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PH.D. THESIS

LIFE CYCLE ASSESSMENT IN CONSTRUCTION INDUSTRY: APPLICATIONS TO STRUCTURAL MATERIALS AND COMPONENTS

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Don’t ever let someone tell you that you can’t do something.
Not even me. You got a dream, you gotta protect it.
When people can’t do something themselves,
they’re gonna tell you that you can’t do it.
You want something, go get it.
Period.
(Will Smith- The pursuit of happiness)

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Naples, April 2014

ABSTRACT

Material, energy, water use and occupation land related to construction industry activities represent a major contribution to the total environmental impact caused by society. In fact, it is estimated that the building sector is responsible for the 30–40% of the society's total energy demand and approximately 44% of the total material use. Consequently, the building sector has to be prioritized to be able to reach a sustainable society within a reasonable period of time.

The present work is included in the context of the assessment of sustainability of construction sector and is aimed at analyzing and quantifying the environmental impact of its related activities at different levels of analysis of the building industry. In detail, the environmental performance is performed by means of a Life Cycle-oriented approach. Two main approaches of Life Cycle Assessment (LCA) for construction applications have been considered: *i)* LCA for Building Materials and Component Combinations (BMCC), i.e. focusing on building materials, and *ii)* LCA of the Whole Process of the Construction (WPC), i.e. considering entire building system or sub assemblages.

The approach *i)* has been applied to evaluate the environmental footprint of recycled and natural concretes. The main purpose has been the computation of the environmental impact of the conventional and innovative building materials in order to quantify the potential environmental benefits (e.g. in terms of CO_2 emissions, raw material usage, waste recycling etc) of new (innovative) solutions.

LCA has been also implemented to evaluate the environmental profile of different retrofit solutions on existing buildings, using approach *ii)*. This work has investigated possible design alternatives for retrofit/renovation operations when structural/functional requirements have to be fulfilled. In detail, the environmental impact of different design options for a typical structural retrofit operation conducted on masonry and reinforced concrete buildings have been assessed.

The scope of this thesis is to illustrate several comprehensive LCA-based approaches that could be effectively used to drive the design of new and existing buildings. The final objective of this contribution is to show how a rigorous environmental analysis can influence decision-making in the definition of the most sustainable design alternatives. The designers can monitor the environmental impact of different design strategies in order to identify the most suitable option.

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1 Chapter I
INTRODUCTION

1.1 *Introduction*

Sustainable development has been defined in Brundtland Report 1987 as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987). The objectives of sustainable development are generally represented in terms of a triple bottom line strategy (Figure 1. 1) that is based on the simultaneous achievement of environmental, economic and social goals.

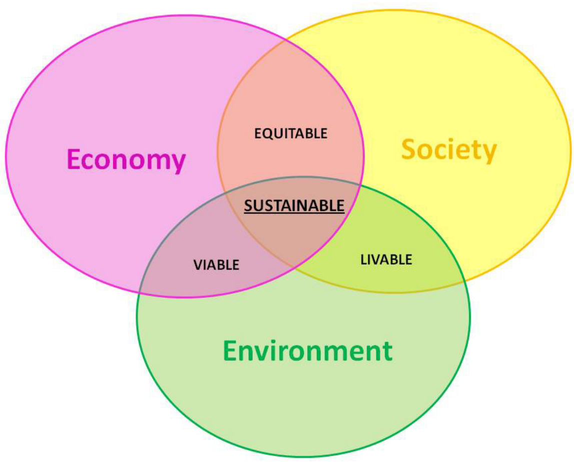

Figure 1. 1:Triple Bottom Line representation

In fact, environmental, social equity and economic demands are considered as the "three pillars" of sustainability (Pope, Annandale et al. 2004) (Figure 1. 2): a sustainability assessment involves an integration of social, economic, and environmental factors.

Figure 1. 2: "Three pillars of sustainability" representation

Several attempts to improve social, economic and environmental related aspects have turned the attention to construction sector. Although it is a highly active industry in both developed and developing countries from economic and social point of view, this sector plays a major role in terms of greenhouse gas emission, non-renewable resource depletion, high energy consumption and waste generation.

In fact, the building sector has a significant influence over the total natural resource consumption and on the emissions released in the atmosphere. In addition, a building uses energy throughout its life, i.e. from its construction to its demolition. The demand for energy in buildings in their life cycle is both direct and indirect. Direct energy is used for construction, use, renovation and demolition; whereas indirect energy is consumed by a building for the production of material used in its construction and technical installations.

Particularly, it is estimated that, in Europe, buildings are responsible for almost 30% of national energy consumption, 40 % of greenhouse emissions and 40 % of the material consumption (Nässén, Holmberg et al. 2007; Pulselli, Simoncini et al. 2007; Sartori and Hestnes 2007).

In order to find out solutions that reduce the environmental impacts related to construction industry, numerous research activities have been mainly focused on the improvement of the environmental performance of buildings. In fact, in order to minimize the environmental impacts of buildings several aspects have been considered:

- ✓ Reducing the consumption of raw/natural materials in terms of re-use and re-cycling of construction materials;
- ✓ Selecting suitable construction materials in terms of mechanical and environmental performances;
- ✓ Selecting suitable building component assembly in terms of energy consumption, emissions and safety of workers and users.

Accordingly, in order to achieve these objectives, decisions have to be properly made at every stage of the life cycle of the buildings. Over the last decades numerous sustainability assessment methods and tools have been proposed, mainly based on the concept of "Life Cycle Thinking" (LCT), depicted in Figure 1. 3.

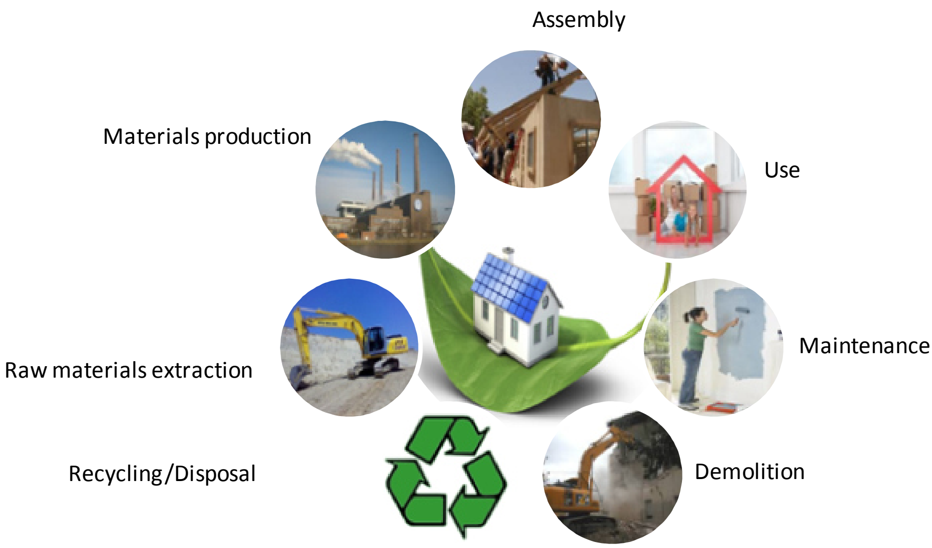

Figure 1. 3: "Life Cycle Thinking" concept

Generally, there are three methodology based on the LCT concept (Klöpffer 2008): Life Cycle Assessment (LCA) (ISO:14040 2006; ISO:14044 2006), Social Life Cycle Assessment (SLCA) (UNEP/SETAC 2009) and Life Cycle Costing (LCC) (Fuller and Petersen 1996; Mearig, Coffee et al. 1999).

The most significant strength of these methods is that they consider the whole product life cycle, in other words, "from the cradle to the grave". In fact, the LCA is a technique for quantifying the environmental aspects associated with a product over its entire life cycle; the LCC is a method of economic analysis for all costs related to building, operating and maintaining a product/service over all life cycle phases; the SLCA is a method to assess the social and sociological aspects of products, their actual and potential positive as well as negative impacts during the life cycle.

Although, for each methodology the step of the analysis and the industrial applications have been widely discussed, only LCA is regulated on ISO standards (ISO:14040 2006; ISO:14044 2006). In fact, these standards describe the principles and framework for conducting and reporting LCA studies. Particularly, the key points of LCA methodology, can be summarized as follow:

- ✓ the entire life cycle of a service or a product that includes the extraction and processing of raw materials, production, and use up to recycling or disposal is considered;
- ✓ all environmental impacts connected with the life cycle, such as air-, water-and soil-emissions, wastes, raw material consumption, or land use are evaluated;
- ✓ the environmental effects (e.g. human health, ecosystem quality, climate change and resources impacts) are quantified in order to give environmentally oriented support to decisions makers.

Since LCA represents a comprehensive and systematic approach to the assessment of the building environmental performance, a remarkable interest is growing to incorporate LCA methods into building construction decision making for selection of most suitable products, as well as for evaluation and optimization of construction and refurbishment processes.

1.2 *Life Cycle Assessment in Building sector*

Research studies employing LCA method are recently increasing, dealing with the environmental assessment of construction material and building performance, their design, construction and refurbishment practices.

Several comprehensive studies, collecting LCA based studies applied to the construction industry, are reported in the works by (Ortiz, Castells et al. 2009; Zabalza Bribián, Aranda Usón et al. 2009; Cabeza, Rincón et al. 2014) who investigated different building applications and assessed the environmental performances of building materials, components and systems related to the overall building life cycle.

Generally, there are two alternative approaches adopted for the application of LCA to the construction industry: LCA for Building Materials and Component Combinations (BMCC) and LCA of the Whole Process of the Construction (WPC) (Ortiz, Castells et al. 2009).

In the first approach, the environmental impact of building materials is evaluated; particularly only the raw materials extraction and manufacturing process are considered. The environmental outcomes of this approach can be used to define the "Environmental Product Declaration" (EPD). In fact, the EPD looks at the relationship between a product and the environment and is based on LCA; it contains information associated with the acquisition of raw materials, energy use, content of materials and chemical substances, emissions into the air, land and water and waste generation.

Other studies have applied LCA technique to study the environmental impact of local materials construction; for example (Jönsson, Tillman et al. 1997) compared the environmental impacts of the production of three flooring materials (linoleum, vinyl flooring and solid wood flooring) in Sweden; (Asif, Muneer et al. 2007) conducted process-based LCA for materials used in residential construction in Scotland: wood, aluminum, glass, concrete and ceramic tiles; similarly (Fabiano and Ximenes 2012) quantify the environmental benefits of the use of wood products in Australia, in comparison with alternative building materials; (Koroneos and Dompros 2007) studied the brick production process in Greece; (Wu, Zhang et al. 2005), discussed the life-cycle environmental impacts of various kinds of cement and steel used in the Chinese building industry. Other examples of LCA studies of building materials and products include floor covering in Germany (Nebel, Zimmer et al. 2006); comparison of ceramic and marble tiles in Italy (Nicoletti, Notarnicola et al. 2002); comparison of bamboo with steel wood in western Europe (van der Lugt, van den Dobbelsteen et al. 2006); the use of nano-sized titanium dioxide coating in glass (Babaizadeh and Hassan 2013); the use of Phase Change materials, PMC, in building in Spain (Aranda-Usón, Ferreira et al. 2013)

In the second approach, the environmental impact of the whole building life cycle is evaluated; in particular, the building material production and assembly (Pre-use phase), the total energy consumption for heating and cooling (Use phase), the energy and materials for refurbishment/maintenance operations (Maintenance phase) and the demolition of the building (End of life phase) are included in the analysis. Several studies have attempted to assess the environmental impact of building systems according to this approach. These efforts have often identified life-cycle phases with the highest environmental impact. These studies are focused on two main directions. One direction focuses on the analysis of new structures; whereas, the other direction, focuses on the analysis of the intervention on existing buildings. With regard to new building structures, many studies concluded that the greatest environmental impact occurs during the use phase; it is estimated that 70-90% of the total environmental burden arises in this phase (Adalberth, Almgren et al. 2001; Peuportier 2001). Other researches showed that the environmental impact of use phase can be significantly reduced by better insulation and by use of renewable energy (Fay, Treloar et al. 2000; Citherlet and Defaux 2007).

Despite research efforts focusing on new buildings, that effectively strengthen common awareness on sustainability goals for future perspectives, intervention on existing buildings cannot be neglected in the light of sustainability purposes and a sustainable valorization of building heritage. However, there are very few studies that actually evaluate the environmental impact of building retrofit; particularly, these studies address the environmental impact of energy retrofit intervention (Ardente, Beccali et al. 2011; Sonetti 2011).

While several studies analyzed whole buildings, other research works focused on building subsystems. For example, (Osman and Ries 2004) evaluated the environmental impact of construction and operations of a cogeneration facility for meeting the energy requirement of building; (Glick 2007) analyzed two heating system solutions for a house. (Muga, Mukherjee et al. 2008) estimated and compared the environmental impact of green roofs with conventional roof.

Other studies, instead, focus only on some life cycle phases of the building life cycle; for instance (Blengini 2009) focused the study on the building end of life phase, investigating an Italian building, which was demolished by controlled blasting; similarly, (O′Brien, Guy et al. 2006) conducted comparative LCA of deconstruction methods for military barracks. (Guggemos and Horvath 2006) and (Bilec, Ries et al. 2006) evaluate the environmental impact of construction phase of different building solutions.

1.3 *Research purposes and outline*

The LCA in the construction sector has different goals related to the possible different scales of the assessment (materials, components, system, whole buildings).

In fact, as shown in Figure 1. 4, stakeholders in this sector are different and have various interests (architects, contracting owners, industrials, construction companies, and public authorities); the scales of the analysis are different (from materials to the buildings construction) but interconnected; scientific contributions involved are multidisciplinary (Lasvaux, Ventura et al. 2014). In this sense, LCA applied to construction sector represents a multidisciplinary and multiscale decision making tool.

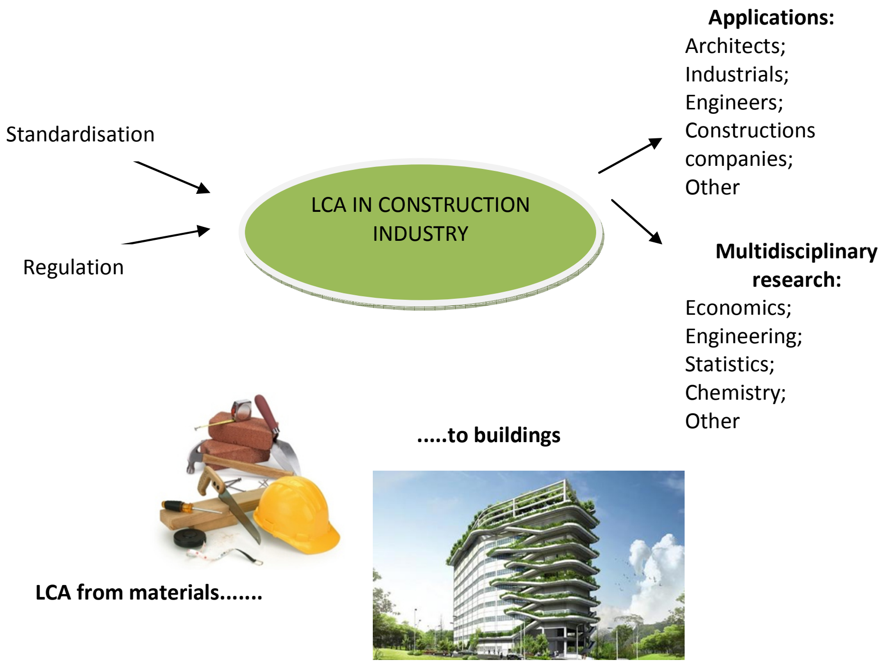

Figure 1. 4: Representation of LCA and construction activities (Lasvaux, Ventura et al. 2014)

Given these considerations, in the present work, different LCA studies are conducted with reference to different building applications. In particular, the LCA based environmental analyses are conducted considering the following variables:

- Scale: from materials to components and systems (Figure 1. 4);
- Life-Time: including material production, installation, use, recycling and disposal of buildings (Figure 1. 3).

Figure 1. 5 shows the logic flow chart of the activities conducted in the present thesis. LCA is performed on different building materials according to the BMCC approach; in addition LCA is conducted on existing buildings, focusing on structural retrofit solutions, according to the modified WPC approach for building sub assemblages. Generally, a WPC approach evaluates the environmental profile of an entire (new) building; instead, a WPC modified approach, as used in this thesis, quantifies the environmental performance of several building renovation strategies applied on existing buildings which involves a certain building sub assemblage.

With regard to building materials, conventional ones are primarily investigated from environmental point of view; for each material investigated, the major contributor to the environmental impact is identified, in terms of element(s) or production processes. Then, new low-impact solutions are hypothesized and analyzed. Indeed, several LCA comparative studies between conventional and innovative materials are conducted. The conventional and innovative materials are analyzed from "cradle to gate", including raw materials extraction and production process (Table 1. 1).

Life Cycle Phases				
Design	*Realization/Production*	*Use*	*Maintenance*	*End-of-life*
Multi-step process: research, conceptualization, feasibility assessment, design requirements, preliminary design, detailed design, production planning, tool design, and finally production	Raw materials extraction, Transport Product process, Assembly	Structural, energy and environmental performance	Planned and extraordinary maintenance	Disposal, Recycling Demolition, Deconstruction
From cradle to gate				
From cradle to grave				

Structural materials | Retrofit options

Table 1. 1: Materials and components system boundary

With regard to buildings, it has been decided to analyze the environmental impact of different design options for a typical retrofit operations on existing buildings. As matter of fact, different type of building renovation strategies conducted on masonry and reinforced structures are investigated. LCA comparative studies between all retrofit solutions are conducted in order to determine which is the most environmental friendly. The environmental performance of each investigated option is quantified, including all life cycle phases, "from cradle to grave": materials production and installation, construction, use, maintenance use, transport and end of life phases are considered (Table 1. 1).

Hereafter, an outline on the activities presented in this thesis is reported:

Chapter II briefly describes the basic concept of LCA according to current ISO standard. The chapter aims at providing a basic knowledge on life cycle assessment. This will be achieved by presenting the four methodological steps of an LCA: Goal and scope definition, Inventory analysis, Impact Assessment, and Results interpretation.

In **Chapter III** and **Chapter IV** the life cycle environmental analyses are conducted according to the BMCC approach with the objective of evaluating the environmental impact of conventional and "innovative" structural materials. Since it is well recognized that concrete is the most commonly used among construction materials, different cases study are investigated to assess its environmental performance with particular emphasis to cement and aggregates usage. In fact, the objective of *Chapter III* is to perform a detailed environmental impact assessment between conventional concrete production and new low-CO_2 binder concrete production (geopolymer concrete). *Chapter IV* aims at investigating the environmental footprint of lightweight recycled concrete using different recycled lightweight aggregates in comparison with existing lightweight concrete made with expanded clay aggregates.

In **Chapter V**, **Chapter VI** and **Chapter VII** the LCA analysis is conducted on existing buildings according to the WPC modified approach; the environmental footprint of different retrofit operations conducted on masonry and reinforced concrete structures is computed. In detail, in the *Chapter V*, the replacement of a typical old wooden roof is considered and three alternative structural solutions are examined: reinforced concrete joists and hollow clay blocks, steel joists and concrete slab and reinforced concrete joists and polystyrene panels. The aim of *Chapter VI* is to quantify the environmental footprint of structural retrofit solutions applied to masonry structures that involves technical operation on masonry walls: local replacement of damaged masonry, mortar injection, steel chain installation and application of grid reinforced mortar. The *Chapter VII* aims at investigating the environmental footprint related to the application of three retrofit techniques on reinforced concrete columns: carbon and steel fabric wrapping and steel jacketing.

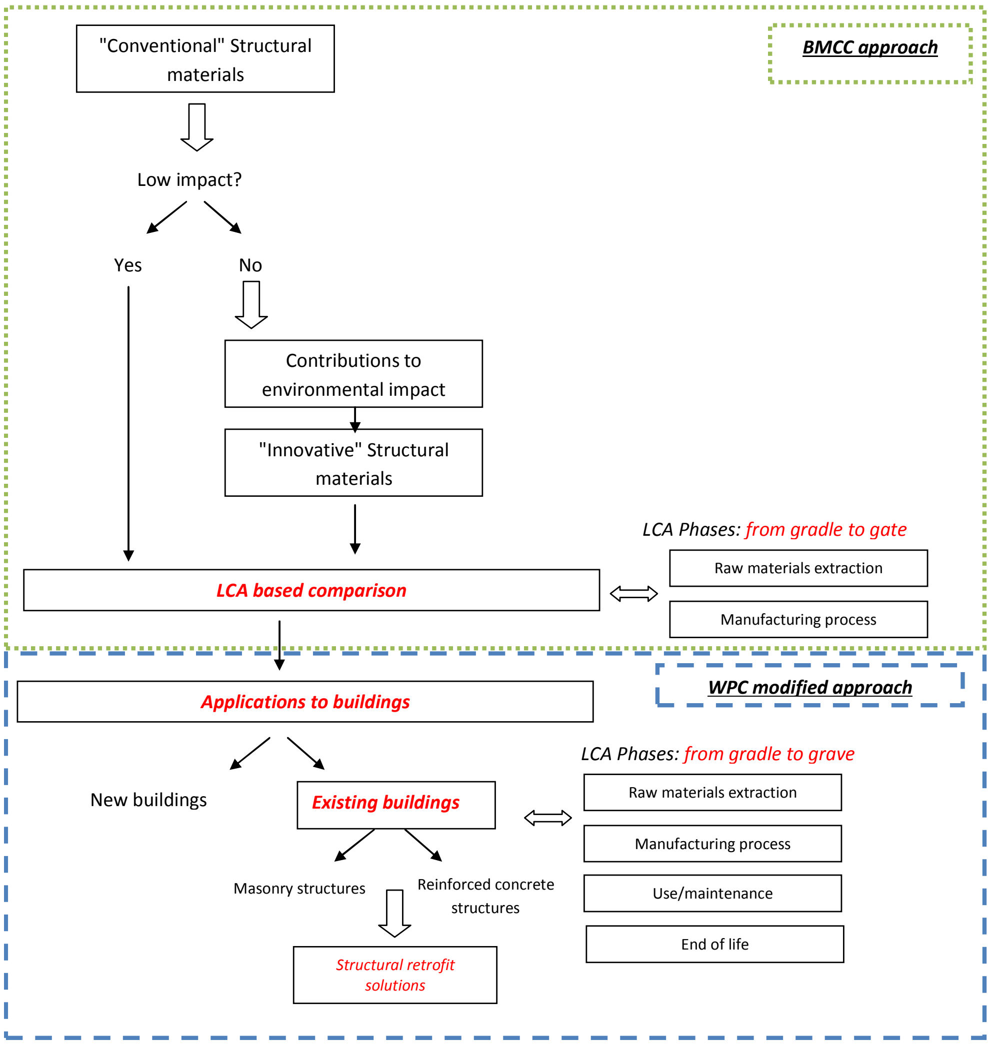

Figure 1. 5: Logical flow chart of the LCA based studies

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2 Chapter II
LIFE CYCLE ASSESSMENT METHODOLOGY

2.1 *Definition*

According to the definitions of standards ISO 14000 series (ISO:14040 2006; ISO:14044 2006), Life Cycle Assessment (LCA) is a methodology that estimates the environmental impact of processes and products during their entire life cycle from "cradle to grave". It is usually regarded as a support tool in different decision making processes since it identifies and evaluates opportunities to obtain environmental improvements.

In detail, LCA can be used in several applications to:

- ✓ identify opportunities to improve the environmental performance of products at various points in their life cycle;
- ✓ inform decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design);
- ✓ select relevant indicators of environmental performance, including measurement techniques and marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

The LCA methodology is divided into four steps, which are represented in Figure 2. 1:

- ✓ Goal and scope definition;
- ✓ Inventory analysis or Life Cycle Inventory (LCI);
- ✓ Impact assessment or Life Cycle Impact Assessment (LCIA);

✓ Results Interpretation.

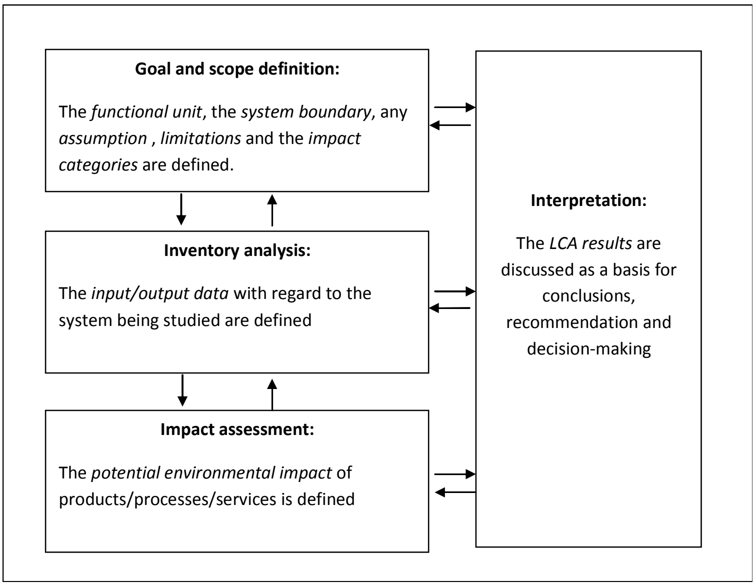

Figure 2. 1: Stages of LCA analysis

2.2 *Goal and Scope Definition*

The first phase of a LCA analysis is the Goal and Scope definition: the objectives, the boundaries of the system, the sources of date and the function unit have to be defined. Particularly, in the goal phase, the purpose of the study, the intended use and users of the results should be clearly defined. In addition, in the scope phase it is important to identify and to define the objective of the study, what to include and what to exclude, the level of detail of the data in the study, to reach the goal of the study.

2.2.1 Functional unit

The definition of the functional unit is of outmost importance when conducting a LCA; in fact, the primary purpose of a functional unit is to provide a reference to which the input and output data and substance flows are normalized. The functional unit has to be defined for LCA single analysis and for LCA comparative analysis. In both cases, two aspects have to be taken into account: the function of the product and the durability or the life span of the product. In fact, the comparisons between different systems can be made on the basis of the same function, quantified by the same functional unit in the form of their reference flows (Input/Output).

2.2.2 System boundary

The System Boundaries have to be set in order to identify the physical extension to which processes are included or excluded from the analysis. Generally, all life cycle phases are considered, "from cradle to grave": raw material extraction, manufacturing production, use and end of life.

However, it is also possible to exclude some life cycle phases from the system boundaries: for example, in " cradle to gate" boundary, the use and the end of life phases are excluded; in "gate to grave" boundary, the extraction of raw materials and the production processes are excluded.

2.2.3 Allocation procedure

Generally, an allocation procedure denotes a partitioning of the input and output flows between products generated within the same production system (e.g. products and by-products). Different allocation procedure can be used:

- Economic allocation based on the economical values of products and by-products;
- Mass allocation based on the mass balance of products and by-products.

2.3 ***Life Cycle Inventory analysis***

The Life Cycle Inventory analysis phase (LCI phase) is the second phase of LCA. It is an inventory of input/output data with regard to the system being studied; particularly, all the environmental inputs and outputs (in terms of flows of substances) are computed and defined at each life cycle stage.

The qualitative and quantitative data of the inventory shall be collected for each unit process that is included within the pre-defined system boundary. The collected data, whether measured, calculated or estimated, are utilized to quantify the inputs and outputs of a unit process. The main data of the LCI analysis include (Figure 2. 2):

- ✓ energy inputs, raw material inputs, ancillary inputs, other physical inputs,
- ✓ products, co-products and waste,
- ✓ releases to air, water and soil,
- ✓ other environmental aspects.

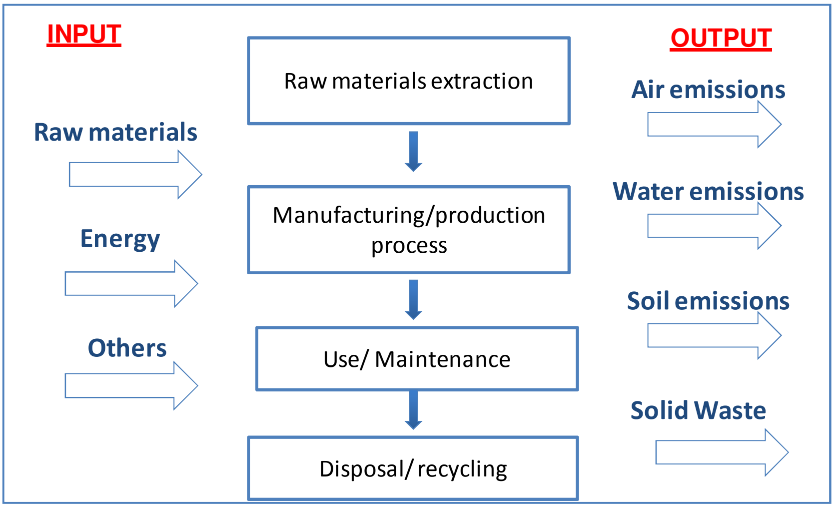

Figure 2. 2: Input and output definition

There are different types of data that can be acquired to conduct a LCI analysis; it is important to distinguish between primary and secondary data. Generally, primary data are data that are measured and gathered in-person and on-site, otherwise, secondary data are data that has been derived from averages, statistical projections, etc. Sometimes, secondary data are not representative of system boundary investigated. Such situation may be caused by inappropriate temporal, geographical or technological correlation between the data used and data needed. In fact, when secondary data are not representative of data needed, several uncertainties (temporal, geographical or technological) in the final estimated environmental impacts are included. In order to consider these uncertainties the "pedigree matrix" has to be completed. In particular, in this matrix data quality levels with a score between 1 and 5 can be considered (Weidema and Wesnæs 1996). For instance, the value 1 represents the minim level of uncertainty: the data used are reliable; otherwise the level 5 represents the maxim level of uncertainty: the data used are not representative of data needed.

Examples of secondary data sources include published literature, other LCI studies and database. For example, the Ecoinvent database (Ecoinvent), with several thousands of LCI datasets in the areas of agriculture, energy supply, transport, biofuels and biomaterials, construction materials, packaging materials, basic and precious metals, metals processing, electronics as well as waste treatment, is one of the most comprehensive international inventory database.

2.4 *Life Cycle Impact assessment*

Life Cycle Impact Assessment (LCIA) is the third phase of LCA. The LCIA is aimed at evaluating the significance of potential environmental impacts using the LCI results. This process associates inventory data to specific environmental impact categories and environmental indicators.

The LCIA phase is composed of mandatory elements, (e.g. classification and characterization) and optional elements (e.g. normalization and weighting)

The first ones assign LCI results to the impact categories (e.g classifying CO_2 emissions into global warming impact categories) and model LCI results within impact categories using science-based conversion factors (e.g., modeling the potential impact of carbon dioxide and methane on global warming).

Instead, the normalization and weighting phases convert characterization results of different impact categories by using numerical factors, based on value-choices. On the other hand the characterization values can be normalized by means of a "reference value" or "normal effect", in order to define the magnitude of each environmental effect; this value is generally represented by the average data on a global, regional or local scale, referred to a specific time interval. Through the normalization it is possible to define the relative weight of each environmental problem.

(Figure 2. 3) shows the elements of the LCIA phase.

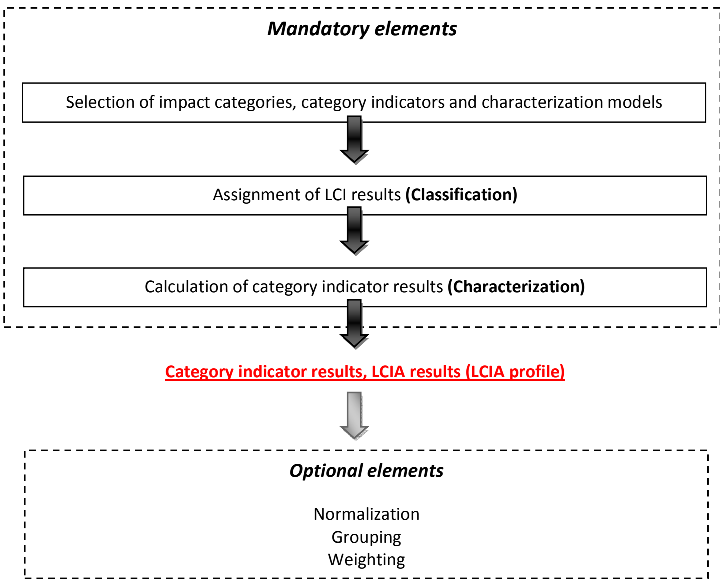

Figure 2. 3: LCIA phases

In addition, different LCIA method can be used: Ecoindicator 99 (Goedkoop, Effting et al. 2000; Goedkoop and Spriensma 2000), ReCIPE (Goedkoop, Huijbregts et al. 2009), EDIP (Hauschild and Potting 2003), Impact2002+ (Jolliet, Margni et al. 2003), etc. These can be divided in three groups:

a. Classical impact assessment methods, such as EDIP, which express the LCI results in mid-point categories;
b. Damage oriented methods, such as Ecoindicator 99, which model the LCI results with endpoint, or damage categories.
c. Midpoint/damage oriented method, such as Impact2002; this method utilizes the advantages of both above approaches; in fact it proposes a feasible implementation of a combined midpoint/ damage approach.

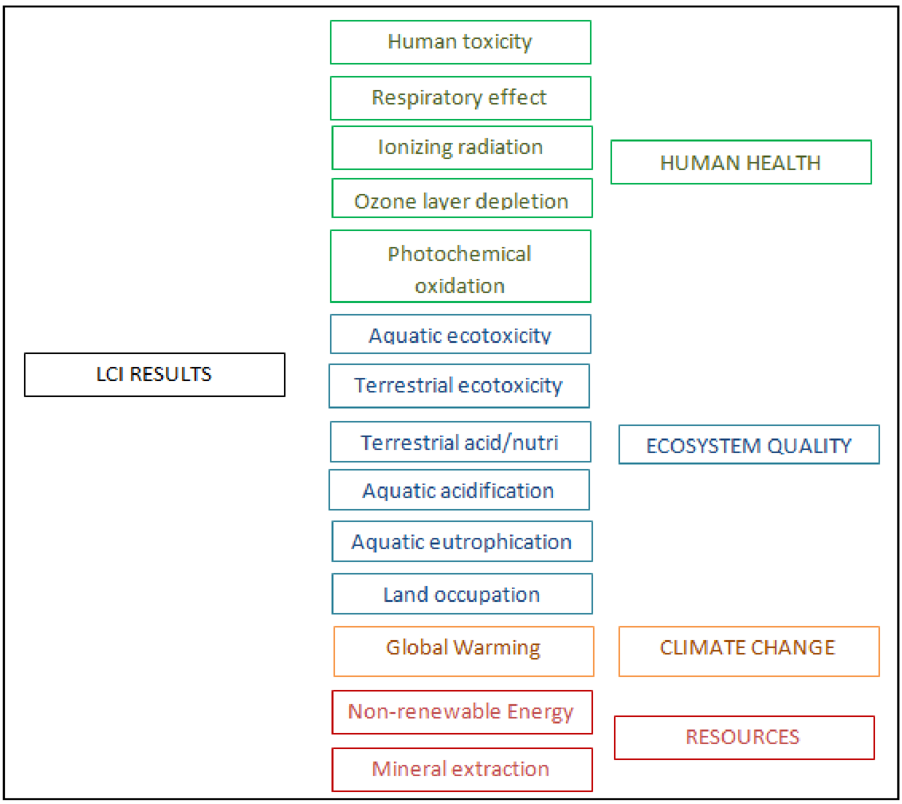

Figure 2. 4: Impact2002+ methodology

Impact2002+ method is a widely diffused method for the LCIA analyses, because, while the midpoint method provides quantitative results, the endpoint method offers results which are easily interpreted by the end-user; its scheme is represented in Figure

2. 4. Particularly, the LCI results can be expressed both though 14 mid-point categories in terms of kg equivalent of reference substance (e.g. Human Toxicity expressed in kg equivalent of chloroethylene) and though end-point category in terms of Human Health (expressed in DALY), Ecosystem quality (expressed in PDF*m^2*yr), Climate Change (expressed in kg eq. CO_2) and Resources damage categories (expressed in MJ) (Table 2. 1).

MidPoint category	Midpoint reference substance	Damage categories	Damage unit
Human toxicity (Carcinogens+ non-carcinogens)	kg eq. Chloroethylene into air	Human health	DALY
Respiratory inorganics	Kg eq. PM 2,5 into air	Human health	DALY
Ionizing radiation	kg eq. Carbon-14 into air	Human health	DALY
Ozone layer depletion	kg eq. CFC-11 into air	Human health	DALY
Photochemical oxidation (Respiratory organics for human health)	kg eq.ethylene into air	Human health	DALY
		Ecosystem quality	PDF*m^2*yr
Aquatic ecotoxicity	kg eq. Thrietylene glygol into water	Ecosystem quality	PDF*m^2*yr
Terrestrial ecotoxicity	kg eq. Thrietylene glygol into water	Ecosystem quality	PDF*m^2*yr
Terrestrial acidification/nutrification	kg eq. SO_2 into air	Ecosystem quality	PDF*m^2*yr
Aquatic eutrofication	kg eq. PO_4 into water	Ecosystem quality	PDF*m^2*yr
Land occupation	m^2 eq organic arable land-year	Ecosystem quality	PDF*m^2*yr
Global warming	kg eq. CO_2 into air	Climate change	kg eq. CO_2
Non renewable energy	MJ total primary non renewable energy	Resources	MJ
Mineral extraction	MJ additional energy	Resources	MJ

Table 2. 1: Mid point/end point categories, reference substances, and damage units used in Impact 2002+

In this thesis Simapro (Simapro) LCA software is used in order to collect, analyze and monitor the sustainability performance of all solutions investigated.

2.5 *Interpretation results*

According to the ISO-Standard, the objective of the life cycle interpretation is to draw conclusions, identify limitations and make recommendations for the intended audience of the LCA.

In order to establish and enhance confidence and the reliability of the LCA results different check methods can be used:

- ✓ contribution check: the contribution of life cycle stages or groups of processes to the total result are examined, in order to identify the element/process (s) that influences the LCA results;
- ✓ completeness check: ensure that all relevant information and data needed for the interpretation are available and complete;
- ✓ sensitivity check: assess the reliability of the final results and conclusions by determining how they are affected by uncertainties in the data, allocation methods or calculation of category indicator results, etc;
- ✓ consistency check: determine whether the assumptions, methods and data are consistent with the goal and scope of the analysis.
- ✓ uncertainties check: determine how uncertainties in data and assumptions progress in the calculations and how they affect the reliability of the results of the LCA.

The interpretation step framework is shows in Figure 2. 5

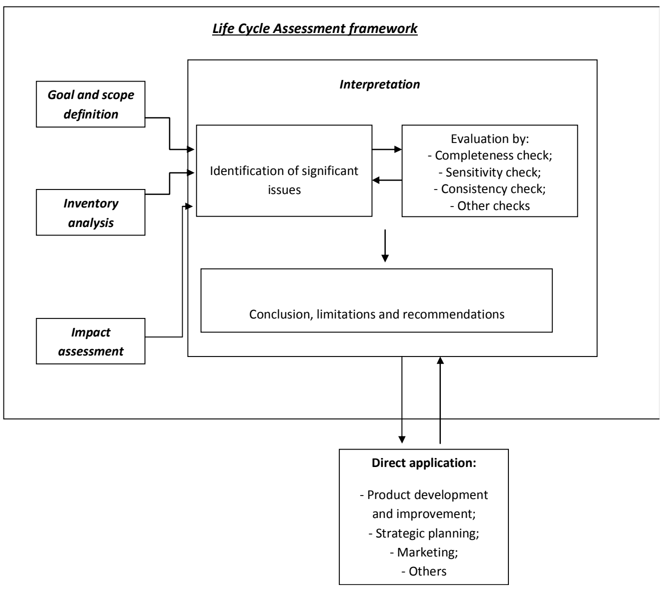

Figure 2. 5: Life cycle interpretation

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3 Chapter III

STRUCTURAL MATERIALS: PRELIMINARY REMARKS ON THE ENVIRONMENTAL IMPACT OF ORDINARY AND GEOPOLYMER CONCRETE

3.1 *Introduction*

Concrete is the most consumed material in the construction sector and the second most consumed substance on Earth after water. In fact, the estimated worldwide concrete consumption was between 21 and 31 billion tons in 2009 (ISOTC71 2005; WBCDSb 2009; WBCSDa 2009). Typically, concrete is produced by using Ordinary Portland Cement (OPC) as binder and its global production in 2009 was around 3,06 billion tones (USGS). It is estimated that the OPC contributes conservatively to 5-8% of global anthropogenic CO_2 emissions; CO_2 emissions are mainly due to the decomposition of limestone and combustion of fossil fuels during cement production. As calculation base, 1 kg cement releases about 0,8 kg of CO_2: 50% from the fuel combustion and 50% from the calcination of $CaCO_3$ (Hoffmann and Jacobs 2007; Limbachiya, Marrocchino et al. 2007; Cabral, Schalch et al. 2010; Marinković, Radonjanin et al. 2010; Fonseca, de Brito et al. 2011; Knoeri, Sanyé-Mengual et al. 2013).

New low-CO_2 binders (Hendriks, Worrell et al. 2000; Choate 2003) are therefore needed to meet the demand for concrete and still reach the CO_2 reduction goals. Among these new binders it is commonly accepted that sulfo-alluminate clinkers and geopolymers represent a highly promising solution.

Geopolymer is a term used to describe inorganic polymers based on alluminosilicates which can be produced by synthesizing pozzolanic compounds or alluminosilicate source materials with highly alkaline solution (Davidovits 1999).

However, although geopolymers are presented by many authors as a solution for pursuing "green concrete", few study have quantified their environmental impact (Davidovits 1999; Duxson, Provis et al. 2007; Habert, d'Espinose de Lacaillerie et al. 2011).

The objective of the present chapter is to perform a detailed environmental impact analysis by means of LCA (ISO:14040 2006; ISO:14044 2006) methodology aimed at investigating standard GEOpolymer (GEO) concrete production and Ordinary Portland Cement (OPC) concrete production.

3.2 *Goal and Scope Definition*

This study investigates the environmental burner of OPC concrete and GEO concrete; particularly, the environmental benefits in terms of CO_2 emissions between the conventional and innovative concrete are evaluated.

The main difference between GEO and OPC concrete is the binder material; in fact, in the first one the binder is produced by mixing fly ash (with high contents of silicon and aluminum - Class F,(ASTM C618 - 12a)) with an alkaline liquid, prepared with sodium silicate and sodium hydroxide (NaOH); in the second one, instead, 100% of cement is used as binder.

The considered system boundary is reduced to the production of the concrete constituent materials and to the concrete production. Therefore, the analysis does not include every stage of the product's life cycle (cradle to grave: constituent production, material production, structure production, service life and end of life) but an intermediate stage (cradle to gate: constituent production – sodium silicate solution production, sodium hydroxide powder solution, mineral addition production, aggregate production, concrete production), as shown in Figure 3. 1 and Figure 3. 2 for OPC concrete and GEO concrete production, respectively.

The functional unit is 1 cubic meter of concrete with a given compressive strength in the hardened state.

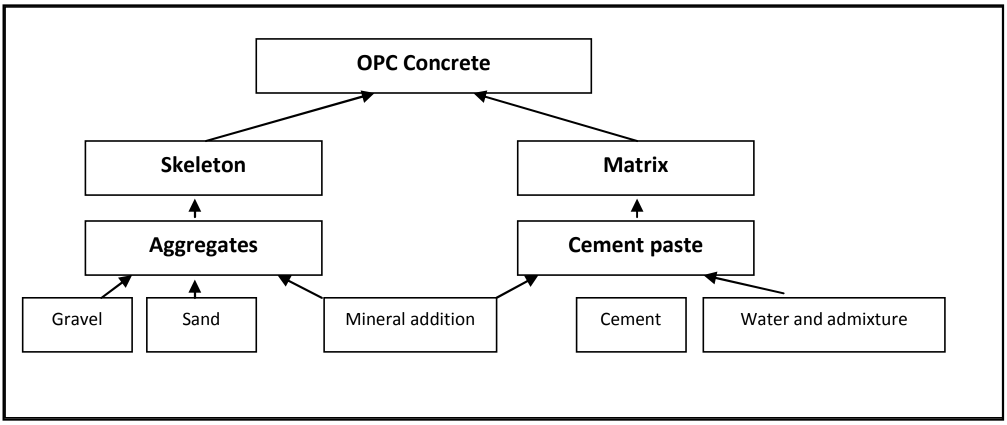


Figure 3. 1: OPC concrete System boundary

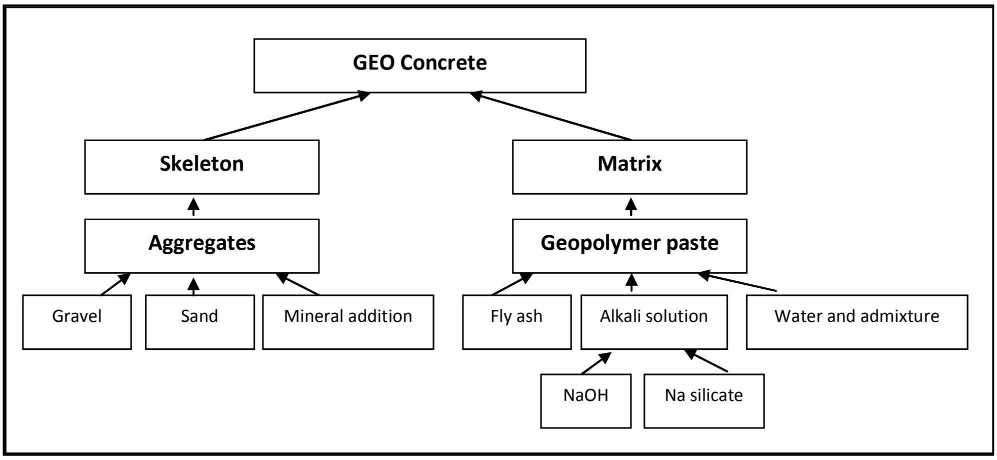


Figure 3. 2: GEO concrete System boundary

3.3 *Inventory analysis*

The different concrete mix designs have been taken from literature (Habert, d'Espinose de Lacaillerie et al. 2011) and are presented in Table 3. 2. Particularly, they consist in compositions extracted from mix-design of GEO concrete, and OPC concrete. All mixes present similar mechanical properties; in fact the compressive strength in all cases is about 35 MPa.

Moreover, the GEO concrete is composed by (Figure 3. 2):

1) Alkali-solutions: mixing of sodium silicate solution and sodium hydroxide;
2) Alluminosilicate component: fly ash (FA). Fly ash is one of the residues generated during combustion of coal and according to European Union (EU

2008) directive is a by-product; thus it can be affected by an allocation coefficient. This coefficient is used to consider the environmental impact of FA associated with production of electricity. It has been chosen to use an economical allocation, based on the economical values of products (electricity) and by-products (FA), in this way the main part of the environmental impact is easily related to the main product while the smaller one to the by-product. The relative price of electricity and fly ash were obtained from Enel data (Enel 2011);

3) Aggregates: gravel and sand;
4) Water;
5) Superplasticizer: the addition of this admixture in GEO concrete involves the increase of the workability of the mixture.

The OPC concrete is composed by (Figure 3. 1):

1) Cement: Ordinary Porland Cement;
2) Water: the water to cement ratio is 0,4;
3) Aggregates: sand and gravel;
4) Superplasticizer: the addition of this admixture in OPC concrete involves the reduction of the water to cement ratio, not affecting the workability of the mixture, and enables the production of self-consolidating concrete.

The input data are mainly based on databases available in the SimaPro 7 (Simapro) LCA software package. In particular, inventory data for concrete, cement products and other building materials, additional materials and use of building equipment were retrieved from Ecoinvent (Ecoinvent).

It is decided to use only secondary data because all materials and their production process involved in the investigated systems are well represented by the available database and well reproduce the European context (Table 3. 1).

Material	Data
Gravel	Gravel round at mine
Sand	Silica sand at plant
FA	Economic allocation
NAOH	Sodium hydroxide, 50% in H_2O, production mix at plant
NA silicate solution	Sodium silicate, furnace process, pieces, at plant
Water	Tap water at user
Admixtures	Superplasticized (data from "concrete, exacting,with de-icing salt contact, at plant")
Cement	Portland cement, strength class Z 42,5 at plant

Table 3. 1: Inventory data

Concrete	Gravel	Sand	Fly ash	NAOH	Na Silicate Solution	Water	Admixture	Cement	Compressive Strength	Density
	[kg]								[Mpa]	[kg/m^3]
GEO1	1294	**554**	408	11	103		6		35	2376
OPC1	1294	**554**				139,2	6	348	35	2341,2
GEO2	1201	**647**	408	17	103	26	6		35	2408
OPC2	1201	**647**				138,8	6	347	35	2339,8
GEO3	1292	**554**	408	17	103	26	6		36	2406
OPC3	1292	**554**				141,6	6	354	36	2347,6
GEO4	1294	**554**	408	21	103	17	16		36	2413
OPC4	1294	**554**				141,2	16	353	36	2358,2

Table 3. 2: Concrete mix design

3.4 *Impact Assessment*

The environmental impacts are evaluated according to midpoint-damage approach within the Impact2002+ (Jolliet, Margni et al. 2003) (Figure 2.4).

When GEO concrete are compared to OPC concrete, the LCA results reveal that these new type of concrete allow a strong reduction of the global warming potential (Figure 3. 3): 300 kg of CO_2 eq for 1 m^3 in case of OPC concrete, while the GEO concrete release 110 kg of equivalent CO_2 for 1 m^3 (Table 3. 3). Concerning other environmental impact categories, GEO concrete show higher impact than OPC concrete (Figure 3. 3).

Substance	Compartment	Unit	OPC 4	OPC 3	OPC 2	OPC 1	GEO 4	GEO 3	GEO 2	GEO 1
CO_2	Air	kg CO_2 eq	305,5	301,7	297,8	296,94	126,7	118,00	119,69	111,78

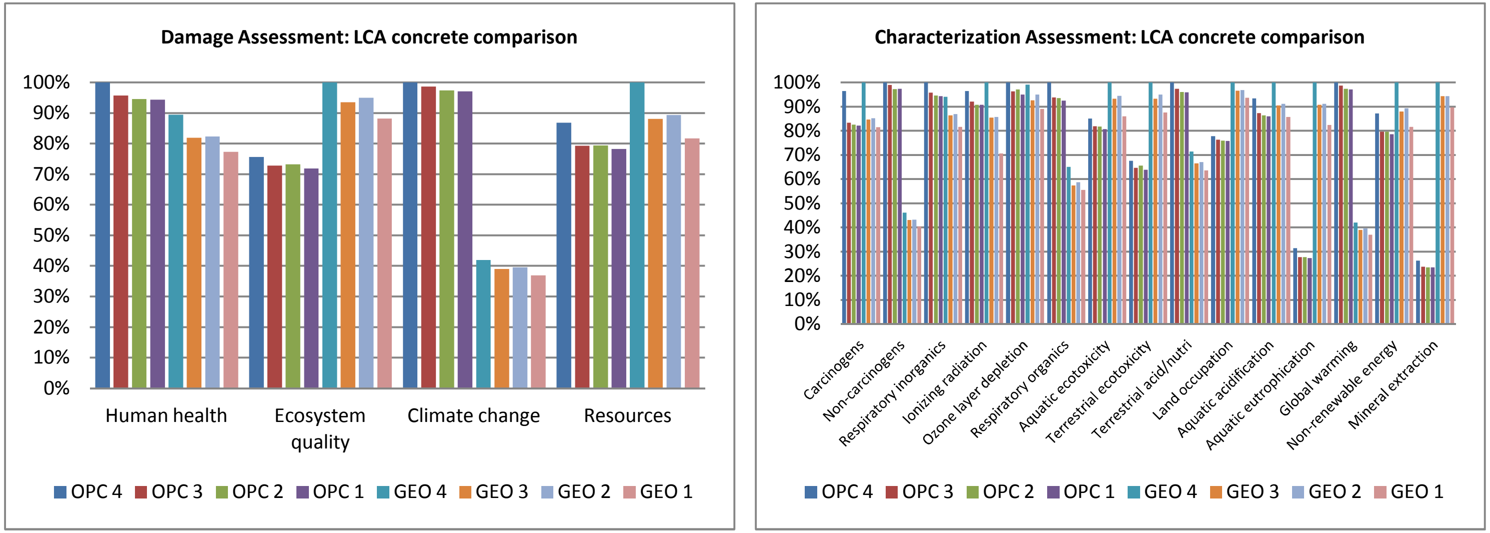
Table 3. 3: CO_2 emissions (kg eq CO_2)

In particular, for Human Health and Climate Change damage categories, OPC concrete have higher environmental impact, while in the other categories the GEO concrete have the greatest environmental impact.

Since the GEO4 has the highest environmental impact, the environmental burden (in terms of mid/end point categories) of this concrete is analyzed and reported in Figure 3. 4,

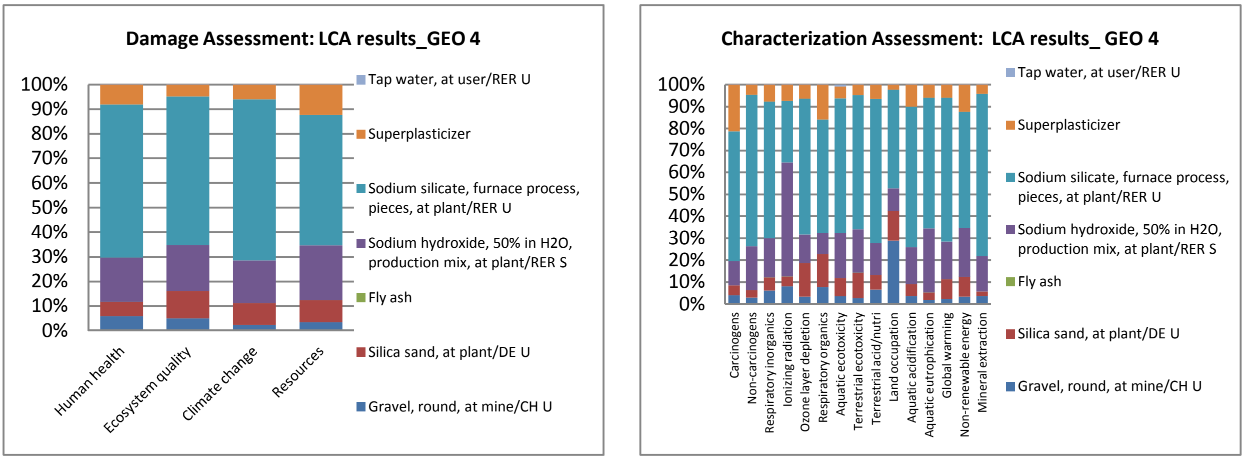
The LCA results highlights that the environmental impact of GEO4 depends on the use of the alkali solution. In fact the environmental burned related to alkali solution is almost 80% of the total burden in all LCA categories, with the 60% that is linked to the sodium silicate. It is mainly due to manufacturing process of sodium silicate, in fact, it is obtained by treating quartz at temperature above 1400 °C (Ingessil). In fact, the sodium silicate is characterized by an enormous energy demand for its manufacturing process.

In order to reduce global warming, OPC concrete may be replaced by GEO concrete, but the use of sodium silicate solution increases all values of the other environmental impact categories.



(a) **(b)**

Figure 3. 3: LCA concrete comparison



(a) **(b)**

Figure 3. 4: LCA results- GEO 4 (a) end-point categories (b) mid-point categories

3.5 *Conclusion*

In this study, different GEO concrete mixtures have been evaluated from the environmental point of view through LCA approach. This study shows that GEO concrete has lower CO_2 emissions than OPC concrete. However this reduction is not sufficient enough to achieve a total "green concrete" because the presence in the mixture of sodium silicate and in general of alkali solution generates a high environmental impact in terms of use of resources and quality of ecosystem. The environmental impact of sodium silicate in the GEO concrete production accounts for around 60% of total environmental burden. In order to reduce the use of sodium silicate, for example, other solutions should be evaluated by investigating magnesium iron slags, ferronickel slags or tungsten mine waste mud as GEO binder.

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4 Chapter IV

STRUCTURAL MATERIALS: A LIFE CYCLE ASSESSMENT ON LIGHTWEIGHT CONCRETE MADE OF RECYCLED LIGHTWEIGHT AGGREGATES

4.1 *Introduction*

Besides cement production, aggregates consumption is also a big contributor to the overall environmental load of concrete material. In fact, the consumption of natural aggregates, as heaviest component in concrete mixes, is constantly and rapidly increasing with increasing concrete production and utilization. In fact, it is estimated that three billion tons of aggregates are produced each year in the countries of European Union (EEA 2008). Inevitably, these considerations give rise to common environmental issues related to the depletion of natural resources and consequently to the availability of natural aggregates.

In addition, construction and demolition (C&D) waste has reached a large and increasing mass fraction of waste in industrialized countries. For example, it is estimated that about 850 million tons of C&D waste are generated in the EU per year, which represent more than 31% of the total waste generation (Fischer and Davidsen 2010). Thus, C&D waste reuse/recycling as concrete aggregates has been considered as a valuable option to substitute the primary conventional aggregates in concrete production as well as reducing the C&D waste generation. C&D recycling, in fact, has the potential to reduce the amount of waste disposed in landfills and to preserve natural resources by avoiding new raw material production (Lawson, Douglas et al. 2001;

Blum and Stutzriemer 2002; Weil, Jeske et al. 2006; Rao, Jha et al. 2007; Hiete, Stengel et al. 2011; Woodward and Duffy 2011). C&D waste has been successfully used as concrete aggregate in ordinary concrete production. In particular, different studies (Hoffmann and Jacobs 2007; Rao, Jha et al. 2007; Li 2008; Poon, Kou et al. 2009) have demonstrated the technical potential of using recycled normal concrete made with C&D waste in different engineering applications, pointing out the consequent environmental benefits. In fact, the environmental comparison analysis between normal conventional and recycled concrete has been assessed in several studies. Furthermore, it is estimated that the production of cement, as explained in the chapter III, is the main contributor to many environmental impacts of all concrete types, including normal conventional and recycled concrete (Hoffmann and Jacobs 2007; Limbachiya, Marrocchino et al. 2007; Cabral, Schalch et al. 2010; Marinković, Radonjanin et al. 2010; Fonseca, de Brito et al. 2011; Knoeri, Sanyé-Mengual et al. 2013). Particularly, the Global Warming Potential (GWP) of recycled concrete is larger than natural/conventional concrete. It is due to the amount of cement used which is related to the larger grain surface area of C&D aggregates (Weil, Jeske et al. 2006; Holcim 2010; Marinković, Radonjanin et al. 2010; Fonseca, de Brito et al. 2011). In addition, transport is also a big contributor to the overall environmental load and directly depends on the transport distances and transport vehicle type (Marinković, Radonjanin et al. 2010). Moreover, (Knoeri, Sanyé-Mengual et al. 2013) analyzed the life cycle impacts of 12 recycled normal concrete mixes and compared them with corresponding conventional concrete mixes. The results showed clear environmental benefits for all recycled concrete options, mainly due to the avoided impact related to the avoided disposal of C&D waste. Other studies have focused on the uses of glassed and plastic waste as aggregates for ordinary concrete (Corinaldesi, Gnappi et al. 2005; Pezzi, De Lice et al. 2006).

Other research activities, instead, have focused on the performances of Recycled Lightweight Aggregate Concrete (RLAC). The main difference between ordinary concrete and lightweight concrete is the bulk density; in the first one, this value usually ranges between 2200 and 2600 kg/m^3, while in the latter it ranges between 300 and 2000 kg/m^3 (Collepardi 2002). Most of these studies focus intensely on the chemical, physical, and mechanical properties of new RLAC material whereas their environmental performance is not considered. For example, (Kralj 2009) presented an experimental study on RLAC made of aggregates containing expanded glass. The values of density, compressive strength and thermal conductivity of the new recycled based concrete were compared with existing lightweight concrete made with expanded clay aggregates. (Chiou, Wang et al. 2006) conducted a similar study on the mechanical properties of LightWeight Aggregates (LWAs) made from sewage-ash sludge and incinerated sludge. Similarly, (de Gennaro, Cappelletti et al. 2006; de Gennaro, Langella et al. 2008; de Gennaro, Graziano et al. 2009) studied the possibility of producing LWAs using different waste products deriving from industrial processes. In detail, the experimental studies (de Gennaro, Cappelletti et al. 2006; de Gennaro, Langella et al. 2008; de Gennaro, Graziano et al. 2009) provided possible opportunities in the reuse of industrial waste and particularly muds coming from both ornamental stone (granite sludges from sawing and polishing operations) and ceramic production (porcelain stoneware tile polishing sludge) for the manufacturing of lightweight expanded aggregates as constituents of structural and/or thermo-insulating lightweight concretes.

On the basis of the results reported in (de Gennaro, Cappelletti et al. 2006; de Gennaro, Langella et al. 2008; de Gennaro, Graziano et al. 2009), the present study aims at investigating the environmental footprint of different lightweight concretes made of different recycled LWAs by means of a LCA methodology (ISO:14040 2006; ISO:14044 2006). In detail, the following steps will be addressed:

1. The environmental performance of recycled and natural LWAs is firstly computed and compared. The recycled LWAs herein investigated are obtained starting from the following geomaterials: Campanian Ignimbrite (Cab70), Dry Powder Mud (DPM), clinoptilolite-rich epiclastite (IZclino), a limestone (CP) and granitoid orthogneiss Serizzo (SER); the natural LWAs are made of expanded (natural) clay.
2. The environmental footprint of recycled and natural lightweight concrete made with the above lightweight inert options is then computed and compared. The proposed lightweight concrete options are suitably designed to guarantee the same structural and mechanical performances.

4.2 *Materials*

4.2.1 Recycled LWAs

Raw materials used to produce LWAs that will be investigated in the present study are the following (Table 4. 1):

1. Two commercial “zeolitites” (rocks with zeolite content higher than 50 wt. %): Campanian Ignimbrite and an epiclastite from Turkey, both supplied by “Italiana Zeoliti s.r.l.” (Pigneto, Modena – Italia);

2. Limestone (LP) waste, from a quarry site located near Pozzano (Sorrento peninsula– Napoli – Italy);
3. Two industrial wastes: a mud deriving from the processing (cutting and sewing) of Serizzo (a granitoid orthogneiss), from Verbania-Cusio-Ossola district (Verbania – Italy) and a mud resulting from porcelain tiles polishing, from Sassuolo industrial district (Modena –Italy).

The chemical, mineralogical and technological characterization of each industrial waste is described as follow:

1.1) Campanian Ignimbrite is the most important and extensive volcanic deposit in southern Italy (Fisher, Orsi et al. 1993). It was emplaced 39.000 yBP (De Vivo, Rolandi et al. 2001; Fedele, Scarpati et al. 2008) as a result of a huge explosive activity during the Quaternary (Barberi, Innocenti et al. 1978). This deposit is characterized by four stratigraphic units (Cappelletti, Cerri et al. 2003; Langella, Bish et al. 2013). Among these, the lithified yellow tuff (LYT) was deeply affected by zeolitization processes, thus leading to a zeolite (phillipsite and chabazite) content of about 60 wt.% (Cappelletti, Cerri et al. 2003; Langella, Bish et al. 2013). The raw material used in this project (de Gennaro, Cappelletti et al. 2006; de Gennaro, Langella et al. 2008) comes from this stratigraphic unit; more precisely, from an active quarry for the production of building stones (masonry unit) near Comiziano (Napoli - Italy), commercialized with Cab70 trade name. X-Ray powder diffraction (XRPD) analyses reveal the presence of phillipsite as predominant phase in association with chabazite and feldspar. Lower amounts of biotite and smectite also occur (de Gennaro, Cappelletti et al. 2006; de Gennaro, Langella et al. 2008; Langella, Bish et al. 2013).

1.2) The Turkish epiclastite, containing clinoptilolite as the main zeolite, comes from the western area of Turkey; the deposit is located in Kirka basin, south of Eskisehir (Sengör, Görär et al. 1985). The lacustrine facies of Kirka basin is characterized by intercalations of detrital sediments and volcanic tuffs, with variable grain size from coarse to fine, altered to clinoptilolite, along with other diagenetic minerals (Yalçin 1989). Clinoptilolite is the most abundant phase, associated with feldspars, quartz, opal-CT, smectite and rare biotite (de Gennaro, Langella et al. 2008).The investigated material comes from the aforementioned tuffaceous levels and its trade name is IZclino.

2.1) The limestone used in this paper was taken from the north-west side of the Sorrento Peninsula, Pozzano locality (Napoli), where well-stratified cretaceous limestones outcrop extensively (Calcaterra and Santo 2004). The XRPD analysis on the investigated material shows the presence of calcite and subordinate dolomite. Insoluble residue (after HCl attack) is constituted by mica, feldspars, kaolinite, pyroxene, iron and titanium oxides.(de Gennaro, Langella et al. 2008).

3.1) The granitoid orthogneiss Serizzo (hereafter SER), derived from metamorphic processes affecting sandy-clay sediments to a depth of about 7 km, is extensively exploited as ornamental stone in the Verbania-Cusio-Ossola district, Southern Alps. The material used for the present investigation is the mud produced by the cutting and sawing of slabs of this stone, classified as industrial waste (DLgs.22/97 ; DLgs.36/03 ; de Gennaro, Graziano et al. 2009). As far as the mineralogical composition of this mud is concerned, it is constituted by quartz, feldspars and biotite, associated with chlorite and pyroxene (de Gennaro, Graziano et al. 2009).

3.2) The second industrial waste (hereafter DPM), used in combination with the above reported materials, is a mud (dried and pulverized, > 180 μm) deriving from porcelain stoneware tiles polishing processes. This material is also classified as industrial waste by the Italian law since 1997 (Suppl.Ord.G.U.R.I.n°38 1997). This mud is prevailingly constituted by the glassy fraction of the porcelain stoneware tiles; the residual crystalline fraction is represented by quartz, again from the tiles, and by silicon carbide (SiC) deriving from the abrasive agent used in the polishing operation. Mullite, zircon and calcite can only be found in very subordinate amounts (de Gennaro, Cappelletti et al. 2006; de Gennaro, Langella et al. 2008; de Gennaro, Graziano et al. 2009).

Raw materials aggregates		Description
Recycled aggregates	**Dry Powdered Mud (DPM)**	Muds from polishing process of porcelain stoneware tiles produced by a polishing plant located in Sassuolo (Modena-Italy)
	Cab70	Cutting and sawing sludges coming from Campanian Ignimbrite, produced in a deposit/quarry site located in Comiziano–Napoli (Italy)
	IZclino	Extraction sludges coming from the Turkish clinoptilolite-bearing epiclastic deposit in Kirka basin, on the South side of the town of Eskisehir
	SER	Cutting and sawing sludges coming from the granitoid orthogneiss in the Verbania-Cusio-Ossola district (Italy)
	CP	Extraction sludges coming from limestone produced in a deposit/quarry site located in Pozzano-Napoli (Italy)
Natural aggregate	**Natural clay**	Produced by LATERLITE SpA, Milan (Italy)

Table 4. 1: Raw materials used for LWAs: source and production description

		Cab70 (%)	IZclino (%)	CP (%)	SER (%)	DPM (%)	Clay (%)
Recycled LWAs	**MIX A**	100					
	MIX B	70				30	
	MIX C	70				30	
	MIX D	60		10		30	
	MIX E		70			30	
	MIX F				50	50	
Natural LWA	**MIX G**						100

Table 4. 2: Mixes composition of LWAs (% w/w of LWAs)

	MIX	LWA				
		Production conditions		Physical and mechanical properties		
		Temperature	Soaking time at Tmax	Bulk Density	H_2O Absorption after 24h	Compressive strength
		[°C]	min	[g/cm^3]	[%]	[MPa]
Recycled LWAs	**MIX A**	1380	5-6	1,01	5,7	0,6
	MIX B	1300	5-6	0,81	1,4	2,94
	MIX C	1300	4-5	0,83	1,19	2,94
	MIX D	1300	5-6	0,62	3,09	0,98
	MIX E	1340	5-6	0,92	2,5	3
	MIX F	1300	5-6	0,68	2,3	1,2
Natural LWA	**MIX G**	1200	5-6	0,60	2,0	2,0

Table 4. 3: Principal properties of LWAs

The production process adopted to obtain recycled LWAs from raw materials of Table 4. 1 is composed of two steps:

4.2.1.1 Compaction and granulation

Compaction and granulation of raw materials and their mix, (see Table 4. 1 and Table 4. 2), were obtained through dry granulation (Figure 4. 1) using a FYSTER compactor and a MRB (briquettes breaker) mill according to the following procedures. The powder material was moistened by adding 3% water by weight and poured into a feed screw hopper, where it is continuously conveyed to the compactor generating the briquettes (Figure 4. 2). These have been further granulated and divided in order to get a grain size fraction ranging between 3 and 8 mm.

4.2.1.2 Thermal treatment: dynamic firing (rotative kiln)

Firing tests were performed in dynamic conditions at the temperatures reported in Table 4. 3; rotation speed and inclination of the kiln (Al_2O_3-based refractory tube, 100 cm long, 6 cm internal diameter and 7 cm external diameter -Figure 4. 3 and Figure 4. 4) have been set to obtain cooking cycles from raw materials to the fired products equal to 40-50 minutes, with a soaking time ranging from 4 to 6 minutes (Table 4. 3). Firing tests were performed on a dried 3-8 mm grain size fraction.

In Figure 4. 5 the recycled LWAs are shown after the production steps.

Figure 4. 1: Fyster dry granulating apparatus

4.2.2 Natural LWAs

Raw material used to produce natural LWA is natural clay (Table 4. 1and Table 4. 2); in particular, expanded clay aggregates are produced by firing natural clay to temperatures of 1200 °C in a rotating kiln. The pellets are rounded in shape and fall from the kiln in a grade of approximately 0–32 mm with an average dry bulk density of approximately 600 kg/m³. The compressive strength value is approximately 2,0 Mpa (Table 4. 3) (Leca and Lecastrutturale — LATERLITE SpA, Milan (LaterliteSPA)).

.

Figure 4. 2: Briquettes and granulate

Figure 4. 3: Laboratory rotative kiln (Nannetti mod. TO-R150-15)

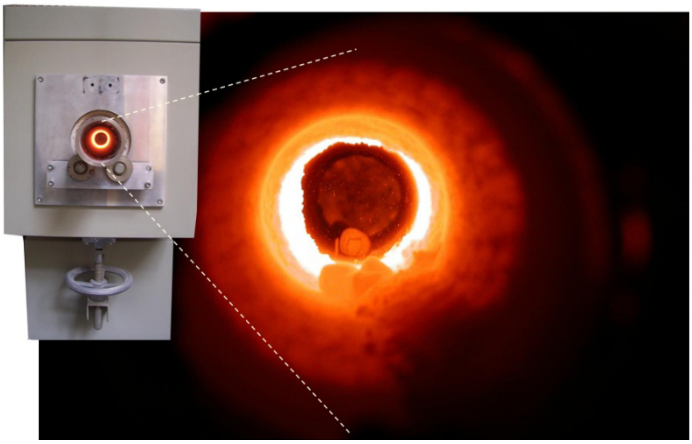


Figure 4. 4: Internal image of the rotative kiln during firing procedures

Figure 4. 5: Recycled LWAs

4.3 *Methodology*

The environmental performance of the different LWAs described in the previous paragraph and corresponding lightweight concrete mixes (recycled and conventional) and of is evaluated by means of a LCA approach. In particular, the LCA is implemented according to (ISO:14040 2006; ISO:14044 2006) which addresses the environmental aspects and potential environmental impacts throughout a product's life cycle, from raw materials acquisition through production, use, end of life treatment, recycling and final disposal (i.e. cradle-to-grave).

4.4 *Goal and Scope definition*

The primary goal of the present study is to define and compare the environmental impact of the production of different types of lightweight concrete material: *i)* Natural Lightweight Aggregate Concrete (NLAC) made with expanded clay and *ii)* Recycled Lightweight Aggregate Concrete (RLAC) made with different recycled LWAs. The corresponding concrete mixes are designed in order to achieve the same structural/mechanical performance, in terms of compressive strength: C20/25 compressive strength class is chosen as a reference mechanical property for the definition of the related functional unit, i.e. 1 m^3 of lightweight concrete. In order to compare these materials, the environmental footprint of the different LWAs, produced starting from both recycled and natural raw materials described in section 4.2.1, is preliminary computed.

In details, 1 kg of LWAs with bulk density values ranging between 600-1000 kg/m^3 is chosen as functional unit.

In Table 4. 4 and Table 4. 5 the investigated concrete types and LWAs are reported, respectively.

Materials		Description	F.U.
Concrete	**Natural Lightweight Aggregate Concrete (NLAC)**	Cementitious conglomerates made of: Ordinary Portland Cement, water, sand and natural LWAs	1 m^3 of concrete with the same strength: class C20/25
	Recycled Lightweight Aggregate Concrete (RLAC)	Cementitious conglomerates made of: Ordinary Portland Cement, water, sand and recycled LWAs	

Table 4. 4: Lightweight concrete description and functional unit

Figure 4. 6 shows the conventional and recycled lightweight concrete production system boundary. Both systems include raw materials production (cement, additive and aggregates production and water supply) and produce 1 m^3 of concrete as final output product. The NLAC system boundary includes the natural LWAs production. The schematic production process related to this inert type is reported in Figure 4. 7 and represents the current production practice of expanded clay aggregates in Italy.

The RLAC system boundary includes, instead, the recycled LWAs production; these LWAs are produced by different recycled raw materials according to the ratios reported in Table 4. 2. In particular, Figure 4. 8 and Figure 4. 9 show the production process of recycled LWAs. Figure 4. 8 focuses on Cab 70, SER, IZclino and CP raw materials production; Figure 4. 9, instead reports the production process of DPM raw material. As mentioned in the section 4.2.1, Cab70, SER, IZclino, CP and DPM are the raw materials used to produce recycled LWAs.

Materials		**Description (% W/W of LWAs)**	**F.U.**
Recycled aggregates	**MIX A**	Recycled LWAs composed by 100% of Cab70	1 kg of LWA with bulk density value ranges between 600-1000 kg/m^3
	MIX B/C	Recycled LWAs composed by 70% of Cab70 and 30% of DPM	
	MIX D	Recycled LWAs composed by 60% of Cab70, 30% of DPM and 10% of CP	
	MIX E	Recycled LWAscomposed by 70 of IZclino and 30% of Cab70	
	MIX F	Recycled LWAscomposed by 50% of Serizzo and 50% of DPM	
Natural aggregate	**MIX G**	Natural LWAs composed by 100% of expanded clay	

Table 4. 5: LWA description and functional unit

According to the European Union directive (EU,2008), a waste may be regarded as by-product if several requirements are met, such as its use in other industrial processes. Thus, in this study, the different wastes used as raw materials are considered as by-product and characterized by means of an allocation coefficient. According to(ISO:14040 2006; ISO:14044 2006), this coefficient is used to consider the environmental impact of:

- industrial waste produced by cutting process of natural stone used to produce Cab 70, SER, IZclino and CP raw materials;
- industrial waste produced by finishing process of porcelain tiles used to produce DPM raw material.

A mass allocation coefficient (%) is assumed for such coefficients that are calculated as the mass ratio (over total mass) between main product and by-product (Chen, Habert et al. 2010). These values are reported in Table 4. 6 and provide the amounts reported in (ANPA 2002).

Mass allocation coefficient [%]		
Materials	**Product**	**By-product**
DPM	89	11
Cab70	75	25
SER	75	25
CP	75	25
IZclino	75	25

Table 4. 6: Mass Allocation coefficient

Moreover, the system boundary of recycled LWAs takes into account the avoided impacts of the described industrial wastes that are re-used for the production of new LWAs instead of being disposed elsewhere. Avoided environmental impacts related to raw material extraction are also included in the system boundary of recycled LWAs production (Figure 4. 8 and Figure 4. 9).

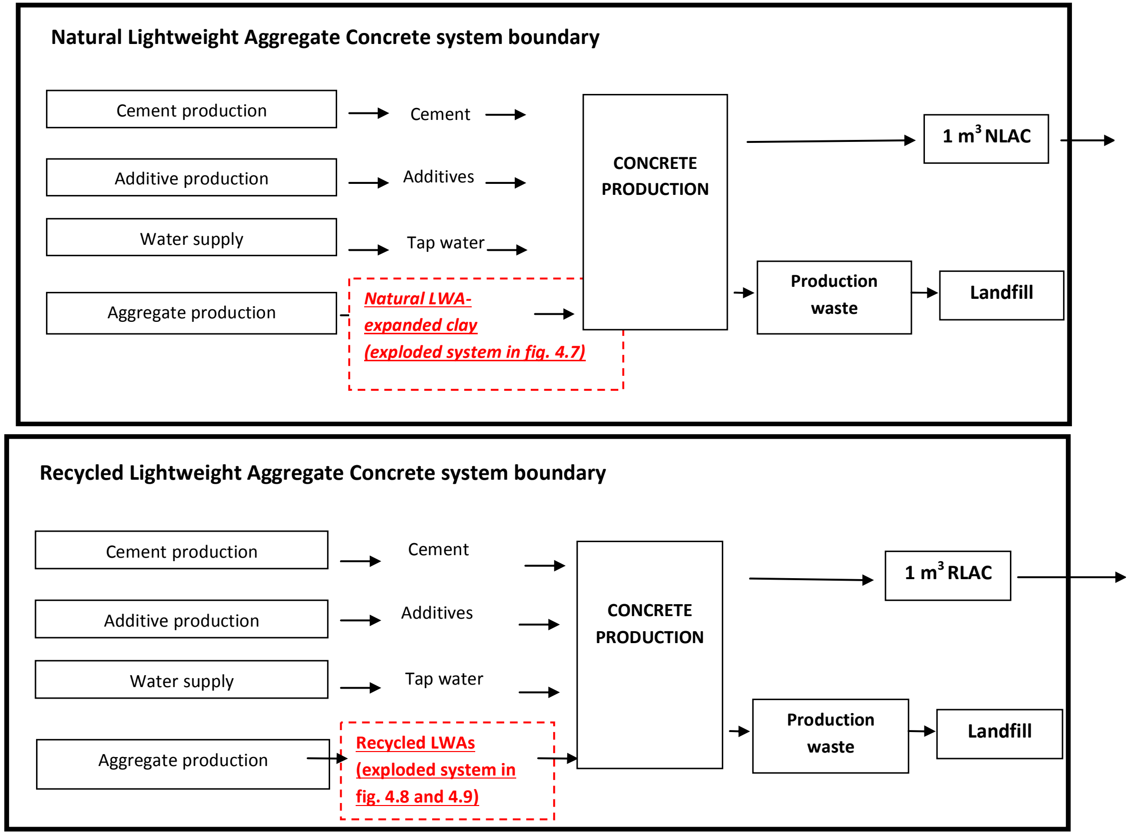


Figure 4. 6: System boundary -NLAC and RLAC production

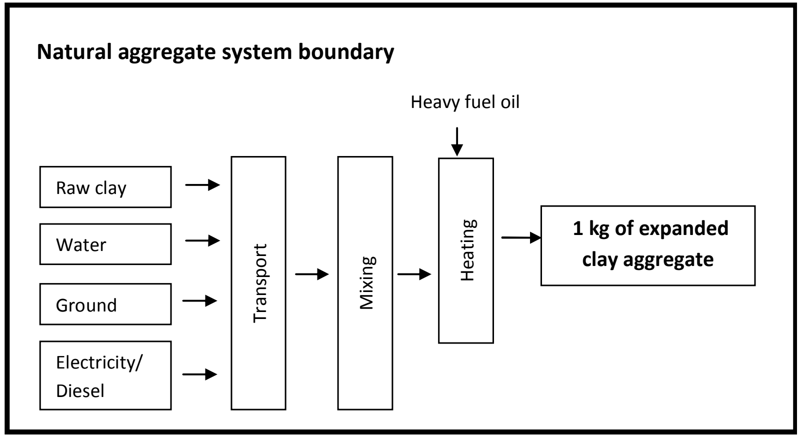


Figure 4. 7: Natural LWA production process

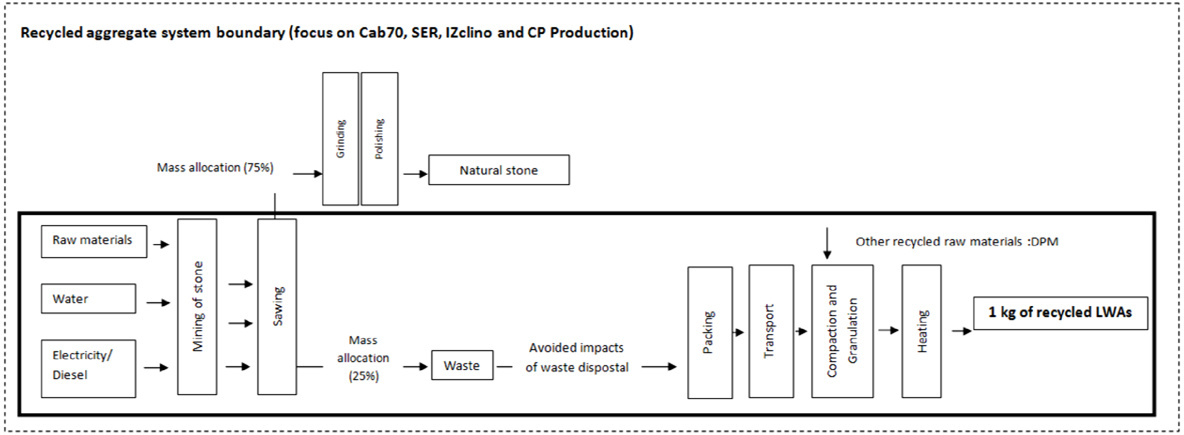


Figure 4. 8: Recycled LWA production process (focus on Cab70, CP, IZclino, Serizzo production)

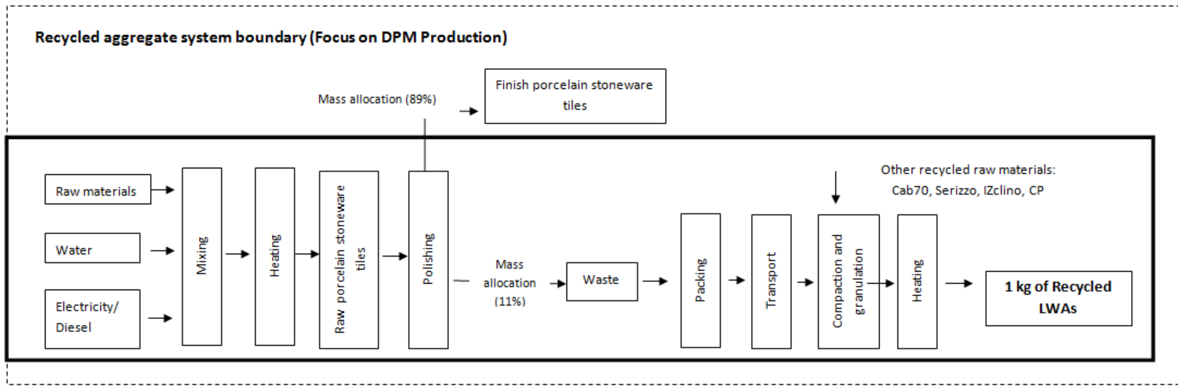


Figure 4. 9: Recycled LWA production process (focus on DPM production)

4.5 *Inventory analysis*

This step of the LCA involves data collection for each unit process regarding all relevant inputs and outputs of energy and mass flow, as well as data on emissions to air, water, ground, etc.

In the present study, secondary data are mainly taken from databases available in the SimaPro 7.3 LCA software package (Simapro). In particular, inventory data for concrete, cement products, other building materials, use of building equipment, transport operation, electricity and fuel consumption are retrieved from Ecoinvent database (Ecoinvent ; Hedemann and König 2007).

Moreover, it is assumed that the NLAC, RLAC and LWAs are produced in Italy, so all the LCI Ecoinvent data are modified on the basis of the information and practices of local suppliers and manufacturers.

4.5.1 Materials

Table 4. 7 and Table 4. 8 summarize the investigated materials, the data sources and assumptions referred to lightweight concrete and LWAs, respectively.

<table>
<tr><th colspan="4">Concrete</th></tr>
<tr><td>NLAC</td><td>Ecoinvent database</td><td>Lightweight concrete block, expanded clay, at plant</td><td rowspan="2">In the ecoinvent database, the “cradle to gate” life cycle analysis of lightweight concrete is included. It includes raw materials extraction and production, their transport to the finishing plant, the air-drying, the packing, the infrastructure and the disposal of wastewater and solid household waste. The main concrete material constituents are: Portland cement, Silica sand, tap water and LWAs. Besides expanded clay, in the present study, recycled LWAs are implemented within the lightweight concrete LCA model. In addition, the transport of each raw material to the finishing plant is not included, except for LWA aggregates; it is assumed that main raw materials (from extraction to production phase) are supplied in the same plant, located in Naples or Modena (Italy) according two transport different scenarios.</td></tr>
<tr><td>RLAC</td><td>Ecoinvent database</td><td>Lightweight concrete block, expanded clay, at plant</td></tr>
</table>

Table 4. 7: Lightweight concrete- materials, data sources and assumptions

LWA Raw materials			
DPM	Ecoinvent database (modified)	Ceramic tile, at regional storage	In the ecoinvent database, the production process of traditional ceramic tiles is reported. The amount of clay and felspar is icluded in percentages of 70% and 30%, respectively. It is considered a heating treatment up to 1050°C for 40-90 minutes. In this study, in order to consider the production of porcelain stoneware tiles, the amount of clay and feldspar has been modified in percentage of 40 and 60%, respectively and a heating treatment up to 1200 °C for 40-90 minutes has been considered. Moreover the output emissions of particulates PM 2,5 has been modified according to the information reported in (Breedveld, Timellini et al. 2007; ARPALombardia 2012), concerning the Italian ceramic tiles industry.
Cab70	Ecoinvent database (modified)	Natural stone plate cut, at regional storage	In the ecoinvent database, the raw material granite, the mining and sawing with diamond wires is included. Granite is an hard rock falling between 5 and 7 on the Mohs Hardness Scale. The Cab 70, instead, is a soft sedimentary rock. Consequently, the value of the cutting/sawing energy reported in the database is accounted for the amounts of 35% of the initial one, based on the difference between hardness values.
IZclino	Ecoinvent database (modified)	Natural stone plate cut, at regional storage	In the ecoinvent database, the raw material granite, the mining and sawing with diamond wires is included. Granite is an hard rock, falling between 5 and 7 on the Mohs Hardness Scale. The IZclino, instead, is a soft sedimentary rock but it is tougher than Cab70. Consequently, the value of the cutting energy is accounted for in the amount of 43% of the initial one, based on the difference between hardness values.
CP	Ecoinvent database (modified)	Natural stone plate cut, at regional storage	In the ecoinvent database, the raw material granite, the mining and sawing with diamond wires is included. Granite and limestone are hard rocks; they in fact, fall between 5-7 and 5 on the Mohs Hardness Scale, respectively. The value of the cutting energy is accounted for in the amount of 89% of the initial one, based on the difference between hardness values.
SER	Ecoinvent database (modified)	Natural stone plate cut, at regional storage	In the ecoinvent database, the raw material granite, the mining and sawing with diamond wires is included. Granite and Serizzo have similar value on Mohs Hardness Scale and consequently it is used the energy value reported in the Ecoinvent database.
Expanded clay	Ecoinvent database	Expanded clay, at plant	In the ecoinvent database, the raw material extraction (clay), the heating treatment in a rotary furnace at 1200 °C and the expansion with heavy fuel oil is included. This industrial process is in agreement with common practice adopted in Italy.

Table 4. 8: LWA raw materials- materials, data sources and assumptions

Two different concrete mixes are investigated: RLAC and NLAC; the different mix design have been derived from previous works of the authors (de Gennaro, Cappelletti et al. 2006; de Gennaro, Langella et al. 2008; de Gennaro, Graziano et al. 2009) and from commercial product datasheets (Leca and Lecastrutturale — LATERLITE SpA, Milan (LateriteSPA)). All concrete materials herein investigated belong, as hypothesis of the analysis, to the same compressive strength class (i.e. C20/25), with the mix details summarized in the Table 4. 9 and related to 1 m^3 of lightweight concrete

Components		NLAC (MIX G)	RLAC (MIX A)	RLAC (MIX B)	RLAC (MIX C)	RLAC (MIX F)	RLAC (MIXD)	RLAC (MIX E)
Diesel (MJ)		26.9	28.3	26	26	21.4	24.7	25.2
Electricity (kWh)		11.1	11.6	10.7	10.7	8.79	10.2	10.4
LWAs (kg)	(MIX G)	Expanded clay 515						
	(MIX A)		Cab70 404					
	(MIX B/C)			Cab70+DPM 259.2	Cab70+DPM 259.79			
	(MIX F)					SER+DPM 306		
	(MIX E)							IZclino+DPM 214.52
	(MIX D)						Cab70+CP+DPM 182.9	
Portland cement Z 42,5 (kg)		330	400	400	350	350	350	350
Water (kg)		181	224	224	161	175	161	161
Silica sand (kg)		675	760	760	833	500	833	833
Superplasticiser (kg)		1.65			4.82		4.82	4.82
Air entraining additive (kg)					33	22	33	33

Table 4. 9: lightweight concrete mix design (1 m^3)

4.5.2 Transport

Only the transport of raw materials for LWAs production is taken into account for NLAC and RLAC mixes. It is assumed that all the other raw materials (cement, additive, fine aggregates etc.), from extraction to production phases, are manufactured in the same plant of lightweight concrete material.

Three different transport scenarios are considered for the LWAs, corresponding to the location of the collecting site of raw (waste-derived) material of Cab70 and DPM. This choice is related to the following consideration: as reported in Table 4. 2 and Table 4. 5 the Cab70 and DPM raw material are always used in the LWAs mixes along with other raw materials. Particularly, in transport scenario 1 it is assumed that lightweight concrete plant is located in Napoli (Italy), corresponding to the collecting area of Cab70 waste. In transport scenario 2 it is assumed that the plant is located in Modena (Italy), corresponding to the collecting area of DPM waste, whereas in the transport scenario 3 the transport phase is completely omitted in the LWAs system boundary due to the hypothesis that lightweight concrete plant is located at the same distance of Cab70 and DPM collecting sites.

Table 4. 10 and Table 4. 11 show the input data for transport operations for all cases of LWAs. Moreover, the return trip is taken into account in terms of 50% of the initial one.

Materials	Distance (Km)	Distance**	Equipment	Data	Database
DPM	626	Sassuolo-Napoli	lorry	Transport lorry 16 t, fleet average	Ecoinvent
Cab70	40	Comiziano-Napoli	lorry	Transport lorry 16 t, fleet average	Ecoinvent
Ser	881	Verbania-Napoli	lorry	Transport lorry 16 t, fleet average	Ecoinvent
CP	35	Pozzano-Napoli	lorry	Transport lorry 16 t, fleet average	Ecoinvent
IZclino	1684	Kirka-Brindisi	barge	Transport barge tanker	Ecoinvent
	375	Brindisi Napoli	lorry	Transport lorry 16 t, fleet average	Ecoinvent
Expanded clay	775	Milano-Napoli	lorry	Transport lorry 16 t, fleet average	Ecoinvent
** distance: from extraction/production to finishing plant					

Table 4. 10: Transport-Scenario 1

Materials	Distance (Km)	Distance**	Equipment	Data	Database
DPM	19	Sassuolo-Modena	lorry	Transport lorry 16 t, fleet average	Ecoinvent
Cab70	610	Comiziano-Modena	lorry	Transport lorry 16 t, fleet average	Ecoinvent
Ser	284	Verbania-Modena	lorry	Transport lorry 16 t, fleet average	Ecoinvent
CP	630	Pozzano-Modena	lorry	Transport lorry 16 t, fleet average	Ecoinvent
IZclino	1684	Kirka-Brindisi	barge	Transport barge tanker	Ecoinvent
	825	Brindisi-Modena	lorry	Transport lorry 16 t, fleet average	Ecoinvent
Expanded clay	179	Milano-Modena	lorry	Transport lorry 16 t, fleet average	Ecoinvent
** distance: from extraction/production to finishing plant					

Table 4. 11: Transport-Scenario 2

4.5.3 Energy

Cutting energy: The values of cutting energy (Table 4. 12) are calculated on the basis of hardness index of starting materials used to produce LWAs. In particular, the energy consumption related to the sawing of these materials is calculated according to the deviation from hardness index of granite rock (Table 4. 8).

LWAs Raw materials	Cutting energy values (kWh)
Cab70	0,196
IZclino	0,241
SER	0,560
CP	0,498

Table 4. 12: Cutting energy values

This energy input is implemented as *"Electricity, medium voltage, production IT, at grid"*, retrieved from Ecoinvent database and referred to electricity production in Italy.

Heating treatment energy: The same energy data is also used to model heating treatment (i.e. thermal treatment by means of dynamic firing through a rotative kiln section 5.2.1.2) for each LWA production. In the case of IZclino "*Electricity, medium voltage, production UCTE, at grid*" is adopted in order to model the cutting energy of raw material in the Turkish region.

4.5.4 Avoided impact

Avoided environmental impacts for modeling recycled LWAs concern the disposal of industrial waste (based on mass allocation calculation) and raw material extraction (natural clay). In particular, the data *"Disposal, inert waste, to inert material to landfill"* (Ecoinvent database) are used to model the avoided disposal of industrial waste coming from natural stone manufacturing in case of Cab70, IZclino, CP and Serizzo aggregates; while the data *"Disposal, hazardous waste, to underground deposit"* (Ecoinvent database) is adopted to model the avoided disposal of industrial waste coming from ceramic tiles manufacturing in case of DPM aggregates.

Figure 4. 10a and Figure 4. 10b show the environmental profile (damage categories) of 1kg of Cab70 and DPM, respectively; the impacts are computed by taking into account the avoided impacts described before. The negative percentages are related to the reduction of emissions in the air/water/soil associated with the avoided disposal of waste.

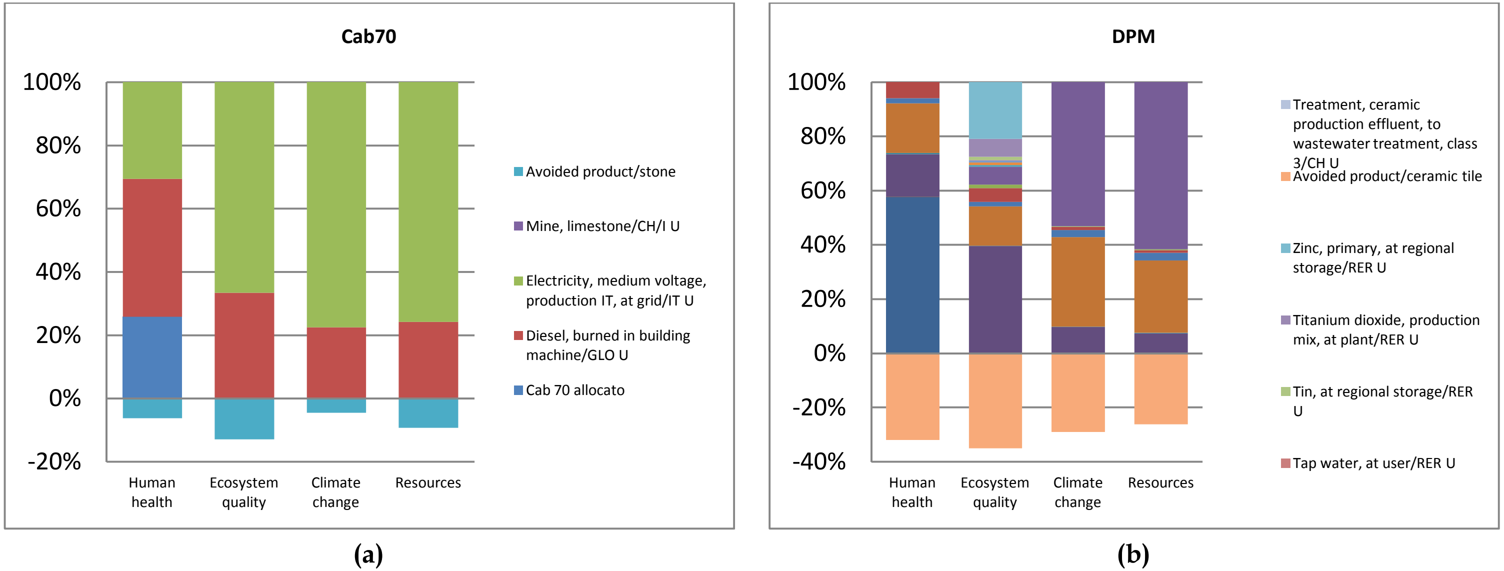


Figure 4. 10: Environmental profile (damage categories) of Cab70 and DPM raw materials, Avoided products. (a): Cab70 raw material; (b) DPM raw material

4.6 *Impact Assessment*

The Impact 2002+ (Figure 2.4) (Jolliet, Margni et al. 2003) methodology is used for the impact assessment phase.

The LCA results are firstly provided in terms of midpoint indicators and then converted into damage indicators.

4.6.1 LCA results of recycled and natural LWAs

As mentioned in the previous paragraphs, the first part of the LCA study involves the comparison between the environmental performance of the recycled and natural LWAs. Then, these LCA results will be used to compare the NLAC and RLAC.

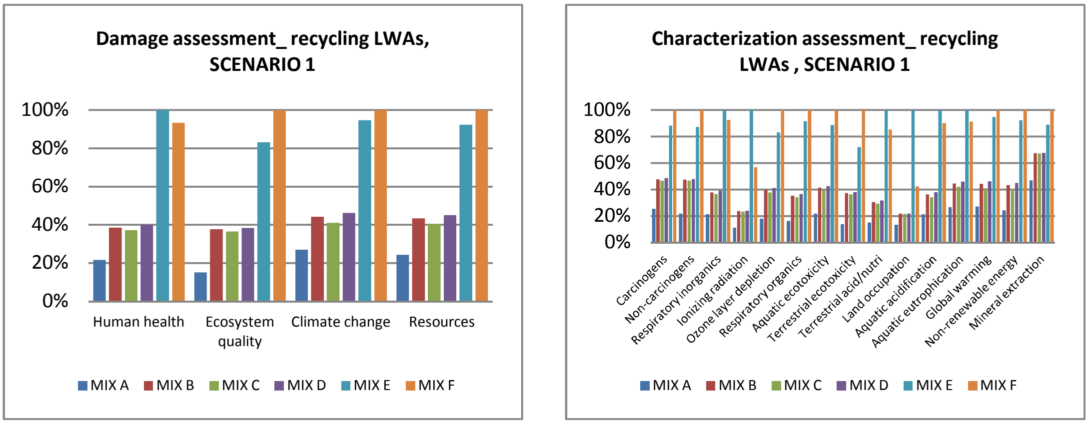
4.6.1.1 Recycled LWAs comparison

a. *Scenario 1* – Figure 4. 11: MIX E and MIX F of LWAs present the major environmental burden in all impact and damage categories. In the Human Health damage category (respiratory inorganics and ionizing radiation midpoint impact categories) MIX E presents the highest environmental impact; this result is influenced by the transport phase of IZclino raw materials and in particular, to nitrogen oxides emission related to the operation (supply of fuel-diesel) of barge. The environmental impact related to transport phase of IZclino is almost 63% of the total burden, with the 42% that is linked to the transport by barge.

   The environmental impact of MIX F in Ecosystem Quality and Resources damage categories is mainly due to the transport of raw materials (SER and DPM) and, in particular, to aluminum and zinc emissions related to the operation of transport by lorry. The impact contribution related to transport phase is about 70% of the total environmental impact.

   MIX E and MIX F present similar environmental load in the Climate Change category; in fact, in both LWAs the corresponding value of this indicator is approximately 0,25 kq eq. of CO_2. In particular, in the MIX F the emissions of CO_2 originate from the transport with lorry of SER and DPM (waste) raw materials (accounting for 0.13 and 0.09 kg eq. of CO_2, respectively), while in the MIX E the impact is divided between the transport with lorry and with barge of DPM and IZclino (accounting for 0.056 and 0.15

kg eq. of CO_2, respectively).

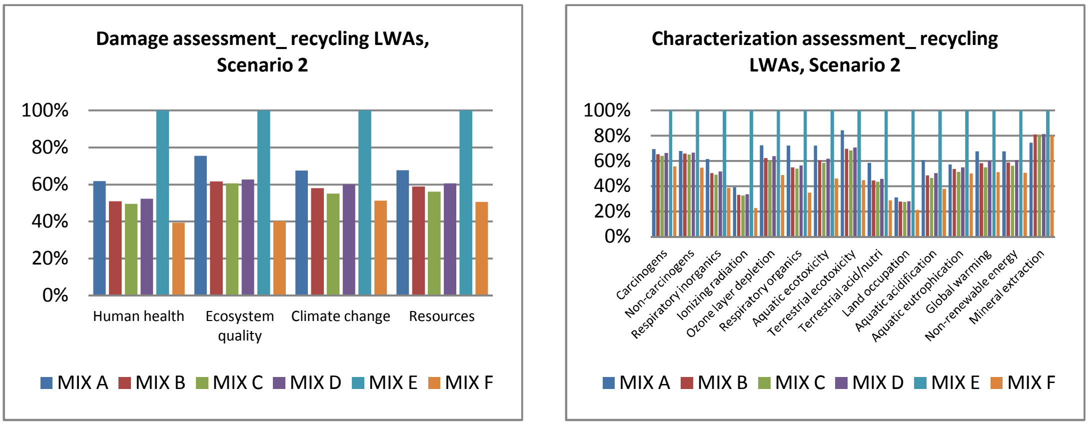


(a) **(b)**

Figure 4. 11: Recycled LWAs- Scenario 1. (a):end-point categories; (b): mid-point categories

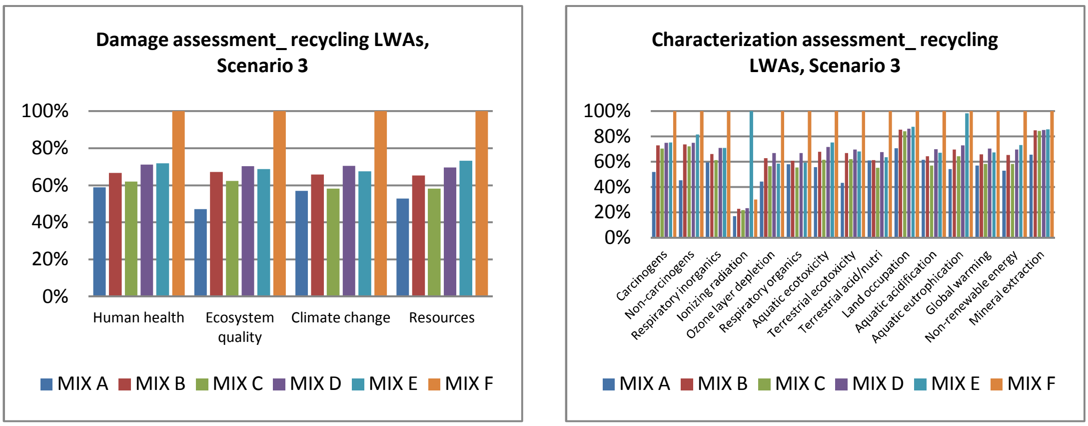
b. *scenario 2* - Figure 4. 12: MIX E presents the worst environmental profile in all mid-point and end-point categories. It is due to the transport of IZclino raw material that involves approximately 80% of total environmental impact. More than 40% of this impact is related to the transport with lorry that, as reported in table 11, is characterized by the greatest distance than other solutions. The environmental impact of MIX F, instead, is lower than other alternatives due to a minor transport distance for raw materials.

c. *scenario 3* –Figure 4. 13: all recycled LWAs show comparable LCA results except for MIX F that involves the major impact in all damage and impact categories. The impact contribution of SER is around the 55% of total burden, where almost 36% is related to energy consumption. As shown in Table 4. 12, in fact, the value of the cutting energy is larger than other alternatives.



(a) **(b)**

Figure 4. 12: Recycled LWAs- Scenario 2. (a):end-point categories; (b): mid-point categories

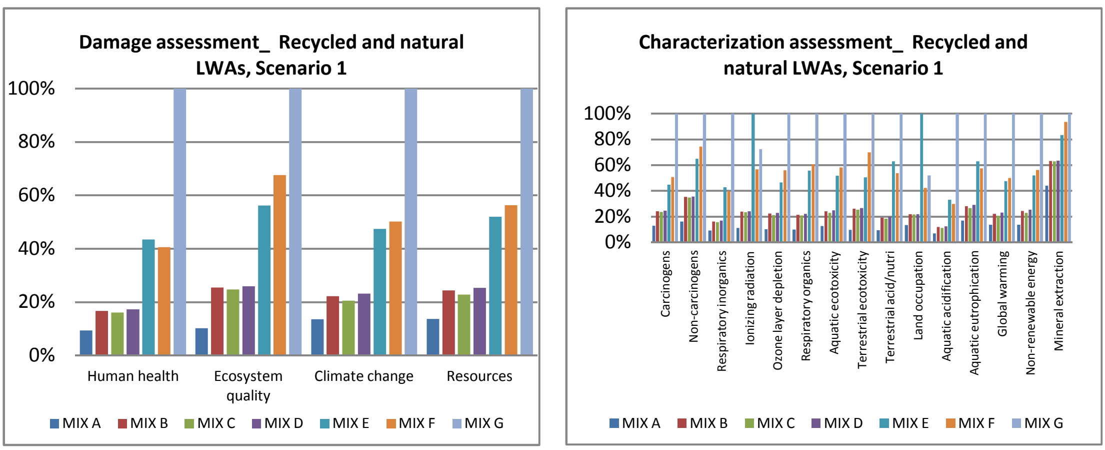


(a) **(b)**

Figure 4. 13: Recycled LWAs- Scenario 3. (a):end-point categories; (b): mid-point categories

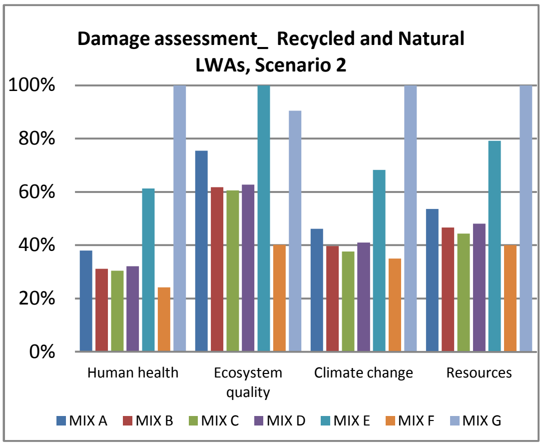
4.6.1.2 Recycled and natural LWAs comparison

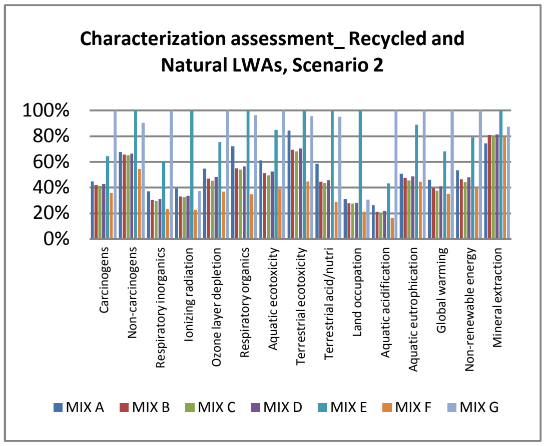
In all three transport scenarios (Figure 4. 14, Figure 4. 15 and Figure 4. 16) MIX G (i.e. natural LWAs) exhibits the highest environmental impact in all mid-point and end-point impact categories. Clay extraction operations along with the manufacturing phase (heating treatment and clay expansion with heavy fuel oil) are responsible for the environmental results in all LCA categories. Avoided impacts that characterize the system boundary of recycled LWAs (related to disposal and raw materials supply) are able to provide several environmental benefits to the overall LCA environmental performance: in all transport scenario (Figure 4. 14, Figure 4. 15 and Figure 4. 16) the recycled LWAs show an environmental impact contribution lower than MIX G. In particular, in the transport *scenario 1* (Figure 4. 14), four recycled LWAs (MIX A, MIX B, MIX C and MIX D) show an environmental impact ranging between 70-90% lower than the impact of natural LWAs (in all damage categories). Moreover, MIX E and MIX F exhibit an environmental impact between 30-60% lower than MIX G. In the transport *scenario 2* (Figure 4. 15), instead, the environmental impact of all recycled LWAs is influenced by the transport phase of Cab70 and IZclino raw materials. In fact, the environmental impact contribution increased by 10 to 50% in almost all damage categories. In addition, MIX E shows the major environmental burden (even greater than natural LWAs) in the Ecosystem Quality damage category due to the zinc emissions in soil related to the transport of IZclino waste material. In the *scenario 3* (Figure 4. 16) all the recycled LWAs show an environmental impact performance 80% lower than the impact of MIX G in all damage and impact categories.



(a) **(b)**

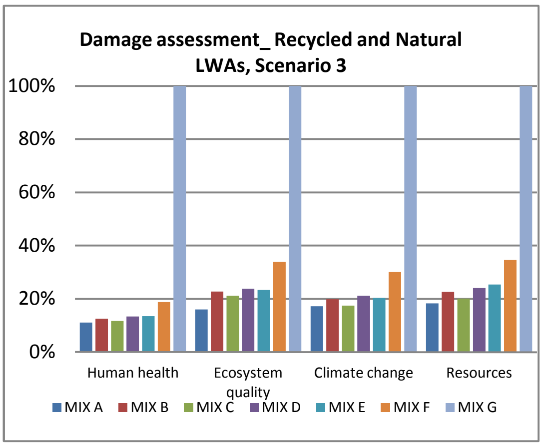
Figure 4. 14: Recycled and natural LWAs- Scenario 1. (a):end-point categories; (b): mid-point categories

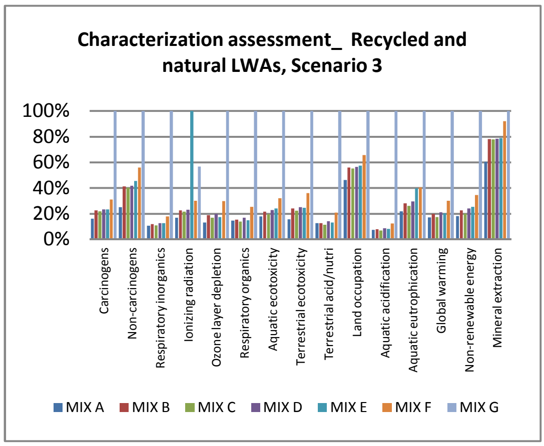




(a) **(b)**

Figure 4. 15: Recycled and natural LWAs- Scenario 2. (a):end-point categories; (b): mid-point categories



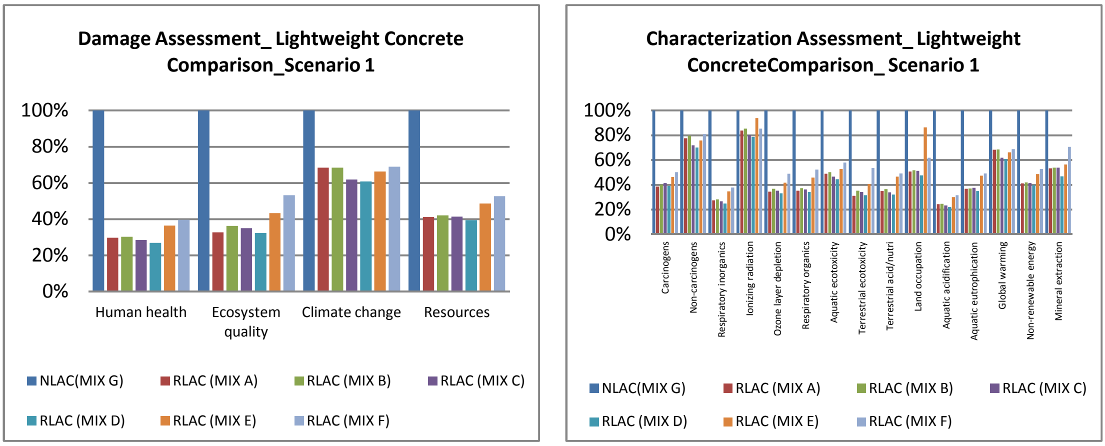


(a) **(b)**

Figure 4. 16: Recycled and natural LWAs- Scenario 3. (a):end-point categories; (b): mid-point categories

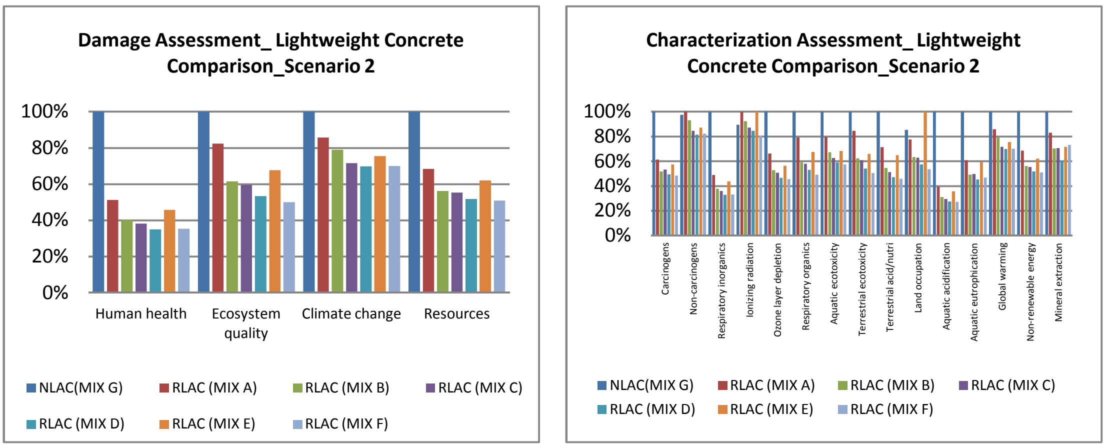
4.6.2 LCA results of NLAC and RLAC

As specified previously, the main objective of this study is to compare the environmental performance of NLAC and RLAC mixes. The results are discussed in terms of damage (End Point) categories, and in terms of impact categories (Mid point).



(a) **(b)**

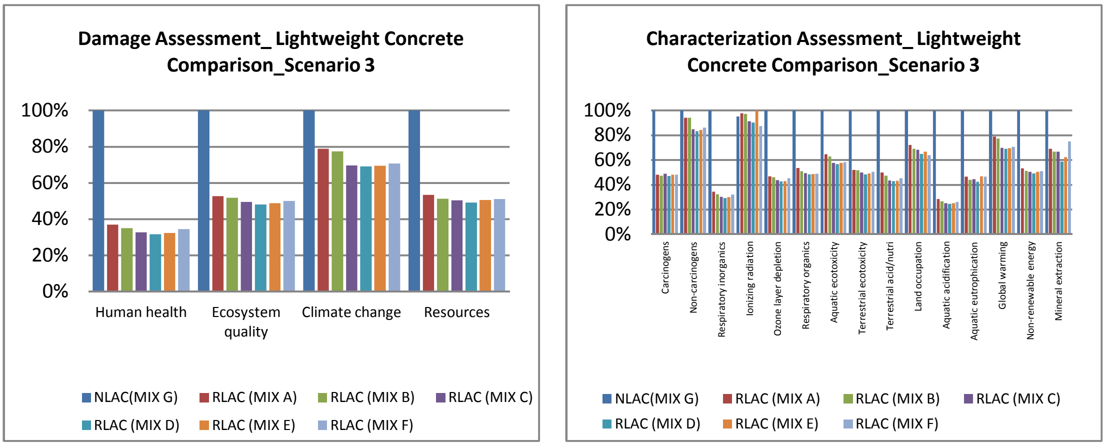
Figure 4. 17: NLAC and RLAC- Scenario 1. (a):end-point categories; (b): mid-point categories



(a) **(b)**

Figure 4. 18: NLAC and RLAC- Scenario 2. (a):end-point categories; (b): mid-point categories

1 m^3 of NLAC is chosen as the reference mix; the goal is to evaluate the potential environmental benefits of RLAC mixes compared to the reference lightweight concrete. All LWA concrete mixes present similar mechanical properties, i.e. the compressive strength class is C20/25 for all investigated lightweight concrete types.



(a) **(b)**

Figure 4. 19: NLAC and RLAC- Scenario 3. (a):end-point categories; (b): mid-point categories

As it can be seen from Figure 4. 17, Figure 4. 18 and Figure 4. 19 the NALC mix in all the damage and impact categories exhibits the largest environmental impact; in addition, all RLAC mixes show similar environmental profiles. The RALC, produced by using MIX D as LWAs, is the solution characterized by the lowest environmental impact in all LCA categories and in each transportation scenarios herein considered. It is mainly due to lower amount of LWAs used in the mix design, as reported in Table 4. 9. In order to evaluate the influence (from the environmental point of view) of LWAs in the lightweight concrete material, a detailed environmental analysis of NLAC (MIX G) and RLAC (MIX D) (considering transport scenario 3) is performed and reported in Figure 4. 20. In terms of end-point assessment, the environmental contribution of expanded clay aggregate production in the NLAC accounts for about 60% of total environmental burden, whereas the environmental impact of recycled LWAs in RLAC (MIX D) is approximately the 10% of the overall impact. In the light of this consideration, it can be pointed out that the use of recycled LWAs to produce 1 m^3 of lightweight concrete of C20/25 strength class may significantly reduce the environmental contribution of LWAs to the total environmental burden in all damage categories.

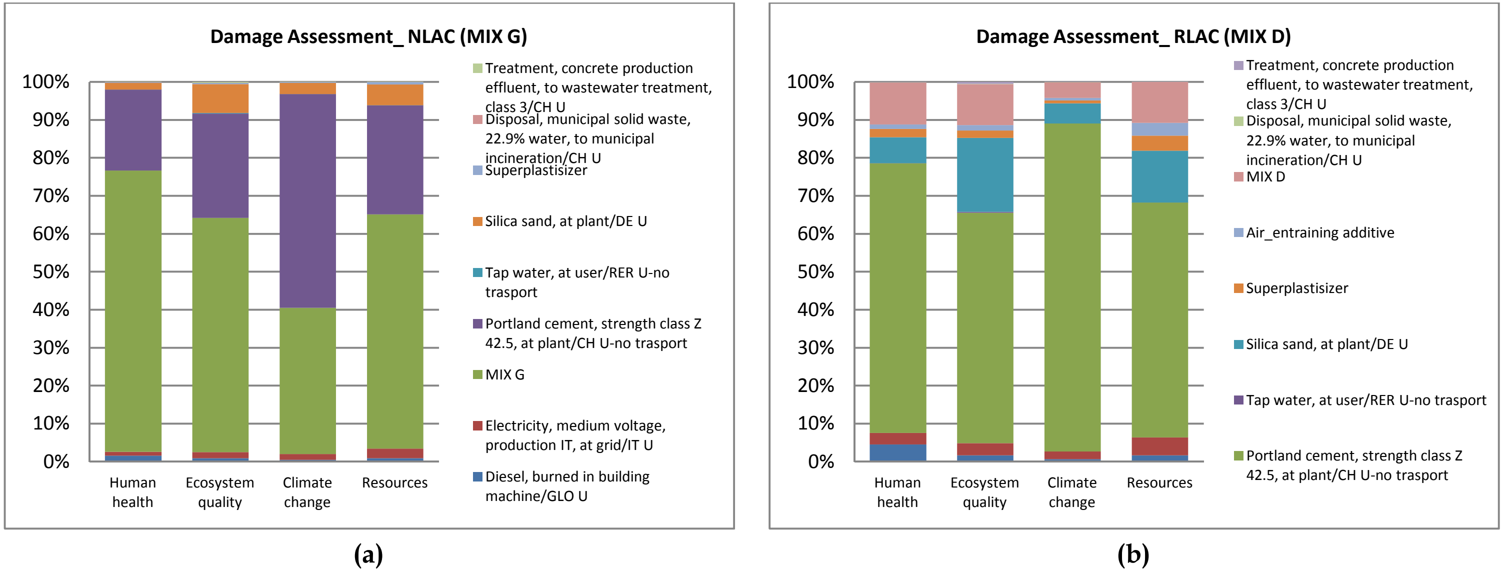


Figure 4. 20: NLAC and RLAC (MIX D), Scenario 3; End-point categories (a):NLAC; (b): RLAC (MIX D)

Moreover, in order to evaluate which material/phases influences the environmental results for NLAC concrete, the process contribution analysis (ISO:14040 2006; ISO:14044 2006) is conducted and the results are presented for each damage categories as follows; Scenario 3 it is chosen for this analysis.

Human Health (HH) category

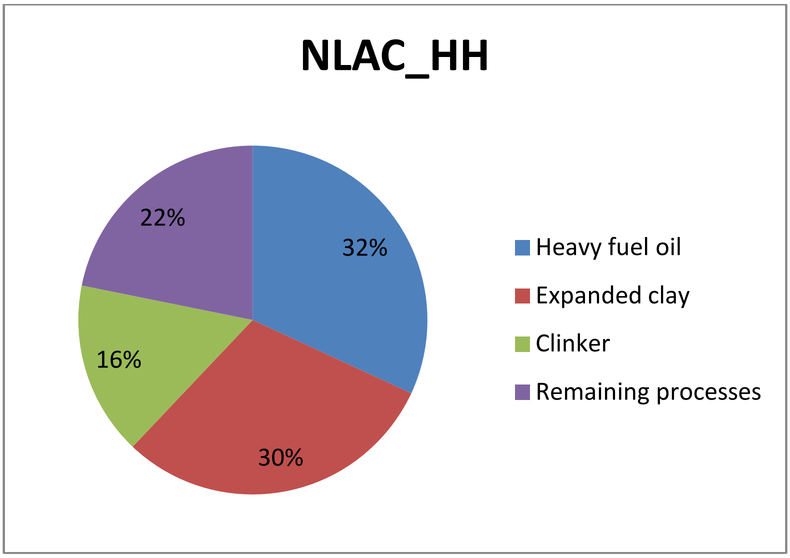


Figure 4. 21: Human Health end-point category results of NALC

The NALC presents the highest environmental impact in the Human Health category (Figure 4. 19) due to the production process of natural LWAs (Figure 4. 20) in the measure of almost 62% of the total burden. In Figure 4. 21, in fact, this contribution is shown to be related to the extraction of clay (30%) and the expansion of clay pellet by means of heavy fuel oil (32%).

Ecosystem Quality (EQ) category

The expansion process of natural LWAs by means of heavy fuel oil affects the LCA results in the Ecosystem Quality category. In Figure 4. 22, in fact, it clearly appears that the expanded clay production involves the highest impact (49%) in this damage category.

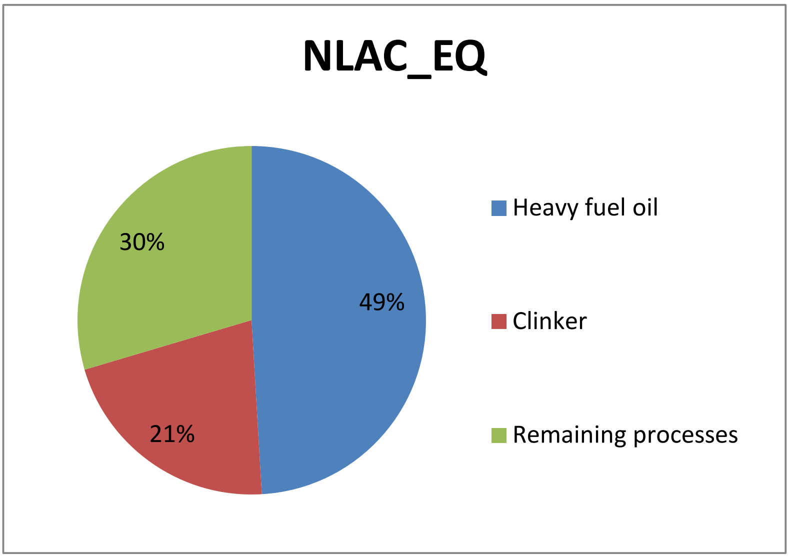


Figure 4. 22: Ecosystem Quality end-point category results of NALC

Climate Change (CC) category

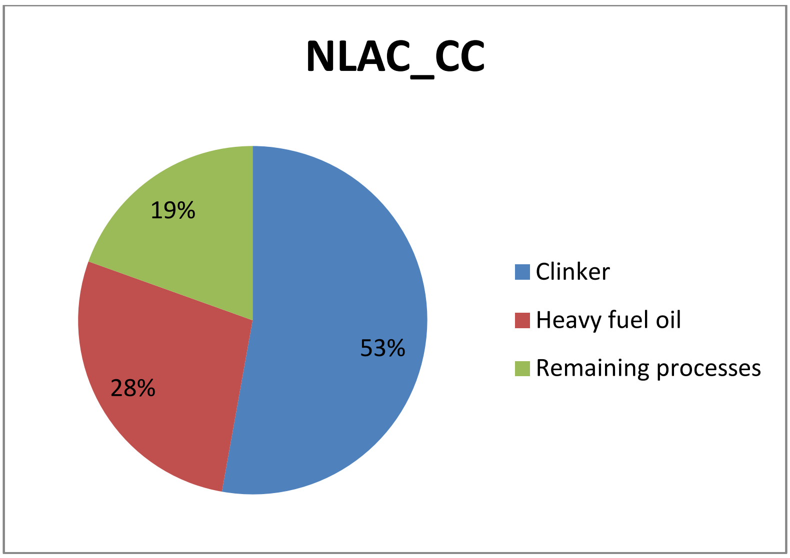


Figure 4. 23: Climate Change end-point category results of NALC

Cement (Clinker) is the main contributor to this damage category accounting for the 53% of the total burden Figure 4. 23. The second largest impact is due to the expansion process of clay pellets (28%).

Resources (R) category

The expanded process of clay pellets with heavy fuel oil is responsible for the major environmental impact in Resources category as shown in Figure 4. 24.

Its impact is almost 65% on total environmental burden and it is related to production of crude oil.

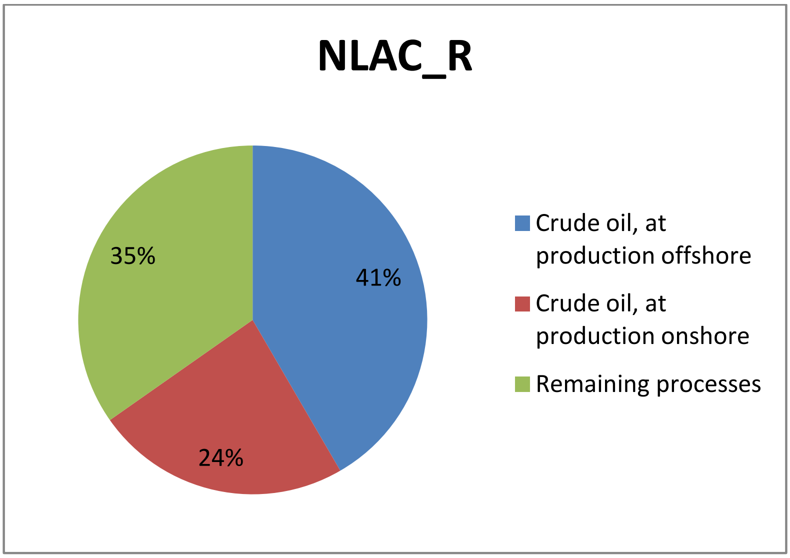
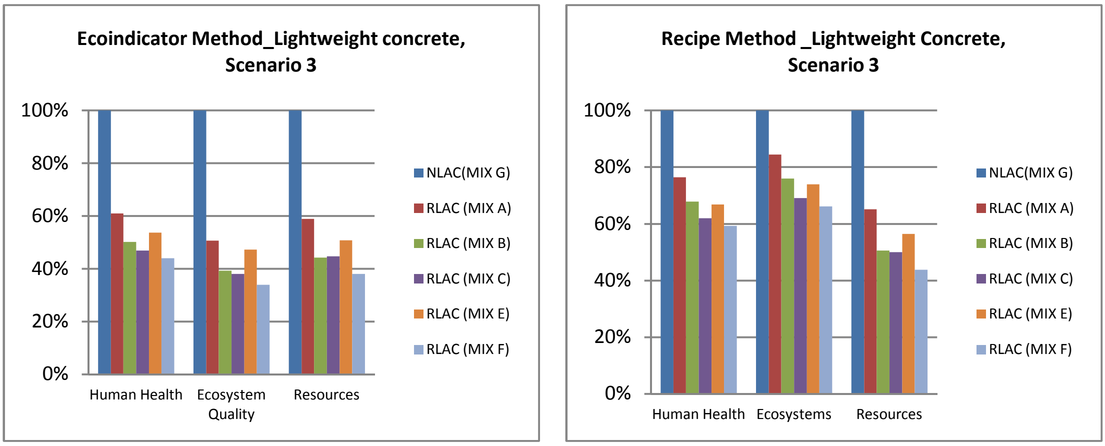


Figure 4. 24: Resources end-point category results of NALC

4.7 *Sensitivity analysis*

The objective of the sensitivity analysis is to assess the reliability of the LCA results, determining how they are affected by uncertainties of the input data, allocation methods, environmental impact assessment methodology in order to properly establish conclusions and recommendations for the study.

In this study, the environmental impact is re-calculated using Ecoindicator99 (Ecoindicator99) and ReCIPE (ReCIPE) LCIA method. The results are reported in Figure 4. 25 for both methods and confirm the previous results obtained with Impact2002+ methodology. In both cases the NALC presents the highest environmental burden in all impact damage categories.



(a) **(b)**

Figure 4. 25: Ecoindicator99 and Recipe results. (a): Ecoindicator method; (b): Recipe method

4.8 *Conclusion*

In the present study the environmental impact of the production of different types of lightweight concrete materials is performed, i.e. NLAC and RLAC made with different recycled LWAs. With regard to LCA of LWAs, the results reveal that the production of recycled LWAs presents a significantly lower environmental burden with respect to the production of natural LWAs, mainly due to potential benefits of avoided impacts (raw material supply and waste disposal). In particular, the clay extraction and the production phase (including heating treatment and clay expansion with heavy fuel oil), influence the environmental results of natural LWAs.

Among the recycled LWAs the transport phase affects the relative efficiency of different mix options.

With reference to 1 m^3 of lightweight concrete of C20/25 strength class, the following outcomes can be pointed out:

1. The NALC mix in all the damage and impact categories presents a larger impact than all RLAC mixes.
2. The environmental impact of expanded clay aggregates in the NLAC production accounts for around 60% of total environmental burden, whereas the environmental impact of recycled LWAs in RLAC is almost 10% of total environmental burden.

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5 Chapter V

APPLICATIONS TO BUILDINGS: LIFE CYCLE OF DIFFERENT REPLACEMENT OPTIONS FOR A TYPICAL OLD WOODEN ROOF

5.1 *Introduction*

It is estimated that in some European area, such as Italy, masonry buildings constitute a significant portion of existing building; in addition, many of them are characterized by an important historical and cultural value.

In general, these structures do not comply with current/national engineering standards and are sometimes subjected to physical and functional degradation over time as well as structural damage from hazardous events. On the other hand, existing buildings continue to be upgraded at a very low rate; it is estimated that the existing European building stock is currently being retrofitted at a rate of approximately 1-3% of total needed per year only (Ascione, de Rossi et al. 2011; Ma, Cooper et al. 2012).

Many governments and international organizations have provided policy guidance, financial assistance and technical support to improve the structural, functional and energy performance of existing buildings (AgenziadelleEntrate ; DOCC&EE ; HUD/U.S.).

At the same time, a significant amount of researches focus on the assessment of the existing building state, analyzing, consequently, different type of building renovation strategies. Building renovation, in fact, has gained increasingly attention as a valuable alternative to demolition, providing opportunities to: upgrade the internal and external building environment, reach energy efficiency, align with more modern accommodations with respect to new standards and increase the value of the existing building. These studies, in particular, focus intensely on the mechanical, functional and energy performance of retrofitted/renovated existing structures.

For example, some authors (Cohen, Goldman et al. 1991; Flourentzou and Roulet 2002; Verbeeck and Hens 2005; Užšilaitytea and Martinaitis 2010; Biekšaa, Šiupšinskas et al. 2011; Sonetti 2011; Xing, Hewitt et al. 2011; Asadi, da Silva et al. 2012) deal with energy efficiency improvement of buildings through different functional retrofit technologies; these mainly consist in adopting strategies to reduce building heating and cooling demand, promoting the use of energy efficient equipment and low energy technologies.

Other research activities include the assessment of other sustainability criteria, such as economical benefits of refurbishment and social aspects (Juan, Kim et al. 2009; Kanapeckiene, Kaklauskas et al. 2011; Raslanasa, Alchimovienėa et al. 2011).

(Boylu 2005; Bosiljkov, Uranjek et al. 2010), instead, investigated structural and functional state of the building prior/after renovation, considering, particularly, earthquake damage.

Given the wide set of possible operations, it should be emphasized that refurbishment and retrofitting of existing buildings often require the fulfillment several mechanical and functional requirements (sometimes prescribed by national laws/standards) that have to be properly taken into account during the design of the operation itself. Among these requirements, a selection of a set of actions should be pursuit also in the light of common goals of sustainable development in the construction sector.

Indeed, the decision making process of a retrofit operation, related to its design and adopted technology, should be intended as a multi-objective multi-criteria optimization problem that usually fairly embodies sustainability purposes in the engineering field(Foxon, Mcilkenny et al. ; Sahely, Kennedy et al. 2005; Waheed, Khan et al. 2009; Menna, Asprone et al. 2013); the best solution, in fact, could be a trade-off among a range of factors, such as energy, economic, technical, environmental, regulations, social, and so forth.

Generally, the overall process of a building retrofit is divided in some steps (Juan, Kim et al. 2009; Kušar 2009) (Figure 5. 1). The first phase should encompass a performance assessment of the facility. Diagnostics tools should be used to identify structural integrity and the current state of individual components of the building in order to define a set of possible refurbishment solutions.

Each solution should be analyzed by using appropriate criteria (quantitatively expressed by proper indicators) considering, simultaneously: financial, environmental, social and structural aspects, in order to implement the optimal retrofit solution.

The resulting selected operation can be also regarded as a valid way to avoid demolition of structure and extend the building lifetime (Figure 5. 2).

As previously mentioned, from structural, functional and energy point of view, several studies have been conducted analyzing retrofit techniques (Ma, Cooper et al. 2012), as well as resulting performance of buildings (ReLuis 2011); however, as far as the author knowledge, no works deal with the LCA of such operations.

Figure 5. 1: Conceptual design of a multi-criteria retrofit decision model

Given these considerations, the present study aims at investigating the environmental footprint of a structural and functional retrofit operation conducted on a masonry structure, assuming that, it is located in Mediterranean area. In particular, the replacement of a typical old wooden roof is considered and three alternative structural solutions are examined: (a) reinforced concrete joists and hollow clay blocks, (b) steel joists and concrete slab and (c) reinforced concrete joists and polystyrene panels. The main objective is to analyze and compare the environmental performance of all the above options which are designed to guarantee the same structural and energy performances, allowing an extension of the lifetime of the existing structure. In the light of these considerations, the LCA (ISO:14040 2006; ISO:14044 2006; Citherlet and Defaux 2007) presented within this study aims at evaluating the environmental performance of a repair/replacement intervention that can be performed with different structural options, all of them designed to guarantee a given set of local requirements and legislation.

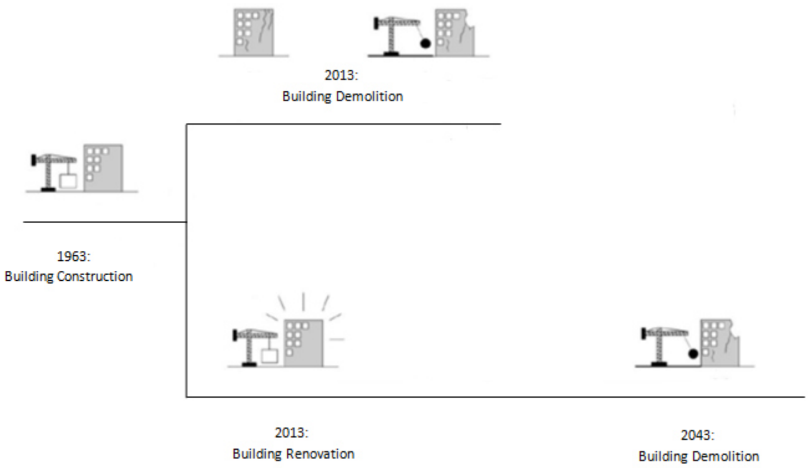


Figure 5. 2: Conceptual design to extend the building lifetime

5.2 *Goal and scope definition*

The environmental impact of the structural and functional retrofit of the case study is assessed in this work by means of a Life Cycle Assessment (LCA) methodology.

As a case study, the replacement of an old wooden roof is considered, belonging to a typical existing masonry building, assuming that it is located in Mediterranean area. The main hypothesis for the comparative study (involving different structural options) is that the roof design is made in order to achieve the same structural performance, in terms of load bearing capacity, and the same thermal properties, in terms of thermal transmission values. In particular, when a repair/replacement intervention is designed for a given building, some requirements have to be met according to national codes and guidelines. In the presented cases, structural requirements regard the live loads that the new roof structure has to withstand, whereas thermal requirements regard the maximum of thermal transmittance requested for repair interventions according to the in force regional legislation (Dlgs311/06 2006).

Considering these two “design constraints”, the flooring configurations of each option differ in terms of thickness values and materials of the flooring components which allow to achieve the above mentioned requirements.

The net flooring area is equal to 25,00 m^2 (5x5 m) and the thickness of the external walls is equal to 40 cm. The assumed live loads are equal to 1.00 kN/m^2 and a life time of 60 years for the flooring systems are considered. The LCA analysis has been conducted for each of the investigated options, including the following phases: the demolition of the existing wooden floor, the construction, the use and the maintenance of the new floor and its demolition/end of life after 60 years of life time (Figure 5. 3).

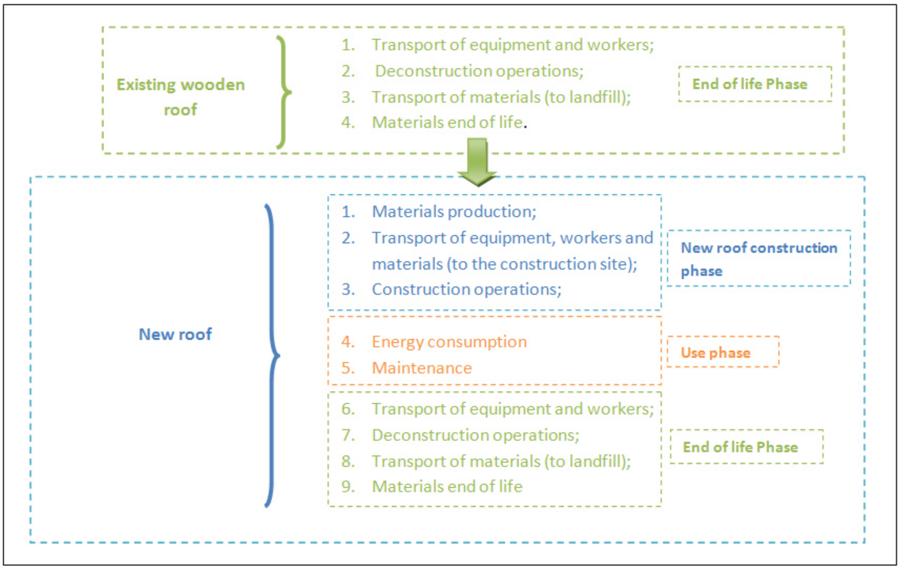


Figure 5. 3: Boundary system

5.2.1 Flooring alternatives: features

Three alternative structural solutions are investigated: (a) reinforced concrete joists and hollow clay blocks, (b) steel joists and concrete slab and (c) reinforced concrete joists and polystyrene panels.

The existing wooden floor (Figure 5. 4) consists of 4 main wood beams with a diameter of 20 cm and a wood slab of 3 cm of thickness, supporting a concrete slab of 10 cm of thickness with a coating of waterproof asphalt. The inner surface is covered with a paperboard ceiling.

The concrete joists width and the clay brick width (solution a or RC clay brick floor-Figure 5. 5) are 10 cm and 40 cm, respectively.

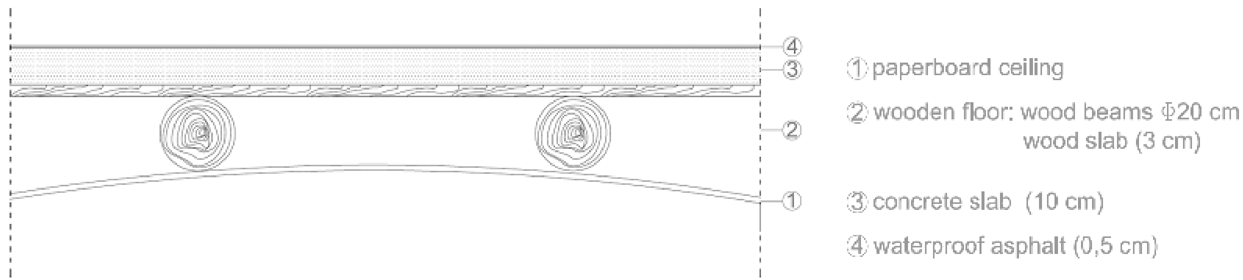


Figure 5. 4: Existing wooden floor – Cross Section

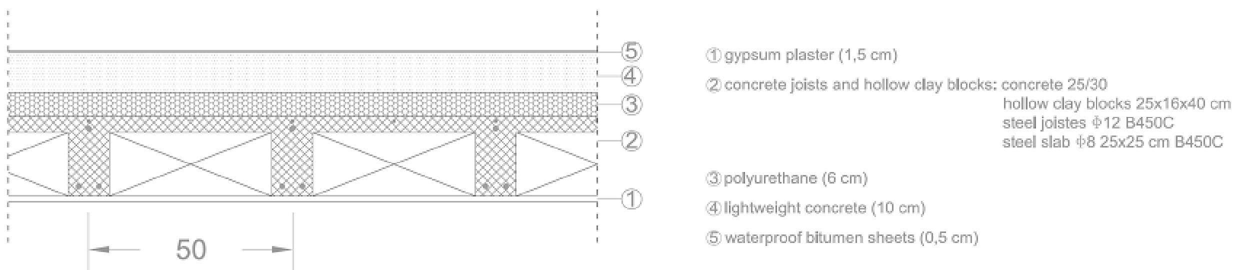


Figure 5. 5: Concrete joists and hollow clay blocks – Cross Section

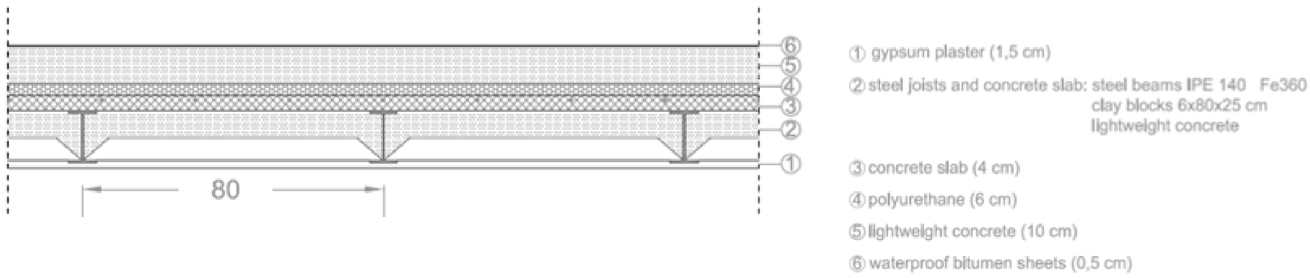


Figure 5. 6: Steel joists and concrete slab – Cross Section

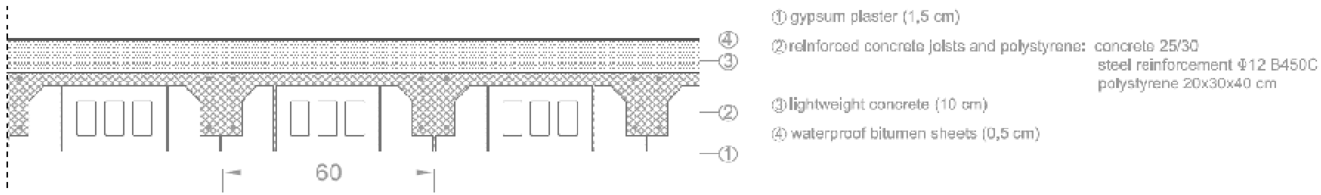


Figure 5. 7: Reinforced concrete joists and polystyrene panels- Cross section

The total floor thickness is 38 cm, made by: 16 cm of joist height, 4 cm of concrete slab, 6 cm of insulating polyurethane, 10 cm of lightweight concrete made of expanded clay and 0.5 cm of waterproof bitumen sheets; a layer 1.5 cm thick of plaster is applied at the inner surface.

In the steel floor (solution b or Steel floor- Figure 5. 6) the total height is 33 cm; it consists of steel beams (IPE 140) placed at 80 cm of span and clay blocks (6 cm high) placed on the bottom flanges of the steel beams. Lightweight concrete is used to fill the space between the steel beams and clay blocks. A reinforced concrete slab of 4 cm is casted on the steel beams. A 3 cm thick polyurethane layer and a 10 cm thick lightweight concrete are placed above. The upper surface is completed with a 0.5 cm thick layer of waterproof bitumen sheets; a 1.5 cm thick layer of plaster is applied at the inner surface.

The last floor solution (solution c or PS floor- Figure 5. 7) is lightened with expanded polystyrene panels, providing also thermal insulation to the system. The expanded polystyrene panels are supported by integrated steel profiles at the edges. The result is a self-supporting joist and a deck forming system. The concrete joists width and the polystyrene panel width are 13 cm and 47 cm, respectively. The total floor thickness is 36 cm, made by: 4 cm of bottom flanges polystyrene panels, 16 cm of joist height, 4 cm of concrete slab, 10 cm of lightweight concrete made with expanded clay and 0.5 cm of waterproof bitumen sheets; a layer 1.5 cm thick of plaster is applied at the inner surface.

The three floor systems are supported on a perimetral reinforced concrete beam having 40 cm of width and 25 cm of height, casted on the existing masonry walls; in order to protect the slabs from external environment, 0.5 cm of waterproof bitumen sheet are used. Bituminous sheets are protected from sunlight by heat-reflecting cover.

According to Figure 5. 3, for the solutions a, b and c the following stages are considered (Figure 5. 8 and Table 5. 1):

1. *Construction phase*: this phase consists of the manufacturing and transportation of building materials, as well as the installation of structural roofs. The quantities of the materials involved in each solution are derived on the basis of the flooring design, guaranteeing the structural/functional requirements explained in the paragraph 5.2; environmental burdens of materials production, instead, is derived from available process in LCA databases (Ecoinvent ; BUWAL250 1998; IDEMAT2001 2001; ELCD 2006), while the construction operations, including equipment/machinery use, are derived from common practices reported in national codes;

building materials are assumed to be produced in existing local plants; for this reason a distance of 15 km is considered for the transportation of such materials from the supplier to the construction site. This phase includes also, the operations related to the construction of the perimetral reinforced concrete beam.

2. *Use Phase*: this stage includes the activities related to the use of house, over the 60-year life span. These activities include the total energy consumption for heating. Actually, the energy demand would depend on the thermo-physical properties of the configuration/materials employed for roof/wall structural elements. In order to simplify the calculation and effectively evaluate the environmental performance of each solution, the following assumptions have been made concerning the thermal performance:

- the thermal performance of existing walls has been considered unchanged after the construction of all roofing system;
- the thermal performance of each roofing solution has been fixed according to the regional requirements (Dlgs311/06 2006); i.e. prescribing a limit value for the thermal transmittance of 0.32 W/m^2K. This intervention represents a significant improvement in the thermal performance of the building compared to the existing situation. In the light of this assumption, the flooring configuration of each solution has been designed (in terms of thickness values of floor components) in order to achieve the fixed transmittance.
- The total thermal flow (i.e. over the entire lifetime of the building) is calculated according to the (UNI:10355 1994) by taking into account the thermal performance of both roof and the walls of the building. In particular, the thermal transmittance of the roof has been considered unchanged for all the three options (as previously explained), whereas for the walls the thermal transmittance has been computed considering tuff walls of 40 cm of width and windows made of typical wooden frames. It is assumed that the heating system is provided by means of a typical gas boiler, commonly used in the area of the investigated case study. Given these assumptions, the total energy request resulted equal to 486000 MJ and it has been calculated considering the whole building lifetime; "*Natural gas, burned in boiled modulating > 100 kW*" from Ecoinvent database (Ecoinvent) is chosen as input data.

The use phase includes also the energy and materials for refurbishment/maintenance operations. In particular, includes the replacement of the bitumen sheet for all solution investigated and the use of acrylic anti-corrosion paints The bitumen sheet is replaced every 5 years whereas acrylic varnish is applied every 6 years.

3. *End of life phase:* in this phase, the demolition of the roof and the final disposal of waste are considered. Three main group of waste materials are sent to recycling: steel products, concrete and polystyrene materials. Steel materials, after physical separation are sent to the steel factory to be recycled in steel bars. The concrete is converted into recycled aggregates and used as filling materials. The polystyrene materials is converted into recycled product; this assumption is referred to the possibility of reusing polystyrene in new elements in PS, or for lightweight aggregates.

Table 5. 1 shows the input data and the hypothesis for each life cycle phase.

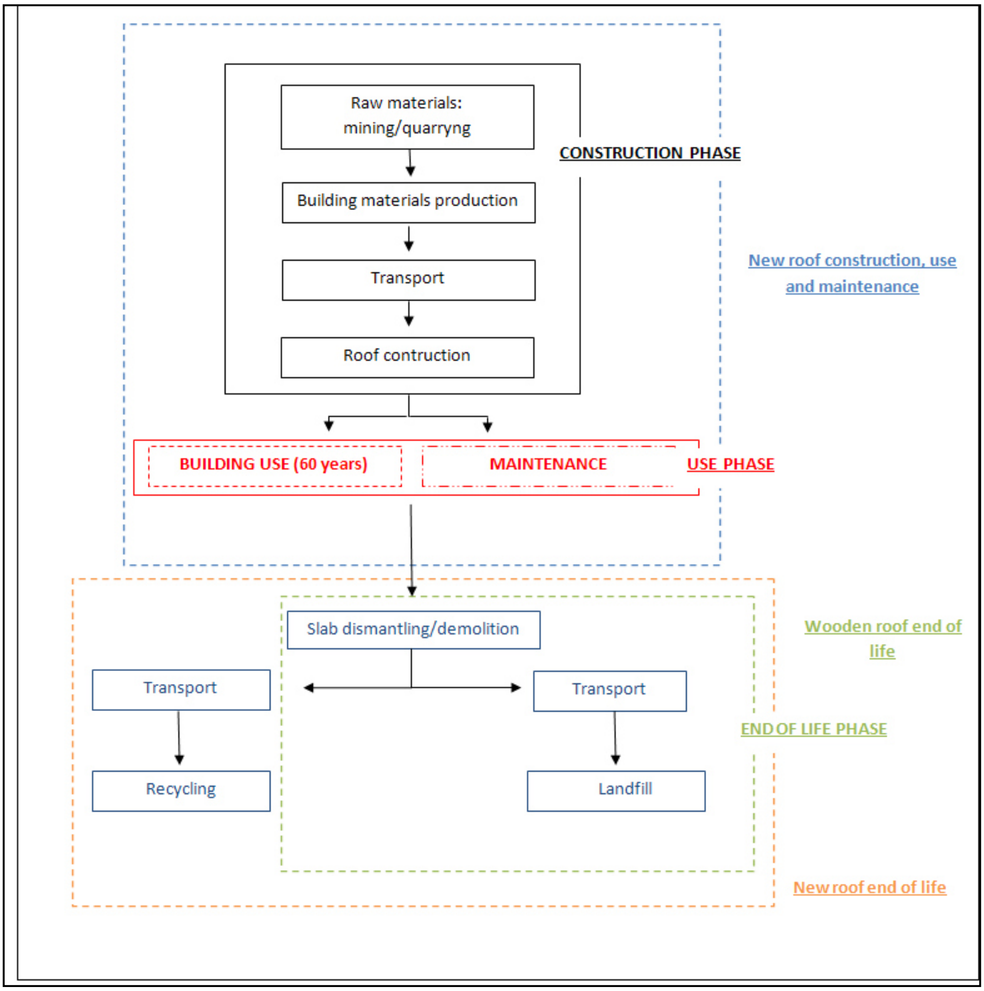


Figure 5. 8: Life cycle roof phases/boundary system I

Life cycle phase	Subsystem	Sources of data and assumptions
CONSTRUCTION PHASE	Building materials production	ECOINVENT , IDEMAT2001 and ELCD databases.
		Primary data from local supplier used for lightweight concrete.
		Quantities derived on the basis of the flooring designs
	Transport	Data for transport operations from Ecoinvent
		Average distance of the worker to the construction site is supposed to be 15 km
		Distance between material supplying site and construction site is supposed to be 10 km
	Roof construction	Data for energy use from BULWAL250
		Energy use for equipment machinery
USE PHASE	Use of electricity and fuel to heating	Italian electricity from BULWAL250
		Quantities derived on the basis of the flooring designs
	Use of energy and materials for refurbishment operations	Inventory data for refurbishment operation for bitumen sheath and steel from Ecoinvent
		Quantities derived on the basis of the flooring designs
END OF LIFE	Floor demolition/deconstruction	Demolition/deconstruction operation and quantities derived on the basis of the flooring designs
		Use of compressed-air hammer from ELCD
	Transport	Distance from construction site to landfill site is supposed to be 30 km
		Distance from construction site to worksite is supposed to be 15 km

Table 5. 1: Life cycle phases data input

5.3 *Inventory analysis*

In the present study, the secondary data are mainly based on databases available in the SimaPro 7.3 LCA software package. In particular, inventory data for concrete, cement products and other building materials, use of building equipment and transport operation, are retrieved from Ecoinvent (Ecoinvent) and (IDEMAT2001 2001; ELCD 2006). The (BUWAL250 1998) database instead, is the source for electricity and fuel consumption. Primary data in terms of avoided products, instead, are used to model the recycling scenarios.

Table 5. 2 summarizes the quantities of the main materials presented in the roofs and the data sources.

Figure 5. 9, shows, instead, the weight composition of the different flooring solutions: concrete is the main material, representing more than 60% in mass for all the options, followed by light concrete, bricks and steel. Other items are: gypsum plaster, bitumen, polystyrene and polyurethane contributing for less than 7%.

Several assumptions have been made regarding the transport phase and end of life scenario.

The transport distance between landfill and construction site is supposed to be 30 km, the materials supply site is located at 10 km from the construction site and the average distance of the workers to the construction sites is 15 km; the daily transport of the building workers is supposed to be done by car or collective transport (e.g. van), in the other cases with lorry.

The return trip is accounted for in terms of 50% of the initial one. The realization time for each roof solution is approximately to 5-7 days. Table 5. 3 shows the input data for transport operation in each life cycle phase.

The main features of the waste scenarios are the following, and are also reported in Table 5. 4:

1. 100% of the steel products is converted in recycling material, in fact, it is recovered at the worksite after demolition. The avoided impact corresponding to steel recycling is considered estimating that on 1000 kg of recycling steel, about 900 kg could replace the production of primary steel. This assumption is made on the data reported in (RICREA).
2. The concrete, brick and polystyrene materials waste are splitted between landfill and recycling scenario. It is assumed a 30-50% of waste materials that can be landfilled and a 50-70% of the waste materials that can be recycled/treated after demolition to produce aggregate on the basis of local

recycling practice (AIPE ; ANPAR ; UNI:10006 2002; UNI:10667-12 2010).

In the case of concrete, for example, *"disposal concrete, to inert landfill"* data from Ecoinvent database (Ecoinvent) is used to model the landfill scenario and primary data is used to represent the recycling scenario. In this case the avoided impact corresponding to concrete recycling is took into account assuming as "avoided product" the production of virgin inert. In this way, the emission and use resource associated with the production of natural gravel and sand are subtracted in the environmental burden of the virgin materials.

In the case of PS materials, *"Disposal, polystyrene to sanity landfill"* is used from Ecoinvent (Ecoinvent) database to model the landfill scenario and primary data to represent the recycling scenario: it is estimated that recycling PS materials could reduce about of 90% the production of virgin plastic materials.

The others materials, such as, polyurethane insulation, bitumen sheath and gypsum plaster are modeled only considering landfill scenario (Table 5. 4).

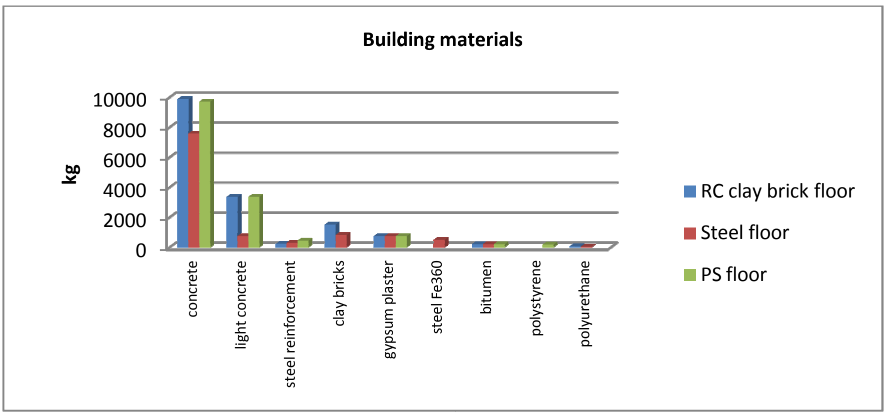


Figure 5. 9: Materials weight

Materials	Floor subsystem	RC clay brick floor [kg]	Steel floor [kg]	PS floor [kg]	Data	Source
concrete	basament	9888	7584	9708	Concrete, normal, at plant/CH U	Ecoinvent
light concrete	light screed	3364	750	3364	Ligthweight concrete, vermiculite expanded	Primary data
steel reinforcement	reinforcing steel bars	232	311	445	Reinforcing steel, at plant/RER U	Ecoinvent
clay bricks	hollow brick	1520	832		Light clay brick, at plant/DE U	Ecoinvent
gypsum plaster	plaster	750	750	750	Gypsum plaster (CaSO4 beta hemihydrates) DE S	ELCD
steel Fe360	IPE 140 beam		506		Fe360 I	IDEMAT2001
bitumen	sheath	210	210	210	Bitumen sealing V60, at plant/RER U	Ecoinvent
polystyrene	polystyrene panel			194	Polystyrene, extruded (XPS), at plant/RER U	Ecoinvent
polyurethane	insulating material	81	41		Polyurethane, rigid foam, at plant/RER U	Ecoinvent

Table 5. 2: Materials amount and data sources

LIFE CYCLE PHASE	DESCRIPTION	EQUIPMENT	DISTANCE [km]*
CONSTRUCTION PHASE	Transport slab materials	lorry 16 t	10
	Transport mobile equipment (e.g.cement mixer)	lorry 28 t	10
	Transport workers	van < 3,5 t	15
MAINTENANCE PHASE	Transport refurbishment materials	van < 3,5 t	10
	Transport workers	van < 3,5 t	15
END OF LIFE PHASE	Transport of waste to landifill	lorry 7,5-16 t	30
	Transport of steel/concrete to factorty	lorry 3,5-7,5 t	15
	Transport workers	van < 3,5 t	15
* to/from construction site			

Table 5. 3: Transport operations data input

Materials	Data	Recycling	Landfill	Percentage
Steel	Primary data	yes	no	100%
Concrete	Disposal concrete, to inert landfill	no	yes	[30-50]%
	Primary data	yes	no	[70-50]%
Polystyrene	Disposal, polystyrene to sanity landfill	no	yes	[30-50]%
	Primary data	yes	no	[70-50]%
Polyutherane	Disposal polyutherane,0.2% water, to inert material landfill	no	yes	[100]%
Bitumen	Disposal bitumen 1.4% water, to inert material landfill	no	yes	[100]%
Gypsum	Disposal gypsum, 19.4% water, to inert material landfill	no	yes	[100]%

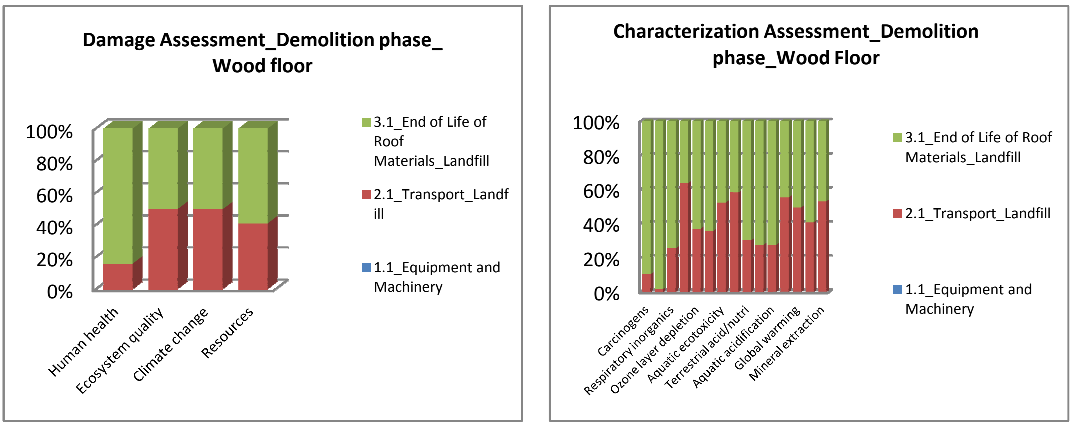
Table 5. 4: Waste data input

5.4 *Impact Assessment*

Impact2002+ (Jolliet, Margni et al. 2003) methodology is adopted to calculate and to quantify the environmental impact of the three flooring solutions (Figure 2.4).

The results are discussed in terms of damage assessment (End point) and in terms of characterization assessment (Mid point).

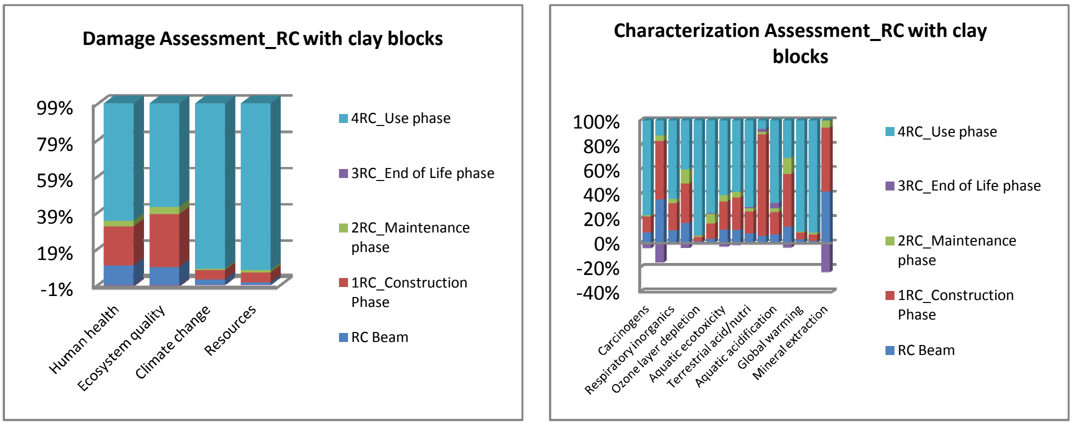
With the regard to the existing wooden floor, the Figure 5. 10 reports the results of LCA analysis where, as expected, the major environmental impact is related to the disposal of waste materials. In fact, it is considered the selective demolition of the wooden floor and it is assumed that all materials are dumped in authorized landfill; it should be pointed out that the landfill scenario for all wooden materials is related to the scarce potential re-use of such material due to the possible damage/deterioration during its service life.



(a) **(b)**

Figure 5. 10: LCA results_Wooden floor (a) end-point categories; (b) mid-point categories

With the regard to the roof replacement solutions, it clearly appears that (Figure 5. 11, Figure 5. 12 and Figure 5. 13), the use phase has the highest environmental impact, ranging between 50-90% of the total burden; the construction phase, indeed, considered as production, manufacturing and transportation of building materials, accounted for 6% to 35% of total impact.



(a) **(b)**

Figure 5. 11: LCA results_Concrete Roof (a) end-point categories; (b) mid-point categories

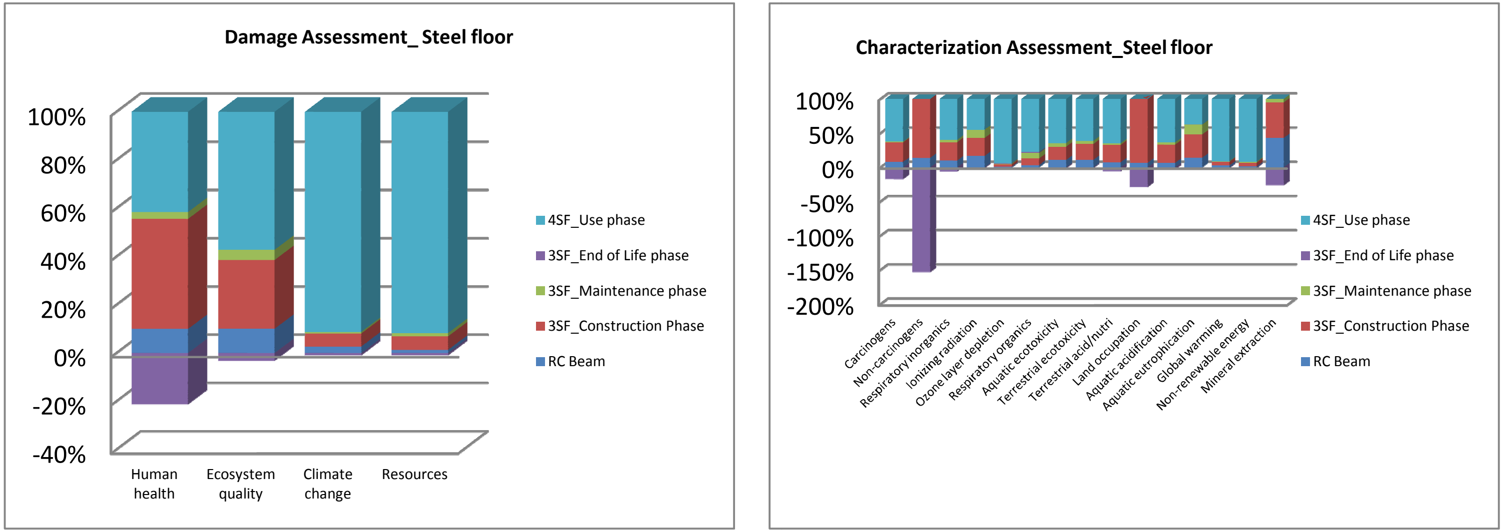
In fact, as already specified in the system boundary definition, it is underlined that the use phase refers to the whole building, whereas the other life cycle phases only refers to the roof system.

These percentages are due, in particular, to materials production phase. In the RC clay brick solution the light clay brick material presents the highest impact, in the steel solution, the major impact is due to the ferrous materials and finally in the polystyrene solutions to the polystyrene materials. These results are shown also in Figure 5. 16, in particular with regard to the Human Health and Ecosystem quality categories, where the construction phase has the major environmental impact.

With regard to the end of life phases, for all the systems, a negative contribution is due to the environmental benefits due related to recycling scenario of building materials (Figure 5. 11, Figure 5. 12 and Figure 5. 13).

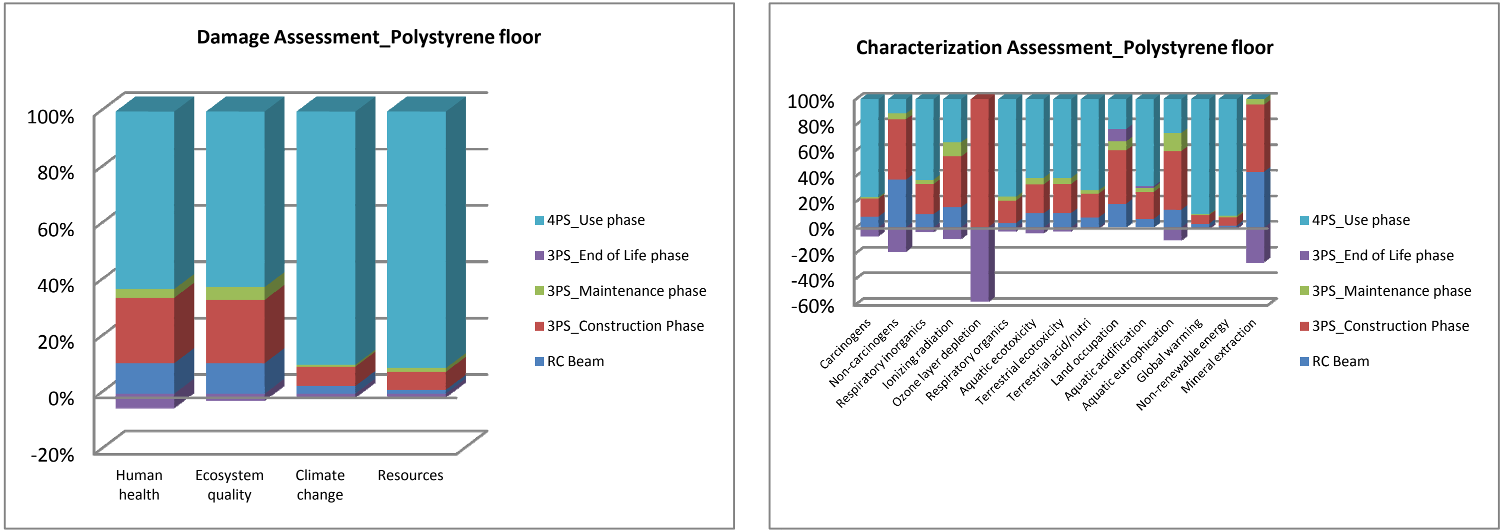
Steel floor solution, in particular, presents the highest recycling potential. In the characterization assessment it is evident (Figure 5. 12) that the environmental credits range between -1 and -153%. The value -153% comes from the non-carcinogens impact category and it is related to the reduction of dioxins emissions in the air.

In the other solutions, instead, the environmental credits range between -2 -24% and -1 -58% for concrete and polystyrene solution, respectively.



(a) **(b)**

Figure 5. 12: LCA results_ Steel Roof (a) end-point categories; (b) mid-point categories



(a) **(b)**

Figure 5. 13: LCA results_ Polystyrene Roof (a) end-point categories; (b) mid-point categories

In the PS floor solution, instead, the benefit is due to the recovery of polystyrene materials. The recycling of polystyrene, in fact, involves a reduction of CO_2 and ethane in atmosphere, and as a consequence, involves environmental benefits in ozone layer depletion impact category (Figure 5. 13).

The second objective of this study is to compare all the above options to determine which is the most environmental friendly. In this specific case, the system boundary includes only the construction, maintenance and end of life phase, while the use phase and the construction of perimeter reinforced concrete beam are excluded from analysis because they represent common activities to all the alternatives, contributing with the same environmental impact (Figure 5. 14). The results are discussed in terms of damage (Mid point), characterization (End Point) assessment and in terms of normalization values.

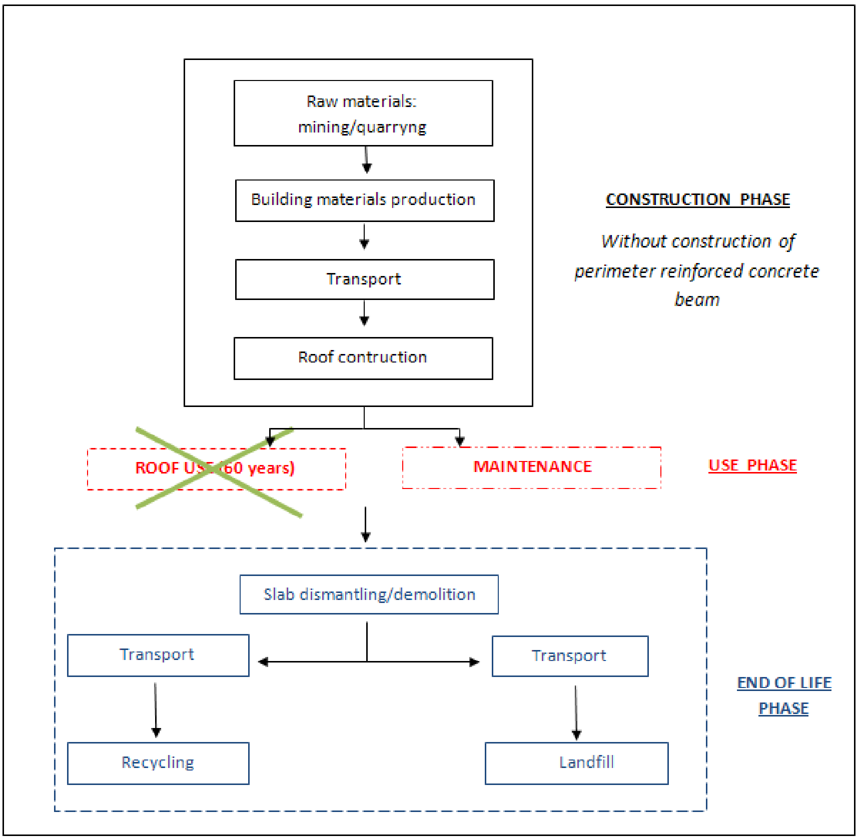
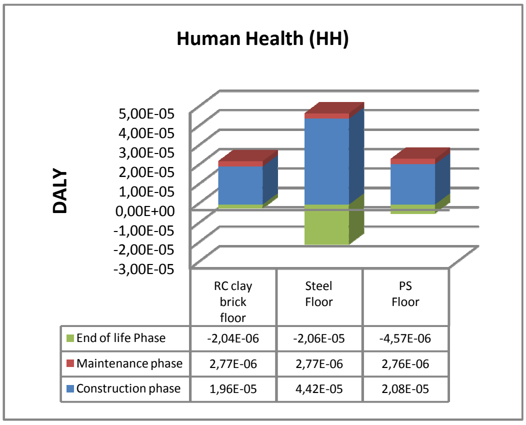
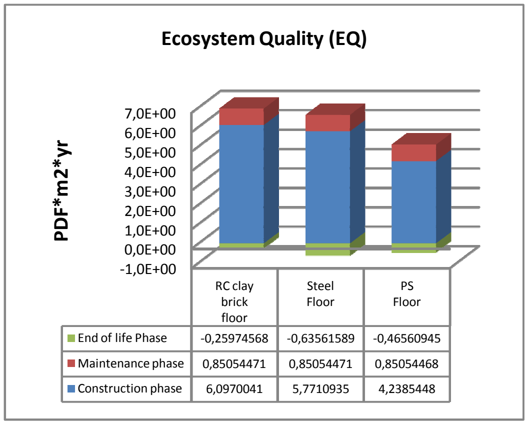


Figure 5. 14: Boundary system II

As it can be seen in Figure 5. 15, the construction phase in all the damage categories presents the largest impact; in order to evaluate which material influences the environmental results of this phase, the contribution analysis (ISO:14044 2006) is conducted and the results are reported in Figure 5. 16.



(a)



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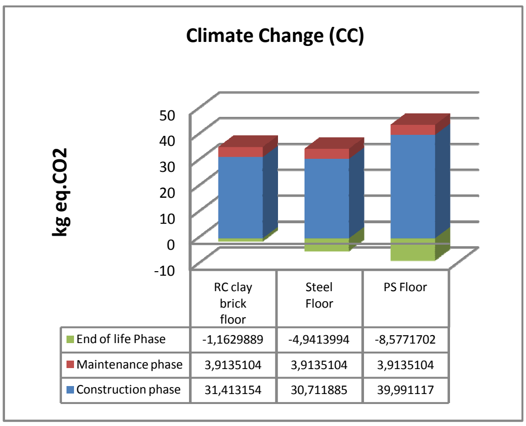
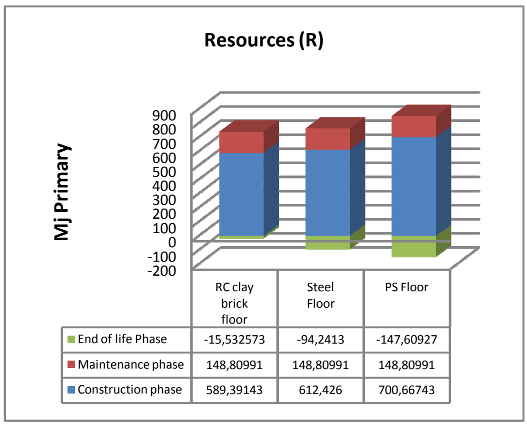


(c)



(d)

Figure 5. 15: Damage Assessment comparison_ roof solutions. (a) HH; (b)EQ; (c) CC; (d) R

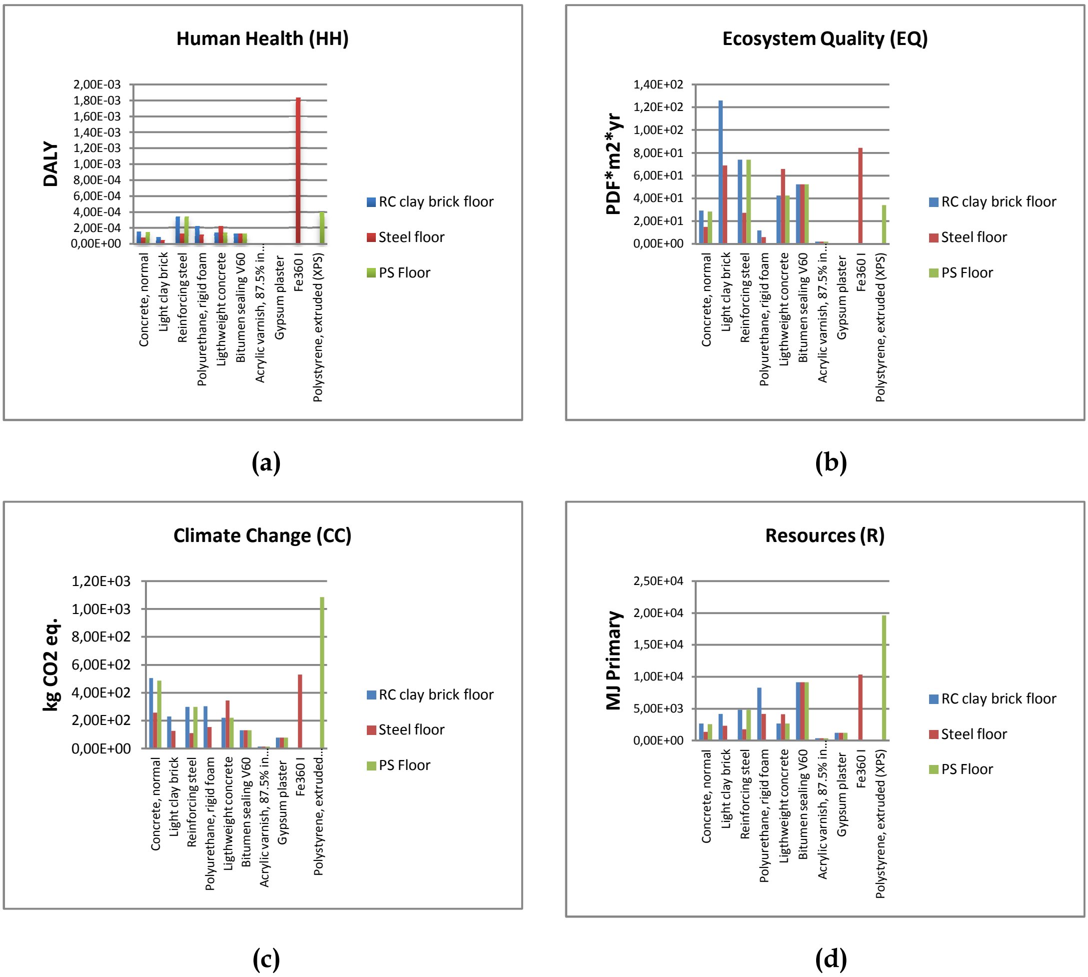


Figure 5. 16: Damage Assessment_ Materials; (a) HH; (b) EQ; (c) CC; (d) R

5.4.1 RC clay brick solution

The RC clay brick solution presents the highest impact in the Ecosystem quality category, caused by aluminum emissions in the soil and occupation of arable land. These emissions are related to light clay production (Figure 5. 16). The nitrogen oxide, particulates in the air and CO_2 emissions linked to concrete and steel materials production, are responsible of the damage in the Human health and Climate Change categories.

Although, in the Resources category the construction phase presents a lower impact than the two alternatives solutions, this system shows the highest impact in this damage category; this is due to the end of life phase that, compared to the steel and polystyrene slabs, does not imply environmental benefits.

5.4.2 Steel floor solution

The steel floor solution shows the highest impact in the Human Health damage category, mainly caused by dioxin and nitrogen oxide emissions in the air produced by refining and melting process of steel metal (Fe 360 I in Figure 5. 16). In this category when the end of life phase is considered, the recycling of steel involves a reduction of dioxin emissions; it can be observed that 2,37E-05 DALY of dioxins are emitted in the air from construction phase, while 1,65E-05 DALY are avoided in the end of life phase when steel materials is recycled. In the Ecosystem quality and Resources categories, the major contribution is due to the use of ferrous materials; the principal substances emitted into the environment are the nitrogen oxides, zinc and coal in ground respectively. In the Climate change category, the principal emission is the carbon dioxide that comes from concrete and steel materials production.

5.4.3 PS floor solution

The last option presents the highest impact in the Climate change category. It is related to the use of polystyrene materials. It clearly appears that, even if the amount of this materials is small (Figure 5. 9), the use of polystyrene has the highest negative effect for the Climate Change and Resources categories, as shown in the Figure 5. 16.

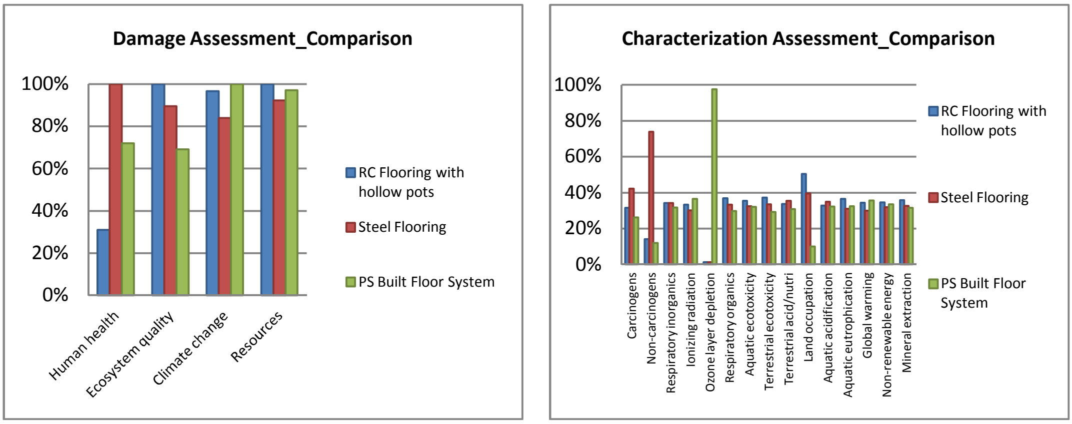
It is mainly due to the production process that includes the melting of polystyrene pearls in the extruder, the discharge through a slot die, the cooling with water and the production with different blowing agents.

In particular, the ethane emissions, are responsible of the major environmental impact in the Climate Change category. In this category when the end of life phase is also considered, the recycling of polystyrene involves a reduction of CO_2 emissions; it is estimated a reduction of 17% of CO_2 compared to the construction phase.

In the resources category, the recycling of polystyrene involves the highest environmental benefits (-147 MJ Primary); for this reason, because the environmental impact of the construction phase is balanced by the avoided impact of the end of life phase, the environmental profile of polystyrene solution is lower than concrete and steel roof solutions.

The nitrogen oxides, aluminum emissions in the air, and oil crude linked to concrete and polystyrene materials production are responsible of impact in Human health and

Ecosystem quality damage categories, respectively.



(a) **(b)**

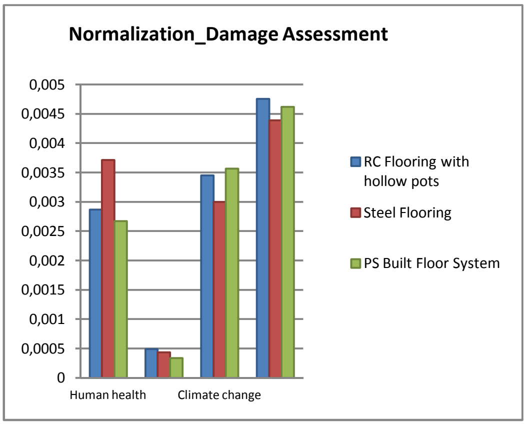
Figure 5. 17: LCA comparison alternative floors (a) end-point categories; (b) mid-point categories

The Figure 5. 17 and Figure 5. 18 summarize the previous results: the three alternatives, in fact, are compared in terms of percentage and normalized values respectively. In these figures the net environmental gain is not reported, but the difference between avoided impact due to the end of life phase and the impact caused by other life cycle steps is considered.

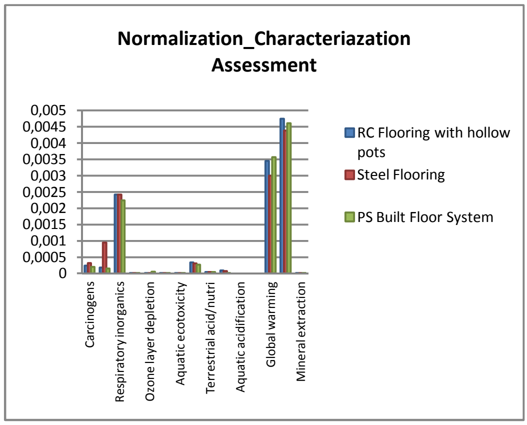
Results in Figure 5. 17a prove that the steel flooring presents the largest environmental burden in the Human health category, the concrete roof, in the Ecosystem quality and Resources categories and, finally, the polystyrene solution in the Climate Change category.

In order to better understand the magnitude and therefore the relative environmental importance of each indicator results, normalization assessment is conducted. The normalization values are calculated dividing the impact per unit of emission by the total impact of all substances of the specific category, per person, per year, for Europe. The normalization unit is expressed in terms of "impact potential per person per year" for each individual impact category .

In the Figure 5. 18 it appears that the investigated roofing options have significance in terms of carcinogens, non-carcinogens and respiratory inorganics, contributing to the Human health damage category and non renewable energy and global warming, contributing to the Resources and Climate Change damage categories respectively, while have a low impact on the Ecosystem quality damage category.



(a)



(b)

Figure 5. 18: Normalization Assessment_ LCA comparison alternative floors (a) end-point categories; (b) mid-point categories

5.5 *Global Warming Potential (GWP)*

Figure 5. 18 shows, also, that the three solutions present similar environmental impact in Climate Change category: the value range between 0,003-0,00035 and, as described in the section 5.4.3, the PS floor solution presents the highest impact in this category, followed by RC clay brick and steel solutions.

When Impact2002+ (Jolliet, Margni et al. 2003) methodology is used, the Global Warming Potential is evaluated over a period of 500 years; in order to consider other specific time interval, for example, 20 and 100 years, Global-warming potential (GWP) methodology is used.

This methodology evaluates the relative measure of how much heat a greenhouse gas traps in the atmosphere and compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide. In this specific case, the GWP of the three solutions are re-calculated and the comparison is done in all time interval, 20, 100 and 500.

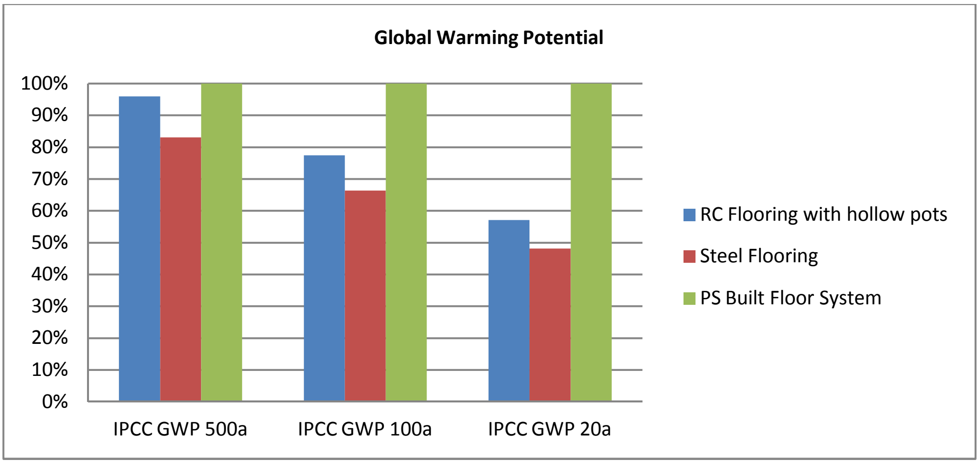


Figure 5. 19: LCA results_ GWP

As can be seen in Figure 5. 19, in all cases, the PS solution presents the major environmental burner, this is due to ethane emissions in the air. The amount of the ethane emissions, according to the LCI phase, are reported in Table 5. 5 for each floor solution, while according to LCIA phase, are reported in Table 5. 6.

Emission	RC clay brick floor	Steel floor	PS floor
Ethane (mg)	0,00726	0,000645	7,19

Table 5. 5: LCI ethane emissions

Roof system	GWP 20y	GWP 100y	GWP 500y
RC clay brick floor	0,0278	0,0104	0,00316
Steel floor	0,0247	0,00923	0,00281
PS floor	27,5	10,3	3,13

Table 5. 6: LCIA ethane emissions in kg eq.CO_2

In the first one they are expressed in mg of ethane, while in the second one they are expressed in kg eq. CO_2; the last values, in particular, are obtained multiply the LCI results to characterization factor. These factor, according to the Intergovernmental Panel on Climate Change (IPCC), depend on the time interval considered and assume the maximum value when 20 years are considered.

For this reason, it is obvious that PS solution presents the highest impact when GWP 20 years is analyzed.

Finally, when the CO_2 emissions are considered, the followed consideration can be done:

1. these unchanged with the time interval, this is due to characterization factor that is always the same;
2. the CO_2 does not affect the GWP, all the system solutions emitted in the environment the same amount. They range between 25-29 kg.

5.6 *Conclusion*

The environmental impact of different options for the replacement a typical old wooden roof is evaluated. In particular, three alternative solutions have been examined: reinforced concrete joist and hollow clay blocks, steel joists and concrete slab and reinforced concrete joists and polystyrene panels; all of them were designed to achieve certain structural and functional requirements. The first objective of this research has been to evaluate the relative environmental impact, in a life cycle perspective, of each alternatives. With the regard to the existing wooden floor demolition, the results of LCA analysis reported that the major environmental impact, as expected, is related to the disposal of waste materials.

In the other solutions, the use phase has the highest environmental impact, ranging between 50-90% of the total burden; the construction phase, instead, considered as production, manufacturing and transportation of building materials, accounted for 6% to 35% of total impact.

When the retrofit solutions comparison is done, the results show that the steel floor solution is the major responsible for the environmental impact in the Human Health damage category, due to carcinogen agents related to refining and melting process of steel metal; the RC clay brick solution presents the highest impact in the Ecosystem quality, and Resources categories caused by emissions provoking terrestrial ecotoxiticity related to light clay production. The PS floor option presents, finally, the highest impact in the Climate change category due to the ethane emissions.

As a final point, author want to emphasize that is not straightforward to indicate the best environmental performance among the proposed structural options considering all the damage categories; the results in fact, reveal that, any of them presents the best impact in terms of LCA performance.

However the scope of the work is to illustrate a comprehensive LCA-based approach that could be effectively used to drive the design of structural and functional retrofit operations on existing buildings. The final objective of this contribution is to show how a rigorous environmental analysis can influence decision-making in the definition of the most sustainable design alternatives.

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6 Chapter VI

APPLICATIONS TO BUILDINGS: A COMPARATIVE LCA-BASED STUDY ON STRUCTURAL RETROFIT OPTIONS FOR MASONRY BUILDINGS

6.1 *Introduction*

As described in the chapter V, in Europe, existing buildings represent a large amount of the total built as well as an important part of cultural heritage in terms of historical, architectural and artistic value. As a consequence building renovation, has gained increasingly attention in the construction industry as well as in scientific field. In fact, several researches have focused on the assessment of the existing building, analyzing, consequently, different type of building renovation strategies. Particularly, these studies, have focused on the mechanical, functional and energy performance of retrofitted/renovated existing structures, while few works address the environmental impact of such interventions (e.g. (Cohen, Goldman et al. 1991; Flourentzou and Roulet 2002; Sonetti 2011)). Given these considerations, the purpose of this chapter is to evaluate the different environmental impact of structural retrofit techniques applied to masonry structures. In particular, four different structural solutions are examined from the environmental point of view by means of a Life Cycle Assessment approach (ISO:14040 2006; ISO:14044 2006): local replacement of damaged masonry, mortar injection, steel chain installation and application of grid reinforced mortar.

In each retrofit solution, the functional units are referred to a suitable quantity: 1 m^2 of masonry wall in the case of local replacement damaged masonry and grid reinforced mortar, 1 m of crack in the case of injection of mortar and 1 m of steel chain in the case of steel chain installation. In this way, the LCA results are normalized and expressed as *"unitary environmental impacts"*. Then, in order to evaluate and compare the total environmental impact related to a retrofit intervention on an existing masonry building, through the investigated options, each environmental outcome should be referred to the exact amount (in terms of multiples of each functional unit), resulting from the structural design and guaranteeing an equivalent structural response of the retrofitted building.

6.2 *Goal and scope definition*

The aim of this study is to quantify the environmental footprint of structural retrofit solutions applied to masonry structures that usually involves technical operation on masonry walls. The mechanism of collapse occurred for example during seismic events, typically, regards the partial or total collapse of the wall (out-of-plane mechanisms) and cracks formations.

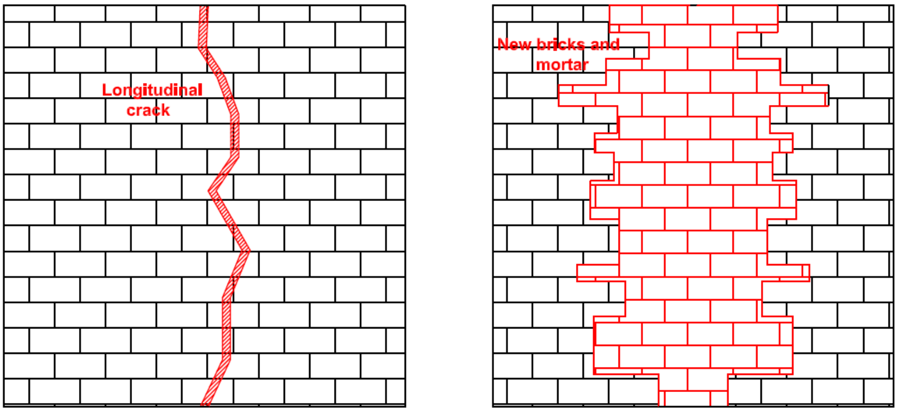
After the major earthquake, which hit L'Aquila (Italy) in 2009 and severely damaged many historic centers mainly made of masonry structures, some retrofit techniques have been employed to repair the previous mentioned types of damage; the main structural retrofits technologies investigated within this study can be summarized as follow: local replacement of damaged masonry of the walls (in the worst cases of damage), mortar injection (in cases when at least the external leaves of the walls appeared in good conditions), steel chain installation and application of grid reinforced mortar (when also the bond between the stones of the external leaves were missing).

The four retrofit techniques are presented in details as follows.

6.2.1 Local Replacement of Damaged Masonry (LRDM- Figure 6. 1)

This technique aims at restoring the wall continuity along cracking lines (substitution of damaged masonry units with new ones) and recovering heavily damaged parts of masonry walls (Figure 6. 1). The materials used are similar in terms of shape, dimensions, stiffness and strength, to those employed in the pristine wall (ReLuis 2011).

The functional unit is 1 m^2 of wall and the system boundary includes different life cycle phases: *the demolition of old wall, the construction of new wall and its demolition after 60 years of life time*, as reported in Figure 6. 2.



(a) **(b)**

Figure 6. 1: Local replacement of damaged masonry retrofit-(a):before retrofit; (b):after retrofit

		Value	Unit
Brick	Length	0.055	m
	Width	0.11	m
	Height	0.235	m
	Volume	0.001422	m^3
	Weight	2.5	Kg
	Specific weight	1730	kg/m3
Wall	Thickness	0.16	m
	Lenght	1	m
	Height	1	m
	Area	1	m^2

Table 6. 1: Brick and wall properties (UNIEN771-1 2011)

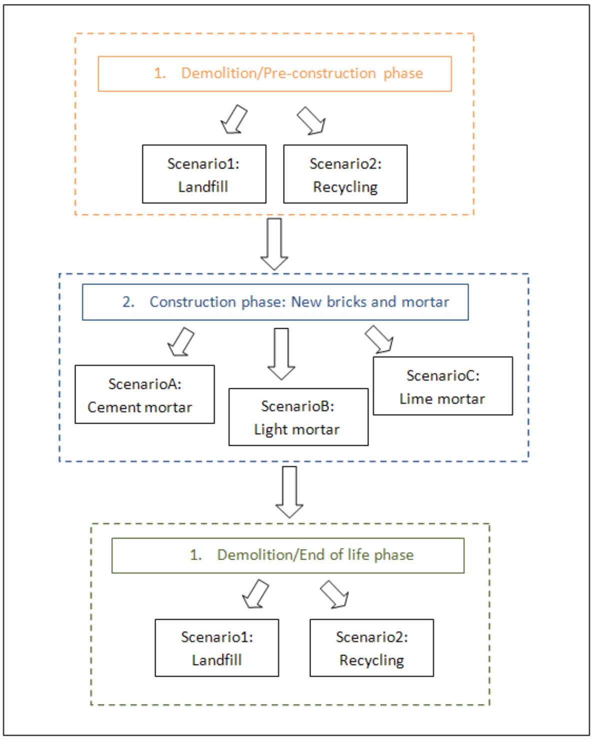


Figure 6. 2: System Boundary_ Local Replacement of Damaged Masonry

According to Figure 6. 1, in the phase 1 *"Demolition and pre-construction phase*", it is assumed that the wall demolition is made with manual operations in order to avoid further brick damage and permanently compromise the integrity and appearance of the wall. In the phase 3 *"Demolition/End of life phase"*, it is assumed that this operation is executed with electrical equipments; in this case, a demolition hammer is considered.

Assumed brick and wall properties are reported in Table 6. 1.

6.2.2 Mortar Injection (MI- Figure 6. 3)

An economical, structurally effective, and aesthetically satisfactory repair of cracks can be accomplished by the injection of fine grout into the wall cracks. By filling the cracks and the surrounding voids inside the wall, the wall strength can be restored and adjacent mortar is not damaged (Figure 6. 3).

The functional unit is 1 crack of 1 m of length, whose dimensions are reported in Table 6. 2; the system boundary includes different life cycle phases: *the preparation phase, the application phase and the wall demolition after 60 years of life time*, as reported in Figure 6. 4.

Before the injection (construction phase), all the crack and void cavity are thoroughly flushed with clean water with high pressure jet cleaner water to remove as much dirty, debris and contaminants as possible and to pre-saturate the areas that have to be grouted (preparation phase) (ReLuis 2011).

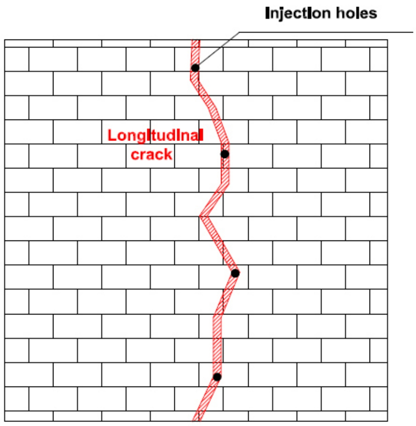


Figure 6. 3: Mortar injection retrofit

In the LRDM and MI retrofit techniques, the *"application phase"* includes different scenarios, referred to the use of different mortar binders. According to (UNIEN998-2 2004) and (UNIEN1015-19 2008) hydraulic mortars with low amount of cement material should be used for such operations. Table 6. 3 the different investigated mortar binders are reported.

Moreover, mortar materials (cement, inert), have been also mixed with water; it is assumed that this mixing operation is executed with an electric mixer.

		Value	Unit
Crack	**Length**	1	M
	Width	0.02	M
	Depth	0.16	M
	Area	0.02	m^2

Table 6. 2: Crack dimensions

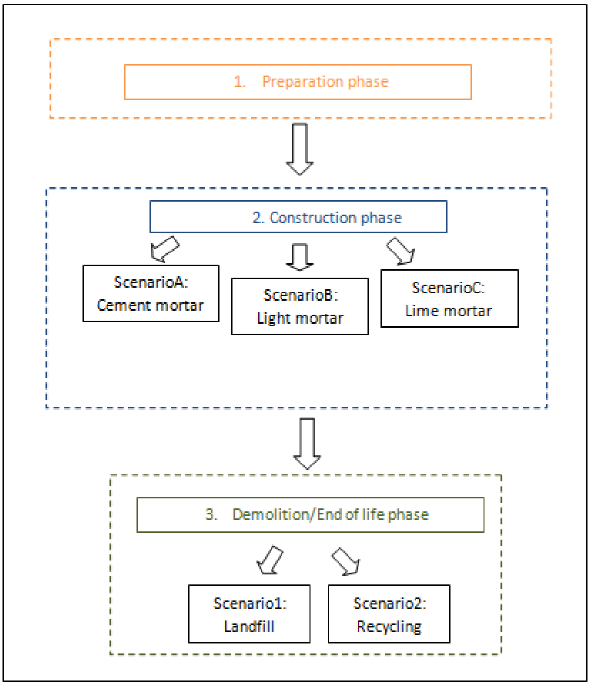


Figure 6. 4: System Boundary_ Mortar Injection

Scenario	Mortar type	Cement content (kg)
Scenario A	Cement mortar	0.2
Scenario B	Light mortar	0.34
Scenario C	Lime mortar	0.56

Table 6. 3: Mortar Binder type

6.2.3 Steel Chain Installation (SCI- Figure 6. 5)

Without a good mechanical connection between parallel walls, a steel chain based operation is usually chosen. An effective connection between walls is useful since it allows a better load redistribution and applies a restraining action towards the walls' overturning. A satisfactory connection is provided by steel chain anchored on the external face of the wall (Figure 6. 5).

The functional unit is a steel chain (Φ 24) with 1 m of length and with 2 steel plates [30x30x2 cm]; the system boundary includes different life cycle phases: *the application of steel chain and the recycling of steel chain after 60 years of life time*, as reported in Figure 6. 6.

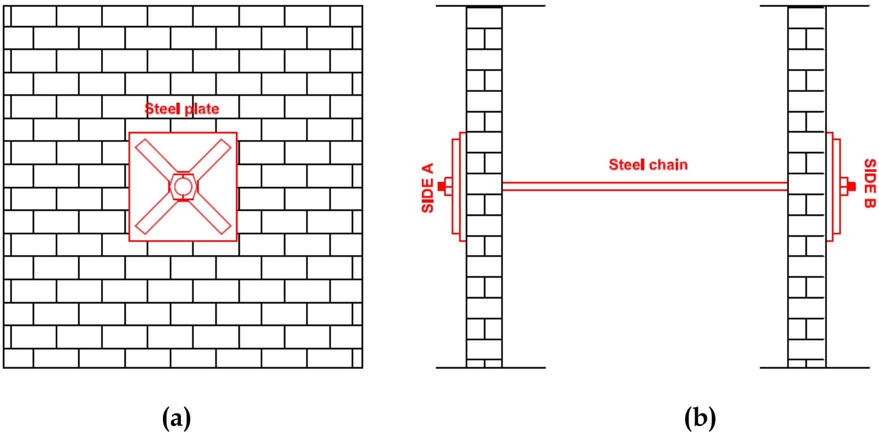


Figure 6. 5: Steel chain installation retrofit-(a):side A view; (b):plan view

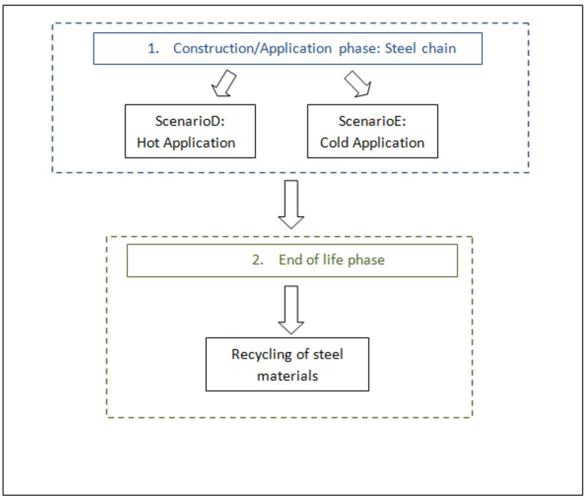


Figure 6. 6: System Boundary_ Steel chain installation

In this case, the preparation phase is not included because, before to apply the steel chain, the masonry walls is usually restored with other retrofit techniques such as LRDM and MI (ReLuis 2011).

The *application phase* includes two scenarios which are referred to the method of steel chain elongation that can be executed with cold (scenario E) or hot operation (scenario D). In details, in the Scenario D, it is assumed that the chain is heated at high temperature in the middle part with a welding gas machinery until the desired elongation is reached. Scenario E considers, instead, the use of a steel sleeve that is placed in the middle part of the steel chain (ReLuis 2011).

6.2.4 Grid Reinforced Mortar application (GRM- Figure 6. 7)

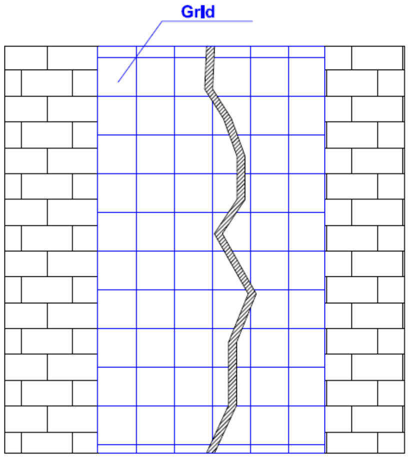


Figure 6. 7: Grid Reinforced mortar

In this technique, a layer of mortar is applied to the external surface of the wall. A reinforcing system, such as steel grid, basalt grid or glass grid, is fixed to the surface by nails or screws up to covering the entire surface. A second layer of mortar is then applied to the entire surface of the wall, covering the reinforcing system and fixing it to the structure (Figure 6. 7).

The functional unit is 1m^2 of grid reinforced mortar; the system boundary includes different life cycle phases: *preparation of the substrate, application of grid reinforced mortar, demolition of reinforced masonry wall after 60 years of lifetime*, as reported in Figure 6. 8. In the preparation phase the wall is thoroughly flushed with clean water to remove as much dirty, debris and contaminants and to pre-saturate the areas that have to be reinforced (ReLuis 2011).

The application phase is modeled considering three scenarios, referred to the use of different reinforcing systems: scenario G for glass fibers grid, scenario H for basalt fibers grid and scenario I for steel cords grid.

These investigated scenarios are designed in order to achieve the same structural performance in terms of shear strength for the retrofitted masonry wall. This condition is achieved by applying a proper number of grid reinforcement layers to obtain the same tensile strength, i.e.≈60 kN/m (Circolaren.617 2009).

In particular, for the scenario G, two reinforcement grid layers need to be applied on the wall external surface since the tensile strength of the glass grid is 30 kN/m. For the scenarios H and I only one reinforcement grid layer is applied on the wall external surface due their tensile strength of approximately 60 kN/m. In Table 6. 4, further information about these reinforcement grids are provided according to manufactures data (CavatortaS.P.A ; MapeiS.P.A.).

Material	Mesh (mm)	F [kN/m]
Steel	12,7x25,4	62.58
Glass	12,7x12,7	30
Basalt	6x6	60

Table 6. 4: Reinforcement grids performances

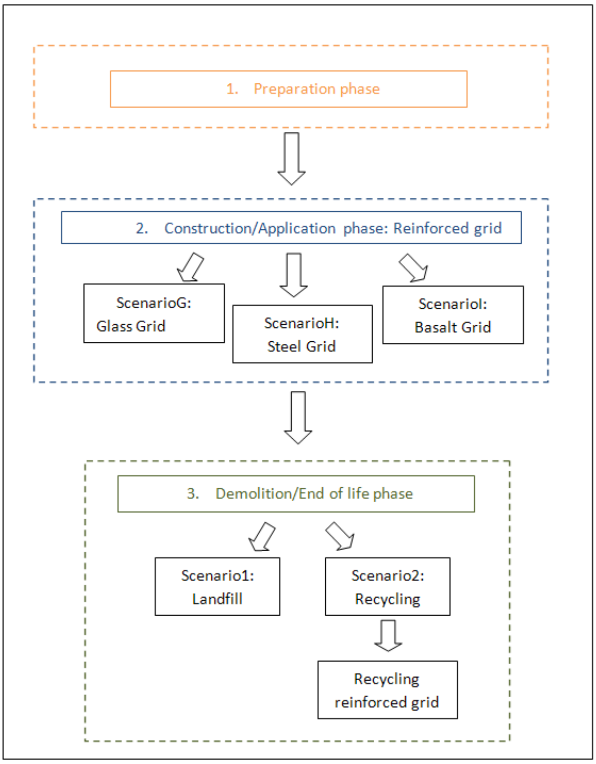


Figure 6. 8: System Boundary_ Grid Reinforced Mortar

6.2.5 End of Life phase: Hypothesis

In all retrofit techniques, the *demolition phase* is divided in two scenarios; in the scenario 1 it is assumed that all materials (100% brick and mortar) are dumped in authorized landfill; in the scenario 2, instead, it is assumed that 10% of the waste wall materials are landfilled and 90% of the waste are recycled.

In particular, brick and mortar are converted into recycling aggregates and used as filling materials, on the basis of the information reported in (ANPAR).

In the retrofit technique SCI, the End of Life Scenario includes only the total recovery of steel materials. The employed steel products, in particular, are converted into recycling material; after physical separation, in fact, they are sent to the steel factory to be recycled in secondary steel materials according to the information reported in (RICREA).

For the retrofit technique GRM, the Scenario 1 includes the grids landfilling, instead in the scenario 2 it is assumed that the grids could be re-used, as they are, in other structural engineering applications.

6.3 *Inventory analysis*

In this study, primary and secondary data are used for the inventory analysis. In particular, primary data are used to model recycling scenarios, steel materials manufacturing (e.g. chain, slab) and reinforced grids production. In order to model recycling scenarios, as mentioned in the last paragraph, the information reported in (ANPAR ; RICREA) are used whereas technical data reported in (GruppoAFVBeltrame) are used to model steel materials manufacturing. Finally, information reported in datasheets of (MapeiS.P.A.) are used to model reinforced grid production.

Secondary data, instead, are retrieved from databases available in the Simapro 7.3 LCA software package. In particular, inventory data for building materials, use of building equipment, transport operation, electricity are retrieved from Ecoinvent database (Ecoinvent).

The amount of materials involved in each retrofit solution along with the set of construction operations, including equipment/machinery use, are derived on the basis of common practice and retrofit design according to the structural/ requirements reported in national codes (CNR-DT200 2004; NTC 2008).

Following tables (Table 6. 5, Table 6. 6, Table 6. 7 and Table 6. 8) summarize the data and materials/energy amount used for each retrofit solutions; moreover, for each life cycle phase the value of “man-days” is reported; this value is calculated as product between the number of workers (n.w.) and the days (d) necessary to realize the operation.

	LRDM retrofit			
Scenario	**Materials/Process**	**Data**	**Amount**	**Unit**
	1. Demolition/pre-construction phase			
Scenario 1: 100% landfill	Landfill(Brick)	Disposal building, brick to final disposal/CH U	346	Kg
	Landfill(Mortar)	Disposal limestone residue, 5% water, to inert material landfill/CH U	67.31	Kg
Scenario 2: 10% landfill; 90% recycling	Landfill(Brick)	Disposal building, brick to final disposal/CH U	34.6	Kg
	Landfill(Mortar)	Disposal limestone residue, 5% water, to inert material landfill/CH U	6.73	Kg
	Recycling(Mortar+Brick)	Primary data	371.98	Kg
	Water	Tap water at user/RER U	10	Kg
	High pressure jet cleaner	Electricity, low voltage, at grid/IT U	0.08	kWh
	Man-days	men needed to apply demolition/pre-construction phase (n.w x d.)	0.25	Nwd
	2. Construction phase			
Scenario A	Brick	Brick at plant/RER U	346	Kg
	Mortar	Cement mortar at plant/CH U	67.31	Kg
Scenario B	Brick	Brick at plant/RER U	346	Kg
	Mortar	Light mortar at plant/RER U	67.31	Kg
Scenario C	Brick	Brick at plant/RER U	346	Kg
	Mortar	Lime mortar at plant/CH U	67.31	Kg
	Man-days	men needed to apply construction phase (n.w x d.)	0.38	Nwd
	3.Demolition/End of life phase			
Scenario 1: 100% landfill	Hammer	Electricity, low voltage, at grid/IT U	0.5	kWh
	Landfill(Brick)	Disposal building, brick to final disposal/CH U	346	Kg
	Landfill(Mortar)	Disposal limestone residue, 5% water, to inert material landfill/CH U	67.31	Kg
Scenario 2: 10% landfill and 90% recycling	Hammer	Electricity, low voltage, at grid/IT U	0.5	kWh
	Landfill(Brick)	Disposal building, brick to final disposal/CH U	34.6	Kg
	Landfill(Mortar)	Disposal limestone residue, 5% water, to inert material landfill/CH U	6.73	Kg
	Recycling(Mortar+Brick)	Primary data	371.98	Kg
	Man-days	men needed to apply demolition/end of life phase (n.w x d.)	0.13	Nwd

Table 6. 5: Local replacement of damaged masonry retrofit: data and amount referred to 1 m^2 of wall

	SCI retrofit			
Scenario	**Materials/Process**	**Data**	**Amount**	**Unit**
	1. Construction/application phase			
	Steel chain	Primary data	3.52	Kg
	Steel slab	Primary data	28.08	Kg
	Steel nails	Primary data	2	Kg
Scenario D	Blowpipe	Welding gas, steel/RER U	0.33	m
	Steel chain	Primary data	3.52	Kg
	Steel slab	Primary data	28.08	Kg
	Steel nails	Primary data	2	Kg
Scenario E	Steel sleeve	Primary data	1.025	Kg
	Man-days	men needed to apply construction/application phase (n.w x d.)	0.5	Nwd
	2. End of life			
	Drill	Electricity, low voltage, at grid/IT U	0.5	kWh
	Recycling steel	Primary data	33.6	Kg
Scenario D:	Man-days	men needed to apply end of life phase (n.w x d.)	0.25	Nwd
Scenario E	Drill	Electricity, low voltage, at grid/IT U	0.5	kWh
	Recycling steel	Primary data	34.6	Kg
	Man-days	men needed to apply demolition/end of life phase (n.w x d.)	0.25	Nwd

Table 6. 6: Steel chain installation: data and amount referred to 1 m of steel chain

Scenario	Materials/Process	Data	Amount	Unit
		MI retrofit		
		1. Preparation phase		
	Water	Tap water at user/RER U	10	Kg
	High pressure jet cleaner	Electricity, low voltage, at grid/IT U	0.08	kWh
	Man-days	men needed to apply preparation phase (n.w x d.)	0.021	Nwd
		2. Application phase		
	Water	Tap water at user/RER U	65	Kg
	High pressure jet cleaner	Electricity, low voltage, at grid/IT U	0.52	Kwh
	Drill	Electricity, low voltage, at grid/IT U	0.032	Kwh
	Compressor	Electricity, low voltage, at grid/IT U	0.04	Kwh
	Pump	Electricity, low voltage, at grid/IT U	0.79	Kwh
Scenario A	Mortar	Cement mortar at plant/CH U	37.83	Kg
Scenario B	Mortar	Light mortar at plant/RER U	37.83	Kg
Scenario C	Mortar	Lime mortar at plant/CH U	37.83	Kg
	Man-days	men needed to apply construction phase (n.w x d.)	0.08	Nwd
		3.Demolition/End of life phase		
Scenario 1: 100% Landfill	Hammer	Electricity, low voltage, at grid/IT U	0.5	kWh
	Landfill(Brick)	Disposal building, brick to final disposal/CH U	346	Kg
	Landfill(Mortar)	Disposal limestone residue, 5% water, to inert material landfill/CH U	67.31	Kg
Scenario 2: 10% Landfill and 90% recycling	Hammer	Electricity, low voltage, at grid/IT U	0.5	Kg
	Landfill(Brick)	Disposal building, brick to final disposal/CH U	34.6	Kg
	Landfill(Mortar)	Disposal limestone residue, 5% water, to inert material landfill/CH U	6.73	Kg
	Recycling(Mortar+Brick)	Primary data	371.98	
	Man-days	men needed to apply demolition/end of life phase (n.w x d.)	0.13	Nwd

Table 6. 7: Mortar injection retrofit: data and amount referred to 1 crack

Scenario	Materials/Process	Data	Amount	Unit
		GRM retrofit		
		1. Preparation phase		
	Water	Tap water at user/RER U	65	Kg
	Pressure washer	Electricity, low voltage, at grid/IT U	0.52	kWh
	Man-days	men needed to apply preparation phase (n.w x d.)	0.007	Nwd
		2. Construction/application phase		
Scenario G	Mortar	Cement mortar, at plant/RER U	15.2	Kg
	Glass grid	Primary data	0.25	Kg
Scenario H	Mortar	Cement mortar, at plant/RER U	15.2	Kg
	Steel grid	Primary data	1.88	Kg
Scenario I	Mortar	Cement mortar, at plant/RER U	15.2	Kg
	Basalt grid	Primary data	0.25	Kg
	Man-days	men needed to apply construction/application phase (n.w x d.)	0.13	Nwd
		3.Demolition/End of life phase		
Scenario 1/G: 100% landfill	Hammer	Electricity, low voltage, at grid/IT U	0.5	kWh
	Landfill Glass grid	Disposal, building,glass sheet, to final disposal/CH U	0.25	Kg
	Landfill(Brick)	Disposal building, brick to final disposal/CH U	346	Kg
	Landfill(Mortar)	Disposal limestone residue, 5% water, to inert material landfill/CH U	67.56	Kg
Scenario 1/H: 100% landfill	Hammer	Electricity, low voltage, at grid/IT U	0.5	kWh
	Landfill Steel grid	Disposal, building, reinforcement steel,to final disposal/CH U	1.88	Kg
	Landfill(Brick)	Disposal building, brick to final disposal/CH U	346	Kg
	Landfill(Mortar)	Disposal limestone residue, 5% water, to inert material landfill/CH U	67.56	Kg
Scenario 1/I: 100% landfill	Hammer	Electricity, low voltage, at grid/IT U	0.5	kWh
	Landfill Basalt grid	Disposal, building,glass sheet, to final disposal/CH U	0.25	kg
	Landfill(Brick)	Disposal building, brick to final disposal/CH U	346	Kg
	Landfill(Mortar)	Disposal limestone residue, 5% water, to inert material landfill/CH U	67.56	Kg
Scenario 2/G: 10% landfill, 90% recycling (Brick and mortar) and 100% recycling grid	Hammer	Electricity, low voltage, at grid/IT U	0.5	kWh
	Landfill(Brick)	Disposal building, brick to final disposal/CH U	34.6	Kg
	Landfill(Mortar)	Disposal, building,glass sheet, to final disposal/CH U	8.25	Kg
	Recycling(Mortar+Brick)	Primary data	385.66	Kg
	Recyclin Glass grid	Primary data	0.25	Kg
Scenario 2/H: 10% landfill, 90% recycling (Brick and mortar) and 100% recycling grid	Hammer	Disposal, building,glass sheet, to final disposal/CH U	0.5	kg
	Landfill(Brick)	Primary data	34.6	Kg
	Landfill(Mortar)	Disposal, building,glass sheet, to final disposal/CH U	8.25	Kg
	Recycling(Mortar+Brick)	Primary data	385.66	Kg
	Recyclin Steel grid	Primary data	1.88	Kg
Scenario 2/I: 10% landfill, 90% recycling (Brick and mortar) and 100% recycling grid	Hammer	Disposal, building,glass sheet, to final disposal/CH U	0.5	kg
	Landfill(Brick)	Primary data	34.6	Kg
	Landfill(Mortar)	Disposal, building,glass sheet, to final disposal/CH U	8.25	Kg
	Recycling(Mortar+Brick)	Primary data	385.66	Kg
	Recyclin Basalt grid	Primary data	0.25	Kg
	Man-days	men needed to apply demolition/end of life phase (n.w x d.)	0.25	Nwd

Table 6. 8: Grid reinforced mortar application: data and amount referred to 1 m^2 of reinforced grid mortar

Several assumptions have been made regarding the transport phase:

- the transport distance between construction site and landfill was supposed to be 20 km;
- the materials supplying site was located at 15 km from the construction site;
- the average distance of the workers to the construction site was 15 km.
- the transport of the building materials and mobile equipment from/to construction site is supposed to be done by lorry, while the transport of building workers is supposed to be done by van.
- the return trip is accounted for in terms of 50% of the initial one.

Table 6. 9 shows the input data for transport operations in each retrofit option.

LRDM retrofit					
	Vehicle	**Scenario 1**	**Scenario 2**	**Unit**	**Distance [km]**
1. Demolition/pre-construction phase (Manual operation)					
Transport workers	van < 3.5 t	2.4		tkm	15
Transport of waste to landfill	lorry 3.5-7.5 t	8.27	0.83	tkm	20
Transport of materials to factory	lorry 3.5-7.5 t		5.58	tkm	15
2. Construction phase					
Transport workers	van < 3.5 t	2.4		tkm	15
Transport mobile equipment and materials	lorry 3.5-7.5 t	6.54		tkm	15
3.Demolition/End of life phase					
Transport workers and mobile equipment	van < 3.5 t	2.84		tkm	15
Transport of waste to landfill	lorry 3.5-7.5 t	8.27	0.83	tkm	20
Transport of materials to factory	lorry 3.5-7.5 t		5.58	tkm	15
MI retrofit					
	Equipment	**Scenario 1**	**Scenario 2**	**Unit**	**Distance [km]**
1. Preparation phase					
Transport workers and mobile equipmemt	van < 3.5 t	2.74		tkm	15
2. Applicationphase					
Transport workers	van < 3.5 t	2.4		tkm	15
Transport mobile equipment and materials	lorry 3.5-7.5 t	2.76		tkm	15
3.Demolition/End of life phase					
Transport workers and mobile equipment	van < 3.5 t	2.84		tkm	15
Transport of waste to landfill	lorry 3.5-7.5 t	8.27	0.83	tkm	20
Transport of materials to factory	lorry 3.5-7.5 t		5.58	tkm	15
SCI retrofit					
	Equipment			**Unit**	**Distance [km]**
1. Construction/application phase					

Transport workers and materials_Scenario E	van < 3.5 t	2.95		tkm	15
Transport workers and materials_Scenario D	van < 3.5 t	2.94		tkm	15
2.Demolition/End of life phase					
Transport workers and mobile equipment	van < 3.5 t	2.84		tkm	15
Transport of materials to factory_Scenario E	lorry 3.5-7.5 t	0.52		tkm	15
Transport of materials to factory_Scenario D	lorry 3.5-7.5 t	0.50		tkm	15
GRM retrofit					
	Equipment	**Scenario 1**	**Scenario 2**	**Unit**	**Distance [km]**
1. Preparation phase					
Transport workers and mobile equipmemt	van < 3.5 t	2.74		tkm	15
2. Construction phase					
Transport workers and materials_Scenario G	van < 3.5 t	2.63		tkm	15
Transport workers and materials_Scenario H	van < 3.5 t	2.66		tkm	15
Transport workers and materials_Scenario I	van < 3.5 t	2.63		tkm	15
3.Demolition/End of life phase					
Transport workers and mobile equipment	van < 3.5 t	2.84		tkm	15
Transport of waste to landfill_Scenario G	lorry 3.5-7.5 t	8.58			20
Transport of waste to landfill_Scenario H	lorry 3.5-7.5 t	8.61			20
Transport of waste to landfill_Scenario I	lorry 3.5-7.5 t	8.58	0.86	tkm	20
Transport of materials to factory_Scenario G	lorry 3.5-7.5 t		5.79	tkm	15
Transport of materials to factory_Scenario H	lorry 3.5-7.5 t		5.81	tkm	15
Transport of materials to factory_Scenario I	lorry 3.5-7.5 t		5.79	tkm	15

Table 6. 9: Transport operations

6.4 *Impact Assessment*

Impact2002+ methodology (Figure 2. 4) (Jolliet et al., 2003) is adopted to calculate and to quantify the environmental impacts of the structural/functional retrofit options.

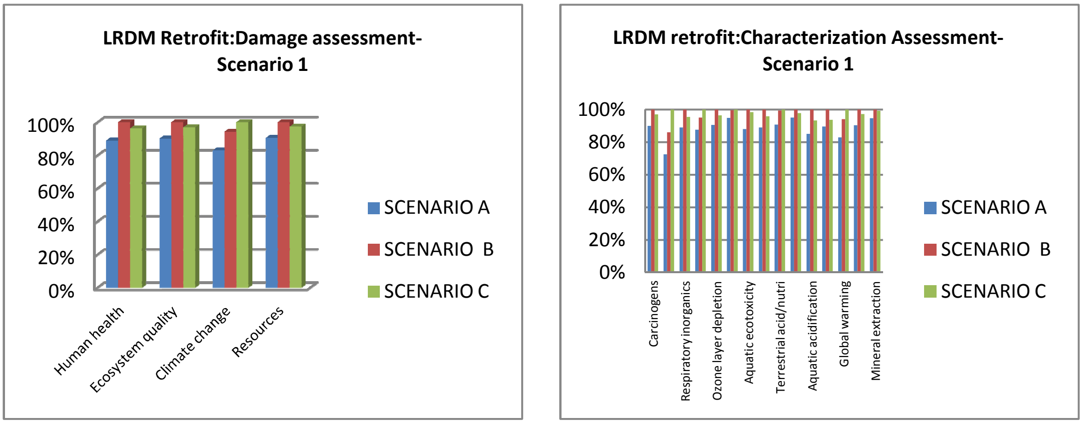
In this study, the results are discussed in terms of damage assessment (End Point) and in terms of characterization assessment (Mid Point) and for each retrofit solution.

6.4.1 LRDM retrofit

In the case of the local replacement of damaged mortar retrofit option, the three scenarios are compared. Figure 6. 9 reports the results of LCA analysis in terms of endpoint and midpoint categories, when scenario 1 is considered; it can be observed that the major environmental load is related to the Scenario B.

Since the main difference of scenarios A, B and C is mortar type used, Figure 6. 10 shows the environmental profile of all mortar materials used and the results are in agreement with Figure 6. 9.

Light mortar (scenario B) has the highest environmental burden in almost all damage categories due to the use of expanded clay materials. In fact, the main environmental emissions that influence Human health, Ecosystem Quality and Resources damage categories (nitrogen oxide, particulates, aluminum) are linked to the firing process of clay in a rotary furnace at 1200 °C.



(a) **(b)**

Figure 6. 9: LCA results_LRDM retrofit, Scenario 1(a) end-point categories; (b) mid-point categories

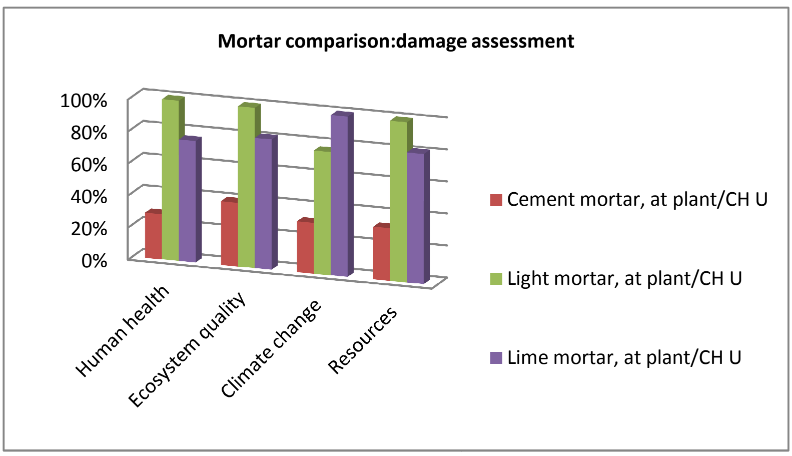
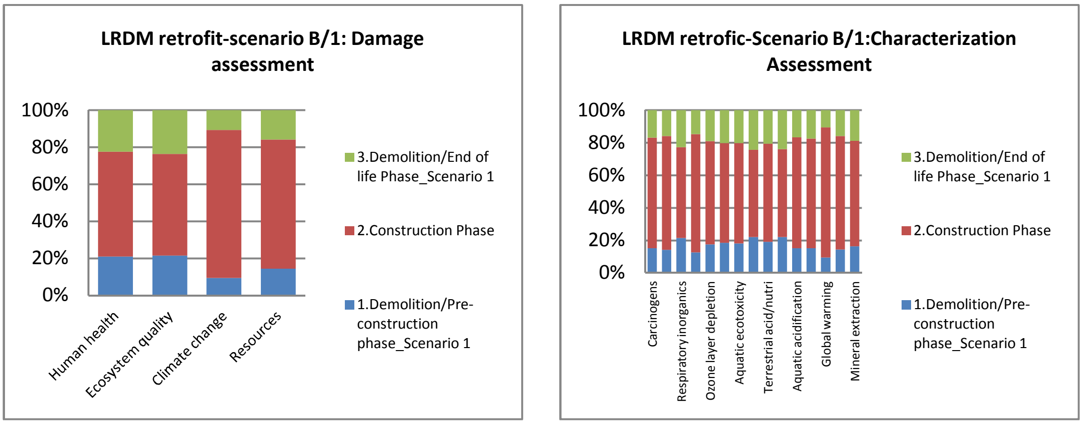


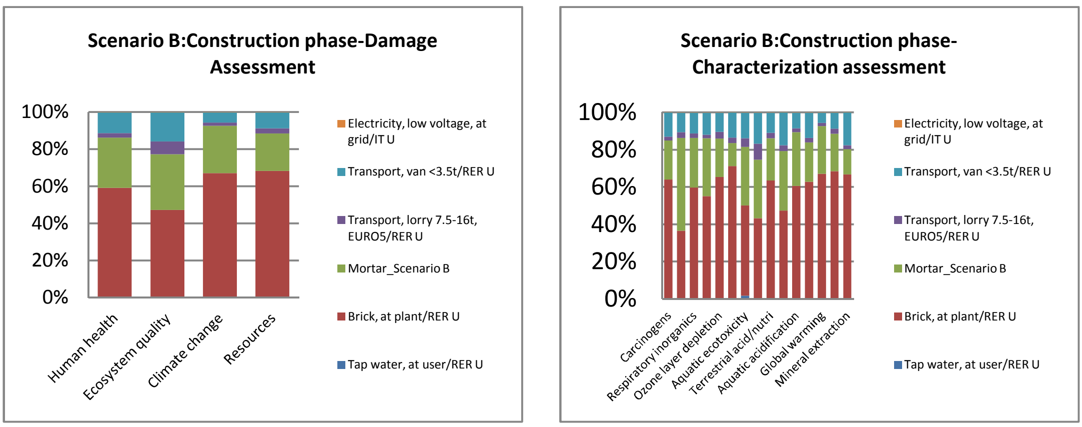
Figure 6. 10: LCA results: mortar comparison in LRDM retrofit option

Lime mortar presents, instead, the highest impact in the Climate Change category; it is related to the amount of CO_2 emissions mainly due to the decomposition of limestone and combustion of fossil fuels during cement production; in this case, the cement amount, as reported in Table 6. 3, is larger than other scenario. Since the scenario B has the highest environmental impact, the environmental burden (in terms of mid/end point categories) for each Life Cycle phases of this Scenario is analyzed and reported in Figure 6. 11.



(a) **(b)**

Figure 6. 11: LCA results, LRDM retrofit: Scenario B/1. (a) end-point categories; (b) mid-point categories



(a) **(b)**

Figure 6. 12: LCA results, LRDM retrofit: Scenario B/Construction phase. (a): end-point categories; (b) mid-point categories

It clearly appears that the construction phase is responsible for the major environmental impact, ranging between 70-80% of total impact. These percentages are due, in particular, to brick and mortar production as reported in Figure 6. 12.

These materials affect the results of the whole construction phase in percentages of 50-60% and 20-30% respectively. When brick material is analyzed, the energy consumption related to firing process, involves the major negative effect; it is estimated, in fact, that 1,24 MJ of natural gas are needed to produce 1 kg of product as reported in Ecoinvent database report (Ecoinvent).

In Figure 6. 14, the comparison between scenario 1 and 2 for end of life management of each LRDM retrofit scenario is reported.

It clearly appears that the recycling of building materials (Scenario 2), generates environmental benefits in all damage assessment categories for all options A, B and C.

In fact, with regard to the End of life phase, a negative environmental contribution in terms of avoided impact is introduced; the avoided impact, correspond to brick and mortar recycling and is taken into account assuming as "avoided product" the production of virgin aggregates. In fact, such recycled aggregates can be used primarily as filling materials while other possible uses in other engineering applications are reported in (UNI EN 13242, 2002). In this way, the emissions and use of resources associated with the production of natural gravel and sand are subtracted from the environmental burden of the construction phase.

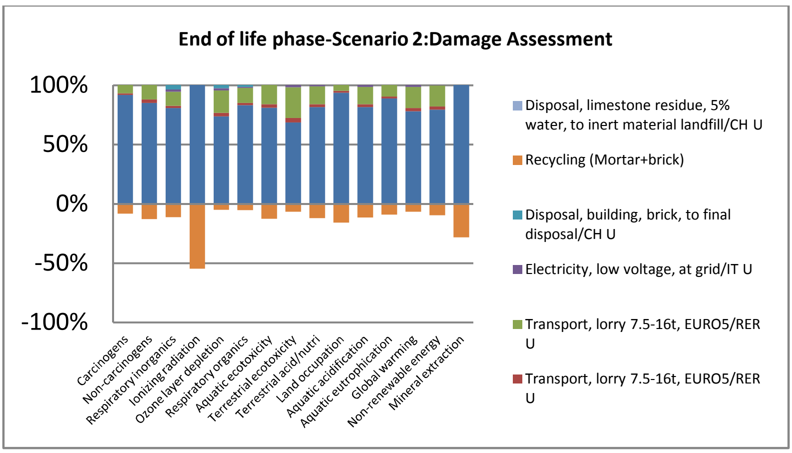
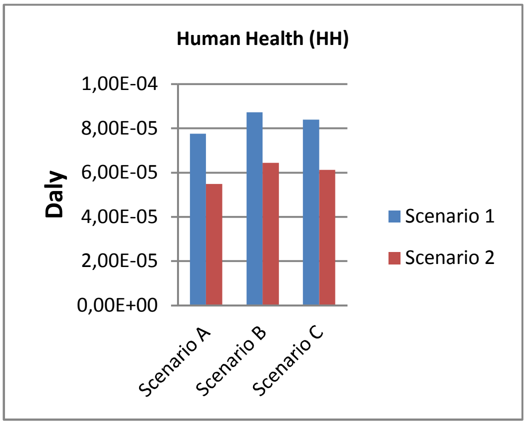


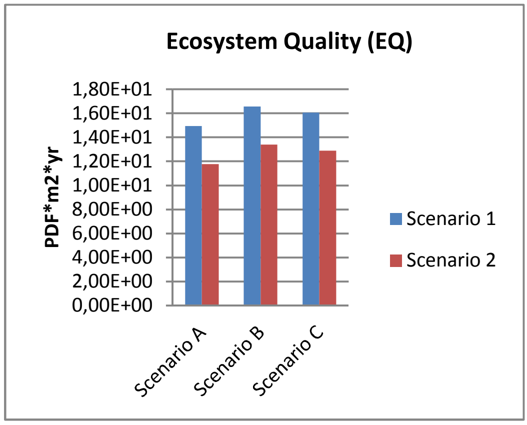
Figure 6. 13: LRDM retrofit: End of Life phase- Scenario 2

In fact, in the characterization assessment of Figure 6. 13, it appears that the environment credit ranges between -10 -60%; the values of -60% comes from the Ionizing Radiation impact category and it is related to the reduction of radon and carbon emissions in the air. In addition, Figure 6. 15 reports the LCA results of

Scenario A in terms of mid/end point categories when recycling of waste wall materials is considered (Scenario 2). As it can be seen in Figure 6. 14, in fact, Scenario A is the best environmental solution, due the use of the mortar with lower impact in the construction phases (Figure 6. 10).



(a)



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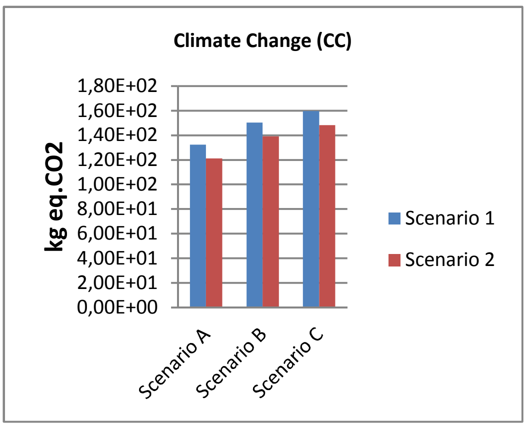
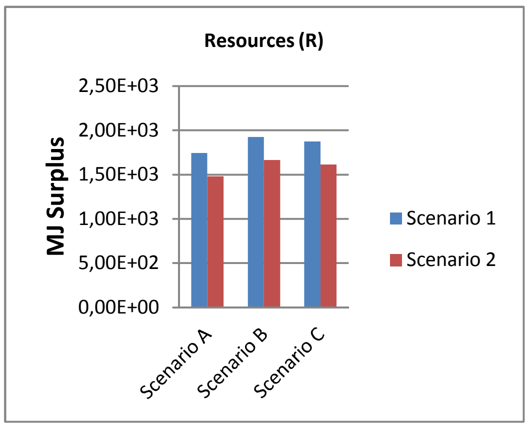
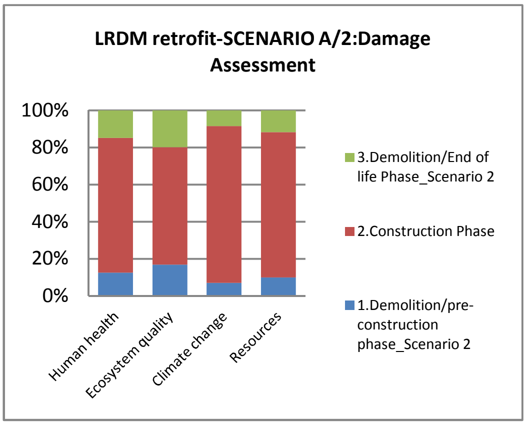


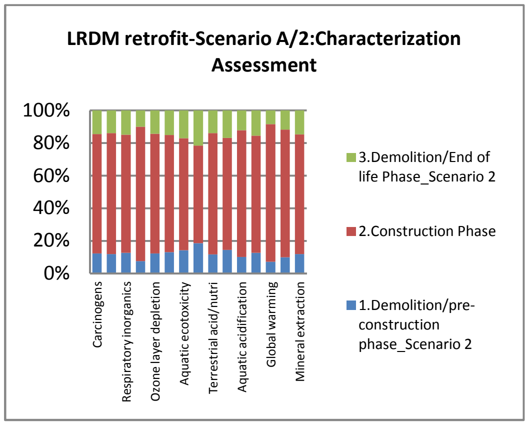
(c)



(d)

Figure 6. 14: LRDM retrofit- Comparison Scenario 1 and Scenario 2. (a) HH; (b) EQ; (c) CC; (d) R





(a) **(b)**

Figure 6. 15: LCA results, LRDM retrofit: Scenario A/ 2 (a) end-point categories; (b) mid-point categories

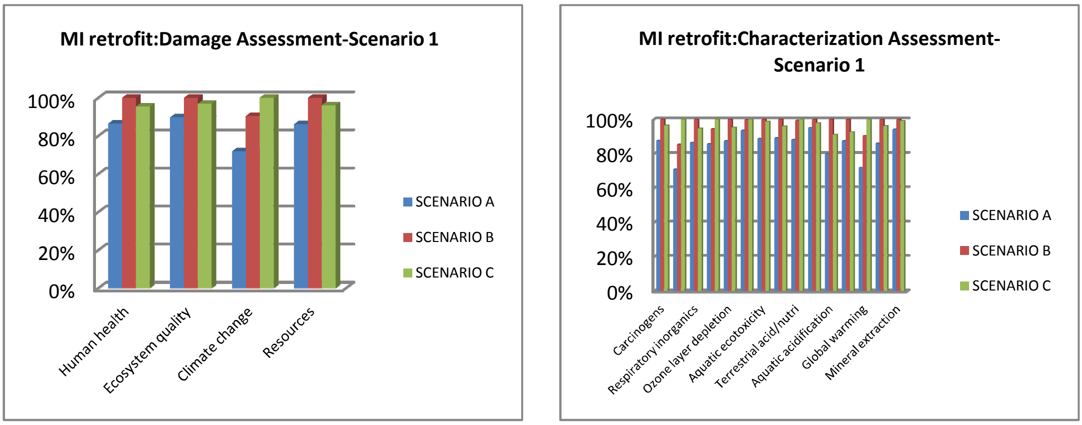
6.4.2 MI retrofit

Figure 6. 16 reports the results of LCA for mortar injection retrofit solution, when scenario 1 is considered; it can be observed that the major environmental load is related to the Scenario B due to the same explanations provided in the previous technique. For this reason, the environmental assessment of this scenario is displayed in Figure 6. 17. In Figure 6. 16 and Figure 6. 17, the environmental results are reported in terms of damage and impact categories.

The end of life phase, considering scenario 1, is responsible for the major environmental load due to the disposal of waste materials in landfill. This result is opposite to the previous case, where the construction phase determined the highest impact.

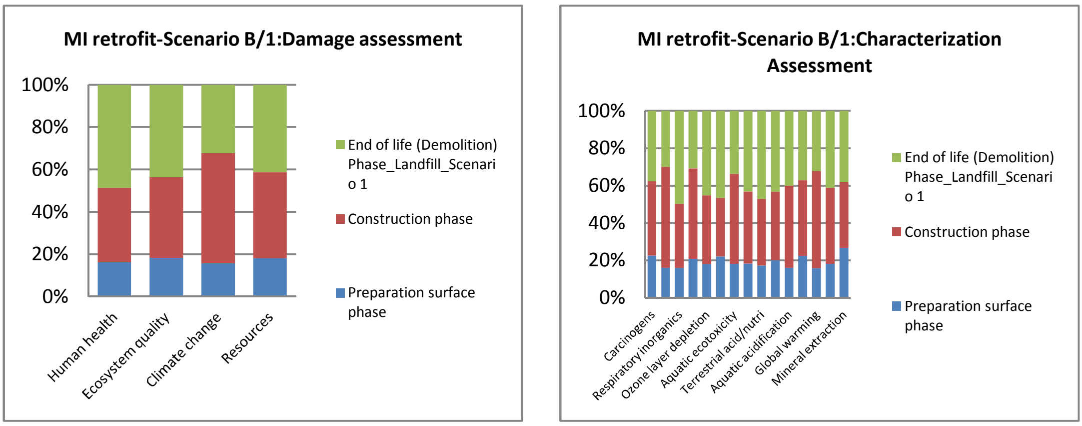
In Figure 6. 18, the comparison between scenario 1 and 2 for end of life management of each MI retrofit scenario is reported. In particular, in all end-point categories, Scenario A presents the lowest environmental burden, due to the lowest environmental impact provided by cement mortar.

In detail, the Figure 6. 19 reports the LCA of Scenario A in terms of mid/end point categories when recycling of waste wall materials are considered (Scenario 2)



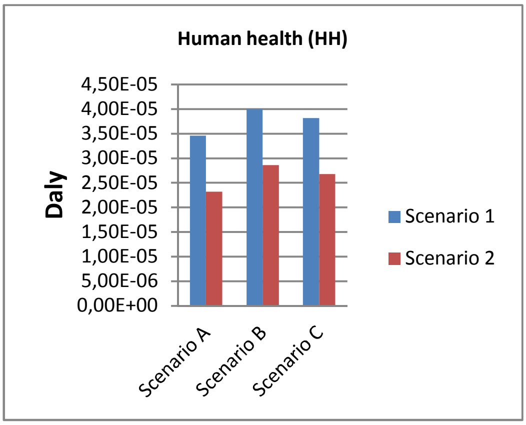
(a) **(b)**

Figure 6. 16: LCA results: MI retrofit -Scenario 1. (a) end-point categories. (b) mid-point categories

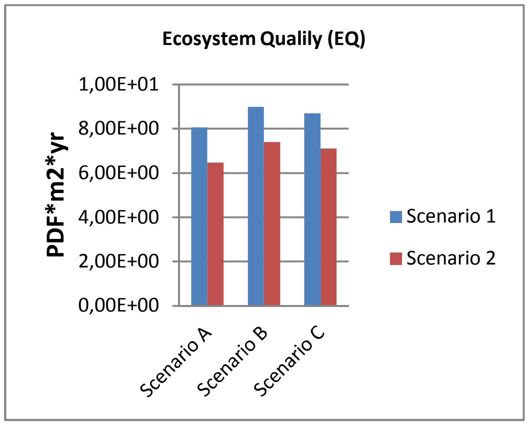


(a) **(b)**

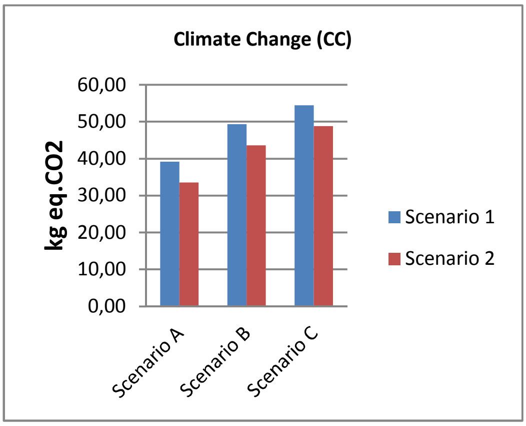
Figure 6. 17: MI retrofit :Scenario B/ 1. (a) end-point categories; (b) mid-point categories



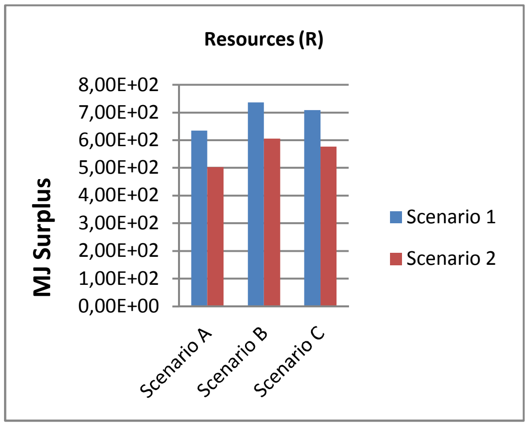
(a)



(b)

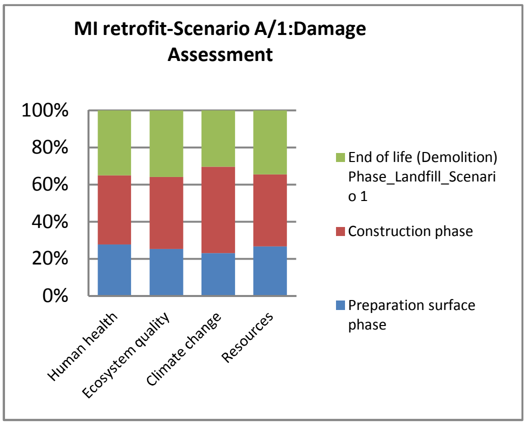


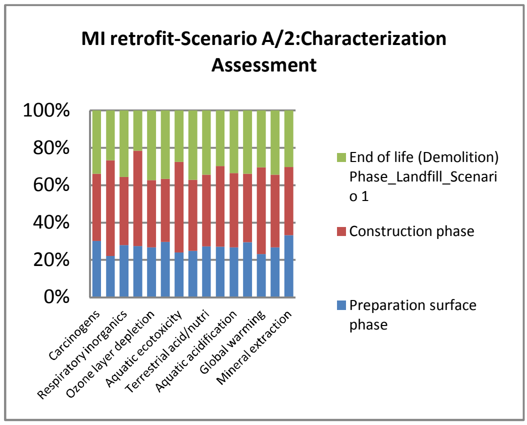
(c)



(d)

Figure 6. 18: MI retrofit-Comparison Scenario 1 and Scenario 2. (a) HH; (b) EQ; (c) CC; (d) R





(a) **(b)**

Figure 6. 19: MI retrofit: Scenario A/ 2. (a) end-point categories; (b) mid-point categories

6.4.3 SCI retrofit

Figure 6. 20 reports the results of LCA of steel chain installation retrofit option; it can be observed that the major environmental load is related to the Scenario E; the main difference of scenarios D and E is the method used for chain elongation.

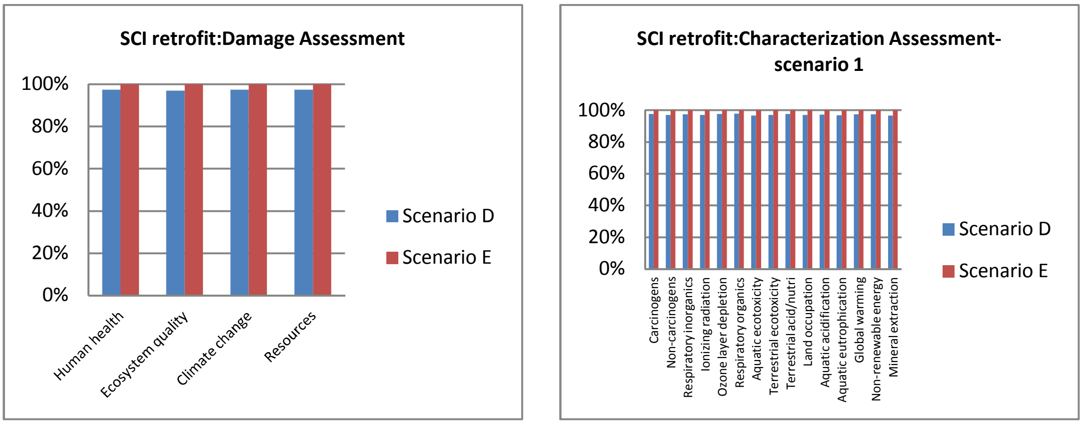
Table 6. 10 shows the environmental impact (percentage values) of each material/product for both scenarios investigated calculated using single point assessment method (ISO:14040 2006; ISO:14044 2006).

	Scenario E [%]	**Scenario D [%]**
Steel chain	13	13
Steel plate	72	74
Nails	7	7
Welding gas	/	0.07
Steel sleeve	3	/
Transport	5	6
Electricity	0.03	0.03

Table 6. 10: LCA results_SCI retrofit-Materials, Energy, Transport impact

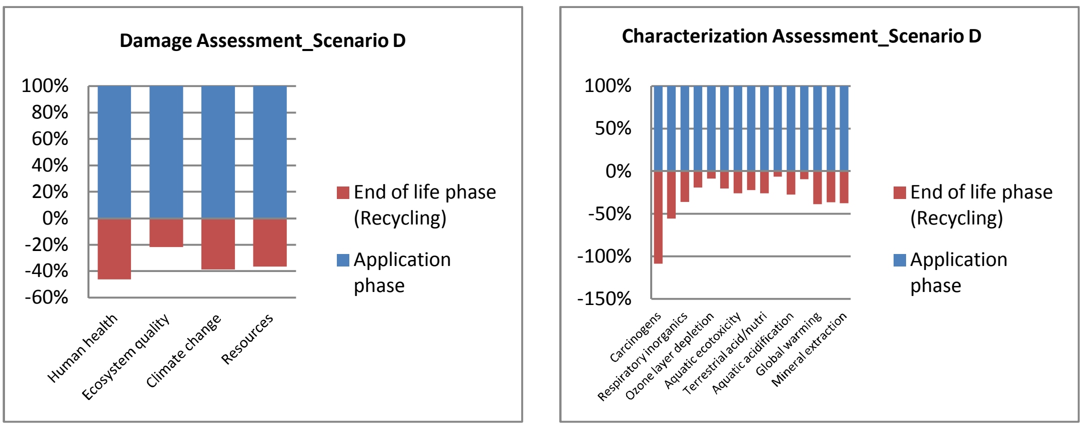
The use of a steel sleeve in scenario E influences the environmental results; its environmental impact corresponds to approximately 3% of total environmental burden if compared with the use of welding gas in the scenario D that involves an impact lower than 1%.

Figure 6. 21 the LCA profile of Scenario D is reported; it clearly appears that the recycling of steel materials, generates environmental benefits in all damage and impact categories. The recycling of steel materials, in fact, involves environmental benefits due to avoided impact of virgin materials production. The main substances not released in the environment (air, soil, water) are reported in Table 6. 10.



(a) **(b)**

Figure 6. 20: LCA results: SCI retrofit-Scenario 1. (a) end-point categories; (b) mid-point categories.



(a) **(b)**

Figure 6. 21: SCI retrofit: Scenario D. (a) end-point categories; (b) mid-point categories

END OF LIFE PHASE	Unit	Caused impact*	Avoided impact**	Total impact***	"Avoided Substance"
Carginogens	kg C2H3Cl eq	-3,64	-3,75	0,11	Hydrocarbons, aromatic
Non-carginogens	kg C2H3Cl eq	-2,66	-2,73	0,07	Dioxins
Respiratory inorganics	kg PM2.5 eq	-0,04	-0,04	0,01	Particulates, < 2.5 um
Ionizing radiation	Bq C-14 eq	-566,56	-754,07	187,52	Radon 222
Ozone layer depletion	kg CFC-11 eq	0,00	0,00	0,00	Methane Halon 1211
Respiratory inorganics	kg C2H4 eq	-0,01	-0,01	0,01	Non methane volatile
Acquatic ecotoxicity	Kg TEG water	-4083,75	-4572,58	488,84	Aluminium (air)
Terrestrial ecotoxicity	Kg TEG soil	-1045,37	-1218,24	172,88	Aluminium (air)
Terrestrial acid/nutri	kg SO2 eq	-0,41	-0,62	0,21	Nitrogen oxides
Land occupation	m2org.arable	-0,09	-0,27	0,18	Occupation forest
Aquatic acidification	kg SO2 eq	-0,13	-0,16	0,04	Sulfur dioxide
Aquatic eutrophication	kg PO4P-lim	-0,01	-0,01	0,00	Phosphate
Global warming	kg CO2 eq	-35,30	-43,72	8,43	Carbon dioxide, fossil
Non-renewable energy	MJ Primary	-554,96	-700,44	145,49	Coal, hard, unspecified, in groud
Mineral extraction	MJ Surplus	-4,87	-5,03	0,16	Nickel

*It includes the impact caused by transport, electricity

** It includes the avoided impact related to recycling steel (100%)

*** it is the algebraic sum of caused and avoided impact

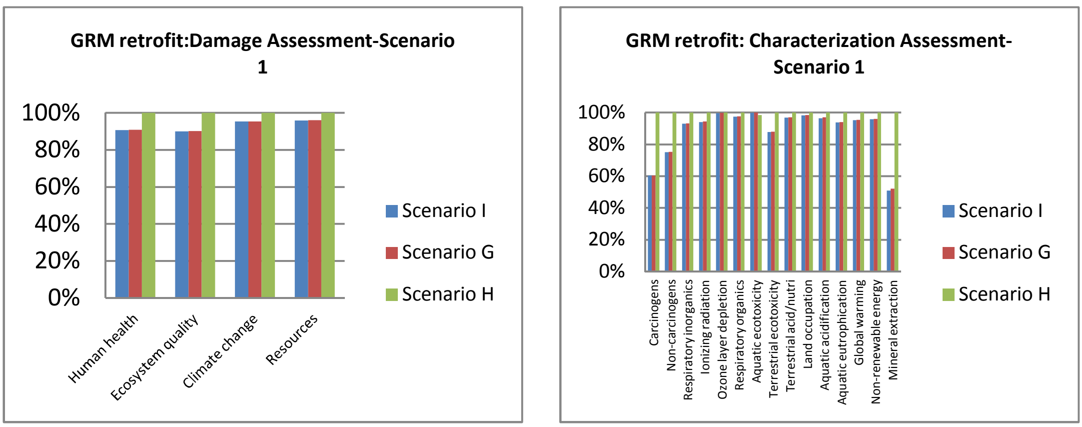
Table 6. 11: SCI retrofit: End of life phase: "Avoided substances"

6.4.4 GRM retrofit

For this retrofit technique, the three previously described scenarios are compared Figure 6. 22). According to Figure 6. 22) (reporting the comparison between each GRM solutions), when Scenario 1 is considered, the steel solution presents the highest environmental impact. In particular, all GRM solutions present the same environmental impact in terms of end of life phase (Figure 6. 23), while, the steel solution presents the highest environmental burden in terms of construction phase (Figure 6. 24).

In addition, when scenario 2 is considered, the steel grid solution presents the lowest impact as shown in the Figure 6. 25; this is mainly due to the end of life phase according to the following considerations:

- The preparation phase is the same in terms of input and output in all retrofit solutions and for this reason it does not affect the results;
- The steel solution presents the highest impact in the construction phase; it is unchanged compared to the previous case (Figure 6. 23);
- In the End of life phase the steel grid recycling, determines environmental benefits in all mid- point categories, and in particular in carcinogens, non-carcinogens, terrestrial ecotoxicity and mineral extraction mid-point indicators, Figure 6. 26.



(a) **(b)**

Figure 6. 22: LCA results: GRM retrofit -Scenario 1. (a) end-point categories; (b) mid-point categories

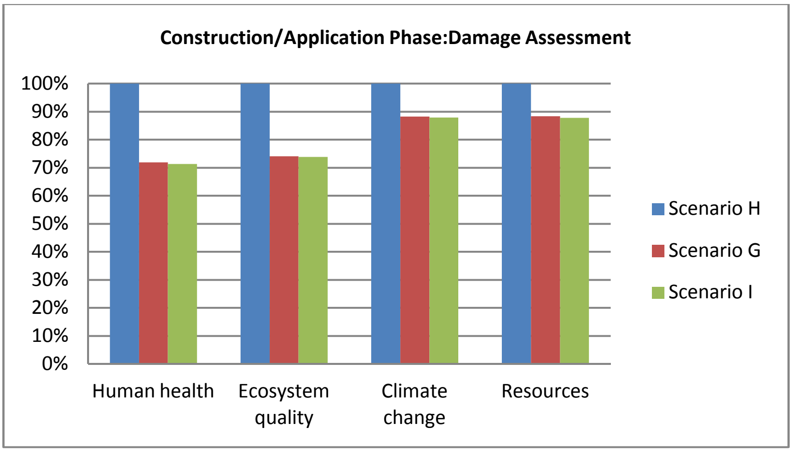


Figure 6. 23: GRM retrofit- LCA results: grid reinforced mortar retrofit -Construction phase

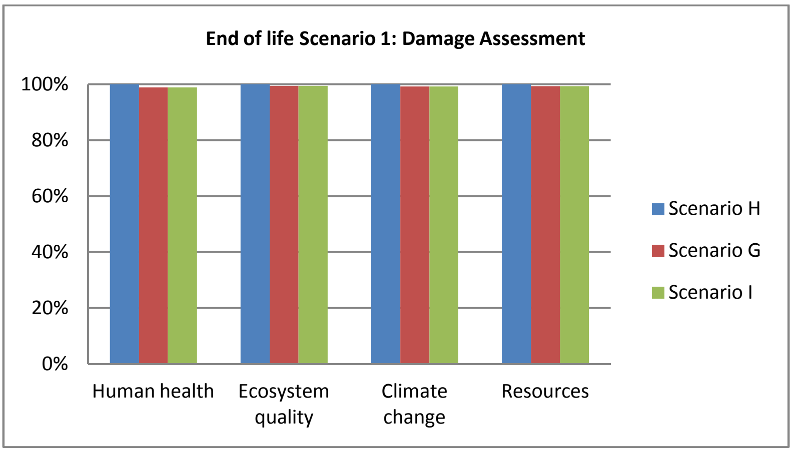
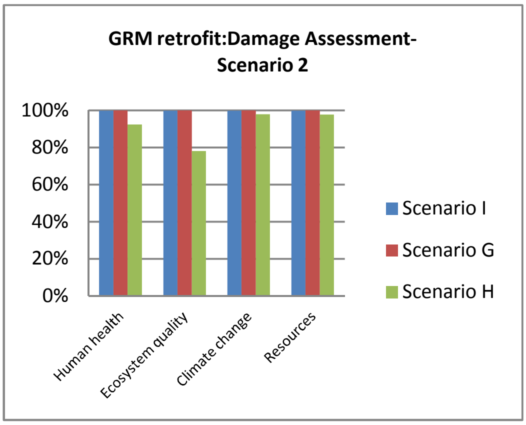
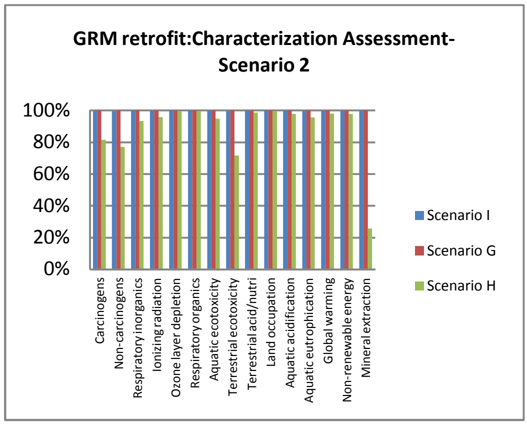


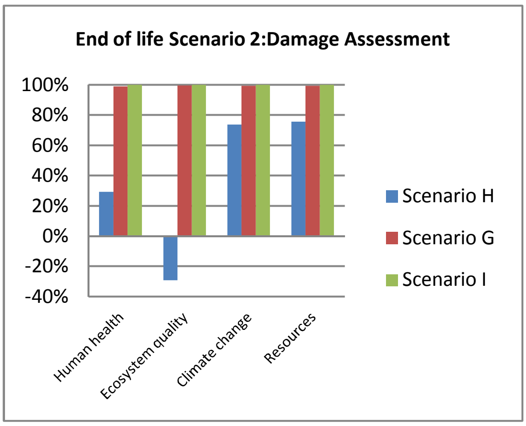
Figure 6. 24: LCA results: GRM retrofit -End of life Scenario 1

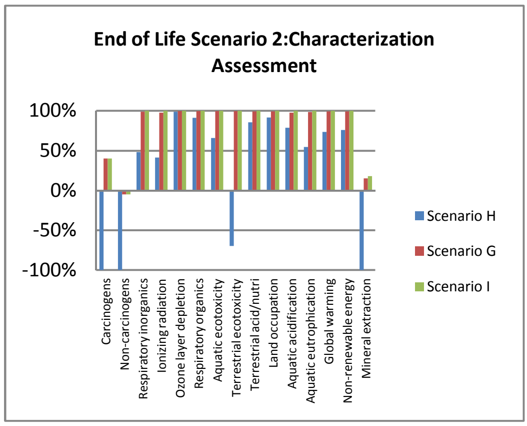




(a) **(b)**

Figure 6. 25: LCA results: GRM retrofit-Scenario 2. (a) end-point categories; (b) mid-point categories





(a) **(b)**

Figure 6. 26: GRM retrofit-End of life phase-Scenario 2. (a) end-point categories; (b) mid-point categories

6.5 *Conclusion*

In the present study, the environmental impact of different technological solutions for typical retrofit operations on masonry structures has been assessed. In particular, four different structural solutions have been examined by means of a LCA approach: Local Replacement Damaged Mortar (LRDM), Mortar Injection (MI), Steel Chain Installation (SCI) and application of Grid-Reinforced Mortar (GRM).

In all retrofit solutions, it clearly appears that the recycling of building materials generates environmental benefits in all damage and impact assessment categories. In particular, the recycling of building materials involves environmental benefits due to avoided impact of virgin materials production.

In the LRDM and MI retrofit options, the use of light mortar (construction phase) is responsible for the major environmental impact in all LCA categories.

In the SCI retrofit option, the scenarios investigated presented similar environmental profiles, with the only difference in the use of steel sleeve which has determined the highest impact, accounting for 3% of total impact.

In the GRM retrofit option, the use of the steel reinforced grid without its recycling at the end of life, produces the highest environmental impact in all LCA categories; on the contrary, when the reinforced grid is re-used in other structural engineering applications, steel GRM solution presents the lowest environmental impact .

Finally, authors want to emphasize that the retrofit options illustrated in this paper and their environmental results can be used in future research activities and in design operation to assess the performance of retrofit strategies of existing building in the light of the goals of sustainable development. This means that when a structural retrofit is needed for a masonry structure, different alternatives can be considered, with the constraint of providing the same (minimum) requested structural enhancement. The LCA-based comparative study can be then conducted considering the outcomes of this study, i.e. multiplying the normalized environmental impacts (computed according to the proper functional unit) by the amounts of materials needed for that option, to identify the solution characterized by the lowest environmental impact.

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7 Chapter VII

APPLICATIONS TO BUILDINGS:LIFE CYCLE ASSESSMENT OF DIFFERENT STRENGTHENING TECHNIQUES APPLIED TO RC COLUMNS

7.1 *Introduction*

Repair and rehabilitation of existing structures are becoming important contributors to construction activities. Some estimates have indicated that in 2010 the worldwide expenditure for maintenance and repair works represented about 85% of the total expenditure in the construction field (S.M. Mourad, M.J. Shannag, 2010). As illustrated in the previous chapters, generally, most of the rehabilitation works consist in repairing old deteriorated structures and/or structures damaged by earthquakes and natural hazards. In fact, the main factors responsible for the deterioration of Reinforced Concrete (RC) structures are: physical aging, chemical aging (e.g. corrosion), load-induced stresses greater than design stresses, inadequate durability and hazardous events (e.g. earthquake, fire); all these phenomena generally lead to a reduction of the service life of the RC structure.

The development of cost-effective and long-lasting repair/retrofit methods can greatly reduce the maintenance request, increase human safety and extend the service life of concrete structures. In addition, the decision to repair or demolish a building should be based also on the economic, social and environmental considerations, according to a sustainability outlook.

In order to avoid high costs of structural replacement and guarantee, at the same time, a given structural performance of an existing building, several strengthening techniques have been developed in the last decades. In particular, various strengthening systems, such as bonding steel or continuous fiber-reinforced composite plates, jacketing, carbon/steel/basalt/glass fabric wrapping have been employed to mainly increase the structural performance of RC structures (Bracci, Kunnath et al. 1997; Seible, Nigel Priestley et al. 1997; Bakis, Bank et al. 2002; Nanni 2003; Teng, Chen et al. 2003; Xiao and Wu 2003; Esfahani, Kianoush et al. 2007; El Maaddawy and Soudki 2008; Li, Gong et al. 2009; Yaqub and Bailey 2011).

These strengthening techniques have been used in several civil engineering applications due to: lightweight, good mechanical properties (stiffness and strength), corrosion-resistant, good fatigue behavior, easy application and virtually endless variety of shapes available.

In recent years, significant research work has been conducted on repairing, strengthening and retrofitting of existing concrete structures with Fiber Reinforced Polymers (FRP) (Seible, Nigel Priestley et al. 1997; Bakis, Bank et al. 2002; Nanni 2003; Teng, Chen et al. 2003; El Maaddawy and Soudki 2008; Yaqub and Bailey 2011). In particular, flexural and shear strengthening of beams, slabs and strengthening of columns have been investigated.

Moreover, other research activities have focused on the application of Steel jacketing strengthening technique on RC columns (Xiao and Wu 2003; Li, Gong et al. 2009). Particularly, this retrofit solution improves flexural strength, shear capacity, stiffness, ductility and axial load carrying capacity.

Many researchers have also emphasized the potential uses of ferrocement laminates for repair and rehabilitation of RC structures (Mourad and Shannag 2012).

However, besides the advantages offered by above strengthening techniques in terms of structural performance and rapid installation, also the environmental benefits of these techniques should be analyzed. Despite that, only very few studies have been conducted to study the sustainability performances of these retrofit solutions (Pimenta and Pinho 2011).

In this contest, the present study aims at investigating the environmental footprint related to the application of three retrofit techniques on RC column: carbon and steel fabric wrapping and steel jacketing. The main objective is to analyze and compare the environmental performance of all the above retrofit options, which are designed to guarantee the same structural performances, in order to identify the solution characterized by the lowest environmental impact.

7.2 *Goal and scope definition*

As case study, the environmental impact of three strengthening techniques applied to RC column is evaluated: Carbon and Steel Fabric Wrapping (CFW and SFW) and Steel Jacketing (SJ). The main hypothesis for the LCA comparative study is that the different strengthening solutions are designed in order to achieve the same structural performance in terms of shear strength of the retrofitted RC column. Particularly, the reinforced solution, applied on RC column, are designed in order to guarantee an increase of shear strength of existing column of about 30 kN. The increased shear strength has been calculated according to the national requirements ((NTC 2008; C.S.LL.PP 2009).

In addition, the LCA conducted for each of the investigated options includes the following phases (from "cradle to grave"): the extraction and processing of raw materials, manufacturing, preparation of the substrate and the installation of the reinforcement. The other life cycle phases such as use, maintenance, end of life and transportation are not included in the analysis.

The details of the strengthening techniques are described as follow:

Carbon and Steel Fabric Wrapping (CFW and SFW)

These strengthening techniques consist in adding an additional layer of composite material around the existing column in order to increase the concrete confinement.

The primary element of a reinforced fabric is the fiber. The fiber can be made of different materials, such as glass, carbon, basalt, steel. The fibers can be placed in a polymeric matrix in order to create a unidirectional sheet. The matrix is often epoxy resin, but other thermoplastic polymers, such as polyester, vinyl ester or nylon, are sometimes used. Figure 7. 1 and Figure 7. 2 show the application of steel and carbon reinforced fabric wrapping on RC columns.

(a) **(b)**

Figure 7. 1: Application of reinforced fabric wrapping on RC column; (a) application of fist layer of reinforcement; (b) application of second layer of reinforcement, (ReLuis 2011)

Figure 7. 2: CFW/SFW applied on RC column

Steel Jacketing (SJ)

SJ includes the use of longitudinal and transverse reinforcement around the existing columns, as shown in Figure 7. 3. This type of strengthening technique improves the axial and shear strength of RC columns. In particular, this is achieved by applying the transverse steel reinforcement around the section of the existing column. Longitudinal L-shaped steel ties are placed on opposite corners (over the entire length of the column) (Figure 7. 3).

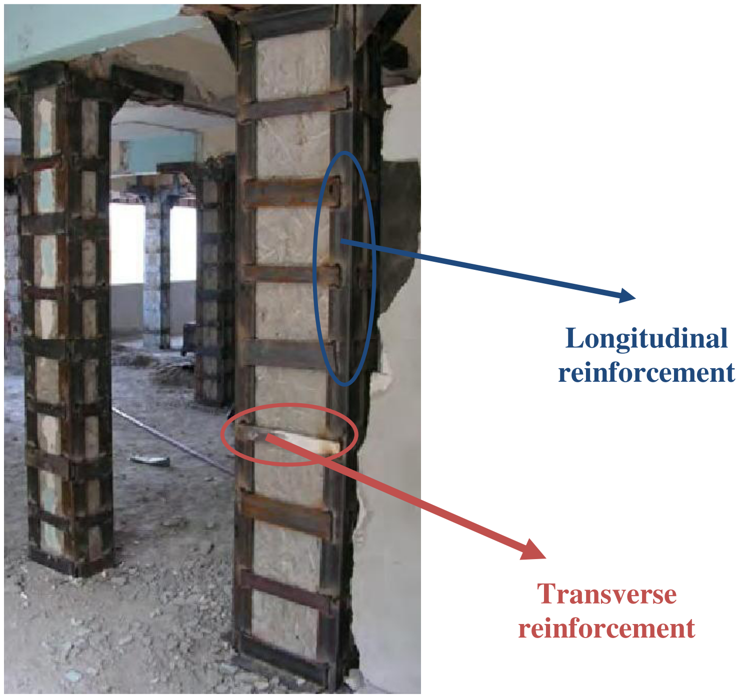


Figure 7. 3: Steel jacketing retrofit: application of longitudinal and transverse reinforcement

As already mentioned, the different strengthening solutions are designed in order to achieve the same structural performance in terms of shear strength for the retrofitted RC column. In fact, the functional unit, chosen for the analysis, is defined as follow: *"application of different strengthening techniques on the RC column in order to increase the shear strength of 30 kN"*. A RC column with a cross section of 30x30 cm and 4 φ 12 as longitudinal reinforcement is considered (Figure 7. 4); the length 1m is also chosen as the reference length of the column to apply the reinforcement.

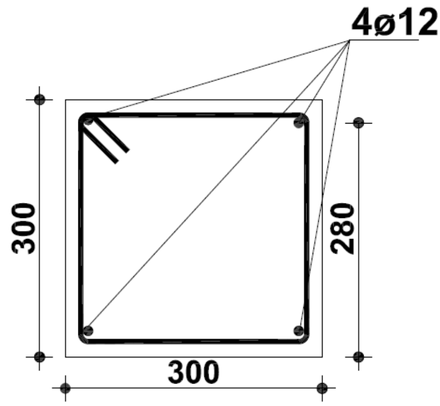


Figure 7. 4: RC column dimensions

The resulting shear strength value due to different strengthening options (V_{Rd}) has been calculated according to Equation 1 for CWF and SWF ((C.S.LL.PP 2009); instead, the Equation 2 (NTC 2008; Circolaren.617 2009) has been used to calculate the increase of shear strength due to the SJ reinforcement.

$$V_{Rd\,CWF/SWF} = \frac{1}{\gamma_{Rd}} * 0{,}9 * d * f_{fed} * 2 * t_f * \left(cotg_\beta + cotg_\theta\right) * \frac{w_f}{\rho_f}$$

Equation 1: Shear strength calculation of CWF and SWF

γ_{Rd} is the safety factor; its value is 1,2 according to (C.S.LL.PP 2009);

d is the effective depth of the column section (Figure 7. 4) and its value is 280 mm;

f_{fed} is the design strength of reinforcement; its value is calculated according to (eq. 3.24 of C.S.LL.PP 2009) and is equal to 475 MPa and 108 MPa for CWF and SWF, respectively;

t_f is the thickness of dry fabric (Table 7. 2); its value is 0,166 mm and 0,7 mm for CWF and SWF, respectively;

β is the inclination angle of fibers respect of column axis; its value is 90°, (Figure 7. 5);

θ is the inclination angle of concrete strut, chosen as 45°(Figure 7. 5);

w_f and p_f are the width and distance of fibers, respectively; their ratio w_f/p_f is equal 1 in case of reinforced sheet; (Figure 7. 5).

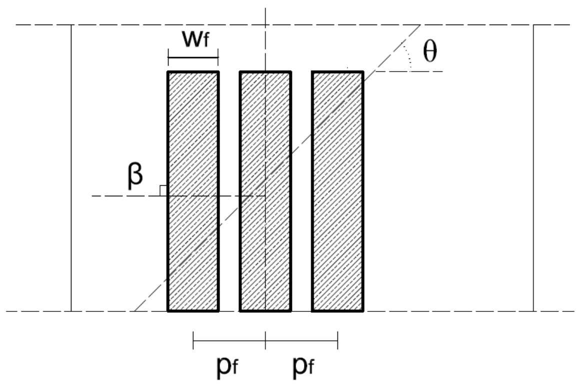


Figure 7. 5: β, θ, ρ_f and w_f representation

Table 7. 2 shows the technical data of CWF and SWF used in the V_{Rd} calculation.

$$V_{Rd\,SJ} = 0.9 * d * \frac{A_{sw}}{s} * 0,5 * f_{ywd} * (cotg_{\alpha} + cotg_{\theta}) * sen_{\alpha}$$

Equation 2: Shear strength calculation of SJ

d is the effective depth of the column section (Figure 7. 4) and its value is 280 mm;

A_{sw} is the area of steel transverse reinforcement and its value is 11,7 mm^2 (Table 7. 3);

s is the distance between two transverse reinforcement; its value is 50 mm (Figure 7. 6);

f_{ywd} is the design strength of transverse reinforcement and its value is 532 MPa;

θ is the inclination angle of concrete strut, chosen as 45° (Figure 7. 6);

α is the inclination angle of transverse reinforcement respect to column axis; its value is 90°(Figure 7. 6).

In Table 7. 3 the dimensions of transverse and longitudinal reinforcement used in the V_{Rd} calculation are reported.

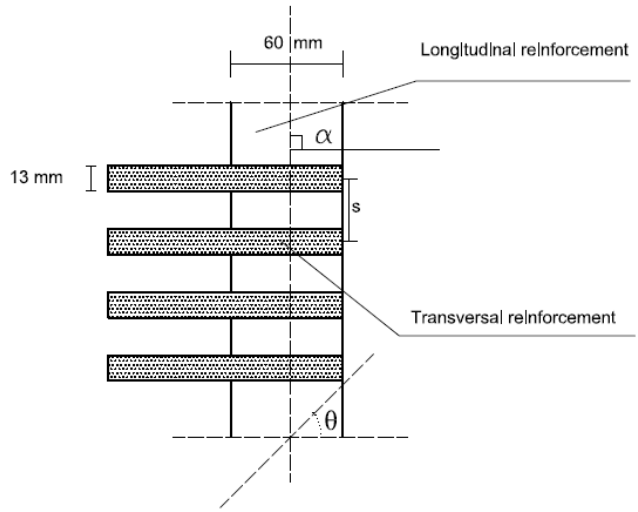


Figure 7. 6 : b, θ, and s representation

The values of V_{Rd}, calculated for each reinforced technique, are reported in Table 7. 1.

	CWF	SWF	SJ
V_{Rd} (kN)	33,16	31,78	31,37

Table 7. 1: V_{Rd}, increase of shear strength

As depicted in Figure 7. 7, Figure 7. 8 and Figure 7. 9, for all strengthening techniques, the following stages are considered:

*Materials production_* this phase includes the raw materials extraction and the manufacturing process of materials used in each retrofit technique;

*Application phase_* this phase consists in the *1*) preparation of the substrate that has to be reinforced and *2*) installation of the reinforcement; in detail:

1) Preparation phase:

- the external surface of RC column is thoroughly flushed with clean water to remove as much dirty, debris and contaminants;
- the damaged or deteriorated concrete is removed;
- the reinforcement bars are treated with anticorrosive cement mortar in order to reduce the iron oxidation;
- new concrete materials is added on external surface of RC column.

2) Installation phase:

- a layer of primer is added on the RC column surface;
- the external reinforcement is applied on RC column.

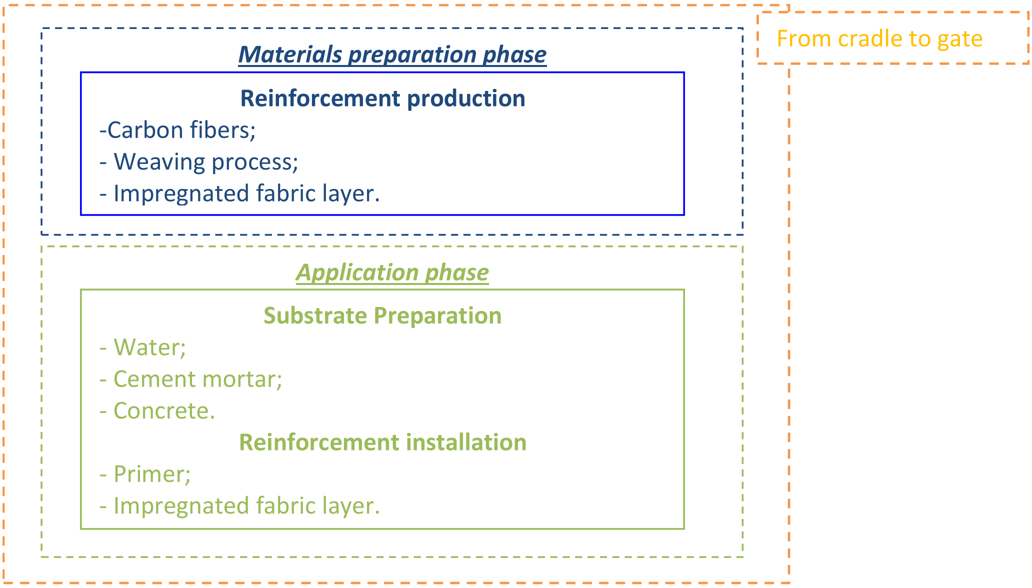


Figure 7. 7: System boundary of CWF strengthening technique

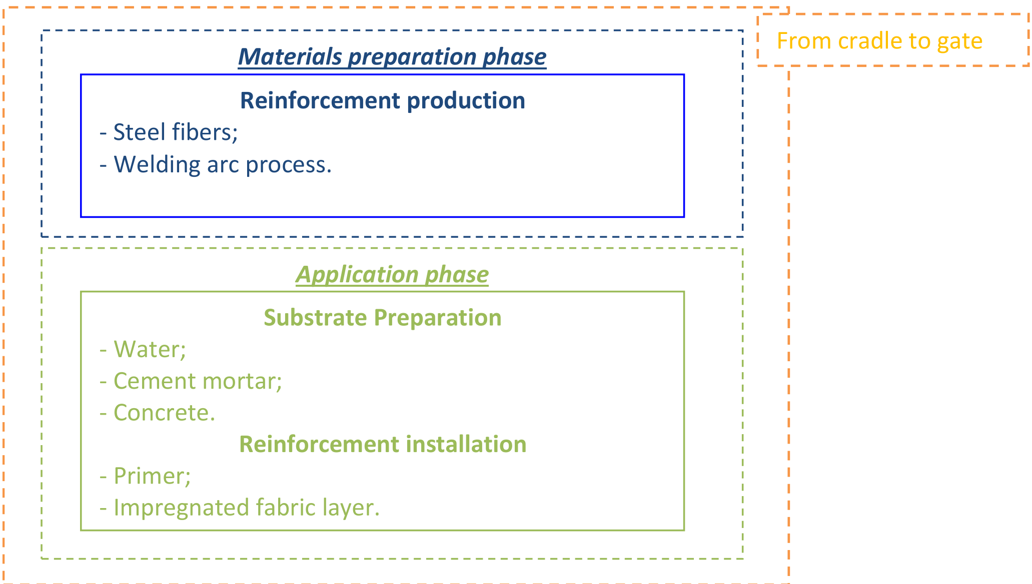


Figure 7. 8: System boundary of SWF strengthening technique

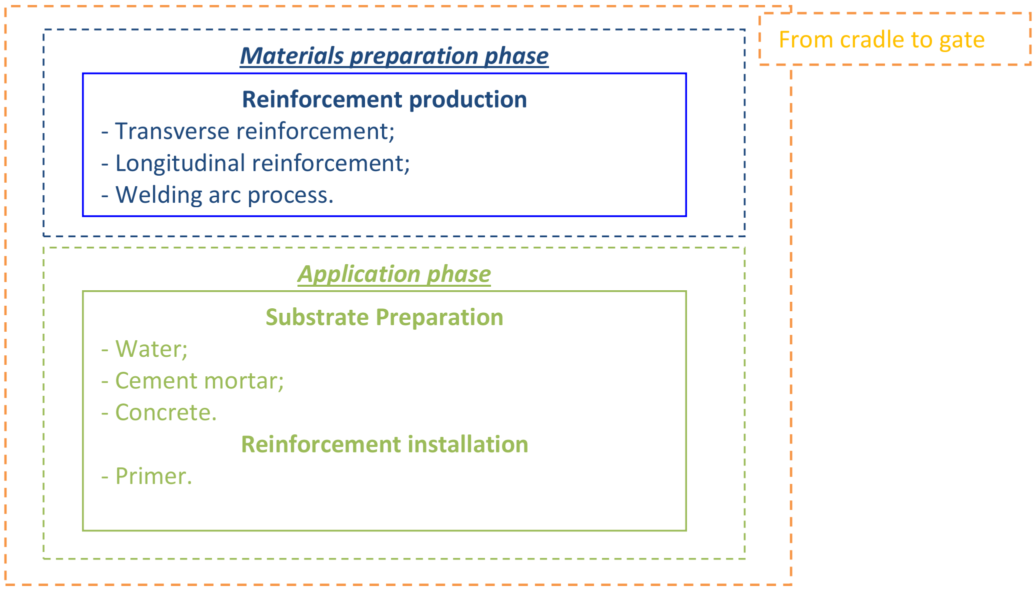


Figure 7. 9: System boundary of SJ strengthening technique

	Unit	**CWF**	**SWF**
Type of fibre		*high-streght carbon fibre*	*high-streght steel fibre*
Weight	g/m^2	300	2100
Density	kg/m^3	1800	7850
Equivalent thickness of dry fabric (t_f)	mm	0,166	0,7
Tensile modulus of elasticity	MPa	230000	210000
Elongation at breakage	%	2	2,6
Design strength of reinforced fibers (f_{fed})	Mpa	475,66	108,09

Table 7. 2: Technical data of CWF and SWF (MapeiS.P.A.)

	Transverse reinforcement	**Longitudinal reinforcement**
b (mm)	13	60
tj (mm)	0,9	6
A (mm^2)	11,7	360

Table 7. 3: Reinforcement dimension of SJ

7.3 *Inventory analysis*

In this work, primary and secondary data are used for the inventory analysis. In particular, primary data are used to model steel materials manufacturing (e.g.

transverse and longitudinal reinforcement) and steel and carbon wrap fabric production. As already mentioned, information reported in datasheets of (MapeiS.P.A.) and in the (ReLuis 2011) guidelines are used to model CWF and SWF production, whereas technical data reported in (GruppoAFVBeltrame ; ReLuis 2011) and in the (ReLuis 2011) guidelines are used to model steel materials manufacturing for SJ technique.

Secondary data, instead, are taken from databases available in the Simapro 7.3 LCA software package (Simapro). In particular, inventory data are retrieved from Ecoinvent (Ecoinvent ; Hedemann and König 2007) and IDEMAT (IDEMAT2001 2001) database. Following tables (Table 7. 4 to Table 7. 9) summarize the data and materials/energy amount used in the reference scenario for each retrofit solutions along with the different life cycle phases investigated (Figure 7. 7 to Figure 7. 9). Different scenario are considered in order to perform sensitivity analysis. Particularly, these scenario are explained in the paragraph 7.3.1.

Table 7. 4 and Table 7. 5 show the inventory data related to CWF retrofit solution; Table 7. 4 reports the data used in the materials production phase whereas Table 7. 5 the data related to the application phase. Table 7. 6 and Table 7. 7 show the inventory data related to manufacturing process of Steel fabric and the application of SWF on the RC column, respectively; finally, Table 7. 8 and Table 7. 9, show the inventory data related to manufacturing process of transverse and longitudinal reinforcement and the application of SJ on the RC column, respectively.

Materials production phase CWF					
	Materials/process	**Data**	**Source**	**Unit**	**Amount**
	Carbon fibers	Carbon fibre I	IDEMAT	kg	0,36
	Manufacturing Process	Weeving cotton	Ecoinvent	kg	0,36
Carbon fabric	Impregnating	Epoxy resin*	Sensitivity analysis	kg	1,44

Table 7. 4: Inventory data-Materials production phase of CWF

Application phase CWF			
1. Preparation phase			
	Ecoinvent data	**Unit**	**Amount**
INPUT			
Water	Tap water, at user	l	40
Mortar	Cement mortar at plant	kg	0,288
Concrete	Concrete normal	m^3	0,024
Energy	Electricity low voltage IT	kWh	0,68
OUTPUT			
Inert waste	Disposal inert waste 5% water to inert material landfill	kg	(0-48)
2. Installation phase			
	Ecoinvent data	**Unit**	**Amount**
INPUT			
Primer	Two-component resin (epoxy and stucco)	kg	2,04

Table 7. 5: Inventory data-Application phase of CWF

Materials production phase SWF					
	Materials/process	**Data**	**Source**	**Unit**	**Amount**
Steel fabric	Steel fibre	Wire, drawing steel*	Sensitivity analysis	kg	2,52
	Process	Welding arc	Ecoinvent	m	2,4

Table 7. 6: Inventory data-materials production phase of SWF

Application phase SWF			
1. Preparation phase			
	Ecoinvent data	**Unit**	**Amount**
INPUT			
Water	Tap water, at user	l	40
Mortar	Cement mortar at plant	kg	0,288
Concrete	Concrete normal	m^3	0,024
Energy	Electricity low voltage IT	kWh	0,68
OUTPUT			
Inert waste	Disposal inert waste 5% water to inert material landfill	kg	(0-48)
2. Installation phase			
	Ecoinvent data	**Unit**	**Amount**
INPUT			
Primer	Two-component resin (epoxy and stucco)	kg	2,04

Table 7. 7: Inventory data-Application phase of SWF

Materials production phase SJ						
	Materials		data	Source	Unit	Amount
Steel jacketing	Tranverse reinforcement	Steel	Reinforcing steel	Ecoinvent	Kg	2,20
		Process	Welding arc	Ecoinvent	m	0,26
	Longitudinal reinforcement	Steel	Reinforcing steel	Ecoinvent	Kg	22,6

Table 7. 8: Inventory data-Materials production phase of SJ

Application phase SJ			
1. Preparation phase			
	Ecoinvent data	**Unit**	**Amount**
INPUT			
Water	Tap water, at user	l	40
Mortar	Cement mortar at plant	kg	0,288
Concrete	Concrete normal	m^3	0,024
Energy	Electricity low voltage IT	kWh	0,68
OUTPUT			
Inert waste	Disposal inert waste 5% water to inert material landfill	kg	(0-48)
2. Installation phase			
	Ecoinvent data	**Unit**	**Amount**
INPUT			
Primer	Two-component resin (epoxy and stucco)	kg	0,84

Table 7. 9: Inventory data-application phase of SJ

The carbon fibers production is implemented as *"Carbon fibre I"* (Table 7. 4) retrieved from IDEMAT database. The steel fibers, in the reference scenario, are implemented as *"wire drawing steel"* retrieved from Ecoinvent database (Table 7. 6) instead, when sensitivity analysis is conducted, are implemented as " *Reinforcing steel, at plant* " retrieved from Ecoinvent database; the steel reinforcement production are implemented as *"Reinforcing steel, at plant*" (Table 7. 8) retrieved from Ecoinvent database.

7.3.1 Sensitivity analysis (S.A.)

In this study, three sensitivity analyses are conducted. According to (ISO:14040 2006) standard, sensitivity analysis is a systematic procedure to estimating the environmental effects of the choices made regarding methods and data on the outcomes of the study.

In detail:

- *S.A Impregnating Resin (SAIR):* Typically, carbon fabric is impregnated in a layer of epoxy resin. In this study different epoxy resin data are used: Ecoinvent epoxy resin and IDEMAT epoxy resin. Given these consideration, two scenario are considered: reference scenario in which Ecoinvent epoxy resin is used and SAIR scenario in which IDEMAT epoxy resin is considered;
- *S.A Steel Fibers (SASF):* In order to model the production process of steel fibers different steel manufacturing process are considered: "wire drawing" process and "reinforcing steel" process, both retrieved from Ecoinvent database. Given these consideration, two scenario are considered: in the reference scenario the steel fibers production are implemented as wire drawing and SASF scenario in which the steel fibers production are implemented as reinforcing steel.
- *S.A LCA comparison :* The comparison, in terms of environmental impact, between all strengthening solutions, is calculated with Impact2002+ LCIA method (Jolliet, Margni et al. 2003). In addition, the environmental burden is also computed using Ecoindicator99, (Ecoindicator99) LCIA methodology. In all cases the LCA comparison is made using reference scenario.

7.3.2 Uncertainties analysis

The standard (ISO:14040 2006) defines uncertainty analysis as a systematic procedure to quantify the uncertainty introduced in the LCA results due to the model imprecision, input uncertainty and data variability. In this study, the uncertainties are due to data quality and, for all data used, three kind of uncertainty are considered:

- Temporal;
- Technological;
- Geographical

These different uncertainties are considered through the "pedigree matrix"; in this matrix the different levels of uncertainty are taken into account. In this study, Monte Carlo technique, is used to quantify and update the uncertainty in LCA results. As a tool of uncertainty analysis, the Monte Carlo simulation is a widely used method to perform error propagation for the LCA analysis (Sonnemann, Schuhmacher et al. 2003; Lo, Ma et al. 2005)

7.4 *Impact Assessment*

In the present study the Impact2002+ methodology (Figure 2.4) (Jolliet, Margni et al. 2003) is adopted to calculate and to quantify the environmental impact of the three strengthening techniques. The LCA results are discussed in terms of damage assessment (End point categories) and in terms of characterization assessment (Mid point categories). The Ecoindicator 99 LCIA method, instead, is used in order to calculate the LCA profile of all solution when sensitivity analysis is performed.

7.4.1 LCA results (Impact2002+)

Figure 7. 10, Figure 7. 11 and Figure 7. 12 report the environmental results of CWF, SWF and SJ retrofit solution, respectively.

In CWF solution, the life cycle phases investigated, i.e. materials production and application phase, are responsible for approximately the same environmental impact; in fact, their environmental impact is almost 50% of total burden in almost damage categories.

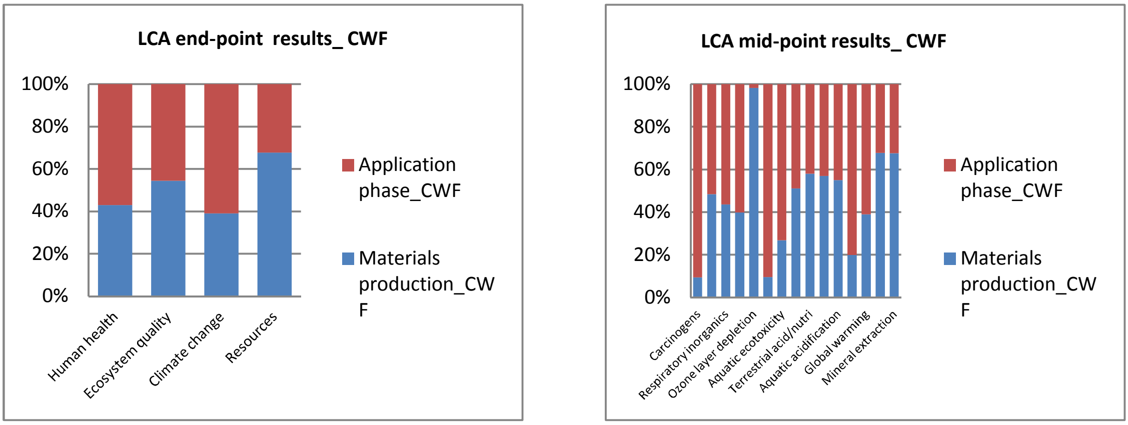
The LCA results of SWF solution are influenced by the application phase; in fact the environmental impact related to this life cycle phase is almost 70% of total burden.

In the SJ solution, the major environmental impact is related to the materials production phase. In fact, its environmental impact accounts for 90% of total environmental burden. Particularly, several considerations on the LCA results of all retrofit solution can be done:

- *CWF solution*: according to Figure 7. 10, the environmental impact of CWF depends on the materials production and installation phases. The LCA results of materials production related to manufacturing process of carbon fabric reveal that the weaving process determines the highest impact in this life cycle phase; its impact is almost 39% of total burden as shown in Figure 7. 13a. In addition, when the LCA is performed on the application phase, the environmental results reveal that the installation phase and, particularly, the application of primer on external surface on RC column, accounts for 65% of total environmental burden , as showed in Figure 7. 13b;

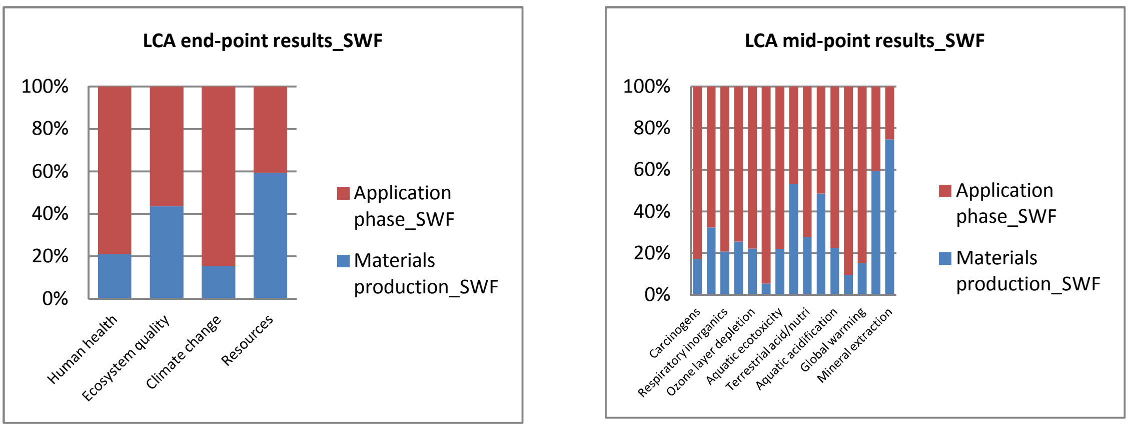
- *SWF solution:* The installation phase with the application of primer on external surface on RC column, involves the highest environmental impact with almost 65% of total burden, as reported in Figure 7. 14.

- *SJ solution:* The steel materials production, related to manufacturing process of transverse and longitudinal reinforcement, involves the highest environmental impact in the materials production phase; its impact is almost 90% of total burden, as reported in Figure 7. 15.



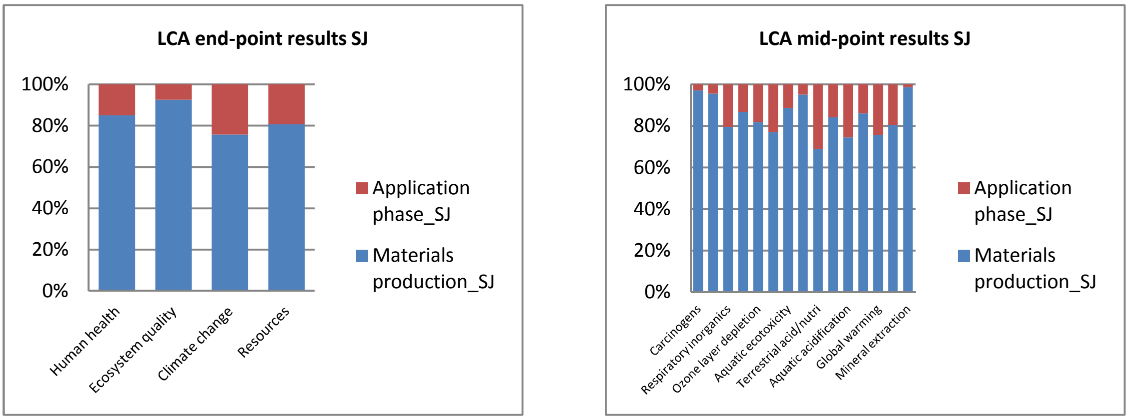
(a) **(b)**

Figure 7. 10: LCA results CWF; (a) End-point categories; (b) mid-point categories



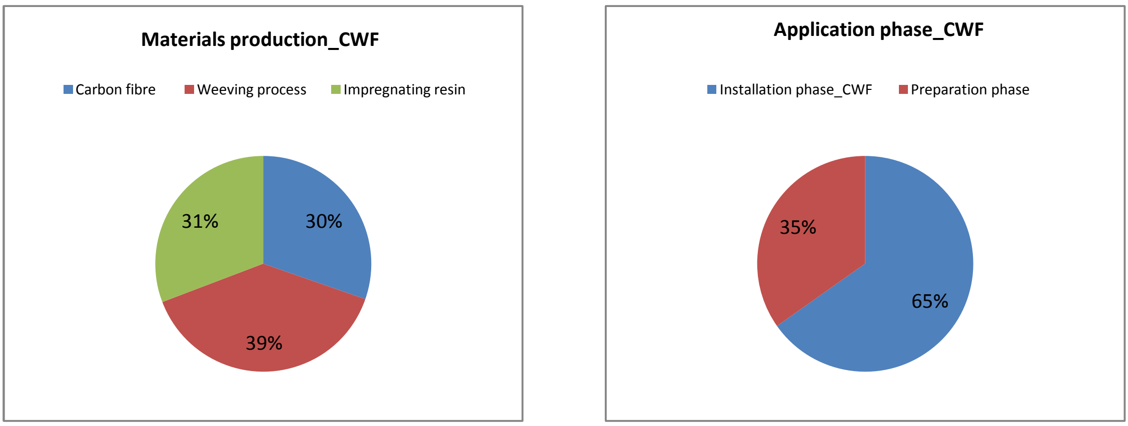
(a) **(b)**

Figure 7. 11: LCA results SWF; (a) End-point categories; (b) mid-point categories



(a) **(b)**

Figure 7. 12: LCA results SJ; (a) End-point categories; (b) mid-point categories



(a) **(b)**

Figure 7. 13: LCA results CWF; (a) Materials production phase; (b) Application phase

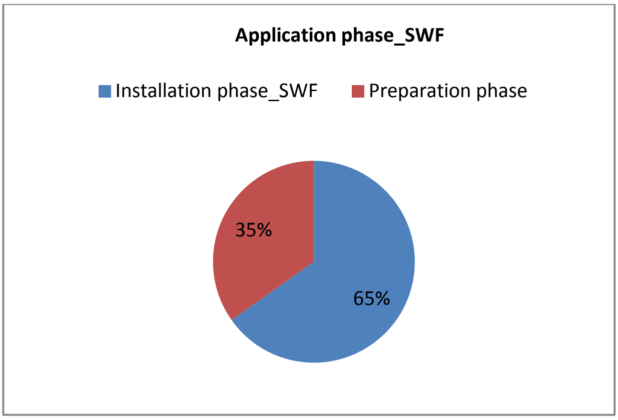


Figure 7. 14: LCA results SWF: Application phase

Figure 7. 16, shows the LCA comparison of all strengthening techniques; as it can be seen, the SJ technique presents the highest environmental impact in almost damage and impact categories; particularly, in the Human Health, Ecosystem Quality and Climate Change end-point categories, CWF and SWF exhibit an environmental impact between 20-80% lower than SJ solution. CWF solution presents the highest impact in Resources damage category; whereas the SWF solution, is the solution characterized by the lowest environmental impact.

The SJ solution presents the highest environmental burden, in terms of materials production phase, as showed in Figure 7. 17.

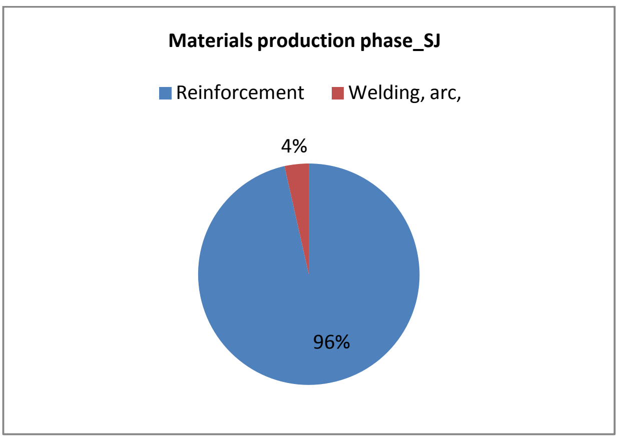


Figure 7. 15: LCA results SJ: Materials production phase

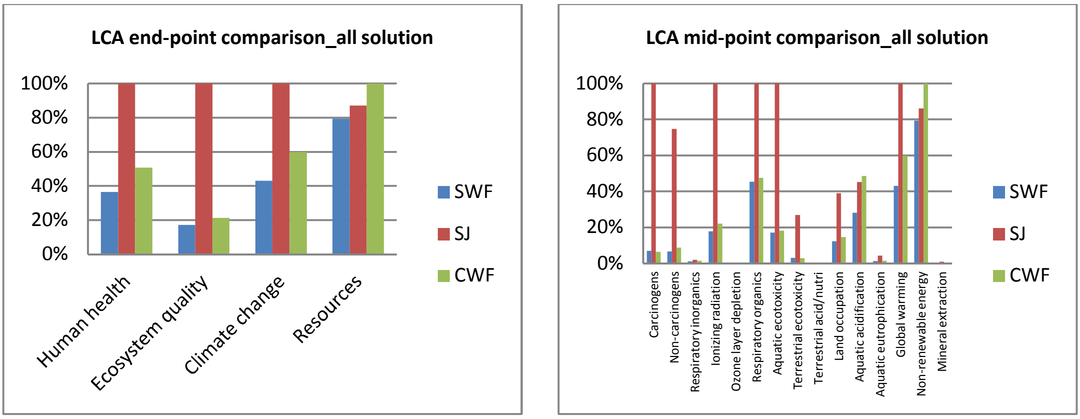


Figure 7. 16: LCA comparison; (a) damage assessment ;(b) characterization categories

In order to evaluate which material/process influences the environmental results of SJ solution in the materials production phase, the contribution analysis (ISO:14044 2006) is conducted. In this way, it is possible to determine which substance and process play a significant role in the LCA results.

This analysis, conducted for each end-point categories, reveals that the reinforcement production (steel materials manufacturing) influences the environmental impact of SJ solution; this result is in agreement with Figure 7. 15 and in detail:

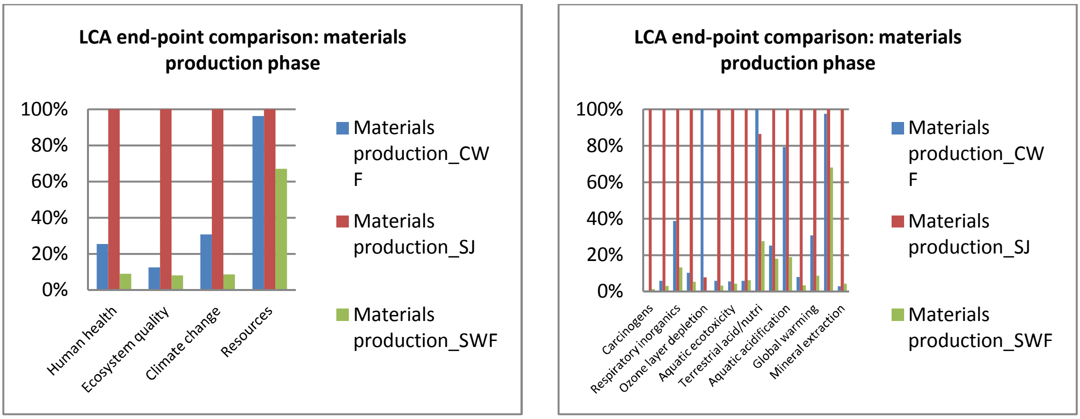
Human health category: the LCA result is influenced by steel materials produced in electric and basic oxygen furnaces ("steel, converter, unalloyed" and "Steel, electric, un- and low-alloyed"); this processes emit in the atmosphere a large amount of dioxins and sulfur dioxide.

Ecosystem quality: the LCA results are influenced by the steel materials production and, in particular, by steel materials produced in basic oxygen furnaces ("steel, converter, unalloyed") that emits in the air and water a large amount of aluminum and zinc emissions.

Climate Change: the steel material produced in basic oxygen furnaces ("steel, converter, unalloyed") influence the LCA results in this end-point category; this material involves a large amount of CO_2 emissions in atmosphere.

Resources: in order to produce steel material ("steel, converter, unalloyed") several non renewable raw materials, such as uranium, coal, oil and gas natural are used.

Finally, CWF presents the highest environmental impact in Resources category, as showed in Figure 7. 16; this environmental result is influenced by epoxy resin and carbon fiber production; the environmental impact of epoxy resin (used as impregnating resin) and carbon fibers account for 70% of total burden in the materials production phase, whereas the epoxy resin (used as primer) account for 26% of total environmental impact in the installation phase.



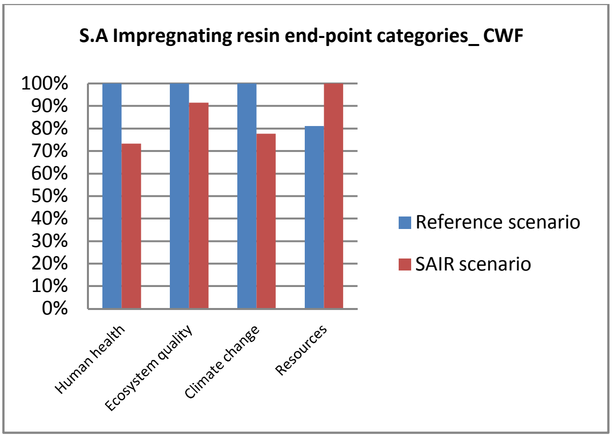
(a) **(b)**

Figure 7. 17: LCA comparison: materials production phase (a) damage assessment ;(b) characterization categories

7.4.2 LCA results- sensitivity analysis

As mentioned in the paragraph 7.3.1, three sensitivity analysis are conducted:

S.A impregnating resin: Figure 7. 18 shows the LCA, in terms of damage assessment, of CWF, when two different epoxy resin (used for fabric impregnation) data are used. The results reveal that the use of IDEMAT epoxy resin- SAIR scenario- presents a lower impact than Ecoinvent epoxy resin- Reference scenario-. Particularly, SAIR scenario exhibits an environmental impact 20% lower than Reference scenario in almost LCA categories, excepted in Climate Change category, where the environmental impact of SAIR scenario is highest than reference scenario.



(a)

Figure 7. 18: S.A. impregnating resin, CWF

Resin system S.A.: Figure 7. 19 shows the LCA results of SWF solution when two different steel manufacturing process are used to produce steel fibers: wire drawing and reinforcing steel hot rolling. In particular, the LCA results reveal that reference scenario (wire drawing process used to model the manufacturing process of steel fibers) presents a lower impact than SASF scenario (reinforcing steel process used to model the manufacturing process of steel fibers). Particularly, the reference scenario involves a reduction of almost 30% of environmental impact of SASF scenario in all damage categories.

S.A. LCA comparison: Figure 7. 20 reports the LCA comparison between all strengthening techniques when Ecoindicator99 LCIA methods is used. The results are in agreement with the previous results (Figure 7. 16): the SJ solutions presents the highest environmental burden in almost damage categories and the CWF solution has the highest impact in Resources category.

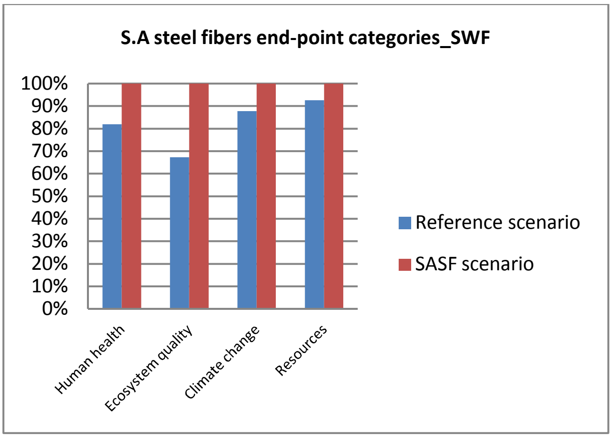
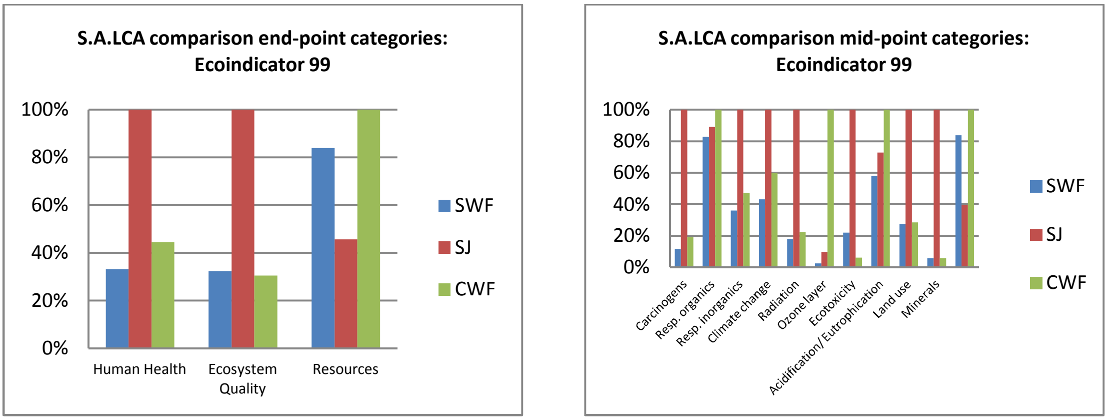


Figure 7. 19: S.A Steel fibers: SWF



(a) **(b)**

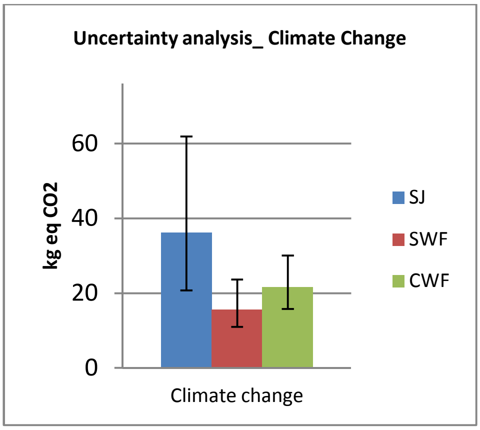
Figure 7. 20: S.A. LCA comparison Ecoindicator99, (a) end-point categories (b) mid-point categories

7.4.3 LCA results- Uncertainties analysis

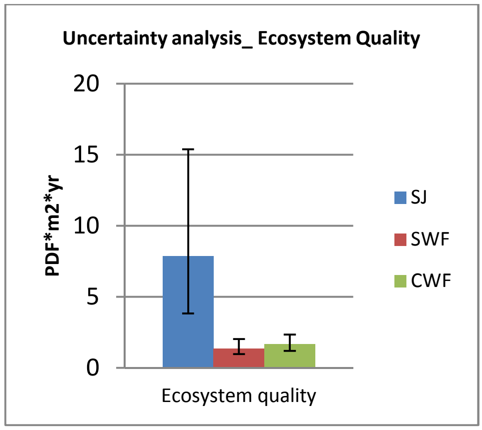
Monte Carlo analysis is the numerical way to process uncertainty data and establish an uncertainty range in the calculated LCA results.

In Figure 7. 21 for each damage category, bars chart are shown with an uncertainty range for each strengthening solution. It clearly appears that all solutions present a high uncertainty in all damage categories. The reason is that data are affected by several uncertainties (temporal, geographical, technical) which are taken into account in all retrofit solution.

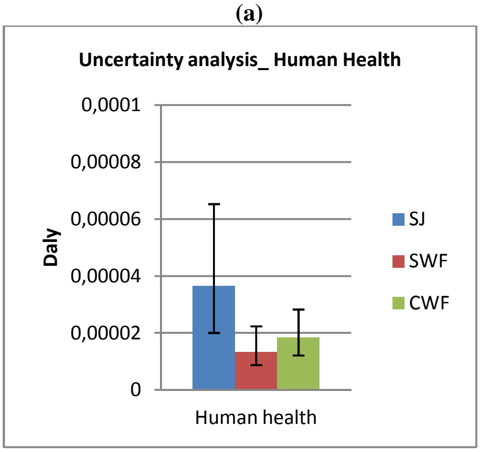
In detail, the uncertainties analysis reveals that the LCA results of SJ solution present the highest uncertainty level in all damage category, whereas the CWF and SWF present similar uncertainty level in all damage category.



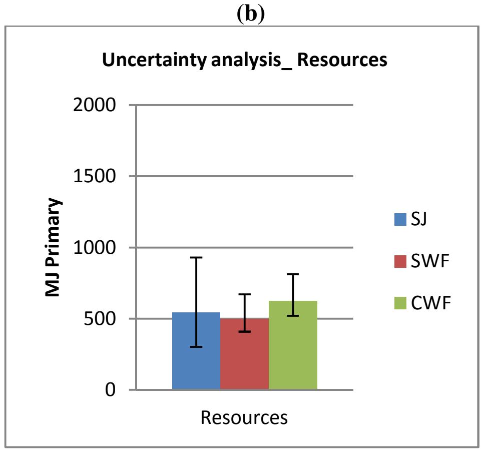
(a)



(b)



(c)



(d)

Figure 7. 21: Uncertainty analysis, (a) Climate change category; (b) Ecosystem quality category;(c) Human Health category;(d) Resources category

7.5 *Conclusion*

In the present study, the environmental impact of different strengthening techniques applied to RC columns has been assessed. In particular, three strengthening techniques have been examined by means of a LCA approach: carbon and steel fabric wrapping and steel jacketing. All of them were designed to achieve the same structural performance in terms of shear strength for the retrofitted RC column. The first objective of this research has been to evaluate the relative environmental impact, in a life cycle perspective, of each alternative. In particular, the LCA results of CWF solution revealed that the materials production (carbon fabric manufacturing) and application phases (application of primer on external surface of RC column) had the same environmental contribution; in fact, their impact is almost 50% of total burden in almost damage categories. In SWF solution, the LCA results were mainly influenced by the application phase, (two-component resin used as primer); in fact this life cycle phase presented an environmental impact of almost 70% of total burden. In the SJ solution, the major environmental impact was related to the materials production phase. In fact, the materials production phase, and in particular, the steel materials manufacturing, accounted for 90% of total environmental burden. When the strengthening solutions comparison is performed, the results showed that the SJ technique in almost the damage and impact categories presents the largest impact; it is mainly due to the refining and melting process of steel metal (materials production phase). The CWF solution, instead, had the highest impact in Resources categories; it was mainly due to epoxy resin, used as impregnating system and carbon fiber production.

7.6 *References*

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CONCLUSION

The work carried out in the present thesis deals with the analysis and the quantification of environmental impact of structural materials and renovation/retrofit techniques applied to building sector by means of a Life Cycle approach. Different scales of the assessment have been explored and discussed, the environmental impact of materials and components considering their overall life cycle (production, realization, use, maintenance, disposal and recycling) has been calculated. In detail, the Life Cycle Assessment (LCA) has been performed for different case studies:

The first level of analysis concerned the LCA ***(Chapter III)***, carried out on new low-CO_2 concrete binder developed to meet the demand for concrete and still reach the CO_2 reduction goals.

The environmental burner of Ordinary Portland Cement (OPC) concrete and GEOpolymer concrete (GEO) has been performed; the aim of this analysis has been to quantify the environmental benefits in terms of CO_2 emissions between the conventional and innovative concrete. In fact, the LCA analysis showed that the new type of concrete allowed a strong reduction of the global warming potential indicator: 290-300 kg of CO_2eq for 1 m^3 in case of OPC concrete, while the GEO concrete release 112-127 of equivalent CO_2 for 1 m^3.

However, this reduction is not sufficient enough to achieve a total "green concrete" because the presence in the mixture of alkali solution generates a high environmental impact in terms of use of resources and quality of ecosystem. For this reason, future developments will include the possibility to choose a different waste material in order to reduce the use of alkali solution; for example, other solutions can be evaluated by investigating magnesium iron slags, ferronickel slags, or tungsten mine waste mud, as geopolymer binder.

Besides cement production, aggregates consumption, in terms of depletion of natural resources and availability of natural aggregates is also a big contributor to the overall environmental load of concrete material. Given these considerations, the environmental impact of the production of different types of lightweight concrete materials has been performed in the ***Chapter IV***. In particular, Artificial Lightweight Concrete (NLAC) and Recycled Lightweight Concrete (RLAC) made with different recycled LightWeight Aggregates (LWAs) have been evaluated from environmental point of view.

With regard to LCA of LWAs, the results revealed that the production of recycled LWAs presented a significantly lower environmental burden with respect to the production of artificial LWAs, mainly due to potential benefits of avoided impacts in terms of raw material supply and waste disposal.

With reference to 1 m^3 of lightweight concrete of C20/25 strength class the LCA results revealed that the NALC mix in all the damage and impact categories presented a larger impact than all RLAC mixes. Particularly, the environmental impact of NALC was influenced by expanded clay aggregates that accounted for around 60% of total environmental burden, whereas the environmental impact of recycled LWAs in RLAC was almost 10% of total environmental burden.

In ***Chapter V, VI, VII***, the environmental analysis focused on the rehabilitation/renovation of existing buildings including masonry and reinforced concrete structures. The environmental impact of different options for the replacement a typical old wooden roof has been evaluated in ***Chapter V***. In particular, three alternative solutions have been examined: reinforced concrete joist and hollow clay blocks, steel joists and concrete slab and reinforced concrete joists and polystyrene panels; all of them were designed to achieve certain structural and functional requirements.

The results showed that the steel floor solution was the major responsible for the environmental impact in the Human Health damage category, due to carcinogen agents related to refining and melting process of steel metal; the concrete solution presented the highest impact in the Ecosystem quality, and Resources categories caused by emissions provoking terrestrial ecotoxiticity related to light clay production. The polystyrene option presented, finally, the highest impact in the Climate change category due to the ethane emissions.

In addition, the environmental impact of different technological solutions for typical retrofit operations on masonry structures has been also assessed in ***Chapter VI***. In particular, four different structural solutions have been examined: Local Replacement Damaged Mortar (LRDM), Mortar Injection (MI), Steel Chain Installation (SCI) and application of Grid-Reinforced Mortar (GRM).

In the LRDM and MI retrofit options, the use of light mortar (construction phase) was responsible for the major environmental impact in all LCA categories.

In the SCI retrofit option, the scenarios investigated presented similar environmental profiles, with the only difference in the use of steel sleeve which determined the highest impact, accounting for 3% of total impact.

In the GRM retrofit option, the use of the steel reinforced grid without its recycling at the end of life, produced the highest environmental impact in all LCA categories; on the contrary, when the reinforced grid is re-used in other structural engineering applications, steel GRM solution presented the lowest environmental impact.

Finally, the environmental impact of different strengthening operations applied to reinforced concrete column has been assessed in ***Chapter VII***. In particular, three solutions have been examined: carbon and steel fabric wrapping and steel jacketing. All of them were designed to achieve the same structural performance in terms of shear strength for the retrofitted RC column. The LCA results showed that the steel jacketing technique in almost the damage and impact categories presented the largest environmental impact; it was mainly due to the refining and melting process of steel metal, instead the Carbon fabric wrapping presented the highest environmental burden in Resources damage category; its environmental impact, was mainly due to manufacturing process of carbon fabric.

The final scope of the present thesis has been to delineate a set of instructions and guidelines in order to provide designers, regulators and engineers valuable environmental information for decision making related to materials and buildings (new and existing) according to sustainability goals. These benchmarks can provide a basis for comparing the environmental performance of materials, components and systems used in building industry.