THE LIFE CYCLE SUSTAINABILITY ASSESSMENT APPROACH APPLIED TO TANGIBLE CULTURAL HERITAGE CONSERVATION

Developing a support instrument for Cultural Heritage Management within a Circular Economy and Life Cycle Thinking perspective

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Abstract

Life Cycle Thinking (LCT) and the Circular Economy (CE) concept might delineate a convergence point between growth and sustainability, in a general context as well as in an urban environment. The CE paradigm, indeed, introduces a new perspective to look at the industrial ecosystem, where the economic growth is decoupled from resource consumption and pollutant emissions as end-of-life materials and products are conceived as resources rather than waste (Sauvé et al., 2015). LCT introduces a holistic viewpoint, which considers all the lifecycle aspects of a product system or a service, from the extraction of the raw materials to the end-of-life of the latter. Both LCT and CE are implementable using a Life Cycle Sustainability Assessment (LCSA) approach where all the three pillars of sustainability (environmental, social and economic) are taken into account in order to set the right targets and improve the efficacy and efficiency of production systems or services. However, the latter are still far from being reached at a global level, due to a lack of practical examples of LCT implementation, to an uneducated mind-set and to missing regulations. In particular, the tangible Cultural Heritage (CH) field is lacking a clear and applicable instrument to support conservation management decisions and the emission of related regulations and directives. The Cultural Heritage field recalls what can be considered another hotspot in the scientific and political agendas, in a sustainable development perspective: urban environment and cities growth management. Recovering, conservation and valorisation of Cultural Heritage - in particular built CH - are part of a transition management process for the urban environment towards more sustainable cities. Being a shared, non-replaceable, unique resource and a common good confronted with important environmental challenges and possible under-funding, looking after CH to avoid neglect and possible decay is a common responsibility. The management of cultural heritage requires continuous conservation and restoration work, involving diverse professionals mainly in technical and scientific activities. A sustainable approach to the processes of Cultural Heritage restoration and conservation involves the selection of safe materials and methods both in terms of human and environmental health but also a quantification of the benefits deriving from the conservation process. It is therefore necessary to create comprehensive models for Cultural Heritage management in order to fulfil environmental, economic and social sustainability criteria.

This study aims to apply the concept of Life Cycle Sustainability Assessment and Management to Cultural Heritage restoration and conservation. Pereira Roders and van Oers (2011) pointed out that Cultural Heritage Management is a relatively young field of research can be considered as being at an earlier stage of development than other related studies, such as the architectural conservation field (Van Oers and Pereira Roders, 2012). If LCA has been extensively applied in the building sector for assessing the environmental performance and impact of construction materials and products throughout the entire life cycle of a construction (Ortiz-Rodrıguez et al., 2010; Sharma et al., 2011), the use of LCA is practically unknown in the field of cultural heritage (Settembre Blundo et al., 2014). Applying the LCSA approach to tangible Cultural Heritage Management allows creating a decision-making instrument tailor made for built CH, in order to implement the recent design process for restoration, providing quantitative outputs as well. On the one side, the LCSA approach ensures to maintain interdisciplinarity, a mandatory requirement for CH related investigations. On the other side, it fulfils the need for one single deliverable unit decipherable by all the parties involved and by non-expert decision makers.

In order to present the attempt and progress on reaching the abovementioned targets, two case studies are investigated: the restoration proposal of the San Felice colonnade within the San Felice complex in Pavia (Italy) and the conservation and requalification process of the Buccola pavilion within the San Lazzaro compound in Reggio Emilia (Italy). It is illstrated how a conveniently adapted Life Cycle Sustainability Assessment approach could be employed both with a predictive purpose, presenting and comparing alternative scenarios, and as a monitoring and diagnostics instrument. Moreover, even if the proposed instrument might require further development and refining, it is far from rigid and allows to mould the

analysis according to the affected stakeholders and the final scope, still respecting some standardization features that enable a more effective and objective management.

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1. *Introduction*

The concepts of sustainability and sustainable development are nowadays extremely hot topics both in the academic and political community as well as among stakeholders of diverse areas. In October 1987, The Brundtland Commission released the "Our Common Future" document, also known as the "Brundtland Report", which coined the meaning of the term sustainable development. In particular, it is defined as an equilibrium between the satisfaction of the present needs and the maintenance of possibility for future generations to meet their own needs; this shall guarantee good living conditions in the long term. Officially introduced for the first time during the Rio Conference organized by the United Nations Environmental Programme (UNEP) in 1992, the interest in sustainable development has widespread rapidly and environmental sustainability is one of the eight Millennium Development Goals (MDGs) of the Millennium declaration that originated from the 2000 UN summit. The other MDGs (eradicate extreme poverty and hunger, achieve universal primary education, promoter gender equality and empower women, reduce child mortality, improve maternal health, combat HIV, malaria and other diseases, global partnership for development) might also be clustered under the concept of social sustainability. On the onset, the concept of sustainability can have an economical interpretation. A business is sustainably managed when it allows exploitation over indefinitely prolonged time. This is possible when the environment and natural resources are exploited sustainably as well and when it is socially acceptable so that local communities and stakeholders in general will not hinder it. In addition - when the population is constantly increasing and the general trend and aim is only economic growth - how is it possible to conciliate sustainability with growth? The answer might be found in the eco-efficiency concept. The definition of eco-efficiency that emerged from the World Business Council for Sustainable Development (WBCSD) workshops, held in Geneva in 1996, is the following: "Eco-efficiency is reached by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing environmental impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity". Moreover, sustainable development is intergenerational, implying the need to take a longer term view. A short-time growth might result in a long-time regression (e.g. because of environmental and social impacts and costs) and vice-versa.

There seems to be an increasing degree of consensus in governance research that both top-down steering by government and the liberal free market approach are outmoded as effective management mechanisms to generate sustainable solutions, but it is at the same time impossible to govern societal change without them (Jessop 1997; Meadowcroft 2005; Pierre 2000). Therefore, new governance models that increase the effect of existing forms of government and planning in the context of long-term change in society are to be organized. This implies a new balance between state, market, and society (Héritier 1999) and hinders the need to switch to a different global paradigm where growth is decoupled from resources consumption. In order to be successful, this switch should translate into a political, social and economic gradual transition, with "short-term innovation [or interventions], local strategies and long-term sustainability visions" (Loorbach, 2010). To promote this transition, it is necessary to find useful and practical instruments that would support decision makers and stakeholders implementing and managing this defying shift.

Life Cycle Thinking (LCT) and the Circular Economy (CE) concept might delineate a convergence point between growth and sustainability, in an urban environment as well as in a general context. The CE paradigm introduces a new perspective to look at the industrial ecosystem, where the economic growth is decoupled from resource consumption and pollutant emissions as end-of-life materials and products are conceived as resources rather than waste (Sauvé et al., 2015). Both LCT and CE are implementable using a Life Cycle Sustainability Assessment (LCSA) approach where all the three pillars of sustainability (environmental, social and economic) are taken into account in order to set the right targets and improve the efficacy and efficiency of production systems or services. However, the latter is still far from being reached at a global level, due to a lack of practical examples, LCT implementation and mindset and missing regulations. In particular, the Built

Cultural Heritage (CH) field is lacking a clear support instrument to conservation management decisions and to the emission of related regulations and directives.

The urban environment and Cultural Heritage were mentioned above as they recall what can be considered another hotspot in the scientific and political agendas, in a sustainable development perspective: urban environment and cities growth management. Cities are the geographical areas where the population density reaches its higher peaks and they constitute a driving power for the economic and social development of most countries: as reported by Peris Moras (2007), already in 2005 they generated 55% of the GNP (Gross National Product) in countries with weaker economies, 73% of the GNP in countries with an average development and 85% in the more developed countries. On the other hand, the high concentration levels of pollutants emitted in urban atmospheres, energy, water and materials consumption as well as waste production in modern metropolitan areas represent a great threat to sustainability. The number of construction works tends to increase. However, this shall be undertaken by attempting to achieve the paradigm of sustainability, demanding an increasing durability and quality of what is being built in order to minimize environmental impacts. Moreover, in many countries (with Europe and Italy in particular in the lead), the space for new constructions is lacking and restoration of old buildings is necessary. Apart from this spatial barrier, every country should focus on their built cultural patrimony conservation. Is buildings' restoration sustainable? Giving a building a longer life span involves energy and new materials consumption: is a more efficient operational phase counterbalancing the restoration intervention impact? How should the benefits of the conservation be valued? Which is the balance among renovation, conservation, and rebuilt?
The concept of sustainable development underpins much current thinking on the problems facing cities and urban areas, including the aforementioned issues of the construction sector. Since the late 1980s, many countries have committed to a sustainable development goal, but are struggling with how to achieve it (Frantzeskaki et al., 2015). Sustainability is at the intersection of multiple domains, due to its concern with aligning social, economic, and environmental values (Kates et al. 2001; Pezzoli 1997). Bulkeley (2010) distinguished some sets of factors causing the persistent nature of the sustainability problems facing urban areas, as well as of the failures of policies to address them. One of them is the "lack of knowledge", as municipalities tend to be focused on the day-to-day operations of their city, and frequently do not allocate resources properly. Another one is the "limited resources (financial, human)", as municipalities generally operate with severe resource constraints, leading them to concentrate them in areas perceived as critical. Without appropriate assessment instruments this perception can be erroneous.

Moreover, recovering, conservation and valorisation of Cultural Heritage (CH) – in particular built CH- is part of a transition management process for the urban environment towards more sustainable cities. According to the HORIZON 2020 - Work Programme 2016 – 2017 -Climate action, environment, resource efficiency and raw materials- actions should be taken in order to harness the full potential of cultural heritage as a production rather than a cost factor and a strategic resource for a sustainable Europe and thus ensure its sustainability, safeguarding, resilience and enhancement. Being a shared, non-renewable, non-replaceable, unique resource and a common good confronted with important environmental challenges, possible over-exploitation and under-funding, looking after CH to avoid neglect and possible decay is a common responsibility. The focus is therefore to maximise its intrinsic economic, cultural and societal value in promoting well-being, cultural diversity and social cohesion.
Cultural Heritage should then be seen as a driver for sustainable growth. According to De La Torre (2002), "the overall challenge is to go far beyond simple conservation, restoration, physical rehabilitation or repurposing of a site and to demonstrate heritage potential as a powerful economic, social and environmental catalyst for regeneration, sustainable development, economic growth and improvement of people's well-being and living environments".
Cultural Heritage restoration certainly allows an improvement in social sustainability but to what extent is it environmentally and economically sustainable? Life Cycle Sustainability Assessment is an extremely useful and widespread instrument to support decision-making and it can be applied also as a support to Cultural Heritage management and urban management in general. Nevertheless, this particular field has been only

marginally investigated and considerable gaps and unclear aspects exists, which requires and focus the interest on more detailed studies and analysis (Van Oers and Pereira Roders, 2012).

1.1. **Built Cultural Heritage and the Life Cycle Sustainability Assessment approach**

The Life Cycle Assessment methodology has been extensively applied in the building sector for assessing the environmental performance and impact of construction materials and products throughout the entire life cycle of a construction (Ortiz-Rodriguez et al., 2010; Sharma et al., 2011). Generally, the building industry consumes a significant quantity of materials and energy, in order to meet the demands of heating, ventilation, and air conditioning. The priority of the EU Task Force “Sustainable industrial policy, construction and raw materials” (2013) include the screening of national buildings regulations to elaborate requirements for a sustainable use of natural resources, and mapping of skills needs for energy efficiency in building renovation. There is a significant opportunity to reinvigorate the construction sector - hardly hit by the economic crisis - in the area of renovation for energy efficiency and performance. However, a vast majority of existing buildings have been constructed before the introduction of EU legislation on energy efficiency and energy performance requirements in national building codes. Furthermore, the number of existing buildings undergoing extensive renovation is relatively modest. As stated, historical buildings usually do not meet perfectly current standards in terms of energetic management and they have many restrictions in terms of construction techniques and typological and functional features. Nevertheless, they have also many sustainable characteristics: i) energy of realization (embodied energy) had already been spent; ii) saving of material resources has already been provided, since they do not need neither of a new land occupation nor the extraction, production and processing of great amount of materials; iii) historical buildings have morphological and technological features appropriate to environment and climate (Cinieri and Zamperini, 2013b). Moreover, the heritage hand-down value is not quantifiable with a simple life cycle assessment approach, which does not take into account the sociocultural significance of a historical building. Indeed, historical built heritage embodies the character of the local tradition and the identity of places, and it constitutes a reference point for the population. Therefore, through the maximization of permanence and the lengthening of the lifetime of cultural heritage, conservation of material cultural contains in itself issues of social sustainability. The preservation of historic neighbourhoods and social housing should also be accompanied by the protection of the social fabric, in order to avoid a very negative social impact. A proper intervention on existing buildings allows the preservation and perpetuation of the intangible culture heritage, which produced the material evidences of historical buildings, promoting, therefore, also the cultural sustainability of refurbishment (Cinieri & Zamperini, 2013a).

The relationship between conservation and development has long been the focus of studies in Economics of Conservation. It is now widely accepted that sustainable urban development can be achieved by improving the quality of the urban environment through the social, economic and ecological factors, but also through the cultural assets (Fusco Girard, 1993; Fusco Girard and Nijkamp, 1997)

Definitions of Cultural Heritage are found in national legislation, norms and guidelines, as well as in the international doctrine, such as the charters of ICOMOS or the recommendations of UNESCO. In its website, UNESCO states that tangible heritage includes buildings and historic places, monuments, artifacts, etc., which are considered worthy of preservation for the future. These include objects significant to the archaeology, architecture, science or technology of a specific culture. Their preservation demonstrates recognition of the necessity of the past and of the things that tell its story. Preserved objects also validate memories; and the actuality of the object, as opposed to a reproduction or surrogate, draws people in and gives them a literal way of touching the past. In Italy, interventions on architectural heritage (buildings subject to protection according to Italian law - (D.Lgs. 42, 2004) are subject to authorization by the competent bodies and derogations are provided to European performance parameters. However this does not regard most of the traditional preindustrial built heritage, that is not officially declared of cultural interest according to law. For this reason laws often seem to be in contrast with actual moral needs of safeguarding, which are progressively spreading to "new patrimonies" (Cinieri & Zamperini, 2013b). As far as the designation as heritage building is concerned, the reference regulation is still the law n. 357 issued in 1997 that states that in order to be designated as Cultural Heritage, a building has to be of public cultural and aesthetic interest and to be older than 50 years. Nevertheless, this does not automatically enforce restrictions on the construction but every building has to be examined by the local Superintendence or competent authority.

Cultural Heritage can be seen as a complex socio-economic system characterized by different elements interacting with each other, like - for instance - people, companies, public institutions and countries. The interaction among these different stakeholders is non-linear and is very difficult to predict due to the dynamic and stochastic nature of these complex systems. A traditional approach to the assessment and management of cultural heritage is therefore not sufficient to analyse and understand its complexity.

The management of cultural heritage requires continuous conservation and restoration work, involving diverse professionals mainly in technical and scientific activities. They are exposed to different environments, materials of varying degrees of conservation and emissions, posing multiple risks of chemical, physical and/or microbiological nature. In addition, materials and energy are consumed involving both potential environmental impacts and financial resources consumption. A sustainable approach to the processes of cultural heritage restoration and conservation involves the selection of safe materials and methods both in terms of human and environmental health but also a quantification of the benefits deriving from the conservation process. It is therefore necessary to create comprehensive models for Cultural Heritage management in order to fulfil environmental, economic and social sustainability criteria. Life Cycle Sustainability Assessment (LCSA) is often used as a useful tool in decision making in various fields and it might be successfully applied also to buildings and built Cultural Heritage management. The culture of restoration and conservation has been gradually permeated by the scientific method, based on hypotheses and testing, which induced an evolution from empirical "traditional" restoration to a more scientific and technological approach (Iaccarino Idelson, 2011). Pereira Roders (2011) developed a design process for restoration that took into account all the necessary aspects of the process (pre-design, design, construction, use, further interventions, and demolition) and from the earliest stages also considered the reuse or recycling of all the used materials. The restoration process is the methodological moment of recognition of Cultural Heritage in its physical form and in its dual aesthetic and historical instance, for conservation, valorization, and transmission to future generations.Nevertheless, the use of LCA and LCSA applications are practically unknown in the field of cultural heritage. In fact, it is quite complex to assess an historical work of art, an architectural monument, or even a contemporary building. It is necessary to have specific tools to manage a large collection of data (Malmqvist et al., 2011). Moreover, this tool must be adapted to the various decisions made throughout the building life cycle, from building design to restoration, maintenance, and conservation (both historical and contemporary). Again, the building structure is not an independent element but exists in a context in which a variety of stakeholders operates being influenced by different factors in their activities at micro, meso, and macro economy level. Therefore, in this vein, every decision-making process aimed at defining interventions on design, recovery, and/or restoration is characterized by marked complexity due to the need of taking multiple requirements and conditions into account simultaneously (Tupenaite et al., 2011).

1.1. **Life Cycle Sustainability Assessment**

Life Cycle Sustainability Assessment is a holistic approach that allows to list and to quantify the potential impacts and benefits associated to the cultural heritage restoration and conservation activities. The operational tool related to LCSA is known as Life Cycle Management (LCM), a product management system closely related to eco-design. Sometimes the terms LCSA and LCM are used to indicate the same tool. According to Remmen et al. (2007) LCM is a product management system aiming to minimize environmental and socioeconomic burdens associated with an organization's product or product portfolio during its entire life cycle and value chain. LCM can be considered as an extension of the original Life Cycle Assessment (LCA) concept, that includes three different aspects: Environmental Life Cycle Impact Assessment (E-LCIA), Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC). Nevertheless, as stated by Zamagni (2012), the LCSA framework is considered a good starting point for integration of the components of sustainability, but much research needs to be directed toward understanding the mutual relations between the different methods that are most often applied independently of each other.

1.1.1. **Environmental Life Cycle Assessment**

When the LCA concept was developed it originally focused mainly on the environmental aspects (including human health) associated to a product. According to the ISO definition: "Life Cycle Assessment is a standard analytical tool which in its complete version, addresses the environmental aspects and potential environmental impacts (i.e. use of resources and environmental consequences of releases related to the functional unit of a product system) throughout a product`s life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal" (ISO 14040, 2006).

The life cycle assessment goal is then to consider all the stages of a product (or service) life, from the production to the dismissal (or recycling or reuse) as well as all the direct and indirect impacts on the environment, human health or other services. It is thereby essential for the boundaries of the analysed product or system to be clearly defined. The most important LCA practical applications are the analysis of the contribution of the life stages to the overall environmental load and the comparison between products. Under this perspective LCA can be seen as an instrument to prioritize improvements of a product or a process and to support decision making over different alternatives or uses of an environmental resource, providing scientific and as far as possible quantitative answers to these issues. It is not a coincidence that in recent years life cycle thinking has become a key focus in environmental policy making.

LCA is officially standardized by the UNI EN ISO 14040-14043 regulations and is also theorized in several publications and reports, the most important probably being the International Reference Life Cycle Data System (ILCD) Handbook, issued by the European Commission's Joint Research Centre in 2010 as a guidance document. More information on the LCA framework will be provided in chapter 3.1.

1.1.2. **Social Life Cycle Assessment**

The Social LCA approach aims to provide a list and assessment of the social impacts of a product, as complete as possible and over the whole life cycle**.** This is probably the most complex and newest aspect of the life cycle thinking as it tries to measure intangible issues or provide quantitative indicators for conditions that are influenced by various factors. Nevertheless, it is a very important theme of sustainability and as such it drew the interest and efforts of organizations such as the UNEP SETAC Life Cycle Initiative that has published guidelines for the Social life cycle assessment of goods and services, closely related to the standardized environmental LCA approach.

According to the UNEP SETAC Guidelines for S-LCA (2009), the types of Impact categories used will correspond to the goal and scope of the study and represent social issues of interest that will be expressed regarding the stakeholders affected. They may cover health and safety, human rights, working conditions, socio-economic repercussions, cultural heritage and governance. The subcategory indicator results are aggregated into impact category results. The information can be aggregated on one resulting end-category that may be Human Well-being or Fairness of relationships. It should be noted that, for the time being, there are no characterization models between subcategories and impact categories that are generally accepted by

S-LCA practitioners. As a consequence, at present, the causal models in social sciences are generally not well developed.

Social impacts can be seen as consequences of positive or negative pressures on social endpoints (i.e. the well-being of the stakeholders). As far as Cultural Heritage is concerned, value has always been the reason underlying heritage conservation, (The Getty Conservation Institute, 2002). It could be inferred that the higher is the level of well-being deriving from the considered cultural heritage element, the higher is the value associated to it. The stakeholders to be taken into account could be either the whole society or the local community. For the time being, there is a lack of recognized and widely accepted methodologies for the assessment of cultural values, as well as difficulties of comparing the results of economic and cultural assessments (Weidema, 2006). As reported by Finkbeiner et al. (2010) many efforts need to be directed to the standardization of a set of social objectives and indicators that take into account individual needs and societal goals. Currently, the large number of social sustainability indicators identified does not allow direct assignment of social indicators to products or processes. According to Settembre Blundo et al., (2014) one of the most important criticalities of S-LCA is embodied in the need to quantitatively relate the existing indicators to the functional unit of the system.

1.1.3. Life Cycle Costing

Life-cycle Costing (LCC) is a technique used to estimate the total cost of ownership of a project or production system. It allows aggregated and comparative cost assessments to be made over a specific period of time, taking into account relevant economic factors in terms of both initial capital costs and future operational and asset replacement cost. LCC is seen alongside LCA as two of the three pillars in an evaluation of sustainability, with the third, social assessment, still in its infancy (Ciroth et al. 2008). According to the SETAC Working group on LCC, three different types of LCC exist: conventional, environmental and societal LCC.

The conventional LCC is, to a large extent, the historic and current practice, in many governments and firms, and is based on a purely economic evaluation, considering various costs associated with a product that is born directly by a given actor (Ciroth et al.2008). External costs are often neglected and it includes the end-of-life only if paid for by the user. It was originally applied by the US DoD to evaluate the total costs in a procurement contract in the 1930s.

Environmental LCC (E-LCC) accounts for all the costs associated with the life cycle of a product regardless the actors involved and who bares the costs. It includes all the present and future money flows that should be internalized because relevant in a perspective decision-making context. The environmental LCC is not a stand-alone technique, but is seen as a complementary analysis to the environmental life cycle assessment. A complementary life cycle assessment (LCA), with equivalent system boundaries and the same functional unit is required (Ciroth et al.2008). The calculation might not be detailed and is complemented with estimates but it allows to take into account and internalize also the global environmental costs associated to a production or a conservation process and to disaggregate the costs per unit process. The adjective "environmental" refers to the costing analysis being performed consistent with the system boundaries of the environmental analysis, as prescribed by the ISO 14040 series. As compared to the conventional, E-LCC can be seen as a tool for both external communication and certification as well as labelling, while conventional LCC is more likely to be used as an internal tool. (Ciroth et al. 2008).

Environmental LCC can be extended to a societal LCC that can be extremely relevant within a Cultural Heritage context, where the value of Cultural Heritage could counterbalance the restoration costs. As noted by Hunkeler at al. (2006), "environmental LCC includes real costs (i.e., costs somebody is already bearing at the time of the decision) to be internalized in the decision-relevant future (i.e. "monetary external costs"). Societal LCC expands the boundaries further to include the internalization of some nonmonetary impacts (nonmonetary external costs) that could, in the long term, be relevant or monetized (e.g. the societal cost of loss of biodiversity)". According to Ciroth et al. (2008), societal LCC uses an expanded macro-economic system and includes a larger set of costs and also includes, as opposed to conventional and environmental LCC, governments and other public bodies that could be indirectly affected through externalities. The societal LCC includes all of environmental LCC plus additional assessment of further external costs, usually in monetary terms. The previous definitions mention only nonmonetary costs, while they lack in taking into account also possible external benefits. According to Kock et al., (2006) societal-LCC can at times be called CBA-type LCC as it resembles the Cost-Benefit Analysis (CBA) tool.

There is no specific legislation in Europe requiring LCC to be taken into account in procurement procedures, but the Most Economically Advantageous Tender (MEAT) mechanism introduces it as an option in public procurement directives. According to the European Commission website, a number of different guidance papers have been produced in the Member States for use by government departments procuring construction works and services. In the private sector, few investors have commissioned construction works on a LCC basis so far.

1.2. Circular Economy and the Material Circularity Indicator

The Circular Economy concept is usually considered as opposed to a linear economy where goods and product services are associated to wastes. Circular economy should be close-looped, regenerative, waste-free and should run on renewable energy. The concept has been developed during the last six years but the term was coined for the first time in 1990 by Pearce and Turner in their book “Economics of Natural Resources and the Environment” even if its roots date back to the early ‘80s when the concept of sustainable development was introduced. Various elements and business principles have been established in order for companies to adhere to and implement Circular Economy, including business models and disruptive technologies. Circular Economy measurement is also underway in more or less mature states. Created in 2010 with the unique mission to spread the widest possible use of Circular Economy, the Ellen MacArthur Foundation defines the latter as: “an industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models” (Ellen MacArthur Foundation, 2013). In its most comprehensive expression, Circular Economy needs to be implemented at all levels and would thus introduce rapid and deep change that would make collaboration necessary. If government and regions decide to progress through ambitious Circular Economy legislation, private actors would need to adapt in a fairly short time and learn to reshape their organizational systems in order to fit in a wider metabolism based on renewable energy and closed loops. As noted by the CIRAIG Circular Economy review of concepts (2015), it can be questioned whether Circular Economy is indeed, as its name indicates, a revolutionary global economic program (i.e. radically changing how resources are generally allocated within the global community), or a new industrial system focused on deeply changing the way business is conducted, techniques are developed and materials flow. Figure 1 shows an attempt to frame the Circular Economy concept compared with other similar or complementary green and sustainability approaches, within a scope versus concreteness graph.

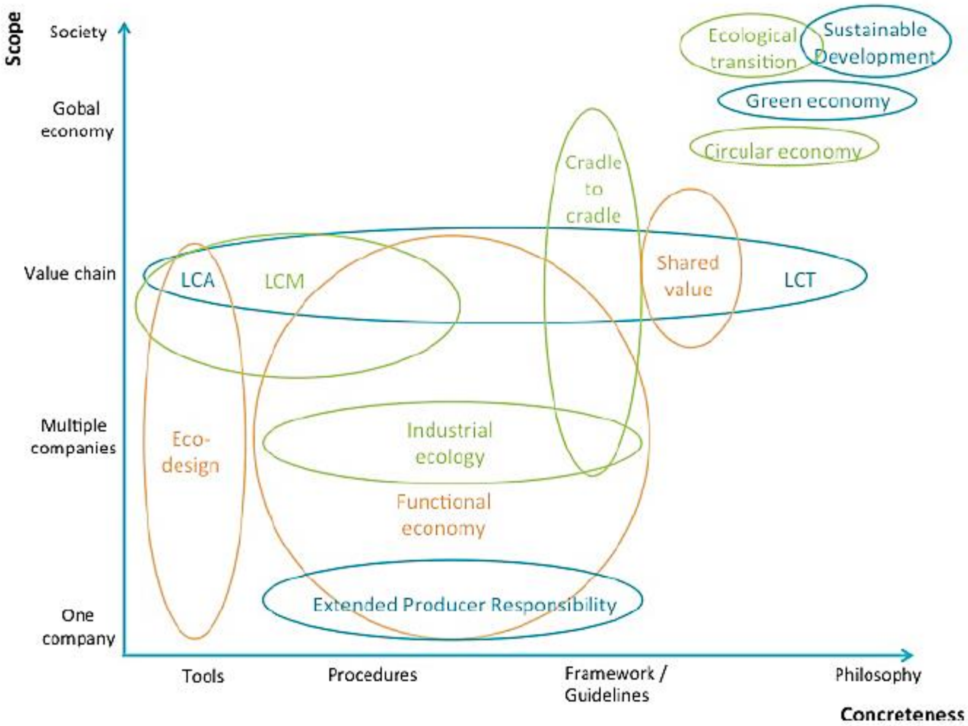


Figure 1. Scope vs concreteness mapping. (From CIRAIG, 2015).

When moving down from a global economy to a value chain perspective circular economy translates into a Life Cycle Thinking (LCT) concept. Life Cycle Thinking can be seen as a mindset or a philosophy that considers the entire life cycle and moves from an individual performance focus (e.g. the single company perspective) to a global one. It is implemented using the Life Cycle Assessment (LCA) instrument or, more widely, the Life Cycle Sustainability Assessment (LCSA) and Life Cycle Management (LCM) approaches, to include also the economic and social aspects.

Circular Economy may indeed embed various components, economic as well as strategic, environmental and perhaps even social, but these need to be better defined and framed.

Nevertheless, the Ellen MacArthur Foundation points out four basic principles of value creation in Circular Economy:

- *'The power of the inner circle'*: a shorter and tighter loop usually results in more savings and potential benefits, because inherent costs such as labor and energy are less important. Thus, more value is retained in the final product because the savings and possible benefits are more abundant than goods produced in longer loops. As an example, a product retains more value after repair and maintenance than by recycling some of its components.

- '*The power of circling longer*': value is created and increases with the frequency a product re-enters a cycle and the length it stays in it.

- *'The power of cascaded use and inbound material or product substitution'*: a cascade loop is created when a product or, more often, a component is used across different product categories. For example, cotton that may be used in a first loop for clothing, then for furniture filling, and ultimately for insulating. Value is created by the difference between the cost (including the embedded costs) of a virgin material and the marginal costs of the material that is brought back into a loop for repurposing.

- '*The power of the pure cycles'*: this value creation principle is mobilized if the end of life of a product has been taken into account during the design phase by ensuring, for example, that the product is easy to take apart and/or is made of non-toxic materials.

In the new concept of CE, recovery and valorization of waste allow reusing materials back into the supply chain, finally decoupling the economic growth from environmental losses (Ghisellini et al., 2016). This issue is confirmed by recent EU documents, which focus on encouraging recycling and recovery strategies all along the lifecycle of a product (EEA, 2016). A growing interest can be also outlined in the US policy looking at the waste management field (Heck, 2006). Furthermore, also emerging economies e such as China - are developing guidelines to support CE strategy by focusing on the national level (Geng et al., 2012).
Although the research about CE has its major contributions only in the last decade, several reviews and general frameworks can be found in the scientific literature. Nevertheless, few studies are focusing on how to measure effectively the "circularity" level of a product, a supply chain or a service. The state of the art about CE shows that, while the concept of CE is being widely explored and several case studies analyze its application in different contexts, the definition of tools and criteria for measuring the level of circularity of products, companies or regions is still lacking (Haas et al., 2015).

Policy intervention through economic incentives and regulatory frameworks, as well as a rise of awareness and skills, is required to guarantee favorable system conditions for this transition. The requirements to be measured can be summed up into five main categories, deducted from a recent European report (EEA, 2016):
a) Reducing input and use of natural resources: the main aim is to reduce the erosion of the natural ecosystem currently caused by linear models. In brief, the objective is to deliver more value from fewer materials. The direct consequence is also the preservation of natural resources, with an efficient use of raw materials, water and energy;
b) Reducing emission levels: this refers to direct as well as indirect emissions;
c) Reducing valuable materials losses: the implementation of closed loop models to recover and recycle products and materials through reverse flows allows preventing waste production, minimizing incineration and landfilling and decreasing energy and material losses;
d) Increasing share of renewable and recyclable resources: the aim is to cut emissions throughout the full material cycle through the use of less raw materials and more sustainable sourcing; another issue is to reach overall less pollution through cleaner material cycles;
e) Increasing the value durability of products: this goal can be reached through the extension of products' lifetime, the adoption of new business models based on use-oriented services (e.g. product leasing and pooling), the re-using of products as well as components, and a high diffusion of material recycling.

Finally, three main fields of intervention of the CE paradigm are currently outlined (Ghisellini et al., 2016): the micro level – referring to single companies or customers-, the meso level - meaning ecoindustrial parks- and the macro level - from cities to nations.

Elia et al. (2016) proposed a taxonomy to classify the different methodologies for measuring the adoption of CE paradigm based on two factors:

- the index-based method typology where the methodology can be based on a single synthetic indicator or on a set of multiple indicators usually divided in several categories;
- the parameter(s) to be measured: four categories have been introduced such as material and energy flow, land use and consumption, and other life cycle based.

According to this classification, Elia et al. (2016) also presented a review of the existing and standardized methodologies that can be used to measure circularity.

Index-based methods focused on material flows

Three techniques have been included in the single indicator category: Water footprint (WF), Material Inputs Per unit of Service (MIPS) and Ecological Rucksack (ER). The WF is an index method applied to measure single-impact information about a product/service, developed in 2002 by Hoekstra and Hung (2002). It indicates potential environmental impacts related to fresh water on the base of a life cycle approach, identifying the total volume of water consumed or polluted over the full supply chain of the good/ service, considering also the current state of the hydrological basin from which the water is provided. The MIPS method allows to measure impacts related to a specific type of material flow (i.e. the material input of a product, a service or a process) based on a cradle-to-cradle approach (Spangenberg et al., 1999): it estimates all the material inputs required for the production, distribution, use, redistribution and disposal of a product/service. Inputs from all the lifecycle phases are referred to the unit of product/service provided. It is usually applied by companies to outline potential savings and environmental impacts, but it can be also applied at more strategic levels. Similarly, the ER is defined as the total sum of material inputs minus the mass of the product: it allows outlining the impact exerted by the goods on the environment. Both methodologies are used to measure the material intensity (i.e. weight of the material in terms of kilograms) requested by a product/service; some authors (Angelakoglou and Gaidajis, 2015; Herva et al., 2011; Spangenberg et al., 1999) suggest to adopt the MIPS calculation when a comparative analysis is requested. These last two methods can be easily applied at the micro level. Two techniques based on multiple indicators have been also included, that is Material Flow Analysis (MFA) and Substance Flow Analysis (SFA). The MFA has been defined as "a systematic assessment of the flows and stocks of materials within a system defined in space and time" (Brunner and Rechberger, 2004). Its main limitations lie in the fact that not all the environmental impacts are explicitly accounted; in addition, the MFA provides information about the quantity of materials used, not about their "quality". The SFA method focuses on estimating the flows and stocks of substances involving a risk for environment and health, through a system defined in space and time (Huang et al., 2012). The rationale is to identify the most hazardous flows in order to elaborate strategies to reduce the related environmental burdens. Unlike the MFA, it focuses on single substances rather than materials and goods. Both for SFA and MFA, their high flexibility allows to easily apply them at the macro, meso and micro level (Herva et al., 2011).

Finally, analyzing methods focused on material flows from a CE perspective, they do not give any information about the impacts related to those material flows, nor about the emissions caused.

Index-based methods focused on energy flows

These methodologies are mainly focused on energy usage, which is an important feature in the CE as defined previously. All methods included in this category Cumulative Energy Demand (CED), Embodied Energy (EE), EMergy Analysis (EMA), EXergy analysis (EXA).are based on a single indicator; The CED is defined as the total amount of energy required to produce a product (or a service) estimated over its whole life cycle: thus, it includes the energy necessary starting from the extraction of raw materials, to manufacturing processes and final disposal (Huijbregts et al., 2006).

The EE index is calculated as the sum of all direct and indirect energy flows necessary to produce a product or a service (Brown and Herendeen, 1996); it is a measure of how much energy is incorporated in the product itself, thus this is a reliable tool to identify inefficiencies due to the energy use (Angelakoglou and Gaidajis, 2015). It is usually indicated as the quantity of non-renewable energy per unit of weight (usually in MJ/ kg).

Differently from the previous methods, the EMA focuses on estimating the total quantity of energy - direct and indirectrequired to produce a product or service estimated in units of only one type of energy, usually the solar energy. Emergy is commonly expressed in solar emergy Joules (seJ); the so called solar transformity factors (expressed in seJ/J) are used to perform such estimations. Thus, this method allows assessing the quantity as well as the quality of the energy required for producing a product/service. EXA is based on the estimation of a single indicator defined as "the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment" (Rosen and Dincer, 2001). Like the EMA, exergy is an indicator of energy quality, not only quantity.

The methods based on energy flow can be suitable especially for energy intensive processes, or in general, when a focus on energy efficiency and renewable sources is needed. Nevertheless, they do not include other environmental impacts (e.g. emissions in air, soil and water, material losses, resource depletion).

Index-based methods focused on land use and consumption

The most widespread methods included in this category are: the Ecological Footprint (EF), the Sustainable Process Index (SPI) and the Dissipation Area Index (DAI). The EF methodology has been developed in the nineties (Rees, 1992): it is a single based index estimating the biological capacity of the planet consumed by a specific human activity or population. In detail, the EF provides a measure of the total amount of productive land required-including demand for food, crops, timber, energy, space for infrastructure and the area needed to absorb carbon emissions generated. It is expressed in global hectares (gha).

Although the EF is a single indicator, it indirectly provides an assessment about the combination of different environmental impacts, such as land-use change, fish consumption, CO_2 emissions. A standardized methodology. Similarly to EF, the SPI methods aims to assess the area necessary to support such human activities in all their life cycle: in detail, it measures the total area needed to embed a product/service, in a sustainable way, into the biosphere (Narodoslawsky and Krotscheck, 1995). Its calculation is based on the mass and energy flows estimated in the reference period; thus, it is space and time dependent. Finally, the DAI derives from the SPI estimation: it represents the total area needed to absorb the output flows of a specific process.

All the methodologies included in this category aim to measure the human pressure on the biosphere caused by process/product/ service through a single index. This feature could represents an advantage for the results communication process, but it represents a limit when a more comprehensive analysis is required.

Other life-cycle analysis methods: single and multiple indicator based impact assessment

The last category includes more generalist index methods: two belong to the single indicator category - Carbon footprint (CF) and Ecosystem Damage Potential (EDP) and three belong to the multiple indicator one, that is Life cycle assessment (LCA), Environmental Performance Strategy Map (EPSM) and Sustainable Environmental Performance Indicator (SEPI). The CF is a well known environmental performance indicator measuring the impact of human activities on global climate, expressed as GreenHouse Gases (GHG) emissions generated by a system, usually assessed and expressed as carbon dioxide equivalent (CO2eq), considering their specific Global Warming Potential (GWP). CF estimation is carried out on a life cycle basis. Several standards have been published to support the CF estimation: one among the others is the GHG protocol published by the World Resources Institute (WRI and WBCSD, 2011). The EDP has been recently developed by the Swiss Federal Institute of Technology to evaluate the impacts on ecosystem due to land use and transformation. It includes several damage functions and characterization factors for land use types. Differently from the CF method, the EDP is usually used to communicate results to an expert audience, as its fully comprehension requires high technical skills. The EPSM is a graphical representation that integrates five footprints (water, carbon, energy, emissions and work environment, which is the number of reported lost days of work per weight unit of product) with a transversal cost-dimension. The objective of the EPSM is to provide a single composed indicator. For each footprint, a maximum target is defined and the value is expressed as a percentage of this target. Results are mapped on a spider diagram, while the cost is considered as the second dimension: it represents the height of the pyramid that has the spider diagram as a base. The volume of the pyramid represents the overall impact and it is called Sustainable Environmental Performance Indicator (SEPI). The weakness of the EPMS is the lack of standardization for some of its components (De Benedetto and Klemes, 2009).

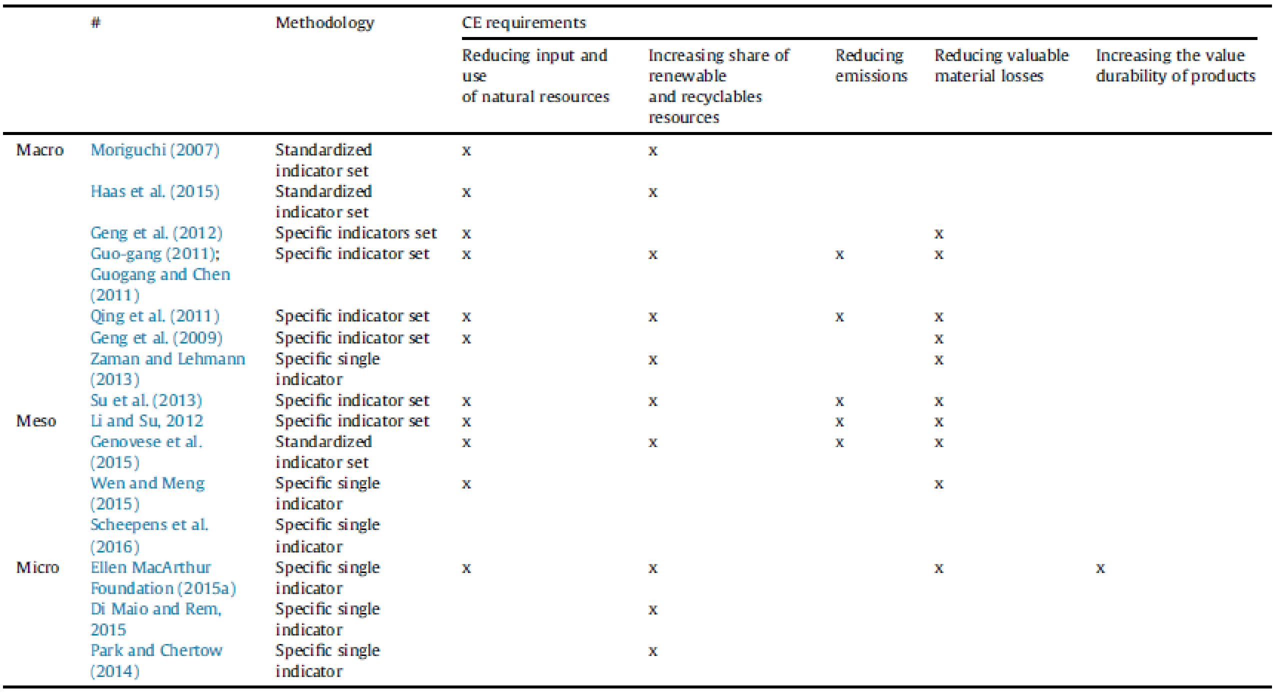
Elia et al. (2016) reviewed the existing literature about index methods used to assess CE strategies among the works published in the last 10 years, selecting only the ones clearly focusing on index based methodologies or sets of indicators to assess the performance of CE strategies. They considered a final total number of 16 articles, categorized firstly according to the field of interventions of the CE paradigm.

At the macro level, several authors adopted the Material Flow Accounting (MFA) or derived indicators to measure the adoption of CE paradigm at the national level. Moriguchi (2007) discussed experiences of the adoption of MFA models from the Japanese national policy. Haas et al. (2015) proposed a quantitative analysis based on the Economy-Wide MFA (EW-MFA) model to assess the circularity level of the European Union referred to 2005. Several studies adopted index methods defined by legislative and/ or technical organizations. Chinese authors have recently published studies based on a specific set of indicators to measure the CE adoption in their country. Geng et al. (2012) discussed benefits and challenges due to the adoption of the so-called “Chinese national CE indicator system”, developed by the National Development and Reform Commission (NDRC). This analysis has been recently integrated in Su et al. (2013) by adding other four categories of indicators, as proposed by the Chinese Ministry of Environmental Protection. Guo-gang (2011), Guogang and Chen (2011) and Qing et al. (2011) proposed an index method for assessing the adoption of CE at the regional level.

Focusing on the city level, Geng et al. (2009) proposed an index method to evaluate the progresses of a CE strategy applied in the city of Dalian (China), while Zaman and Lehmann (2013) adopted the so-called “circular city metabolism” measured trough a “zero-waste index, based on how circular is the waste management process in a city, to compare the performance of three cities worldwide.

At the meso level, recent studies proposed different index methods to measure the CE paradigm level of adoption in specific industrial sectors. Li and Su (2012) proposed a five categories index method, defined as economic development, resources exploiting, pollution reducing, ecological efficiency and developmental potential - to assess the circularity level of Chinese chemical enterprises. Wen and Meng (2015) focused on evaluating the contribution of adopting industrial symbiosis to support CE in industrial parks: the authors proposed a Resource Productivity (RP) indicator - derived from the Substance Flow Analysis (SFA) approach - for assessing the CE paradigm level of adoption characterizing the Chinese printed circuit boards industry. Differently, Genovese et al. (2015) adopted a standardized index method - i.e. an hybrid LCA model combining traditional LCA with an environmental input-output analysis - to compare performances of circular production systems in two process industries, i.e. food and chemical. Scheepens et al. (2016) applied the LCA Eco-cost and Value Ratio (EVR) model as a single indicator, to assess the level of CE adoption in a regional water recreation park.

At the micro level, the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015a) recently proposed an index, called Material Circularity Indicator (MCI), to measure how restorative flows are maximized and linear flows minimized, considering also the length and intensity of the product use. Di Maio and Rem (2015) introduced a single index to measure the circularity level of a product, i.e. the Circular Economy Index (CEI) defined as the ratio between the material value obtained from recycled products and the one entering the recycling facility. Park and Chertow (2014) proposed a single indicator characterizing each material defined as Reuse Potential Indicator (RPI), which indicates how much a material is “resourcelike” rather than “waste-like” according to the current available technologies.



	#	Methodology	CE requirements				
			Reducing input and use of natural resources	Increasing share of renewable and recyclables resources	Reducing emissions	Reducing valuable material losses	Increasing the value durability of products
Macro	Moriguchi (2007)	Standardized indicator set	x	x			
	Haas et al. (2015)	Standardized indicator set	x	x			
	Geng et al. (2012)	Specific indicators set	x			x	
	Guo-gang (2011); Guogang and Chen (2011)	Specific indicator set	x	x	x	x	
	Qing et al. (2011)	Specific indicator set	x	x	x	x	
	Geng et al. (2009)	Specific indicator set	x			x	
	Zaman and Lehmann (2013)	Specific single indicator		x		x	
	Su et al. (2013)	Specific indicator set	x	x	x	x	
Meso	Li and Su, 2012	Specific indicator set	x		x	x	
	Genovese et al. (2015)	Standardized indicator set	x	x	x	x	
	Wen and Meng (2015)	Specific single indicator	x			x	
	Scheepens et al. (2016)	Specific single indicator					
Micro	Ellen MacArthur Foundation (2015a)	Specific single indicator	x	x		x	x
	Di Maio and Rem, 2015	Specific single indicator		x			
	Park and Chertow (2014)	Specific single indicator		x			

Table 1. Cicular Economy measurments methods. Literature review and critical analysis. (From Elia et al., 2016).

By focusing on studies on the micro level, all studies adopt not standardized single index methods to measure performances of recycling, reuse and flow circularity. Thus, these indicators are all linked to two particular requirements of CE, i.e. the use of recyclable resources and the input of natural resources. As shown in Table 1 only the Material Circularity Indicator proposed by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015a) shows an attempt to include in the analysis the loss of materials and the product durability.

Ghisellini et al. 2015 performed a literature mining of CE studies, electing them according to several integrated criteria: (1) chronological order, (2) topics of interest (circular economy origins, principles, implementation at different scales (micro, e.g. company or consumerlevel; meso, e.g. eco-industrial parks level; macro, e.g. city, province, region, nation), (3) comparison to present economic growth and alternative patterns (steady state economy and economic degrowth), (4) problems and challenges.
A further selection based on the content of abstracts, weighting the representativeness also on the basis of the authors' names (by excluding papers with similar content) and geographical area, led to the election of 155 most representative articles that were grouped according to the different topics of interest. Figure 2 provides a snapshot of the different groups of topics, focusing first on two conceptual groups (CE Models and CE principles) and then on how these concepts are investigated across three main “scales” (micro: single processes; meso: eco-industrial parks; and macro: local, regional and national economies), (Ghisellini et al., 2015).

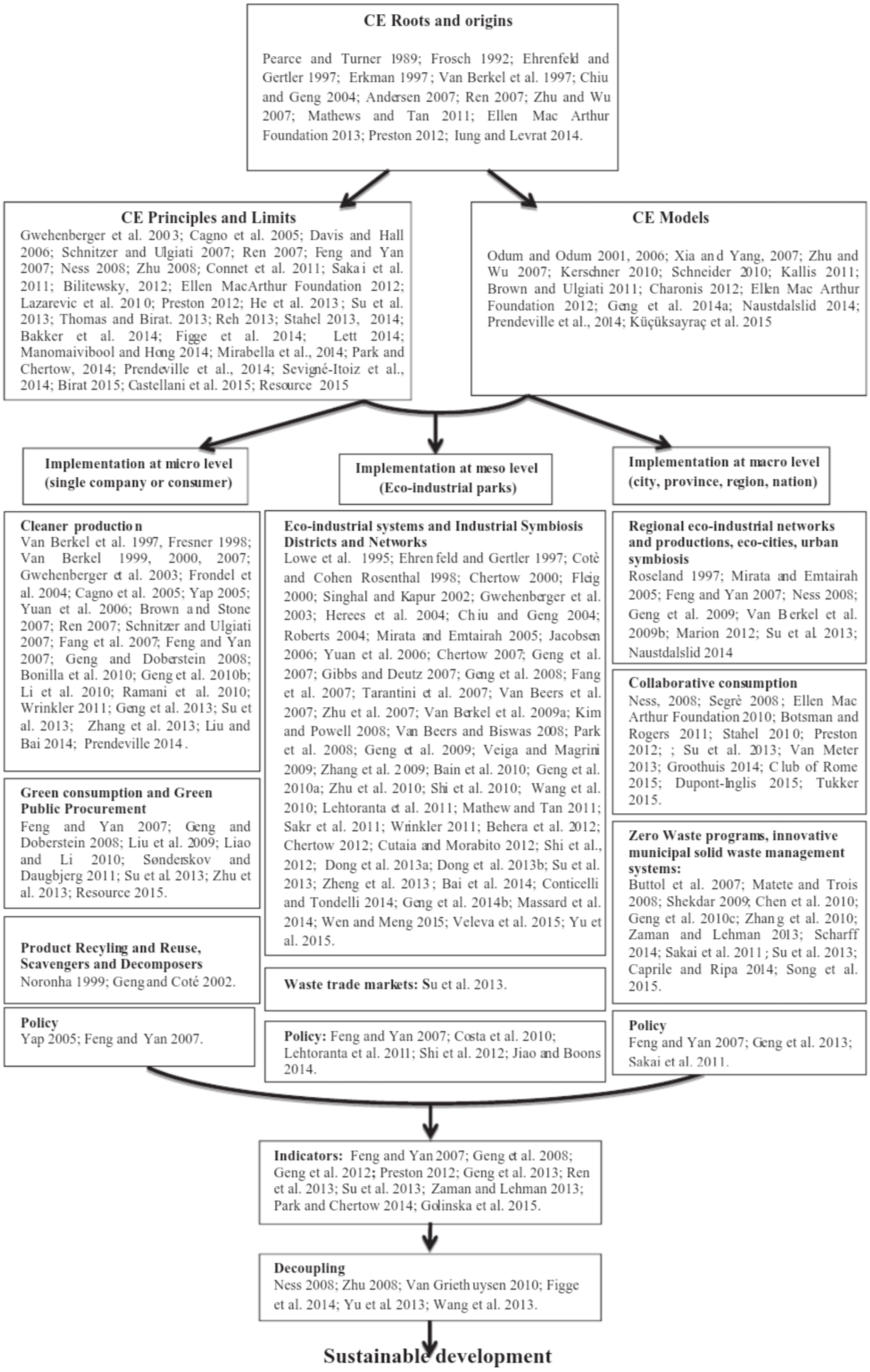


Figure 2. Classification of studies rewieved by Ghisellini et al., (2015) according to the different subjects and categories converging to Circular Economy. (From Ghisellini et al., 2015).

In this quiet intricate and yet not completely picture, it might be helpful to focus on a more restricted application area (micro scale) and verify how the Circular Economy concept can be implemented and assessed in the considered field of interest. When considering the construction field, in particular, it would be interesting to analyze if the demolition of an old building and the subsequent construction of a new one would bear less life cycle impacts compared to the restoration of the old building. The new building would probably be more efficient during the operational phase (due to less energy consumed) but the dismissal of the old materials and the construction activities would cause a considerable impacts as well. The answer to this issue is probably case specific, as a considerable amount of variables would be part of the system boundaries. But as far as CH buildings are concerned, the demolition is not taken into account due to the associated loss of the cultural value: the main point to consider is then which solutions could and should be implemented in order to diminish the energy loss during the operational phase and which materials and restoration interventions are associated to less wastes, which translates into lower impacts. The conservation intervention could be considered a product life extension, in line with the circular economy approach. Moreover, a complementary single indicator to measure circularity be associated to the Life Cycle Sustainability Assessment results. The above mentioned Material Circularity Indicator proposed by the Ellen MacArthur Foundation seems to be the most suitable one, as it relates to the micro economic level and it focuses on material restoration rate (but also proposes complementary material risk indicators). This indicator might be particularly useful in the construction field, where a wide range of materials with different pro and cons is available. Moreover, within the micro level indicators, it is the only one that considers the reduced input and use of natural resources, the reduction of valuable material losses and the durability of the products and material used.

The Material Circularity Indicator

As previously stated, the MCI focuses on material flow both at product and company level. It is based on four principles:

- Using feedstock from reused or recycled sources
- Reusing components or recycling materials after the use of the products
- Keeping products in use longer (e.g. by reuse or redistribution)
- Making more intensive use of products (e.g. via service performance models)

One-hundred percent efficiency is considered when a material is reused, while different efficiency percentages are associated to different recycling processes.

MCI provides an indication of how much a product circulates but it does not take into account the type of materials involved. Moreover it does not provide information on other impacts of the product. For this reason, as recommended also by the Ellen MacArthur Foundation, it should be complementary with other indicators. Complementary indicators may indeed be derived from a LCA approach. “As circular economy is also about creating and retaining value from products and materials, this methodology also provides guidance on assessing the profitability impact of moving to more circular business models” (Ellen MacArthur Foundation, 2015a).

The MCI for a product measures the extent to which linear flow has been minimized and restorative flow maximized for its component materials, and how long and intensively it is used compared to a similar industry-average product. The MCI can have values that go from 0 to 1. It equals to 0 when a product is manufactured using only virgin feedstock and ends up in a landfill, which makes it a fully linear product. It equals to 1 when the considered product is fully circular, which means any product that contains no virgin feedstock, is completely collected for recycling or component reuse (and the recycling efficiency is 100%).

Two different approaches are possible when calculating a MCI:

- A **whole product approach** is not differentiating between the different components and materials of a product.

- A **comprehensive approach** considers a breakdown of components and materials.

According to the Ellen MacArthur Foundation, Granta Design and Life methodology (2015),The MCI of a product (whole product approach) can be calculated using the following formula:

$$MCI^*_P = 1 - LFI \cdot F(X) \tag{1.3.1}$$

Where:

LFI stands for Linear Flow Index

F(X) is a function of the Utility X

The Utility has two components, one accounting for the lenght of the product's use phase and another for the intensity of use. In terms more familiar to the LCA practitioners, the lenght of the product use phase might be defined as the life-span and the intensity of use as the functional unit, both normalized according to the industry average. The Utility formula is :

$$X = \left(\frac{L}{L_{av}}\right) \cdot \left(\frac{U}{U_{av}}\right) \tag{1.3.2}$$

Where:

L is the Lifetime

L_{av} is the industry average lifetime

U is the number of functional unit achieved during the use of the product (on average)

U_{av} is the industry average

The function F is then calculated as:

$$F(X) = \frac{0.9}{X} \tag{1.3.3}$$

The reason of this formula will be explained once analyzed the second component of the MCI calculation, the Linear Flow Index. The LFI measures the proportion of material flowing in a linear fashion, i.e. sourced from virgin materials and ending up as unrecoverable waste.

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \tag{1.3.4}$$

In the above LFI formula, the numerator corresponds to the amount of material flowing in a linear fashion, while the denominator represents the total mass flow (the amount of material flowing in a linear fashion plus the amount of material flowing in a restorative way). Indeed:

V is the Virgin feedstock

W is the overall amount of unrecoverable waste

M is the mass of the finished product

W_f is the waste generated to produce any recycled content used as a feedstock

W_c is the waste generated in the recycling process

In calculating the overall mount of unrecoverable waste W, simply adding and together W_f and W_c could result in double counting some or all the waste generated during the recycling processes. In order to avoid double counting, a 50:50 approach is used, to assign 50% of Wf to the product(s) from which the recycled feedstock came from and 50% of Wc to the product that will use the material which is collected and recycled. Hence, the overall amount of unrecoverable waste is given by the formula:

$$W = W_0 + \frac{W_F + W_C}{2} \qquad (1.3.5)$$

W_0 is the unrecoverable waste that ends up in a landfill or is used for energy recovery.

In order to ensure that $0 \leq LFI \leq 1$ and that LFI still represents the right proportion when the efficiency of the recycling process(es) is lower than 1, the term $W_f - W_c/2$ needs to be included in the denomination of the equation. This is necessary because of the following reasons :

- owing the 50 :50 approach, half of W_c is neither part of the linear flow nor the restorative flow, as it is not assigned to the product being recycled but to a different product that will use the recycled material as feedstock. Hence $W_c/2$ is not part of the total mass flow and needs to be subtracted from 2M.
- W_f is not part of the mass M of the product but is needed additionally to create the recycled feedstock and is therefore part of the total mass flow. Again, because of the 50:50 approach, the actual amount that needs to be added is $W_f/2$.

The formulas used to calculate the virgin feedstock (V_f), the unrecoverable waste (W_0), the quantity of waste generated in the recycling process (W_c) and the waste generated to produce any recycled content used as a feedstock (W_f) are hereby reported:

$$V = M(1 - F_R - F_U) \qquad (1.3.6)$$

Where :

F_r is the fraction of feedstock derived from the recycled sources

F_u is the fraction of feedstock derived from the reused sources

$$W_0 = M(1 - C_R - C_U) \qquad (1.3.7)$$

Where :

C_r is the fraction of the mass of the product being collected for recycling

C_u is the fraction of the mass of the product going into component reuse

$$W_0 = M(1 - C_R - C_U \qquad (1.3.8)$$

Where :

E_c is the efficiency of the recycling process

$$W_F = M\frac{(1 - E_F)F_R}{E_F}, \qquad (1.3.9)$$

Where :

E_f is the efficiency of the recycling process used to produce recycled feedstock

W_f is the quantity that enters the system ; for this reason E_f is also in the denominator (while the other waste quantities are leaving the system).

The derivation of the LCI equation is then easily explained when $E_c=E_f=1$. This implies $Wc=Wf=0$ and $LFI=V+W/2M$. In this case, $0 \leq V \leq M$, $0 \leq W \leq M$ and the total mass flow is equal to 2M. So the maximum value of 1 for LCI occurs when V and W are both equal to M, that is, when the is no recycled (or reused) content and 100% collection for recycling (or reuse).

The utility function is chosen in such a way that improvements of the utility of a product (e.g. by using it for a longer time) have the same impact on its MCI as a reuse of components leading to the same amount of reduction of virgin material and unrecoverable waste in a given period of time. This means that decreasing the linear flow by a constant factor c should have the same impact as increasing the utility by a factor c. The function F should hence have the form a/x for some constant a. Setting a=0.9 ensures that the MCI takes, by convention, the value 0.1 for a fully linear product (i.e. LFI=1) whose utility equals the industry average (i.e. x=1). If the utility of a product is lower than the industry average (i.e. x<1), this decreases the MCI. This means that, for a product with LFI=1 and x<1, the MCI will be smaller than 0.1 and quickly approaching to zero. This allows the MCI to differentiate between a fully linear product whose values for lifespan and functional units are equal to an industry average product of similar type and a fully linear product with a shorter lifespan or less efficient functional unit than the industry average. The effects of the chosen product utility function on the MCI values are shown graphically in Figure 2.

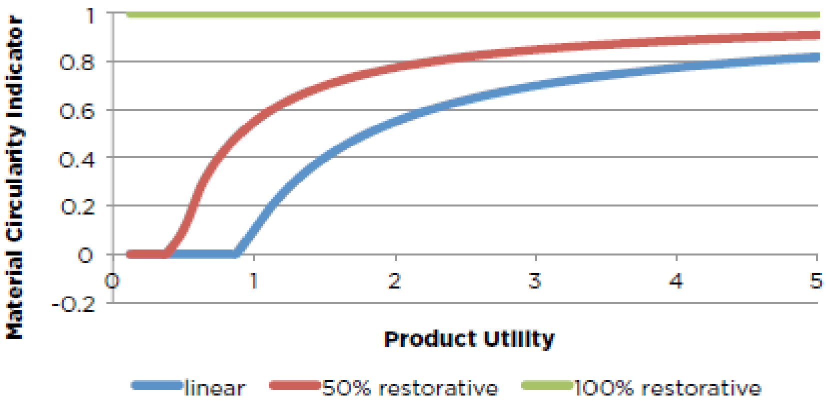


Figure 3. Product Utility effect on the Material Circularity Indicator. (From Ellen MacArthur Foundation, 2015).

In case of a product produced using a certain number of components, the comprehensive approach can be adopted and the MCI can be built up summing over each part or material x when calculating the virgin feedstock, the waste components and the LFI. The final MCI formula remains unvaried. When analyzing a whole restoration process, the same approach could be used, adding up every material employed in the construction site.

One last important aspect to underline is that the value of MCI_p^* could be negative for products with mainly linear flows (i.e. $LFI \approx 1$) and an utility lower than an average product (i.e. $x<1$). In order to avoid this issue the MCI is defined as:

$$MCI_p = \max(0, MCI^*_p) \tag{1.3.10}$$

This means that two “very linear” products cannot be compared properly to each other, as they both might get an MCI=0. However, as stated by the Ellen MacArthur Foundation (2015), the MCI methodology is not designed for this kind of products, which should eliminate this particular approach problems. Moreover, as previously stated, some complementary indicators are necessary to be associated to the MCI. LCA in particular allows to overcome some stated limitations of the MCI methodology. For instance, as the indicator does not explicitly favour closed loops, (for example, the material recovered for recycling does not need to return to the original manufacturer), LCA consider the burdens of transportation. When using the MCI indicator it is assumed that the mass of the product does not chane from the manufacture to the end of use, while LCA takes into account material losses. Last but not least, the scarcity and uniqueness of the materials used is not considered by the MCI method, nor, to be true in the majority of the LCA impact methods. At the same time, the LCA related approaches of Life Cycle costing and Social LCA might take this aspect into account, embedded into the price or explicited within sociocultural indicators.

2. Aim of the study

This study aims to apply the concept of Life Cycle Sustainablity Assessment and Management to Cultural Heritage restoration and conservation. To our knowledge, this field has been only marginally explored with this particular approach. Pereira Roders and van Oers (2011) pointed out that Cultural Heritage Management is a relatively young field of research can be considered as being at an earlier stage of development than other related studies, such as the architectural conservation field (Van Oers and Pereira Roders, 2012). If LCA has been extensively applied in the building sector for assessing the environmental performance and impact of construction materials and products throughout the entire life cycle of a construction (Ortiz-Rodrıguez et al., 2010; Sharma et al., 2011), the use of LCA is practically unknown in the field of cultural heritage (Settembre Blundo et al., 2014). The modern concept of conservative restoration of monuments dates back to 1794, when the French National Convention issued a decree for the conservation of monuments (Sette, 1996). In the following decades and centuries, the culture of restoration and conservation was gradually permeated by the scientific method, based on hypotheses and testing, which induced an evolution from empirical “traditional” restoration to a more scientific and technological approach (Iaccarino Idelson, 2011). The so-called “stylistic” restoration approach was proposed, theorized, and practiced in France by E.Viollet-le-Duc in the mid-nineteenth century. It contrasted with the earlier conservative approach as it aimed at recovering the formal values of the “era and area” of origin of the monument (Hearn, 1990) while the “stylistic” restoration completely ignored the passage of time and, therefore, the different historical and artistic works that may stratify the artefact to search for an ideal “stylistic unit” (Lamberini, 1986). Finally, modern architectural restoration can be traced back to the approach known as“scientific”, based on the awareness that a formal knowledge of what is being restored is necessary before starting conservation. The study of the monument is therefore focused on a reconstruction of its historical chronology (Boito, 1883). The leading theorist of restoration in the twentieth century was Cesare Brandi, who postulated a critical view based on recognition and respect for cultural heritage in terms of both historical and aesthetic authenticity (Brandi, 1977).This led to a restraint in reconstructive activity with an emphasis on conservation based on “preventive” restoration. More recently Pereira Roders (2007) developed a design process for restoration which introduced the concept of the life cycle of historical buildings, taking into account the pre-design, design, construction, use, further interventions, and demolition aspects and considering the reuse or recycling of all the materials employed, from the early stages of the design process.

Applying the LCSA approach to tangible Cultural Heritage Management allows to create a decision-making instrument tailor made for built CH, in order to implement the recent design process for restoration, providing quantitative outputs as well. As a consequence, decision makers and managers could possibily opt for the most suitable solution from a sustainable and circular perspective. On the one side, the LCSA approach ensures to maintain interdisciplinarity, a mandatory requirement for CH related investigations. On the other side, it fulfils the need for one single deliverable unit decipherable by all the parties involved and by non-expert decision makers.

The scope is also to present the results so that all the singular aspects can be quantified separately (purely environmental, direct and indirect costs of the different phase or scenarios, cultural aspects) but also aggregated, using a common monetary unit, similarly to a Cost- Benefit Analysis (CBA). CBA is an economic tool for determining whether the benefit of an investment or a policy outweights its cost. The tool aims at expressing all positive and negative effects of an activity in a common unit, namely money, from a social, as opposed to a firm’s point of view. Thus, in a perfect market, costs and benefits would indicate to any decision-maker every relevant information for economic welfare (Wrisberg et al., 2002). This allows evaluating the eco-efficiency and efficacy of the considered solution(s).

In order to present the attempt and progress on reaching the abovementioned targets, two case studies are investigated:

- The restoration proposal of the San Felice colonnade within the San Felice complex in Pavia;
- The conservation and requalification process of the Buccola pavilion within the San Lazzaro compound in Reggio Emilia.

The first study is based on hypotheses and assumptions and should be interpreted as an illustration of how LCSA can represent a fundamental tool in order to evaluate the feasibility and sustainability of a restoration project. In addition - as three restoration techniques are analysed - it also allows to compare the impacts, costs and social issues associated to different column restoration interventions.

The second study is based on an actual restoration process and represents an *a posteriori* (ex post) analysis: the results of the analysis can be used as a support assessment tool for future restoration projects. Moreover it is important to present an example based on real data from a construction site that take into account the changes and variation that often occur compared to the original project.

Furthermore, it is important to note that - as far as cultural heritage is concerned – there are no guidelines suggesting the proper impact categories to take into account. If numerous examples of LCA performed on products of the building sector have been produced, its application to cultural heritage restoration is relatively new. Moreover, very few studies take into account also the social value and sustainability of the restoration process - as required under a Life Cycle Management (LCM) perspective. The two case studies considered could then represent a contribution to the process of selection and/or creation of indicators and related impact categories to be used in CH-LCM. In particular, social and cultural indicators specific for cultural heritage will be created as well as a methodology to achieve a monetization of those indicators that can be applied in the life cycle costing analysis.

Last but not least, the colonnade and the pavilion differ in two fundamental aspects:

- they date back to different historical periods: this aspect is interesting when performing the S-LCA analysis as different values for the social and cultural indicator should be calculated;
- the pavilion is a closed building while the colonnade is simply an architectural element: this allows to use two different approaches for the definition of the system's boundaries and functional unit. For the pavilion, the life cycle of all the elements of the building will be taken into account, while for the colonnade the life cycle will account only for the materials associated to the restoration process and the previously existing elements will not be considered. Also, an energy balance calculation will be performed to evaluate the energy saving associated to the Buccola building after the restoration process.

As the restoration project of the Buccola pavilion is not recent (it dates back to 2007), few attention has been committed to sustainable materials and solutions: for this reason and due to the fact that the operational phase of a building is usually associated to the greatest life cycle impacts it is interesting to investigate the impact of the hypothetical installation and use of a renewable energy technology. Not all the new technologies can be used within cultural heritage buildings as they are under the superintendence authority that wouldn't allow visual or deep structural alterations. This is why the technology choice fell on building integrated photovoltaic glasses. The Buccola pavilion is characterized by a large number of windows, which makes it particularly suitable for this solution. In addition, also the LCA of the production of this relatively new photovoltaic technology might be stimulating on its own. A sensitivity analysis is therefore performed using a Building Integrated Photovoltaic (BIPV) solar cell, in order to calculate the energy savings (and consequent benefits) that could be obtained during the operational phase of the university building. The particular BIPV solar cell chosen was the dye synthetized TIFAIN tile: the original data were taken from Cardani Morando (2015) and adapted to be implemented in the Buccola pavilion case study.

To sum up, the particular features of the two chosen case studies allow investigating and comparing different aspects and viewpoints of the newborn field of Life Cycle Management of Cultural Heritage and the proposed approach allows providing quantitative and complementary informations that can, eventually, be integrated.

3. *Method description*

The two studies are undertaken using the software SimaPro version 8.0.5 developed by Prè Consultants. The software includes and allows to combine different databases and impact assessment methods. When necessary, the databases can be updated or improved with personal information and the impact methods can be modified. The database used is Ecoinvent, released by the ecoinvent Association, previously known as the ecoinvent Centre, the Swiss Centre for Life Cycle Inventories.

Before starting with the actual case studies analysis, it is useful to describe the conceptual framework used in LCM that originates from the LCA approach and is valid both for E-LCA and S-LCA.

3.1. **LCA framework**

According to the ISO standard 14044 the LCA consists of four phases, shown in Figure 3.

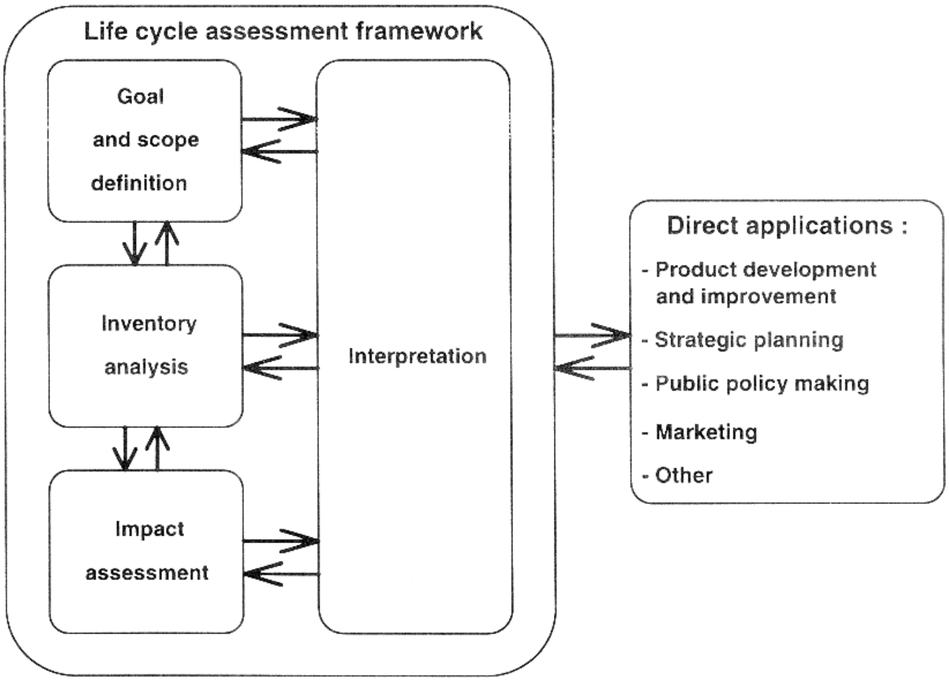


Figure 4. LCA phases (from ISO, International Organization for Standardisation, 2006).

- ***Goal and Scope of the study***

In this phase the reasons for performing the LCA are defined and the product or service considered is precisely described. This will influence some further aspects, like the database and the impact assessment method choice as well as the interpretation of the results. For example, ISO 14042 suggests that weighting should be avoided in case of a public comparison between two products. If two or more services are to be compared, it is essential to choose and define a suitable functional unit. It is not always an easy task to define the boundaries of a system and the aspects that reflect its main function but it is of fundamental importance, especially when comparing two different products.

- ***Life Cycle Inventory (LCI)***

The Life Cycle Inventory phase is basically a data collection phase that includes background and foreground data. Foreground data are the data of the system itself and therefore need to be precise while background data will not drastically influence the result and can be rougher. Data are collected through questionnaires and databases. Databases include also capital goods (trucks, injection moulding machines, infrastructures, etc.) and are very useful to provide background data or emissions associated to background data. A wide (and constantly increasing) number of databases exist and many are included in SimaPro as libraries. For example Ecoinvent (Swiss centre of life cycle inventory) contains more than 4000 processes, is very well documented and includes capital goods and uncertainty data; ELCD, released by EC-JCR (European Commission-Joint Research Centre), is produced by voluntary inputs from the industry sector and contains data on materials, energy carriers, transport and waste management and the US LCI, released by NREL (National Renewable Energy Laboratory), contains a great number of processes like Ecoinvent and has a high transparency.

LCI is certainly a fundamental step of LCA that will affect its overall results but, on the other hand, it represents simply a list of input from and output to nature. From this (often long and technical) list it is difficult to draw any conclusion or evaluation. This leads to the application of the Impact Assessment phase of LCA.

- ***Life Cycle Impact Assessment (LCIA)***

The ISO 14040 standard defines a LCA as "*a compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system through its life cycle*". From this definition it is clear that impact assessment is an integral part of LCA.

LCIA is defined as the phase in LCA aimed at understanding and evaluating the magnitude and the significance of the potential environmental impacts of a product system (PRè Consultants, 2010). Different steps are involved in the evaluation of the potential impacts: in order to obtain the final output of the assessment - the endpoint that is presented to the final user – one are several midpoints are chosen between the LCI results and the endpoint. Different impact methods use different midpoints and endpoints. The most common endpoints are Impact categories. A single impact category is characterized by a certain number of impact indicators that represent the midpoints of our assessment. In general, indicators close to the inventory results have lower uncertainty because only a small part of the environmental mechanism needs to be modelled but they are more difficult to interpret while indicators close to the endpoint have higher uncertainty but can be easily understood by, for example, decision makers. Endpoints can also be issues of environmental concern, like human health, extinction of species, availability of resources for future generations etc. that can help in the selection of impact categories as long as the environmental model that links the impact category to the endpoint is clearly described.

SimaPro features different impact assessment methods: each method contains a different combination of impact categories and indicators that in certain cases can be aggregated into a single score. The preference for one method should be established based on the scope of the research (significant impact categories) and on the desired level of aggregation (single scores or detailed scores) which -in turn- depends on the final audience of the LCA results.

The basic structure of impact assessment methods in SimaPro is:

1. Classification
2. Characterization
3. Damage assessment (optional)
4. Normalization

5. Weighting

Classification

As previously mentioned, the results obtained from a LCI are a list of substances emitted to the environment that contribute to one or more impact categories. The classification step involves a simple allocation into categories of the impacts caused by the inventory substances. A single substance can contribute to more than one impact category.

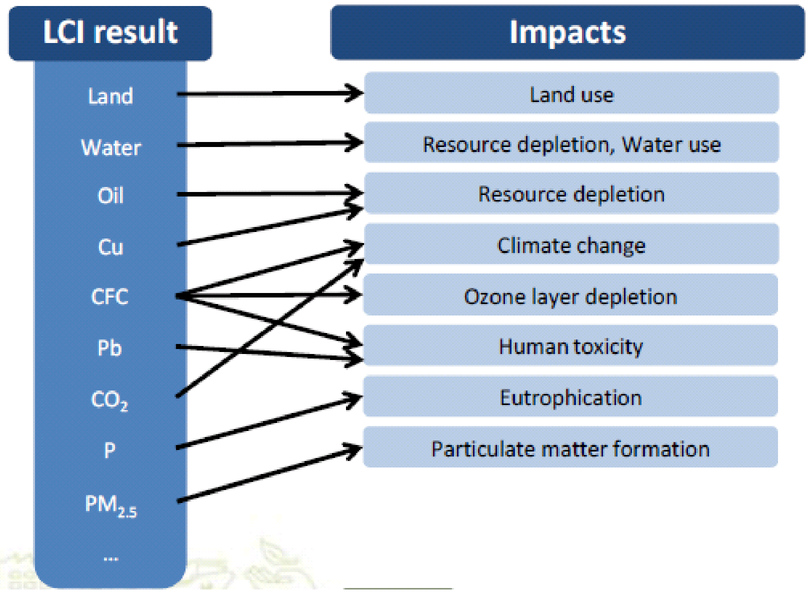


Figure 5. Example of classification into impact categories (from PRè Consultants).

Characterization

The quantities of the LCI substances are multiplied by a characterization factor that expresses the relative contribution of a particular substance to the considered impact category. For example, according to the Global Warming Potential Factors reported by the Intergovernmental Panel on Climate Change (IPCC) 1 Kg of methane is equivalent to 25 kg of CO2 (IPCC,2007) as CH4 is considered 25 times stronger than CO2 as a greenhouse gas. Therefore, the characterization factors used for carbon dioxide and methane in the impact category Climate Change are 1 and 25 respectively. This means the release of 1 kg methane causes the same amount of climate change as 25 kg CO2. The total results of a specific impact category are called Impact category indicators.

Damage assessment

In the damage assessment step, Impact category indicators are combined into a Damage category (e.g. Human Health or Ecosystem Quality). Impact Category Indicators with a common unit can be added. For example, in the Eco-indicator 99 method, all impact categories that refer to Human Health are expressed in DALY (disability adjusted life years). In this method it is allowed to add DALYs caused by carcinogenic substances to DALYs caused by climate change. Damage assessment is a relatively new step in impact assessment. It has been added to make use of the so called 'endpoint methods', such as the Eco-indicator 99 and the EPS2000.

Normalization

Many methods allow the impact category indicator results to be compared with a reference value. The results are normalized, therefore divided by the reference value. A commonly used reference is the average yearly environmental load in a country or continent, divided by the number of inhabitants. However, also other references can be chosen. Once normalized the impact category indicators can be compared directly as they all have the same unit. Normalization can be applied on both characterization and damage assessment results.

Weighting

The Impact (or Damage) category indicator results can be multiplied by weighting factors and eventually summed up to create a total or single score. Weighting is possible only with some impact assessment methods and it can be applied with or without normalization. Weighting factors assignment is obviously a subjective step. The main weighting options are:

- *Distance to target*

The ratio of the current environmental load to the reduction target is used as a weighting factor. Both scientific and political targets can be used.

- *Monetisation*

The willingness to pay in order to avoid damage is used.

- *Panel weighting*

Opinions of selected groups of people are collected through surveys.
It is important to note that in ISO 14042 classification and characterisation are described as obligatory elements of an impact assessment while normalisation and weighting are defined as optional elements.

- ***Interpretation***

The International Organization for Standardization (ISO, 14044) has defined the following two objectives of the Life Cycle Assessment framework interpretation:

- analyze results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA and report the results of the life cycle interpretation in a transparent manner;
- provide a readily understandable, complete, and consistent presentation of the results of an LCA study, in accordance with the goal and scope of the study.

In addition, the results analysis should include uncertainty and sensitivity analysis as well as a process contribution investigation, as underlined in the ISO standard 14044.

After the general LCA framework has been describe, it is interesting to investigate the features of the specific Impact Assessment Method used in this study.

3.2. Life Cycle Inventory – Allocation issue and Ecoinvent database system models

The Ecoinvent database is provided by The Swiss Centre for Life Cycle Inventories and it aims to be “the most relevant, reliable, transparent and accessible” LCI database worldwide (Ecoinvent report n.1(v3),2013). It comprises LCI data covering all the economic activities. The first step of the Ecoinvent project were taken during the late 1990ties, harmonising and completing several existing public Swiss databases and resulting in the release of the first Ecoinvent version in 2003. The Ecoinvent version used in this study is the version 3.0, released in 2013.

One of the LCA challenges is the existence of by-products associated with the manufacturing of the product of interest. To convert multi-product outputs into single outputs, three scenarios are possible:

- MULTI-OUTPUT

The most common multi-output solution is *Allocation*, where the potential damage is allocated among the products according to economic, mass, or energy allocations.

Another option is *Splitting*, where the potential damage is splitted at a defined point. For example, in a recycling scenario the splitting point can be set after the transportation to the recycling facility and the possible crashing of the recyclable material, so that the damage of the actual recycling process is charged to the secondary raw material producer in a different life cycle.

- AVOIDED PRODUCT

A by-product can be replaced by an avoided product. For example synthetic leather can be considered an avoided product within meat production with leather as a by-product.

- TOTAL DAMAGE

In this particular scenario, no allocation is considered. The potential damage is entirely associated to the considered “main” product, regardless of the by-products produced.

For the life cycle inventory analysis it is common to distinguish between consequential and attributional modelling (Weidema and Ekvall, 2009). The Ecoinvent database supports both types of modelling. In particular, it comes with three different system models (Weidema et al., 2013):

- CUT-OFF BY CLASSIFICATION

The underlying philosophy of this approach is that primary (first) production of materials is always allocated to the primary user of a material. If a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. As a consequence, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes. For example, recycled paper only bears the impacts of waste paper collection and the recycling process of turning waste paper into recycled paper. It is free of any burdens of the forestry activities and processing required for the primary production of the paper. This approach, used also in the previous versions of Ecoinvent (1 and 2), uses the average supply of the single products and it uses the economic allocation (based then on the market value) to convert multi-product outputs into single product outputs. The average supply is also called unconstrained supply as it does not consider restrictions caused by the market or the technology. The products, materials and energy are therefore considered always available (even if rare or scarce). The underlying philosophy is that a producer is fully responsible for the disposal of its wastes, and that he does not receive any benefit (or burden) for the provision of any recyclable materials.

In the SimaPro software, the processes that are created using this approach, are indicated with the extension ALLOC, REC.

- ALLOCATION AT THE POINT OF SUBSTITUTION (APOS**)**

As the Cut-off by classification approach, the APOS system model uses the average supply and the economic allocation. It follows the attributional approach in which burdens are attributed proportionally to specific processes. Wastes (and by-products) are allocated at the point of substitution. The benefit from recycling materials is attributed to the market processes that provide the secondary materials or by-products (such as heat or electricity from the incineration of waste).

This approach was also available in Ecoinvent v2 and is identified in SimaPro with the extension ALLOC, DEF.

- CONSEQUENTIAL MODEL

This system model uses substitution (also known as “system expansion”) to substitute by-products outputs. It includes only activities to the extent that they are expected to change in the long-term as a consequence of small changes in demand. The consequential model uses the constrained supply of products (based on market activity data and on information about technology level) and the system expansion in order to avoid allocation and convert multi-product datasets into single-product datasets. In a constrained market, a change in demand does not always corresponds to a change in supply but it can cause a change in consumption elsewhere. By-product markets are constrained because their production volumes depend on the production volumes of the reference products: it is the demand for the reference product that drives the production. Because of the constrained supply of products, the allocation of by-products is avoided by using substitution, i.e a product which replaces or substitutes the by-product of the reference product is identified. The emissions of that replacing product are then subtracted from the reference product emissions.

To sum up we can state that the consequential approach looks at the marginal consequences in the future, while the previous attributional approaches represent a snapshot of the impacts at the moment. This approach can be quiet complicated to use, as it demands a deep knowledge of the product- system studied at present and over time and/or to take thorny decisions.

3.3. IMPACT 2002 + and its modified versions

The impact assessment methods list is quiet long as various universities, research institutes, private companies and institutions have developed their own methods. The main method chosen in this study to investigate cultural heritage management is IMPACT 2002+. Resulting from a combination of four different methods (Impact 2002, Eco-Indicator 99, CML and IPCC) IMPACT 2002+ is relatively comprehensive; moreover it presents both Impact and Damage categories, allowing to choose between midpoint or endpoint outputs. The version of the method used, had already been modified by the LCA Working Group of the University of Modena and Reggio Emilia, in order to take into account some impacts that are negletcted in the original version of the method and to quantify the economic cost of the externalities (i.e. environmental impacts) associated to a product or process life cycle and it will be further modified according to the needs of the present study. In particular:

- in order to assess the value of a cultural heritage building or good, social and cultural indicators together with the related characterization and normalization factors are created;
- a monetization of the above mentioned social and cultural indicators is developed;
- economic indicators will be created in order to perform a LCC analysis;

The energy needs and efficiency of the renovated building will be estimated using the trial version of the EC700 Edilclima software, which allows calculating buildings energy performances, according to the UNI/TS 11300-1:2014 standard.

<u>IMPACT 2002 +</u>

- Impact assessment methodology originally developed at the Swiss Federal Institute of Technology.
- Improved by Quantis in 2012.
- Midpoint and endpoint indicators.

- Combination of four different methods: Impact 2002, Eco-Indicator 99, CML and IPCC.
- Originally fourteen midpoint categories (now seventeen) and four damage categories.
- Normalization factor based on the total environmental load of an average European citizen per year within each impact/damage category.
- Weighting default =1

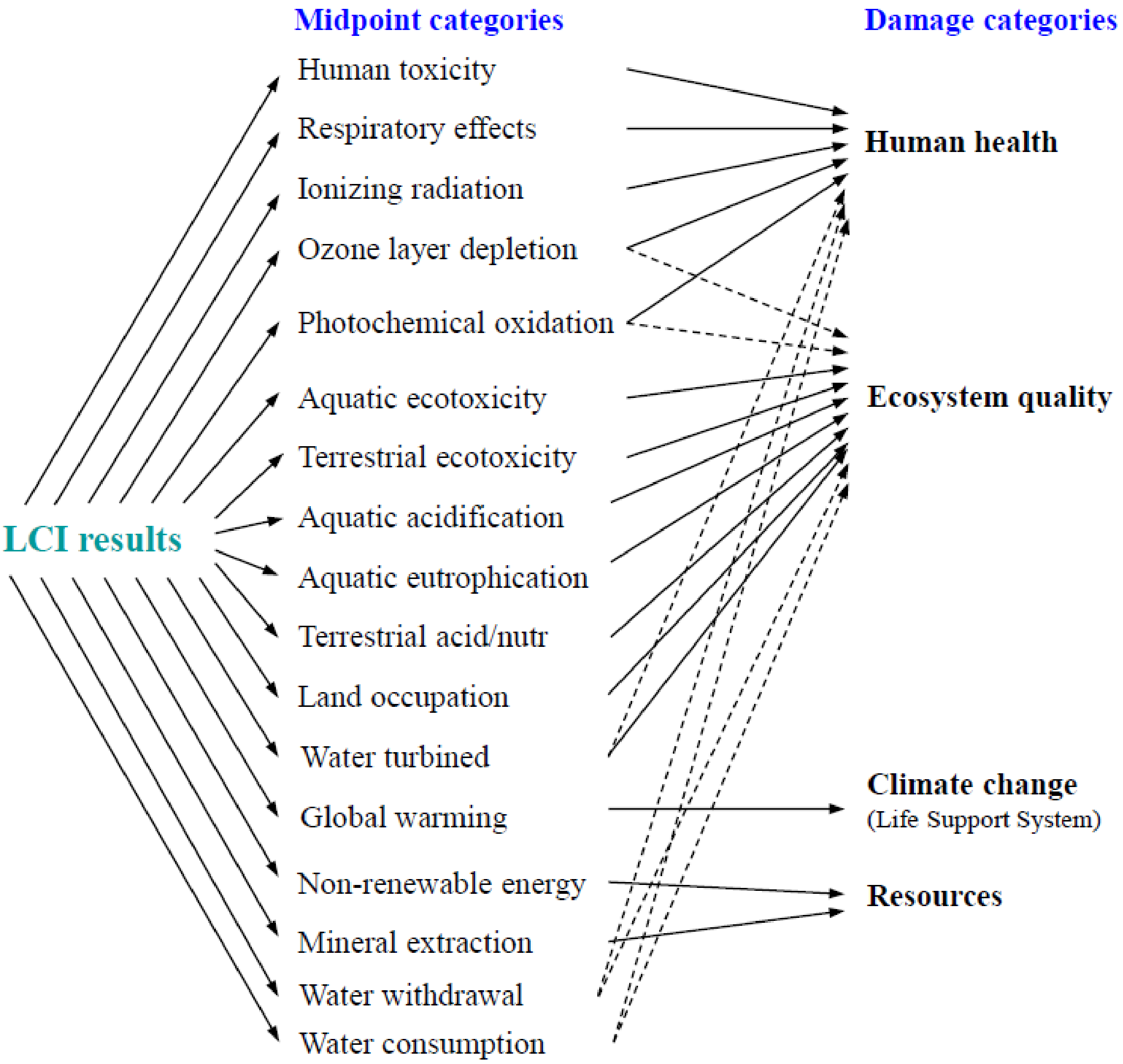


Figure 6. Overall scheme of the IMPACT 2002+ vQ.2.2 framework, linking LCI results via midpoint categories, (from Jolliet et al., 2013).

- An arrow symbolizes that a relevant impact pathway is known and quantitatively modeled.
- Impact pathways between midpoint and damage levels that are assumed to exist, but that are not modeled quantitatively due to missing knowledge or that are in development or that are double counting are represented by dotted arrows.

In default studies, the damage assessment of water withdrawal and consumption is not performed due to the complexity to evaluate the regionalization component of the study.

Midpoint category	***Midpoint reference substance***	***Damage category***	***Damage unit***	***Norm. damage unit***
Human toxicity (carcinogens + non-carcinogens)	kg Chloroethylene into air-eq	*Human health*	DALY	Points
Respiratory (inorganic)	kg PM2.5 into air-eq			
Ionizing radiation	Bq Carbon-14 into air-eq			
Ozone layer depletion	kg CFC-11 into air-eq			
Photochemical oxidation (= Respiratory (organics) for human health)	kg Ethylene into air-eq	*Ecosystem quality*	PDF*m2*y	Points (=pers*y)
Aquatic ecotoxicity	kg Triethylene glycol into water-eq			
Terrestrial ecotoxicity	kg Triethylene glycol into soil-eq			
Terrestrial acidification/nitrification	kg SO2 into air-eq			
Aquatic acidification	kg SO2 into air-eq			
Aquatic eutrophication	kg PO43- into water -eq			
Land occupation	m2 Organic arable land-eq*y			
Global warming	kg CO2 into air-eq	*Climate change*	Kg CO$_2$ into air$_{eq}$	
Non-renewable energy	MJ or kg Crude oil-eq (860 kg/m3)	*Resources*	MJ (surplus) energy	
Mineral extraction	MJ or kg Iron-eq (in ore)			

Table 2. IMPACT 2002+. Midpoint framework details.

As previously stated, the IMPACT 2002+ version used in this study had been previously modified by the LCA Working Group of the University of Modena and Reggio Emilia. The implemented updates are hereby listed.

Modified IMPACT 2002+: additional impact categories

The IMPACT 2002+ version used in this study had been previously modified by the LCA Working Group of the University of Modena and Reggio Emilia. The implemented updates are hereby listed.

- In the **Mineral Extraction** impact category the following substances were introduced: *Silver, in ground, Silver, 0,01% in crude ore, in ground, Gravel, in ground, Sand, in ground, Lithium, in ground, Bromine, in ground* and different typologies of aquifer waters.

- In the **Land occupation** impact category the *Transformation from* and *Transformation to* entries (corresponding to the already existing related *Occupation* entries) were added.
- The **Radioactive waste** impact category was added, referring to the different radioactive waste typologies and related occupied volume. The charachterization and normalization factors associated were the same one used in the EDIP 2003 impact method (Potting et al., 2005). The employed weighting factor value is equal to one, as for the other IMPACT 2002+ categories.
- The substance *Deads due to nuclear incident* is added to take into account the possibility of a nuclear incident. The corresponding impact category is called **Deads due to nuclear incident** as well. Assuming that the average age of the deceased person is 50 years old, each dead causes 30 DALYs loss. For the corresponding **Nuclear Incident** damage category, the normalization and weighting factors considered are the Human Health damage category ones.

Modified IMPACT 2002+: LCC and and Societal LCC calculation

The IMPACT 2002+ method has been modified by the LCA Working group of the University of Modena and Reggio Emilia in order to take into and quantify the external costs associated to the environmental impacts.

The following criteria are used:

- For the **Human Health** damage category the average European citizen salary is considered
- For the **Ecosystem Quality** the costs of the reintroduction of three different animal species is taken into account (average value)
- As far as the **Resources** are concerned, the average cost of an electric kWh in Europe is used
- For the **Climate Change** damage, the CO_2 market price 8according Carbon emission trading market) is considered

To be more prescise, the following damage assessment coefficients are used:

Human Health

- Carcinogens: 31150 € / DALY * 2.8E-6 DALY / kg C_2H_3Cleq = 0.08722 € / kgC_2H_3Cleq
- Non carcinogens: 31150 € / DALY * 2.8E-6 DALY / kg C_2H_3Cleq = 0.08722 € / kgC_2H_3Cleq
- Respiratory inorganics: 31150 € / DALY*7E-4 DALY / kg PM2.5 eq = 21.805 €/ kg PM2.5 eq
- Ionizing radiation: 31150 € / DALY*2.1E-10 DALY / Bq C14 eq = 6.5415E-6 €/ Bq C14 eq
- Ozone layer depletion: 31150 € / DALY*1.05E-3 DALY / CFC-11 eq = 32.7075 €/ CFC-11 eq
- Respiratory organics: 31150 € / DALY*2,13E-6 DALY / C_2H_4 eq = 0.0663495 €/ C_2H_4 eq

Ecosystem quality

- Aquatic ecotoxicity: 4.5906E-3 € / PDF*m^2*yr * 5.02E-5 PDF*m^2*yr / kg TEG water = 2.3044812E-7 € / kg TEG water
- Terrestrial ecotoxicity: 4.5906E-3 € / PDF*m^2*yr * 7.91E-3 PDF*m^2*yr / kg TEG soil = 3.6311646E-5 € / kg TEG soil
- Terrestrial acid/nutri: 4.5906E-3 € / PDF*m^2*yr * 1.04 PDF*m^2*yr / kg TEG soil = 4.774224E-3 € / kg SO_2 eq
- Land occupation: 4.5906E-3 € / PDF*m^2*yr * 1.09 PDF*m^2*yr / kg TEG soil = 5.003754E-3 € / m^2org.arable

Climate change

- Climate change: 7.81E-3 € / kg CO_2 eq

Resources

- Non-renewable energy: 0.0208 € / MJ primary * 1 MJ primary / MJ primary = 0.0208 € / MJ primary
- Mineral extraction: 0.0208 € / MJ primary * 1 MJ primary / MJ surplus= 0.0208 € / MJ surplus

As far as the normalization factors (nf) are concerned, thy are calculated as follows:

Human Health

- Nf = 141 $DALY^{-1}$/ 31150 € / DALY = 4.526484751E-3$€^{-1}$

Ecosystem quality

- fn = 7.3E-5 $(PDF*m^2*yr)^{-1}$ / 4.5906E-3 € / $(PDF*m^2*yr)$ = 0.01590206 $€^{-1}$

Climate change

- fn = 0,000101 $(kg\ CO_2\ eq)^{-1}$ / 7.81E-3 € / kg CO_2 eq = 0.012932138 $€^{-1}$

Resources

- fn = 0.00000658 MJ^{-1} / 0.0208 € / MJ = 3.163461538E-4 $€^{-1}$

The internal costs can be calculated as well, simply introducing the cost items as indicators with a monetary unit.

Finally, the social costs or benefits re taken into account through the monetization procedure of the sociocultural indicators, that takes advantage of a Willingness To Pay analysis. For more information on this modification, please refer to the chapter 4.1.4.

Modified IMPACT 2002+: Nanomaterials impacts

The modification to take into account of the nanomaterials impacts was elaborated by Pini, 2014.

In order to identify a preliminary definition of human health characterization factors NIOSH recommendations (NIOSH, 2011) and IARC classification (IARC, 2010) have been considered:

- NIOSH (*National Institute for Occupational Safety and Health*) recommended an occupational exposure limits (REL) of 0.3 mg/m3 for ultrafine (including engineered nanoscale) TiO2 as a TWA concentration for up to 10 hrs/day during a 40-hour work week and it suggested a lower level in order to reduce the risks of lung cancer of 1/1000.

- IARC (*International Agency for Research on Cancer*) reviewed TiO2 and concluded that it is a "possibly carcinogenic to humans".

Eco-indicator99 method calculates the damage to Human Health caused by carcinogenic substance through three main steps of fate analysis, effect analysis and damage analysis (Goedkoop & Spriensma, 2001).

This framework has been here taken into account to determine the potential damage to Human Health caused by nano-TiO_2 emissions releases to outdoor environment and also to freshwater compartment.IMPACT 2002+ method has been modified, adding a new substance, *Particulates, < 100 nm*, released in the different compartment of interest and adding e related new impact category for each compartment. For the new impact categories, a damage factor was calculated referring to the above-mentioned framework. Normalization and weighting factors remain unchanged. For more information about the damage categories and characterization and damage factors, please refer to Pini, 2014.

4. *Case studies*

4.1. The San Felice colonnade

The cloister is located inside the San Felice Complex in Pavia (Italy),that is hosting the Faculty of Economics of the University. The actual age of the complex is unknown but Church's structure – an undivided main body with tripartite apsis, standing above a crypt – suggests it belongs to the Longboard period. The most ancient information dates back to VIII cen., when the complex was a monastery.

A complete remake started in the 2nd half of XV cen. On the initiative of the Abess Andriola Barrachis with the patronage of Bianca Maria Sforza Visconti: the new complex is organized around a quadrangular colonnade, parallel to the church. The present structure of the complex is due to the intervention of Leopoldo Pollak in the late XVIII cen. when the convent was transformed into an orphanage building (function maintained until the 1860s). The colonnade and the refectory structures have been preserved since the XV century's interventions. Finally, in 1939 the colonnade was restored by Pietro Aschieri.

At present, the colonnade has a poor conservation state, with structural failure of many columns, that require a restoration intervention.

4.1.1. Goal and scope definition

The scope of this LCSA study is the assessment of the environmental damage due to the restoration of an ancient building element, taking into account also the sociocultural advantages as well as the associated internal and external costs.

The Functional Unit considered is the restoration process of the colonnade columns and the system boundaries go from the acquisition of the raw materials and equipment necessary for the restoration interventions to the end of life scenarios. Emissions to air, water and soil are considered as well as transportation and scrap treatment.

In this particular case, the following LCA perspective applicable to the construction sector LCA is chosen: only the restored architectural elements (new components and dismissal of old ones) are considered without taking into account the previous components that benefit of a longer life span. This approach is consistent with the functional unit that considers the conservation project of the columns of the cloister and excludes therefore a change in the operational phase of the building that would take advantage also of the old materials.

4.1.2. Inventory and data

<u>Background data</u>

34 columns: 30 perimetral columns + 4 angular columns

Dimensions:

Shaft diameter: 39.4 cm

Base diameter: 44.3 cm

Height: 231 cm

Capital height: 31 cm

Base height: 49 cm (upper portion) + 5.0 cm (lower portion)

Figure 7. San Felice column. Structural failure detail.

The 4 angular columns are composed of a central squared section and 2 adjoinng circular sections. Side of squared section: 54.1 cm. Chord of circular sectors: 39.4 cm. Height of circular sectors: 9.8 cm.

Assumptions on the foreground data

Figure 8. San Felice colonnade. Arch supports.

Hypothesis. An x-ray analysis performed to evaluate the conservation state of the columns gives the following results:

- All the columns need an external surface restoration. Smoothing, re-use and new material addition is considered.
- 40% of the columns need an endurance restoration through fissures filling and clamping.
- 15% of the columns need an endurance restoration through axial drilling and a steel bar insertion.

Figure 8 shows the colonnade restoration intervention flowchart.

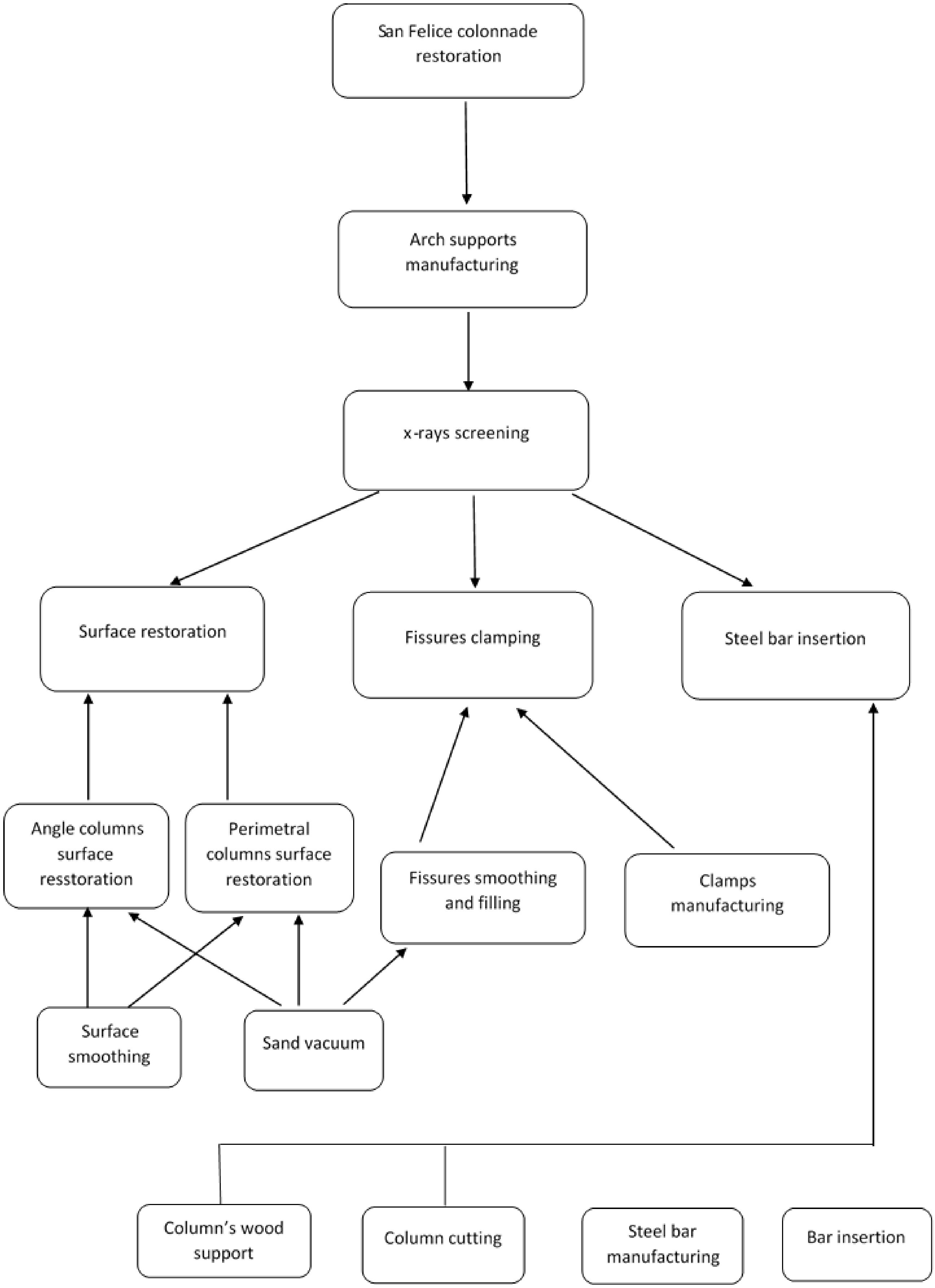


Figure 9. San Felice colonnade restoration's flowchart.

4.1.3. Environmental Impact Assessment

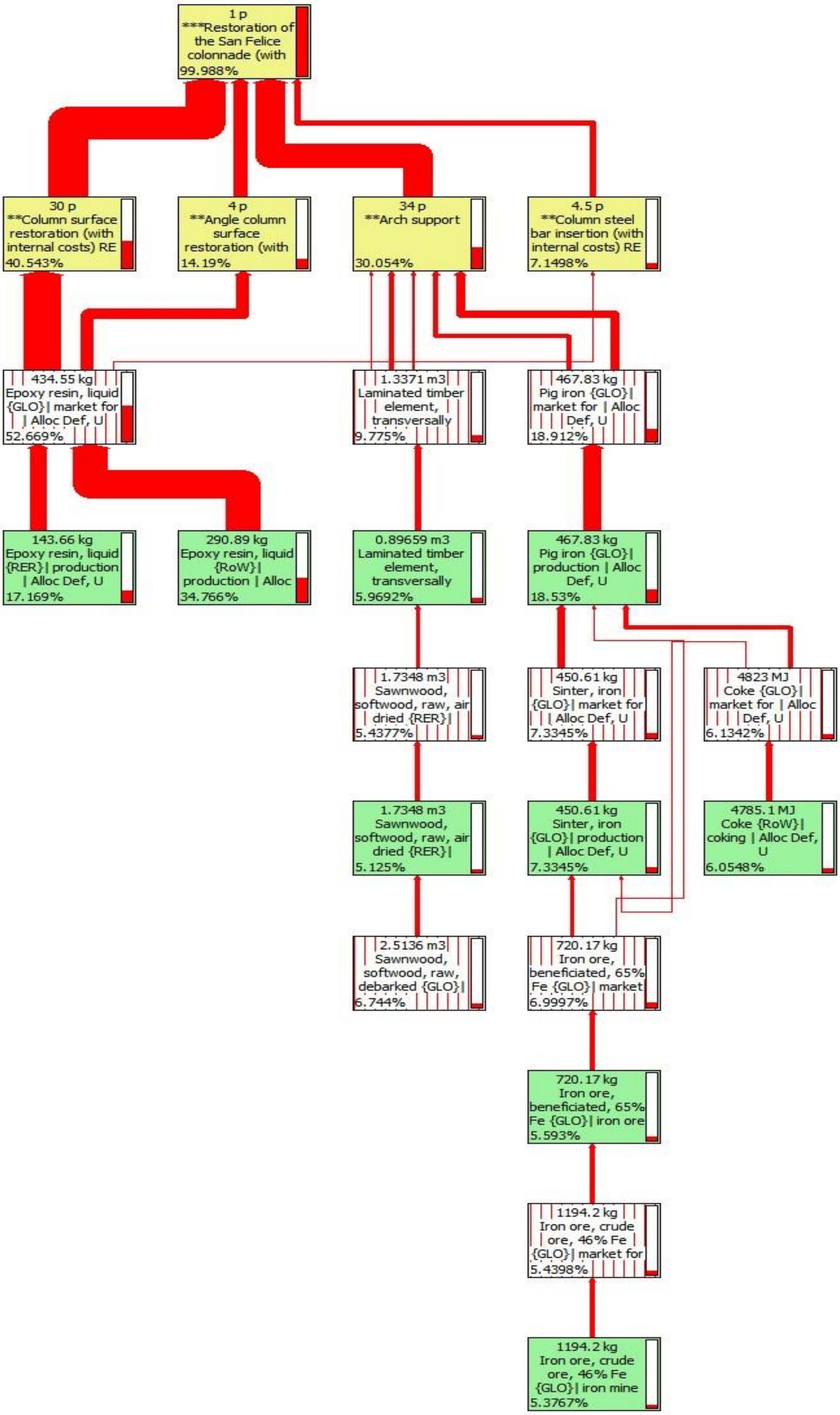


Figure 10. Network of the process Restoration of the S. Felice colonnade. Modified IMPACT 2002+. Cut off: 5%.

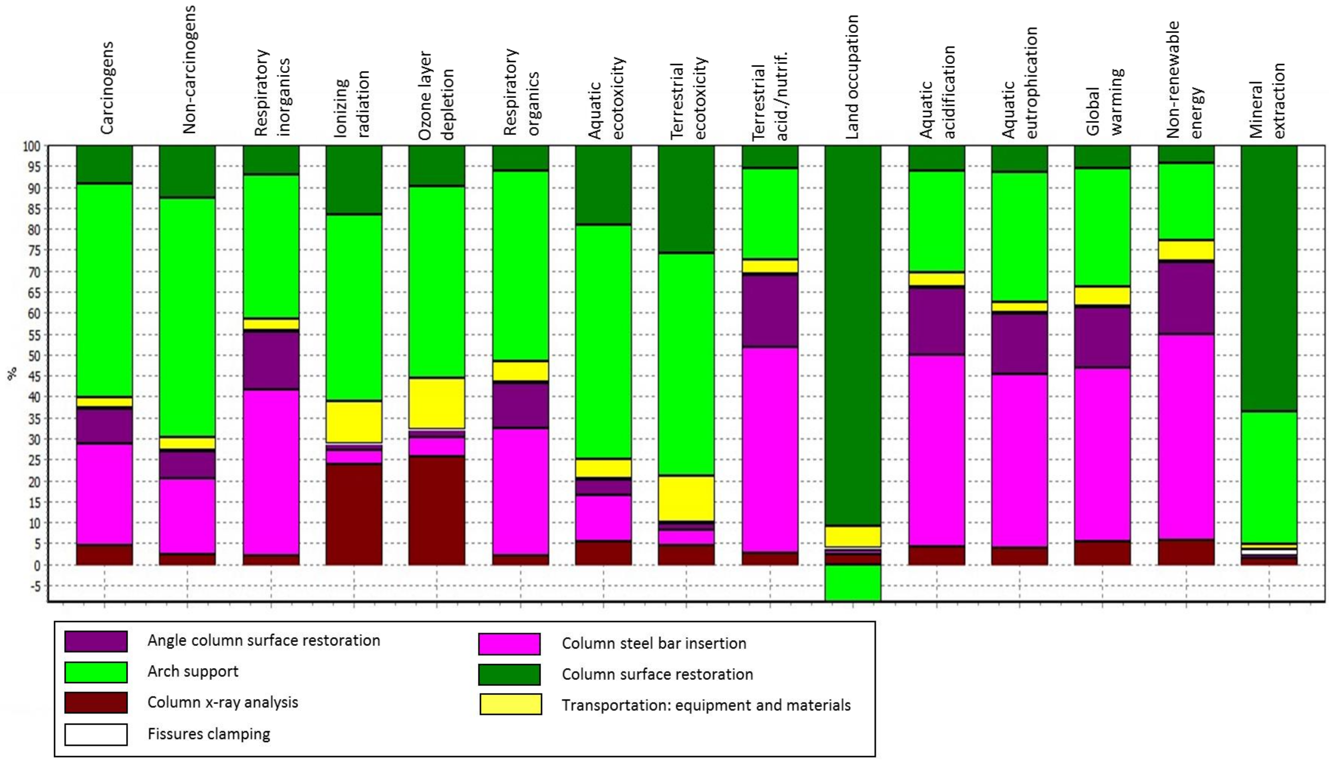


Figure 11. Characterization results per impact category of the process Restoration of the S. Felice colonnade. Modified IMPACT 2002 +.

The first reported results are midpoint ones, in particular, the characterization results, divided per impact category (Figure 11). In Table 3, the same results are explicited with the related unit figures, underlyining the restoration process that affects the most the relative impact category.

Impact category	**Unit**	**Total**	****Column x-ray analysis**	****Column surface restoration**	****Angle column surface restoration**	****Fissures clamping**	****Transportation: equipment and materials**	****Arch support**	****Column steel bar insertion**
Carcinogens	kg C2H3Cl eq	142.5798	6.4461	34.3778	12.0424	0.3546	3.6905	72.4457	13.2227
Non-carcinogens	kg C2H3Cl eq	88.7609	2.1532	16.1075	5.6695	0.2669	2.7690	50.5455	11.2492
Respiratory inorganics	kg PM2.5 eq	11.5612	0.2425	4.5748	1.5978	0.0314	0.3111	3.9881	0.8154
Ionizing radiation	Bq C-14 eq	21976.0862	5250.3011	733.3683	312.3667	31.6116	2206.7085	9793.9686	3647.7613
Ozone layer depletion	kg CFC-11 eq	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000
Respiratory organics	kg C2H4 eq	3.7536	0.0787	1.1450	0.4028	0.0067	0.1875	1.6997	0.2332
Aquatic ecotoxicity	kg TEG water	300053.4009	16171.0217	32869.9793	11790.0181	477.6684	14110.3161	167256.2799	57378.1172
Terrestrial ecotoxicity	kg TEG soil	101528.1879	4603.2944	3657.5184	1568.8600	284.1515	11427.3704	53901.2268	26085.7665
Terrestrial acid/nutri	kg SO2 eq	143.0808	4.0087	70.0596	24.4787	0.3956	5.1104	31.2814	7.7464
Land occupation	m2org.arable	148.8114	4.0100	1.6233	0.7820	0.0547	8.3606	-14.6937	148.6744
Aquatic acidification	kg SO2 eq	31.6620	1.3287	14.5127	5.0691	0.0870	0.9967	7.7691	1.8987
Aquatic eutrophication	kg PO4 P-lim	0.9724	0.0370	0.4040	0.1410	0.0024	0.0232	0.3006	0.0641
Global warming	kg CO2 eq	5657.3631	308.6503	2336.1687	818.8421	16.5219	269.7720	1600.2265	307.1814
Non-renewable energy	MJ primary	91568.8714	5265.8591	45002.3948	15753.0923	249.1853	4408.9086	16862.2238	4027.2074
Mineral extraction	MJ surplus	690.9043	9.5816	3.7740	1.5609	8.9697	9.5687	219.2806	438.1688

Table 3. Characterization results per impact category of the process Restoration of the S. Felice colonnade. Modified IMPACT 2002 +.

The results of the substance and process contribution analysis are reported for each impact category.

- The **Carcinogens** total impact is equal to 142.5798 kg C2H3Cl eq and it is allocated as follows: 58.47% is caused by 23.567 g of *Hydrocarbons, aromatic* in air (38.93% of this amount is associated to the Column surface restoration intervention and, in particular, Epoxy resin, liquid {RoW}| production | Alloc Def, U, the process that describes the epoxy resin production outside the European union, is responsible for 65.18% of the intervention impacts); 28.99% is caused by 1.1686 g of *Benzo(a)pyrene* in air (92.48% of this amount is associated to the Arch support construction and, in particular, Coke {RoW} | coking | Alloc Def, U, the process that describes coke treatment in order to produce the pig iron to build the pipes and other components of the supports, is responsible for 99.29% of the supports impacts).
- The **Non carcinogens** impact corresponds to 88.761 kg C2H3Cl eq and is allocated as follows: 55.75% is caused by 5.6904 um of *Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-* in air, (66.3% is emitted during the Arch support process, and, in particular, 78.32% during the Sinter, iron {GLO} | production | Alloc Def, U subprocess, used within the pig iron production, the material of the pipes and other supports components) and 25.39% is caused by 41.515 g of *Antimony* in water (61.01% is emitted during the Column surface restoration process and, in particular, 96.23% during the Process-specific burdens, municipal waste incineration {RoW} | processing | Alloc Def, U process, that defines the impacts due to the dismissal of an average incineration residue, due to the epoxydic resin production.
- The **Respiratory inorganics** impact corresponds to 11.561 kg PM2.F5 eq and is allocated as follows: 30.12% is caused by 3.4817 kg of *Particulates, <2.5um* in air, (36.8% is emitted during the Arch support process, and, in particular, 26.44% during the in Coke {RoW} | coking | Alloc Def, U subprocess, used within the pig iron production, the material of the pipes and other supports components); 25.32% is caused by 701.57 mg of *Nitrogen oxides* in air (50.51% is emitted during the Column surface restoration process and, in particular, 64.36% during Epoxy resin, liquid {RoW}| production | Alloc Def, U subprocess); 23.34% is caused by 5.0378 kg of *Particulates, >2.5um, and <10um in air* (41.71% is emitted during the Column surface restoration process and, in particular, 65.55% during the Epoxy resin, liquid {RoW}| production | Alloc Def, U, subprocess; 11.11% is caused by 8.1731 kg of *Particulates, > 10um* in air (63.34% is emitted during the Arch support process and, in particular, 31.13% during the Iron ore, crude ore, 46% Fe {GLO}| iron mine operation, crude ore, 46% Fe | Alloc Def, U, subprocess, that represents the extraction of the iron used to produce the steel bar).
- The **Ionizing radiation** impact corresponds to vale 21976 Bq C-14 eq and is allocated as follows: 61.34% is caused by 1.1796E5 kBq of *Radon-222* in air (43.99% is emitted during the Arch support process, and, in particular, 97.26% during the in Tailing, from uranium milling {GLO}| treatment of | Alloc Def subprocess, that represents the residues deriving from the extraction of uranium, that is found in the laminated wood, used for the supports production; 37.41% is caused by 8.2222 kBq di *Carbon-14* in air (45.5% is emitted during the Arch support process and, in particular, 58.88% during Low level radioactive waste {CH}| treatment of, plasma torch incineration | Alloc Def process, that represents the radioactive wastes released during oil extraction).
- The **Ozone layer depletion** impact corresponds to 0.0002 kg CFC-11 eq and is allocated as follows: 35.38% is caused by 4.4645-6 kg of *Methane, bromotrifluoro-, Halon 1301* in air, (43.73% is emitted during the Arch support process, and, in particular, 57.62% during the Petroleum {RoW}| and gas production, on-shore | Alloc Def, subprocess, involved in the production of the fuel used for the sea transport of the supports' laminated and pig iron); 25.32% is caused by 701.57 mg of *Nitrogen oxides* in air (50.51% is emitted during the Column surface restoration process and, in particular, 64.36% during Epoxy resin, liquid {RoW}| production | Alloc Def, U subprocess); 25.66% is caused by 6.5176E-6 kg of *Methane, bromochlorodifluoro-, Halon 1211* in air (67.9% is emitted during the Column x-ray analysis process and, in particular, 63.21% during the Transport, pipeline, long distance, natural gas {RU}| processing | Alloc Def subprocess, that considers the natural gas transport, necessary for the electricity production used for the x-ray analysis; 18.16% is caused by 5.5355E-5 kg of *Methane, chlorodiluoro- HCFC- 22* in air

(85.48% is emitted during the Arch support process and, in particular, 96.14% during Coke {RoW}| coking | Alloc Def, subprocess, that is involved in the supports' pig iron production).

- The **Respiratory organics** impact corresponds to 3.7536 kg C2H4 eq and is allocated as follows: 94.97% is caused by 5.9324 kg of *NMVOC, non methane volatile organic compounds, unspecified origin* in air, (44.47% is emitted during the Arch support process, and, in particular, 54.68% during the Coke {RoW}| coking | Alloc Def, subprocess, involved in the production of pig iron, the material of the pipes and other supports components).
- The **Aquatic ecotoxicity** impact corresponds to 300053.4009 kg TEG water and is allocated as follows: 36.73% is caused by 0.031528 kg of *Aluminium* in ground, (67.4% is emitted during the Arch support process, and, in particular, 92.3% during the Wood ash mixture, pure {CH}| treatment of, landfarming | Alloc Def, U, subprocess, involved disposal of the ashes derived form the combustion of the scraps caused by the supports' wood cutting); 24.02% is caused by 0.14612 kg of *Aluminium* in air (73.3% is emitted during the Arch support process and, in particular, 64.41% during the Blasting {RoW}| processing | Alloc Def subprocess, that describes the blasting operations in the iron and coal mines; the two materials are then used for the supports' iron pig production); 10.68% is caused by 3.7777 kg of *Aluminium* in water (42.14% is emitted during the Arch support process and, in particular, 32.28% during Tap water, at user {Europe without Switzerland}| tap water production and supply | Alloc Def, U, subprocess, that describes the water use in the supports' iron prodcution).
- The **Terrestrial ecotoxicity** impact corresponds to 101528.1879 kg TEG soil and is allocated as follows: 26.19% is caused by 0.004497 kg of *Zinc* in soil (47.01% is emitted during the Arch support process, and, in particular, 74.05% during the Wood ash mixture, pure {CH}| treatment of, landfarming | Alloc Def, U, subprocess, involved disposal of the ashes derived form the combustion of the scraps caused by the supports' wood cutting); 23.55% is caused by 0.1562 kg of *Aluminium* in soil (73.3% is emitted during the Arch support process and, in particular, 64.41% during the Blasting {RoW}| processing | Alloc Def subprocess, that describes the blasting operations in the iron and coke mines; the two materials are then used for the supports' iron pig production); 18.2% is caused by 3.0128 kg of *Aluminium* in air.
- The **Terrestrial acidification/nutrification** impact corresponds to 143.0808 kg SO2 eq and is allocated as follows: 19% is caused by 26.2345 kg of *Nitrogen oxides* in air and 10.32% to 14.7659 kg of *Sulfur dioxide* in air.
- The **Land occupation** impact corresponds to 148.8114 m2org.arable and is allocated as follows: 410.4% is caused by 6051.6 m2a of *Occupation, forest, intensive* in raw (72.62% is due to the Arch support process and, in particular, 49.92% to the Softwood, CO2-removal and land use {RoW}| softwood forestry, CO2-removal and land use | Alloc Def, U, subprocess, that takes into account the wood consumed for the supports, production), 88.65% is caused by 43.574 m2 of *Transformation, to forest intensive* in raw (72.53% of the occupation is linked to the Arch support process, in particular, 53.62% to the Softwood, CO2-removal and land use {RoW}| softwood forestry, CO2-removal and land use | Alloc Def, U subprocess, that considers the wood used for the supports manufacturing), 53.77% is caused by 2.5282 m2 di *Transformation, to arable* in raw (54.05% of the occupation is linked to the Column x-ray analysis process, in particular, 88.35% to the Electricity, high voltage {IT}| heat and power co-generation, biogas, gas engine | Alloc Def, U subprocess, that considers the electricity consumption for the x-ray analysis), 19.87% is caused by 38.373 m2a of *Occupation, traffic area, rail/road embankment* and 14.38% is caused by 27.759 m2a of *Occupation, traffic area, road network.* This damage is counterbalanced by the fothcoming processes, allocated as follows: -434.9% is caused by 20.447 m2 of *Transformation, from arable* (-85.18% is due to the Arch support process, in particular, -73.55% to the Soybean {RoW}| production | Alloc Def, U process that considers the oil involved in the cutting of the supports' wood) and -89.26% is caused by 43.839 m2 of *Transformation, from forest, extensive* (-72.54% is due to the Arch support process, in particular, -53.29% to the Softwood, CO2-removal and land use {RoW}| softwood forestry, CO2-removal and land use | Alloc Def, U, subprocess that considers the wood used for the supports manufacturing).
- The **Aquatic acidification** impact corresponds to 31.6620 kg SO2 eq and is allocated as follows: 50.83% is caused by 28.9654 kg of *Nitrogen oxides* in air and 46.65% is caused by 14.7703 kg of *Sulfur dioxide* in air.

- The **Aquatic eutrophication** impact corresponds to 0.9724 kg PO4 P-lim and is allocated as follows: 52.78% is caused by 5.0135 kg of *COD, Chemical Oxygen Demand* in water (70.08% is due to the Column surface restoration process, in particular, 66.62% to the Epoxy resin, liquid {RoW}| production | Alloc Def, U subprocess, that describes the production of epoxy resin outside the European Union) and 42.01% is caused by 2.3723 kg of *Phosphate* in water (61.05% is due to the Arch support process, in particular, 47.47% to the Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Alloc Def, U subprocess, that describes the landfill treatment of the spoil deriving from the mining of coal, involved in the supports' pig iron production).
- The **Global Warming** impact equals to 5657.3631 kg CO2 eq and is allocated as follows: 95.12% is caused by 5381.4 kg of *Carbon dioxide, fossil* in air (41.39% is due to the Column surface restoration process, in particular, 56.56% to the Epoxy resin, liquid {RoW}| production | Alloc Def, U subprocess, that that describes the production of epoxy resin outside the European Union).
- The **Non-renewable energy** impact equals to 91568.8714 MJ primary and is allocated as follows: 51.09% is caused by 1161 m3 of *Gas, natural/m3* in raw (59.06% is due to the Column surface restoration process, in particular, 66.03% to the Epoxy resin, liquid {RoW}| production | Alloc Def, U subprocess, that describes the production of epoxy resin outside the European Union), 24.61% caused by 492.07 kg of *Oil. Crude* in raw (45.08% is due to the Column surface restoration process, in particular, 63.49% to the Epoxy resin, liquid {RoW}| production | Alloc Def, U subprocess, that describes the production of epoxy resin outside the European Union) and 14.62% is caused by 701.01 kg of *Coal, hard* in raw (58.97% is due to the Arch support process, in particular, 34.92% to the Hard coal {CN}| mine operation | Alloc Def subprocess, that considers the coal mining, necessary for the supports' pig iron production).
- The **Mineral extraction** impact equals to 690.9043 MJ surplus ed and is allocated as follows: 84.74% is caused by 17.119 kg of *Nickel, 1.98% in silicates, 1.04% in crude ore* in raw (72.14% is due to the Column bar insertion process, in particular, 99.999% to the Ferronickel, 25% {GLO}| production | Alloc Def subprocess, that considers the production of ferronickel, necessary for the steel manufacturing).

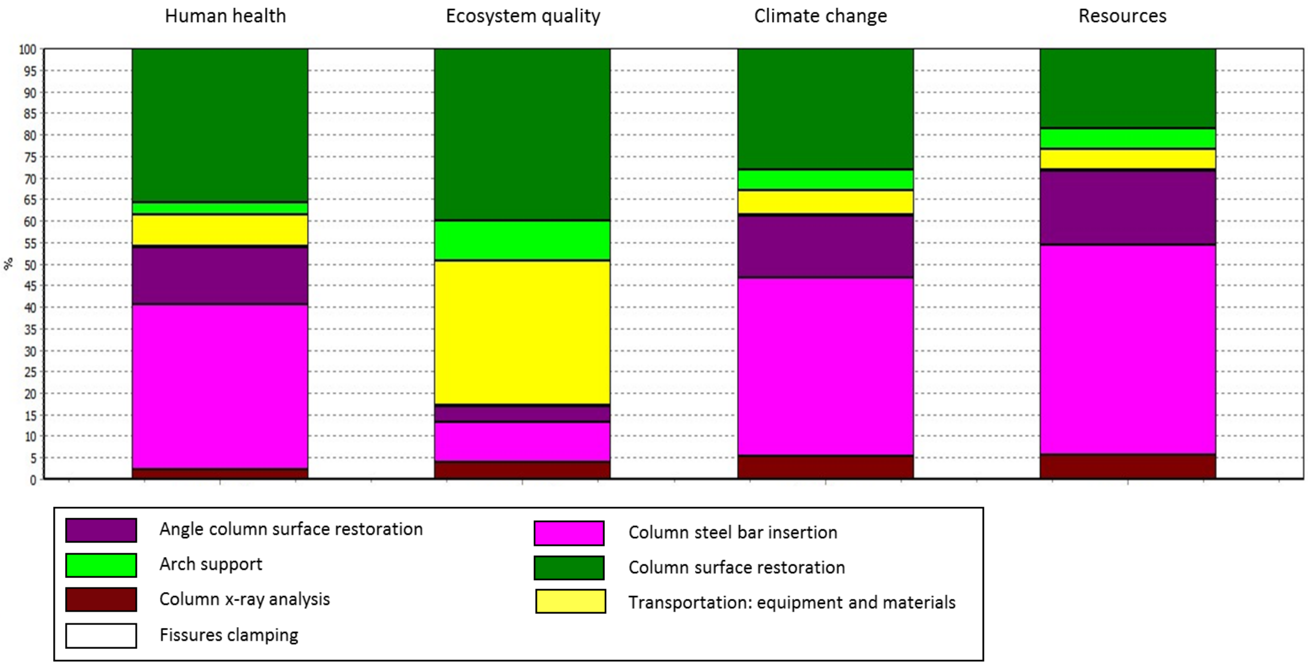


Figure 12. Characterization results per damage category of the process Restoration of the S. Felice colonnade. Modified IMPACT 2002 +.

Damage category	Unit	Total	**Column x-ray analysis	**Column surface restoration	**Angle column surface restoration	**Fissures clamping	**Column steel bar insertion	**Transportation: equipment and materials	**Arch support
Human health	DALY	0.0088	0.0002	0.0033	0.0012	0.0000	0.0002	0.0031	0.0006
Ecosystem quality	PDF*m2*yr	1129.1591	45.7638	105.2125	39.3118	2.7427	105.5267	451.2715	379.3301
Climate change	kg CO2 eq	5657.3631	308.6503	2336.1687	818.8421	16.5219	269.7720	1600.2265	307.1814
Resources	MJ primary	92259.7758	5275.4407	45006.1689	15754.6532	258.1550	4418.4773	17081.5044	4465.3762

Table 4. Characterization results per damage category of the process Restoration of the S. Felice colonnade. Modified IMPACT 2002+.

The Environmental Impact Assessment gives the following damage assessment characterization results:

• the **Human Health** damage is equal to 0.0087534 DALY and it is allocated as follows: 27.84% is caused by *Particulates, <2.5 um* emitted in air, 23.40% is caused by *Nitrogen oxides* in air, 21.58% is caused by *Particulates, >2.5um, and < 10 um* in air and 10.27% is caused by Particulates, >10 um in air. Column surface restoration is the process that produces the highest potential damage (0.0033463 DALY that correspond to 38.23%). The most affected impact category is Respiratory inorganics (0.0080928 DALY that correspond to 92.45%).

• the **Ecosystem quality** damage is equal to 1129.1591 PDF*m2*yr and it is allocated as follows: 58.95% is caused by Occupation, forest, intensive, 18.65% is caused by Zinc emitted in ground, 17.23% is caused by Aluminium in ground, 13.27% is caused by Aluminium in air. Arch support is the process that produces the highest potential damage (451.27 PDF*m2*yr that corresponds to 39.97%) followed by Colum steel bar insertion (379.33 PDF*m2*yr that corresponds to 33.59%). The most affected impact category is Terrestrial ecotoxicity (803.09 PDF*m2*yr that corresponds to 71.12%).

• the **Climate change** damage is equal to 5657.3631 kg CO2 eq. and it is allocated as follows: 95.12% is caused by Carbon dioxide, fossil in air. Column surface restoration is the process that produces the highest potential damage (2336.2 kg CO2 eq that corresponds to 41.3%).

• the **Resources damage** is equal to 92259.7758 MJ primary and it is allocated as follows: 50.71% is caused by Gas, natural/m3, 24.43% is cause by Oil, crude, 14.51% is caused by Coal, hard. Column surface restoration is the process that produces the highest potential damage (45006 MJ primary, that corresponds to 48.78%). The most affected impact category is Non-renewable energy (91569 MJ primary that corresponds to 99.25%.

The damage categories can be normalized and the results are shown in Figure 12.
In particular:

- The damage on **Human health** is 1.17 times the average yearly health damage caused by the activities of a European citizen.

- The damage to **Ecosystem quality** is 0.05 times the average yearly environmental load of a European citizen.

- The **Climate change** damage is 0.56 times the average damage caused by the activities of a European citizen.

- The damage on **Resources** is 0.59 times the average yearly environmental load of a European citizen.

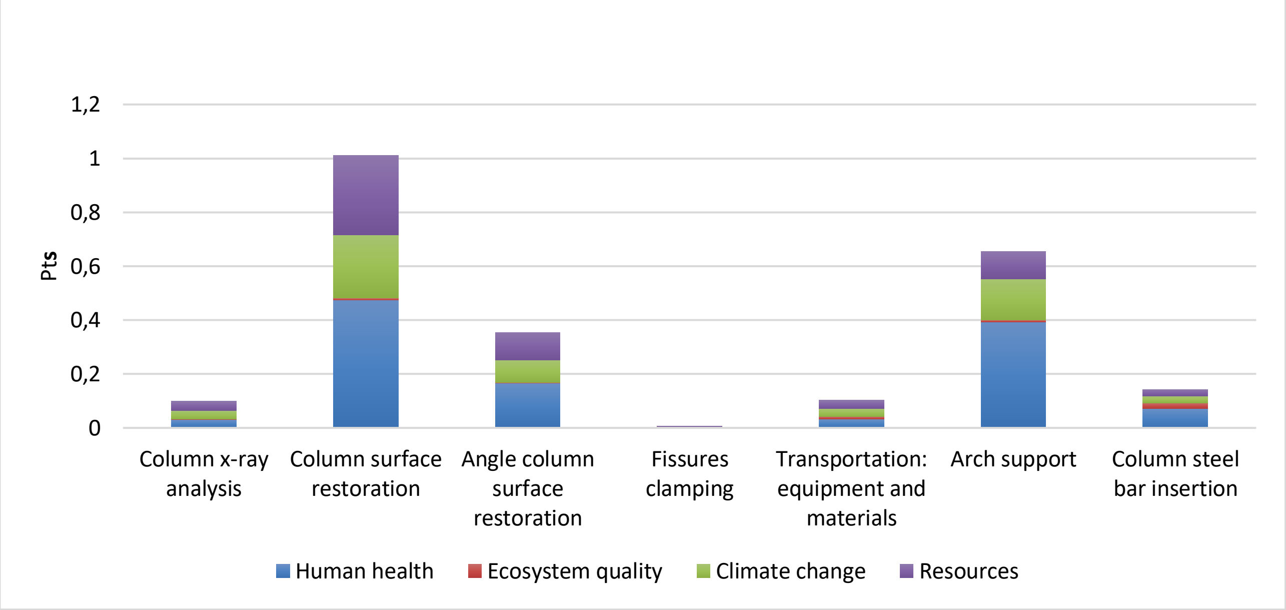


Figure 13. Normalized damage and single score results of the process Restoration of the S. Felice colonnade. Modified IMPACT 2002 +.

- **Comparison among the different types of column restoration:**

As the different restoration interventions are applied to a different number of columns, it is interesting to compare the life cycle results using the same functional unit for all the type of interventions, i.e. the restoration of one single perimetral column.

The Angle column surface restoration intervention is not included in this analysis, as the dimensions of the angle columns are bigger and this increases the environmental impacts associated to this process compared to the other ones. Nevertheless, the included processes are the same ones used in the perimetral columns surface restoration that is taken into account in this comparison.

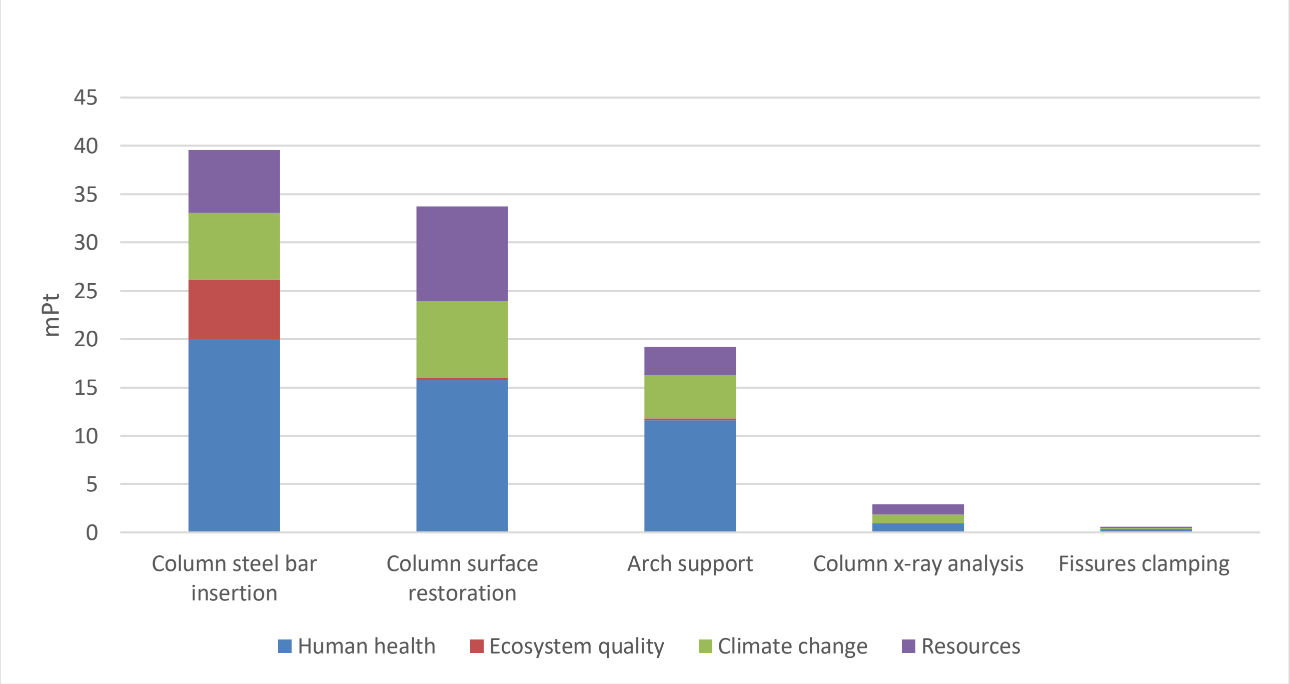


Figure 14. San Felice colonnade restoration. Interventions comparison. Single score results. IMPACT 2002+, modified version.

The higher environmental burden is associated with the Column steel bar insertion procedure, followed by the Column surface restoration, the Column cutting and steel bar insertion, the Arch support life cycle, the Column x-ray analysis and , finally, the Fissures clamping (Figure 13).

The damage allocation of the single score within the different categories is shown in Table 5.

Damage category	**Column steel bar insertion**	**Column surface restoration**	**Arch support**	**Column x-ray analysis**	**Fissures clamping**
Total	100.00	100.00	100.00	100.00	100.00
Human health	50.62	46.64	59.07	28.44	48.43
Ecosystem quality	15.52	0.76	4.39	3.45	2.89
Climate change	17.39	23.32	21.55	32.22	24.12
Resources	16.47	29.27	14.99	35.88	24.56

Table 5.San Felice colonnade restoration. Intervention comparison. Damage categories allocation. Modified IMPACT 2002+.

The most affected Damage category is **Human health** for all the processes, except the Column x-ray analysis, (that causes the higher damage to the Resources category).

As shown in Figure 14, the intervention that affects the most the Human Health and Ecosystem Quality categories is the Column steel bar insertion while Climate change and Resources are mainly affected by the Column surface restoration.

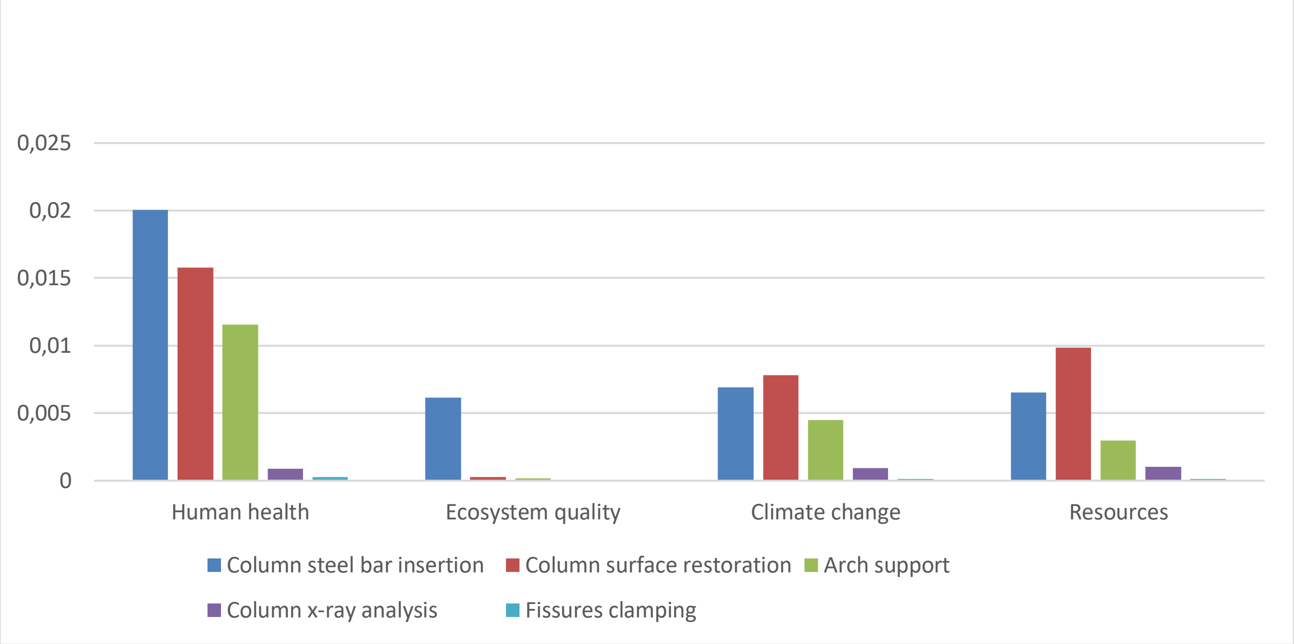


Figure 15. San Felice colonnade restoration. Interventions comparison. Damage assessment, normalized results. IMPACT 2002+, modified version.

The pre-normalized calculated damages (and the respective units) for each category are reported in Table 6, while the process contribution and substance contribution analysis are shown in Table 7 and 8, respectively.

Damage category	*Unit*	***Column steel bar insertion*	***Column surface restoration*	***Arch support*	***Column x-ray analysis*	***Fissures clamping*
Human health	DALY	0.0001423	0.0001119	9.24048E-05	5.74035E-06	1.97991E-06
Ecosystem quality	PDF*m2*yr	84.2955879	3.5070829	13.2726905	1.3459946	0.2285562
Climate change	kg CO2 eq	68.2625331	77.8722892	47.0654866	9.0779512	1.3768288
Resources	MJ primary	992.3058346	1500.2056190	502.3971865	155.1600234	21.5129134

Table 6. San Felice colonnade restoration. Interventions comparison. Damage assessment results. Modified IMPACT 2002+.

Process	*Unit*	***Column steel bar insertion*	***Column surface restoration*	***Arch support*	***Column x-ray analysis*	***Fissures clamping*
Total of all processes	mPt	39.6493	33.72031	22.05737	2.845474	0.576467

Ferrochromium, high-carbon, 68% Cr {GLO}| production | Alloc Def, U	mPt	5.300606	0.001645	0.202427	0.001711	0.041484
Ferronickel, 25% Ni {GLO}| production | Alloc Def, U	mPt	2.483131	0.001252	0.114185	0.001126	0.019299
Softwood, CO2-removal and land use {RoW}| softwood forestry, CO2-removal and land use | Alloc Def, U	mPt	1.55321	0.000226	0.517941	0.000515	3.82E-05
Wood ash mixture, pure {CH}| treatment of, landfarming | Alloc Def, U	mPt	1.402272	0.001006	0.546403	0.007779	0.000367
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Def, U	mPt	1.336239	0.006356	0.113291	0.0042	0.009136
Epoxy resin, liquid {RoW}| production | Alloc Def, U	mPt	1.206771	21.10042	0.005324	7.77E-05	0.256046
Iron ore, crude ore, 46% Fe {GLO}| iron mine operation, crude ore, 46% Fe | Alloc Def, U	mPt	0.995983	0.017442	3.463739	0.028583	0.003865
Petroleum {RoW}| and gas production, off-shore | Alloc Def, U	mPt	0.959765	0.080439	0.522261	0.066884	0.002929
Diesel, burned in building machine {GLO}| processing | Alloc Def, U	mPt	0.900129	0.024826	0.379544	0.006448	0.001694
Log, energy wood, split, measured as solid wood under bark {RoW}| heat production, mixed logs, at wood heater 6kW | Alloc Def, U	mPt	0.872281	0.000158	0.311566	0.000643	2.84E-05
Hard coal {CN}| mine operation | Alloc Def, U	mPt	0.689891	0.011958	0.814561	0.015306	0.003376
Softwood, CO2-removal and land use {NORDEL}| softwood forestry, CO2-removal and land use | Alloc Def, U	mPt	0.683285	9.92E-05	0.227851	0.000227	1.68E-05
Softwood, CO2-removal and land use {Europe without NORDEL (NCPA)}| softwood forestry, CO2-removal and land use | Alloc Def, U	mPt	0.683285	9.92E-05	0.227851	0.000227	1.68E-05
Electricity, high voltage {CN}| electricity production, hard coal | Alloc Def, U	mPt	0.63218	0.014606	0.306836	0.010443	0.002684
Electricity, low voltage {IT}| market for | Alloc Def, S	mPt	0.627447	0	0	0	0

Transport, freight, sea, transoceanic ship {GLO}| processing | Alloc Def, U	mPt	0.62256	0.039188	0.70464	0.009443	0.001823
Coke {RoW}| coking | Alloc Def, U	mPt	0.613258	0.010732	2.144053	0.017692	0.002345
Epoxy resin, liquid {RER}| production | Alloc Def, U	mPt	0.595974	10.42061	0.002629	3.84E-05	0.12645
Transport, freight, light commercial vehicle {RoW}| processing | Alloc Def, U	mPt	0.571255	0.005156	0.212531	0.000591	8.38E-05
Electricity, high voltage {RoW}| electricity production, hard coal | Alloc Def, U	mPt	0.553835	0.008156	0.171501	0.018713	0.002957
Waste plastic, mixture {CH}| treatment of, municipal incineration | Alloc Def, U	mPt	0.512558	0.943044	0.265781	8.14E-05	0.035778
Log, energy wood, split, measured as solid wood under bark {RoW}| heat production, mixed logs, at furnace 30kW | Alloc Def, U	mPt	0.405183	7.36E-05	0.144725	0.000299	1.32E-05
Soybean {RoW}| production | Alloc Def, U	mPt	-0.47172	-0.0023	-0.95501	-0.00165	-6E-05
Remaining processes	mPt	15.91992	1.035113	11.61274	2.6561	0.066095

Table 7. San Felice colonnade restoration. Interventions comparison. Process contribution to single score. Cut off 1%. Modified IMPACT 2002+.

The process that - alone - is associated to the highest potential damage is <u>Epoxy resin, liquid {RoW}| production | Alloc Def, U</u> (21.1 mPt), used for the *Column surface restoration*, while the process that causes the highest potential damage within the *Column steel bar insertion* intervention is <u>Ferrochromium, high-carbon, 68% Cr {GLO}| production | Alloc Def, U</u> (5.3 mPt), involved in the steel bar production.

Substance	*Unit*	***Column steel bar insertion*	***Column surface restoration*	***Arch support*	***Column x-ray analysis*	***Fissures clamping*
Total	mPt	39.6493	33.7203	22.0574	2.8454	0.5764
Particulates, < 2.5 um (air)	mPt	8.6198	4.0349	3.7195	0.1932	0.0908
Carbon dioxide, fossil (air)	mPt	6.5408	7.5000	4.4859	0.8740	0.1336
Nitrogen oxides	mPt	3.3547	5.0245	1.7949	0.2091	0.0695
Particulates, > 2.5 um, and < 10um (air)	mPt	2.9355	3.7036	2.8016	0.0447	0.0582
Occupation, forest, intensive	mPt	2.9275	0.0005	1.0378	0.0021	9.74E-05
Gas, natural/m3	mPt	1.9269	6.0609	0.6875	0.6157	0.0783
Sulfur dioxide (air)	mPt	1.6781	1.6135	0.9332	0.2064	0.0261
Oil, crude	mPt	1.6075	2.2640	0.8076	0.1117	0.0305
Coal, hard	mPt	1.5905	0.5098	1.5453	0.1650	0.0130

Particulates, > 10 um (air)	mPt	1.3476	0.8489	2.3614	0.0568	0.0160
Chromium (air)	mPt	1.1948	0.0004	0.0444	0.0004	0.0088
Aluminium (soil)	mPt	0.7988	0.0026	0.2839	0.0203	0.0003
Zinc (soil)	mPt	0.7220	0.0223	0.2705	0.0051	0.0005
Hydrocarbons, aromatic (air)	mPt	0.6770	0.4272	0.2731	0.0626	0.0083
Transformation, to forest, intensive	mPt	0.6345	0.0001	0.2239	0.0004	2.07E-05
Nickel, 1.98% in silicates, 1.04% in crude ore	mPt	0.6176	0.0003	0.0283	0.0002	0.004
Uranium	mPt	0.5819	0.8821	0.1751	0.1138	0.0122
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p- (air)	mPt	0.4337	0.1312	0.4564	0.0067	0.0061
Transformation, from forest, extensive	mPt	-0.6387	-0.0001	-0.2254	-0.0004	-2.1E-05
Transformation, from arable	mPt	-0.7496	-0.0078	-1.2901	-0.1031	-0.0004
Remaining substances (air)	mPt	2.8476	0.7007	1.6417	0.2597	0.0190

Table 8. San Felice colonnade restoration. Interventions comparison. Substance contribution to single score. Cut off 1%. Modified IMPACT 2002+.

As far as the substance contribution is concerned, the highest potential impact is due to Particulates, < 2.5 um (8.6 mPts). This particulate is emitted to air mainly during the activities linked to the *Column steel bar insertion* intervention, in particular during the production of Ferrochromium, high-carbon, 68% Cr {GLO}| production | Alloc Def, U.

4.1.4. Social LCA: Impact Method proposal to assess the value of Built Cultural Heritage

The establishment of the economic value of Cultural Heritage has always been problematic due to the public nature of cultural heritage goods that causes a market failure, a situation in which the market and the price system do not reflect the impact produced by a good on the individual welfare. According to Moreschini (2003) this is mainly caused by the following circumstances:

- no one can be excluded from exploiting/using the good and the use of the good from an individual does not prevent another individual to do the same,
- public goods are associated to high positive externalities, i.e. benefits that are not associated to a direct cost for the beneficiary.

All this aspects make very difficult to estimate a price that describes the costs and especially the benefits of a public good as cultural heritage.

A commonly used method to establish the value of a public good is the Willingness To Pay (WTP). According to Pierce (1993), even if the WTP is not a perfect estimator for the economic value of a cultural or environmental good, it can be a useful instrument to determine the management, regulation and financing strategies within the public administration sector. The WTP method is then in line with the economic theory's assumption that the collective welfare is determined by the satisfaction of personal needs and preferences. Nevertheless, within the proposed modified version of the IMPACT2002+ method, we chose not to use the WTP as a first step to assess the sociocultural value of the Built Cultural Heritage in favour of non-monetary indicators that are – when possible – calculated based on some established reference values. This decision is due to the awareness that some reliability issues affect the WTP methods, no matter which kind of questionnaire or indicator is used. Moreover, we aimed to build an as far as possible standardized and reproducible method, compatible with the LCA guidelines. The WTP is though used for the monetization procedure of the sociocultural indicators within the LCC analysis.

4.1.4.1. Sociocultural indicators: impact and damage assessment

During an expert panel meeting among members or the Superintendence for historical goods of Modena and Reggio Emilia and members of the LCA Working Group of the University of Modena and Reggio Emilia, some appropriate sociocultural indicators were chosen and classified into Impact Categories. A characterization factor was then established to express the relative contribution of each indicator to the considered Impact Category. The values of all the characterization factors are assumed within a range from 0.1 to 1 during a round table within the LCA Working group members; a specific stakeholders analysis and interview will follow in the future. In the damage assessment phase, each Impact Category is associated to a Damage Category. In this case, the characterization factor is negative in order to signal the social and cultural benefits of Cultural Heritage restoration. The normalization factors are calculated as the inverse ratio of the maximum value that the impact/damage categories can acquire. For the Maintenance of Cultural Assets and Human Well-being categories, the maximum value corresponds to the sum of the maximum characterization values of all the sociocultural indicators. For the Building Function and Maintenance of the urban fabric categories, a mutual exclusion of the sociocultural indicators is assumed (i.e. a building cannot be a hospital and a house at the same time or it cannot be located inside and outside the urban centre): the maximum value is then equal to 1 (that corresponds to the building's best function or optimal position). The sociocultural indicators, Impact/Damage Categories, characterization and normalization factors are summarized in Table 9.

Impact category	***Sociocultural indicator***	***Charact. Factor***	***Damage category***	***Damage assess. Factor***	***Normalization Factor***
Cultural value of building	Age of building	1	**Maintenance of cultural assets**	-1	0.35714286
	Historical evidence	1			
	Aesthetic value	0.8			
Building function	Cultural building	0.6	**Building Function**	-1	1
	Hospital and Health building	0.9			
	Housing	1			
	Public building	0.7			
	Religious building	0.7			
	Scholastic building	0.8			
	Social building	0.6			
	Sport building	0.5			
	Alimentation	1	**Human well-being**	-1	0.1315789

Human well-being	Cultural heritage hand down	0.5			
	Education	0.8			
	Figurative arts	0.5			
	Institutional relations	0.8			
	Interpersonal relationships	0.8			
	Listening to music	0.5			
	Reading	0.5			
	Relax	0.8			
	Sexuality	1			
	Sport	0.4			
Urban value	Building location in the outskirt	0.4	**Maintenance of the urban fabric**	-1	1
	Building location inside the urban centre	1			
	Building location outside the urban centre	0.1			

Table 9. S-LCA of Cultural Heritage. List of the proposed sociocultural indicators, impact and damage categories, normalization and characterization factors.

As far as the weighting is concerned, the following factors are used: 1 for the Maintenance of cultural assets and Human well-being damage category and 0.5 for the Building Function and Maintenance of the urban fabric ones. Human well-being and Maintenance of cultural assets are assumed have a greater influence in the determination of the sociocultural value for obvious reasons related to the intrinsic nature of the sociocultural indicators that have as first stakeholder the whole society and the because of the unique value of cultural assets that cannot be reproduced once lost.

4.1.4.2. Sociocultural Indicators: values rating

In this chapter a description of the proceedings, reference values or assumptions used to establish the values of the sociocultural indicators is provided. As previously stated, in order to make it more intelligible, a particular case study is taken as example: the hypothetical restoration intervention of the columns of the San Felice colonnade in Pavia, Italy. The colonnade is part of a former monastery complex, now used as a university location.

In this particular case, the colonnade is considered as an architectural element on its own and not as a part of the university building. This choice is due to the fact that the life cycle functional unit of this study is limited to the restoration of the columns and does not include the other elements of the court (i.e. the frescos, the pavements, the lighting and the well). Moreover it is consistent with the CH-LCM approach used in this study that considers only the materials, processes, energy use and end of life of the restoration intervention, without taking into account the previous materials and components. Last but not least it allows avoiding allocation problems.

- Age of Building

The chosen reference value used to calculate the value of the Age of Building indicator is the age of the Pyramid of Cheops in Egypt that dates back to 2540 BC. As there are no official archives that testify which is the most ancient existing architecture in the world, the choice fell on one of the most

known and most ancient constructions, that meets all the criteria to be part of the UNESCO World Heritage List [9].
The year of construction of the San Felice complex is unknown. The most ancient information go back to the VIII century. The date used to estimate the Age of Building indicator value in this study is 1450, when the building – including the colonnade – underwent a complete reconstruction. The indicator's value (x) can then be obtained using a simple ratio:

$$1/Arb=x/(CY-Acb)$$

Where:
Arb ≡ Age of the Reference Building
CY ≡ Current Year
Acb ≡ Age of the Considered Building

x=(2016-1450)/(2540+2016)=0.123959 (with 1 being the maximum value and 0 the lowest one).

- Historical evidence

In order to establish the value of the Historical evidence indicator we referred to the Cultural Heritage catalogue of SIRBeC, the Lombardy region's Information System for cultural goods. SIRBeC took a census of 16622 architectural goods in Lombardy.
These goods are divided in six architectural categories: fortified architecture, industrial and productive architecture; residency, tertiary and services; religious and ritual architecture, rural architecture; infrastructures and plants. Considering that the category with the highest number of registered goods is residency, tertiary and services (6946), a value from 0.1 to 1 is assigned according to the number of built heritage elements belonging to a specific category on the Lombard territory. Table 2 shows the value associated to different number of testimonies ranges (valid for the Lombard territory).

Number of architectural heritage elements	***Value***
1	1
2 – 10	0.9
11 – 50	0.8
51 – 100	0.7
101 – 250	0.6
251 – 500	0.5
501 – 1000	0.4
1001 – 2000	0.3
2001 - 4000	0.2
4001 -7000	0.1

Table 10. Values associated to different ranges of built CH testimonies (number of testimonies in Lombardy based on the SIRBeC catalogue).

The colonnade is an example of religious and ritual architecture, a category that counts 3367 registered goods in Lombardy and falls within range 2001 – 4000, with an associated value of 0.2.
It is important to note that the SIRBeC census does not include all the architectural goods in the Lombard territory but it is the sole official source. For this reason, the indicator value was calculated without taking into account the time capsule of the colonnade – the period from XIII and XVII century, corresponding to the Italian Renaissance – for which only 414 architectural goods are registered. Nevertheless, a correction that accounts for the material is suggested: 0.1 additional points for refined materials and 0.2 additional points if the materials are extremely rare. The indicator value is therefore increased of 0.2 to consider the scarcity of the Angera stone used to build the colonnade. The Angera stone is a sedimentary rock mainly composed of dolomite that was widely employed in the Lombard architecture. The caves – located on the eastern shore of Lake Maggiore – were abandoned in 1600 because of the stability risk they caused to the aboveground Borromeo fortress (Gulotta et al., 2013)

- Aesthetic value

For this particular indicator we did not find any reference value. The indicator input is therefore the result of a subjective assessment. We assumed that - once restored - the colonnade would have a relatively high aesthetic value of 0.8 (with 1 being the maximum value).

- Cultural building

The value of this indicator - associated to the Building function impact category – is assessed using a dummy variable: 1 when it represents the final use of the building or 0 in the opposite case. This is valid also for the remaining eight Building function indicators listed hereafter.

- Hospital and Health building
- Housing
- Public building
- Religious building
- Scholastic building
- Social building
- Sport building

- Alimentation

The value of this indicator - associated to the Human well-being impact category – is usually assessed using a dummy variable: 1 when it represents the main activity carried out in the building or 0 in the opposite case. This is valid also for the following remaining Human well-being indicators.

- Cultural heritage hand down
- Education
- Figurative arts
- Institutional relations
- Interpersonal relationships
- Leisure activities
- Sport

- Building location in the outskirt

The value of this indicator - associated to the Urban value impact category – is assessed using a dummy variable: 1 when it represents the present location of the building or 0 in the opposite case. This is valid also for the following remaining Urban value indicators.

- Building location inside the urban centre
- Building location outside the urban centre

Table 11 summarizes the values used for the colonnade assessment as well as the methodologies used to establish them.

Impact category	***Sociocultural indicator***	***Value***	***Calculation method***
Cultural value of building	Age of building	0.1239	The maximum value (1) is assumed for a building as ancient as the the Pyramid of Cheops in Egypt (2540 a.C.) → (2540+2014) = 4554 years Age of the colonnade → (2014-1450) = 564 years 1:X = 4554: 564
	Historical evidence	0.4	CH catalogue of SIRBeC → census of 16622 architectural goods . Correction that accounts for the scarcity Angera stone → + 0.2
	Aesthetic value	0.8	Personal assumption [0;1]
Building function	Cultural building	0	Dummy variable: 1 (final use of the building) or 0
	Hospital and Health building	0	Same as above
	Housing	0	Same as above
	Public building	0	Same as above
	Religious building	0	Same as above
	Scholastic building	0	Same as above
	Social building	0	Same as above
	Sport building	0	Same as above
Human well-being	Alimentation	0	Dummy variable: 1 (main activity carried out in the building) or 0
	Cultural heritage hand down	1	Same as above
	Education	0	Same as above
	Figurative arts	0	Same as above
	Institutional relations	0	Same as above
	Interpersonal relationships	0	Same as above
	Listening to music	0	Same as above
	Reading	0	Same as above
	Relax	0	Same as above
	Sexuality	0	Same as above
	Sport	0	Same as above
Urban value	Building location in the outskirt	0	Dummy variable: 1(present location of the building) or 0

	Building location inside the urban centre	1	Same as above
	Building location outside the urban centre	0	Same as above

Table 11. Values of the proposed sociocultural indicators. Method description and rating for the San Felice colonnade.

4.1.4.3. Results and discussion

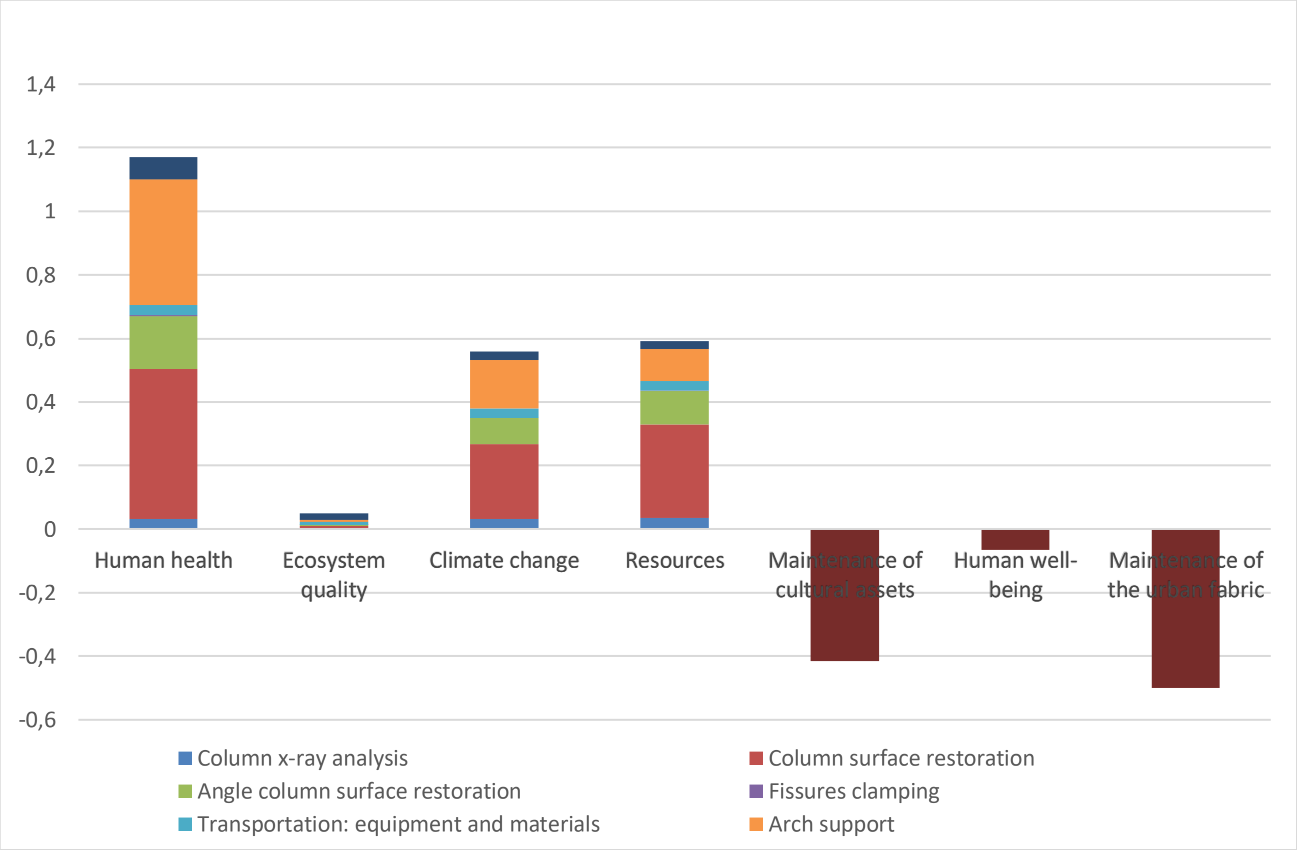


Figure 16. San Felice colonnade restoration. Normalized damage categories results (E-LCA) and sociocultural assessment results. Modified IMPACT 2002+ and proposed sociocultural indicators framework. The two assessments ought not to be aggregated or compared.

According to the normalization results:

- The **Maintenance of cultural assets** benefit is 0.41566 times the maximum cultural value of a building, corresponding to the sum of the highest aesthetic value, the highest value associated to the building age and the highest value associated to the historical evidence.

- The **Human well being** benefit is 0.06579 times the maximum human well-being value assessed as a result of the building use, which corresponds to the sum of the different human well-being indicators considered.

- The **Building function** benefit is 0 times the value associated to housing, here considered as the most important building function.

- The **Maintenance of the urban fabric** benefit is 1, equal to the maximum urban value of the building (location within the city centre).

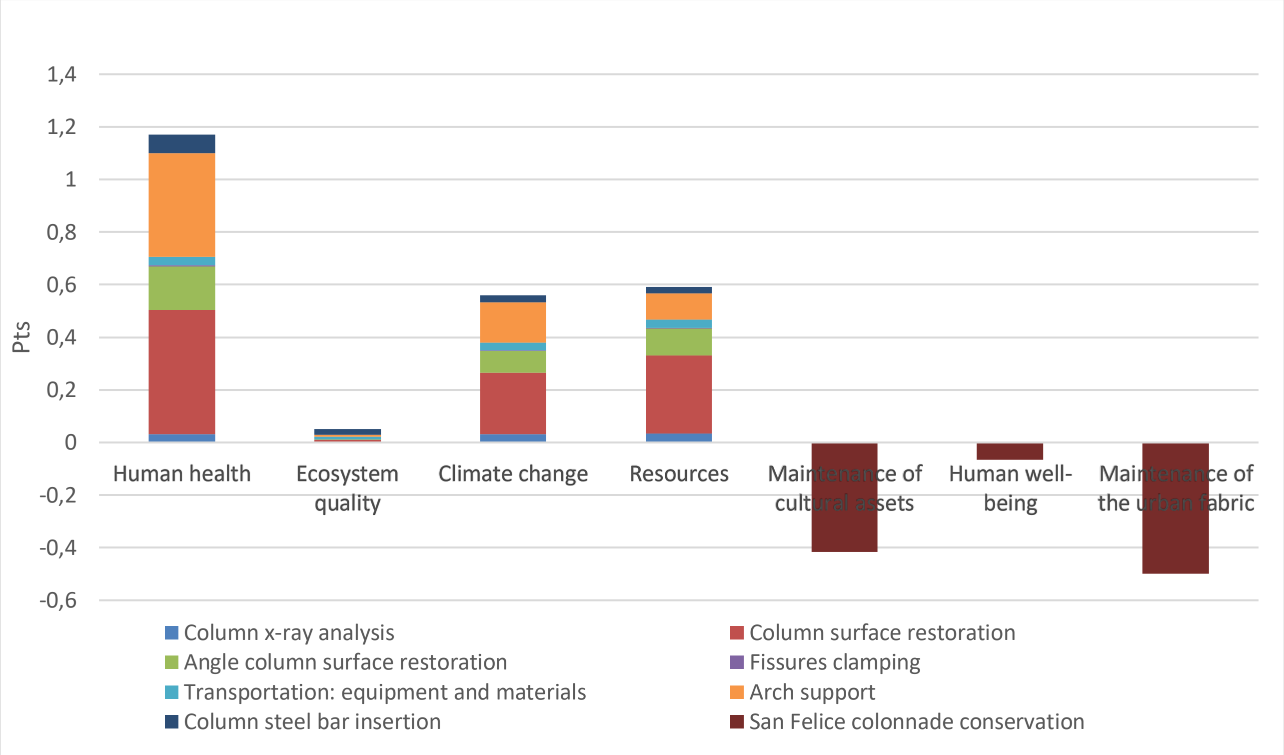


Figure 17. San Felice colonnade restoration. Weighted damage categories results (E-LCA) and sociocultural assessment results. Modified IMPACT 2002+ and proposed sociocultural indicators framework. The two assessments ought not to be aggregated or compared.

According to the weighting results, the total social value of the colonnade is equal to -0.98145 Pt, of which 50.95% is due to Maintenance of the urban fabric, 42.35% to Maintenance of cultural assets and 6.7% to Human well-being.

4.1.5. Societal LCC: sociocultural indicators' monetization proposal

Following the environmental and social LCA, the life cycle sustainability assessement is completed with the societal Life Cycle Costing, an assessment that includes the internal, external and monetarized social benefits of the considered product system.

In this chapter the monetarization procedure used to establish the economic value of the sociocultural indicators used within the San Felice colonnade case study is described.

4.1.5.1. Monetisation procedure

- Maintenance of cultural assets

Pearce and Mourato (1998) estimated the WTP values for CH conservation and restoration all over the world. Moreschini (2003) elaborated these values and found out the maximum and minimum WTP for five different categories of Built CH. The minimum WTP for groups of historical monuments is 0.01% of the annual salary while the maximum WTP is 0.2%. Considering that the average yearly European salary amounts to 31150€, the average WTP is estimated: 31150*(0.0001+0.00.2)/2=32.71€.

This amount should be allocated according to the number of stakeholders (e.g. the residents of a city or a region) and the number of monuments present in the specific area.

In 2014, the municipality of Pavia had a population of 71297 residents, of which 89.1% were above 15 years old (www.comuni-italiani.it) and, according to the SIRBeC census, the territory hosts 49 testimonies of religious and ritual architecture. The Characterization Factor (CF) for the Maintenance of Cultural Assets damage category is equal to:

$$CF = R_m * R_{>15} * ES_y * R_{ys} / T_a \qquad (4.1.5.1.1)$$

Where:

R_m ≡ N. of Residents of the Considered Municipality

$R_{>15}$ ≡ Ratio of Residents above 15 years of age

ES_y ≡ Average Yearly European Salary (€)

R_{ys} ≡ Average Ratio of Yearly Salary citizens are willing to pay for CH conservation and restoration all over the world

T_a ≡ N. of Testimonies of the same Architecture typology

According to the above mentioned figures:

CF= 71297*0.891*31150*0.00105/49 = 42403€

- Building function

In order establish the economic value of the Building Function damage category, the WTP for housing, which is the indicator with the highest characterization factor within the Building Function impact category, was estimated using the average rental expenditure in Europe – 2163€ per citizen is used as a proxy (http://www.confcommercio.it/archivio-notizie#notarget). The average period of rental payment is assumed to be 55 years (80-25). The Characterization Factor for this Damage category is equal to:

$$CF=RE*RP \qquad (4.1.5.1.2)$$

Where:

RE ≡ Average European Rental Expenditure (€)

RP ≡ Average lifetime Rental Period (y)

CF=2163*55=118965€

(We remind that the building function's indicators are mutually exclusive and this figure corresponds to the maximum value of the building function that will be allocated according the impact category characterization factors)

- Human well-being

Diener and Chan (2011) estimated that high levels of subjective well-being (SWB) can add 4 to 10 years to life compared with low levels of subjective wellbeing.

SWB refers to how people experience the quality of their lives. Studies in this field differ substantially in the measurement of SWB. Very few studies use measures of SWB besides self-report. Moreover, SWB can be affected by personality and genetic among other issues. At the same time the indicators of the Human Well-Being category (Alimentation, Cultural heritage hand down, Education, Figurative arts, Institutional relations, Interpersonal relationships, Listening to music, Reading, Relax, Sexuality, Sport) certainly play an important role in the determination of SWB. These indicators are closely related to aspects different from the simple presence of a building allowing performing such activities (e.g. wealth and social organization) but SWB surely benefits from the presence of such dedicated structures. Taking all this into consideration, the maximum benefit in terms of increased life expectancy due to the well-being associate to cultural heritage conservation is 2 years. This corresponds to half of the lowest value found by Diener and Chan. The economic value of this benefit can be calculated based on the average yearly European salary of 31150€.

$$CF= ES_y * IE_l \tag{4.1.5.1.3}$$

Where:

IE_l ≡ Increased Life Expectancy

CF=31150*2 = 62300€.

- Maintenance of the urban fabric

In order to establish the characterization factor of the Maintenance of the urban fabric category we used the hedonic prices method. This method is based on the idea that the price of a house will increase with the proximity to a natural good. Indeed, Gibbons et al. (2014) showed that increasing distance to natural amenities is unambiguously associated with a fall in prices of English houses. In default of other studies, we assumed a parallelism between CH and environmental goods. The latter are used as a proxy for CH goods.

The maintenance of the urban fabric and the consequent value of a house in the city centre is not barely associated to the presence of historical monuments. It is linked to a great number of variables like the presence of a business improvement district, of services such as transportation and public parks, of plazas and other meeting points, of schools, gyms, bars, amusements, houses of God and so on. For this reason, we assumed that the contribution of CH to the maintenance of the urban fabric is equal to 1%.

The number of houses in the municipality of Pavia was 37991 in 2011. Considering that the city centre area is around 10% of the municipality area, we accounted for 3799 houses. The value of the colonnade should be calculated relative to the number of historical monuments of the city centre (221 according to the SIRBeC catalogue). A correction of -50% is applied as the total number of monuments is higher than the number of registered monuments and some monuments (like the cathedral) have a greater value. In this particular case, the Allocation based on the number of Historical Monuments (A_{hm}) is:

$A_{hm}=1/(221*1.5)= 1/331.5=0.003$

The price difference within houses due to the distance natural amenities calculated by Gibbons et al. (2014) is ~ 100000 £ ~ 125000 €. This figure is consistent with the real estate price difference in the Pavia province among the houses of the cheapest and more expensive district (1850 € /m2, which means 148000€ for a 80m2 house).

The Maintenance of the urban fabric characterization factor is then:

$$CF = I_{hp} * H_{ca} * A_{muf} * A_{hm} \tag{4.1.5.1.4}$$

Where:

I_{hp} ≡ Increase of Hedonic Price of housing

H_{ca} ≡ N. of Houses in the Considered Area

A_{muf} ≡ Allocation of the contribution of CH to the Maintenance of the Urban Fabric

CF= 125000*3799*0.01*0.003= 14325€

4.1.5.2. Results and discussion

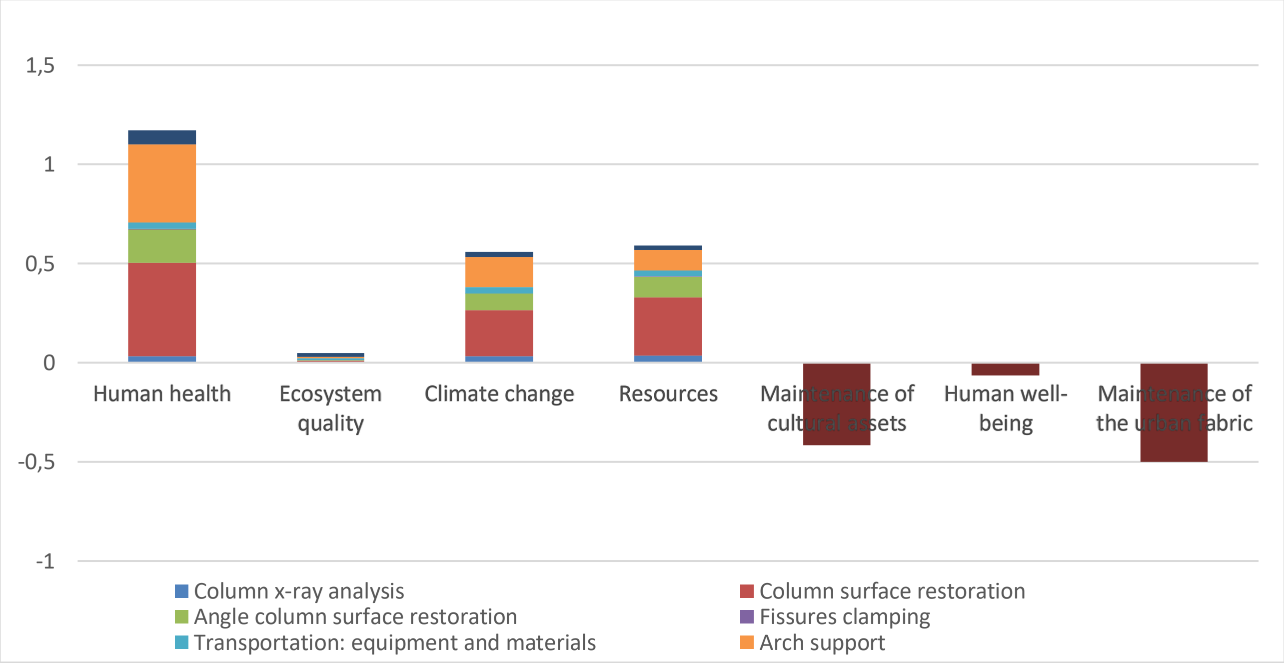


Figure 18. San Felice colonnade restoration. Normalized damage categories results (E-LCA) and monetarized sociocultural benefits. Modified IMPACT 2002+ and proposed sociocultural indicators framework. The two assessments ought not to be aggregated or compared.

Figure 18 shows the normalized results of the environmental LCA and Social LCA (red blocks).

The results of the environmental LCA are briefly analysed as their discussion deviates from the scope of this paper. The normalization results calculated with IMPACT 2002+ allow comparing the potential damage caused by the restoration of the colonnade with the damage produced by a single European citizen over one year, allocated within four damage categories: Human Health, Ecosystem Quality, Climate Change and Resources. The potential damages are 1.22, 0.09, 0.58 and 0.61 times the damage caused by an average European citizen, respectively.

As far as the social LCA is concerned, according to the normalization results:

- The **Maintenance of cultural assets** benefit is equal to 41.6% of the maximum benefit deriving from the cultural value of a building, corresponding to the sum of the highest aesthetic value, the highest value associated to the building age and the highest value associated to the historical evidence.
- The **Human well-being** benefit corresponds to 6.6% the maximum human well-being value assessed as a result of a building use, which corresponds to the sum of the different human well-being indicators considered.
- The **Maintenance of the urban fabric** benefit is 1, equal to the maximum urban value of the building (location within the city centre).

All the contemplated benefits must be interpreted as the result of the colonnade restoration, therefore the conservation of the built cultural heritage considered that would otherwise be lost.

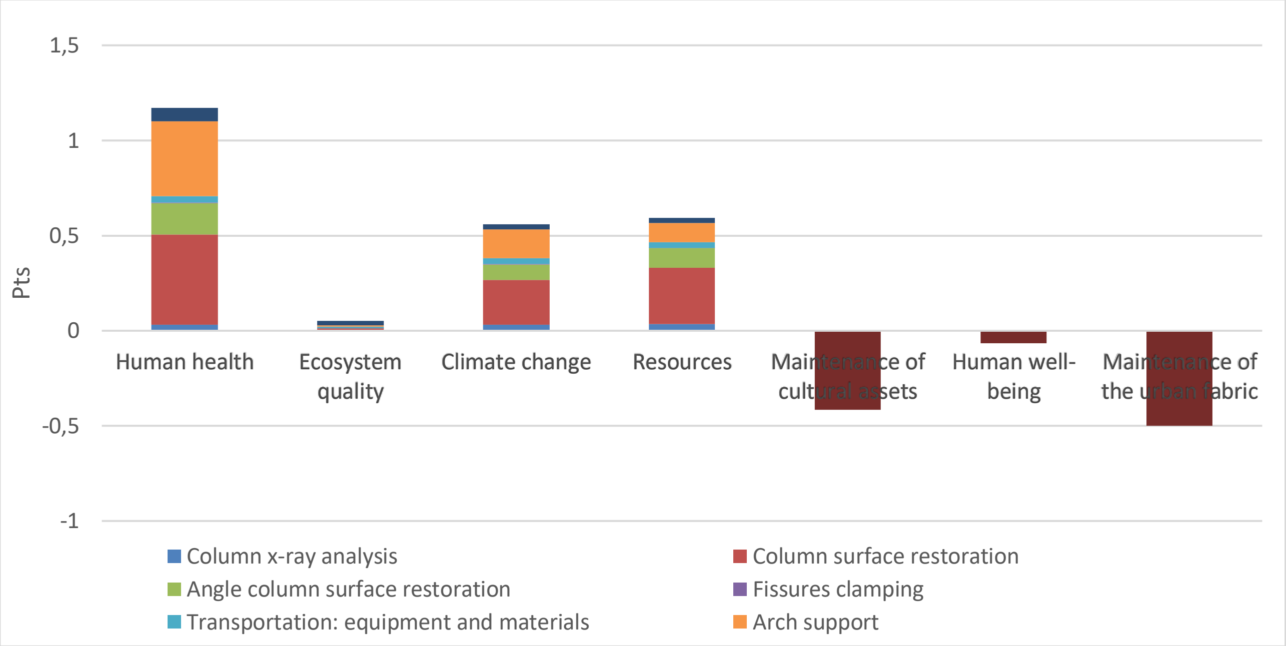


Figure 19. San Felice colonnade restoration. Weighted damage categories results (E-LCA) and monetarized sociocultural benefits. Modified IMPACT 2002+ and proposed sociocultural indicators framework. The two assessments ought not to be aggregated or compared.

According to the weighting results (Figure 19), the total social value of the colonnade is equal to -0.98145 Pt, of which 50.95% is due to Maintenance of the urban fabric, 42.35% to Maintenance of cultural assets and 6.7% to Human well-being.

Figure 19 shows the normalized and weighted results of the Societal-LCC, with the internal costs, external costs (i.e. monetarized environmental impacts), and monetarized sociocultural benefits.

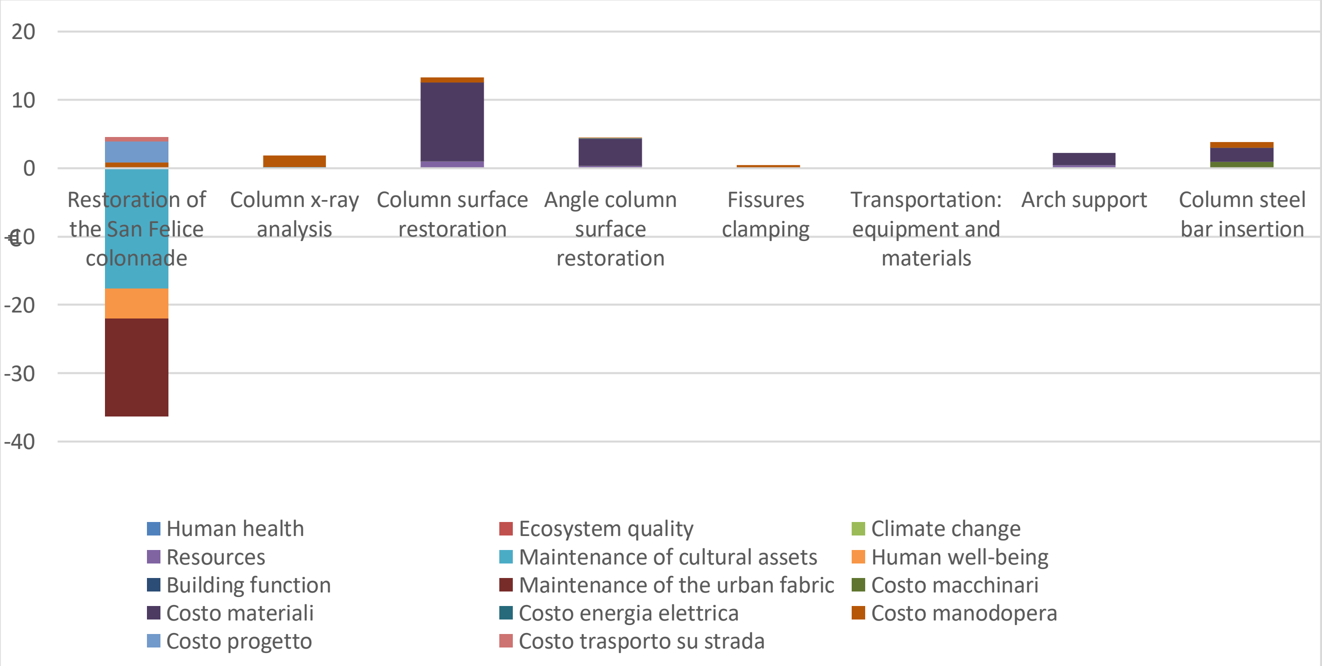


Figure 20. *San Felice colonnade restoration. Conventional and Environmental Life Cycle Costing results. Modified IMPACT 2002+ for LCC.*

The internal costs all allocated according to the equipment, transportation, materials, energy, project and labour costs. The total amount of the internal costs is ~ 28.800 €, of which 67% is due to the materials' cost. The higher environmental costs affects the Resources (~ 1900€), but the total environmental costs corresponds to about 1/10 of the internal costs. The sum of internal and external costs is equal to about 31000€.
The monetarized benefits deriving from the conservation intervention amount to ~ 36330€, with a positive balance of more than 5000€ in favour of the restoration intervention.
All the Societal-LCC figures, calculated using the modified version of IMPACT 2002+ for the E-LCC and the proposed framework for the monetisation of the sociocultural benefits, are summarized in Table 12.

As previously mentioned, this study proposes a standardized methodology allowing the assessment of the social and economic value of built cultural heritage. The indicated methodology is implemented within a modified version of the existing LCA impact method IMPACT 2002+, while the aforestated goal was triggered by the lack of recognized or widely accepted such methodologies following through the increasing demand for quantitative results. Moreover, we believe that a standardization attempt is of great importance in the case of CH sociocultural and economic value assessment. Indeed standardization allows a fair comparison of the outputs of different analysis. This would provide a useful support to decision-making and cultural heritage conservation management.

A further recommendation could be to create distinct versions of the methodology in order to reflect the perspectives associated to different categories of individuals in the modern society, similarly to the Eco-indicator 99 versions built on three out of the five archetypes proposed by the so called "Cultural Theory", a widely used support in policy making (Dutch Ministry of housing, spatial planning and the enrvironment, 2000). By doing so different values of the characterization and weighting factors can be compared within a sensitivity analysis simply confronting the outputs resulting from the different versions and decision makers would be offered a more sensitive instrument according to their needs.

To conclude – even if there is still a considerable work to be done – this proposal provides a contribution to the development of a common method to assess the value of built CH. Moreover, the same methodology can provide a comparison of different restoration interventions both from an environmental and economic point of view and represents therefore a very useful operational tool for an *a priori* assessment.

Method	***Costs***	***Human Health*** *[ELU] [€]*	***Ecosystem production capacity*** *[ELU]*	***Abiotic stock resource*** *[ELU]* ***Resource*** *[€]*	***Biodiversity*** *[ELU]* ***Ecosystem quality*** *[€]*	***Climate change*** *[€]*	***Total*** *[€]*
Modified IMPACT 2002 +	Ext.	272.67	/	1919	5.1835	44.184	**2241.038**
	Int.	**28817.36** (67.3% materials)					
	Int. + Ext.	**31058.4**					
	Soc.	**- 36337.5** (48.5% Maintenance of cultural assets)					
	Balance	**- 5279.14**					

Table 12. Societal-LCC figures, calculated using the modified version of IMPACT 2002+ for the E-LCC and the proposed framework for the monetisation of the sociocultural benefits.

4.1.6. Pietra d'Angera: Material Circularity Indicator

The previously described Material Circularity Indicator is calculatd to reflect the circularity of the Angera stone, the material used to assemble the San Felice columns. This is an applicative example on an ancient material, as the employment of probably less efficient but original materials during conservation and restoration intervention is envisaged to be extremely frequent if not mandatory. This indicator might be used as a complementary output to be coupled to the LCA results, in order to have a even more complete picture. In this particular case, the MCI is calculated only for the Angera stone, but –as previously seen- it might be calculated for the restoration intervention as a whole.

In the considered case study, the Angera stone is not recycled but it is partially removed from the polished column surface and 80% of the removed quantity is reused.

Considering 1 kg of material and the previous assumptions, the virgin feedstock V is equal to 0.2 kg and the unrecoverable waste W0 is equal to 0.2 kg as well. This gives a linear flow index LFI equal to 0.2. In order to calculate the MCI, the utility function must be estimated as well. Recalling the utlity X formula: X=L/Lav*U/Uav, only the lifespan L is considered as, in this particular case, there is no suitable measurement for the functional unit U. Normally, the lifespan of the considered material should be compared with the average lifespan of the construction materials but it does not seem correct to compare an ancient and original material with the industrial average, also because there is no alternative to the use of this particular material. For this reason the utility is considered equal to 1.

The resulting Material Circularity Indicator for the Angera stone is equal to 0.82.

4.2. The Buccola Pavilion

The Buccola Pavilion is one of the buildings of the San Lazzaro area, in Reggio Emilia (Italy), which served as a psychiatric hospital since 1827. In particular, the pavilion was built in 1932 to host the female workers.
During World War II, the San Lazzaro campus was bombed several times - due to its vicinity to the airport and to the aeronautical "Reggiane" industries. In particular, 42 bombs destroyed the Golgi section and severely damaged the other buildings. In 1978, the "Basaglia Law" enforced the shutdown of all the psychiatric hospitals in Italy: the enclosure walls of the institution were demolished and the city opened the gates of the San Lazzaro.

Figure 21. Buccola pavilion after the restoration intervention. Front entrance view.

The Buccola Pavilion restoration project started in 2002, but the construction site opened only in 2006 at it was executed only in 2007. The restored pavilion is at present a university building location of the University of Modena and Reggio Emilia (as well as the majority of the other buildings of the San Lazzaro campus). In particular, the Buccola pavilion hosts classrooms and offices of the Engineering department. Before the restoration intervention, the pavilion was unoccupied and in precarious conditions.

Figure 22. Buccola pavilion. Seamstresses department. 1936.

Figure 23. Topographic map of the San Lazzaro area. 1:2000. (From Servizio Ortofoto Agea 2011).

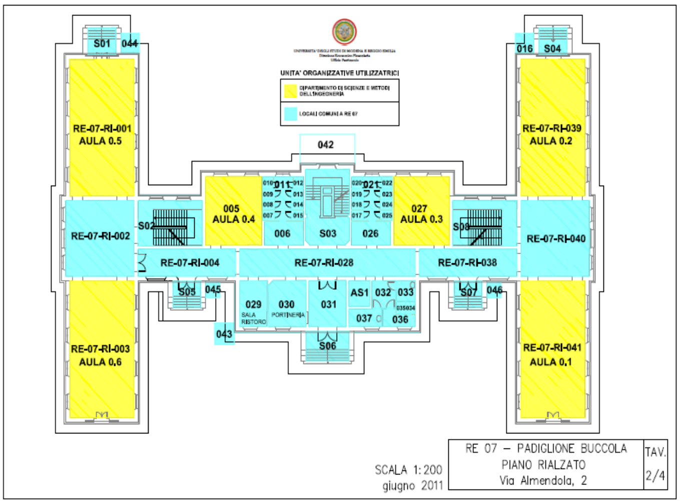


Figure 24. Buccola pavilion. Raised ground floor plan. UNIMORE technical document.

Construction date	1932
Survey plan	2001
Restoration intervention	2007
Number of floors	4 (basement, ground floor, first floor, crawl space)
Gross heated volume	12573 m3
Net area	2264 m2 (2 floors)
Total Height	9.8 m

Table 13. Buccola pavilion, restoration project details and shell data.

4.2.1. Goal & Scope definition

The aim of this LCA study is the assessment of the environmental damage due to the restoration of a cultural heritage building, taking into account also the sociocultural advantages as well as the associated internal and external costs.

The *Functional Unit* is the restoration process of the pavilion with the subsequent additional replacement of the materials characterized by a life span shorter than 100 years, that is the considered life span of the restored building. In this case, only the new additional materials are taken into account, as the dismissed materials and old materials in good conditions are associates to the life cycle of the "old" already existing building. However, the impacts of the dismissal of the old materials will be included in a further analysis with a different functional unit.

The system boundaries go from the acquisition of the raw materials and equipment necessary for the restauration interventions to the end of life scenarios. Emissions to air, water and soil are considered, as well as transportation and scrap treatment.

The data for this study have been collected from documentation of the Province of Reggio Emilia and during site inspection. The calculation has been perfomed using the software SimaPro v8.04 and the Ecoinvent database v3.1, with the additional use of the UNIMORE database when needed. Finally the impact method adopted is IMPACT 2002+, v. 2.12.

4.2.2. Life Cycle Inventory: Assumptions and processes

The Ecoinvent database offers the opportunity to use both "market" processes and "production" processes. Both are used in this study: when the products or raw materials are produced directly on the building site (e.g. cement mortar) or when their origin is known (for example when they are produced by a local firm), then the production dataset is used, otherwise the market dataset is used.

Ecoinvent allows to use regionalised data as well, even if geographical data specific for the desired countries are not always available. As a general rule, we used Italian data (actually quiet scarce); when the latter were not available, European or Swiss data were used (considered reliable due to the geographical vicinity) and global data were considered as a last option.

As the life span of the building is assumed to be extended of 100 years due to the restoration intervention, it is not possible to know the future technological scenario for the End of Life (EoL) of the materials used during the restoration. For this reason we chose to use the present best available technology scenario: all the materials than can potentially be recycled are associated to a recycling process (even if this does not represent the common practice).

Moreover, the EoL allocation for the recycling processes is treated as follow: as a closed loop approach (i.e. the secondary material displaces the use of the virgin material within the same life cycle) is not possible, an open loop is considered with an allocation at a chosen splitting point (Guinée, 2004). In this particular case, only the transportation and – where applicable- shredding or chipping are taken into account while the burden of the actual recycling process is ascribed to the secondary raw material production. This softens the cut-off or recycled content approach where no burden at all associated to the recycling process and to the producers of a potential waste but -at the same time -takes into account the potential benefit deriving from the use of a recycled material at the global level.

A splitting point allocation is preferred to an economic one because it is difficult to predict the future price both of the secondary materials and of the waste materials for recycling and likewise because the market price is regulated by laws that often do not consider the environmental impacts or at least put them in the background.

As previously mentioned, the functional unit considered in this LCA study is the restoration process of the pavilion with the subsequent additional replacement of the materials characterized by a life span shorter than 100 years. Table 1 provides a list of the restoration interventions taken into account with the associated amount. In most cases, the unit considered is p, which stands for one piece. According to the life span of the considered process, one or more pieces are necessary. For example, the heating plant is assumed to last 50 years, so 2 pieces are considered. When the whole process is assumed to have a life span of 100 years but some subprocesses or materials need to be replaced for maintenance, their amount is conveniently allocated over 100 years.

Table 14. Buccola Pavilion restoration intervertion. List of the considered processes over a lifespan of 100 years. The use phase is not included.

Processes	Amount	Unit	Details and notes
_Bricklaying 1 m3	70	m3	Total volume of walls erected during the restoration process. Lifespan 100y
_Safety stairs	2	p	Concrete safety stairs that connect the raised floor to the first floor. 2 stairs (east and west). Lifespan 100y
_Floor coverings	1	p	Coverings of the floor with porcelain grès and cement "marmiglia". Lifespan 100y. Polished every 5y
_Floor reinforcement	620	m2	Some existing floors need to be reinforced. Lifespan 100y
_Heating plant (without electricity)	2	p	New floor and ceiling fancoils are installed, as well as new circulation pumps. Lifespan 50y
_Drainage system	1	p	Drainage system replacement: PVC pipes, neoprene covering, concrete, prefabricated cement shafts and IMHOFF septic tanks. Lifespan 100y
_Power plant	2	p	The entire power plant is replaced. Lifespan 50y
_Ventilation pant	1	p	The estimated heating plant duration is 50 y. The new building life span is 100y.
_Roof	2	p	A part of the exhisting tiles and wooden structure is replaced. A chemical barrier is created. Lifespan 50y
_Windows	1	p	English window frames (estetically identical to the original ones) with double glasses are fitted. Lifespan of the glasses 100y. Lifespan of the wooden frames 50y
_Doors	2	p	Doors are supposed to last 50 years over a life span of 100 years. Front and back entrance doors, inner wood doors are replaced and some fire doors are added.
_Plastering and painting of walls	1	p	Walls are re-covered with plaster every 50y and repainted every 3 y (internal walls) or every 5 y (external walls). Allocation for every process over 100y
_Elevator	1	p	New elevator for 6 persons. Lifespan 100y
_Sheet metal works	4	p	Sheet metal works for rain drainage. Lifespan 25y

Table 2 to 25 show all the processes and subprocesses that were created in the SimaPro software. For all the subprocesses taken directly from the Ecoinvent database, please refer to the Ecoinvent website.

Table 15. Bricklaying (1m3).

Processes	**Amount**	**Unit**	**Details and notes**
Brick {RER}| production | Alloc Def, U	1041,67	kg	Production of a generic brick, considered dimensions 8x12x24 cm. Weight of each brick= 3kg. (20% of the demolished bricks are supposed to be in good conditions and therefore reused.)
Cement mortar {RoW}| production | Alloc Def, U	347,22	kg	1cm of mortar between two bricks, (sand and cement). About 0,8 kg of mortar per brick
Tap water {Europe without Switzerland}| market for | Alloc Def, S	284,72	kg	About 3 litres of water every 25 kg of mortar and 0.82 kg of water for kg of plaster
Electricity, medium voltage {IT}| market for | Alloc Def, U	1,12	kWh	Electric engine cement mixer. Power 1,5 HP = 1,12 KW. Use time: 1h
Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Alloc Def, U	69444,44	kgkm	Transportation of bricks and mortar to the building site. 50km
Waste brick {CH}| treatment of, recycling | Alloc Def, U	1041,67	kg	80% of the bricks are damaged after demolition and are recycled instead of reused. The processes considered are energy for demolition and particulate emission during demolition.
Waste mineral plaster {CH}| treatment of, collection for final disposal | Alloc Def, U	489,58	kg	Mortar cannot be recycled and is sent to an inert materials landfill. Particulate emission from demolition, transportation and landfill deposit are included in the process. Mortar weight + 50% of the water weight (assuming that 50% of the water evaporates during dry out).

Table 16. New internal cement safety stairs. One in each side of the building.

Processes	**Amount**	**Unit**	**Details and notes**
Sawnwood, board, hardwood, air dried, planed {CH}| planing, board, hardwood, air dried | Alloc Def, U	0,20	m3	Wood boards to allow concrete spraying. Reused 5 times (allocated). Specific weight 800 kg/m3
Concrete, normal {CH}| production | Alloc Def, U	7,00	m3	Concrete (already includes the EoL). Specific weight 2600 kg/m3
Reinforcing steel {GLO}| market for | Alloc Def, U	728,00	kg	Reinforcing bars
Cast iron {RER}| production | Alloc Def, U	158,78	kg	Pig iron railing
Transport, freight, lorry >32 metric ton, EURO4 {RER}| transport, freight, lorry >32 metric ton, EURO4 | Alloc Def, U	962339,00	kgkm	Railing, wood boards and reinforced concrete transportation to the building site. 50km

Machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators {GLO}| machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Alloc Def, U	3,00	hr	Operation of the cement mixer lorry
_Casting, iron	158,78	kg	Processing of iron
_Steel, preparation for recycling	728,00	kg	EoL steel. Transportation and energy for crashing
_Waste concrete gravel, preparation for recycling	18200,00	kg	EoL concrete. Energy and emissions for dismantling and transportation
_Iron, preparation for recycling	158,78	kg	EoL iron. Transportation and energy for crashing
Waste wood, post-consumer {CH}| treatment of, sorting and shredding | Conseq, U	160,00	kg	Includes transportation, sorting and shredding of wood

Table 17. Floor coverings.

Processes	**Amount**	**Unit**	**Details and notes**
Porcelain Grès	1641,88	m2	Porcelain grès floor. Allocation (100/50y)
Cement tile {CH}| production | Alloc Def, U	17284,00	kg	Cement floor. 50kg/m2 (Thickness 2 cm). 345,68 m2
Ceramic tile {CH}| production | Alloc Def, U	854,20	kg	Cement baseboard. 427,2 m; h=10 cm; 20kg/m2
Adhesive mortar {GLO}| market for | Alloc Def, U	2333,20	kg	Adhesive mortar for tiles
Polishing powder {GLO}| market for | Alloc Def, U	19,04	kg	Floor scrubbing and polishing. 629,68 m2. Approximately 800 to 1,200 sq. ft. per jar of polishing powder (1 sq. ft. = 0,093 m2) 1 jar = 1.55 lb.(1lb = 0,4536 kg) http://www.baneclene.com/catalog/euro-polish.html Polished every 25 y (allocation 100/25)
Electricity, medium voltage {IT}| market for | Alloc Def, U	528,00	kWh	Electricity for floor scrubbing and polishing. Power: 5,5 kW. Use time 24 h. http://www.orsiflaviosrl.com/levigatrice.htm. Weight 90kg. Life span 20000 h
Tap water {CH}| market for | Alloc Def, U	252,00	l	Water for the polishing powder. 1l/10 m2
Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	5054320,00	kgkm	Transportation of the tiles from the production factory to the seller. 50 km
Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	5129222,08	kgkm	Transportation of all the materials to the building site. 50 km. 50 kg/m2
_Waste concrete gravel, preparation for recycling	101086,40	kg	EoL porcelain grès, cement and ceramic tiles. Includes energy for demolition and handling in sorting plant and particulates emission

Waste cement in concrete and mortar {CH}| treatment of, sorting plant | Alloc Def, U	2333,20	kg	EoL of adhesive mortar
_Dust disposal in sanitary landfill (from Lignite ash {CH}| treatment of, sanitary landfill | Alloc Def, U)	99,38	kg	EoL dust from floor scrubbing (0,1% of the tiles weight)
Used air filter decentralized unit, 180-250 m3/h {CH}| treatment of used air filter, decentralized unit, 180-250 m3/h | Alloc Def, U	1,00	p	EoL filter of the floor machine's aspirator
Emissions			
Particulates, > 2.5 um, and < 10um (indoor)	0,50	kg	Emissions from floor scrubbing. The floor machine is connected to a vacuum cleaner. 0,1% of the floor tiles is scrubbed and 1% of the powder is emitted indoor. Half of the power is > 10 um and half is between 2.5 and 10 um
Particulates, > 10 um (indoor)	0,50	kg	Emissions from floor scrubbing. The floor machine is connected to a vacuum cleaner. 0,1% of the floor tiles is scrubbed and 1% of the powder is emitted indoor. Half of the power is > 10 um and half is between 2.5 and 10 um

Table 18. Floor reinforcement

Processes	**Amount**	**Unit**	**Details and notes**
_Electrowelded steel net (from concrete, sole plate and foundation {CH}| production | Alloc Def, U) ok	1,00	m2	Electrowelded steel net (taken from a modified process that refers to the whole floor) The area refers to the entire floor area covered by the net. Weight 12.32 kg
Cement mortar {CH}| production | Alloc Def, U	54,00	kg	Thickness 3 cm. Specific weight mortar 1800 kg/m3
Reinforcing steel {RER}| production | Alloc Def, U	0,66	kg	TECNARIA Steel connectors
Tap water, at user {Europe without Switzerland}| tap water production and supply | Alloc Def, U	6,48	kg	Water used for mortar: about 3 liters every 25 kg of mortar
Machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators {GLO}| market for | Alloc Def, U	0,17	hr	Crane and cement mixer operation. The process includes the allocation of the machine. 10 min of operation for every m2 of floor
Impact extrusion of steel, cold, 2 strokes {RER}| processing | Alloc Def, U	0,66	kg	Connectors processing
Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	3348,95	kgkm	Transportation of steel net, mortar ans steel connectors to the construction site. 50 km

_Steel, preparation for recycling	12,98	kg	EoL steel. Includes transportation and chipping energy
_Waste concrete gravel, preparation for recycling	54,00	kg	EoL concrete. Energy and emissions for dismantling

Table 19. Heating plant (without electricity). The existing pipes and the cast iron radiators are not replaced.

Processes	**Amount**	**Unit**	**Details and notes**
_Fancoil (floor)	22,00	p	N. 22 floor fancoils. Power 100W. Weight40 Kg. Dimensions 600x900x250 mm. Lifespan 50 y
_Fancoil (ceiling)	10,00	p	N. 10 ceiling fancoils. Power 110 W. Weight 20 Kg unit + 2,5 kg panel. Unit dimensions 298x575x575 mm. Panel dimensions 30x720x720 mm. Lifespan 50y
_Circulation pump 20W (from Pump, 40W {CH}| production | Alloc Def, U)	2,00	p	Lifespan water circulation pump 20000 h. 20000/8h/5d/4w/5m = 25y. Weight 3 kg.
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Rec, S	55550,00	kgkm	Transportation of fancoils and water circulation pumps to the building site. 50km

Table 20. Sabiana floor fancoil.

Processes	**Amount**	**Unit**	**Details and notes**
Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U	8,71	kg	Polyethylene for external shell, condensation bucket bacinella, fan and switches. Specfic weight 0,95 Kg/dm3
Air filter, decentralized unit, 180-250 m3/h {GLO}| market for | Alloc Def, U	5,00	p	Polypropilene air filter. Replaced every 10 years
Steel, low-alloyed {GLO}| market for | Alloc Def, U	14,32	Kg	Steel for inner structure and electric engine. Specific weight 7.85 kg/dm3
Copper {GLO}| market for | Alloc Def, U	3,58	Kg	Copper for the heat exchanger. Specific weight 8.9 Kg/dm3
Metal working, average for chromium steel product manufacturing {RER}| processing | Alloc Def, U	14,32	kg	Steel copper
Blow moulding {RER}| production | Alloc Def, U	8,71	kg	Polyethylene processing
Sheet rolling, copper {RER}| processing | Alloc Def, U	3,58	Kg	Copper processing
Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Alloc Def, U	2660,93	kgkm	Transportation of steel, copper, PE to the processing factory. 100km

_Plastic material, preparation for recycling	8,71	kg	EoL polyethylene
_Air filter, preparation for recycling	5,00	p	EoL air filter
_Steel, preparation for recycling	14,32	kg	EoL steel
_Copper, preparation for recycling	3,58	kg	EoL copper

Table 21. Sabiana ceiling fancoil.

Processes	**Amount**	**Unit**	**Details and notes**
Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U	29,57	kg	Polyethylene for external shell, condensation bucket bacinella, fan and switches. Specfic weight 0,95 Kg/dm3
Air filter, decentralized unit, 180-250 m3/h {GLO}| market for | Alloc Def, U	5,00	p	Polypropilene air filter. Replaced every 10 years
Steel, low-alloyed {GLO}| market for | Alloc Def, U	11,07	Kg	Steel for inner structure and electric engine. Specific weight 7.85 kg/dm3
Copper {GLO}| market for | Alloc Def, U	3,58	Kg	Copper for the heat exchanger. Specific weight 8.9 Kg/dm3
Metal working, average for chromium steel product manufacturing {RER}| processing | Alloc Def, U	11,07	kg	Steel copper
Blow moulding {RER}| production | Alloc Def, U	29,57	kg	Polyethylene processing
Sheet rolling, copper {RER}| processing | Alloc Def, U	3,58	Kg	Copper processing
Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Alloc Def, U	4421,51	kgkm	Transportation of steel, copper, PE to the processing factory. 100km
_Plastic material, preparation for recycling	29,57	kg	EoL polyethylene
_Air filter, preparation for recycling	5,00	p	EoL air filter
_Steel, preparation for recycling	11,07	kg	EoL steel
_Copper, preparation for recycling	3,58	kg	EoL copper

Table 22. Drainage system.

Processes	**Amount**	**Unit**	**Details and notes**

Polyvinylchloride, suspension polymerised {RER}| polyvinylchloride production, suspension polymerisation | Alloc Def, U	991,25	t	PVC drainage pipes (material production). 711 linear metres. Diameter between 100 and 280 mm (weighted average=0,074m). Specific weight= 1400 t/m3. Thickness=0,003m. Estimated lifespan: 70 y. Allocation over 100y. http://www.pvc.org/en/p/pvcs-physical-properties
Extrusion, plastic pipes {RER}| production | Alloc Def, U	991,25	t	PVC drainage pipes (extrusion). Estimated lifespan: 70 y. Allocation over 100y. http://www.pvc.org/en/p/pvcs-physical-properties
Synthetic rubber {GLO}| market for | Alloc Def, U	0,39	Kg	Neoprene covering for pipes junctions. 12 linear metres. Neoprene thickness: 0,5cm. R=10 cm. Specific weight= 1.3 g/cm3. Estimated life span: 25 y. Allocation over 100y.
Concrete, sole plate and foundation {RoW}| production | Alloc Def, U	13,38	m3	
Concrete block {RoW}| production | Alloc Rec, S	5,28	kg	Prefabricated cement shaft. Inner dimensions 40x40 cm
Concrete block {RoW}| production | Alloc Rec, S	2,16	kg	Prefabricated cement shaft. Inner dimensions 60x60 cm
Concrete block {RoW}| production | Alloc Rec, S	5,76	kg	Prefabricated cement shaft. Inner dimensions 80x80 cm
Concrete block {RoW}| production | Alloc Rec, S	3,00	kg	Prefabricated cement shaft. Inner dimensions 100x100 cm
Concrete, sole plate and foundation {RoW}| production | Alloc Def, U	7,18	m3	IMHOFF septic tank. Inner dimensions: 2,3m (diameter)*3m (height). Thickness: 0,1m.
Excavation, hydraulic digger {RER}| processing | Alloc Def, U	748,00	m3	Neoprene covering for pipes junctions. 12 linear metres. Neoprene thickness: 0,5 cm. R=10 cm. Specific weight= 1.3 g/cm3. Estimated life span: 25 y. Allocation over 100y.
Transport, freight, lorry >32 metric ton, EURO3 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Alloc Def, U	49564,25	tkm	Transportation of PVC pipes, neoprene covering, concrete, prefabricated cement shafts and IMHOFF septic tanks to the building site, 50km
Transport, freight, lorry >32 metric ton, EURO3 {RER}| transport, freight, lorry >32 metric ton, EURO3 | Alloc Def, U	99124,78	tkm	Transportation of PVC to the extrusion factory. 100km
_Waste concrete gravel, preparation for recycling	49,37	t	EoL of concrete
_Plastic material, preparation for recycling	991,25	t	EoL of PVC pipes
Waste rubber, unspecified (waste treatment) {CH}| treatment of waste rubber, unspecified, municipal incineration | Alloc Def, U	0,39	kg	EoL of neoprene

Table 23. Power plant.

Processes	**Amount**	**Unit**	**Details and notes**
Cable, three-conductor cable {GLO}| production | Alloc Def, U	1028,60	m	Electric clables. Perimeter 253,74m. Average floor height 4,8m (1,04 kg/m). Life span 50y
Polyvinylidenchloride, granulate {RER}| production | Alloc Def, U	10,58	t	PVC external conduit. Dimensions 6x1,5cm. Thickness 1mm. Length 42m. Density 1400 t/m3. Life span 25y
Polyvinylidenchloride, granulate {RER}| production | Alloc Def, U	4,28	t	PVC junction boxes, 10x15x3cm. Thickness 1mm. 34 boxes. Density 1400t/m3. Life span 25y
Polyvinylidenchloride, granulate {RER}| production | Alloc Def, U	4,49	t	PVC sockets and switches 6X8X5cm. Thickness 0.001m. 34 sockets and 34 switches. Life span 25y
Copper {RER}| production, primary | Alloc Def, U	4,08	kg	Switches copper contacts. 20g for every switch. Life span 25y
Steel, low-alloyed, hot rolled {RER}| production | Alloc Def, U	22,64	kg	Steel screws. 2 screws for every switch and socket and 2 screws every m of conduit. Lifespan 50y
Polyvinylidenchloride, granulate {RER}| production | Alloc Def, U	3,25	t	Switchboard. Dimensions 40x50x10cm, thickness 2mm. Lifespan 25 y
Copper {RER}| production, primary | Alloc Def, U	0,20	kg	Switchboard copper contacts 0.1kg. Life span 25y
Steel, low-alloyed, hot rolled {RER}| production | Alloc Def, U	0,10	kg	Switchboard screws. 0.1kg. Life span 50y
Blow moulding {RER}| production | Alloc Def, U	22,61	t	PVC prcessing
Wire drawing, copper {RER}| processing | Alloc Def, U	4,28	kg	Copper processing
Section bar rolling, steel {RER}| processing | Alloc Def, U	22,74	kg	Steel processing
Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Def, U	969,21	tkm	Transportation of PVC items and screws to the construction site. 50km
Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Alloc Rec, S	53701,20	kgkm	Transportation of cables and copper contacts to the construction site. 50km
Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Def, U	2263,65	tkm	Transportation of PVC, copper and steel to the processing factories.
Used cable {GLO}| treatment of | Alloc Def, U	1069,74	kg	EoL cables. Inlcudes manual treatment facility and electricity to sort plastic and copper.
_Steel, preparation for recycling	22,74	kg	EoL steel. Includes transportation and chipping energy.

_Plastic material, preparation for recycling	22,61	t	EoL PVC. Includes transportation and chipping energy.
_Copper, preparation for recycling	4,28	kg	EoL copper. Includes transportation and chipping energy.

Table 24. Ventilation plant

Processes	**Amount**	**Unit**	**Details and notes**
Ventilation duct, steel, 100x50 mm {RER}| production | Alloc Def, U	360,00	m	Ventilation ducts, linear. Weight= 1.5 kg/m
Ventilation duct, elbow 90 degrees, steel, 100x50 mm {RER}| production | Alloc Def, U	18,00	p	Ventilation ducts, angle. Weight per element = 0.27 kg
Ventilation duct, connection piece, steel, 100x50 mm {RER}| production | Alloc Def, U	64,00	p	Ventilation duct conjunctions. Weight per element = 0.2 kg
Air filter, central unit, 600 m3/h {RER}| production | Alloc Def, U	80,00	p	Air filters for central unit. Weight of each filter = 0,4kg. Filters are replaced every 5 years
Air filter, decentralized unit, 180-250 m3/h {RER}| production | Alloc Def, U	320,00	p	Air filters for decentralized unit. Weight of each filter = 0,22 kg. Filters are replaced every 5 years.
Ventilation control and wiring, central unit {RER}| production | Alloc Def, U	4,00	p	Air treatment plant, central unit. Weight = 4.6 kg. Allocation = 100/25 y
Ventilation control and wiring, decentralized unit {RER}| production | Alloc Def, U	16,00	p	Air treatment plant, decentralized unit. Weight = 2.18kg. Allocation = 100/25y
Room-connecting overflow element, steel, approx. 40 m3/h {RER}| production | Alloc Def, U	46,00	p	One for each room . Weight = 1.1 Kg. Allocation = 100/50 y
Exhaust air roof hood, steel, DN 400 {CH}| production | Alloc Def, U	2,00	p	Chimneys for exhausted air.
_Steel, preparation for recycling	608,26	kg	EoL Steel of ventilation ducts.
Used air filter central unit, 600 m3/h {CH}| treatment of used air filter, central unit, 600 m3/h | Alloc Def, U	80,00	p	EoL air filters, central unit.
Used air filter decentralized unit, 180-250 m3/h {CH}| treatment of used air filter, decentralized unit, 180-250 m3/h | Alloc Def, U	320,00	p	EoL air filters, decentralized unit.
Used ventilation control and wiring central unit {CH}| treatment of used ventilation control and wiring, central unit | Alloc Def, U	4,00	p	EoL central unit.
Used ventilation control and wiring decentralized unit {CH}| treatment of	16,00	p	EoL decentralized unit.

used ventilation control and wiring, decentralized unit | Alloc Def, U			
Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	38197,00	kgkm	Transportation of all the ventilation plant elements to the construction site. 50 km

Table 25. Roof restoration.

Processes	**Amount**	**Unit**	**Details and notes**
Silicon tetrahydride {GLO}| market for | Alloc Def, U	20,40	kg	Chemical barrier against humidity, silane based solution. 0,5 kg/m. 40,8 m http://www.mapei.com/IT-IT/Prodotti-per-il-risanamento-di-edifici-in-muratura/Realizzazione-di-barriera-chimica-orizzontale-contro-l-umidit%C3%A0-di-risalita-capillare/MAPESTOP
Tap water {Europe without Switzerland}| market for | Alloc Def, U	306,00	kg	Water for the silane based solution. Diluition ratio 1:15
Electricity, low voltage {IT}| market for | Alloc Def, U	750,00	Wh	Energy for the PRESS PUMP SYSTEM injection tool. 300 injectors, 3 pumps (50W). Operation time 5 h
Cement cast plaster floor {CH}| production | Alloc Def, U	5460,00	kg	Humidity removing cement cast plaster. Thickness 2,5cm. 1300 kg/m3 (The process includes water).
Sawnwood, beam, hardwood, kiln dried, planed {CH}| planing, beam, hardwood, kiln dried | Alloc Def, U	46,00	m3	Wood roof structure.
Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U	4,51	kg	Steel for nails and supports. 7,8 kg/dm3
Impact extrusion of steel, cold, deformation stroke {RoW}| processing | Alloc Def, U	4,51	kg	Steel processing
Roof tile {RER}| production | Alloc Def, U	41796,00	kg	Damaged roof tiles replacement. 60% of the tiles. Specific weight 60 kg/m2 http://www.copertureinlaterizio.it/cop/PRODOTTI_Coppi_Formati_e_tipologie.aspx
Transport, freight, lorry >32 metric ton, EURO4 {RER}| transport, freight, lorry >32 metric ton, EURO4 | Alloc Def, U	2458025,33	kgkm	Transportation of the new tiles and beams to the building site. 50km
Waste wood, post-consumer {GLO}| market for | Conseq, U	36800,00	kg	EoL wood beams. Includes trasportation, sorting and shredding
Waste brick {CH}| treatment of, recycling | Alloc Def, U	41796,00	kg	EoL roof tile.
_Steel, preparation for recycling	4,51	kg	EoL steel

Table 26. Windows.

Processes	Amount	Unit	Details and notes
_Glasses	590,50	m2	Safety glass, double glazing, pvb sheet. 100y
_Window frames	1384,84	m2	English type window frame. Wood. 50 y

Table 27. Windows' frames.

Processes	Amount	Unit	Details and notes
_English window frame (from Window frame, wood, U=1.5 W/m2K {RER}| production | Alloc Def, U)	1,00	m2	English window frame, natural wood. Thickness 65x80mm. 2 shutters.
Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Alloc Def, U	4010,00	kgkm	Transportation of the frame to the recycling facility. 1m2 of visible wooden window frame weights 80,2 kg

Table 28. Windows' double glasses.

Processes	Amount	Unit	Details and notes
Glazing, double, U<1.1 W/m2K, laminated safety glass {RER}| production | Alloc Def, U	1,00	m2	Safety glass, double glazing, pvb sheet
_Glass, preparation for recycling	644500,00	kgkm	EoL glass. 1m2 of visible glazing area has a final weight of 20 kg. 50 km

Table 29. Doors.

Processes	Amount	Unit	Details and notes
_Entrance door front	1	p	Oak front entrance door. 210x300 cm. Arch glass fanlight 70 cm
_Entrance door back	1	p	Oak back entrance door. 140x270 cm
_Fire door 120x210 wood cladding	11	p	DECOS fire door with rock wool mattresses (80mm thick) Dimensions: 120x210cm. Wood cladding on both sides

_Fire door 120x210	13	p	DECOS fire door with rock wool mattresses (80mm thick) Dimensions: 120x210cm
_Wood door 120x210	20	p	Inner wood door, thickness 5cm. 2 shutters 120(60+60)x210cm. Thickness 5cm
_Wood door 90x210	8	p	Inner wood door w90x210cm, thickness 5cm
Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Alloc Def, U	273799,5	kgkm	Transportation of the doors to the construction site. 50km

Table 30. Oak front entrance door.

Processes	**Amount**	**Unit**	**Details and notes**
Sawlog and veneer log, hardwood, debarked, measured as solid wood {RER}| market for | Alloc Def, U	0,25	m3	210x300x4cm. Oak specific weight 1 t/m3
Brass {CH}| production | Alloc Def, U	5,50	kg	Brass for lock. Specific weight 8.6 kg/dm3
Glazing, double, U<1.1 W/m2K, laminated safety glass {RER}| production | Alloc Def, U	0,77	m2	Fanlight. Arch, r= 70 cm. Specific weight of glass 2.5 kg/dm3
Window frame, wood, U=1.5 W/m2K {RER}| production | Alloc Def, U	0,11	m2	Fanlight frame. 5 cm
Power sawing, with catalytic converter {RER}| processing | Alloc Def, U	0,25	hr	Wood sawing. 15 min.
Shaving, hardwood, measured as dry mass {CH}| planing, beam, hardwood, air dried | Alloc Def, U	252,00	kg	Wood shaving
Wood preservation, dipping/immersion method, water-based, outdoor use, no ground contact {RER}| wood preservation, dipping/immersion, water-based preservative, outdoor use, no ground contact | Alloc Def, U	1,26	kg	Wood, treatment. Preservative 100g/m2
Casting, brass {CH}| processing | Alloc Rec, U	5,50	kg	Brass processing
_Brass sorting and pressing for recycling	5,50	kg	Brass sorting and pressing for recycling

Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Alloc Def, U	275,00	kgkm	Transportation of brass from the decommission site to the sorting and pressing facility. 50km
Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO6| Alloc Def, U	12875,00	kgkm	Transportation of wood and brass to the processing factory. 100km
Waste wood, post-consumer {GLO}| market for | Conseq, U	252,00	kg	Includes transportation, sorting and shredding of wood

Table 31. Back entrance door.

Processes	**Amount**	**Unit**	**Details and notes**
Sawlog and veneer log, hardwood, debarked, measured as solid wood {RER}| market for | Alloc Def, U	0,15	m3	140x270x4cm, Oak specific weight 1 t/m3
Brass {CH}| production | Alloc Def, U	5,50	kg	Brass for lock. Specific weight 8.6 kg/dm3
Power sawing, with catalytic converter {RER}| processing | Alloc Def, U	0,25	hr	Wood sawing, 15 min
Shaving, hardwood, measured as dry mass {CH}| planing, beam, hardwood, air dried | Alloc Def, U	151,20	kg	Wood shaving
Wood preservation, dipping/immersion method, water-based, outdoor use, no ground contact {RER}| wood preservation, dipping/immersion, water-based preservative, outdoor use, no ground contact | Alloc Def, U	0,76	kg	Wood, treatment. Preservative 100g/m2
Casting, brass {CH}| processing | Alloc Rec, U	5,50	kg	Brass processing
_Brass sorting and pressing for recycling	5,50	kg	Brass sorting and pressing for recycling
Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Alloc Def, U	275,00	kgkm	Transportation of brass from the decommission site to the sorting and pressing facility. 50km
Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO6| Alloc Def, U	15670,00	kgkm	Transportation of wood and brass to the processing factory. 100km

Waste wood, post-consumer {GLO}| market for | Conseq, U	151,20	kg	Includes transportation, sorting and shredding of wood

Table 32. DECOS fire door (120x210)

Processes	**Amount**	**Unit**	**Details and notes**
Steel, low-alloyed, hot rolled {RER}| production | Alloc Def, U	86,12	kg	Steel for shutters and handle. Specific weight: 7.8 kg/dm3
Urea formaldehyde foam, in situ foaming {GLO}| market for | Alloc Def, U	0,44	kg	Heat expanding sealing foam. Urea formaldehyde is used as a proxy as is it less flammable than other insulating materials. Specific weight: 1.32 kg/m3
Rock wool {GLO}| market for | Alloc Def, U	5,90	kg	Rock wool mattresses. Specific weight 90 kg/m3
Sinter, iron {GLO}| production | Alloc Def, U	21,30	kg	Inner iron structure. Specific weight 7.85 kg/dm3
Steel, low-alloyed, hot rolled {RER}| production | Alloc Def, U	16,80	kg	Steel springs for door shutting. 4 springs
Metal working, average for steel product manufacturing {RER}| processing | Alloc Def, U	102,92	kg	Steel press-bending and spring processing
Welding, arc, steel {RER}| processing | Alloc Def, U	4,60	m	Iron welding
Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Rec, S	19,53	kg	Painting, 1mm thick. 9m3/l and 1380 kg/l. Doors are re-painted every 4 years
Tap water, at user {CH}| tap water production and supply | Alloc Def, U	2,44	kg	Water for acrylic varnish
Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Alloc Def, U	10752,32	kgkm	Transportation of iron and steel to the processing factory. 100km
_Steel, preparation for recycling	102,92	kg	EoL steel
_Iron, preparation for recycling	21,30	kg	EoL iron
Waste mineral wool {CH}| treatment of, collection for final disposal | Alloc Def, U	5,90	kg	EoL rock wool

Table 33. DECOS fire door (120x210) with wood cladding.

Processes	**Amount**	**Unit**	**Details and notes**
Steel, low-alloyed, hot rolled {RER}| production | Alloc Def, U	86,12	kg	Steel for shutters and handle. Specific weight: 7.8 kg/dm3
Urea formaldehyde foam, in situ foaming {GLO}| market for | Alloc Def, U	0,44	kg	Heat expanding sealing foam. Urea formaldehyde is used as a proxy as is it less flammable than other insulating materials. Specific weight: 1.32 kg/m3
Rock wool {GLO}| market for | Alloc Def, U	5,90	kg	Rock wool mattresses. Specific weight 90 kg/m3
Sinter, iron {GLO}| production | Alloc Def, U	21,30	kg	Inner iron structure. Specific weight 7.85 kg/dm3
Steel, low-alloyed, hot rolled {RER}| production | Alloc Def, U	16,80	kg	Steel springs for door shutting. 4 springs
Sawlog and veneer log, hardwood, debarked, measured as solid wood {RER}| market for | Alloc Def, U	0,03	m3	Wood for cladding. Oak specific weight 1t/m3
Power sawing, with catalytic converter {RER}| processing | Alloc Def, U	0,25	hr	Wood sawing. 15 min.
Metal working, average for steel product manufacturing {RER}| processing | Alloc Def, U	102,92	kg	Steel press-bending and spring processing
Welding, arc, steel {RER}| processing | Alloc Def, U	4,60	m	Iron welding
Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Rec, S	19,53	kg	Painting, 1mm thick. 9m3/l and 1380 kg/l. Doors are re-painted every 4 years for 100years.
Tap water, at user {CH}| tap water production and supply | Alloc Def, U	2,44	kg	Water for acrylic varnish
Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Alloc Def, U	12422,32	kgkm	Transportation of iron and steel to the processing factory. 100kn
_Steel, preparation for recycling	102,92	kg	EoL steel
_Iron, preparation for recycling	21,30	kg	EoL iron
Waste mineral wool {CH}| treatment of, collection for final disposal | Alloc Def, U	5,90	kg	EoL rock wool
Waste wood, post-consumer {CH}| treatment of, sorting and shredding | Conseq, U	26,85	kg	Includes transportation, sorting and shredding of wood.

Table 34. Inner wood door (120x210)

Processes	Amount	Unit	Details and notes
Door, inner, wood {RER}| production | Alloc Def, U	2,52	m2	Inner wood door. Life span 50 y
_Brass sorting and pressing for recycling	5,6	kg	Brass sorting and pressing for recycling
Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Alloc Def, U	280	kgkm	Transportation of brass from the decommission site to the sorting and pressing facility. 50km
Waste wood, post-consumer {CH}| treatment of, sorting and shredding | Conseq, U	56,448	kg	End of life of wood door.

Table 35. Inner wood door (90x210)

Processes	Amount	Unit	Details and notes
Door, inner, wood {RER}| production | Alloc Def, U	1,89	m2	Inner wood door. Life span 50 y
_Brass sorting and pressing for recycling	4,8	kg	Brass sorting and pressing for recycling
Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Alloc Def, U	240	kgkm	Transportation of brass from the decommission site to the sorting and pressing facility. 50km
Waste wood, post-consumer {CH}| treatment of, sorting and shredding | Conseq, U	42,336	kg	End of life of wood door.

Table 36. Plastering and painting of walls.

Processes	Amount	Unit	Details and notes
Base plaster {RoW}| production | Alloc Def, U	827.51	t	Plastering of external walls. Perimeter 281m Height of the building from ground 12m. Windows area 416,6m2. Plaster 2cm thick. Specific weight 1400kg/m3

Base plaster {RoW}| production | Alloc Def, U	984,87	t	Plastering of internal walls. Height of raised and first floor 9,7m. Separating internal walls 121m. Windows area 382m2. Plaster 2cm thick. Specific weight 1400kg/m3
Cover plaster, mineral {RoW}| production | Alloc Def, U	457,26	t	Cover plaster for internal walls. 0,5cm thick. Specific weight 1300kg/m3. Re-covered every 50 years
Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Def, U	7781,67	kg	Painting of internal walls. Walls painted only for 1.5m from ground. Area of windows within the painted part of the wall 95,5m2. Painting 1mm thick. 9m3/l and 1380 kg/l Walls re-painted every 3 years for 100years.
Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Def, U	153,68	t	Painting for external walls. 2 mm thick. Re-painted every 5 years. http://www.brignola.it/ita/pdf/pittura%20acrilica.pdf
Tap water {Europe without Switzerland}| market for | Alloc Def, U	80731,23	kg	Water for acrylic painting. 87,5% dilution.
Tap water {Europe without Switzerland}| market for | Alloc Def, U	1861,11	t	About 0.82 kg of water for kg of plaster (1l of water assumed 1kg)
Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Alloc Def, U	121555,42	tkm	Transportation of cover plaster; sand, lime and cement (to produce the base plaster) and paints to the construction site. 50km
Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Def, U	16146,25	tkm	Transportation of acrylic varnish weight to the inert material landfill. 100km
Waste mineral plaster {CH}| treatment of, collection for final disposal | Alloc Def, U	2269,64	t	Plaster cannot be recycled and is sent to an inert materials landfill. Particulate emissions from demolition, transportation and landfill deposit are included in the process.
Waste emulsion paint (waste treatment) {CH}| treatment of, inert material landfill | Alloc Def, U	161,46	t	Acrylic varnish cannot be recycled and is sent to an inert material landfill.

Table 37. Elevator (capacity: 6 persons)

Processes	**Amount**	**Unit**	**Details and notes**
Steel, chromium steel 18/8, hot rolled {RER}| production | Alloc Def, U	0,83	ton	Steel cabin. Dimensions 2x2,5x2,4m
Steel, chromium steel 18/8, hot rolled {RER}| production | Alloc Def, U	0,18	ton	Pulley

Steel, chromium steel 18/8, hot rolled {RER}| production | Alloc Def, U	0,00	ton	Pulley's pivot
Steel, chromium steel 18/8, hot rolled {RER}| production | Alloc Def, U	0,61	ton	Cables. Life span 25y
Steel, chromium steel 18/8, hot rolled {RER}| production | Alloc Def, U	1,77	ton	Elevator's structure
_Engine (10kW)	2,00	p	Engine, 10kW. Weight 10kg. Life span 50y
Steel, chromium steel 18/8, hot rolled {RER}| production | Alloc Def, U	1,52	ton	Pistons
Heavy fuel oil, at regional storage/RER U	8,76	ton	Grease. Changed every 7 years.
Excavation, skid-steer loader {RER}| processing | Alloc Def, U	17,58	m3	Foundations. Dimensions: 2,6x2,6x2,6m. 1m of concrete and 1 m of anti-seismic rubber.
Concrete, normal {CH}| production | Alloc Def, U	6,76	m3	Concrete for foundations. Specific weight 2300kg/m3
Reinforcing steel {RER}| production | Alloc Def, U	0,00	ton	Reinforcing bars
Styrene-acrylonitrile copolymer {RER}| production | Alloc Def, U	8,21	ton	Rubber dissipators. Rubber specific weight 1200kg/m3. Diameter 1.5m. Height 1.5m. Thickness 0,03m. Steel thickness 0.001m. Allocation 100/25 y
Reinforcing steel {RER}| production | Alloc Def, U	0,44	ton	Dissipators' discs. Steel.
Reinforcing steel {RER}| production | Alloc Def, U	0,16	ton	Steel plate between the structure and the dissipators. Dimensions 1x2x0.005m
Lead {GLO}| market for | Alloc Def, U	0,83	ton	Lead counterweight (=cabin's weight)
Casting, steel, lost-wax {RoW}| casting, steel, lost-wax | Alloc Def, U	0,18	ton	Processing of pulley
Drawing of pipe, steel {RER}| processing | Alloc Def, U	0,00	ton	Processing of pulley's pivot
Sheet rolling, steel {RER}| processing | Alloc Def, U	0,83	ton	Processing of cabin steel
Wire drawing, steel {RER}| processing | Alloc Def, U	0,61	ton	Processing of cables
Section bar rolling, steel {RER}| processing | Alloc Def, U	1,77	ton	Processing of elevator's structure
Drawing of pipe, steel {RER}| processing | Alloc Def, U	1,52	ton	Processing of pistons
Section bar rolling, steel {RER}| processing | Alloc Def, U	0,00	ton	Processing of reinforcing bars
Blow moulding {RER}| production | Alloc Def, U	8,21	ton	Processing of antiseismic structure
Sheet rolling, steel {RER}| processing | Alloc Def, U	0,44	ton	Processing of dissipators' discs
Sheet rolling, steel {RER}| processing | Alloc Def, U	0,16	ton	Processing of dissipators' plate
Casting, brass {CH}| processing | Alloc Def, U	0,83	ton	Processing of counterweight

Transport, freight, lorry >32 metric ton, EURO3 {RER}| transport, freight, lorry >32 metric ton, EURO3 | Alloc Def, U	778566,12	tkm	Transportation of all the materials to the building site. 50 km
Transport, freight, lorry >32 metric ton, EURO3 {RER}| transport, freight, lorry >32 metric ton, EURO3 | Alloc Def, U	1557132,24	tkm	Transportation of all the materials to the processing factories. 100 km
Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {GLO}| market for | Alloc Rec, U	0,00	ton	EoL lead (counterweight). Recycling, only transportation is considered.
Waste mineral oil (waste treatment) {CH}| treatment of, hazardous waste incineration | Alloc Def, U	8,76	ton	End of life: oil (grease)
_Waste concrete gravel, preparation for recycling	15548,00	kg	End of life: concrete (foundations)
_Plastic material, preparation for recycling	8,21	ton	End of life: rubber (dissipators)
_Steel, preparation for recycling	5,52	ton	End of life: steel (cabin, pulley, pulley's pivot, structure, dissipators' discs and plate, pistons, cables, reinforcing bars).

Table 38. Sheet-metal works.

Processes	**Amount**	**Unit**	**Details and notes**
Copper {GLO}| market for | Alloc Def, U	1275,27	kg	Supply and installation of copper drainpipes and chimney pipes 6/10. Diameter 10 cm. 758 linear metres. Copper specific weight 8.93kg/dm3
Copper {GLO}| market for | Alloc Def, U	4,00	kg	Fastening
Metal working, average for copper product manufacturing {RER}| processing | Alloc Def, U	1281,00	kg	Processing of copper drainpipes and chimney pipes
Tin {GLO}| market for | Alloc Def, U	14,56	kg	Tin for soldering. 7,28 kg/dm3
Electricity, low voltage {IT}| market for | Alloc Def, U	90,00	Wh	Electricity for soldering. 30W
Copper {GLO}| market for | Alloc Def, U	0,60	kg	Rectangular chimney pipes. 25x25cm. H 30cm. 8 pipes
_Copper, preparation for recycling	1295,60	kg	Recycling of copper, only sorting and pressing are taken into account as the melting process is allocated to the user of the secondary material (it includes the tin used for soldering that will be part of the secondary alloy)
Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Alloc Def, U	129471,56	kgkm	Transport of pipes to the construction site. 50 km

Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Alloc Def, U	128100,3	kgkm	Transport of copper to the processing factory. 100km

4.2.3. Environmental Life Cycle Assessments results

Figure 25 shows the network tree of the LCA of the Buccola Pavilion restoration (100y), without use phase process. The width of the arrows is proportional to the potential impact associated to the considered process and the damage is expressed in points, as calculated with the impact method.

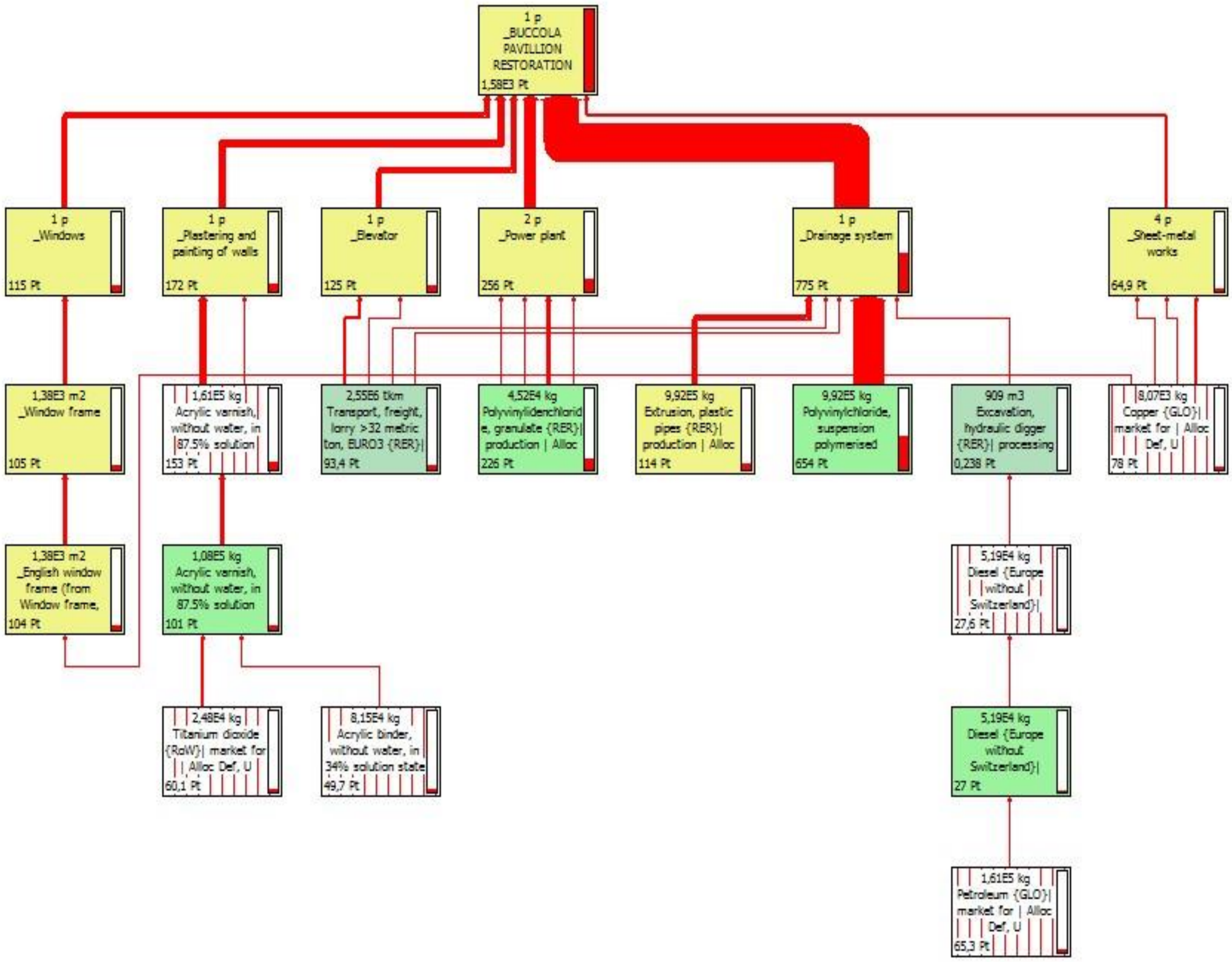


Figure 25. Buccola Pavilion restoration (100y), without-use phase, LCA network. IMPACT 2002+. Cut off: 1%.

As explicit in Figure 26, that shows the single score results, partitioned according to the different intervention processes and to the four IMPACT2002+ damage categories, the Drainage system process is responsible for almost half of the potential damage of the restoration intervention (49.03% of the total damage, that equals to 1.58 kPt). This is mainly due to the oil and natural gas consumption during the polyvinylchloride production process, which is then used for the plastic pipes production. Table 39 shows in detail the percentages of impact associated to the different processes with regard to the total score and to the four damage categories. The most affected damage category is Resources (37.6%), followed by Human health (34.1%), Climate change (23.7%) and Ecosystem quality (4.62%).

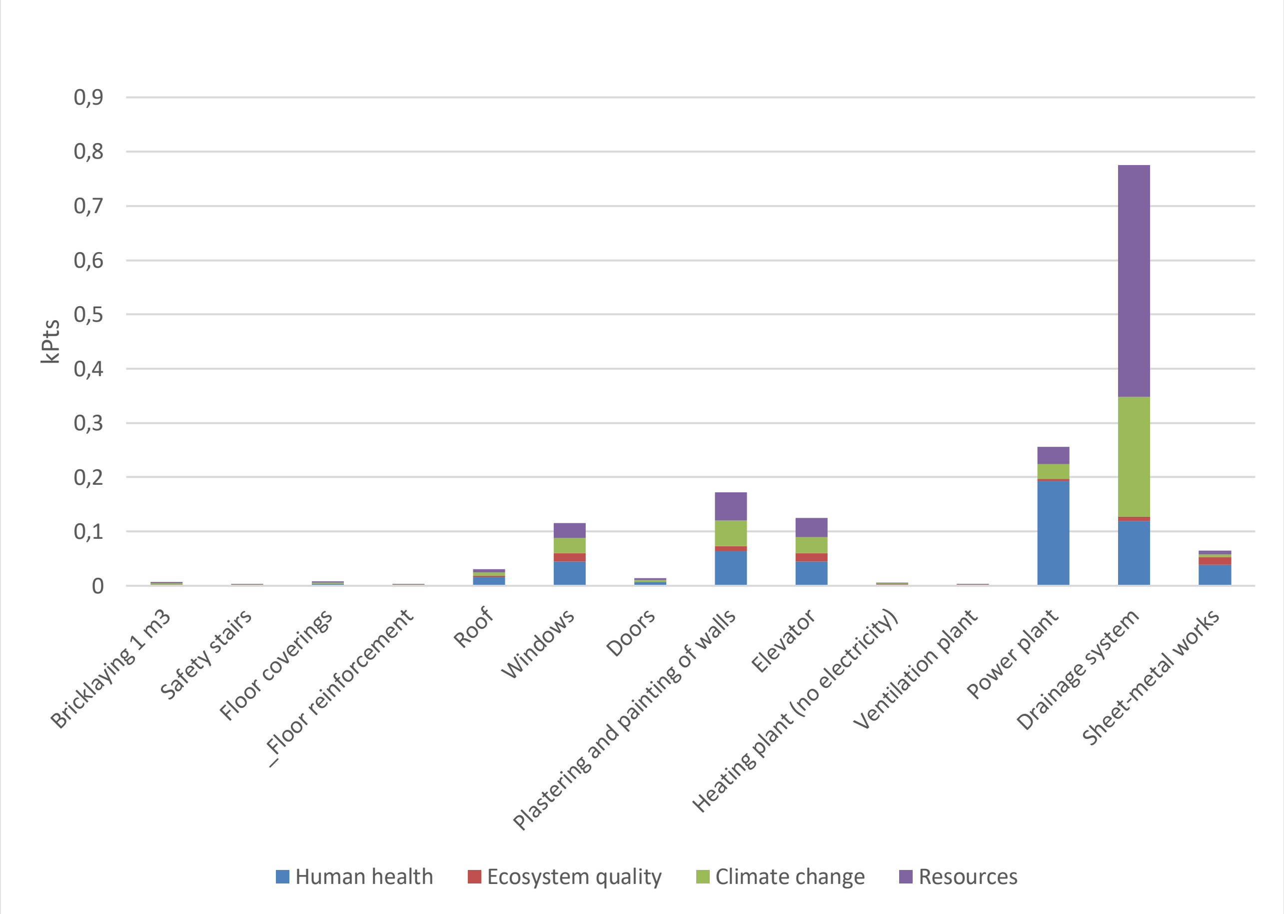


Figure 26. Buccola Pavilion restoration (100y), single score results. No use-phase included. IMPACT 2002+.

Table 40 reports the damage assessment results, while Table 41 shows the impact assessment results, for each restoration intervention process. As far as the process contribution analysis is concerned (Table 42), more than 40% of the total potential impacts are caused by the polyvinylchloride production, used in the plastic pipes of the drainage system; about 14% is associated to the polyvinyldenchloride production, used in the power plant; almost 2% of the impacts is caused by the transportation of the elevator (including its maintenance and replacement) and 1.3% is linked to the electricity production deriving from coal burning, the majority of which is used for copper production that is employed in the English windows' frames. Table 43 shows the substance contribution analysis. Oil and gas extraction, are causing more than 67% of the total potential impacts, while the uranium emissions are associated to 18% of the impacts. All these substances are involved in the drainage system life cycle, the first two in the production of the PVC pipes and the second one is embedded in the concrete shafts and septic tanks.

When observing the results of the Buccola pavilion restoration LCA, including the use-phase in the system boundaries, as expected, the calculated impacts increase considerably (more than 50kPt). This is due to the energy consumption of the heating plant, in particular to the electricity consumption of the fancoils and the circulation pumps. As the building is connected to a district heating system, which is considered a renewable energy production (even if the heat dispersion is sometimes higher than planned) and the district heating falls out of the boundaries of the analysis, in this particular case no impact or energy consumption is taken into account for the heat production. Table 44 shows the single score and damage categories scores of the scenario that includes the use-phase. Table 45 reports the process contribution analysis. The heating system process is associated to 96.9% of the total impacts and the subprocesses responsible of the majority of the impacts are all electricity production ones, or closely related.

Table 39. Buccola Pavilion restoration (100y), single score and normalized damage assessment results, percentages of impact. No use phase included. IMPACT 2002+.

Damage category	Total	Bricklaying 1 m3	Safety stairs	Floor coverings	Floor reinforcement	Roof	Windows	Doors	Plastering and painting of walls	Elevator	Heating plant (without electricity)	Ventilation plant	Power plant	Drainage system	Sheet-metal works
Total	100.00	0.41	0.17	0.55	0.20	1.92	7.29	0.86	10.87	7.90	0.35	0.16	16.18	49.03	4.10
Human health	34.10	0.36	0.21	0.63	0.20	2.98	8.35	1.19	11.89	8.37	0.51	0.24	35.83	22.00	7.25
Ecosystem	4.62	0.33	0.26	0.40	0.23	4.51	21.14	1.41	11.79	20.60	1.01	0.57	5.60	12.25	19.90
Climate change	23.70	0.69	0.23	0.68	0.30	1.55	7.39	0.86	12.78	7.98	0.23	0.13	7.12	58.95	1.10
Resources	37.6	0.29	0.08	0.42	0.13	0.86	4.58	0.49	8.63	5.86	0.22	0.07	5.39	71.79	1.20

Table 40. Buccola Pavilion restoration (100y), damage assessment results. No use phase included. IMPACT 2002+.

Damage category	Unit	Total	_Bricklaying 1 m3	_Safety stairs	_Floor coverings	_Floor reinforcement	_Roof	_Windows	_Doors	_Plastering and painting of walls	_Elevator	_Heating plant (without electricity)	_Ventilation plant	_Power plant	_Drainage system	_Sheet-metal works
Human health	DALY	3,82E+00	1,38E-02	8,13E-03	2,41E-02	7,55E-03	1,14E-01	3,19E-01	4,55E-02	4,54E-01	3,20E-01	1,93E-02	9,04E-03	1,37E+00	8,41E-01	2,77E-01
Ecosystem quality	PDF*m2*yr	1,00E+06	3,33E+03	2,56E+03	4,04E+03	2,29E+03	4,51E+04	2,12E+05	1,41E+04	1,18E+05	2,06E+05	1,01E+04	5,67E+03	5,61E+04	1,23E+05	1,99E+05
Climate change	kg CO2 eq	3,71E+06	2,57E+04	8,50E+03	2,53E+04	1,10E+04	5,76E+04	2,74E+05	3,19E+04	4,74E+05	2,96E+05	8,45E+03	4,65E+03	2,64E+05	2,19E+06	4,09E+04
Resources	MJ primary	9,04E+07	2,64E+05	7,41E+04	3,76E+05	1,13E+05	7,76E+05	4,14E+06	4,44E+05	7,80E+06	5,30E+06	1,95E+05	6,55E+04	4,87E+06	6,49E+07	1,09E+06

Table 41. Buccola Pavilion restoration (100y), characterization results. No use phase included. IMPACT 2002+.

Impact category	Unit	Total	_Bricklaying 1 m3	_Safety stairs	_Floor coverings	_Floor reinforcement	_Roof	_Windows	_Doors	_Plastering and painting of walls	_Elevator	_Heating plant (without electricity)	_Ventilation plant	_Power plant	_Drainage system	_Sheet-metal works

Respiratory organics	Ozone layer depletion	Ionizing radiation	Respiratory inorganics	Non-carcinogens	Carcinogens
kg C2H4 eq	kg CFC-11 eq	Bq C-14 eq	kg PM2.5 eq	kg C2H3Cl eq	kg C2H3Cl eq
3979,278	0,219188	39115702	3327,59	415178,4	111783,4
8,91E+00	2,23E-03	1,88E+05	1,79E+01	1,83E+02	2,68E+02
4,03E+00	4,93E-04	8,52E+04	9,26E+00	2,47E+02	3,33E+02
1,02E+01	3,36E-03	2,65E+05	2,78E+01	4,25E+02	1,21E+03
3,37E+00	1,01E-03	2,07E+05	9,57E+00	1,64E+02	1,23E+02
1,53E+01	-9,94E-04	1,91E+06	1,53E+02	1,88E+03	4,68E+02
1,32E+02	2,81E-02	6,12E+06	3,87E+02	9,02E+03	7,59E+03
1,81E+01	2,21E-03	4,80E+05	5,29E+01	1,20E+03	1,78E+03
1,85E+02	5,48E-02	6,03E+06	5,57E+02	9,30E+03	1,30E+04
1,95E+02	4,74E-02	2,90E+06	4,02E+02	7,78E+03	5,53E+03
6,16E+00	1,27E-03	1,38E+05	1,93E+01	1,26E+03	7,87E+02
2,46E+00	4,54E-04	5,24E+04	1,05E+01	3,52E+02	2,51E+02
1,82E+02	1,10E-02	2,81E+06	3,13E+02	3,40E+05	6,99E+04
3,18E+03	4,54E-02	1,71E+07	1,10E+03	1,44E+04	6,62E+03
3,37E+01	2,23E-02	8,14E+05	2,66E+02	2,85E+04	3,88E+03

Aquatic eutrophication	Aquatic acidification	Land occupation	Terrestrial acid/nutri	Terrestrial ecotoxicity	Aquatic ecotoxicity
kg PO4 P-lim	kg SO2 eq	m2org.arable	kg SO2 eq	kg TEG soil	kg TEG water
1132,114	19233,24	172897,6	64751,44	91032932	4,96E+08
1,81E+00	8,12E+01	3,49E+02	3,55E+02	3,21E+05	7,90E+05
1,29E+00	3,09E+01	8,87E+01	1,31E+02	2,90E+05	5,54E+05
3,83E+00	1,24E+02	3,58E+02	4,28E+02	3,72E+05	5,17E+06
1,01E+00	4,19E+01	2,05E+02	2,05E+02	2,30E+05	6,40E+05
1,38E+01	2,60E+02	-1,91E+03	9,40E+02	5,73E+06	1,73E+07
8,80E+01	2,04E+03	1,15E+05	6,07E+03	9,71E+06	6,67E+07
1,35E+01	1,98E+02	1,48E+03	6,10E+02	1,46E+06	5,58E+06
1,02E+02	3,86E+03	9,50E+03	9,38E+03	1,11E+07	2,00E+08
3,36E+01	1,65E+03	1,81E+04	8,89E+03	2,22E+07	3,32E+07
2,43E+01	1,08E+02	2,84E+02	2,53E+02	1,19E+06	3,05E+06
5,01E+00	9,69E+01	1,16E+02	5,03E+02	6,29E+05	1,06E+06
1,20E+02	1,74E+03	4,34E+03	4,63E+03	5,70E+06	2,88E+07
1,36E+02	7,09E+03	2,26E+04	2,87E+04	8,17E+06	6,92E+07
5,89E+02	1,91E+03	2,53E+03	3,66E+03	2,39E+07	6,46E+07

Mineral extraction	Non-renewable energy	Global warming
MJ surplus	MJ primary	kg CO2 eq
772591,6	89605692	3706802
4,77E+02	2,63E+05	2,57E+04
1,60E+03	7,25E+04	8,50E+03
2,92E+03	3,73E+05	2,53E+04
6,06E+02	1,12E+05	1,10E+04
7,19E+02	7,75E+05	5,76E+04
5,77E+04	4,08E+06	2,74E+05
1,41E+04	4,30E+05	3,19E+04
3,69E+04	7,76E+06	4,74E+05
1,02E+05	5,20E+06	2,96E+05
2,07E+04	1,75E+05	8,45E+03
3,90E+03	6,16E+04	4,65E+03
6,88E+04	4,80E+06	2,64E+05
2,57E+04	6,49E+07	2,19E+06
4,37E+05	6,51E+05	4,09E+04

Table 42. Buccola Pavilion restoration (100y), process contribution analysis. No use phase included. IMPACT 2002+. Cut off: 1%.

Total of all processes	Process
%	Unit
1,00E+02	Total
4,13E-01	_Bricklaying 1 m3
1,69E-01	_Safety stairs
5,52E-01	_Floor coverings
1,95E-01	_Floor reinforcement
1,92E+00	_Roof
7,29E+00	_Windows
8,59E-01	_Doors
1,09E+01	_Plastering and painting of walls
7,90E+00	_Elevator
3,54E-01	_Heating plant (without electricity)
1,64E-01	_Ventilation plant
1,62E+01	_Power plant
4,90E+01	_Drainage system
4,10E+00	_Sheet-metal works

Transport, freight, lorry >32 metric ton, EURO3 {RER}| transport, freight, lorry >32 metric ton, EURO3 | Alloc Def, U	Polyvinylidenchloride, granulate {RER}| production | Alloc Def, U	Polyvinylchloride, suspension polymerised {RER}| polyvinylchloride production, suspension polymerisation | Alloc Def, U	Remaining processes
%	%	%	%
1,98E+00	1,39E+01	4,09E+01	4,18E+01
7,05E-04	2,49E-07	3,40E-06	4,07E-01
3,91E-04	2,22E-07	2,15E-06	1,66E-01
2,29E-03	2,65E-06	5,41E-06	5,42E-01
4,35E-04	1,13E-06	2,02E-06	1,93E-01
7,99E-04	8,92E-07	6,98E-06	1,91E+00
7,64E-03	3,96E-05	9,96E-03	6,74E+00
9,07E-04	1,38E-05	3,53E-05	8,29E-01
2,57E-02	2,25E-04	3,22E-04	1,04E+01
1,82E+00	6,83E-06	3,97E-05	5,99E+00
1,96E-04	2,95E-06	7,43E-06	3,47E-01
1,28E-04	4,64E-07	3,35E-04	1,56E-01
1,15E-03	1,39E+01	2,29E-05	2,22E+00
1,19E-01	6,00E-06	4,09E+01	7,94E+00
5,45E-04	3,11E-05	9,00E-05	4,04E+00

Electricity, high voltage {CN}| electricity production, hard coal | Alloc Def, U
%
1,31E+00
5,12E-03
2,63E-03
6,97E-03
2,21E-03
8,33E-03
5,40E-01
2,94E-02
4,78E-01
8,95E-02
6,98E-03
7,55E-03
2,65E-02
4,77E-02
6,13E-02

Table 43. Buccola Pavilion restoration (100y), substance contribution analysis. No use phase included. IMPACT 2002+. Cut off: 1%.

Remaining substances	Total of all compartments	Substance
		Compartment
%	%	Unit
1,06E+00	1,00E+02	Total
1,26E-03	2,92E-01	_Bricklaying 1 m3
2,45E-03	8,20E-02	_Safety stairs
4,59E-02	4,16E-01	_Floor coverings
1,26E-03	1,25E-01	_Floor reinforcement
6,01E-03	8,58E-01	_Roof
9,38E-02	4,58E+00	_Windows
1,92E-02	4,91E-01	_Doors
7,91E-02	8,63E+00	_Plastering and painting of walls
1,22E-01	5,86E+00	_Elevator
2,37E-02	2,16E-01	_Heating plant (without electricity)
4,83E-03	7,25E-02	_Ventilation plant
8,54E-02	5,39E+00	_Power plant
8,90E-02	7,18E+01	_Drainage system
4,87E-01	1,20E+00	_Sheet-metal works

Coal, brown	Coal, hard	Uranium	Gas, natural/m3	Oil, crude
Raw	Raw	Raw	Raw	Raw
%	%	%	%	%
2,13E+00	1,04E+01	1,85E+01	3,23E+01	3,55E+01
8,42E-03	3,07E-02	1,92E-02	1,39E-01	9,32E-02
1,25E-03	3,10E-02	9,04E-03	1,01E-02	2,81E-02
4,42E-03	3,70E-02	2,32E-02	2,09E-01	9,61E-02
1,48E-03	2,41E-02	2,20E-02	1,22E-02	6,42E-02
4,41E-02	2,67E-01	2,24E-01	2,41E-01	7,62E-02
2,24E-01	1,29E+00	7,55E-01	1,06E+00	1,15E+00
1,47E-02	1,79E-01	5,58E-02	1,13E-01	1,10E-01
1,87E-01	1,91E+00	6,78E-01	2,33E+00	3,45E+00
5,62E-02	4,42E-01	2,05E-01	8,79E-01	4,16E+00
4,71E-03	3,75E-02	2,26E-02	5,87E-02	6,90E-02
1,85E-03	2,52E-02	6,45E-03	1,93E-02	1,49E-02
1,26E-01	7,52E-01	1,10E+00	1,86E+00	1,46E+00
1,44E+00	5,21E+00	1,53E+01	2,52E+01	2,46E+01
1,76E-02	1,96E-01	1,07E-01	2,08E-01	1,87E-01

Table 44. Buccola Pavilion restoration (100y), single score and normalized damage assessment results, percentages of impact. Use phase included. IMPACT 2002+.

Damage category	Unit	Total	_Bricklaying 1 m3	_Safety stairs	_Floor coverings	_Floor reinforcement	_Roof	_Windows	_Doors	_Plastering and painting of walls	_Elevator	_Heating plant - electricity	_Ventilation plant	_Power plant	_Drainage system	_Sheet-metal works
Total	%	100,0000	0,0130	0,0053	0,0174	0,0062	0,0605	0,2302	0,0271	0,3430	0,2493	96,8552	0,0052	0,5108	1,5473	0,1295
Human health	%	26,8858	0,0039	0,0023	0,0068	0,0021	0,0321	0,0898	0,0128	0,1279	0,0901	25,8156	0,0025	0,3855	0,2366	0,0779
Ecosystem quality	%	3,4772	0,0005	0,0004	0,0006	0,0003	0,0066	0,0308	0,0021	0,0172	0,0300	3,3328	0,0008	0,0082	0,0179	0,0290
Climate change	%	33,0940	0,0052	0,0017	0,0051	0,0022	0,0116	0,0552	0,0064	0,0955	0,0597	32,3483	0,0009	0,0532	0,4406	0,0082
Resources	%	36,5430	0,0035	0,0010	0,0049	0,0015	0,0102	0,0543	0,0058	0,1024	0,0696	35,3585	0,0009	0,0640	0,8522	0,0143

Table 45. Buccola Pavilion restoration (100y), process contribution analysis. Use phase included. IMPACT 2002+. Cut off: 1%.

Process	Unit	Total	_Bricklaying 1 m3	_Safety stairs	_Floor coverings	_Floor reinforcement	_Roof	_Windows	_Doors	_Plastering and painting of walls	_Elevator	_Heating plant - electricity consumption - 50 y	_Ventilation plant	_Power plant	_Drainage system	_Sheet-metal works

Natural gas, high pressure {RU}| natural gas production | Alloc Def, U	Electricity, high voltage {IT}| electricity production, oil | Alloc Def, U	Electricity, high voltage {IT}| electricity production, hard coal | Alloc Def, U	Electricity, high voltage {IT}| electricity production, natural gas, at conventional power plant | Alloc Def, U	Remaining processes	Total of all processes
%	%	%	%	%	%
7,63E+00	8,09E+00	1,14E+01	1,71E+01	2,80E+01	1,00E+02
4,55E-04	1,20E-05	1,69E-05	2,53E-05	1,09E-02	1,30E-02
1,80E-05	2,65E-06	3,75E-06	5,59E-06	4,89E-03	5,35E-03
6,21E-05	1,94E-05	2,74E-05	4,09E-05	1,64E-02	1,74E-02
2,26E-05	7,33E-06	1,04E-05	1,55E-05	5,33E-03	6,17E-03
8,12E-04	2,97E-05	4,20E-05	6,26E-05	5,62E-02	6,05E-02
1,75E-03	3,51E-04	4,97E-04	7,40E-04	2,02E-01	2,30E-01
1,60E-04	1,73E-05	2,44E-05	3,65E-05	2,46E-02	2,71E-02
2,75E-03	1,85E-04	2,61E-04	3,89E-04	2,99E-01	3,43E-01
4,68E-04	7,93E-05	1,12E-04	1,67E-04	2,20E-01	2,49E-01
7,62E+00	8,09E+00	1,14E+01	1,71E+01	2,63E+01	9,69E+01
3,38E-05	2,31E-06	3,28E-06	4,88E-06	4,78E-03	5,17E-03
6,25E-04	2,41E-04	3,41E-04	5,08E-04	5,01E-01	5,11E-01
4,17E-03	1,48E-03	2,09E-03	3,13E-03	1,98E-01	1,55E+00
1,98E-04	1,67E-05	2,36E-05	3,52E-05	1,26E-01	1,29E-01

Uranium ore, as U {RNA}| uranium mine operation, underground | Alloc Def, U	Natural gas, unprocessed, at extraction {GLO}| production | Alloc Def, U	Electricity, high voltage {RU}| electricity production, lignite | Alloc Def, U	Natural gas, high pressure {RoW}| natural gas production | Alloc Def, U	Natural gas, high pressure {DZ}| natural gas production | Alloc Def, U	Hard coal {RoW}| mine operation | Alloc Def, U
%	%	%	%	%	%
1,67E+00	1,75E+00	1,85E+00	4,59E+00	5,23E+00	5,38E+00
8,60E-05	6,84E-05	1,42E-04	1,80E-04	1,19E-04	1,16E-04
3,88E-05	1,49E-05	1,68E-05	3,92E-05	4,87E-06	7,34E-05
7,88E-05	4,24E-05	5,08E-05	1,12E-04	2,06E-05	8,08E-05
1,01E-04	1,41E-05	1,67E-05	3,71E-05	7,38E-06	5,30E-05
4,13E-04	1,24E-04	2,51E-04	3,26E-04	2,15E-04	1,92E-04
3,33E-03	1,23E-03	1,48E-03	3,23E-03	6,20E-04	3,74E-03
1,99E-04	1,66E-04	1,84E-04	4,37E-04	4,22E-05	4,30E-04
2,77E-03	2,71E-03	3,19E-03	7,13E-03	6,71E-04	4,92E-03
8,04E-04	4,12E-04	6,01E-04	1,08E-03	1,52E-04	1,35E-03
1,65E+00	1,74E+00	1,84E+00	4,57E+00	5,22E+00	5,36E+00
2,72E-05	2,24E-05	3,14E-05	5,90E-05	8,66E-06	6,45E-05
1,66E-03	2,77E-04	3,61E-04	7,27E-04	3,28E-04	1,62E-03
1,01E-02	1,41E-03	1,67E-03	3,71E-03	2,14E-03	9,05E-03
4,43E-04	2,21E-04	3,95E-04	5,74E-04	4,79E-05	5,26E-04

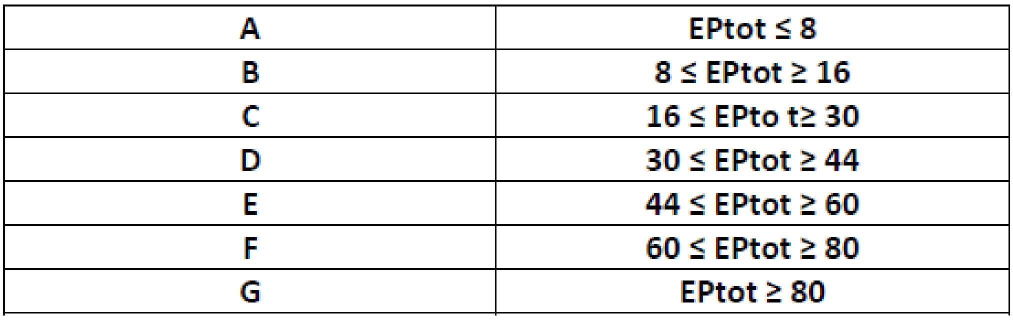
Polyvinylchloride, suspension polymerised {RER}| polyvinylchloride production,	Petroleum {RME}| production, onshore | Alloc Def, U	Petroleum {RoW}| petroleum and gas production, on-shore | Alloc Def, U	Uranium ore, as U {RoW}| uranium mine operation, underground | Alloc Def, U	Natural gas, high pressure {NL}| petroleum and gas production, on-shore | Alloc Def, U
%	%	%	%	%
1,30E+00	1,42E+00	1,43E+00	1,57E+00	1,63E+00
1,07E-07	3,18E-04	3,21E-04	8,11E-05	1,84E-04
6,80E-08	1,01E-04	1,02E-04	3,67E-05	5,13E-06
1,71E-07	1,86E-04	1,88E-04	7,44E-05	1,89E-05
6,37E-08	2,27E-04	2,29E-04	9,54E-05	6,31E-06
2,20E-07	5,17E-04	5,23E-04	3,90E-04	3,29E-04
3,14E-04	3,49E-03	3,53E-03	3,15E-03	6,12E-04
1,11E-06	3,09E-04	3,13E-04	1,88E-04	4,11E-05
1,02E-05	7,58E-03	7,67E-03	2,62E-03	7,37E-04
1,25E-06	1,17E-02	1,18E-02	7,59E-04	1,43E-04
5,95E-03	1,39E+00	1,40E+00	1,55E+00	1,62E+00
1,06E-05	4,20E-05	4,25E-05	2,57E-05	1,12E-05
7,22E-07	5,27E-04	5,33E-04	1,57E-03	2,63E-04
1,29E+00	3,68E-03	3,72E-03	9,57E-03	1,82E-03
2,84E-06	4,46E-04	4,51E-04	4,18E-04	5,07E-05

4.2.4. Energy performance analysis

This chapter will analyse the heating energy consumption of the pavilion, after the conservation intervention. In order to calculate the energy needs of a building the Energy Performance index (EPi) is used. The EPi represents the total primary energy consumption over the entire year. It is expressed as kWh/m2*year for residential buildings or as kWh/m3 year for non-residential buildings and it takes into account the energy necessary for heating (and eventually cooling), production of sanitary warm water and electricity consumption during the use phase the building. In order to consider the primary energy consumption, a conversion factor is used for each energy vector. The energy consumption is then calculated according to a standard use of the building and is not a result of real data observation. Moreover it is a function of the particular climate zone where the building is located and of the building features (e.g. materials, orientation, heating system and similar).

As far as the regulations are concerned, in Europe the reference directive is the Directive 2002/91/EC, also known as the Directive on the energy performance of buildings (EPBD). It came into force on January, 4th 2003 and was inspired by the Kyoto Protocol. In Italy it was implemented only in 2005 with the D.Lgs n. 192/2005 followed by D.Lgs. n. 331/2006, D.P.R. n. 59/2009 and D.M. 26/06/2009. The D.Lgs 59/2009 recalls the technical norm UNI/TS 11300 to perform the calculation. The Directive 2002/91 was integrated with the new Directive 2010/31/EU (effective in May 2010) with the same goals of the old one but with some integrations especially in the new Zero Energy Buildings and introducing a common methodology for the calculation of the energy efficiency. As far as the existing buildings are concerned, the main news is that all the public buildings with a total surface < 500 m2 have to exhibit an energy performance certificate.

Table 46. Energetic efficiency classes. Building category E.7. Linee guida per la certificazione energetica DM 26-06-2015.



A	**EPtot ≤ 8**
B	**8 ≤ EPtot ≥ 16**
C	**16 ≤ EPto t≥ 30**
D	**30 ≤ EPtot ≥ 44**
E	**44 ≤ EPtot ≥ 60**
F	**60 ≤ EPtot ≥ 80**
G	**EPtot ≥ 80**

The Buccola pavilion was built in 1939 and is bound to the Cultural Heritage regulations. It was restored in 2007 (even if the original project goes back to 2002 and some variations were added afterwards). When possible the original window's frames have been restored, new windows frames were created using the same material and no external coat has been added. For this reason, higher transmittance and EP values are expected compared to the limit values proposed by the norm for reconstruction or complete building restoration. As previously stated the building is located in Reggio Emilia, corresponding to the E climate zone, with a heating period that goes form mid-October to mid-April. The energy conversion factors used are equal to 2.17 for electricity and 1 for district heating (UNI TS 11300, part 1 and 2). The standard inner temperature considered is 20°C. Table 47 shows the data used for the energy performance calculation.

Table 47. Buccola pavilion. Climate zone and building features.

Climate zone	E	15 October – 15 April
Degree days	2556	
Inner temperature	20° C	Winter
Gross heated volume	12711 m3	Raised and first floor
Net area (2 floors)	2264 m2	
Heating system	District heating	Substation in the basement floor and heat exchanger
Heating units	Fancoils and radiators	22 ground fancoils 10 ceiling fancoils 18 radiators in the restrooms

Ventilation	Mechanical	Air handling units in the basement and crawl space
Domestic hot water	District heating and boilers	6 electric boilers

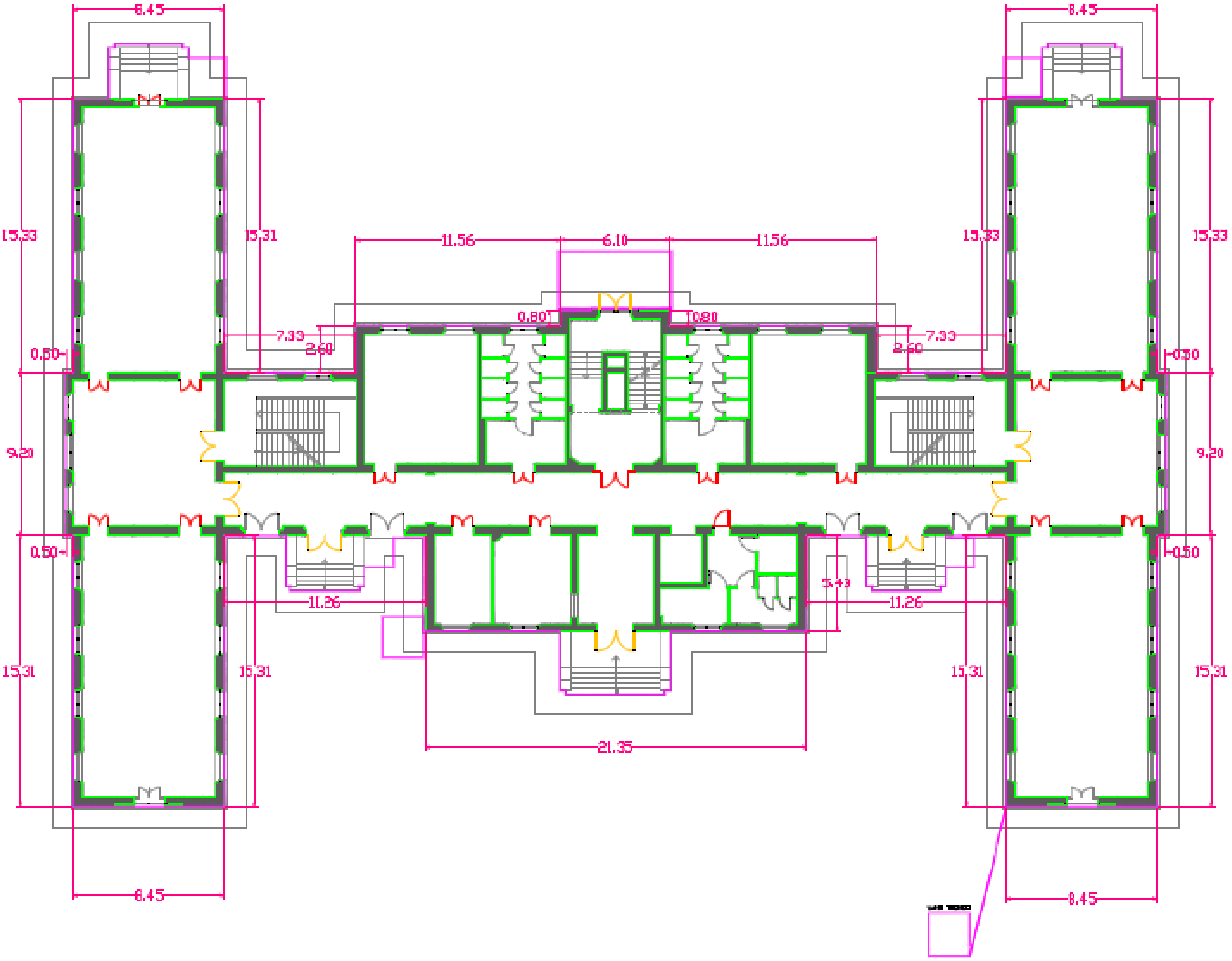


Figure 27. Buccola pavilion. Raised ground floor plan.

The degrees day are calculated according to the following formula:

$$DD = \sum_{month} [(\theta_i - \theta_{e,month}) \cdot D_{month}]$$

Where:

θ_i is the building's inner project temperature, 20°C for the residential buildings according to the regulation,

$\theta_{e,month}$ is the mean outer monthly temperature, that is recorded for the different Italian provinces in the VI chart of the UNI 10349 regulation,

D_{month} is the number of days of the months included in the considered climatic zone, according to the season of interest.

The energy consumption for heating and domestic hot water production is calculated using the Edilclima EC700 software (trial version). This software allows to calculate buildings energy performances, according to the UNI/TS 11300-1:2014 standard, using climate and building shell data as a input. The building features are used for the calculation parameters are hereby listed.

Figure 28. Buccola pavilion. View of the external wall thickness.

- ***Vertical and horizontal walls***

External walls

The external walls are 45 cm thick and they have the following stratigraphy (inside → outside):

- gypsum and lime plaster
- solid brick
- external lime plaster

Upper floor

The upper floor is 30 cm thick and it has the following stratigraphy

(inside → outside):

- gypsum and lime plaster
- hollow-core concrete floor
- partially ventilated crawl space
- brick curved tiles

Floor between the raised ground floor and the basement

This floor is 30 cm thick and the basement is a non-heated space at a fixed temperature of 10° C. It has the following stratigraphy (inside → outside):

- gres floor
- hollow-core concrete floor
- partially ventilated crawl space
- gypsum and lime plaster

- ***Windows***

Raised ground floor

Windows 2,4x1,4 (m)	30	3,36	100,8	m2

Windows 2,5x1,2 (m)	7	3	21	m2
Windows 2,5x1,8 (m)	2	4,5	9	m2
Windows 3,7x2 (m)	6	7,4	44,4	m2
French door	4	5,3	21,2	m2

Table 48. Buccola pavilion. Raised ground floor windows number and dimensions.

First floor

Windows 2,4x1,4 (m)	30	3,36	100,8	m2
Windows 2,5x1,2 (m)	4	3	12	m2
Windows 2,5x1,8 (m)	14	4,5	63	m2
Windows 3,7x2 (m)	0	7,4	0	m2
French door	2	5,3	10,6	m2

Table 49. Buccola pavilion. First floor windows number and dimensions.

The window frame is made of hard wood and the glasses are double glazed units of 4-8-4 mm, with air filling the gap.

Figure 29. Buccola pavilion. Picture of the wooden English windows.

Moreover, the following assumptions were considered:

Use time of the spaces	9	h
Concentration rate	0.5	pers./m2
External air flow rate (rooms)	25.2	m3/h per person
Inner temperature (winter)	20	°C

Table 50. Buccola pavilion. Energy performance calculation assumptions.

- ***Heating system***

The Buccola pavilion is heated through a district heating. The heating system has two heating subunits in the basement floor of the building, that are distributing heat to 32 fancoils in the study rooms, corridors and offices and 18 radiators in the bathrooms. Table 51 sums up the distribution of the heating units.

Unit type	Power	Raised ground floor	First floor
Floor fancoils	100 W	22	-
Ceiling fancoils	110 W	-	10
Radiators	-	9	9

Table 51. Buccola pavilion. Heating units power and distribution.

Figure 30. Sabiana CRC floor fancoil.

The energy lost due to transmission across the bulding shell corresponds to the heat required (Qh,nd) to maintain the desired inner comfort temperature (established as 20° C during winter). Qh,nd calculated using EdilClima is equal to 851074 KWh/ year. This value does not reflects the actual energy consumed to heat the building, as both the heating system efficiency and an analysis of the actual operational conditions are not included. This value is compatible with the actual average energy consumption obtained from the energy university bills from 2012 to 2015, which is 524.5 MWh per year (on site data collection). The actual value is considerably lower as the heating system is actually working only for 12 hours per day (personal information from the building manager). At the same time, it includes the heat loss expected due to additional manual ventilation (windows opened by students or professors) and the actual district heating efficiency in Reggio Emilia. The actual EPtot of the Buccola pavilion, as calculated with the EdilClima software, is 67.16 KWh/m3 year (F class).

4.2.5. Building Integrated Photovoltaic: renewable energy scenario

As previously stated, one of the objective of the Circular Economy is the use of renewable energy. For this reason, the effects of the application of a green technology are observed in an alternative hypothetical scenario, as a sensitivity analysis.

TIFAIN (photovoltaic integrated glass tiles for innovative architectural application) is a collaborative project between research institutions and companies aimed to develop Building Integrated PhotoVoltaic (BIPV) façade elements. The project started in 2015. From a technological point of view, the TIFAIN PV tiles use the Dye-Sensitised Solar Cells (DSSC) technology and might also be called “Grätzel Cells” after their pioneer, Michael Grätzel, who discovered it in 1988. The original “Grätzel cell is a “sandwich” structure where two smooth conductive glasses (foto-catode and anode) enclose a nanostructured TiO2 film, combined with dye. This internal layer (called “active layer”) is immersed in an electrolytic solution. Figure 31 shows the general functioning of a DSCC cell. In contrast to the conventional photovoltaic systems where the semiconductor assume both the task of light absorption and charge carrier transport, the two functions are separated in a DSCC cell. Light is absorbed by a sensitizer, which is anchored to the surface of a wide band semiconductor. Charge separation takes place at the interface via photo-induced electron injection from the dye into the conduction band of the solid. Carriers are transported in the conduction band of the semiconductor to the charge collector. The use of sensitizers having a broad absorption band in conjunction with oxide films of nanocrystalline morphology permits to harvest a large fraction of sunlight. Nearly quantitative conversion of incident photon into electric current is achieved over a large spectral range extending from the UV to the near IR region. (Grätzel, 2003).

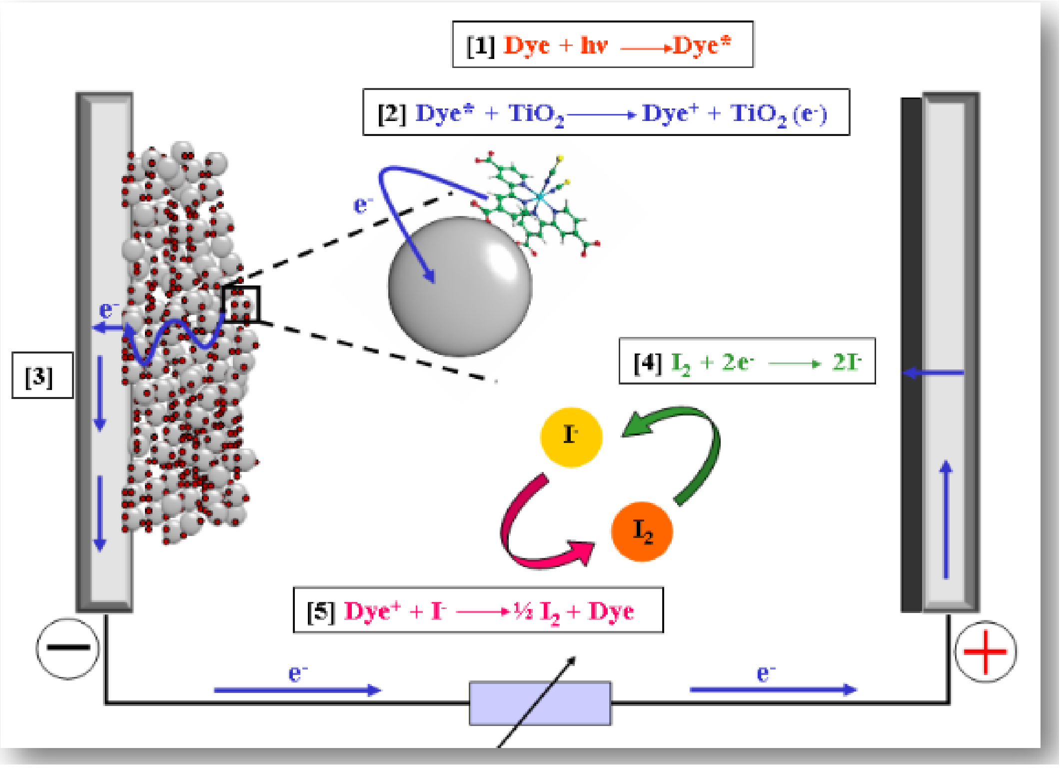


Figure 31. DSSC electricity production. From http://docplayer.it/5653904-Smart-windows-ed-edilizia-sostenibile.html

The data used within this analysis were obtained from the laboratory studies of the MIB SOLAR group of the Bicocca University in Milan by Cardani Morando (2015) and were adapted to the Buccola pavilion case study. The production process of the TIFAIN tile is very similar to the standard DSSC cells, with the exception of the type of support used. The standard DSCC are assembled using a float glass treated with a Transparent Conductive Oxide (TCO), while the TIFAIN tiles are assembled using as electrode a glass that is molded in order to optimize the solar radiation. This technique allows to obtain personalized shapes without renouncing to the maximum radiation absorption. Besides an improvement of the cell's efficiency, less active material is required, as it is laid down only in the regions that are actually reached by the solar radiation.

This particular application of BIPV is particularly suitable to be integrated in the Buccola pavilion as it can be use to replace the windows glasses. Not only the pavilion has a high number of windows on the four sides of its shell but, more importantly, this solution does not have a visual impact on the aspect of the pavilion and the heritage restrictions are not violated. The cells can be shaped as tiles that can fit the English windows wooden frame.

The LCA and LCC of the TIFAIN tiles production and installation is performed, first as a separate analysis and then integrating the results within the Buccola pavilion restoration LCSA, considering also the use-phase during the restored pavilion lifespan. A stand-alone system is considered, as the pavilion energy consumption is concentrated exclusively during the daytime.

As far as the functional unit and system boundaries are concerned, the production of a single TIFAIN tile is taken into account. The tile dimensions are 10x10cm. The production, use-phase and end-of life are considered, including the raw materials acquisition, emissions and energy use for the vacuum system and lab plants. A common assumption in PV lifetime environmental impact analysis – also recommended by the IEA-PVPS – is that the average panel lifespan is 30 years (Frischknecht et al., 2016). Being the best available information, this datum is considered an acceptable proxy for the TIFAIN tiles.

When referring to the whole restoration intervention, the area available in the considered building for the transparent PV tiles installation is 280.8 m2, that corresponds to the total windows glasses area (without frame). This means that over the conventional period of 100 years, the total number of tiles used for the Buccola pavilion would be equal to 280.8*100/30 = 936 tiles.

The data relative to materials and energy used during the production of the tile are primary data from the MIB SOLAR lab, while the data relative to the emissions and end of life are estimated. As far as the end of life is concerned, recycling of "regular" PV panels is still infrequent; moreover, the TIFAIN cell is only a prototype that uses nanoparticles that are still under examination in terms of environmental and human health damage. For this reason a disassembly of the tile's materials is not taken into account and for the EoL process a residual material landfill is considered. It is important to noticed that the lifespan of the restored building is 100 years and it is very probable that a technological improvement will allow a recycling process of the TIFAIN tile. Nevertheless, the present state of the art is the onl available datum and it is used for the whole lifespan.

The databased used for this analysis is Ecoinvent 3.3. When the necessary processes are missing and the data are present, new *ad hoc* processes created, otherwise the best proxy is used. The LCA software adopted is SimaPro, v.8.0.5. The methods used are a modified version of IMPACT 2002+ that takes into account the potential impacts associated to the use of nanomaterials (Pini, 2014) and a second modified version that implements a monetarization of the calculated environmental impacts. The IMPACT 2002+ and its modifications are previously described in the methods chapter.

Figure 32 reports the flowchart of the TIFAIN tile production processes. In particular, once obtained the glass tile of the desired shape and dimension, the TCO deposition phase on the future electrode can start. The TIFAIN cell use the Indium-Tin Oxide (ITO), a solid solution widely employed as transparent conductor in several fields, especially optics and electronics. ITO basically replaces the aluminium contacts of the traditional PV cells with the advantage of a higher efficiency: indeed, its transparency features allows its deposition over all the tile surface and avoids the creation of blind areas. It is deposited using a particular process called magnetron sputtering, that allows to deposit the desired thin layer of ITO ions. The ITO layer created in the lab is 800nm thick but with an industrial process it could be thinner and completely transparent. Once covered with the ITO layer, the tile undergoes a series of washings and baths, finalized to remove possible slag ad prepare the product for the further treatments. At first, the tile is submerged in an ethanol and water solution at room temperature for about a minute, then it is submerged in a $TiCl_4$ bath at a 70°C temperature for 30 minutes. The third step is an ethanol and water solution washing (with a different concentration comparing to the first one). Then the active layer of TiO_2 is layed using a serigraphic process, after which the tile undergoes a first thermic treatment at 120°C and then a secondo ne at 500°C, for a total time of 2 hours. After these treatments the tile temperature is lowered to 80°C with a monitored cooling and it is subsequently left at room temperature until the heat is completely lost. Once the thermic treatment is finished, the tile is bathed in a dye and ethanol solution tank for 20 hours, to allow a complete absorption of the dye in the TiO_2 layer. The following step involves the counterelectrode production, that uses a float glass treated with Fluorin-Tin Oxide (FTO), where a layer of platinum paste is deposited using a serigraphic process. Again, the glass undergoes a thermic treatment up to 500°C. The last operation is the drilling of small cavities necessary for the introduction of the electrolyte. The electrode and the counterelectrode are sealed together with different resins and thermic treatments (up to 110°C and 60°C). Finally, the electrolyte can be injected into the cell and the holes are sealed with a last thermic treatment (120°C). The last necessary step is the application of electric silver paste contacts.

Tables 52 to 69 show the inventory processes and amounts used for the life cycle assessment of the TIFAIN tile.

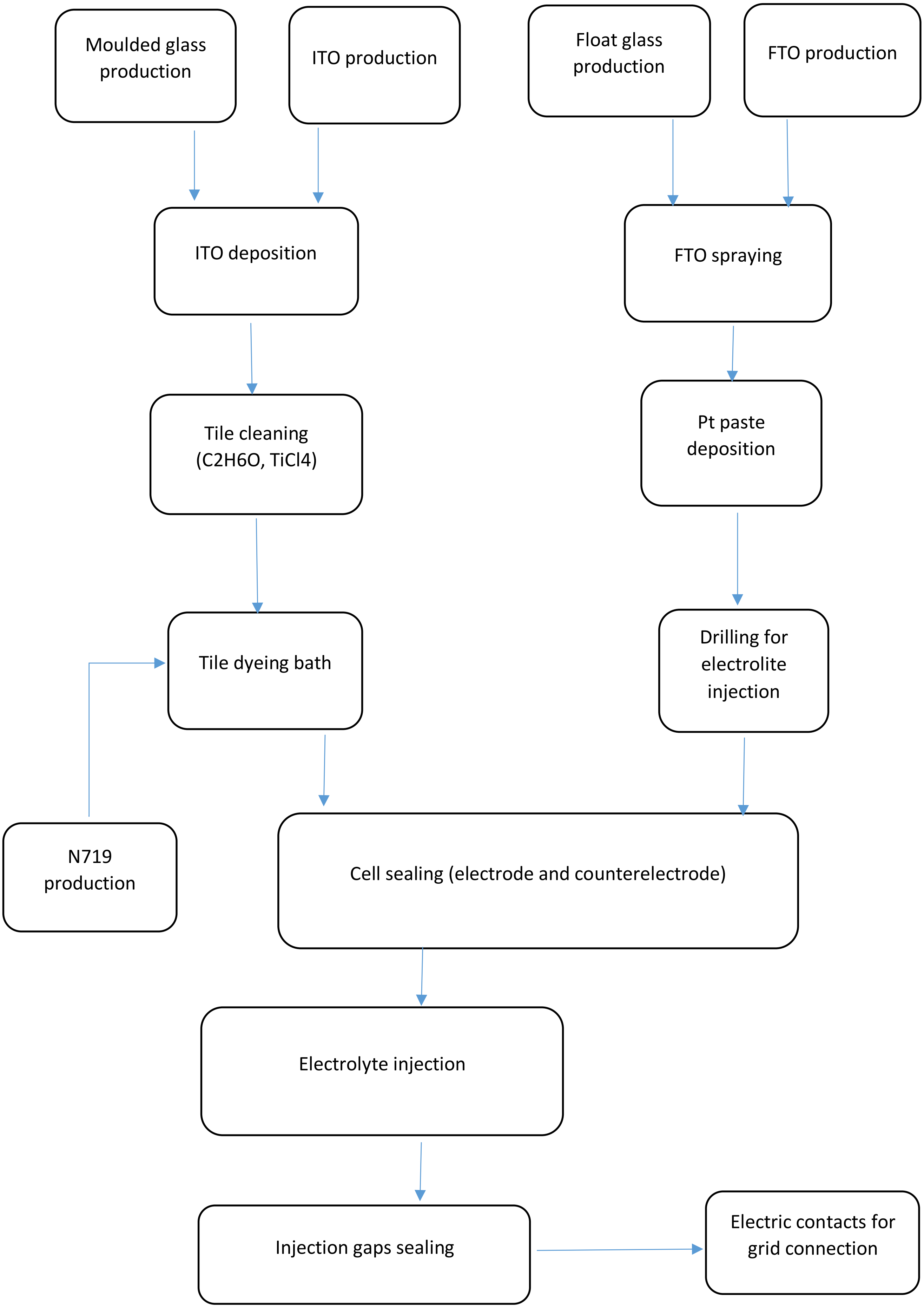


Figure 32. TIFAIN tile production flowchart. (Adapted from Cardani Morando, 2015).

Table 52. TIFAIN tile production. Inventory analysis.

Processes	Amount	Unit	Comments
_Tifain PV Electrode production	1	p	Moulded glass tile with ITO and NanoTiO2 deposition and dyeing bath
_Tifain PV Counterelectrode production	1	p	Float glass with FTO spraying and Pt paste deposition
_Cell sealing	1	p	Sealing with silicone
_Electrolite injection and gaps sealing	1	p	Cloridric acid injection
_Electric contacts	100	cm2	Silver contacts for grid connection
_Tifain EoL	1	p	NO recycling conseidered

Table 53. TIFAIN electrode production. Inventory analysis.

Processes	Amount	Unit	Comments
_Molded glass	1,00E+02	cm2	Molded glass production witout EoL
_Indium Tin Oxide (ITO)	1,16E-01	g	Production of ITO, a transparent conductive oxide
_ ITO deposition	1,16E-01	g	ITO sputtering on the electrode glass
_Tile cleaning	1,00E+02	cm2	First wash, bath and second wash to remove the manufacturing resdues from the tile. It is washed in an ethanol solution and immerged in a titanium tetrachloride bath
_Nano TiO2 deposition	1,20E+02	cm2	Nano TiO2 applied on both sides over an active area of 60cm2. 1% water solution
_High temperature fixing	1,00E+02	cm2	Tile heating up to 120°C for 5 min, twice. Heating up to 500°C with controlled cooling down to 80°C
_Tile dyeing bath	1,00E+02	cm2	Dye (N719) + ethanol bath. 20h at room temperature

Table 54. TIFAIN molded glass production. Inventory analysis.

Processes	Amount	Unit	Comments
Packaging glass, white {RER w/o CH+DE}| production | Alloc Def, U	2,34E+02	g	Area: 100cm2
Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Alloc Def, U	2,34E+01	kgkm	Glass transportation to the TIFAIN production location

Table 55. Indium Tin Oxide (ITO) production. Inventory analysis.

Processes	Amount	Unit	Comm.ents
In2O3	1,05E-01	g	99%
SnO2	1,17E-02	g	1%

Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW | Alloc Def, U	5,77E+01	J	Heating up to 1910°C
_Bag filter (1800Nm3/h)	2,60E-05	p	Lifespan: 9600h. Operation time for ITO production: 0,25h.
Electricity, low voltage {IT}| market for | Alloc Def, U	2,56E-01	KWh	Electricity for vacuum system operation
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	1,14E+00	kgkm	Bag filters transportation. Filter weight: 437,9kg, 100km
_Filter dust disposal	1,14E-02	g	EoL of the exhausted filters dust
Emissions			
Heavy metals, unspecified	3,51E-05	g	In and Sn molecules emitted during the fusion phase. Supposed emissions mass: 1%. Filter efficiency: 97%.

Table 56. ITO deposition. Inventory analysis.

Processes	Amount	Unit	Comments
Vacuum pump	1,00E-05	p	Lifespan: 30000h. Operation time: 0.3h. Power:0,28kW. Weight: 10.5kg
Magnetron sputtering	5,00E-05	p	Lifespan: 30000h. Sputtering time: 1.5h. Power 25W
Electricity, low voltage {IT}| electricity voltage transformation from medium to low voltage | Alloc Def, U	1,22E+02	Wh	Electricity for vacuum creation and sputtering
_Bag filter (1800Nm3/h)	1,56E-04	p	Lifespan: 9600h. Operation time: 1.5hh.
Electricity, low voltage {IT}| market for | Alloc Def, U	1,54E+00	kWh	Electricity for the vacuum system operation
Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Def, U	6,85E+00	kgkm	Bag filters and vacuum pump transportation. Filter weight: 437,9kg, 100km
_Filter dust disposal	1,13E-03	g	Eol of the exhausted filters dust. Filter efficiency: 97%. Emitted particles: 1%
Emissions			
Heavy metals, unspecified	3,48E-05	g	Particles released into air during the process

Table 57. Nano TiO2 deposition (water solution 1%). Inventory analysis.

Processes	Amount	Unit	Comments

_NanoTiO2, 1% water solution	1,00E-01	g	2 layers (5 µm each). Process previously created by the LCA Working Group team
Polyester resin, unsaturated {RER}| production | Alloc Def, U	8,96E-02	g	Serigraph mesh screen. Dimensions: 350*400*0,5mm. Lifespan: 1000 prints. Printing time for one Tifain tile: 30sec. Density: 1,28g/cm3
Compressed air, 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, average generation | Alloc Def, U	1,25E+01	l	Mesh impermeabilization. 50l/min. 15sec
_Serigraphic printer	2,78E-07	p	Serigraphic printer to fix the Nano TiO2 solution on the glass. Lifespan: 30000h. Use time for one Tifain tile: 30sec. Weight: 200kg. http://www.brbspa.it/aurel-reflow-af8-900/brochure
Electricity, low voltage {IT}| market for | Alloc Def, U	1,83E+00	Wh	Electricity consumption of the serrigraphic printer. Power: 440W. Time: 15 sec
Electricity, low voltage {IT}| market for | Alloc Def, U	1,26E-02	KWh	Electricity for the vacuum system
_Activated carbon filter (Q=1800Nm3/h)	3,47E-06	p	Filter lifespan: 2400h. Weight: 245kg
_Bag filter (1800Nm3/h)	8,68E-07	p	Bag filter for metal powders. Lifespan:9600h. Weight: 437.9 kg
Ethanol, without water, in 95% solution state, from fermentation {CH}| ethanol production from sugar beet molasses | Alloc Def, U	9,04E+01	g	EtOH for the fixing environment
Electricity, low voltage {IT}| electricity voltage transformation from medium to low voltage | Alloc Def, U	8,91E+01	kJ	Electricity for the EtOH evaporation. Boiling °t: 78,3 °C. E=m*cp*DT, m:1kg, cp:2460J/kg*k. Latent heat of vaporization:854kJ/kg
Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO6 | Alloc Def, U	1,38E-01	kgkm	Transport of the mesh screen, printer, filters. 100km
_Filters dust disposal	8,59E-01	g	Vacuum system's used filters disposal
Emissions			
Particulates, <100 nm	3,00E-09	g	During the NanoTiO2 deposition 0.1% of np is lost : 99.7% is collected on the vacuum system filters while 0.3% is emitted to the atmosphere
Ethanol (high pop.)	4,52E-02	g	1% of EtOH evaporates during heating : 95% is collected on the vacuum system filters while 5% is emitted to the atmosphere

Table 58. TIFAIN tile cleaning. Inventory analysis.

Processes	Amount	Unit	Comments

Ethanol, without water, in 95% solution state, from fermentation {CH}| ethanol production from sugar beet molasses | Alloc Def, U	1,26E+02	g	Tile immersion in EtOH solution. 2 immersions of 1min each. 800ml for 10 cleaning processes
TiCl4 (liquid)	1,38E+02	g	TiCl4 bath. 800ml for 10 cleaning processes
Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | Alloc Def, U	3,63E+00	MJ	Bath heating at 70°C for 30min.
Electricity, low voltage {IT}| market for | Alloc Def, U	8,00E-01	kWh	Electricity for the vacuum system
_Activated carbon filter (Q=1800Nm3/h)	2,22E-04	p	Filter lifespan: 2400h. Weight: 245kg.
_Bag filter (1800Nm3/h)	5,56E-05	p	Bag filter. Lifespan:9600h. Weight: 437.9 kg
Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Def, U	7,88E+00	kgkm	Filters transportation. 100km
Spent solvent mixture {GLO}| market for | Alloc Def, U	2,64E+02	g	EoL of ethanol and TiCl4
_Filters dust disposal	2,51E+00	g	Vacuum system's used filters disposal
Emissions			
Ethanol	3,16E-02	g	0,5% of ethanol evaporates. Filter efficiency: 95%
Metals, unspecified	4,14E-02	g	0,1% of TiCl4 is emitted into air. Filter efficiency: 97%

Table 59. High temperature fixing. Inventory analysis.

Processes	Amount	Unit	Comments
Electricity, low voltage {IT}| electricity voltage transformation from medium to low voltage | Alloc Def, U	1,50E+00	kWh	Heating up to 120°C for 5 min, twice. Heating up to 500°C with controlled cooling down to 80°C

Table 60. Electrode dyeing bath. Inventory analysis.

Processes	Amount	Unit	Comments
Ethanol, without water, in 95% solution state, from fermentation {CH}| ethanol production from sugar beet molasses | Alloc Def, U	3,16E+00	kg	Ethanol for the bath. Vol: 4l. Density: 0,789g/cm3. Evaporation rate: 0,0242g/min.
N719	1,00E-03	g	Dye
Electricity, low voltage {IT}| market for | Alloc Def, U	2,05E+01	KWh	Electricity for the vacuum system
_Activated carbon filter (Q=1800Nm3/h)	8,34E-03	p	Filter lifespan: 2400h. Weight: 245kg

Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Alloc Def, U	3,42E-03	tkm	Transport of the filters from the producing firm to the tile producers. 100km
_Filters disposal	2,90E-02	kg	Carbon filters disposal
Spent solvent mixture {GLO}| market for | Alloc Def, U	3,16E+00	kg	EoL of ethanol left in the bath bucket
Emissions			
Ethanol (high pop.)	1,45E-01	g	95% of the evapotarated EtOH is retained by the filter

Table 61. TIFAIN counterelectrode production. Inventory analysis.

Processes	Amount	Unit	Comments
_Float glass production	1,00E+02	cm2	Couterelectrode glass production
_FTO spraying	1,00E+02	cm2	Fluorin Tin Oxide spraying
_Platinum paste deposition	6,00E+01	cm2	Pt paste deposition and fixing on the functional area
_Drilling for electrolite injection	1,00E+02	cm2	Micro-holes drilling

Table 62. Float glass production. Inventory analysis.

Processes	Amount	Unit	Comments
Tempering, flat glass {RER}| processing | Alloc Def, U	5,50E+01	g	Flat glass sheet. Dimensions: 10*10*0,22cm3. Specific weight: 2,5g/cm3. No EoL included in the process
Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW}| transport, freight, lorry 7.5-16 metric ton, EURO6 | Alloc Def, U	5,50E+00	kgkm	100km

Table 63. Fluorine Doped Tin Oxide (FTO) spraying. Inventory analysis.

Processes	Amount	Unit	Comments
_FTO (Fluorine Doped Tin Oxide) solution	3,43E+00	g	Quantity of FTO solution sprayed on the float glass
Electricity, low voltage {IT}| market for | Alloc Def, U	2,10E-03	kWh	Electricity for the vacuum system
_Activated carbon filter (Q=1800Nm3/h)	5,79E-07	p	Filter lifespan: 2400h. Weight: 245kg
_Bag filter (1800Nm3/h)	1,45E-07	p	Lifespan:9600h. Weight: 437.9 kg
_Spraying machine	4,63E-08	p	Weight: 241 kg. Lifespan 30000h
Electricity, low voltage {IT}| market for | Alloc Def, U	1,78E-02	kWh	Electricity consumption for the spraying machine use. Time: 5 sec. Power: 12,8 kW

Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Def, U	5,84E+00	kgkm	Transportation of the glass and of the FTO solution. 100km
Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Def, U	2,17E-02	kgkm	Transportation of the filters and the spraying machine. 100 km
Ash from deinking sludge {CH}| treatment of, residual material landfill | Alloc Def, U	1,03E-03	g	Eol of the powders retained by the filters
Emissions			
Particulates, < 2.5 um	1,03E-03	g	1% of emissions. Filter's efficiency=97%.

Table 64. Platinum paste deposition. Inventory anlaysis.

Processes	Amount	Unit	Comments
Electricity, low voltage {IT}| electricity voltage transformation from medium to low voltage | Alloc Def, U	4,94E+04	J	Heating up to 500°C
Electricity, low voltage {IT}| market for | Alloc Def, U	1,23E-02	KWh	Electricity for the vacuum system
_Bag filter (1800Nm3/h)	1,26E-06	p	Lifespan:9600h. Weight: 437.9 kg
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	5,52E-02	kgkm	Filters trasport. 100km
Ash from deinking sludge {GLO}| market for | Alloc Def, U	2,97E-04	mg	EoL of the heavy metals retained by the filters
Ash from deinking sludge {CH}| treatment of, residual material landfill | Alloc Def, U	3,22E+01	mg	EoL of the ethanol retained by the filters
Emissions			
Heavy metals, unspecified	3,00E-06	mg	Emissions during heating. Filter's efficiency 97%
Ethanol	3,25E-01	mg	Emissions during heating. Filter's efficiency 97%

Table 65. Drilling for electrolyte injection. Inventory analysis.

Processes	Amount	Unit	Comments
Electricity, low voltage {IT}| electricity voltage transformation from medium to low voltage | Alloc Def, U	6,67E-03	kWh	6 holes. Drill power 4kW. Time 6 sec
Waste glass sheet {CH}| treatment of, collection for final disposal | Alloc Def, U	2,59E-02	g	EoL of glass residues

Table 66. TIFAIN tile sealing. Inventory analysis.

Processes	Amount	Unit	Comments
_Epoxy resin fixing	4,00E+01	cm2	Fixing over the non-functional area

_Perimeter sealing	1,00E+00	p	Perimeter sealing. Heating up to 60°C

Table 67. Electrolite injection and gaps sealing. Inventory analysis.

Processes	Amount	Unit	Comments
_Electrolyte injection	1	p	Cloridric acid injection
_Gaps sealing	1	p	Sealing with silicone

Table 68. Electric contacts. Inventory analysis.

Processes	Amount	Unit	Comments
Silver {CA-QC}| gold-silver mine operation with refinery | Alloc Def, U	7,55E-02	g	Plate dimensions: : 0.6*0.6* 0.01cm. Specific weight: 10,49 g/cm3. 2 plates.
Polyester resin, unsaturated {RER}| production | Alloc Def, U	8,96E-02	g	Serigraphic screen. A: 350*400*0,5mm. Specific weight: 1,28g/cm3.
_Serigraphic printer	2,78E-07	p	Power: 440W.Lifespan: 30000 h. Weight: 200kg
Electricity, low voltage {IT}| market for | Alloc Def, U	1,22E-02	KWh	Electricity for the serigraphic printer and the vacuum system
_Bag filter (1800Nm3/h)	8,68E-07	p	Lifespan: 9600h. Weight: 437.9 kg
Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW}| transport, freight, lorry 7.5-16 metric ton, EURO6 | Alloc Def, U	9,00E+00	kgkm	Transportation of serigraphic printer and screens, bag filters. 100km
Ash from deinking sludge {CH}| treatment of, residual material landfill | Alloc Def, U	7,48E-04	g	EoL of silver paste retained by the filter
Emissions			
Heavy metals, unspecified	2,27E-05	g	1% of emissions. Filter's efficiency: 97%

Table 69. TIFAIN end of life. Inventory analysis.

Processes	Amount	Unit	Comments
Waste cement, hydrated {CH}| treatment of, residual material landfill | Alloc Def, U	2,91E+02	g	No recycling is considered

The second LCA is performed on the restoration intervention of the Buccola pavilion, considering a scenario where the TIFAIN tiles are installed in the window frames of the building. It is therefore necessary to calculate the number of tiles necessary and the energy production of the tiles during the lifespan of the restored building. Once again, the present best available technology is considered to be employed for the future 100 years, while it is probable that at technological improvement would occur. However, future inventory data canot be predicted and the use of the present technology as a proxy represents a conservative approach in terms of impact outputs.

A common assumption in PV lifetime environmental impact analysis – also recommended by the IEA-PVPS – is that the average panel lifespan is 30 years (Frischknecht et al., 2016). Being the best available information, this datum is considered an acceptable proxy for the TIFAIN tiles. The area available in the considered building for the transparent PV tiles installation is 280.8 m2, that corresponds to the total windows area, without including the frame. This means that over the conventional period of 100 years, the total number of tiles used for the Buccola pavilion would be equal to 280.8*100/30 = 936 tiles.

As far as the electric production is concerned, the global formula to estimate the electricity generated in output of a photovoltaic system is (http://photovoltaic-software.com/PV-solar-energy -calculation.php):

$$E = A * r * H * PR \tag{4.2.5.1}$$

Where:

E = Energy (kWh)

A = Total solar panel Area (m²)

r = solar panel yield or efficiency(%)

H = Annual average solar radiation on tilted panels (shadings not included)

PR = Performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75)

r is the yield of the solar panel given by the following ratio: electrical power (in kWp) of one solar panel divided by the area of one panel. H, the annual average solar radiation on tilted panels, can have a value between 200 kWh/m².y of Norway and 2600 kWh/m².y of Saudi Arabia.

PR, the Performance Ratio, is a very important value to evaluate the quality of a photovoltaic installation because it gives the performance of the installation independently of the orientation, inclination of the panel and it includes all the possible losses. The detailed losses that gives the PR value (depend on the site, the technology, and sizing of the system) can be the following:

- Inverter losses (4% to 10 %)
- Temperature losses (5% to 18%)
- DC cables losses (1 to 3 %)
- AC cables losses (1 to 3 %)
- Shadings (0 % to 80%, specific to each site)
- Losses at weak radiation (3% to 7%)
- Losses due to dust, snow etc. (2%)
- Other possible losses

The annual average solar radiation measured in Reggio Emilia (Italy) is 1415 KWh/m2 (http://www.pannellisolari.bologna.it/nuovo-conto-energia/esempi/radiazione-solare-media-giornaliera.html), while the TIFAIN tile efficiency tested in the lab was equal to 11%.

Considering these figures, the electrical energy generated by a single TIFAIN tile (1m2) within 1 year is equal to:

E= 1*0.11*1415* 0.75 = 116.7375 kWh/y

The total area of the Buccola windows glasses (without frame) is 280.8 m2, which would give an annual electric output of about 32780 kWh per year.

Considering a 2% efficiency loss every year, the total estimated amount of electricity produced over a 100 years life span equals to 2542774 kWh.

- *Results*

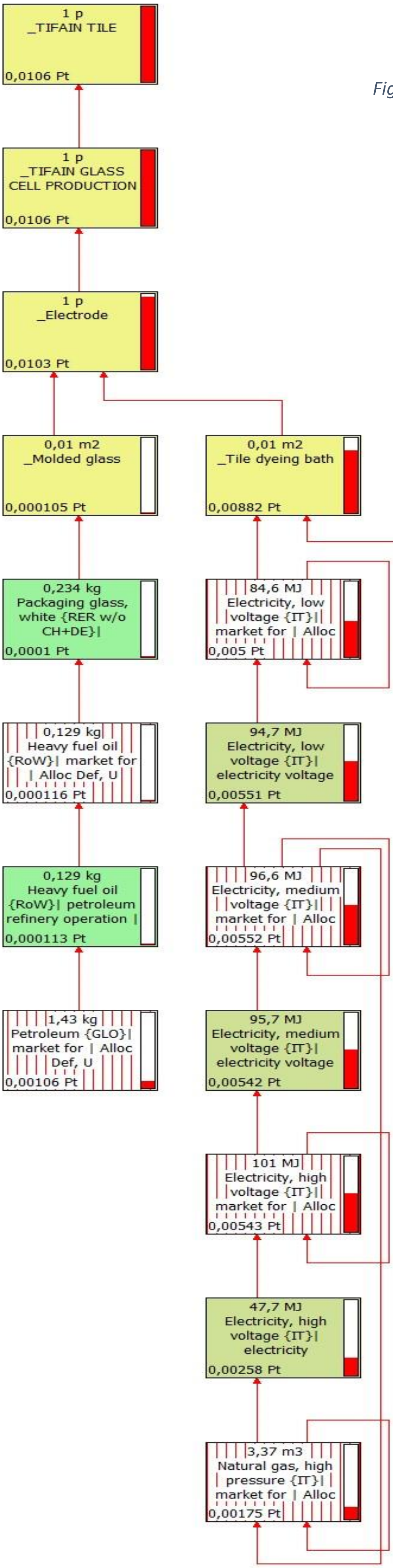


Figure 33. TIFAIN tile production network. Modified IMPACT 2002+. Cut off: 5%.

Table 70. TIFAIN tile production. Single score and damage categories results (Pts). IMPACT 2002+.

Damage category	Unit	Total	_Electrode	_Counterelectrode	_Cell sealing	_Electrolite injection and gaps sealing	_Electric contacts	_TIFAIN EoL
Total	mPt	9,20	8,92E+00	1,12E-02	2,28E-01	1,36E-02	2,33E-02	5,85E-03
Human health	mPt	2,34	2,26E+00	3,09E-03	6,06E-02	3,25E-03	1,32E-02	4,89E-03
Ecosystem quality	mPt	0,45	4,52E-01	4,53E-04	5,75E-03	3,15E-04	9,34E-04	1,73E-04
Climate change	mPt	3,80	3,72E+00	3,68E-03	7,73E-02	3,80E-03	4,52E-03	2,42E-04
Resources	mPt	2,58	2,49E+00	3,95E-03	8,45E-02	6,27E-03	4,63E-03	5,43E-04

Translated into percentages, the single score results (Table 71) show that the process associated to the majority of the impacts is the electrode production (almost 97% of the total potential impacts. As far as the damage categories are concerned, the most affected one is the Climate change (41%), followed by Resources and Human health. Only 5% of the damage falls into the Ecosystem quality cateGory. As far as the process contribution is concerned, the electricity production (from natural gas, coal and oil) is responsible to more than 20% of the potential impacts. About 95% of the electricity is demanded during the electrode production process, for the vacuum system operation and the different heating treatments. The spent solvent mixture, associated to more than 10% of the potential impacts, is used as a proxy for the end-of life of the ethanol solution.

Table 71. TIFAIN tile production. Single score and damage categories results (%).

Damage category	Unit	Total	_Electrode	_Counterelectrode	_Cell sealing	_Electrolite injection and gaps sealing	_Electric contacts	_TIFAIN EoL
Total	%	100,00	96,94	0,12	2,48	0,15	0,25	0,06
Human health	%	25,48	24,56	0,03	0,66	0,04	0,14	0,05
Ecosystem quality	%	4,99	4,91	0,00	0,06	0,00	0,01	0,00
Climate change	%	41,39	40,42	0,04	0,84	0,04	0,05	0,00
Resources	%	28,14	27,05	0,04	0,92	0,07	0,05	0,01

Table 72. TIFAIN tile: Damage assessment. IMPACT 2002+.

Damage category	Unit	Total	_Electrode	_Counterelectrode	_Cell sealing	_Electrolite injection and gaps sealing	_Electric contacts	_TIFAIN EoL
Human health	DALY	1,66E-05	1,60E-05	2,19E-08	4,30E-07	2,31E-08	9,35E-08	3,47E-08
Ecosystem quality	PDF*m2*yr	6,29E+00	6,19E+00	6,20E-03	7,88E-02	4,32E-03	1,28E-02	2,36E-03
Climate change	kg CO2 eq	3,77E+01	3,68E+01	3,65E-02	7,65E-01	3,77E-02	4,47E-02	2,39E-03
Resources	MJ primary	3,94E+02	3,78E+02	6,01E-01	1,28E+01	9,53E-01	7,03E-01	8,25E-02

Table 73.TIFAIN tile production. Impact categories, characterization results. Impact 2002+.

Impact category	Unit	Total	_Electrode	_Counterelectrode	_Cell sealing	_Electrolite injection and gaps sealing	_Electric contacts	_TIFAIN EoL
Carcinogens	kg C2H3Cl eq	5,98E-01	5,72E-01	9,27E-04	1,93E-02	1,72E-03	2,62E-03	1,03E-03
Non-carcinogens	kg C2H3Cl eq	4,77E-01	4,47E-01	3,33E-04	4,43E-03	2,98E-04	1,46E-02	1,02E-02
Respiratory inorganics	kg PM2.5 eq	1,93E-02	1,87E-02	2,60E-05	5,14E-04	2,46E-05	6,43E-05	4,45E-06
Ionizing radiation	Bq C-14 eq	3,94E+02	3,78E+02	6,51E-01	1,41E+01	5,63E-01	7,72E-01	3,88E-02
Ozone layer depletion	kg CFC-11 eq	3,58E-06	3,45E-06	5,25E-09	1,15E-07	2,98E-09	6,49E-09	8,73E-10
Respiratory organics	kg C2H4 eq	1,70E-02	1,68E-02	1,02E-05	1,66E-04	2,06E-05	2,36E-05	2,34E-06
Aquatic ecotoxicity	kg TEG water	2,78E+03	2,73E+03	2,15E+00	3,43E+01	1,70E+00	8,33E+00	7,76E+00
Terrestrial ecotoxicity	kg TEG soil	3,88E+02	3,78E+02	6,25E-01	7,26E+00	3,58E-01	1,13E+00	7,07E-02
Terrestrial acid/nutri	kg SO2 eq	3,50E-01	3,38E-01	4,81E-04	1,00E-02	5,18E-04	1,39E-03	1,01E-04
Land occupation	m2org.arable	2,50E+00	2,48E+00	5,94E-04	8,47E-03	7,92E-04	1,86E-03	1,20E-03

Aquatic acidification	kg SO2 eq	1,07E-01	1,03E-01	1,58E-04	3,34E-03	1,63E-04	2,99E-04	2,01E-05
Aquatic eutrophication	kg PO4 P-lim	3,61E-03	2,91E-03	4,01E-06	6,36E-05	4,01E-06	6,33E-04	5,45E-07
Global warming	kg CO2 eq	3,77E+01	3,68E+01	3,65E-02	7,65E-01	3,77E-02	4,47E-02	2,39E-03
Non-renewable energy	MJ primary	3,92E+02	3,77E+02	5,94E-01	1,28E+01	9,51E-01	6,97E-01	8,24E-02
Mineral extraction	MJ surplus	1,21E+00	1,18E+00	6,74E-03	1,12E-02	1,53E-03	5,77E-03	7,27E-05

Table 74. TIFAIN tile production. Process contribution percentages. Cut off: 1%.

Process	Unit	Total	_Electrode	_Counterelectrode	_Cell sealing	_Electrolite injection and gaps sealing	_Electric contacts	_TIFAIN EoL
Total of all processes	%	100,00	96,94	0,12	2,48	0,15	0,25	0,06
Electricity, high voltage {IT}| electricity production, natural gas, at conventional power plant | Alloc Def, U	%	9,10	8,63	0,02	0,44	0,00	0,00	0,00
Spent solvent mixture {RoW}| treatment of, hazardous waste incineration | Alloc Def, U	%	6,60	6,60	0,00	0,00	0,00	0,00	0,00
Electricity, high voltage {IT}| electricity production, hard coal | Alloc Def, U	%	6,10	5,79	0,01	0,30	0,00	0,00	0,00
Natural gas, high pressure {RU}| natural gas production | Alloc Def, U	%	5,08	4,87	0,01	0,20	0,00	0,00	0,00
Electricity, high voltage {IT}| electricity production, oil | Alloc Def, U	%	4,32	4,10	0,01	0,21	0,00	0,00	0,00
Spent solvent mixture {CH}| treatment of, hazardous waste incineration | Alloc Def, U	%	3,97	3,97	0,00	0,00	0,00	0,00	0,00
Active coal E3	%	3,47	3,47	0,00	0,00	0,00	0,00	0,00
Hard coal {RoW}| mine operation | Alloc Def, U	%	3,18	3,03	0,01	0,14	0,00	0,00	0,00
Natural gas, high pressure {DZ}| natural gas production | Alloc Def, U	%	2,87	2,73	0,01	0,14	0,00	0,00	0,00

Natural gas, high pressure {RoW}| natural gas production | Alloc Def, U	%	2,85	2,72	0,01	0,12	0,00	0,00	0,00
Charcoal {GLO}| production | Alloc Def, U	%	2,04	2,04	0,00	0,00	0,00	0,00	0,00
Heat, central or small-scale, natural gas {CH}| heat production, natural gas, at boiler condensing modulating <100kW | Alloc Def, U	%	1,99	1,99	0,00	0,00	0,00	0,00	0,00
Natural gas, high pressure {DE}| natural gas production | Alloc Def, U	%	1,83	1,83	0,00	0,00	0,00	0,00	0,00
Natural gas, high pressure {NL}| petroleum and gas production, on-shore | Alloc Def, U	%	1,55	1,51	0,00	0,04	0,00	0,00	0,00
Petroleum {RoW}| petroleum and gas production, on-shore | Alloc Def, U	%	1,43	1,38	0,00	0,04	0,00	0,01	0,00
Petroleum {RME}| production, onshore | Alloc Def, U	%	1,42	1,37	0,00	0,04	0,00	0,01	0,00
Electricity, high voltage {RU}| electricity production, lignite | Alloc Def, U	%	1,33	1,28	0,00	0,05	0,00	0,00	0,00
Uranium ore, as U {RNA}| uranium mine operation, underground | Alloc Def, U	%	1,16	1,11	0,00	0,04	0,00	0,00	0,00
Process-specific burdens, hazardous waste incineration plant {RoW}| processing | Alloc Def, U	%	1,10	1,10	0,00	0,00	0,00	0,00	0,00
Uranium ore, as U {RoW}| uranium mine operation, underground | Alloc Def, U	%	1,09	1,04	0,00	0,04	0,00	0,00	0,00
Natural gas, unprocessed, at extraction {GLO}| production | Alloc Def, U	%	1,08	1,04	0,00	0,05	0,00	0,00	0,00
Clinker {RoW}| production | Alloc Def, U	%	1,04	1,03	0,00	0,00	0,00	0,00	0,00
Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW | Alloc Def, U	%	1,03	1,03	0,00	0,00	0,00	0,00	0,00

As the electrode production is the process associated to the higher impact, it might be interesting to focus the analysis on this particular process. The results are reported in Table 75 and Table 76.
The dyeing bath of the electrode is the subprocess that causes the majority of the potential impacts due to the electrode production (86%). During this process electricity is consumed for the vacuum system operation that runs for a longer amount of time compared to the other processes and the ethanol solution has to be properly dismissed (a proxy is used in this case). These two subprocesses are responsible for about 20% and 10% of the total potential impacts associated to electrode production process.

Table 75. Electrode production. Process contribution %. IMPACT 2002+. Cut off: 1%.

Process	Unit	Total	_Molded glass	_Indium tin oxide (ITO)	_ITO deposition	_Nano TiO2 deposition	_Tile cleaning	_High temperature	_Tile dyeing bath
Total of all processes	%	100,00	0,97	0,82	4,62	0,44	4,24	2,68	86,23
Electricity, high voltage {IT}| electricity production, natural gas, at conventional power plant | Alloc Def, U	%	8,91	0,00	0,09	0,60	0,03	0,30	0,48	7,41
Spent solvent mixture {RoW}| treatment of, hazardous waste incineration | Alloc Def, U	%	6,81	0,00	0,00	0,00	0,00	0,53	0,00	6,28
Electricity, high voltage {IT}| electricity production, hard coal | Alloc Def, U	%	5,97	0,00	0,06	0,40	0,02	0,20	0,32	4,96
Natural gas, high pressure {RU}| natural gas production | Alloc Def, U	%	5,02	0,02	0,04	0,27	0,03	0,17	0,21	4,27
Electricity, high voltage {IT}| electricity production, oil | Alloc Def, U	%	4,23	0,00	0,04	0,28	0,01	0,14	0,23	3,51
Spent solvent mixture {CH}| treatment of, hazardous waste incineration | Alloc Def, U	%	4,10	0,00	0,00	0,00	0,00	0,11	0,00	3,99
Carbone attivo E3	%	3,58	0,00	0,00	0,00	0,00	0,09	0,00	3,48
Hard coal {RoW}| mine operation | Alloc Def, U	%	3,12	0,01	0,03	0,21	0,01	0,13	0,15	2,58
Natural gas, high pressure {DZ}| natural gas production | Alloc Def, U	%	2,82	0,01	0,03	0,19	0,01	0,10	0,15	2,34
Natural gas, high pressure {RoW}| natural gas production | Alloc Def, U	%	2,81	0,01	0,03	0,18	0,01	0,12	0,13	2,33
Charcoal {GLO}| production | Alloc Def, U	%	2,10	0,00	0,00	0,00	0,00	0,05	0,00	2,04
Heat, central or small-scale, natural gas {CH}| heat production, natural gas, at boiler condensing modulating <100kW | Alloc Def, U	%	2,06	0,00	0,00	0,00	0,00	0,05	0,00	2,00
Natural gas, high pressure {DE}| natural gas production | Alloc Def, U	%	1,88	0,00	0,00	0,00	0,03	0,06	0,00	1,79
Natural gas, high pressure {NL}| petroleum and gas production, on-shore | Alloc Def, U	%	1,56	0,01	0,01	0,06	0,01	0,05	0,05	1,37

Petroleum {RoW}| petroleum and gas production, on-shore | Alloc Def, U	%	1,43	0,03	0,01	0,06	0,01	0,05	0,04	1,23
Petroleum {RME}| production, onshore | Alloc Def, U	%	1,41	0,03	0,01	0,06	0,01	0,05	0,04	1,21
Electricity, high voltage {RU}| electricity production, lignite | Alloc Def, U	%	1,32	0,01	0,01	0,07	0,01	0,05	0,05	1,13
Uranium ore, as U {RNA}| uranium mine operation, underground | Alloc Def, U	%	1,14	0,01	0,01	0,06	0,01	0,05	0,05	0,95
Process-specific burdens, hazardous waste incineration plant {RoW}| processing | Alloc Def, U	%	1,14	0,00	0,00	0,00	0,00	0,07	0,00	1,07
Uranium ore, as U {RoW}| uranium mine operation, underground | Alloc Def, U	%	1,08	0,01	0,01	0,06	0,01	0,05	0,04	0,90
Natural gas, unprocessed, at extraction {GLO}| production | Alloc Def, U	%	1,07	0,01	0,01	0,07	0,00	0,05	0,05	0,89
Heat, central or small-scale, other than natural gas {RoW}| heat production, anthracite, at stove 5-15kW | Alloc Def, U	%	1,07	0,00	0,00	0,00	0,00	0,06	0,00	1,00
Clinker {RoW}| production | Alloc Def, U	%	1,07	0,00	0,00	0,01	0,00	0,02	0,00	1,04

Table 76. Electrode production. Process contribution %. IMPACT 2002+. Cut off: 1%.

Substance	Compartment	Unit	Total	_Molded glass	_Indium tin oxide (ITO)	_ITO deposition	_Nano TiO2 deposition (water solution, 1%)	_Tile cleaning	_High temperature fixing	_Tile dyeing bath
Total of all compartments		%	100,00	0,62	0,56	3,47	0,35	4,37	2,18	88,46
Carbon dioxide, fossil	Air	%	93,87	0,60	0,53	3,30	0,32	4,15	2,08	82,89
Methane, fossil	Air	%	1,98	0,01	0,02	0,10	0,01	0,08	0,07	1,69
Carbon monoxide, fossil	Air	%	1,58	0,00	0,00	0,01	0,00	0,06	0,00	1,50
Methane, biogenic	Air	%	1,54	0,00	0,00	0,00	0,00	0,04	0,00	1,49

As far as the LCC is concerned, the direct costs of the production of the tile and the external costs are included. Table 77 shows the external costs disaggregated according to the different damage categories and production processes, as calculated using the modified version of IMPACT 2002+ to include externalities. The total external cost for a single tile production is equal to 9.30€. Looking at the internal cost, no specific data were available but it was estimated using the assessment of Kalowekamo et al. (2008) as a proxy. The estimated average tile cost considered is 99€/m2. The LCC results for a single tile manufacturing give a total output of 108.3€.

Table 77. TIFAIN tile production externalities. Modified IMPACT 2002+.

Damage category	Unit	Total	_Electrode	_Counterelectrode	_Cell sealing	_Electrolite injection and gaps sealing	_Electric contacts	_TIFAIN EoL
Human health	€	5,86E-01	5,67E-01	8,28E-04	1,51E-02	8,10E-04	1,89E-03	1,14E-04
Ecosystem quality	€	1,92E-02	1,90E-02	1,74E-05	1,13E-04	1,67E-05	8,73E-05	7,99E-06
Climate change	€	2,97E-01	2,90E-01	2,85E-04	5,98E-03	2,94E-04	3,49E-04	1,87E-05
Resources	€	8,39E+00	8,07E+00	1,27E-02	2,74E-01	2,02E-02	1,48E-02	1,72E-03
Total	€	9,30E+00	8,95E+00	1,38E-02	2,95E-01	2,13E-02	1,71E-02	1,86E-03

When the whole restoration intervention is considered, the total number of tiles (necessary to cover the 280.8m2 of glasses area of the pavilion) is taken into account, with the addition of the inverters, over a 100 years life span, both for the LCA and LCC analysis. The additional installation cost is included in the LCC as well. The whole intervention single score and damage categories LCA scores are shown in Table 78, while the LCC results are shown in Table 79. The inverters are associated only to 5.32% of the total potential impacts of the BIPV solution manufacturing. The estimated monetary savings thanks to the photovoltaic electricity production over the 100 years functional unit amount to 533982.54€.

Table 78. Buccola restoration intervention. TIFAIN installation, single score and damage categories. 100y lifespan.

Damage category	Unit	Total	Inverter, 2.5kW {RER}| production | Alloc Def, U	_TIFAIN tiles	_TIFAIN EoL	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Alloc Def, U
Total	Pt	9,099233	0,484533	8,608039	0,005474	0,001187
Human health	Pt	2,444022	0,248752	2,19043	0,004578	0,000262
Ecosystem quality	Pt	0,500942	0,070909	0,429745	0,000162	0,000127
Climate change	Pt	3,642802	0,077405	3,564779	0,000226	0,000392
Resources	Pt	2,511466	0,087466	2,423085	0,000508	0,000407

Table 79. TIFAIN LCC. Installation and maintenance of all the BIPV elements over 100 years lifespan.

Buccola pavilion restoration: TIFAIN installation and maintenance (100y lifespan, no use-phase)				
		First installation	First installation	100 y
Internal costs (€)	Tiles manufacturing	27799	32929	109763
	Inverters (20kW)	3600		
	Installation and maintenance manpower	1530		
External costs (€)	100 y	9012		
Total costs (€)	100 y	118775		

4.2.6. Monetary value of Cultural Heritage: micoreconomic approach

The lack of recognized and widely accepted methodologies for the assessment of cultural values, was already highlighted in the Getty Conservation report in 2002 but – to our knowledge – this void has not been filled, yet. This breach is probably due to the difficulties that raise comparing and combining the results of economic and cultural values assessments, not to mention that different possible approaches to establish the economic value exist and they all have different limitations and implications. Moreover, the public nature of Cultural Heritage goods makes it very difficult for them to be associated to a market price. Optimal allocation of goods in a free market economy requires that everything can be bought and sold and that those who do not pay can be excluded from the use of the good (Fullerton, 1991). If, however anyone can consume the good regardless of whether they have paid or not – as it is usually the case for built Cultural Heritage - then the market mechanism will fail because of the "free rider" problem. Last but not least, built Cultural Heritage comprises a great variety of goods, which makes it questionable whether a common method would be suitable for all the Cultural Heritage categories. At the same time, it is important to be able to compare the benefits and costs of different interventions in order to establish priorities.

Considering that "*value has always been the reason underlying heritage conservation*" (Getty, 2002) and considering the gap in the methodology, the aim of this study is to propose a generalized approach to establish the socio-economic value associated to a heritage building, to be integrated within a LCSA of possible conservation interventions. The monetary unit is the most suitable one as it allows to compare the calculated value with the results of the Life Cycle Costing assesment (split in internal and external costs) and at the same time it is "understandable" by the different layers of stakeholders involved and, above all, by the decision makers. Moreover, a generalized approach might be useful in order to set Conservation Management priorities, as it allows comparisons when for example the budget is limited but more than one building requires a restoration intervention.

In order to progress towards a generalized methodology to establish the value of a heritage building, it is fundamental to investigate the different approaches that have been previously used and establish which ones are suitable to our scope, which ones should be discarded and which ones can be adapted.

In the last two decades, economists indeed dedicated growing attention on the estimation of the economic value of cultural heritage and services (Kaminski, McLoughlin, & Sodagar, 2007; Navrud & Ready, 2002; Noonan, 2003; Venkatachalam, 2004) but the focus was mainly concentrated on particular case studies.

According to Mazzanti (2003),"*within a micro-economic framework, survey based economic valuation tools aimed at eliciting (stated) preferences over cultural goods are relevant to cultural policy making—especially for financing, conservation activities and management of cultural institutions (Museums, Archaeological sites, Monuments*)". Indeed, some studies (Snowball, 2008; Noonan, 2003) used two microeconomic approaches to estimate the value of Cultural Heritage: the contingent valuation (CV) or the closely related choice experiment (CE) approach. Both methods are based on a hypothetical scenario and use questionnaires/ surveys. If the CV method is used to state stakeholders' willingness to pay contingent on the specific scenario proposed, the CE method is used to assess people's preferences, as discrete choices in a multi-dimensional framework. A utility index regression is then used to find the marginal WTP (if any) deriving from different improvement scenarios. The limitation of this approach seems to be its applications only for CH buildings where an entrance fee (hypothetical or not) could be envisaged. The final output is an average marginal WTP, deriving by marginal changes and not an absolute value to be associated to the considered CH building. A total marginal WTP could be obtained forecasting the number of future visitors. This does not allow to quantify the sociocultural and subsequent monetary value of heritage buildings that are not turistic attractions (and do not have an entrance fee) but that add a value to the service they contribute to give.

Other studies (Deodhar, 2004; Narwold et al., 2008; Ruijgrok, 2006; Coulson and Leichenko, 2001 and Moro et al., 2011) used the Hedonic Prices approach. Unlike CV and CE, the HP approach takes advantage of indirect observation, specifically revealed preferences. The preferences are observed through the real estate market value. Eventually, econometric models can also use GIS based HP technique to find a regression coefficient for the distance from a CH building. Some HP studies, investigate the direct effect of the designation of a property as CH, in terms of marginal impact on its price. Deodhar (2004) found out that a 12% premium was associated to houses being designated as Cultural Heritage in Kung-ring-gai, an historical district of Sydney (Australia). Narwold et al. (2008) found that designation as a historical property created a 16% increase in single family detached housing value in San Diego, California). Ruijgrok (2006) reported that- in the town of Tiel in the Netherland - houses with a national or municipal monument status increased their value of almost 15%. Another part of the literature focuses on the indirect effects of the neighbourhood houses prices located near a heritage building. Coulson and Leichenko (2001) reported that each additional designated house within a census tract in Albilene, Texas increases the value of each house in that census tract by 0.14 %.

Lazrak et al. (2014) reported that *"After controlling for transaction-related, structural and spatial characteristics, monuments are found to make a positive and significant contribution to house value of approximately 21 per cent, over non-monuments. This direct effect means that potential buyers, according to the baseline estimates, are willing to pay an additional €33,600 in the year 2000 prices to purchase an average priced monument. The indirect effect which is measured by the monument density within a 50-metre radius is significant in the first model. One additional monument increases house prices within a 50- metre radius by 0.24 per cent in the baseline model"*. This was investigated in the Dutch urban area of Zaanstad. Moro et al. (2011) found out that, in the Great Dublin area *"The distance to nearest historical buildings, churches and memorials is negatively associated with the house price and it is statistically significant. Proximity to archaeological site does not seem to have any effect on property value. The property value decreases by 0.8% and 0.5% as the distance to historical buildings, churches and memorials increases by 100 meters, respectively. At the sample mean, this compares to a fall of about €4600 and €2900 in the house price for every additional 100 meters. Heritage sites characteristics such as whether the access is free, whether the heritage site was built prior 1500 and whether it is under State care do not have a statistically significant effect at any conventional level"*

As far as the maximum distance at which an effect on the real estate properties is observed or taken into account, little discrepancies arises from the different studies: Larzak et al. (2014) considers a radius of 50 m, even if "Different radius specifications were tested but it seems plausible to choose relatively steep distance decay." Moro et al. (2011 did not mention a distance limitation but consider an order of magnitude of hundreds of metres. Cavailhès et al. (2009) found out that –for landscape attributes- most objects located more than 70m away have insignificant hedonic prices, with the exception of farmland and transport network, which are significat up to 280 m away.

The HP method has limitations as well: many of the mentioned studies struggled with the problem of a limited number of observations and limited information about housing and neighbourhood characteristics. Omitted variables, multicollinearity, endogeneity and spatial heterogeneity problems may also arise but particular econometric models – like the fixed effect ones- can be used to address these issues (Cavailhès at al., 2009). Moreover, as noted by Moro et al. (2011) *"the hedonic price method is based on a number of restrictive assumptions, including the assumption of equilibrium in the housing market, perfect information of the characteristics of all the alternative sites, no transaction and mobility costs."* At the same time *"disequilibrium conditions would constitute an econometric problem for the estimation of the effect of heritage sites on house* *prices only if disequilibrium is correlated with heritage sites, which seems unlikely".* At the same time the HP approach allows for georeferenced data which is an important feature when assessing the value of CH buildings that are immovables, therefore closely linked to the local features.

A significant aid to overcome the gap in the valuation of a cultural heritage building can be found in the environmental economics' concept of Total Economic Value (TEV), used to associate a value to environmental services and goods.
The term "total economic value" probably appeared for the first time in an essay by Peterson and Sorg in 1987, "Toward the measurement of total economic value" and it is an attempt to overcome the traditional evaluation of environmental goods, exclusively based on the direct use value attributed to goods, considering direct benefits enjoyed by final consumers (Cavuta, 2000). TEV can be defined as the "*sum of the values of all the services flows that natural capital generates both now and in the future*" (Brander et al., 2010).
More speficically, TEV is the sum of the Direct Use Value, Indirect Use Value, Option Value, which can be seen as indicators of the Use Value category and two indicators that falls in the Non-Use Value category, the Bequest Value and the Existence Value (Fig.1) As suggested by their name, the direct and indirect use value refers to the direct or indirect exploitation of the resource, while the option value refers to the value of the possible future uses of the resource. The bequest value always refers to a possible future use but for the next generations and the existence value should measure the intrinsic value of the resource, indipendent from its use or consmption by the stakeholders. The same framework and concept can be adopted to calculate the economic value of Cultural Heritage buildings: the challenge lies in finding out which values of the considered indicators can be inferred in practice and how to calculate them, using an as far as possible standardized and reproducible approach (i.e. that would not consists of mainly subjective evaluations from expert panels).

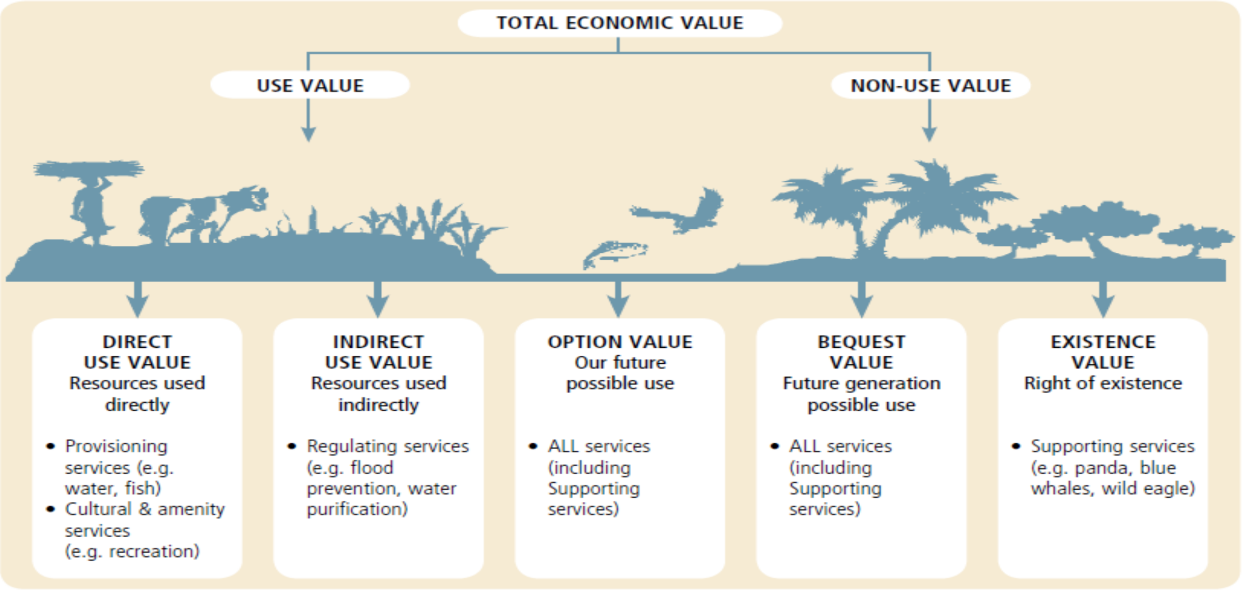


Figure 34. Total Economic Value framework (from Smith et al., 2006).

The literature review and above mentioned considerations, lead to the following appraisals:

- The Hedonic Pricing results obtained from the different reviewed studies are taken into account and an average value is found. A building endures an average price increase of 16% due to its designation as cultural heritage. This figure can be used to calculate the economic value of the considered heritage building, using as a reference to the market price of a building with the same size and features with the exception of the historical status, located in the same area (this figure should be easily traceable on the real estate market).

- The revealed preferences methods are not further investigated as – as previously stated- they are not useful to assess the value of CH building not associated to an entrance fee and they are closely bound to specific scenarios and case studies.

- Moreover, an approach based on the reparation and maintenance costs is considered. The idea is that the marginal costs of reparation and/or maintenance (compared to a new and efficient building) will represent the WTP to preserve the cultural value. Heritage buildings are indeed safeguarded and restrictions apply on the possible interventions (like on thermal insulation coatings, or roof photovoltaic panels) and some elements are restored instead of replaced with less expensive or more efficient ones.

These approaches can be summed up and framed into a TEV assessment. The market value assessment (calculated using the direct hedonic pricing analisys), together with the reparation and maintenance costs, are a proxy of the Direct Use value, while the indirect hedonic prices analysis represents a proxy of the Indirect Use one. Future restoration interventions and use scenarios might be representative of the Option value. Unfortunately, the Non-use value is not included within this microecnomic approach. A macroeconomic framework should be considered to calculate the intangible value of Cultural Heritage.
The TEV obtained is then used as a proxy of the monetization of the sociocultural value of the building; the latter can be compared and coupled with the economic cost of the conservation intervention and of the possible following use phase. When both the life cycle internal and external costs are considered, a Life Cycle Sustainability Assessment of the heritage building conservation is performed.

A specific case study is used to implement the proposed approach: the restoration intervention of the Buccola pavilion, located in Reggio nell' Emilia, Italy. The pavilion -one of the heritage buildings of the San Lazzaro area, a former psychiatric hospital - was built in 1932 and restored in 2007, to host some rooms and offices of the University of Modena and Reggio Emilia. Before the restoration intervention, the pavilion was closed and condemned. In this example an ex poste analysis was performed (with the benefit of a greater data availability) but the method might be more useful for an ex ante analysis. During the restoration intervention, little attention was to the use of sustainable materials or energy efficient solutions. This is partly due to the restrictions imposed by the Superintendence over Cultural Heritage buildings but also to scarce focus on sustainability matters and probably to budgeting constraints. For this reason but also to show the potential of the proposed approach in the results presentation (that offer an easy interpretation for all the stakeholders), a scenario where the regular windows glasses are replaced by building integrated photovoltaic glasses is presented, as well. The choice of the photovoltaic glasses is motivated by the big window area of the pavilion and by their influential effect on the aesthetic of the heritage building, where restrictions on possible improvement interventions apply.

4.2.7. Results presentation and recommendations

a. Environmental LCC results

The environmental LCC is here defined as the sum of the restoration intervention cost, the use phase cost and the monetization of the associated environmental impacts.
Total internal cost of the restoration intervention is equal to 2.650.000€ and the associated externalities amount to 3.058.610€. The high externalities value is mainly associated to the high resource consumption (2.930.000€). The calculated district heating cost over 100 years is 7.659.666€, the electricity consumption cost for the fancoils functioning (including the circulation pump operation) is 27.888.000€ and associated externalities amount to 30.963.400€.

b. Monetarized sociocultural value

The monetarized sociocultural value of the heritage building is calculated using the TEV framework previously described:

- *Reparation and Maintenance cost*

The maintenance costs can be calculated comparing the actual use phase energetic costs with the hypothetic operational phase costs of an equivalent building classified as energetically efficient. As previously mentioned, the surplus cost can be considered a willingness to pay to maintain the heritage features of the building, or to maintain it as close as possible to the original construction project. According to the Italian guidelines for the energetic classification, [linee guida per la certificazione energetica DM 26-06-2015], the Energetic efficiency index (EP) of a class A university building should be less than 8 KWh/m3.

A	**EPtot ≤ 8**
B	**8 ≤ EPtot ≥ 16**
C	**16 ≤ EPto t≥ 30**
D	**30 ≤ EPtot ≥ 44**
E	**44 ≤ EPtot ≥ 60**
F	**60 ≤ EPtot ≥ 80**
G	**EPtot ≥ 80**

Table 80. Energetic efficiency classes. Building category E.7. Linee guida per la certificazione energetica DM 26-06-2015.

The actual EPtot of the Buccola pavilion, as calculated with the EdilClima software, is 67.16 KWh/m3 year (F class). The ΔEP is then 59.16 KWh/m3 year. Considering that the pavilion volume is equal to 12711 m3, the life span taken into account for the LCA analysis (100 years) and the district heating price in Reggio nell'Emilia in 2016 equals to 0.09 €/KWh, the additional internal cost amounts to 6.767.844€. The additional external costs are not included as district heating is used.

No future discount or inflation costs are taken into account, in line with the majority of the LCC methods. Moreover, the 100 years lifespan is conventional and appropriate for the E-LCA of the whole building, but a sensitivity analysis with different lifespan is possible and recommended when technological improvements might be forecasted.

In this particular case study, only one element is suitable to calculate the Reparation cost: the pavilion wooden English window frames that are rebuilt to look exactly like the original ones, instead of installing new "present day" windows that would be less costly and more efficient. The supply and installation of English windows, wood shutter restoration, sanding plastering and painting costed 281703€, while the installation of regular windows would have costed 186.120€ (360 €/m2), so in this case the willingness to pay equals to 95.583€.

- *Hedonic Price value*

An investigation in the real estate market prices showed that the average price per squared metre of regular large sized buildings, with brick walls, developed over two or three floors and surrounded by a park in the Reggio nell'Emilia area is 1200 €/m2. According to the Hedonic Pricing studies results, the pavilion would increase its value of 16% because of its heritage classification, which translates in 411.648 € of additional value.

- *Total Heritage Value and Total Economic Value*

The estimable total Heritage Value preserved restoring the Buccola pavilion is then equal to the sum of all the previously calculates values, which equals to 7.275.075€. In order to consider the TEV, the direct (non-heritage) real estate value of the building must be added; the final result is 9.847.875€.

c. Sensitivity analysis: Photovoltaic glasses

As previously mentioned, the effect of a green technology application is verified within a sensitivity analysis. The choice fell on the TIFAIN (Tessere Integrate di vetro Fotovoltaico per applicazioni Architettoniche Innovative) tiles, transparent Dye-Synthetized Solar Cells that can replace the windows glasses without undermining the heritage features of the building. The technology still has to be implemented in the large scale, so Politecnico di Milano laboratory data are used as a proxy. The measured tiles efficiency equals to 11%.
With the TIFAIN tiles installation, the environmental externalities of the restoration works rise of 8436€ but over the 100 years of use-phase they diminish of 33038400€; the installation cost equals to 32930€ (comprehensive of the tiles production, the inverter and the labor cost).

d. Final results

The final results are reported in Table 81 to 84 and in form of intuitive graphs that allow to have a straightforward vision of the cost-benefit ratio of the possible solutions taken into account, in order to compare them and support the decision making process (Figures 35 and 36).

From the results of this particular case study, the heritage value of the Buccola pavilion, calculated with a microeconomic approach, overcomes the restoration life cycle cost (internal + external); when we consider the Total Economic Value associated to the pavilion, the cost-benefit ratio is roughly 1:2. The use-phase results are taken into account as well and they can be compared with the results of a different hypothetic scenario, represented by a BIPV solution. As expected, even if the green technology life cycle is not impact free, it deeply diminish the external costs of the use-phase. Figure 36 reports the external costs on the y axe instead of the total cost: this representation is useful when the interest focuses in measuring the eco-efficiency of different possible scenarios. The 100 years lifespan is conventionally used in buildings life cycle assessment but different lifespans and use-phases can be chosen within a sensitivity analysis.
It is also important to notice some limitations and issues related to the proposed methodology. As previously noticed, one of the aim was to find a general method that would be suitable for different buildings and would not necessarily recall the possibly subjective expert judgement: even if the generalization certainly adds a bias on the precision of the analysis, it is necessary in order to be able to perform *ex ante* analysis that can be used as a support in decision making. It is also important to note that there is a risk of biased results that t not be included in the statistical significance level due to the high number and complexity of variables, to the imperfect nature of the real estate market, to the possible lack of awareness of historic value (for stakeholders). Additional hedonic prices studies might be useful to have more refined (and statistically significant) values and to verify possible geographical areas behaving as outliers. The ideal final output would be to have regionalized results. The most important limitations of this methodology is probably that it is reliable mainly for recent heritage buildings and not for “proper” historical monuments, as some important features like the age of the building, its conservation state and the subcategory typology are not taken into account (or not significant in the reference studies). It is indeed a microeconomic valuation methods that employs market techniques to quantify the willingness to pay for the direct and indirect use of the built Cultural Heritage assets but not intangible benefits like the assets existence and the heritage hand-down value, that might not be included or be only partially included (according to the stakeholder perception). According to Mazzanti (2003) the latter are macroeconomic benefits that arise at a systemic level, involving society (the region or the country of reference) as a whole, as opposed to the microeconomic benefits that accrues to individuals as users of Cultural Heritage.
Another possible criticism on the methodology could pertain to the maintenance cost calculation: in the specific case study, we showed how a green solution could improve the building energetic consumption without undermining the aesthetic value of the building. With this scenario, the willingness to pay to maintain the heritage value of the building would apparently drop (as the Maintenance costs component would diminish). The Maintenance cost WTP is a measure of how much the stakeholders are ready to pay - and not

how much they actually pay - to maintain the building heritage features. In this particular case study, the *ex poste* analysis tells us that the calculated maintenance costs figure is a conservative measure as the maintenance cost is actually sustained by the stakeholders, who are then willing to pay at least this amount of money. Even if the bills cost would drop with a BIPV solution, the heritage value of the building would remain the same. When performing an *ex ante* analysis it is therefore recommended not to underestimate the heritage building value, i.e. not taking into account extremely innovative technologies during the maintenance costs calculation.

BUCCOLA PAVILION RESTORATION PROCESS (100y lifespan, no use-phase)	
	Actual restoration
Internal costs (€)	2650000
External costs (€)	2074485
Total costs (€)	4724485

Table 81. Buccola pavilion restoration and requalification intervention. Conventional and Environmental LCC. Modified IMPACT 2002+.

BUCCOLA PAVILION RESTORATION PROCESS (100y lifespan, with use-phase)		
	Actual restoration	BIPV solution
Internal costs (€)	38197666	109763
External costs (€)	33119800	9012
Total costs (€)	71317466	118775

Table 82. Buccola pavilion restoration and requalification intervention and BIPV sensitivity analysis scenario. Conventional and Environmental LCC. Modified IMPACT 2002+.

BUCCOLA PAVILION HERITAGE VALUE (Microeconomic approach, 100y lifespan)	
Hedonic price value (€)	411648
Reparation costs (€)	95583
Maintenance costs (€)	6767844
Total heritage value (€)	7275075

Table 83. Buccola pavilion. Historic building value according to the proposed microeconomic approach assessment.

BUCCOLA PAVILION TOTAL ECONOMIC VALUE (Microeconomic approach, 100y lifespan)	
Total heritage value	7275075
Pavilion direct (non-heritage) value	2572800
TEV	9847875

Table 84: Buccola pavilion Total Economic Value assessment.

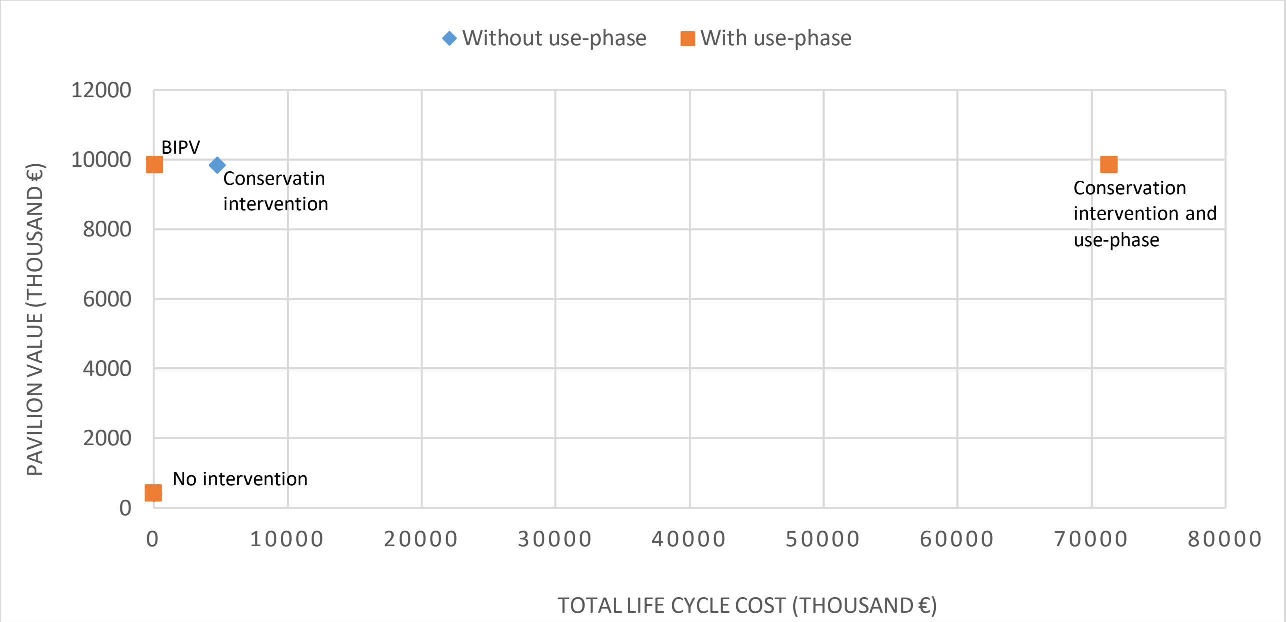


Figure 35. Buccola pavilion. Total costs/benefits ratio of different life cycle scenarios, according to the proposed microeconomic approach assessment.

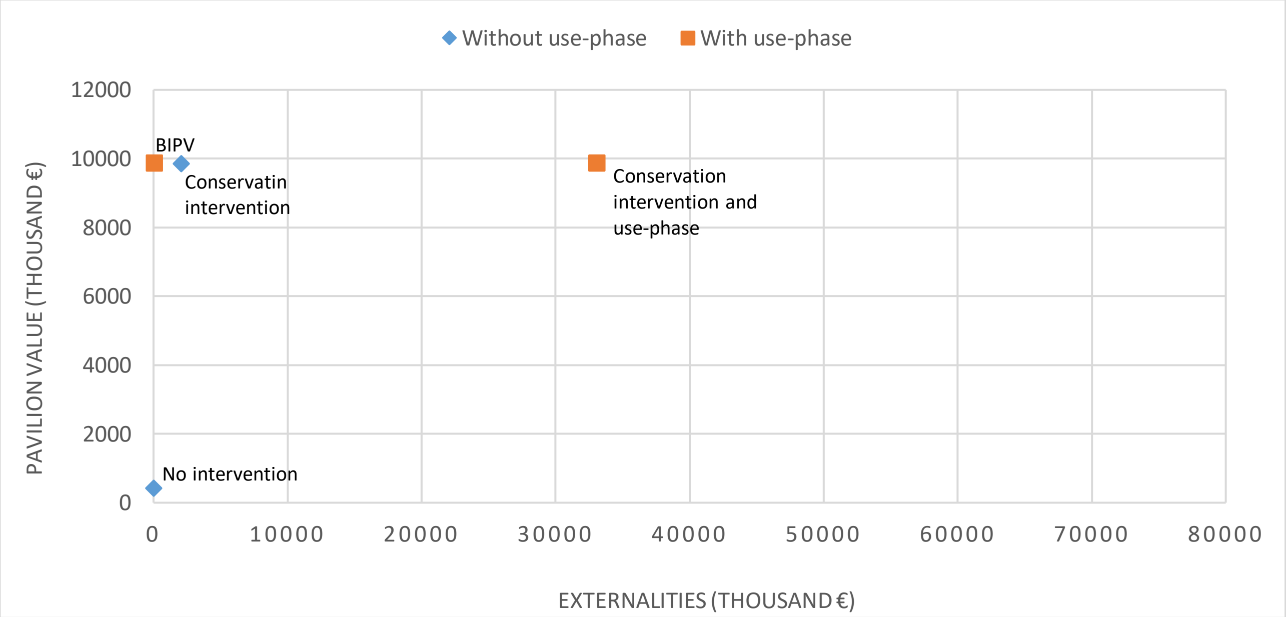


Figure 36. Buccola pavilion. Eternal costs/benefits ratio of different life cycle scenarios, according to the proposed microeconomic approach assessment.

5. Discussion and conclusions

The Life Cycle Assessment approach can be employed to assess the environmental load of a restoration, conservation or requalification intervention, of a demolition and following reconstruction, or of the upkeep of the present building conditions, from the raw materials extraction to the end-of-life processes. In addition, the potential impacts of the operational phase during the extended lifespan of the building can be determined as well. From this starting point it is possible deepen the assessment and characterize the more "environmental friendly" materials and interventions, analysing different scenarios within a sensitivity analysis. However, the restoration process also embodies the "methodological moment of recognition of Cultural Heritage in its physical form and in its dual aesthetic and historical instance, for conservation, valorisation, and transmission to future generations" (Pereira Roders, 2011). If the technical and direct economic aspects necessary for the environmental and costing assessment can be acquired as foreground data, the sociocultural aspects are much more difficult to identify and quantify. At the same, this identification and quantification is necessary to fulfil the requirements of a sustainable growth, in line with the Life Cycle Thinking philosophy and Circular Economy approach. The dynamic nature of the sustainability concept requires for decision makers and managers to be flexible and willing to modify their path according to the scenarios changes, the stakeholders' needs and the technological progress, always taking into account the long-time effects and developments. For the aforementioned reasons, this study proposes a methodological approach aimed to take into account and quantify both the potential impacts and benefits of a heritage building management intervention. The proposed approach was implemented using two different case studies, chosen for data availability and for the different characteristics of the two subjects (the restoration of a XV century colonnade and the conservation and requalification intervention of an early XX century building), that allow to show that the approach can be implemented for different categories of heritage testimonies. For the calculation of the heritage sociocultural and socioeconomic value, two different frameworks were used for the two case studies (macroeconomic for the colonnade and microeconomic for the building) but both the frameworks can be implemented to associate a value to different testimonies of tangible heritage goods. Both the approaches have beneficial aspects on the one side and improvement necessity on the other side; the choice of the framework should depend to the requirements of te final addressee of the results. For example, the macroeconomic framework allows the assessment of non-monetary sociocultural aspects (as a midpoint outcome) and a following monetization procedure (endpoint outcome) but still requires some subjective experts evaluations. The microeconomic framework allows only a direct monetary assessement and it is less sensitive on some important features like the age of the heritage good but subjective evaluations are overlooked. The best practice would probably correspond to the implementation of both frameworks, which are not mutually exclusive. Table 85 reviews the possible outcomes that may be delivered with the proposed life cycle sustainability assessment based approach. The flexibility of the latter allows to consider the single results on their own or complementarily but the main contribution is probably the quantitative (as opposed to simply qualitative) analysis to estimate the value of the considered heritage building or element. Moreover, it is also possible to integrate all the outputs together, obtaining a single monetary outcome, in line with the holistic nature of the LCT perspective. By taking into account the externalities involved in the life cycle of the considered intervention, the monetary outcome should reflect the circularity of the cultural heritage managerial decision, as well. Last but not least, the LCA methodology allows an additional partitioning of the results, in order to analyze the sustainability and efficiency of the materials employed and/or of the single intervention sub-processes.

	Possible non-monetary units outputs	*Sub-categories*	*Units*	*Possebly monetary unit outputs*	*Sub-categories*	*Units*		
Impacts	**E-LCA**	Midpoint results	Impact categories units (e.g. C_2H_3Cl eq)	-	-	-	LCSA	
		Endpoint results	Damage categories units (e.g. DALY)	-	-	-		
		Normalization / single score results	Pts	**E-LCC**	Externalities quantification	€		Societal LCC
	-	-	-	**Conventional-LCC**	Internal costs	€		
Benefits	**S-LCA for Built CH**	Sociocultural indicators	Pts (≠ from the E-LCA Pts)	**Socioeconomic benefits**	Monetization of the socioeconomic indicators	€		
	-	-	-	**Monetary assessment of CH**	Monetary value calculated using the TEV framework	€		

Table 85. Life Cycle Sustainability Assessment applied to tangible Cultural Heritage. Possible outputs according to the proposed assessment framework.

The above mentioned outcomes can serve as a support to the different phases of the whole Cultural Heritage Management decision-making process, both as an *ex ante*, *in itenere* and *ex poste* assessment, as shown in Table 86. The decisions listed in Table 86 can be taken capitalizing the outputs listed in Table 85, according to the involved stakholders requirements or to the decision-makers needs (often related to budget restrictions and/or to priorities perspectives).

Analysis typology	*Project phase*	*Intervention categorization*	*Examples*
Predictive	Project planning	Best budget allocation (2 or more projects)	e.g. more than one building requires intervention but budget restraints exist
		Decision among different intervention typologies	Restoration and conservation; Requalification; Demolition and reconstruction (when the considered building is not officially classified as CH)
		Decision among different intervention scenarios	Type of materials, heating and ventilation plants, insulations etc.
Monitoring	Executive project	Actual project choice and implementation	*In itinere* analysis, project updates when more precise data are available
	Management process (*ex poste*)	Maintenance and conservation	New planning and/or monitoring of the maintenance interventions
		Improvements	e.g. green technology/more innovative materials

Table 86. Cultural Heritage management decision making processes. Possible implementations of the proposed assessment framework as a support instrument.

A positive aspect of the conservation, restoration or requalification of a building or an architectural element is that the end-of-life of the preexisting materials is postponed, so that their life span is longer and they could head for a more efficient and aware management. This is one of the principles of Circular Economy, which is implemented and assessed in the proposed approach both with the application of the LCA methodology and of the Material Circularity Indicator (MCI). A further development, hereby proposed, could be the estimation of characterization factors for the different building materials, based on their average lifespan, in order to obtain spreadsheets reporting “Utility factor” values, to be used within the Material Circularity Indicator calculation. The MCI can indeed be adopted as an additional and complementary indicator for the final sustainability assessment output. Moreover, when regulations compel the use of an original material, the associated costs and potential LCA impacts might turn out to be larger compared to an innovative and “greener” material. In this scenario, the suggestion of associating the value 1 to the Utility of an original material (as no alternative is viable), might mitigate this effect in the final analysis.

Cultural Heritage Conservation Management falls within the wider picture of governance of the urban areas. The term ”governance” was used for the first time by Kooiman (1993) and today, especially in Western European states, it refers to the current practice of governments to increasingly develop policies in interaction with a diversity of societal actors (Loorbach, 2010). In other words, interaction between all sorts of actors in networks often produces (temporary) societal consensus and support upon which policy decisions are based. This mechanism is far from trivial, especially in light of the complex and persistent problems that Western societies face, for which, according to Loorbach (2010) “sustainable development can neither be planned nor emerge spontaneously”. Moreover, there seems to be an increasing degree of consensus in governance research that both top-down steering by government (“the extent to which social change can be effected by government policies”) and the liberal free market approach (“the extent to which social change can be brought about by market forces”) are outmoded as effective management mechanisms to generate sustainable solutions at the societal level by themselves, but it is at the same time impossible to govern societal change without them (Jessop 1997; Meadowcroft 2005; Pierre 2000; Scharpf 1999). In light of the ambition of realizing long-term sustainable development, prescriptive governance models need to take into account that: i) All societal actors exert influence and thus direct social change. Society is shaped as well through agency and interaction in networks, (the so-called “governance); ii) Top-down planning and market dynamics only account for part of societal change; network dynamics and reflexive behavior account for other parts; iii) Steering of societal change is a reflexive process of searching, learning, and experimenting, (Loorbach, 2010). The approach proposed in this study sides with the current governance tendency, interwining both macro and microeconomics aspects: top-down planning, conducted taking advantage of down-top indicators (i.e the sociocultural indicators used to asses the San Felice Colonnade value) and/or taking advantage of down-top evaluation perspectives (i.e. the monetarization of the value of historical buildings, used in the Buccola pavilion case study). The societal actors involved are indeed always taken into account, as they are the stakeholders that will benefit directly or indirectly of the CH conservation.

As a practical example, this methodology might be employed as a support for the calculation of the so-called “Standard Cost”, used to allocate funding among universities. The Standard Cost was introduced with the “Gelmini reform” (law 240/2010) and it was implemented for the first time in 2014 (counting for 20% of the Fondo di Finanziamento Ordinario – Ordinary Funding). It is calculated taking into account five factors: I) the education and research activities, in terms of the professors and research staff available for the student’s support; II) educational, organizational and instrumental services, including the presence of technical and administrative staff available for the student’s support; III) the educational, research and service infrastructures for the different study domains; IV) additional cost entries relative to specific study domains (foreign language assistants, tutors etc.); V) the k factor, an equalization factor, proportional to the welfare status of each student of the region where the university is located. From this short description it is evident that the Standard Cost factors are basically calculated according to the number of current students but never refer to other components, like the conservation costs of the Cultural Heritage infrastructures managed by the universities. A standardized assessment of Cultural Heritage buildings, quantified adopting a stakeholders’ perspective, might be profitable for the introduction of this important factor.

In conclusion, this study illustrates how a conveniently adapted Life Cycle Sustainability Assessment approach can be employed with a predictive purpose, analyzing and comparing alternative scenarios and as a monitoring and diagnostics instrument, as well. Moreover, the proposed framework is far from rigid and allows to mould the analysis according to the affected stakeholders and the final scope, still respecting some standardization features that enable a more effective and objective management. It is therefore possible to choose whether to adopt a macroeconomic and/or a microeconomic approach to assess the sociocultural value of a building. In addition, once the instrument is improved and perfected, it will be possible to opt – within the macroeconomic approach- for more or less conservative characterization factors, which are aimed to represent different stakeholders’ typologies perspectives. As stated above, the proposed approach must certainly be perfected, conveniently choosing the aforementioned characterization factors, performing and revising a greater number of hedonic pricing studies, possibly clustered according to geographical areas, enlarging the construction materials and processes LCA databases (relative to both old and innovative materials). Nevertheless, even if the resolution and precision of the proposed methodology still has to be improved, its ductility allows to present results that can be easily interpreted and, at the same time, to adapt the analysis according to the addressee requirements and to the final aim of the investigation.

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