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Long service life or cascading? The environmental impact of maintenance of wood-based materials for building envelope and their recycling options

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ABSTRACT

A major restraint in choosing bio-based materials (i.e. wood-based) for external use, is the lack of confidence that architects, designers and customers have toward these materials. In particular, the limit state of bio-based materials, which defines the frequency of maintenance operations, might be reached earlier for wood than for other materials (i.e. concrete). On the other hand, resource and energy scarcity together with increasing concern for climate change consequences are raising the demand for competitive bio-based materials in the built environment as substitutes for other energy-intensive materials. Therefore, novel and traditional protective treatments are used to improve the performance of woody materials for outdoor use. Nonetheless, the environmental and economic burden of such treatments is often unknown. The number of LCA (life cycle assessment) studies on the topic is low, with geographically sparse data and non-uniform assessment protocols. This study provides a novel approach to assess the in-service performance, maintenance requirements and end-of-service-life options for over one hundred bio-based materials for façades. The protection techniques of the materials under examination include: chemical modification, thermal treatment, impregnation, hybrid treatments, and surface treatments (bio-film, coating and nanocoating). Natural, untreated wood and composite materials such as wood-plastic composites are included as well. The in-service environmental performance is analysed by considering the amount of material, energy, water and waste that are used and/or produced to maintain one square meter of façade. The options for end-of-service-life include: panel manufacturing, pelletizing, animal bedding, liquefaction, insect conversion, fungal conversion, combustion, incineration, gasification and pyrolysis, anaerobic digestion, fermentation, composting and landfilling. For each material group, the possibility for cascading use is assessed. The overall goal is to increase the confidence in bio-based building materials by tackling environmental issues related to wood modification processes.

Keywords: Life cycle assessment, bio-based materials, façade, building use-phase, end of service-life, cascade use.

1. INTRODUCTION

Bio-based building materials (i.e. wood, modified wood) are likely to outperform other energy-intensive, non-renewable materials considering the environmental impact of their production processes (Petersen and Solberg, 2005).

The bio-based materials are made out renewable resources (wood) and therefore store carbon, but they also hold potential for multiple re-use cycles and eventually energy recovery at the end of their service life. Non-bio-based materials, such as steel or concrete, require more resources in terms of environmental and economic cost and energy for reuse compared to timber. The policies about building construction codes are increasingly concerned with environmental criteria, since climatic change is becoming an unequivocal threat to our cities and societies and space for landfill waste is decreasing (Tarantini *et al.* 2011). The plans for the improvement of environmental sustainability, especially regarding the end of life strategies of building materials, are current issues in different fields of legislation. For example, European regulations have been dealing with "green public procurement" (GPP) since 2003, when a first proposal was developed to promote the application of national plans for the GPP (COM 2003/302). Later on, the proposal was confirmed by two directives (2004/17/CE and 2004/18/CE) that enacted to regulate the public procurement (ICLEI 2016).

Common procedures and specific documents for each field of the public procurement have been produced by the European committees (Cleaning products and services, Furniture, Office Building Design, Construction and Management, Wall Panels, Transport). Italy was the first European country with specific rules for the public administration in order to promote the use of bio-based materials (Rebaudengo *et al.* 2017; Italian Ministry of Environment 2017). According to minimum environmental criteria, sustainability became a new parameter to evaluate and compare the score of the offers and the projects in a public procurement. The initial target of 50% assigned contracts including green requirements (GPP criteria) by 2012 was not been met, but the trends indicate the continuous increase of contracts with a special focus on the environmental aspect using GPP criteria (IPOL 2017). Nonetheless, several drawbacks still hinder the broad application of green criteria (i.e. economic issues), a topic recently addressed in order to provide policy makers with improvement strategies (Testa *et al.* 2016).

Regarding the private sector, the requirements in terms of sustainability (not mandatory as for the public procurements) are already included in the most important rating systems: LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method for buildings) and ARCA (architecture, comfort and environment). The added value for the green building design regarding the environmental product declaration (EPD) and life cycle assessment (LCA) represent a high ratio compared to the total score of a project. For instance, according to LEED and ARCA protocols, where the maximum score for a project is 110 points, the total score for the sustainability of "Materials & Resources" is 14 points, while for BREEAM the value related to the sustainability of the materials is 20% on a maximum percentage of 110%.

Along with the increase in the policies supporting sustainability, the development and advancement of wood modification processes resulted in greater availability of modified wood products on the market (Sandberg *et al.* 2017). Yet, the environmental and economic burden of the treatments that are applied to protect wood (i.e. chemical, thermal, impregnation, coatings) are often undisclosed, as there is a lack of available environmental product declarations (EPD) specific for each modification process. Moreover, the maintenance operations of these materials during the service life could also represent an overlooked source of environmental impact. However, the issue of maintenance, i.e. discolouration prevention, is common to other materials as well, especially when particular colours (bright red, yellow, green) are used to coat plaster or plastic coatings.

Life cycle assessment (LCA) is an increasingly used tool in the construction sector to reveal the environmental costs of a product or process, but only few studies are available regarding LCA of modified wood (Sandberg *et al.* 2017). The comparison among maintenance scenarios for different façade materials should be performed at the early stages of a building design. Different methods, software tools and inventories are available for LCA. However, the classical approaches to perform LCA on buildings are represented by either the comparison of different façades by using a common method (Sierra-Pérez *et al.* 2016), or by the comparison of both facades systems and LCA methods (Tellnes et al. 2014). These classical approaches for LCA are rather static and do not represent the dynamic nature of a building service life well. Therefore, there is a need for dynamic models that better represent the frequency of maintenance operations throughout the service life of a building (Grant *et al.* 2014). The development of user-friendly decision-support tools based on LCA has been approached in few cases (Kovacic *et al.* 2016). The relevance of replacement frequency and maintenance has been highlighted in some studies (Grant *et al.* 2014, Grüll *et al.* 2011). For an increased use of bio-based materials is essential to address their full life-cycle, including reuse and, ultimately, disposal (Srubar *et al.* 2012). Indeed, compared with other building materials, bio-based materials (i.e. modified wood) have several options for re-use and recycling after end of service life, even in high value new products such as furniture. The re-use of wood products in a high-efficiency scenario can reduce the greenhouse gases (GHG) emissions by over 50% (Bais-Moleman *et al.* 2018). The options for re-use depend predominantly on two criteria: the intake of chemicals with modification processes, preservatives and/or coatings, and the state of the material at the end of service life, that is closely linked to the maintenance during service life. In general, the following options for re-use are possible for wood-based products: combustion, digestion, pyrolysis, fermentation, gasification, liquefaction panel manufacturing, animal bedding, pelletizing, fungal and insect conversion, composting and landfilling. Some of them are well established commercial technologies, however some (e.g. conversion by insects into high value protein source) are still under experimental trials (Sandak and Sandak 2016). At present, the production of panels with recycled wood and the combustion of waste wood for energy recovery are the primary options for re-use. For example, in Italy, a consortium created in the mid-90s, promotes the reuse of wood from the industrial and domestic packaging, in order to produce panels for the furniture industry. The huge quantity of material (1.705.000 tons of recycled wood on a total amount of 2.811.000 tons of wooden packaging produced per year) obtained with this procedure shows the big potential of cascade use of wood waste with up-cycling process (www.rilegno.org 2018). In this work we propose i) a novel approach for LCA, providing the framework for dynamic, customized LCA of the maintenance of bio-based facades, and ii) a conceptual basis to define re-use scenarios for bio-based materials, with highlighted consideration for the re-use of wood products.

2. EXPERIMENTAL METHODS

2.1 Bio-based materials database

Within the BIO4ever project, a database of 120 bio-based building materials for cladding was established. This database includes bio-based materials with traditional and novel wood protection techniques, such as chemically modified wood, thermally modified wood, impregnated wood. Allover, 32 different categories for treatments are represented in the database, as can be seen in Table 1. Some of the materials, mostly those provided by private companies, are cladding products available on the market, others are under development and were provided mostly by research institutes. The provenance is mostly Europe, with the exception of New Zealand and Costa Rica. The EPDs of the materials, were available only in few cases.

Table 1: Material categories represented in the Bio4ever Project.

Treatment category	Number of items	Treatment category	Number of items
Acetylated	3	Particleboard + Bamboo	1
Acetylated + translucent coating	5	Polylactic acid	1
Acetylated + white opaque coating	2	Resin	4
Bamboo	2	Silicate	2
Biofilm	1	Thermally treated	18
Surface carbonization	2	Thermally treated + impregnation	2
Wood-ceramics composite	1	Thermally treated + silicate	1
Fiberboard	1	Thermally treated + translucent coating	4
Impregnated	20	Thermally treated + wax	2
Impregnated + thermally treated	2	Thermally treated + white opaque coated	1
Furfurylated	2	Translucent coating	12
Nanocoating	2	Tricoya + dark opaque coating	1
Nanocoating + Lineseed oil	1	Tricoya + white opaque coating	2
Natural (no treatment)	18	Wax	1
Oil-heat treated	1	White opaque coating	3
Paraffin heat-treated	1	Wood-plastic composite	1
		Total	**120**

The database was compiled in order to identify the features of each material that influence the maintenance operations during use phase and the future options for re-use after the service life: presence of chemicals, presence of substances other than wood (i.e. plastic, ceramics), coatings and varnish. These features are relevant to the calculation of environmental impact because they affect the input and output of the production process, thus the life cycle of the final product. For example, when considering the sanding operation of a façade the output emitted to the environment is different for natural, coated or impregnated wood. For instance, in the first case (natural wood) the output of the process consists in the disposal of wood sawdust, while in the second case (coated wood) the waste paint removed is mixed with the sawdust and will have different effects on the environment based on the type of chemicals present in it. The third case (impregnated wood) is again different from the previous, because the wood sawdust is mixed with the impregnation chemicals. The influence of material characteristics on end-of-life options is discussed more in details in paragraph 2.3.

2.2 Interactive LCA

A life cycle inventory (LCI) was prepared for all the operations that are necessary for the maintenance and refurbishing of a façade. These operations include: cleaning, sanding and re-coating. The replacement of cladding was considered as a separate case and calculated differently (as described below). For each operation a table was prepared with all inputs (energy, materials) and outputs (waste flows, materials for the re-use) considering different scenarios. For example, the LCI for the re-coating operations was compiled for different types of coating (i.e. acrylic, alkyd solvent-base and alkyd water-based) and for different working options (i.e. manual re-coating, pressure-machine mechanical re-coating). The list of factors (input and output) and their references in the Ecoinvent Version 3 (Wernet *et al.* 2016) libraries is presented in Table 2.

Table 2: References of the features of the SimaPro libraries used to calculate each maintenance module.

Operation	**Element**	**Unit**	**Category**	**SimaPro reference**
Cleaning with water-pressure machine and detergent	Water	kg	Input from technosphere (material/fuel)	*Tap water, at user {Europe without Switzerland}| market for | Conseq, U*
	Energy	kWh	Input from technosphere (electricity/heat)	*Electricity, medium voltage {IT}| market for | Alloc Def, S*
	Detergent	kg	Input from technosphere (material/fuel)	*Soap {GLO}| market for | Conseq, U*
	Waste water	kg	Output to technosphere (waste and emissions)	*Waste water - untreated, EU-27 S*
	Contaminated water	kg	Output to technosphere (waste and emissions)	*Waste water - untreated, organic contaminated EU-27 S*
Cleaning with water-pressure machine without detergent	Water	kg	Input from technosphere (material/fuel)	*Tap water, at user {Europe without Switzerland}| market for | Conseq, U*
	Energy	kWh	Input from technosphere (electricity/heat)	*Electricity, medium voltage {IT}| market for | Alloc Def, S*
	Waste water	kg	Output to technosphere (waste and emissions)	*Waste water - untreated, EU-27 S*
Sanding natural wood	Abrasive media	kg	Input from technosphere (material/fuel)	*Corn stover, at field/kg/US*
	Energy	kWh	Input from technosphere (electricity/heat)	*Electricity, medium voltage {IT}| market for | Alloc Def, S*
	Waste sawdust	kg	Known output to technosphere	*Landfill of untreated wood EU-27*
Sanding impregnated wood	Abrasive media	kg	Input from technosphere (material/fuel)	*Corn stover, at field/kg/US*
	Energy	kWh	Input from technosphere (electricity/heat)	*Electricity, medium voltage {IT}| market for | Alloc Def, S*
	Waste treated wood	kg	Known output to technosphere	*Landfill of wood products (OSB, particle board) EU-27*
Sanding coated wood	Abrasive media	kg	Input from technosphere (material/fuel)	*Corn stover, at field/kg/US*
	Energy	kWh	Input from technosphere (electricity/heat)	*Electricity, medium voltage {IT}| market for | Alloc Def, S*
	Waste paint	kg	Known output to technosphere	*Waste paint on wood (waste treatment) {CH}| treatment of, collection for final disposal | Alloc Def, S*
Re-coating manually with acrylic paint	Paint	kg	Input from technosphere (material/fuel)	*Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Conseq, U*
	VOC	kg	Emissions to air	*VOC, volatile organic compounds*
Re-coating manually with water-based alkyd paint	Paint	kg	Input from technosphere (material/fuel)	*Alkyd paint, white, without solvent, in 60% solution state {GLO}| market for | Conseq, U*
	VOC	kg	Emissions to air	*VOC, volatile organic compounds*
Re-coating manually with solvent-based alkyd paint	Paint	kg	Input from technosphere (material/fuel)	*Alkyd paint, white, without water, in 60% solution state {GLO}| market for | Conseq, U*
	VOC	kg	Emissions to air	*VOC, volatile organic compounds*
Mechanical coating	Compressed air	m^3	Input from technosphere (material/fuel)	*Compressed air, 600 kPa gauge {GLO}| market for | Conseq, U*
	All other input/output are the same as for manual re-coating, with the three paint options (acrylic, water-based alkyd, solvent-based alkyd)			
Replacement	New metal screws	kg	Input from technosphere (material/fuel)	*_65 Fabricated metal products, except machinery, EU27*
	Energy	kWh	Input from technosphere (electricity/heat)	*Electricity, medium voltage {IT}| market for | Alloc Def, S*
	Waste metal screws	kg	Output to technosphere (waste and emissions)	*Landfill of ferro metals EU-27*

These fixed maintenance base-blocks were defined as "maintenance modules", which can be used to build and customize the LCA of each specific real-case of façade. Figure 1 depicts a schematic representation of the maintenance modules together with the values that were used for the calculations (amount of each factor). These values can be changed and adapted to real case-scenarios. The inventory was then used to calculate the LCA, by means of the SimaPro 8.0.2 software with the EPD 2008 method for each maintenance module. The functional unit for the calculation was 1 m^2 of façade. The system boundaries for the maintenance modules coincide with the use phase of the façade. The idea that underpins this concept is that maintenance is the sum of operations multiplied by their frequency in time. Both operations and frequency depend on three main factors: the intrinsic properties of the material and its use (i.e. thermal wood cladding for a façade), the macro- and micro-climatic factor (weathering potential in a specific location, and in a specific part of the façade, i.e. south-exposed, protected by design), and the owner (final user) attitude towards aesthetical and economic issues. Since the combination of these three factors is unique, the traditional case-study LCA approach is rather unsuitable.

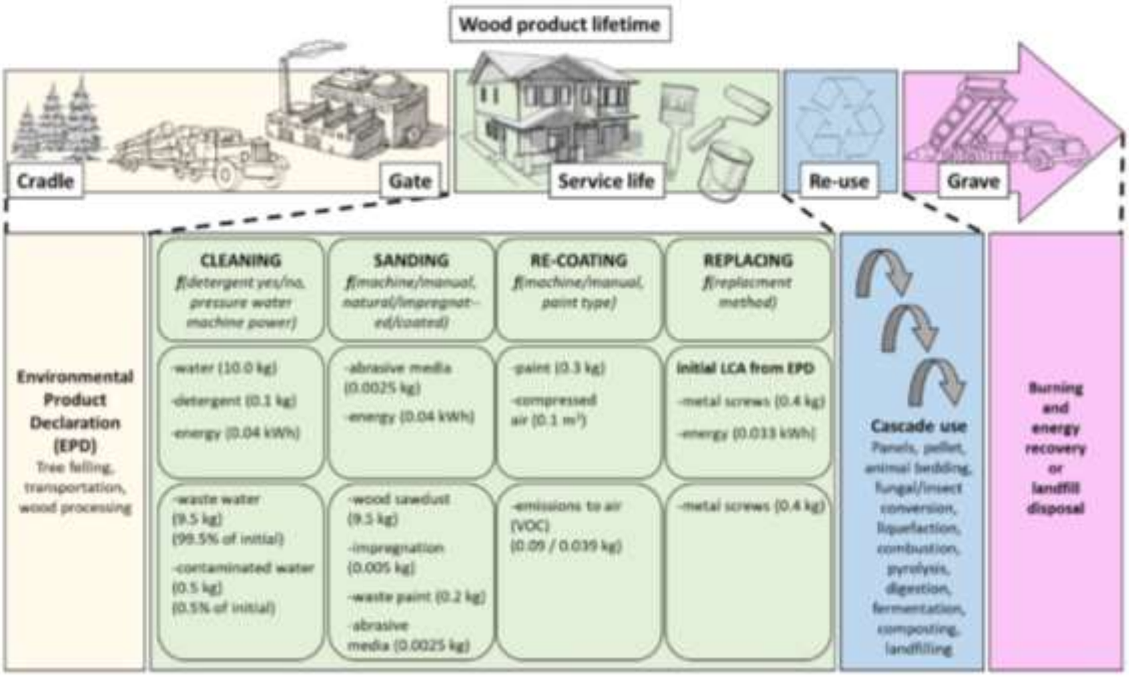

Figure 1: The modules considered for maintenance are: cleaning, sanding, re-coating, replacing.
In brackets examples are given of the values for each input/output element for a functional unit of 1 m^2 of façade. These values can be determined directly by the user in the interactive LCA.

2.2.1 Cleaning module

The cleaning operations were tested with and without the use of a detergent in addition to the water. Specific detergent products for cladding are available on the market and the amount of product is normally function of the water which is used to clean the façade (5-10 ml/l). The use of water only will produce as outcome water waste, while the use of detergent will result in the presence of organic and inorganic water contamination. These two options were tested in two different scenarios. Additionally, the use of electricity was included, due to the fact that professional or home-made cleaning of façade is usually done with pressure-machine (power 1,5-2 kW, work efficiency 0,015-0,025 h/m^2).

2.2.2 Sanding module

The sanding operations were assessed with three different scenarios, all including sandblasting with pressure machine (power 1,5-5,5 kW, work efficiency 0,025-0,008 h/m^2) and a natural abrasive media. The energetic consumes depend on the power of the air compressor, usually to sandblast wooden surfaces compressors having a power of 1,5/5,5 kW are used. The work efficiency depends on the surface material, the power of the air compressor, the abrasive used and the nozzle size. Usually for 1 m^2 of façade 0,5/1,5 minutes are needed. Sanding a wooden façade could be also done manually by means of electrical sanding-machines, thus saving the abrasive material. There are several abrasives available on the market: glass beads, plastic beads, grains of aluminium oxide, silicon carbide, dry ice pellets. The best option for wood is corn cob or walnut shells, because it results in a mild treatment more suited for wood. Furthermore, using agricultural waste materials for sanding operations have environmental and economic benefits. Corn cob, in particular, is resistant and can be reused more times in sanding operations by using sandblasting machines that allow to recover the abrasive material during the sandblasting, as reported in technical manual of commercial blasting machines. The quantity of abrasive depends on the surface material, the power of the air compressor, the type of abrasive used and the nozzle size. For a 6 mm nozzle about 160 kg/h of corn cob are consumed, for a 9 mm nozzle 300 kg/h are consumed. The differences among the three sanding options are based on the different type of waste flow: 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. On average, less of 0,1 mm to 0,5 mm of surface is removed in this way, the depth of sanding depends also on the severity of the surface degradation. It is noticeable that using different techniques to achieve a uniform surface (i.e. paper-sending, sandblasting) results in different surface aesthetical effects. In this case, the use of sandblasting with natural abrasive (i.e. corn cob) will result in a “brushed surface” effect. Finally, the three scenarios were calculated considering the re-use of the abrasive media. Usually, this operation is a preliminary step before re-coating.

2.2.3 Re-coating module

For re-coating three options were tested, which include acrylic and alkyd paints, water- or solvent-based. There are several paintings and primers available on the market, which belong to one of the aforementioned categories of paints. Moreover, all scenarios were calculated for the options: hand-painting or machine-painting (spray-machine with compressed air). As for sandblasting and cleaning, the work efficiency and the energetic consumes are entangled and depend also on material properties such as the porosity and wettability of the surface.

2.2.4 Replacing module

For the replacement operations, the environmental impact was given by the environmental indicators for production as from EPDs (when EPD was available), plus the environmental costs of operations for replacement. The last ones including metal screws, new (input) and replaced (output) and the energetic needs for the use of screwdriver. It has to be acknowledged that the efficiency of replacement depends, to a large extent, on the façade system that was used at the first installation of the façade. In fact, some systems do not allow the substitution of small portion of cladding elements, being all elements connected together. Other systems, usually more expensive, are made in ways that allow the substitution later for smaller portion, in order to restrict the substitution to the damaged element only, with a considerable reduction of maintenance costs (environmental, economic).

2.2.5 Test of case-scenarios

Four case-scenarios were tested, with two different materials for facades, both tested for high and low maintenance, as summarized in Table 3, in all cases assuming the same time-span of the service-life (20 years). In Case 1, we hypothesized a high-frequency maintenance, due to the high aesthetical standards of the owners, harshness of climate, and the anticipated low performing material (natural wood, without treatments). The maintenance in this case is composed of different operations, including cleaning, sanding and recoating, which are considered to be done together because usually sanding is a preliminary step for the recoating, and the substitution of a portion of façade with new cladding elements. The environmental (and, likely, economical) cost is high, but the aesthetical function is maintained until the end of the service life and the dismissed material can be re-used for new products of relatively high value, thus saving energy and new row materials. In Case 2, the same façade made of natural untreated wood has low-frequency maintenance, due to mild climatic conditions and high tolerance of the owner. Thus, the maintenance operations are reduced to cleaning. The environmental cost is low, but a question mark hangs over the possibility for re-use, because re-use could be compromised by the bad conditions of the material dismissed. Case 3 and Case 4 consider the maintenance of a façade realized with chemically treated wood, therefore almost maintenance-free, as reported in technical reports (Menzies 2013). Here, the difference between the two scenarios is determined by climate (harsh versus mild) and the aesthetical standard of the owner (high versus low), but only cleaning operations are considered. The maintenance frequency and the determinant factors in the four scenarios are summarized in Table 3. For all scenarios, the GWP impact was calculated by selecting the chosen maintenance modules, and then multiplying them for the forecasted maintenance frequency. It is important to notice that the impact of the new material for replacement was obtained in different ways for natural wood and for chemically modified wood. In the first case (natural wood) the value was calculated with the SimaPro software by selecting the input feature "*Sawnwood, softwood, kiln dried, planed {RER}| market for | Alloc Def, S*". For the chemically modified wood, data on the environmental impact, which are of public domain in EPD (environmental product declaration) documents of commercial products were used. Therefore, due to the different methods of calculation direct comparison between natural wood and chemically modified wood was impossible. However, within the same material it was possible to compare the worst-case scenario with the best-case scenario.

Table 3: Conditions of climate, material type, tolerance of the owner (aesthetical standard) for the four case-scenarios.

	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 frequency*	Every 2 years	Every 5 years	Every 2 years	Every 5 years
Sanding + Re-coating frequency*	Every 6 years	Every 10 years	Never until end of service life	Never until end of service life
Replacing frequency*	Every 12 years	Never until end of service life	Never until end of service life	Never until end of service life

*Frequency in 20 years of service life

2.3 End of service life options for re-use and disposal

A system was defined to calculate the weight of each end-of-life (EOL) option in terms of environmental protection and best use of resources. The system takes into account for each EOL option the factors that where identified to be the most relevant in defining environmental risks and/or detriment that come along with re-use processes. These factors were the following:

- the potential for a secondary product to be further used (multiple cascading),
- the secondary product requirements in terms of additives that have high environmental impact,
- the possibilities to obtain a secondary product without processing the dismantled material or the need for further processing and, in this case, the energy required for the process,
- the possibility to recover energy.

3. RESULTS AND DISCUSSION

3.1 Maintenance modules

Overall, 24 maintenance modules were assessed with the SimaPro software. The results indicate the factors that are major contributions to each environmental indicator. For example, the use of chemicals, such as detergents for cleaning the façade, or the use of solvent-based painting for re-coating, has a great influence in increasing the global warming potential.

3.1.1 Cleaning

The results for the cleaning module are reported in Figure 2 (Global Warming Potential, GWP), and in Table 4 (six Impact Categories or environmental impact indicators).

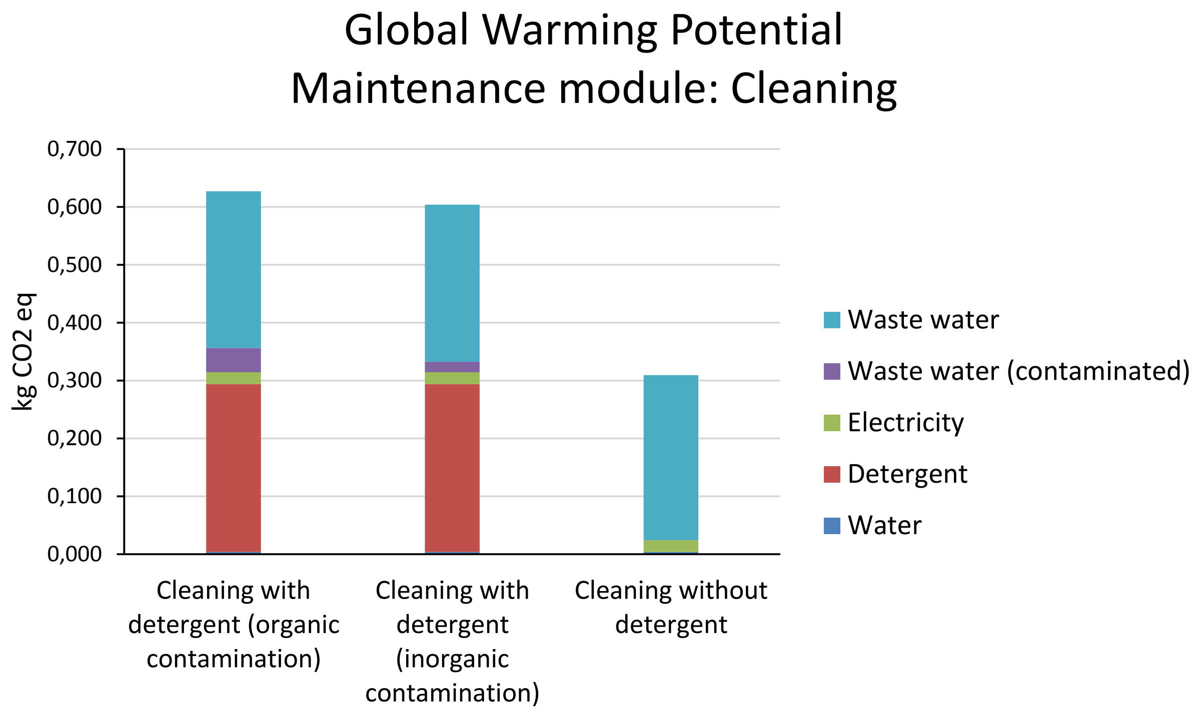

Figure 2: The graph shows, for three cleaning options, the contribution of each input and output to the Global Warming Potential expressed as kg of CO_2 equivalent.

Table 4: Total values for each Impact Category (environmental impact indicators), and contribution of each input/output features to the total.

Module name	Impact category	Unit	Total	Water	Detergent	Electricity	Waste water (cont.)	Waste water
Cleaning with detergent (organic cont.)	Global warming (GWP100)	kg CO2 eq	0,627	0,004	0,290	0,021	0,042	0,271
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	0,000	0,000	0,000	0,000
	Photochemical oxidation	kg C2H4 eq	0,000	0,000	0,000	0,000	0,000	0,000
	Acidification	kg SO2 eq	0,001	0,000	0,001	0,000	0,000	0,001
	Eutrophication	kg PO4--- eq	0,001	0,000	0,000	0,000	0,000	0,000
	Non-renewable, fossil	MJ eq	2,110	0,056	0,922	0,197	0,123	0,813
Cleaning with detergent (inorganic cont.)	Global warming (GWP100)	kg CO2 eq	0,604	0,004	0,290	0,021	0,018	0,271
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	0,000	0,000	0,000	0,000
	Photochemical oxidation	kg C2H4 eq	0,000	0,000	0,000	0,000	0,000	0,000
	Acidification	kg SO2 eq	0,001	0,000	0,001	0,000	0,000	0,001
	Eutrophication	kg PO4--- eq	0,001	0,000	0,000	0,000	0,000	0,000
	Non-renewable, fossil	MJ eq	2,042	0,056	0,922	0,197	0,054	0,813
Cleaning without detergent	Global warming (GWP100)	kg CO2 eq	0,310	0,004		0,021		0,285
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000		0,000		0,000
	Photochemical oxidation	kg C2H4 eq	0,000	0,000		0,000		0,000
	Acidification	kg SO2 eq	0,001	0,000		0,000		0,001
	Eutrophication	kg PO4--- eq	0,000	0,000		0,000		0,000
	Non-renewable, fossil	MJ eq	1,109	0,056		0,197		0,855

As already mentioned before, it can be noticed that the main impact is due to the use of detergent products. The organic contamination has higher impact on GWP than the inorganic one. The impact categories of “ozone layer depletion”, “photochemical oxidation”, “acidification”, and “eutrophication” have a near-zero impact, while the most affected categories are “Global warming potential” and “Non-renewable, fossil”.

3.1.2 Sanding

The results for the sanding module are reported in Figure 3 (Global Warming Potential, GWP), and in Table 5 (six Impact Categories or environmental impact indicators).

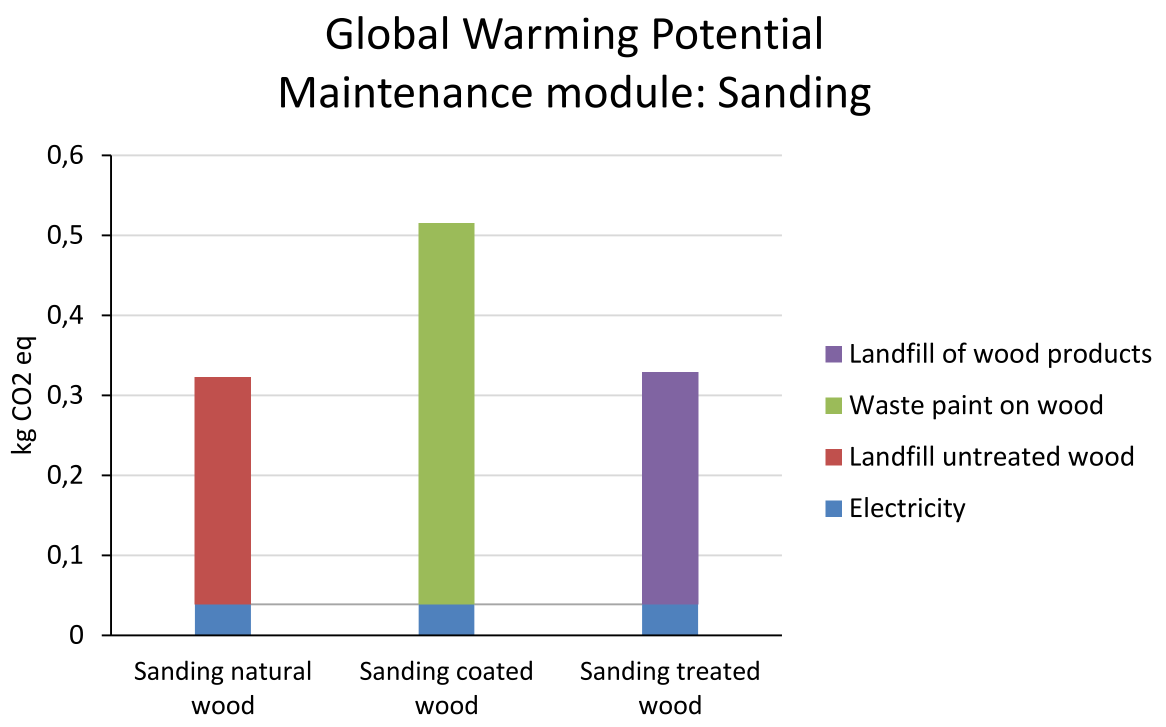

Figure 3: The graph shows, for three sanding options, the contribution of each input and output to the Global Warming Potential expressed as kg of CO_2 equivalent.

Table 5: Total values for each Impact Category (environmental impact indicators), and contribution of each input/output features to the total.

Module name	**Impact category**	**Unit**	**Total**	**Electricity**	**Disposal of waste product**
Sanding natural wood	Global warming (GWP100)	kg CO2 eq	0,323	0,039	0,284
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	0,000
	Photochemical oxidation	kg C2H4 eq	0,000	0,000	0,000
	Acidification	kg SO2 eq	0,000	0,000	0,000
	Eutrophication	kg PO4--- eq	0,000	0,000	0,000
	Non-renewable, fossil	MJ eq	0,837	0,614	0,223
Sanding coated wood	Global warming (GWP100)	kg CO2 eq	0,515	0,039	0,476
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	0,000
	Photochemical oxidation	kg C2H4 eq	0,000	0,000	0,000
	Acidification	kg SO2 eq	0,000	0,000	0,000
	Eutrophication	kg PO4--- eq	0,000	0,000	0,000
	Non-renewable, fossil	MJ eq	0,657	0,614	0,043
Sanding impregnated wood	Global warming (GWP100)	kg CO2 eq	0,329	0,039	0,290
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	0,000
	Photochemical oxidation	kg C2H4 eq	0,000	0,000	0,000
	Acidification	kg SO2 eq	0,000	0,000	0,000
	Eutrophication	kg PO4--- eq	0,000	0,000	0,000
	Non-renewable, fossil	MJ eq	0,837	0,614	0,223

The results for the sanding operation show that, interestingly, the disposal of natural wood and of treated wood is similar in terms of impact (global warming potential), and that the highest carbon footprint is given by the disposal of waste paint on wood.

3.1.3 Re-coating

The maintenance module concerning the re-coating shows that the bigger difference is given by the type of paint, while the use of compressed air for the mechanical painting has a contribution to global warming potential which is only slightly higher than the manual painting (Figure 4 and Table 6).

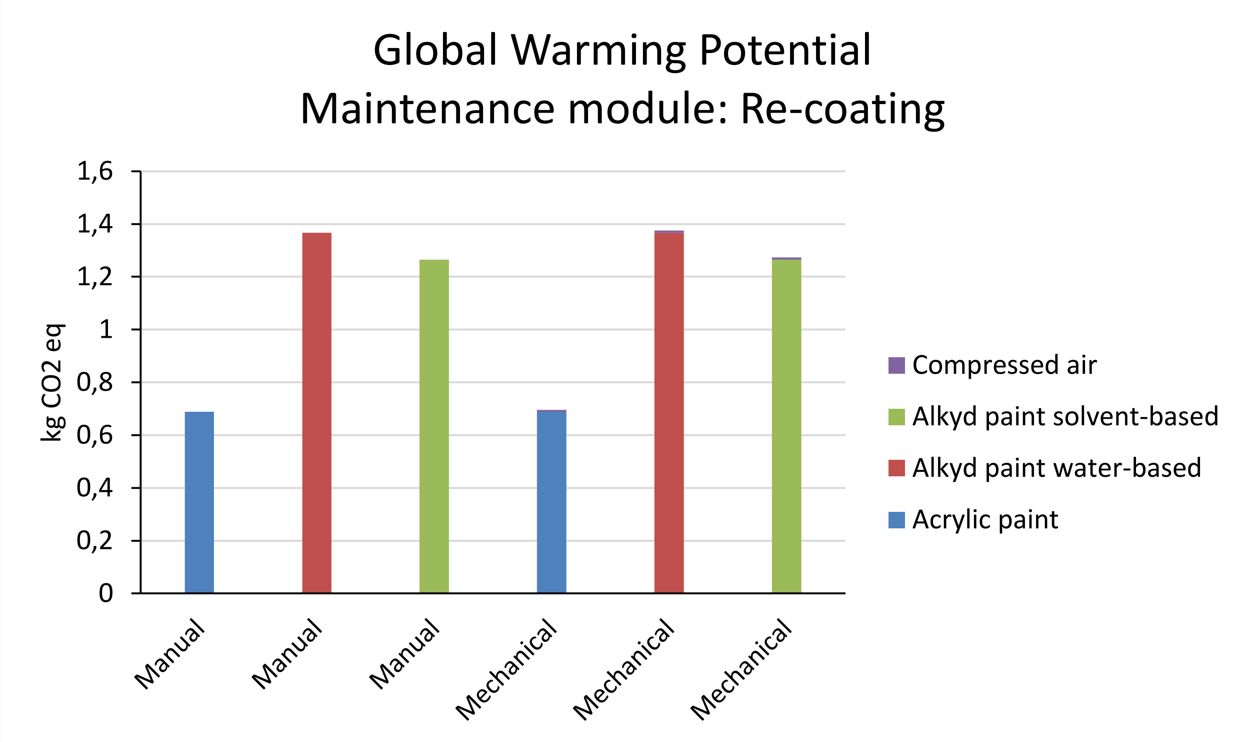

Figure 4: The graph shows, for six re-coating options, the contribution of each input and output to the Global Warming Potential expressed as kg of CO_2 equivalent.

Table 6: Total values for each Impact Category (environmental impact indicators), and contribution of each input/output features to the total.

Module name	Impact category	Unit	Total	Paint	Compressed air
Manual coating acrylic paint	Global warming (GWP100)	kg CO2 eq	0,688	0,688	
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	
	Photochemical oxidation	kg C2H4 eq	0,001	0,001	
	Acidification	kg SO2 eq	0,003	0,003	
	Eutrophication	kg PO4--- eq	0,002	0,002	
	Non-renewable, fossil	MJ eq	12,450	12,450	
Manual coating alkyd water-based paint	Global warming (GWP100)	kg CO2 eq	1,367	1,367	
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	
	Photochemical oxidation	kg C2H4 eq	0,002	0,002	
	Acidification	kg SO2 eq	0,005	0,005	
	Eutrophication	kg PO4--- eq	0,004	0,004	
	Non-renewable, fossil	MJ eq	17,411	17,411	
Manual coating alkyd solvent-based paint	Global warming (GWP100)	kg CO2 eq	1,265	1,265	
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	
	Photochemical oxidation	kg C2H4 eq	0,002	0,002	
	Acidification	kg SO2 eq	0,005	0,005	
	Eutrophication	kg PO4--- eq	0,003	0,003	
	Non-renewable, fossil	MJ eq	18,386	18,386	

Module name	Impact category	Unit	Total	Paint	Compressed air
Mechanical coating acrylic paint	Global warming (GWP100)	kg CO2 eq	0,696	0,688	0,008
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	0,000
	Photochemical oxidation	kg C2H4 eq	0,001	0,001	0,000
	Acidification	kg SO2 eq	0,003	0,003	0,000
	Eutrophication	kg PO4--- eq	0,002	0,002	0,000
	Non-renewable, fossil	MJ eq	12,592	12,450	0,142
Mechanical coating alkyd water-based paint	Global warming (GWP100)	kg CO2 eq	1,376	1,367	0,008
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	0,000
	Photochemical oxidation	kg C2H4 eq	0,002	0,002	0,000
	Acidification	kg SO2 eq	0,005	0,005	0,000
	Eutrophication	kg PO4--- eq	0,004	0,004	0,000
	Non-renewable, fossil	MJ eq	17,553	17,411	0,142
Mechanical coating alkyd solvent-based paint	Global warming (GWP100)	kg CO2 eq	1,274	1,265	0,008
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	0,000
	Photochemical oxidation	kg C2H4 eq	0,002	0,002	0,000
	Acidification	kg SO2 eq	0,005	0,005	0,000
	Eutrophication	kg PO4--- eq	0,003	0,003	0,000
	Non-renewable, fossil	MJ eq	18,528	18,386	0,142

3.1.4 Installation and replacement operations

The impact of the operations for the installation are shown in Table 7. As already mentioned, the impact of the replacement will result by adding the impact of the new product used for replacing the old material. The environmental impact of these operation will result from the portion (%) of façade to be replaced.

Table 7: Total values for each Impact Category (environmental impact indicators), and contribution of each input/output features to the total.

Module name	Impact category	Unit	Total	Fabricated metal products	Electricity	Landfill of ferro metals
Installation operations	Global warming (GWP100)	kg CO2 eq	1,628	1,596	0,032	
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	0,000	
	Photochemical oxidation	kg C2H4 eq	0,002	0,002	0,000	
	Acidification	kg SO2 eq	0,006	0,006	0,000	
	Eutrophication	kg PO4--- eq	0,000	0,000	0,000	
	Non-renewable, fossil	MJ eq	18,987	18,480	0,506	
Replacement operations	Global warming (GWP100)	kg CO2 eq	1,634	1,596	0,032	0,006
	Ozone layer depletion (ODP)	kg CFC-11 eq	0,000	0,000	0,000	0,000
	Photochemical oxidation	kg C2H4 eq	0,002	0,002	0,000	0,000
	Acidification	kg SO2 eq	0,006	0,006	0,000	0,000
	Eutrophication	kg PO4--- eq	0,001	0,000	0,000	0,000
	Non-renewable, fossil	MJ eq	19,049	18,480	0,506	0,062

3.2 Case scenarios

Table 8 shows the results of the four maintenance scenarios that were simulated. As expected, the highest impact in terms of GWP is given by the natural wood in the worst-case scenario. In the best-case scenario for natural wood, the total impact is reduced of 45% by drastic reduction of the cleaning operations and by avoiding replacement. In the case scenarios using chemically modified wood the impact is reduced roughly by half, when reducing the maintenance operations. As already mentioned, these two last scenarios (chemically modified wood) are not directly comparable with the upper ones (natural wood), because of different calculation for material replacement. For instance, some EPD include in the calculations the combustion credit for energy recovery at the end of service life, thus lowering the initial impact for the chemical treatment of wood.

Table 8: For each case-scenario the GWP is given, relative to the production, installation, and maintenance operations. The repetition times are relative to the frequency (see Table 3). The production value is referred to 1 m^3 of material, therefore it was multiplied by 0,025 to estimate the impact for 1 m^2 of façade (considering a cladding thickness of 25 mm).

Scenario	Operation	GWP [kg CO2 eq]	Repetition times during service life (20 years)	GWP (x times in 20 years)
Case 1 - Harsh climate, demanding owner, natural wood	Production (EPD)	237,48		5,94
	Installation	1,63		1,63
	Cleaning (with detergent, organic contamination)	0,63	6	3,76
	Sanding (natural wood)	0,32	2	0,65
	Re-coating (mechanical, alkyd water-based)	1,38	2	2,75
	Replacing (25%)		1	1,48
	Replacement operations (25%)	1,63	1	0,41
	Total			16,62
Case 2 - Mild climate, tolerant owner, natural wood	Production (EPD)	237,48		5,94
	Installation	1,63		1,63
	Cleaning (without detergent)	0,31	2	0,62
	Sanding (natural wood)	0,32	1	0,32
	Re-coating (manual, acrylic paint)	0,69	1	0,69
	Total			9,20
Case 3 - Harsh climate, demanding owner, chemically modified wood	Production (EPD)	59,57		1,49
	Installation	1,63		1,63
	Cleaning (with detergent, organic contamination)	0,63	9	5,64
	Sanding (natural wood)		0	0,00
	Re-coating (mechanical, alkyd water-based)		0	0,00
	Replacing (25%)		0	0,00
	Replacement operations (25%)		0	0,00
	Total			8,76
Case 4 - Mild climate, tolerant owner, chemically modified wood	Production (EPD)	59,57		1,49
	Installation	1,63		1,63
	Cleaning (without detergent)	0,31	3	0,93
			0	0,00
			0	0,00
	Total			4,05

In figure 5 and 6, a graphical representation is given on how the GWP is growing during 20 years of service life of a façade under maintenance. The starting point on the y-axis is referred to the sum of production of new material and installation. The height of each step is proportional to the impact of the maintenance operations. It is clear that in the best-case scenario the impact is lower at the end of the considered period of time.

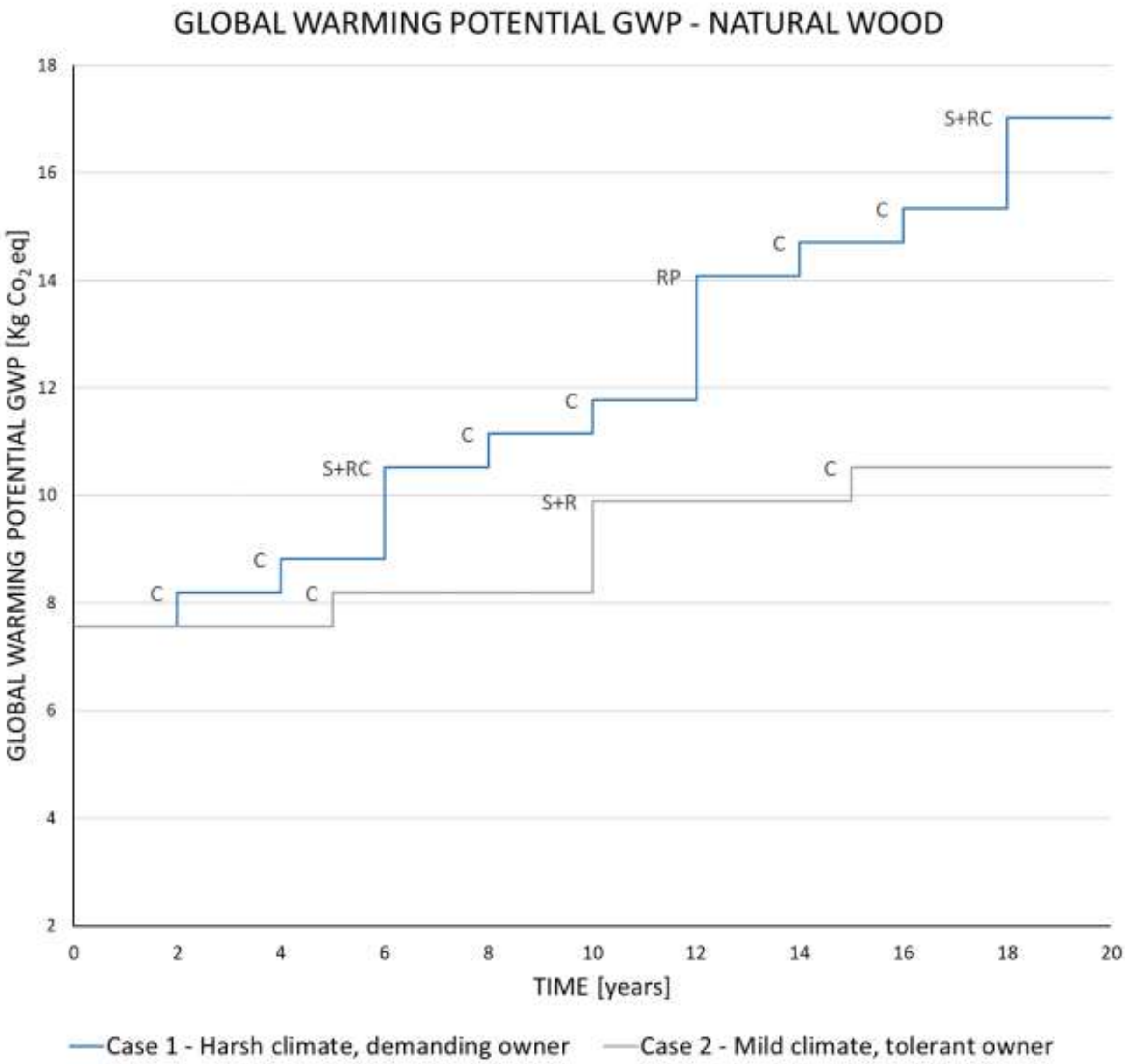

Figure 5: Global warming potential in 20 years of maintenance of a natural wood façade in worst and best scenario; Capital letters indicate the different operations: “C” for cleaning, “S+RC” for sanding and recoating, “RP” for replacement.

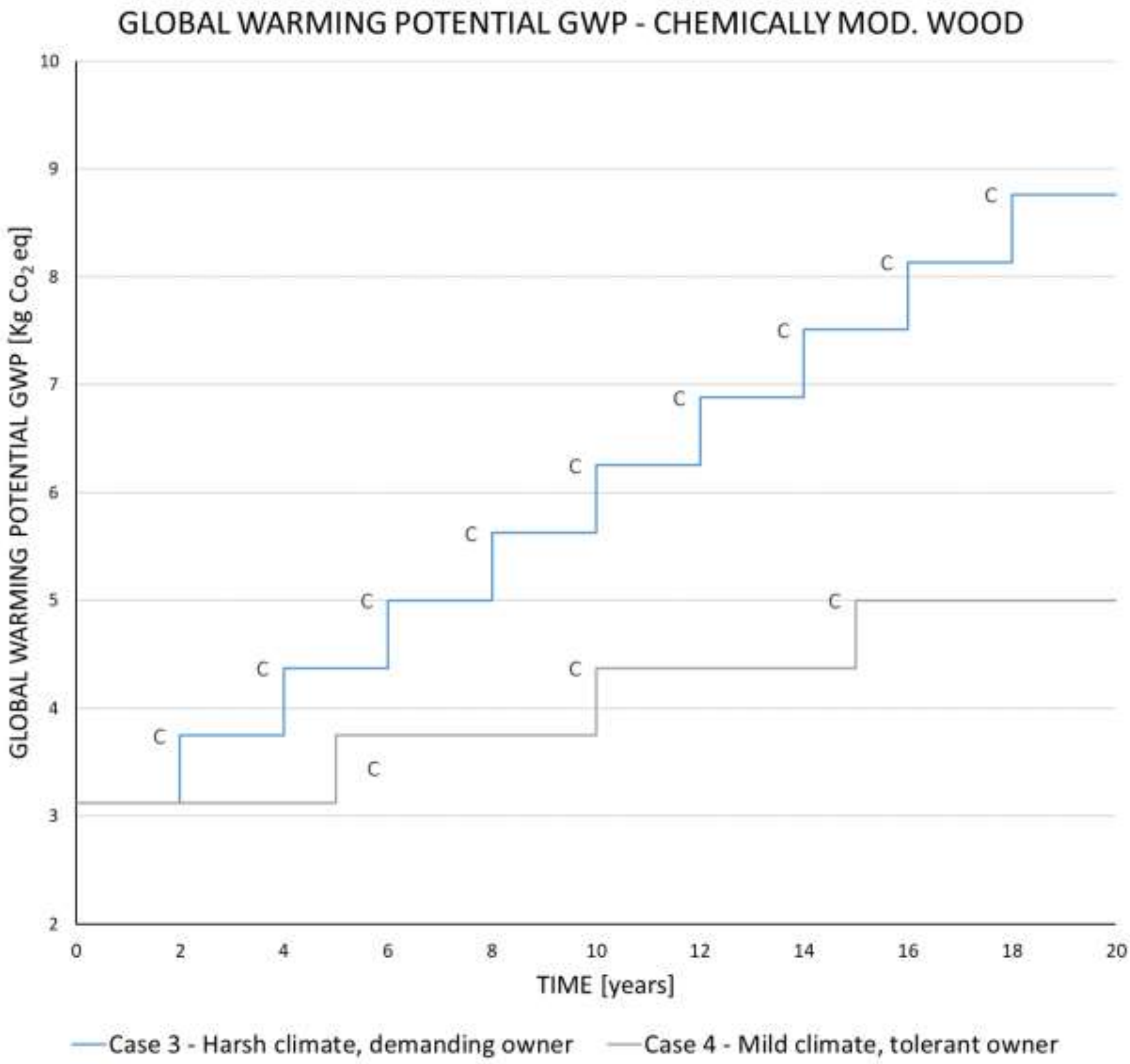

Figure 6: Global warming potential in 20 years of maintenance of a chemically modified wood façade in worst and best scenario. Capital letters indicate the different operations: "C" for cleaning

Figure 7 and 8 present the relative share of impact (GWP) of each operation. In case 1, production and cleaning have a great impact on the total maintenance over a 20-year timespan. In case 2, the maintenance impact is much lower, and the larger impact is due to the initial production and installation environmental cost. The difference between case 3 and case 4 is due to the frequency of cleaning operations, since no other maintenance module was considered.

Figure 7: Relative share of the environmental impact (GWP) for the installation and maintenance operations of natural wood façade in worst and best scenario.

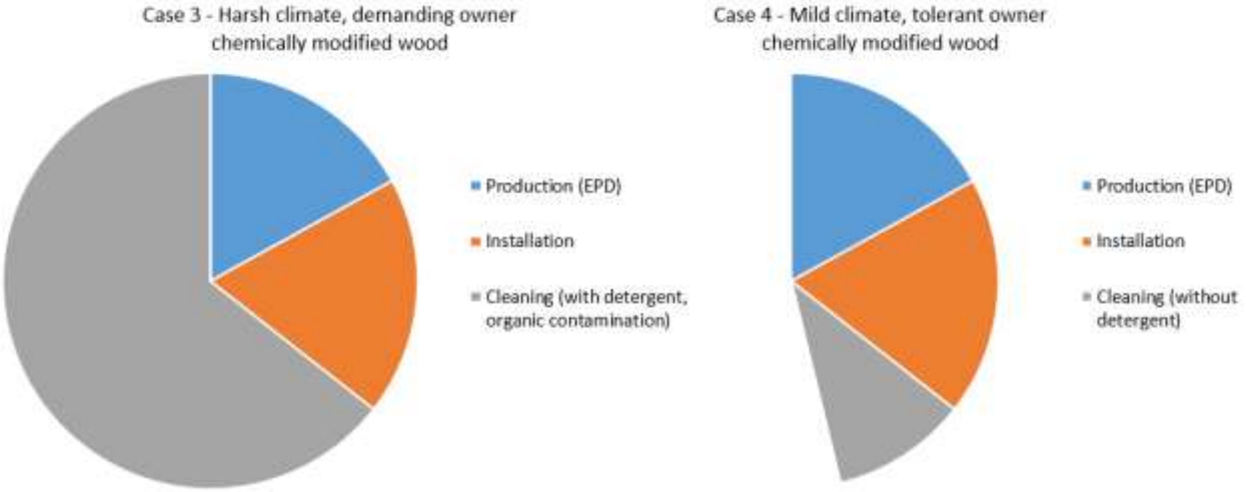

Figure 8: Relative share of the environmental impact (GWP) for the installation and maintenance operations of chemically modified wood façade in worst and best scenario.

4. CONCLUSIONS

In this study a novel approach for a customized, interactive LCA of facades use-phase was presented and tested. The basic blocks for maintenance operations can be combined and multiplied by the maintenance frequency, being specific the combination of climate, material properties and owner needs. The environmental costs of maintenance operations should not be overlooked, nor should be overestimated. These aspects should be carefully planned and forecasted by interactive, dynamic simulations already during the design phase of a building. By designing the different maintenance modules, cleaning, sanding, re-coating and replacing, we were able to i) identify which factor of each operation is contributing more to the environmental impact, and ii) we provide a scheme that can be used to make real-case simulations, by changing the input and output values, and the combination and the frequency of the operations.

The lack of comprehensive data about wood modifications processes in the LCI, and the impossibility of comparing EPD values of commercial products highlighted weakness of the recent LCA calculations. The proposed model, even if far from being comprehensive could be used as a starting point for optimization of facades maintenance. Future research combining interactive LCA calculation with simulation of facades aesthetic performance are conducted within BIO4ever (http://www.bio4everproject.com/) and BIM-boost (https://innorenew.eu/project/building-information-modelling/) projects. In the second case, the concept of interactive LCA assessment for facade during its service life is integrated with the Building Information Modelling (BIM) software.

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