Life cycle assessment of bio-based façades during and after service life: maintenance planning and re-use

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ABSTRACT

New developments in the field of wood protection, coupled with the European political determination to lower the environmental impact of the building sector, designates wood and bio-based materials as an excellent option for building façades. Despite that, the share of wood in the European wood construction market is low, with the exception of some North European countries. For that reason, it is necessary to increase a confidence in bio-based façades by demonstrating their environmental performances during and after the service life by means of solid scientific tools and experimental evidences. As a pilot study, we investigated the interactive LCA in two maintenance scenarios (high and low intensity), assuming two diverse cladding bio-materials (untreated sawn wood and chemically modified wood). A dedicated software tool was developed for the needs of these analysis allowing dynamic simulation of environmental impact and immediate visualization of the LCA contributions. The end-of-life options were assessed with a different approach. Firstly, several alternative scenarios for re-use that are available on the market were identified and listed. Secondly, we established a weight-based expert system expressing importance/advantage of each scenario in order to classify each end-of-life option according to its provision of environmental benefit. Finally, we assessed the suitability of each defined end-of-life option for all evaluated bio-based materials.

INTRODUCTION

The construction sector 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. Aggregate, concrete and bricks are the most used construction materials in Europe, covering 45%, 42% and 6.7% of the total volumes respectively. At the same time, the share of timber structures accounts for only 1.6% of the total (Herczeg *et al.* 2014). Energy consumption of buildings in developed countries comprises 20-40% of the total energy use, more than industry and transport sectors (Pérez-Lombard *et al.* 2008). To reduce the use-phase costs of buildings, the selection of optimal building envelope systems can be crucial. However, materials for building envelope can have a high manufacturing costs (both economic and environmental). It is reported in several studies that the bio-based building materials have lower embodied energy than traditional ones (Kovacic *et al.* 2016, Lugt and Bongers 2016, Lupíšek *et al.* 2015, Werner and Richter 2007, Zabalza Bribián *et al.* 2011). Moreover, as bio-based materials are renewable, these are suitable at the end of service life for diverse paths of re-use (Thonemann and Schumann 2018). In spite of the economic crises, the production of some now well-established engineered wood products for structural use, such as cross-laminated timber (CLT), is intensively growing in Europe and globally (Brandner *et al.* 2016). Moreover, the improvements of the new wood-based products make these suitable to substitute some fossil-based raw materials. It is foreseen that there is a potential to doubling the added-value of the wood industry by 2030 (Hetemäki and Hurmekoski 2016). Furthermore, recent technological developments allow mass production of wood-based products (modified wood) that still few years ago were at the prototype stage (Mantanis 2017, Sandberg *et al.* 2017). The environmental impact of the production phase is disclosed for some modified wood products in dedicated EPD documents or LCA-related literature. For example, the carbon footprint of 1 m^3 of chemically modified wood can vary between 258 and 511 kg CO_2eq (Lambert and Daae 2015, Vogtlander 2015), while that of 1 m^3 of thermally modified wood can be between 131 and 133 kg CO_2eq (Ferreira *et al.* 2018). Nevertheless, the data differ greatly based on wood species, process-specific inputs and outputs, type of production plant, transportation, among the others. The environmental impact of the service life of wood-based façades has been rarely assessed, also because it is complicated to properly define the service-life duration, the limit state for maintenance operations and, consequently, to calculate the maintenance frequency (Grüll *et al.* 2011). In order to fill this gap, we developed a software tool that calculates the environmental impact of the maintenance of wood-based façades. The system was tested on two case scenarios of maintenance: high frequency/intensity and low frequency/intensity for two diverse wood-based façade solutions.

EXPERIMENTAL

Life cycle assessment (LCA) method was applied to four elementary maintenance operations typically executed on façades: cleaning, sanding, recoating and replacing (Petrillo *et al.* 2018). Figure 1 presents a graphical representation of the abovementioned operations/modules, including summary of the life cycle inventory data as used for environmental impact computation. All the modules can be combined together in an interactive LCA, where the user can define several variables describing the real-life scenario of the façade usage. The intensity of maintenance, material performance, local macroclimate as well as the owner's tolerance for aesthetical deficiencies are particularly important factors affecting the LCA results. We tested the cleaning operations considering both presence or absence of a detergent in addition to the water. Therefore, the output can be only water or water contaminated with the detergent. These two options were tested in two different scenarios. The use of electricity was included to account for the use of pressure-machine (power 1,5-2 kW, work efficiency 0,015-0,025 h/m^2) in the cleaning operations. The sanding operations include sandblasting with pressure machine (power 1,5-5,5 kW, work efficiency 0,025-0,008 h/m^2) and a natural abrasive media, such as corn cob or walnut shells. The type of waste flow can be different: only sawdust in the case of sanding natural, untreated wood, sawdust and waste paint in the case of coated wood, sawdust with chemicals in the case of impregnated wood. Three scenarios were calculated considering the re-use of the abrasive media. Usually, this operation is a preliminary step before re-coating.

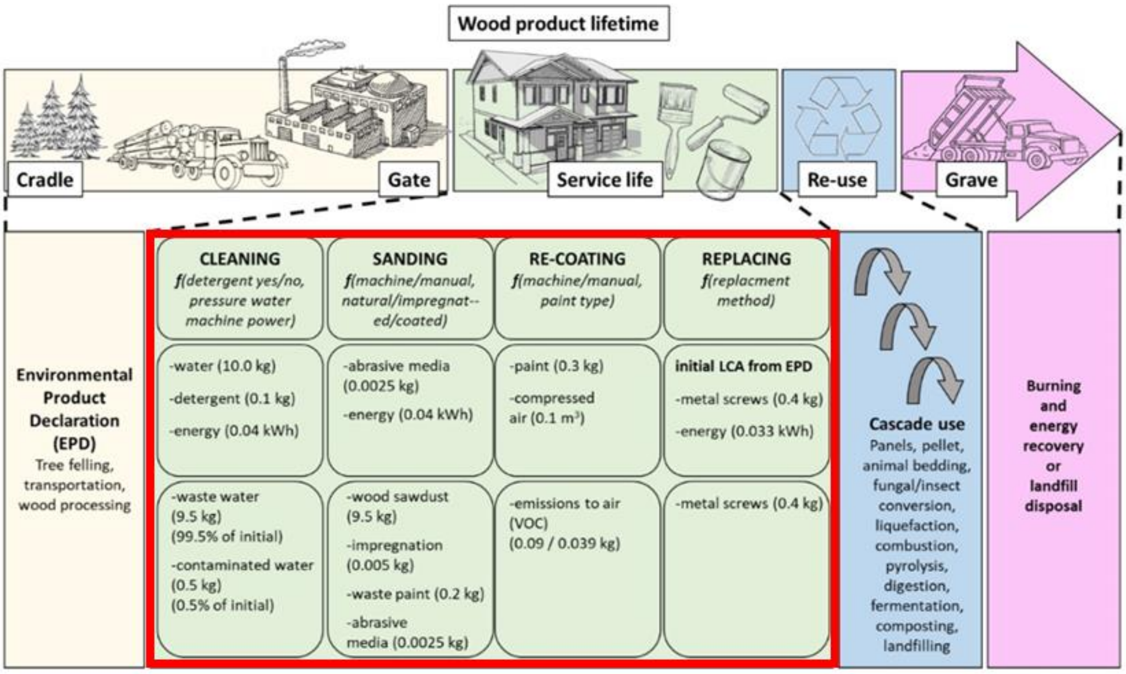

Figure 1: Lifetime of wood products with emphasis on service life. Maintenance modules are described in terms of input and output of materials and natural resources (life cycle inventory) (Petrillo et al. 2018).

The options for re-coating were based on acrylic and alkyd paints, water- or solvent-based. Moreover, all paint types were calculated for the options: hand-painting or machine-painting (spray-machine with compressed air). For the replacement operations, we considered the substitution of 25% of the façade in terms of the new material (data from available EPDs) and the environmental impact of the operations for replacement (metal screws, screwdriver energy demand). Then, we hypothesised two maintenance scenarios: high level of maintenance, due to harsh climate and high esthetical standard, and low level of maintenance, due to mild climate and low aesthetical standard. Based on practitioners' experience, scientific literature and technical data provided by material producers, we defined the maintenance options and their frequency in the four cases, as represented in Table 1.

Table 1: Condition for simulation of four case scenarios in 20 years of service life

	Case 1	**Case 2**	**Case 3**	**Case 4**
Climatic conditions	Harsh	Mild	Harsh	Mild
Material type	Natural wood (conifer)	Natural wood (conifer)	Chemically modified wood	Chemically modified wood
Owner aesthetical standard	High	Low	High	Low
Cleaning (times in 20 years)	6	2	9	3
Sanding + Re-coating frequency (times in 20 years)	2	1	0	0
Replacing frequency (times in 20 years)	1	0	0	0

Finally, we defined a system to weight different end-of-life (EOL) scenarios. The system takes into account for each EOL option the factors which are relevant for the calculation of LCA, such as: the potential for multiple re-use, the demand of additives for the new use, the energy required for the process and, finally, the possibility to recover energy at the end of the re-use cascade.

RESULTS AND DISCUSSION

The results indicate that the environmental impact of the use phase can vary greatly due to the climate and user, as represented in Fig. 2.

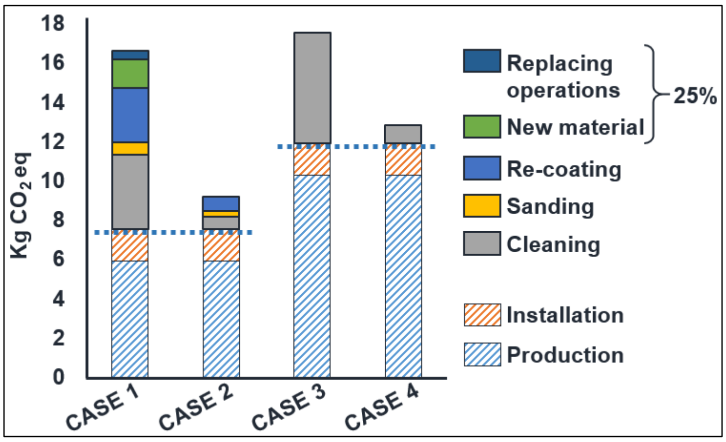

Figure 2: Environmental impact of production, installation and maintenance of 1 m^2 of façade made with untreated wood (case 1 and case 2) and chemically modified wood (case 3 and case 4) in high maintenance scenario (case 1 and case 3) and low maintenance scenario (case 2 and case 4).

For high frequency and intensity of maintenance, the total environmental impact of the natural wood façade and that of the chemically modified wood façade are comparable. In fact, the lower impact of the production of natural wood in comparison to the chemically modified wood is compensated by the higher impact of the maintenance operations for natural wood façade. However, in the mild climate, the natural wood has sensitively lower impact than chemically modified wood. The proposed system for interactive LCA is suitable for every possible combination of climate, material, design and customer aesthetical standard. Finally, in Table 2 we present the selection of the end-of-life scenario.

Table 2: End-of-life (EOL) features and their weights based on environmental impact. The total score indicates the environmental friendliness for each end-of-life option.

	Allow re-use	**Require additives**	**Reuse without processing**	**Reuse with processing**	**High energy**	**Low energy**	**Energy recovery**	**No energy recovery**	
Weights for EOL feature	**10**	**-5**	**7**	**3**	**-5**	**-1**	**5**	**-7**	**Total score**
Landfilling	0	0	1	0,1	0	1	0	0,9	**0**
Composting	0	0	0,1	0,9	0,1	0,9	0,2	0,2	**2**
Liquefaction	0,8	1	0	1	1	0	0,7	0,2	**3**
Fermentation	0,2	0	0,1	0,5	0,1	0,9	0,8	0,2	**5**

	Allow re-use	**Require additives**	**Reuse without processing**	**Reuse with processing**	**High energy**	**Low energy**	**Energy recovery**	**No energy recovery**	
Anaerobic digestion	0,2	0	0,2	0,5	0,2	1	0,8	0,2	**6**
Combustion	0	0	0,1	0,9	0,1	1	1	0	**7**
Incineration	0	0	0,1	0,9	0,1	1	1	0	**7**
Pelletizing	0,4	0	0	1	0,9	0	1	0	**8**
Gasification	0,2	0	0,1	0,9	0,2	1	1	0	**8**
Pyrolysis	0,2	0	0,1	0,9	0,2	1	1	0	**8**
Animal bedding	0,5	0	0	1	0,1	0,9	0,5	0,1	**8**
Panel manufacturing	0,9	0,5	0,2	0,8	0,8	0,2	1	0,1	**10**
Fungal conversion	0,7	0	0,8	0,4	0,1	0,9	0,4	0,2	**13**
Insect conversion	0,7	0	0,6	0,8	0,2	0,9	0,5	0,1	**14**
Re-use in solid products	1	0	1	0,1	0,1	1	1	0,1	**20**

CONCLUSIONS

In conclusions, the interactive LCA system that we propose allows rational choice of material and maintenance operation during service life. In fact, based on the location it will be possible to forecast a realistic maintenance plan, which will be customized according to the aesthetical expectation of the user.

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