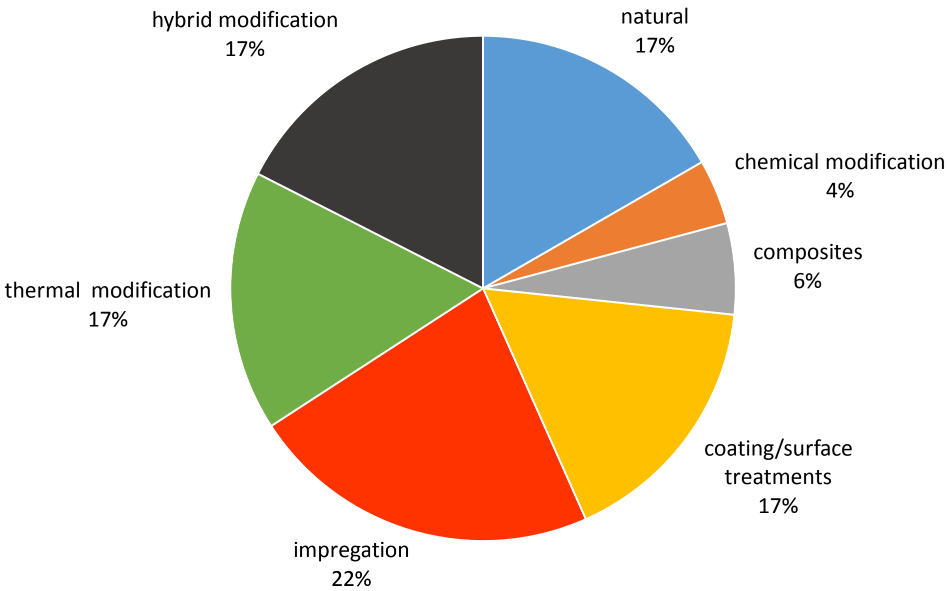

Figure 2: Categories of facades materials investigated within BIO4ever project.
Note: hybrid modification include combination of at least two different treatments.

2.2 Samples characterization

A multi-sensor measurement chain for the acquisition of properties at different scales (molecular, microscopic, macroscopic) includes:

- Photogrammetry
- VIS, near and mid infrared spectroscopies and hyperspectral imaging
- IR thermography
- Surface characterization (colour, gloss, wettability, roughness)

Investigated bio-materials were characterized before, during and after degradation by biotic and abiotic agents (natural weathering in San Michele, Italy (46°11’15’’N, 11°08’00’’E), in order to provide experimental data to be used for better understanding the bio-materials performance/degradation as a function of time. Each month high resolution photos were acquired to capture the real progress of appearance change.

2.3 Modelling and visualization

The amount of solar radiation and the moisture content forecast on the façade surface was simulated with support of a FEM (Finite Element Method) software (COMSOL Multiphysics V.5.3). The 3D model of a house, as shown in Fig. 3, has been defined as a simple geometry representative of a small single family building with a gable roof and with some shade elements (balcony, pillars, eaves).

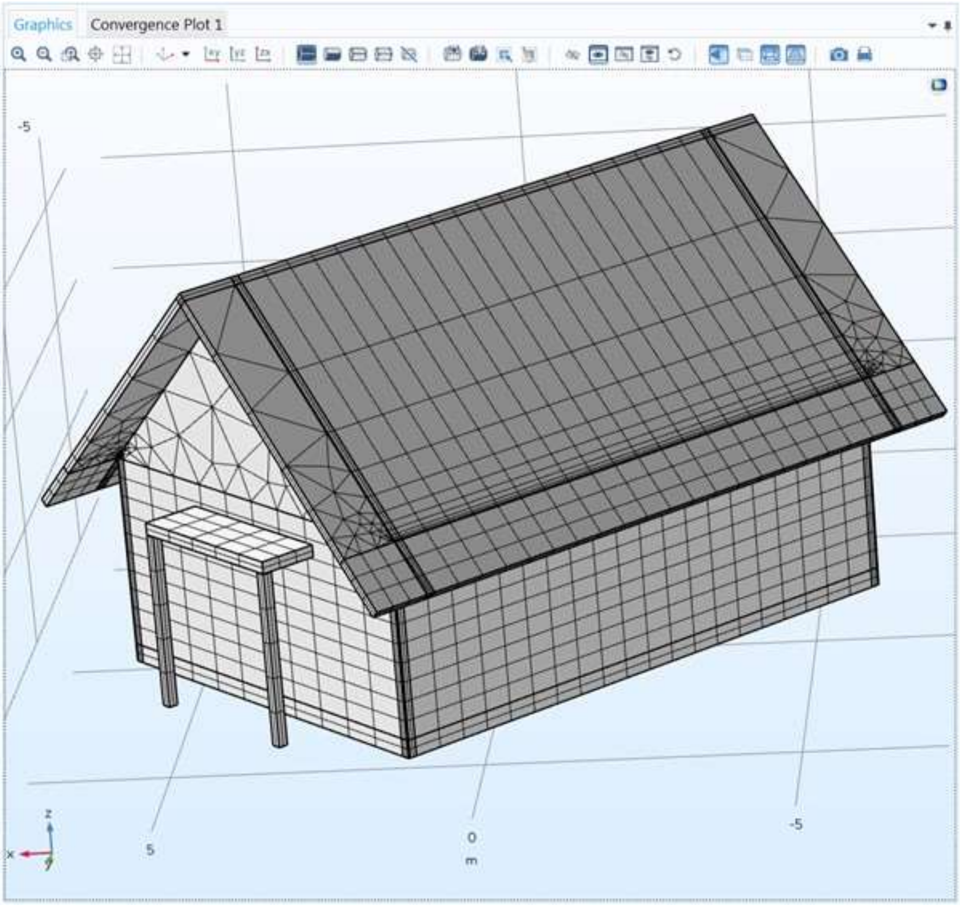

Figure 3: 3D model of the house with defined mesh as used for numerical simulation.

The weather data (relative humidity of air, diffuse and direct solar irradiance, sun path during the day) were calculated according to the ASHRAE 2013 database, being a part of the software (Fig. 4). With the ambient setting window, the option “ambient data from weather data” allows the selection of the location from a list of more than 6000 weather station all over the world.

In order to set a correct simulation, the thermal proprieties of the material were defined according to the reference literature values available for different wood species. The emissivity of the material was defined in two spectral bands, namely solar (short wavelength λ <2.5[μm]) and ambient (long wavelength λ >2.5[μm]).

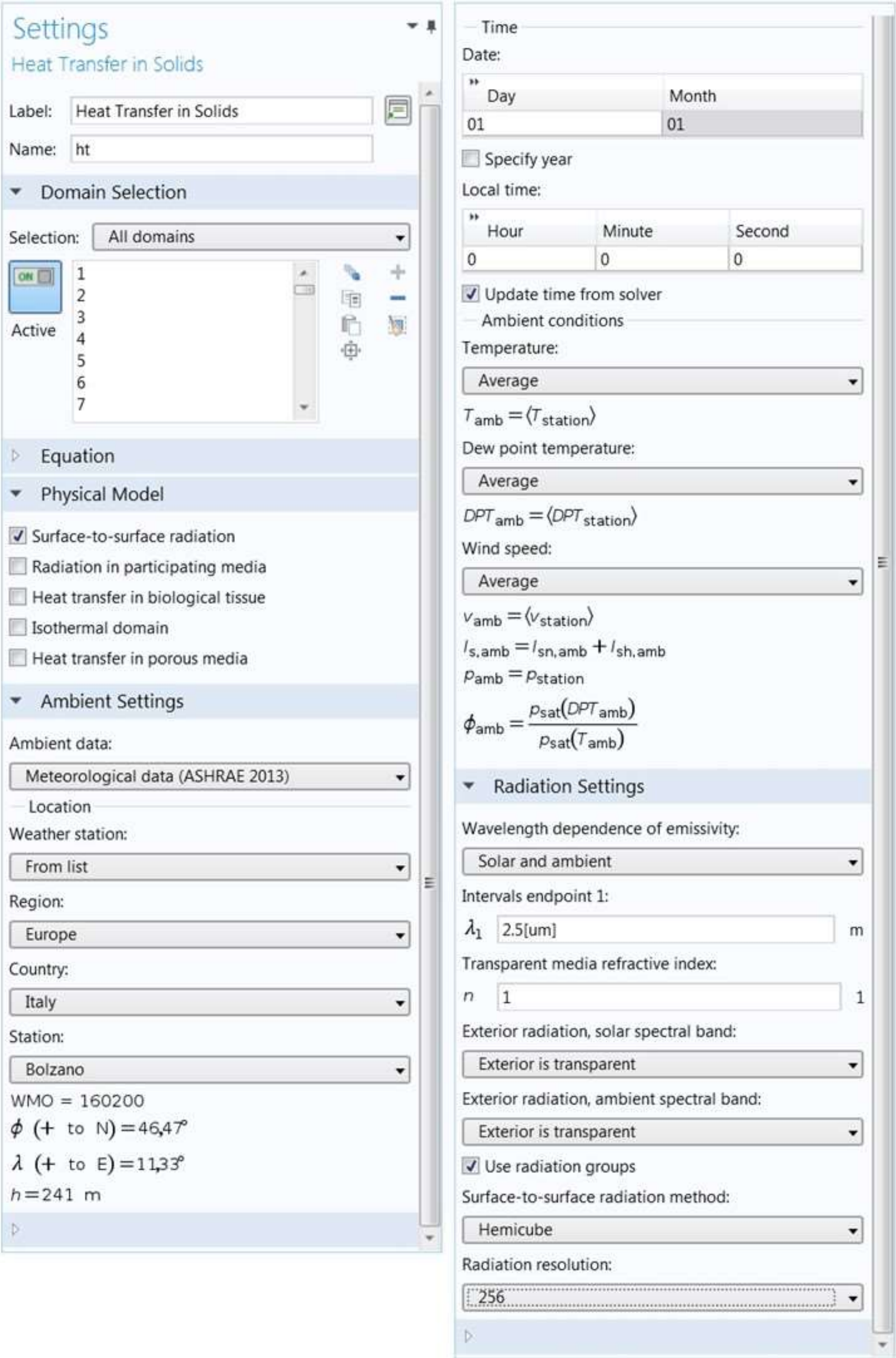

Figure 4: Print screen of the weather data ASHRAE 2013 used for simulation.

3. RESULTS AND DISCUSSION

3.1 Materials appearance during weathering

The intensity of weathering depends on timber species, design solution, function of product and finishing technology applied for wood protection, and on the specific local conditions. The corrosion rate of wood is low; approximately 6mm per century in case of European softwood species (Williams, 2005). The progress of natural weathering and appearance change of investigated samples is visible on Fig. 5. Some materials appear to not change the outlook, however several of these changed (usually become pale and less saturated), like in the case of natural wood, or acetylated wood.

Figure 5: Experimental samples during natural weathering (southern exposure). Note: up, left: new samples set, up, right: 4 months, bottom, left: 8 months, bottom, right: 12 months of exposure.

The weathering progress of all experimental samples was visually evaluated by the panel of experts, prior to extensive laboratory characterization. Results of the visual grading performed after one year of natural weathering are summarized in Table 1. The grade was assigned for each sample according to 5 points scale, where: grade 1 reflects the perfect conservational stage, while grade 5 indicates highly damaged material recommended to be substituted. It should be noticed that the aesthetical performance highly depends on the exposure direction. Samples exposed to south and east were more degraded then those exposed to the west and north directions.

Table 1: Results of the visual assessment of experimental samples exposed to one-year natural weathering at four cardinal directions (number of samples within each material category classified at given a grade)

		South					**East**					**North**					**West**					
	Grade	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	
Category	**Chemical Modification**	4	1	0	0	0	2	3	0	0	0	1	4	0	0	0	4	1	0	0	0	
	Coating & Surface Modification	12	4	2	3	0	10	9	2	0	0	13	5	2	1	0	12	5	1	3	0	
	Composites	4	2	1	0	0	4	3	0	0	0	4	3	0	0	0	4	2	1	0	0	
	Hybrid Modification	13	5	1	1	0	15	5	0	0	0	15	4	1	0	0	15	4	1	0	0	
	Impregnation	11	13	2	1	0	16	10	1	0	0	16	7	4	0	0	17	8	1	1	0	
	Natural	13	5	1	1	0	12	6	1	1	0	12	7	1	0	0	15	5	0	0	0	
	Thermal Modification	10	8	1	0	1	10	9	1	0	0	11	8	0	0	1	8	7	3	2	0	
	Total counts	67	38	8	6	1	69	45	5	1	0	72	38	8	1	1	75	32	7	6	0	

The surface colour change is an apparent consequence of biomaterial's weathering. Fig. 6 presents a typical trend of RGB colour changes, measured separately for early and late wood of Norway spruce (*Picea abies*) along 12 months of natural weathering. It is evident that early wood is more susceptible to degradation due to specific anatomical structure (Mohebby and Saei 2016).

Similar curves were assessed for each biomaterial investigated within BIO4ever project. Such an extensive database allows determine specific kinetics of aesthetic changes for every material category and consequently dose-response model. The weather dose *D* is defined as an amount of "energy" provided to the system that affected the changes of material due to weathering. The value of *D* is a function of the combined surface temperature, solar radiation and moisture content. The value of response is numerically determined on the base of the given material state parameters, such as *CIE L*, *CIE a*, *CIE b*, *CIE* ΔE, near infrared spectrum or RGB colour coordinates (Sandak *et al.* 2017a). The BIO4ever sample sets are additionally used for creating of the model surface morphology maps (pattern or texture) for all investigated biomaterials.

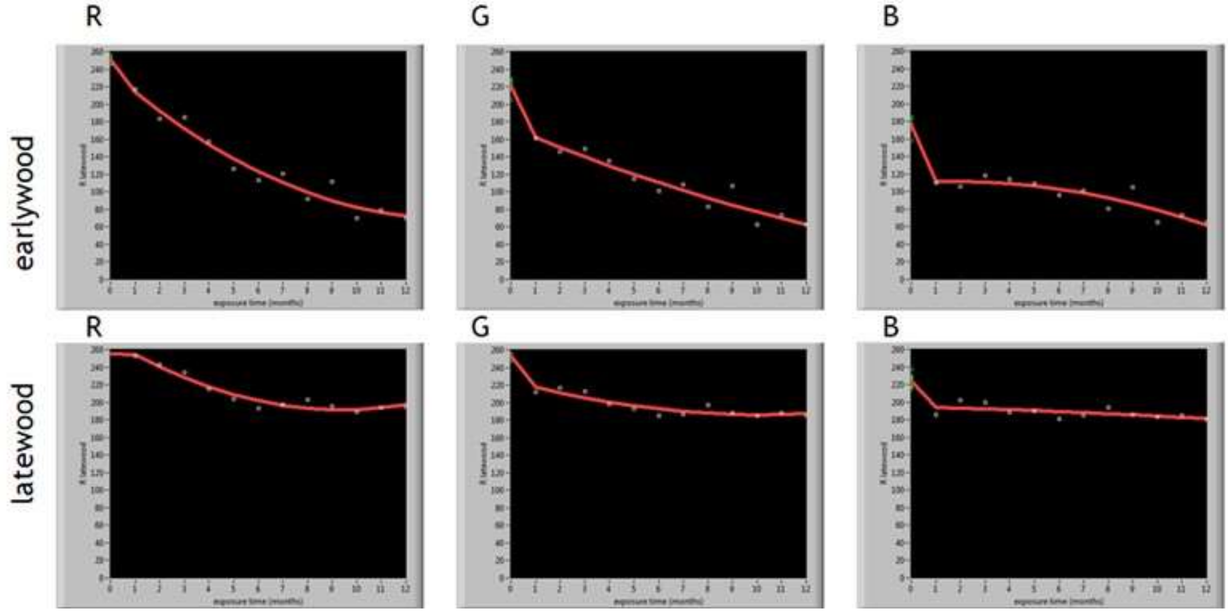

Figure 6: Curves of the RGB colour changes for early and latewood during one year of weathering.

3.2 Modelling of the weathering progress

The numerical simulation for one-year long exposure of the model building was carried out in order to quantify effect of weathering factors in different seasons. Each point of the mesh, as presented in Figure 3, was independently resolved considering combined effects of sun irradiation, air relative humidity, air temperature and exposure/shading at each time during the year. Both, heat and mass transfer multiphysics modules were implemented for the simulation.

The mesh was defined with square elements in order to compromise a decent mesh quality with a minimum number of elements, thus restricted number of DOF (degrees of freedom). The number of DOF is one of the essential parameters that influence time needed to numerically resolve the model, or to find the numerical solution of the equations set with iterative methods. This operation is usually carried out directly in the “mesh editor” where the specific distribution is defined by the user. The time dependent analysis was carried out with a time step of one hour and were conducted with a standard iterative solver. Interpolations between the nodes values were performed in order to map the values out of the mesh points. Example results of the surface temperature distribution and the sun-related surface irradiation in two diverse seasons (winter and summer) are presented on Fig. 7 and 8 respectively.

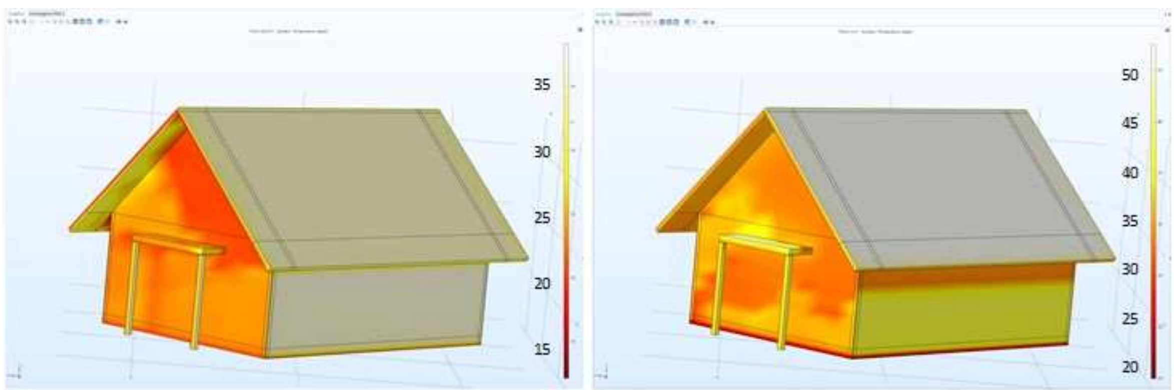

Figure 7: Simulation of surface temperature in January (left) and June (right).

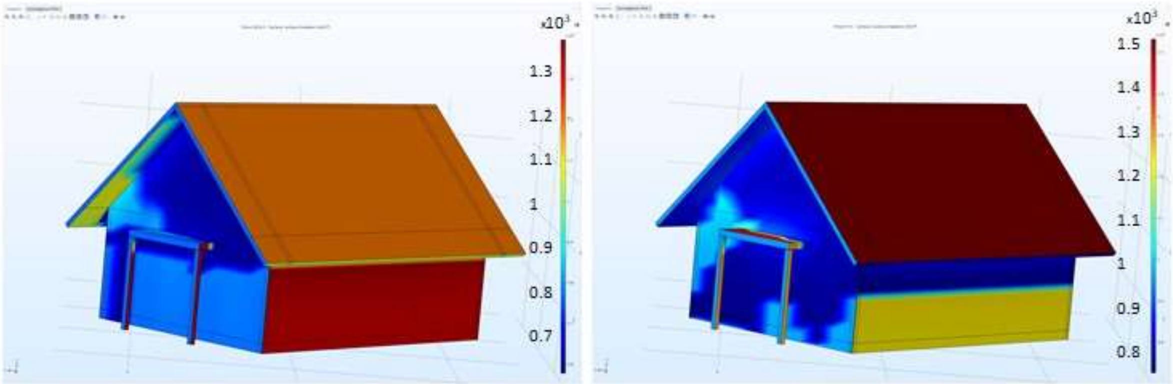

Figure 8: Simulation of surface radiation in January (left) and June (right).

3.3 Visualization software development

Outputs of the FEM model, containing surface temperature distribution, solar irradiation and surface moisture maps were converted in to single parameter corresponding to the weather dose *D*. The dose map was extracted (unfolded) for each wall of the building and was then considered as an input data for the visualisation tool capable of simulating the weathering results in each pixel of the 3D building model. The software was originally developed in LabView 2017 programming language (National Instruments), but it is recently adopted for the BIM architecture. At this stage of the software development, all the available data regarding appearance change of each biomaterial in time, weather dose map and specific building layout (UV surface map) are merged together allowing 3D model visualization. Figure 9 present the summary of software system, including brief description of the user input needed for complete appearance visualization.

Time series of pictures that were acquired during exposure of tested materials are used for the interactive simulation of facades appearance. Software users will be able to choose a material from the database, select the building location and then simulate the structure look at the brand new stage (Fig. 10). Numerical simulations performed in COMSOL, in combination with other custom algorithms, allow visualization of the appearance changes related to the period of service, specific exposure direction, microclimate, but considering also architectonical detailing of the structure. By changing the geographical location of the building site, the software will automatically re-compute the orientation of the incident sunlight over the course of the intended period.

Furthermore, by combining with other software functionalities developed within BIO4ever project, future users will be properly guided regarding the realistic maintenance scheduling as well as possible recycling/reuse options (Petrillo et al. 2018) for the wide range of biomaterials. Consequently, the software will be compatible with Building Information Modelling philosophy and will provide new complementary dimensions for the BIM utilities, such as 6D (sustainability) and 7D (facility management).

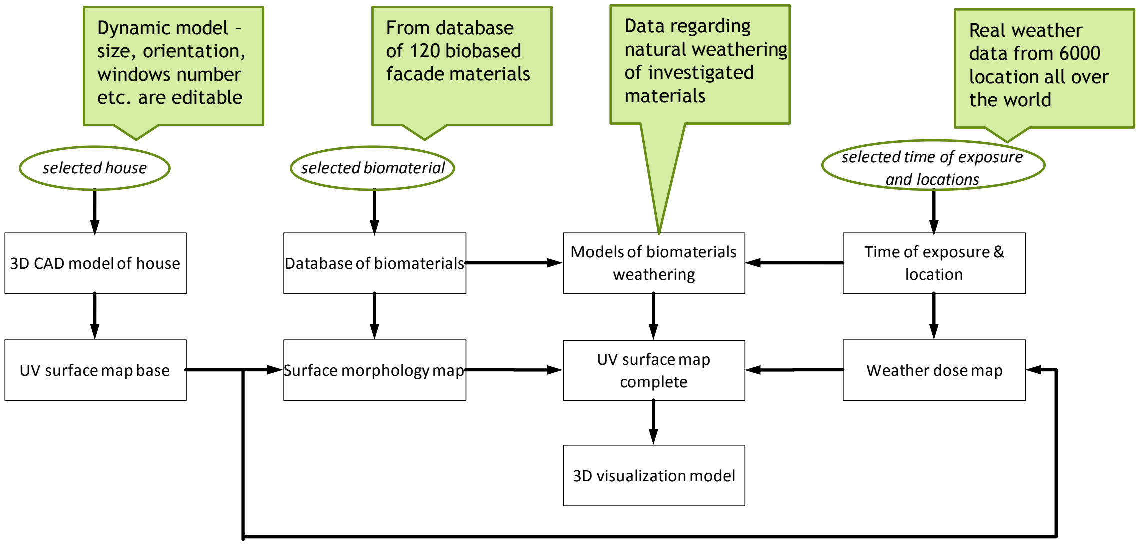

Figure 9: Software flow implemented within BIO4ever project (Sandak *et al*. 2017b)

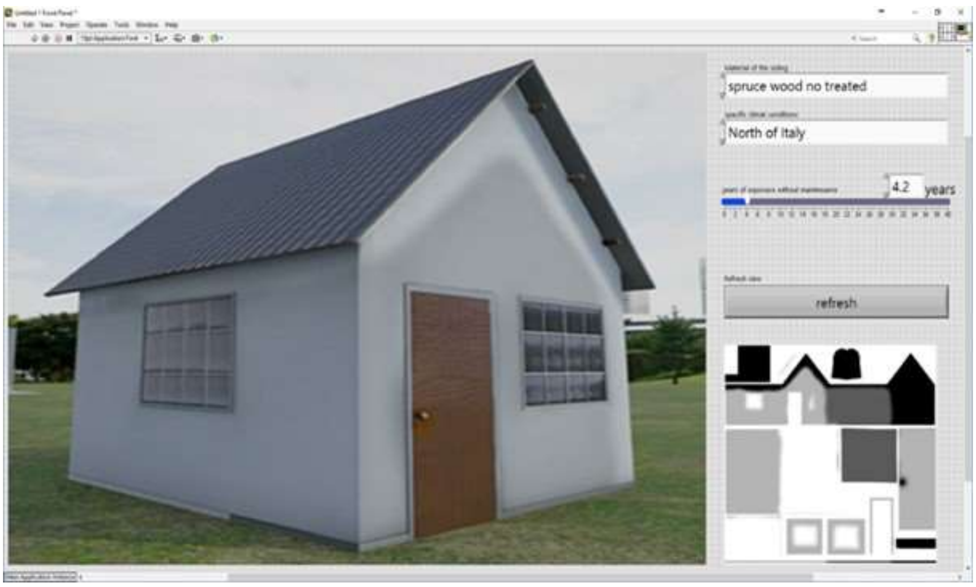

Figure 10: Print screen of the pre-alpha version of the BIO4ever software (Sandak *et al*. 2017b)

4. CONCLUSIONS

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 expertise and best practices. The surface deterioration is unavoidable, but its negative impact can be minimized by the appropriate maintenance or replacements. The definition of proper strategy in terms of cost and benefit can be analysed only if all the technical parameters (material properties) and human factors (acceptability of the appearance that influence the intervals between the maintenance) are combined in the first steps of the design. Furthermore, the big portfolio of bio-based building materials allows selection of materials that require minimum maintenance effort.

The objective evaluation under realistic conditions of various biomaterials usable for facades performed within BIO4ever project was conducted in order to create comprehensive database. It contains list of technical materials characteristics as well as degradation pattern of their changes during the use phase. Calculation of weathering response specific for each tested material, combined with numerical modelling of climatic effect on building facades allowed realistic simulation of the façade appearance considering at simultaneously time, geographic location and intrinsic material characteristic. Reliable performance models, allowing aesthetical visualization of buildings along their service lifetime are indispensable to convince architects, developers and investors for confident use of building biomaterials.

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