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Applicability of Life Cycle Assessment methodology to conservation works in historical building: the case of cleaning

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Abstract

The Life Cycle Assessment (LCA) represents a suitable methodology to evaluate quantitatively the environmental impact related to a product or a process and it can be used as a guiding tool to make effective environmental sustainability choices. While the LCA-based methods are more and more diffused in the assessment and selection of materials for new constructions, they are still scarcely applied in the field of conservation and repair of historical buildings, although these buildings, especially in Europe, represent a high percentage of the building stock.

In the present paper, the LCA method was applied to the field of the restoration, with particular reference to cleaning technologies and materials, in order to investigate if LCA can be applied in this field. The analysis of results pointed out the different environmental impact of the cleaning methods investigated (ascribed to different impact categories), but also the shortcomings and proxies arising from the lack of specific database. The impact of the waste treatment stage was also analysed, in order to highlight the main impact spots related with the end of life of materials and equipment. Results showed that, for some cleaning methods, the impacts related to manufacturing and disposal are very similar, which emphasizes the importance of performing LCA including the end of life scenarios. Finally, an evaluation of externalities was performed, to provide a monetary value of the environmental damage.

Keywords: LCA, cleaning, heritage buildings, energy consumption, global warming potential, resources depletion, materials, technologies.

Abbreviation list

Aq. acid.	Aquatic acidification
Aq. ec.	Aquatic ecotoxicity
Aq. eutr.	Aquatic eutrophication
Carc.	Carcinogens

ELU	Environmental Load Unit
EoL	End of Life
FU	Functional Unit
Glo. war.	Global warming
GWP	Global Warming Potential
Ion. rad.	Ionizing radiation
IPCC	International Panel on Climate Change
Land oc.	Land occupation
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
Min. ext.	Mineral extraction
mPt	milli-Points
Non-carc.	Non carcinogens
Non-ren. en.	Non-renewable energy
Oz. lay. dep.	Ozone layer depletion
Resp. in.	Respiratory inorganics
Resp. or.	Respiratory organics
Terr. a/n	Terrestrial acid/nutri
Terr. ec.	Terrestrial ecotoxicity

1. Introduction and research aim

"Sustainable cities and communities" is one of the seventeen Sustainable Development Goals that United Nations adopted within the "Agenda 2030" plan of action, in order to promote a global sustainable development by the integration of its three dimensions: environmental, social and economic [1]. Cities play a key role in achieving this goal, also because more than 60% of humanity presently lives in cities and this number is expected to grow, so it is crucial to make them prosperous, safe and inclusive [2]. Furthermore, the cities, especially through their architecture and buildings, maintain the historical and cultural value of society and keep the heritage of the past. As opposed to demolition of existing buildings and construction of new ones, restoration and rehabilitation can represent a viable alternative to reduce the environmental impacts of the building industry, for instance in terms of consumption of raw materials for new constructions and treatment of the waste derived from demolition; moreover, architectural rehabilitation preserves and valorises architectural heritage that otherwise would be irreversibly lost [3]. In addition, the integration of these preservation issues into public policies and strategic plans can transform cultural heritage from a “static object” to be purely safeguarded and preserved into an active driver for the development of sites or clusters [4].

However, it is undeniable that historical buildings are responsible for a high energy consumption during their operational phase, due to low thermal insulation of the envelope, low efficiency of existing Heating, Ventilation and Air Conditioning (HVAC) systems, etc. [5], and they also require maintenance and repair interventions. This impact cannot be neglected, especially in Europe, where historical buildings represent a high percentage of the building stock; a better understanding of this impact is of paramount importance towards the improvement of the overall sustainability of existing buildings.

The evaluation of the environmental impact of conservation practices have been carried out in some literature papers [6], while the assessment of the impact of conservation works carried out in heritage buildings is still quite limited.

A first attempt towards such evaluation was made by the Green Building Council (GBC) Italy, a no profit organisation founded in 2008 with the aim of implementing sustainable practices into the Italian building sector. In addition to the promotion of the LEED certification system (where LEED is the acronym of “Leadership in Energy and Environmental Design”) and the development of a certification specific for the Italian context, the GBC Italy has established a new rating system for historical buildings, named ‘GBC Historic Buildings’ [7]. This protocol can be applied to those buildings that were built before 1945, that is considered the beginning of the building industrialisation in Europe, or even later for those that exhibit historical or cultural value. It is a voluntary scheme for the evaluation of the sustainability related to significant activities in the field of restoration, rehabilitation and recovery of buildings. It is noteworthy that ‘restoration’ (or ‘conservation’) interventions are generally carried in heritage buildings, in compliance to well established conservation principles such as minimum intervention and authenticity, while the terms ‘rehabilitation’ and ‘recovery’ are generally used to describe retrofitting and major renovations of historic buildings that are not necessarily heritage buildings.

This ‘GBC Historic Buildings’ protocol is based on six categories: historic significance, sustainability of the site, water management, energy and atmosphere, materials and resources, indoor quality, design innovation and regional priorities. Each category is divided into different subcategories called “credits”, in order to assign them different scores, depending on the environmental impact of the specific activities. The results obtained by adding the scores corresponds to four levels of certification: Base (40-49 points), Silver (50-59 points), Gold (60-79) and Platinum (>80 points) [7], as in the LEED system.

The GBC Historic Building represents an innovative tool that allows to link sustainability issues to cultural and historical aspects of restoration, based on the common goal of promoting and preserving cultural heritage for the future generations. However, this protocol is a qualitative rating system and it does not provide any quantitative information about the environmental impacts associated to the human activities. Conversely, the Life Cycle Assessment (LCA) represents a suitable methodology to evaluate quantitatively the environmental impact related to a product or a process and it can be used as a guiding tool to make effective sustainability choices.

The impact of historic buildings in terms of energy consumption and saving [4] and environmental loads [8-9] and the strategies aimed at reducing such impact [9-10] were investigated in several papers, considering the entire life cycle of buildings from the LCA perspective. Also several studies in building refurbishment [11] and restoration [12], repair mortar and concrete [13-14] and recycled material use [15-16], or generally in sustainable maintenance for heritage buildings [17] have been performed. Approximately in the last two years, a number of papers started to investigate the environmental impact of conservation interventions and materials [18-22], highlighting the great significance of extending the LCA approach also to this field.

However, it should be pointed out that there are many obstacles in applying the LCA methodology in the field of conservation works, which derive from the specificity of the subject of the study. First of all, each restoration operation is completely case-specific and it depends on the physical, chemical and mechanical properties of the substrate, the history of the building, any previous conservation interventions, etc. It may involve the use of a wide variety of materials and technologies and sometimes, due to a lack of specific inventory data on them, it is difficult to precisely represent each particular operation. In addition, it is important to highlight that many restoration activities are craftsmanship activities and therefore there are many variables that are difficult to control, if compared to standard industrial activities.

It is noteworthy that these methodological issues should not represent an obstacle for a correct and wide LCA implementation. On the contrary, they can represent a challenging starting point for the setting up of ad hoc databases in order to make the LCA totally applicable in this sector. The LCA approach in restoration works should be increasingly developed in the future to support design, buildings' environmental certification and all kind of construction-related activities evaluation, such as public procurements.

As a contribution towards the LCA implementation in the conservation field, a first study was carried out by the authors to evaluate the environmental impact of cleaning procedures, which are commonly performed in any repair work and hence represent an important step in the repair process [23]. In the previous analysis, the research was focused on the evaluation of a high number of different cleaning technologies, investigating how the different types materials and equipment that can be used by the professionals (supporting mixtures, solvents, mechanical equipment, hand tools, etc.) contribute to the environmental impact. Starting from that previous analysis, the present work is aimed at investigating the applicability and reliability of the Life Cycle Assessment to the field of the restoration, with particular reference to cleaning. In this paper, only a limited number of cleaning techniques was selected, and the research was focussed on the possible shortcomings and proxies arising from the lack of a specific database, on a sensitivity analysis concerning LCA application and on the influence of the waste treatment stage. Including the waste treatment stage allowed to highlight the main impact spots related with end of life of materials and equipment, and the relative weight of the end of life stage with respect to the manufacturing and operational stages. Furthermore, an evaluation of externalities was performed by using the EPS 2015dx (Environmental Priority Strategies) assessment method, to provide a monetary value of the environmental damage.

2. The methodology applied

2.1 The object of the analysis: cleaning methods selected

In the previous study [23], the most diffused cleaning procedures in current practice of restoration works were identified, based on the experience of the authors in this field and on the suggestions of some professionals involved in this study. These procedures were sorted into six groups: water-based methods (1 free, with nebula spray, and 3 supported methods), solvent-based methods (4 free, with different solvents, and 2 supported methods), poultices (36 different combinations of poultice materials and active ingredients), ion-exchange resins, mechanical methods (4 methods, with different hand tools or mechanical equipment) and laser cleaning. A total of 52 cleaning methods was analysed. Within each group, no significant differences were found, except for the solvent-based methods [23]. Based on those results, the present study takes into account one type of cleaning method for each group and two for the solvent-based methods, as shown in Table 1. These cleaning methods were used to investigate more in depth the applicability and sensitivity of the LCA analysis.

Cleaning method	Label	Short description
Water-based methods	WATER	Nebula spray with deionised water
Solvent-based methods	SOLVENT-A SOLVENT-B	Acetone (free) Solvent gel (supported)
Poultices	POULTICE	Cellulose + water + EDTA
Ion-exchange resins	RESIN	Ion-exchange resins
Mechanical methods	MECHANICAL	Micro-sandblasting
Laser cleaning	LASER	Laser cleaning

Table 1 – Cleaning methods selected for the analysis.

The cleaning with deionised water consists of a mild wash with droplets (nebula spray) to remove especially gypsum deposits, thanks to the physical action owing to water run-off. Solvents are more appropriate for dissolving dark layers containing organic substances with similar polarity and can be used both free and supported (solvent gel). Regarding the first ones, the liquid solvent is directly applied to the surface by cotton balls, while regarding the second ones, the solvent is jelled and then applied to the surface. Another cleaning technique, frequently used for the removal of crusts and extraction of salts, is poultice, in which an absorbent support (mostly cellulose, but also clay) soaked with water and cleaning agents, is applied and left on the surface to soften and detach the deposits/crusts. Ion-exchange resins are used for the removal of black crust and limescale formations through an ion-exchange mechanism activated by water. Mechanical methods include different techniques based on an abrasive action, ranging from micro- and hydro-sandblasting to scalpel and engraving pen; the effectiveness of these methods strongly depends on the worker's ability. Laser cleaning exploits a laser ray which allows to vaporize black crusts and layers, after a preliminary wetting aimed at increasing their darkness.

2.2 Life Cycle Assessment

According to the original definition provided by Setac [24] the Life Cycle Assessment of a product can be defined as a methodology to evaluate the environmental burdens by identifying and quantifying energy and materials used and wastes released to the environment, including the entire life cycle of the product. LCA can be conveniently used in several applications in order to identify specific environmental hotspots or to compare different scenarios. All inputs and outputs have to be considered during all the processes' phases. Figure 1 schematically summarizes the LCA approach.

2.2.1 Goal and scope definition

The main purpose of LCA results is considered since the beginning during definitions of the goal and scope.

The goal of an LCA states the intended application and the reasons for carrying out the study, the intended users and whether the results are to be used for internal purpose or for disclosure to any stakeholders, while the scope includes several items related with the correctness of the study and of all assumed procedures. Allocation method and data requirements and quality apart, the main items that have to be defined for a correct LCA are functional unit and system boundary.

The present study is intended to provide an insight on the applicability of the LCA approach to the field of conservation work, with particular refence to cleaning, so the goals are twofold: i) to investigate if the LCA analysis can be applied to the selected materials and technologies and if problems arise in this analysis; ii) to evaluate the reliability of the results obtained and to compare the different cleaning methods selected. Concerning the goal i), the analysis was carried out from the point of view of professionals involved in the conservation process (architects, engineers and conservation companies), so considering the input data that they can have access to in real practice.

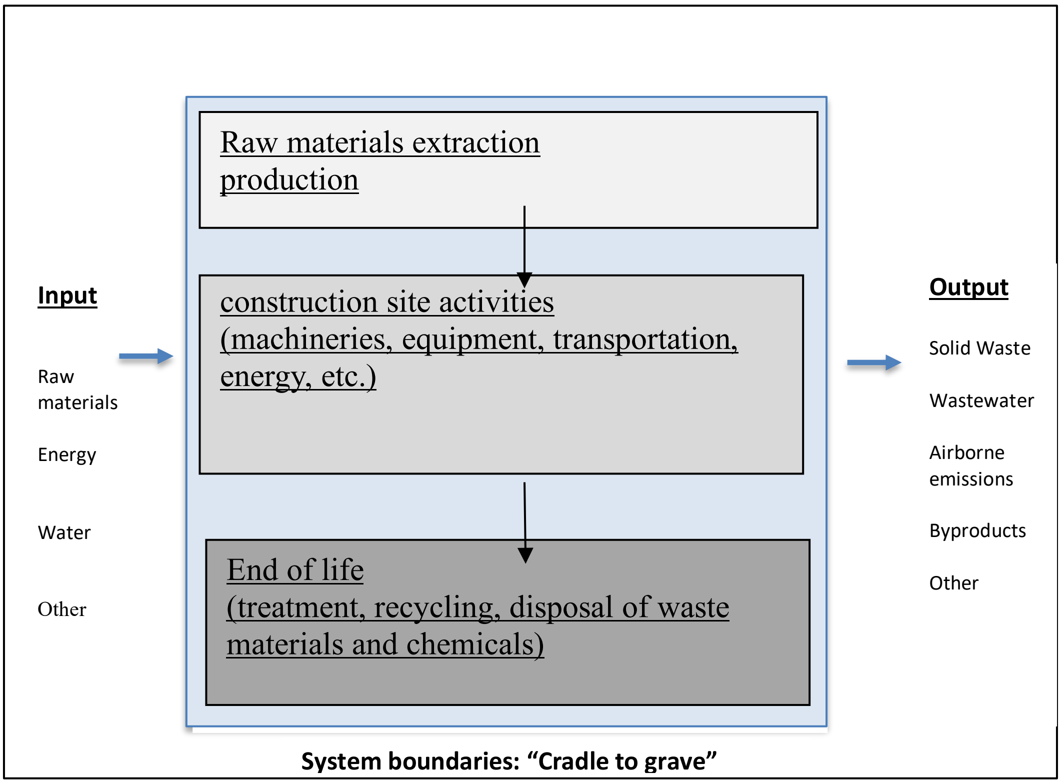


Figure 1. LCA scheme

Functional unit

The functional unit (FU) is a fundamental element for the LCA analysis [25-26]. It defines the quantification of the identified function of the product and represents the reference unit to which all input and output flows are referred to, providing a quantitative description of the performance of the product systems [27]. The definition of the functional unit is a critical point of the study, because the reliability of the comparison between different product or processes strongly depends on its choice. This issue is particularly challenging in the conservation field, due to the considerable difficulty in comparing different cleaning technologies; in fact, there are several variables to take into account, starting from the nature of the deposit that has to be removed, its thickness and hardness, which may require different cleaning durations and/or materials' amounts. Moreover, also the nature of the substrate affected by the deposit (cracked, powdering, etc.) and the possible presence of previous conservation materials (consolidants, protectives, etc.) must be considered in repair works, as well the boundary conditions on site, therefore sometimes a cleaning technology is more appropriate than another one, and the selection of the method is based on this. However, the evaluation of the environmental impact of cleaning requires the definition of a functional unit, so in this study the FU corresponding to the cleaning of one square meter of a plain vertical surface affected by a ‘normal black crust’ has been selected, based on the experience of a company working in the conservation field since many years [23]. In fact, the same level of cleaning effectiveness shall be provided in order to ensure the comparability of the cleaning methods. This involves different types and amounts of materials, equipment, energy consumption and duration, which are specific of each method and lead to an equal result in term of cleaning.

System boundaries

In this study, an approach “from cradle to grave”, according with the ISO definitions [25-26] has been assumed. All inputs were considered from raw material extraction to their back to environment as waste or emissions, evaluated in terms of their end of life. In fact, the system boundaries cover the construction site activities with regard to materials, machineries, equipment, all transportation activities to the site and energy consumption. Several assumptions and results of the processes were made, according to the previous study [23]. In particular, in this issue a robust additional analysis has been carried out, including the waste processes, in order to evaluate the incidence of end of life treatment phase. Including the final waste treatment is usually quite challenging in LCA analysis applied to building works, owing to the lack of specific information and the complexity in the collection of data regarding the transport and the disposal scenario of waste materials, packaging and equipment. For this reason, waste treatment is often not included in LCA analysis. In this paper, the LCA analysis was carried out both with and without the end of life stage, to investigate whether it has a significant impact in the results.

2.2.2 Life Cycle Inventory

In this study, data quality has been considered as a priority, both for primary and secondary data collection. The primary data have been gathered directly from an Italian company operating in the restoration field (Leonardo srl); these data concern the amount of materials used in each cleaning operation, the electricity consumption and the duration of the operations. Secondary data have been obtained from the Ecoinvent 3.4 database [28], especially for materials, chemicals and background processes, such as transport, electricity production and waste treatment. When the specific materials and chemicals used in cleaning were not included in the database, similar products were selected and a sensitivity analysis was carried out to evaluate the impact of this change of materials. This evaluation was carried out at the LCIA level, as its purpose was the investigation of the shortcoming arising from the lack of specific database and not the assessment of the cleaning technology having the lowest environmental impact in absolute terms. The GWP was chosen for the sensitivity analysis, because global warming is one of the most critical and challenging environmental problems today, so the evaluation was addressed to understand how the results of the environmental impact change with the method selected and what relevance the various methods give to this category.

A working site located in the city of Bologna was considered in this study. In order to take into account the geographical location, an energy mix referred to the Italian context was selected, while for the other processes a reference European context was considered. The processes related to machineries, tools and personal protective equipment (PPE) used in each activity were modelled *ad hoc*, according to the available technical datasheets of the market products, including also the information about their packaging.

The inventory analysis has been modelled using SimaPro 8.5.2.2 software [29], following the "Allocation at the point of Substitution" (APOS) approach, which is an attributional approach where the burdens are attributed proportionally to the processes [30]. The attributional approach was chosen because it considers all the materials and physical flows related to the life cycle of the specific product or process under study and it provides the environmental impact directly associated with that system in a status quo condition.

Table 2 reports some of the most significant inventory analysis data.

Waste management represents a critical point in the end of life phase. In the previous study [23], this parameter was not considered, while in the present paper two scenarios, with and without waste treatment, were analysed. About the first scenario assumptions, regarding the end of life of tools, machineries and packaging, a complete treatment process has been considered, including the transportation to the recycling plant.

Cleaning method	**Material**	**Amount [kg]**	**Machinery**	**Power [kW]**	**Time [min]**	**PPE**
WATER	Deionised water	5	Nebula sprayer	-		Gloves
			Compressor	2,2	10	
			Demineralizer	0.37	10	
SOLVENT-A	Acetone	3	-	-		Gloves
	Cotton	0.5	-	-		Glasses
						Mask
SOLVENT-B	Deionised water	0.15	Demineralizer	0.37	20	Gloves
	Carbopol®	0.02	Blender	0.7	10	Glasses

	Ethomeen® (oxyethylene)	0.2	Brush	-		Mask
	Solvent (ethanol)	1	Sponge	-		
	Deionised water (washing)	25				
POULTICE	Deionised water	7	Demineralizer	0.37	40	Gloves
	Cellulose pulp	0.6	Brush	-		Glasses
	EDTA	0.21	Sponge	-		Mask
	Deionised water (washing)	25	Nylon film	-		
RESIN	Deionised water	0.5	Demineralizer	0.37	60	Gloves
	Resin	1.5	Brush	-		Glasses
	Deionised water (washing)	20	Sponge	-		Coverall
MECHANICAL	Sand	5	Micro sandblaster with compressor	2.2	10	Gloves
						Glasses
			Extractor fan	1.29	10	Mask
						Earmuffs
						Coverall
LASER	Deionised water	10	Demineralizer	0.37	10	Gloves
			Laser equipment	3.7	180	Glasses
						Coverall

Table 2 –Some significant data collected during the inventory analysis.

Also the treatment of waste materials and chemicals used for the cleaning operations, was considered, as shown in Table 3. Wastewater apart, further output such as emissions into the atmosphere specifically produced by cleaning operations were not included because they were considered negligible. The wastewater treatments were chosen in agreement with the company operating in the restoration field, that provided also other inventory data, according to their usual disposal practices.

Cleaning method	**Material**	**Waste treatment**
WATER	Deionised water	Wastewater treatment (95%)
SOLVENT-A	Acetone + cotton	Hazardous waste incineration
SOLVENT-B	Solvent gel	Hazardous waste incineration
	Deionised water (final surface washing)	Wastewater treatment
POULTICE	Poultice	Hazardous waste incineration
	Deionised water (final surface washing)	Wastewater treatment
RESIN	Resin + deionised water	Hazardous waste incineration
	Deionised water (final surface washing)	Wastewater treatment
MECHANICAL	Sand	Recycling of inert material

Table 3 – Waste treatment of materials and chemicals used for the cleaning operations.

2.3.3 Impact assessment methods

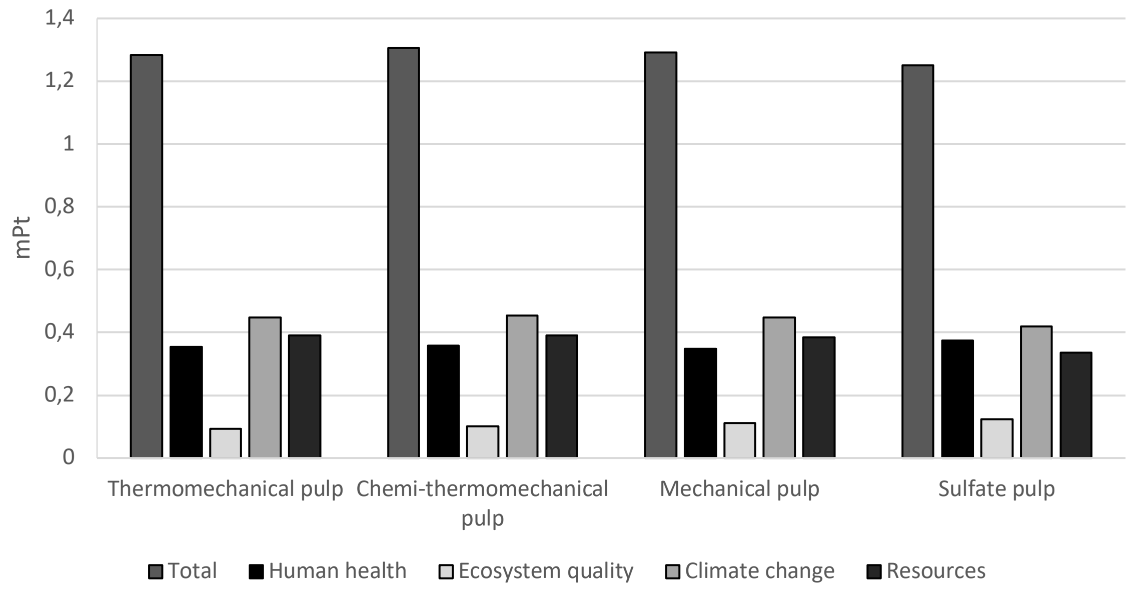
The calculation method IMPACT 2002+ [31] was used to compare the different cleaning methods both in terms of midpoint and endpoint analysis. Both midpoint and endpoint analysis were considered in order to provide a twofold level of interpretation of the results. The endpoint analysis is more understandable and particularly useful for decision-making, due to the fact that it considers the environmental impacts at the end of the cause-effect chain. The midpoint approach has been used too, to give more detailed results with a focus on specific impact categories. Then, a comparison with further three methods, namely CML-IA baseline [32], IPCC GWP 100a [33] and TRACI 2.1 [34], was carried out in terms of the Global Warming impact category. In addition, in order to evaluate the external costs related to the different techniques, a further assessment with EPS 2015dx [35] method was performed.

3. Results and discussion

A critical point in performing Life Cycle Assessments is the availability of precise information and the consistency between inventory data and databases. This fact is relevant especially for those activities that involve specific products and materials, such as in this study. Whereas the LCA provides a representation of reality as detailed as possible, it is still a model and involves simplifications and choices by practitioners. For these reasons, it was necessary to make some approximations, due to a lack of specific data for conservation works within the Ecoinvent database. In particular, some of the chemicals and materials used in the cleaning procedures were not present, which was critical especially for the supported solvent-based methods. The Carbopol® gelling agent, a polymer obtained from polyacrylic acid, was not present in the database and a generic acrylic acid was selected. Similarly, the Ethomeen® surfactant, a polyethoxilated amine that acts as a neutralizing base for Carbopol, was modelled by using the data available for diethanolamine. Moreover, ethanol was chosen as representative of the solvents used.

Concerning the poultice cleaning, the most critical issue is that cellulose pulp (one of the most used material for poulticing) is not included in the database, thus a comparison was carried out among the cleaning with different types of pulp available in the Ecoinvent database, namely thermomechanical, chemo-thermomechanical, mechanical and sulfate pulps, assuming the same amount of pulp. The results of the sensitivity analysis, carried out with IMPACT 2002+ assessment method and shown in Figure 2, highlight that there are no significant differences, so the use of different pulps does not affect considerably the outcomes of the cleaning procedure. Consequently, a generic and common thermo-mechanical pulping device was considered in the following analyses.

a)



b)

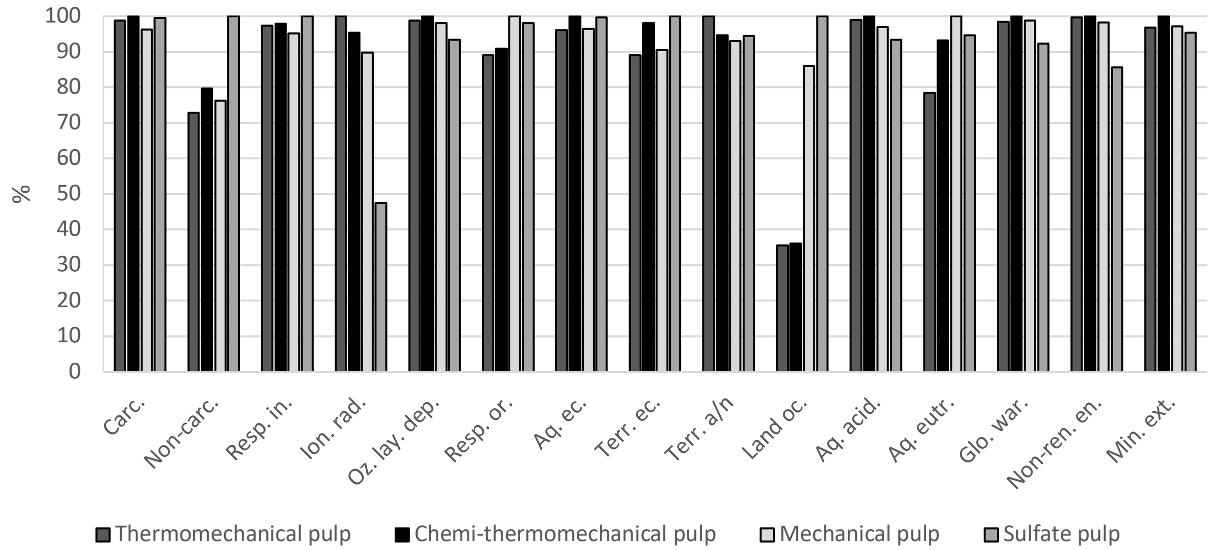
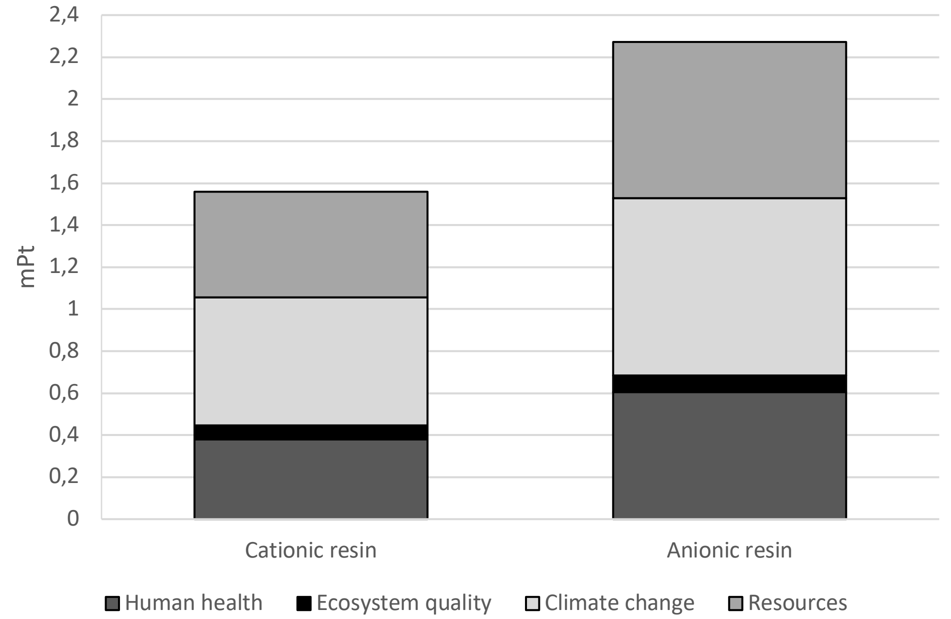


Figure 2- The results of the comparison between the cleaning of 1 sqm of surface with different type of pulp, with IMPACT 2002+ assessment method in terms of a) damage categories and b) impact categories.

Concerning the techniques based on resins, both cationic and anionic resins can be used, their effectiveness depending on the specific nature of the black crust to remove. Then, as for the poultices, throughout a sensitivity analysis, a comparison between the cleaning with a cationic and anionic resin has been performed. Figure 3 shows an increase of about 46% of the damage in terms of score for the anionic resin compared to the cationic one. As anionic resins are more used for the cleaning of black crusts, an anionic resin was considered for the following LCA analysis.

a)



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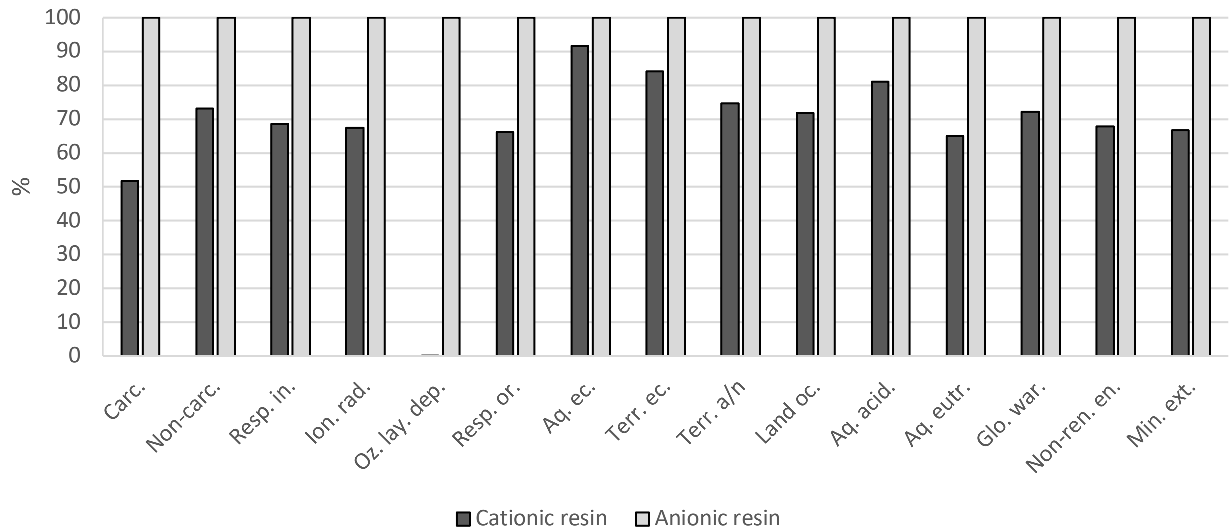


Figure 3 - The results of the comparison between the cleaning of 1 sqm of surface with a cation and anionic resin, with IMPACT 2002+ assessment method in terms of a) damage categories and b) impact categories.

Concerning the tools and machineries used for the activities, the previous study [23] showed that the main impacts are basically due to the energy consumption during the use phase rather than to their manufacturing and transport, thus it is essential to consider both the technical information provided by the datasheets and the actual duration of the activity, in order to accurately calculate the electricity consumption, especially for energy-intensive technologies.

Taking into account the considerations above reported, the LCA analysis carried out for the 7 selected cleaning methods and the results are reported in Figure 4, where the most significant results are collected. In particular, the most significant impact categories were considered, i.e., those giving the highest impact as Carcinogens, Ozone Layer Depletion and Global Warming, and the water use (in all the cleaning methods, the end of life – EoL – was included in the analysis). The analysis highlights that for Carcinogens impact category the most harmful method is the free-solvent cleaning (0.408 kg C_2H_3Cl eq), especially due to atmospheric emissions of aromatic hydrocarbons during the production of the acetone. This is followed by the cleaning with resins (0.180 kg C_2H_3Cl eq) and solvent gels (0.160 kg C_2H_3Cl eq), due to atmospheric emissions of aromatic hydrocarbons respectively arising from the production of natural gas used for the production of the methanol present in the anionic resin and from the production of ethylene needed for the ethanol. For Ozone Layer Depletion impact category, the resins show a much higher value (2.577E-4 kg CFC-11 eq) than all other cleaning methods, especially due to atmospheric emissions of tetrachlolomethane from the production of the trichloromethane for the anion resin. The free-solvent methods are responsible for the major impacts in the Global Warming impact category (17.0 kg CO_2 eq), owing to the atmospheric emissions of carbon dioxide from fossil sources during the production of acetone; the resins and laser methods rank second and third (8.4 kg CO_2 eq and 5.4 kg CO_2 eq), due to atmospheric emissions of carbon dioxide from fossil sources respectively arising from the incineration of the resin and from the production of electricity used during the laser cleaning. Regarding the water use, contrary to what can be expected, the cleaning with deionised water exhibits the lowest water consumption (2.6 m^3), while the most water-consuming technique is the laser (63.7 m^3); this is especially due to the fact that this indicator takes into account the water use at each stage of the life cycle and for each type of utilization, for example also for the electricity production needed in this case for the laser operation.

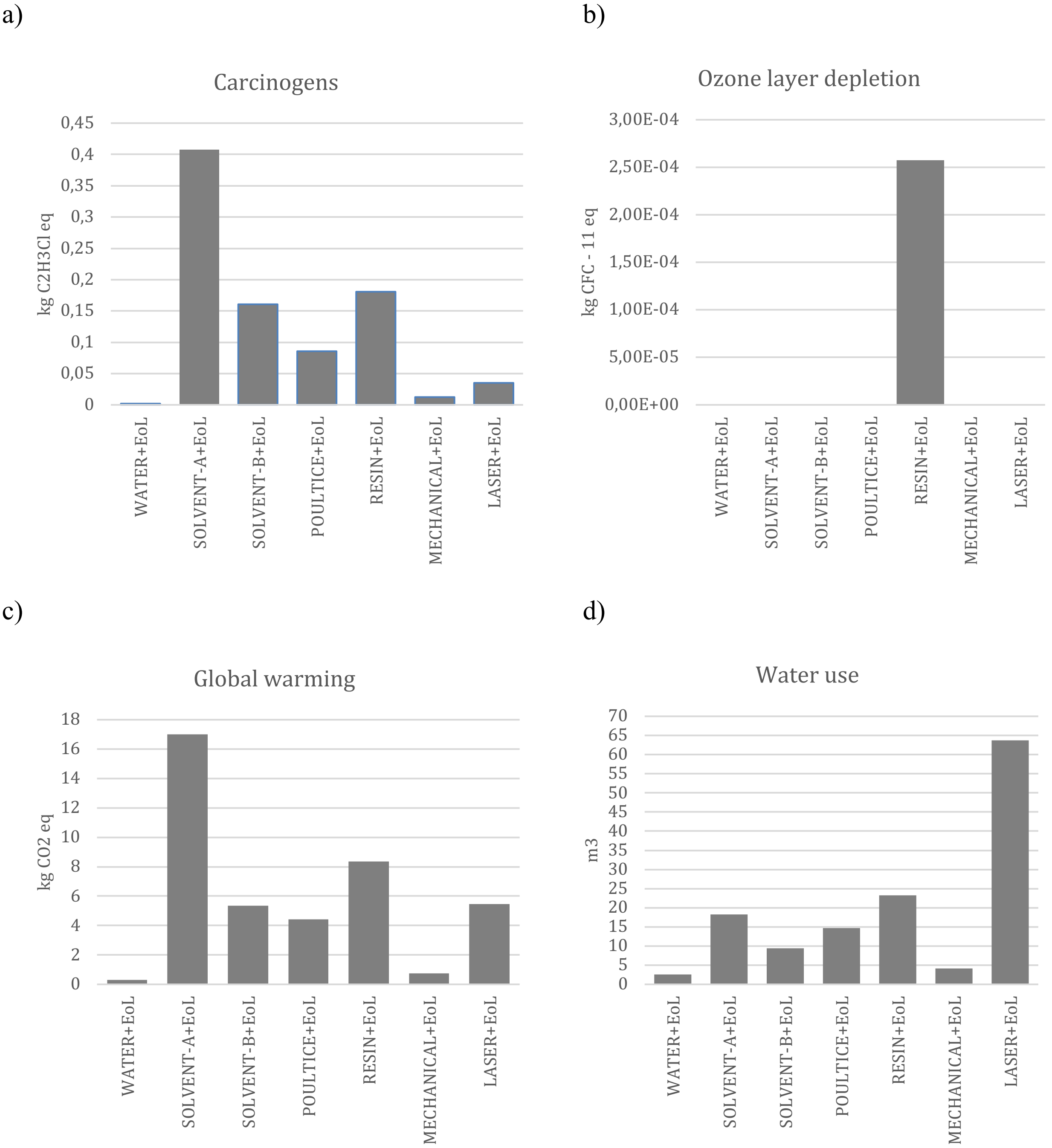
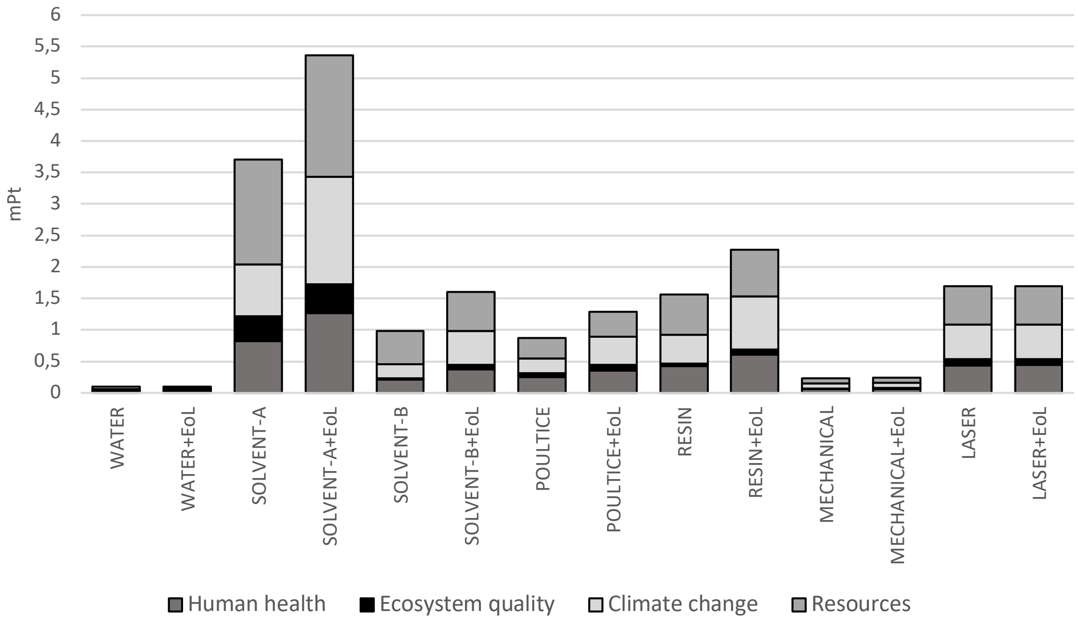


Figure 4 - Results of the midpoint analysis with IMPACT 2002+ assessment method for the impact categories: a) Carcinogens; b) Ozone Layer Depletion; c) Global Warming Potential. The analysis of the Water use, related to the cleaning of 1 sqm of surface, is reported in d).

Some further interesting results were found when comparing the same cleaning methods in the two scenarios: with and without waste treatments, as shown in Figure 5 in terms of Single Score.



Cleaning operation	Damage without EoL processes (mPt)	Damage with EoL processes (mPt)	Difference [%]
WATER	0.98E-01	1.03E-01	5.3
SOLVENT-A	37.11E-01	53.63E-01	44.5
SOLVENT-B	9.86E-01	15.99E-01	62.2
POULTICE	8.75E-01	12.84E-01	46.7
RESIN	15.62E-01	22,72E-01	45.4
MECHANICAL	2.32E-01	2.40E-01	3.5
LASER	16.90E-01	16.91E-01	0.0

Figure 5 - Comparison between processes including and not including the end of life processes (suffix +EoL), with IMPACT 2002+ assessment method, related to the cleaning of 1 sqm of surface.

As expected, the scenario including the end of life processes involves a higher impact for all the techniques, due to the environmental burdens related to the waste treatment. However, the difference varies depending on the specific cleaning method; the major difference is related to the solvent gels (+62.2%) followed by poultices (+46.7%), resins (+45.4%) and acetone (+44.5%). Lower differences can be noticed in the other techniques (+5.3% for deionised water, +3.5% for micro-sandblasting and basically no difference for laser). The increase of the impact for the first four methods is due to the incineration of hazardous wastes, i.e. the consumables used for the cleaning. In particular, for the cleaning with resins and solvent gels, an in-depth analysis highlighted that the environmental damage related to their production is similar to that of their disposal.

Moreover, as shown in Fig. 5, the impact of the waste treatment affects partially the ranking of the different cleaning methods in terms of impact; free solvent-based methods remain responsible for the main impact in both cases but they are followed respectively by the laser cleaning and the resins, in the scenario with end of life treatments and inversely by the resins and the laser cleaning in the

other scenario. The following lowest part of the ranking remains unchanged for both scenarios.
An element of subjectivity in the LCA analysis is the selection of the assessment method. Several methods are implemented in LCA software and viable for the analysis, but it is not straightforward to compare the results obtained with different methods. In fact, some methods provide a "midpoint" evaluation, i.e. impact categories, focussing on those environmental mechanisms that occur early in the cause–effect chain such as emissions or extractions that lead to the so-called primary changes in the environment. Primary changes could result in secondary and then tertiary changes later in the cause-effect chain, for example human health and ecosystem quality in terms of damage categories as highlighted by endpoint perspective [30, 36]. Moreover, within both midpoint and endpoint methods, different categories and subcategories can be considered, with different units of measure, different substances may be included or not, with different characterisation factors [37]. Therefore, the results of the comparison between methods is not easy to be understood and require close attention; however, it can be interesting to note if there are some common trends between methods, considering the same impact categories with the same units. In the present work, a further analysis has been performed, considering three assessment methods (IMPACT 2002+, CML-IA baseline, IPCC GWP 100a, TRACI 2.1) and focussing on the common impact category of Global Warming. In this analysis, also the waste treatments have been included. Figure 6 highlights that, for all the techniques, the different assessment methods give comparable results, but the analysis with IMPACT 2002+ gives lower values that the others for all the considered cleaning operation.

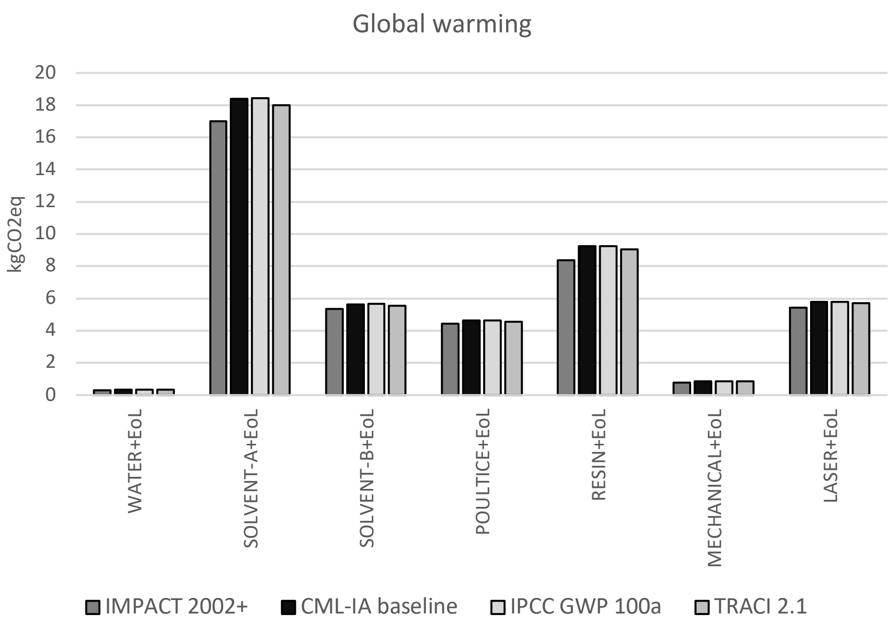


Figure 6 – Results of Global Warming impact category respectively with IMPACT2002+, CML-IA baseline, IPCC GWP 100a and TRACI 2.1 assessment methods, related to the cleaning of 1 sqm of surface.

In addition to the assessment of the environmental impacts, the evaluation of the externalities related to the process under study can be useful to obtain a more detailed analysis that takes into account also the external costs. In fact, considering the externalities, i.e. the indirect costs and economic impacts related to the environmental issues and not directly quantifiable, gives an added value to an LCA study that has the ambition to consider the entire cycle of a process. In this study, the analysis of the externalities has been performed with EPS 2015dx (Environmental Priority Strategies) assessment method which provides a monetarisation of the impacts. The external costs are assessed based on the willingness to pay to restore environmental changes and the monetary measurement is the ELU which corresponds to one Euro (= 1Pt). The results of the calculation show that free solvent methods are responsible for the main impact (5.62 Pt), followed by resins (3.73 Pt), laser (2.38 Pt), solvent gels (2.36 Pt), poultices (2.09 Pt), micro-sandblasting (0.45Pt) and deionised water (0.18Pt). Moreover, Figure 7 highlights that Abiotic resources and Human health are the most affected damage categories (68.9% and 30.35% respectively). In particular, the cleaning with free solvents is the largest contributor to the impacts in both damage categories, for Abiotic Resources due to the crude oil needed for the production of acetone while for Human Health due to the emissions of carbon dioxide from fossil sources in air again during the production of acetone.

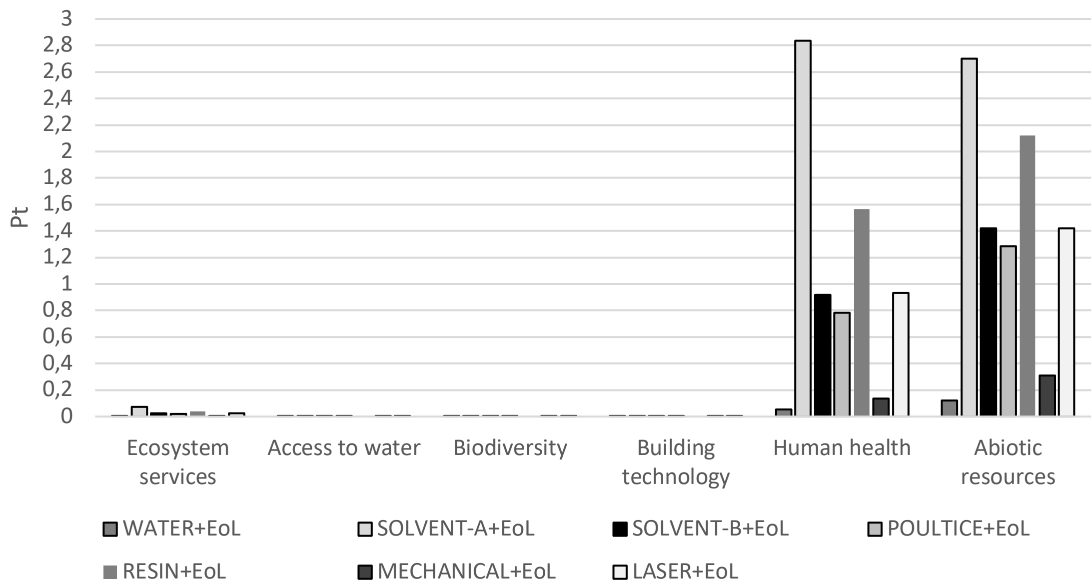


Figure 7 – Weighting results of the evaluation of the externalities with EPS 2015dx related to the cleaning of 1 sqm of surface.

4. Conclusions

Seven cleaning methods, different from the point of view of both cleaning principle and materials/equipment employed, were analysed by the LCA approach. These methods represent the most diffused ones in the conservation of historic buildings and hence they can be considered representative for this field. The results of the LCA analysis allow to derive the following remarks.

- The environmental impact of cleaning has never been investigated so far, to the authors' best knowledge, hence some of the specific products and materials employed are not present in the Ecoinvent database and it was necessary to make some approximations. For some of the materials not present in the database (Carbopol® gelling agent and Ethomeen® surfactant), the most similar chemicals were selected, but a sensitivity analysis was not possible. In the case of the cellulose pulp used for the poultice and not reported in the database, it was shown that the selection of different pulps has basically no influence and the final impact does not change. Conversely, in the case of the ion-exchange resin, the impact of cleaning with an anionic resin is much higher (+46%) with respect to cationic resin, although the kind of resin must be selected on the basis of the nature of the black crust to remove and not only of the environmental impact of the method.

- The impact of the different cleaning methods is strongly different, being maximum for free solvent methods (SOLVENT-A), followed by laser, and minimum for the water-based method (nebula spray) and micro-sandblasting, if the end-of-life treatments are not included. However, the contribution of the cleaning methods to the different impact categories are different, as displayed in Figure 4. In fact, for Carcinogens and Global Warming impact categories, the free solvent methods involve the highest impacts, while the resins are dominant in term of impact regarding Ozone Layer Depletion category. Conversely, the analysis of the water use shows that laser is in the first place, especially due to the water consumption for the production the electricity, which is needed during all the cleaning operation.
- The impact of the cleaning methods is very different if waste treatment (end of life scenario) is included in the analysis, as expected. However, it is noteworthy that difference varies depending on method, being maximum for cleaning based on solvent gels (+62.2%) followed by poultices, resins and acetone (+46.7%, +45.4% and +44.5% respectively) which is mainly due to the incineration of hazardous waste, i.e. the consumables used for the cleaning. For the techniques that do not involve hazardous wastes, the difference is negligible. A more in-depth analysis showed that for the cleaning with resins and solvent gels, the environmental damage related to their manufacturing is comparable to that of their disposal. Moreover, including the impact of the waste treatment partially affects the ranking of the different cleaning methods.
- The comparison of the results of the Global Warming obtained by different assessment methods (IMPACT 2002+, CML-IA baseline, IPCC GWP 100a and TRACI 2.1) highlights that the results are quite similar and the ranking among the cleaning technologies is basically the same. This emphasizes the usefulness of the LCA as a support tool for the selection of materials and technologies for cleaning.

The results show that the LCA is actually applicable to conservation works, with particular reference to cleaning, although some limitations still exist, such as the limited data availability in the databases. This research also showed how critical is the selection of the FU is in the conservation field, as the working operations are dependent on the skilfulness and experience of the conservators involved. The FU used in this study, namely the cleaning of one square meter of a plain vertical surface affected by a 'normal black crust', was selected on the basis of the experience of the authors and some professionals working in the conservation field since many years, but this aspect should be improved in the future. The extension of the LCA analysis to other stage of the conservation work, such as repointing with repair mortars and renders, consolidation and protection are presently under investigation.

The diffusion of the environmental impact assessment may largely contribute to a more sensible selection of materials and technologies in the conservation and repair of historic buildings, but also to the set-up of improving measures to reduce the environmental impact, thus promoting the sustainability awareness also in this important field.

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