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Exterior wall Sustainable Improvement

Comparing different solutions through an LCA

Supervisor: Valentina Villa
Elisabetta Palumbo

Candidate: Paola Alice Rosa Cavallaro

To my parents,

first sponsors of my life.

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ABSTRACT

The built environment is currently responsible for nearly 40 percent of global energy- and process-related CO_2 emissions. Each building element affects a building's environmental performance through its passive contribution to both operational energy demand and embodied energy and emissions during each life cycle phase. This has led to encouraging all stakeholders in the AEC industry value chain to transparently understand where and when carbon emissions are generated and can be minimised. More informed decisions can be made through tools such as life cycle assessment. LCA analyses the environmental impact during the entire life cycle of a product/service/process. Using LCA, the embodied energy of a building (energy consumed during production, construction and replacement of building components) can be calculated in terms of kgCO2eq.

This thesis considers the most widely used opaque external envelope solutions in the residential sector: a traditional masonry wall, a CLT wood wall and a drywall. All of these are applied to a case study: a new residential building located in Milan. All solutions were analysed by following the building project and construction phases provided by EN 15978. Each phase, from the product phase, through construction and use to end of life, was analysed and improved in terms of kgCO2 emissions. In order to perform the calculations, material's Environmental Product Declaration (EPD) and OneClick LCA software were used.

In conclusion, the thesis aims to highlight how LCA results are key factors in more informed decision making. Effective decisions for the development of low-impact buildings can in fact already be evaluated at the initial design stage.

1. INTRODUCTION

1.1 PARADIGM SHIFT

The construction sector has always been in a continuous and inevitable development that faithfully reflects the change of the values, which society is based on. For centuries, the Vitruvian triad has been the paradigm of architectural theory and practice. The three pillars on which it stands:

- firmitas (solidity and permanence),
- utilitas (function, intended use) and
- venusta (perfection of beauty)

have been repeatedly reinterpreted and, time by time, re-weighted.

Since the last quarter of the XX century, the construction sector has had to face radical changes in society such as: the advent of computers and today the issues of sustainability and climate change. All the changes, have entailed a real change in our modus operandi. The increase of the "environmental awareness" of society, caused a growth in the demand for environmentally friendly products by consumers, industries and the building which are all started evaluating how their activities affect the environment. It is in this context that the classical Vitruvian triad needs to be implemented in order to be applied to the modern world. The three principles on which it is based no longer satisfy the needs of today's society, and new parameters are needed to take into account new factors not present at Vitruvius's era.

The design of new buildings today cannot be carried out without consideration of further factors, such as environmental performance: interest has increased in the development of methods and techniques that make it possible to understand, evaluate and consequently reduce the possible environmental impacts of: production of products, their use stage, and their disposal once their operational life end. This latter factor, together with economic performance and social benefits represent the three pillars of sustainable development.

For the purpose of this thesis only the environmental performance will be analysed.

Within these circumstances companies developed a new way of proceeding: the design and production of new products will be followed by evaluation of their "life cycle" or "**Life Cycle Assessment**" (LCA). The LCA evaluates the potential environmental impacts of production / system / service related to human health, to ecosystem quality and resource depletion, also considering the economic and social impact. The goal of a life cycle analysis is therefore to define a complete picture of the interactions of a product or service with the environment that surrounds it throughout its life cycle. The LCA analysis is based on quantitative indicators, divided into categories of environmental impact, which evaluate the consumption of resources and emissions on water, soil and air. Depending on calculation method adopted to perform the LCA assessment, there are different impact categories, concerning human and environmental health[1].

[1] ARCA, chapter 2.2. LINEE GUIDA ARCA PER LA LIFE CYCLE ASSESSMENT (LCA)

Symbol	Meaning	Unit of Measurement
GWP	Global Warming Potential	Kg CO_2/m^3
AP	Acidification Potential	Kg SO_2/m^3
EP	Eutrophication Potential	Kg PO_4/m^3
ODP	Ozone Depletion Potential	Kg CFC_{11}/m^3
POCP	Photochemical Ozone Creation Potential	Kg C_2H_4/m^3
PEInr	Primary Energy Index (non-renewable)	MJ/m^3

Table 1: Impact categories, symbols, and units of measurement

Despite all the possible calculation LCA allows, the main application is the assessment of the Carbon foot print given by the GWP indicator. This may be due to the framework supplied by the introduction of the 17 sustainable goals (17SGs) by the United Nation in September 2015 (deepened in chapter1.3). In particular, Goal 13: CLIMATE ACTION[2], encourage taking urgent action to combat climate change and its impact. It puts its attention to the energy -related CO_2 which are the main contributors to the global warming.

1.2 GLOBAL WARMING POTENTIAL

Climate change is a long-term change in the average weather patterns on Earth (including precipitation, temperature, and wind). "Global warming" is one aspect of climate change which refers to the long-term rise in global temperatures due to human activities, primarily fossil fuel burning, which increases heat-trapping greenhouse gas levels in Earth's atmosphere. Global warming has negative effects on ecosystems, people, and economies and, as a result, reducing its effects has become a major concern for governments and organizations worldwide.

The temperature increase over the globe is broadly distributed, affecting nearly all land and ocean areas. In 2021, 87% of the Earth's surface was significantly warmer than the average temperature during 1951-1980, 11% was of a similar temperature, and only 2.6% was significantly colder[3].

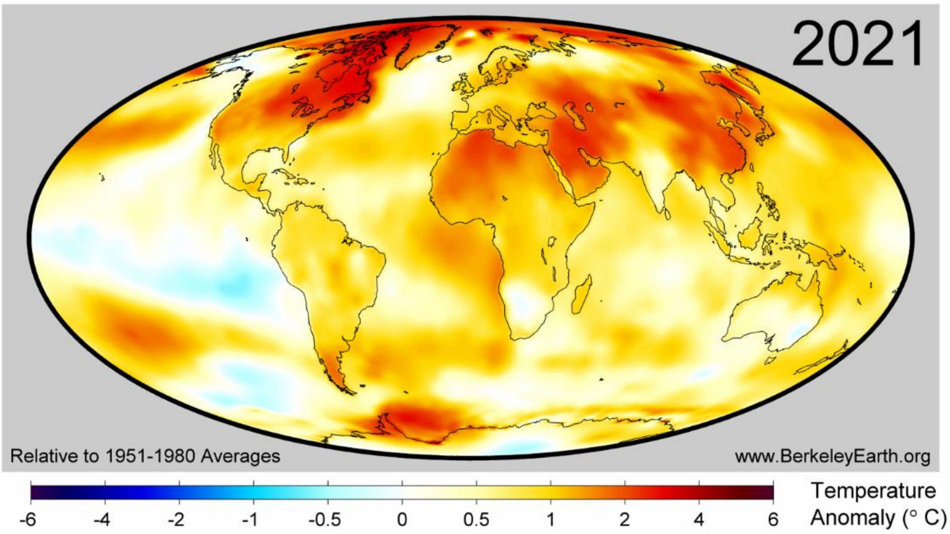

Figure 1: Local temperature increase in 2021 relative to the average temperature in 1951-1980

[2] https://sdgs.un.org/goals/goal13 [19/06/2022]
[3] Global Temperature Report for 2021 - Berkeley Earth [19/06/2022]

The most known emissions which contribute to global warming are greenhouse gases (GHG) emissions. Greenhouse gases are gases that trapping heat into the atmosphere contribute to warming up the planet and to the rise of average temperatures across the world. The most dominant greenhouse gas is carbon dioxide (CO_2) but there are several others – methane, nitrous oxide, and smaller trace gases such as hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6) – which have contributed a significant amount of warming to date. Greenhouse gases are measured in 'carbon dioxide-equivalents' (CO_2e), which attempt to convert the warming impact of the range of greenhouse gases into a single metric.

To convert non-CO_2 gases into their carbon dioxide-equivalents we multiply their mass (e.g., kilograms of methane emitted) by their 'global warming potential' (GWP). GWP measures the warming impacts of a gas compared to CO2; it basically measures the 'strength' of the greenhouse gas averaged over a chosen time horizon. The standard way to do this is to evaluate the GWP over a 100-year timescale (GWP_{100}). For example, if methane has a GWP_{100} value of 28, we would multiply methane emissions in tonnes by 28 to get its CO_2e figure.

Total greenhouse gases are then measured as the sum for all the gases.

The world emits around 50 billion tonnes of greenhouse gases each year, measured in carbon dioxide equivalents (CO_2eq). If current emissions trends are not altered, global temperatures are expected to rise a further 1.4 to 5.8° C (2.5 to 10.4° F) by 2100, according to the Intergovernmental Panel on Climate Change (IPCC). To figure out how we can most effectively reduce emissions and what emissions can and cannot be eliminated with current technologies, we need to first understand where emissions come from[4].

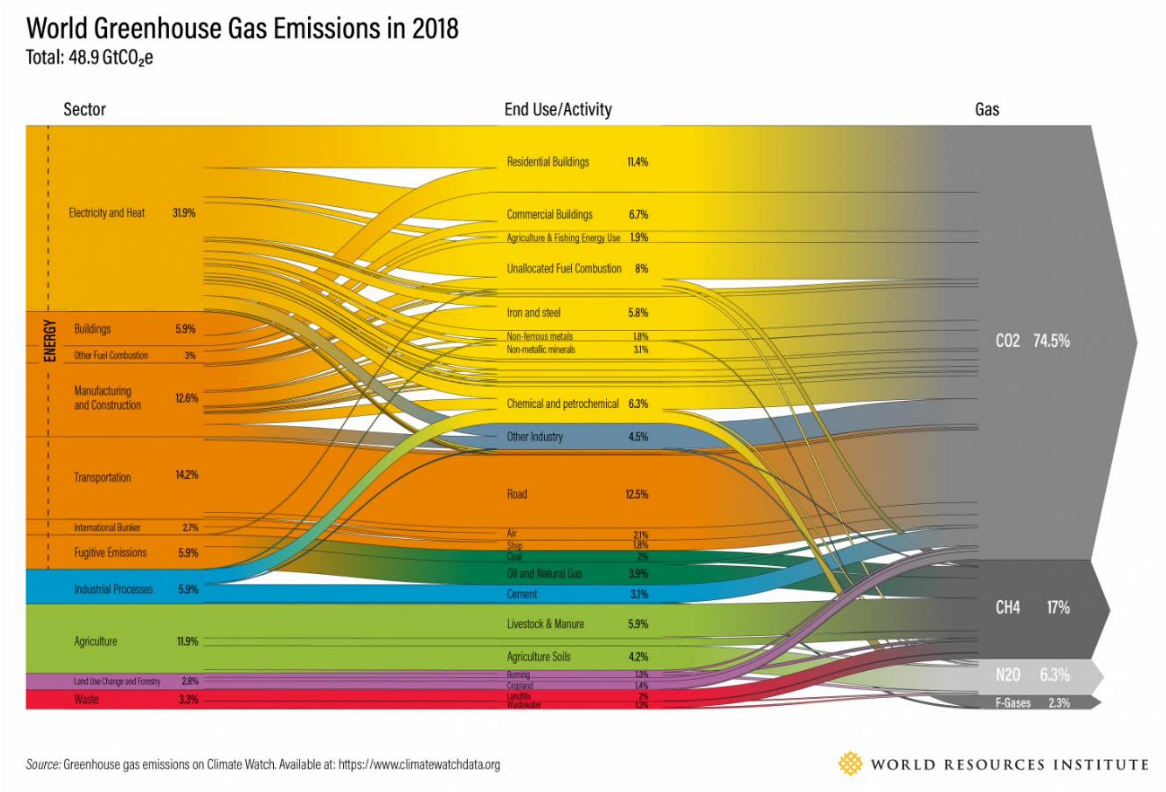

Figure 2: World Greenhouse Gas Emissions in 2018

[4] World Resources Institute, chapter 1. Navigating the numbers, Greenhouse Gas Data, and International climate Police

The chart above describes the sources and activities across the global economy that produce greenhouse gas emissions, as well as the type and volume of gases associated with each activity. The left side of the figure shows that energy-related emissions (which come from the production and combustion of coal, oil, and natural gas) account for about 76 percent of the world total. At the sector level, the largest contributors to global emissions are electricity and heat (31.9 percent), transportation (14.2 percent), and manufacturing and construction (12.6 percent). The chart also shows emissions by "activity" or end-use (middle column). Here, the largest emissions come from road transport (12.5 percent) and residential buildings (11.4 percent). Many of these sources include direct emissions (such as fossil fuel combustion, industrial process emissions) as well as indirect emissions (such as electricity consumption). The data in the chart includes the six major GHGs. Carbon dioxide (CO_2) contributes the largest share of the global total (74.5 percent), followed by methane (CH_4, 17 percent) and nitrous oxide (N_2O, 6.3 percent). Most of the energy and land-use activities result in CO2 emissions, although there are also significant CH_4 emissions from agriculture sector. About 2.3 percent of global emissions are from fluorinated gases (SF_6, HFCs, PFCs).

It is clear from this breakdown that a range of sectors and processes contribute to global emissions. This means there is no single or simple solution to tackle climate change. To reach net-zero emissions we need innovations across many sectors.

The built environment is implicated in many sectors of GHG emissions due to its characteristic fragmented value chain made up of different segments such as manufacturing, construction, real estate, users, and financing all coming together to achieve the primary purpose of delivering buildings. The construction system consists of different subgroups where companies are categorized according to the different levels: Company, Sector, Segment, System[5].

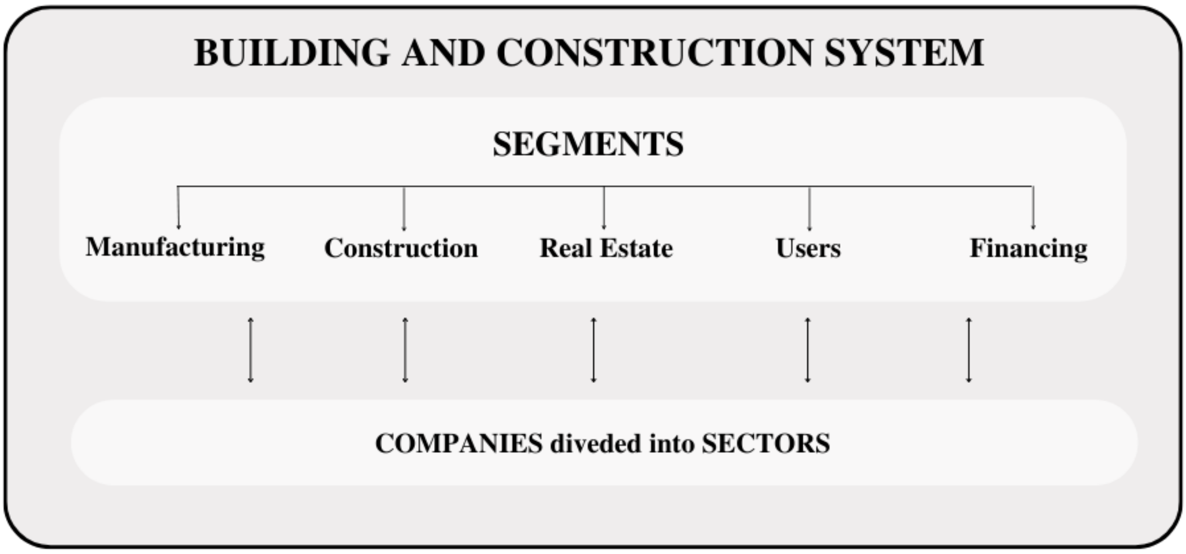

Figure 3: The building system carbon Framework

Companies are the individual entities providing services to buildings based on their specific line of business. **Sectors** represent the traditional way of grouping companies from the same business sector. For example, material sectors (i.e., concrete, steel, glass) or professional categories (i.e., engineers, architects, investors, property developers). **Segments** group different

[5] Wbcsd (world business council for sustainable development), page:4. The Building System Carbon Framework

sectors of the value chain together, based on their specific role and characteristic. Sectors within the same segment have relatively similar functions and objectives.

- Manufacturing provides the elements of the buildings. It includes building materials, construction elements and equipment.
- Construction is responsible for creating the buildings. It includes architecture, engineering, and construction companies.
- Real Estate has a transactional or ownership relationship to the buildings. It includes property developers, asset owners, facility managers and brokers.
- Users are the occupiers of the buildings. It includes final users of buildings (i.e., hotel, retail).
- Finance mobilizes financial capital for the buildings. It includes investors, financial institutions, and insurance companies.

System represents the highest level, which accounts for all the stakeholders, companies, sectors, and segments that play a role in building and construction.

Talking about energy and related CO2 emissions in the building value chain, there are four "hotspots" being:

- Operational energy: energy consumption by occupants during the use phase
- Embodied energy: manufacturing of materials and equipment
- Direct emissions: Carbon emissions released by companies in this value chain
- Indirect emissions: indirect emissions from the process of generating the electricity consumed

It should be noted that direct and indirect emissions of a company, for the GHG protocol, are reported as indirect upstream or downstream value chain emissions of another company. Therefore, the emissions of other parts of the building are part of the responsibility and reporting of another company. It is essential for companies within this value chain to engage and collaborate. That way, they can collectively mitigate the carbon emissions of the whole building system and individually achieve their own carbon reduction targets.

Another aspect to underline is that an European legislative focus on energy efficiency in the operational stage has significantly decreased the operational GHG emissions for new and renovated buildings. As more buildings are constructed and renovated to higher energy efficiency standards, the GHG emissions embodied within building materials increase in both absolute and relative terms. The reason is that more materials and services are often used to achieve high in use performance. It is important that both embodied carbon and operational emissions are considered, monitored, and regulated.

1.3 WORLD'S ANSWER

In September 2015 all United Nations (UN) members States adopted the 2030 Agenda for Sustainable Development, a plan of action for people, planet, and prosperity. At its heart are the **17 Sustainable Development Goals** (SDGs) and 169 targets, which are an urgent call for action by all countries in a global partnership.

Figure 4: 17 Sustainable Development Goals

In the 2030 Agenda for Sustainable Development, Member States express their commitment to protect the planet from degradation and take urgent action on climate change. The Agenda also identifies, climate change as "one of the greatest challenges of our time" and worries about "its adverse impacts undermine the ability of all countries to achieve sustainable development. **Sustainable Development Goal 13** aims to "take urgent action to combat climate change and its impact", it focusses on the integration of climate change measures into national policies. The 13th goal is composed by five targets to create action to combat climate change.

In December 2015, the 21st Session of the Conference of the Parties (COP21) convened in Paris, adopted the **Paris Agreement**, the first-ever universal, legally binding global climate change agreement. The EU and its Member States are among the close to 190 Parties to the Paris Agreement. The agreement was formally ratified on 5 October 2016, thus enabling its entry into force on 4 November 2016. Its goal is to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. To achieve this long-term temperature goal, countries aim to reach global peaking of greenhouse gas emissions as soon as possible to achieve a climate neutral world by mid-century. The Paris Agreement is a landmark in the multilateral climate change process because, for the first time, a binding agreement brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects. The Paris Agreement works on a 5- year cycle of increasingly ambitious climate action carried out by countries. Starting in 2020 every five years, countries submit their plans for climate action known as Nationally Determined Contributions (NDCs) [6] in which they communicate actions they will take to reduce their Greenhouse Gas emissions. NCDs form the

[6] https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs#NDC-Synthesis-Report [1/10/2022]

basis for countries to achieve the objectives of the Paris Agreement, containing information on targets, and policies and measures for reducing national emissions and on adapting to climate change impacts.

On 13 November 2021, COP26 concluded in Glasgow with all countries agreeing the Glasgow Climate Pact to keep 1.5°C alive and scales up action on dealing with climate impacts, but it will only be delivered with concerted and immediate global efforts.[7]

As showed before, the building and construction sector has a vital role to play as it is responsible for 39 percent of global carbon emissions. Most of these emissions occur when a building is in operation from energy used to heat, cool, and power them. But a significant amount also comes from "embodied carbon": emissions as a result of material manufacturing and construction processes, building maintenance and renovation, and when buildings are demolished. In the next thirty years, global building stock is expected to almost double, so we must act now to reduce "upfront carbon" the emissions generated before new buildings are use.

The World Green Building Council proposed for all buildings and infrastructure to be net zero emissions across their entire lifecycle by 2050. This means that by 2030, along with zero operating emissions, new buildings and infrastructure must have at least 40 percent less embodied carbon with significant up front carbon reduction. And by 2050, new buildings and infrastructure must have 100 percent net zero embodied carbon.

Official IPCC (Intergovernmental Panel on Climate Change) definition of Net Zero CO2 emissions:

> *"Net zero carbon dioxide (CO2) emissions are achieved when anthropogenic CO2 emissions are balanced globally by anthropogenic CO2 removals over a specified period"* [8]

According to IPCC Special Report the concept of "net zero" considers that although some sectors of the economy may aspire to function properly without emitting emissions, others - such as agriculture, construction, or aviation - will inevitably continue to emit gases that alter the climate. For this reason, it recognises strategies that make it possible to achieve a negative number of emissions - thus removing the amount of excess greenhouse gases from the atmosphere.

In this context the European Commission has developed Level(s), a voluntary reporting framework to improve the sustainability of buildings. Level(s) provides a set of common indicators and metrics for measuring the environmental performance of office and residential buildings, which considers their full 'life-cycle.' Industry and political leaders have welcomed Level(s) promotion of the principle of "think globally, act locally," ensuring that action taken at an individual building level makes a measurable impact on issues such as climate change, resource efficiency, water efficiency, resilience, and health. By introducing Level(s) as a pan-European framework, the European Commission hopes to create a great awareness and demand for sustainability.

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[7] UK Government, UN CLIMATE CHANGE CNFERENCE UK 2021. COP26: THE NEGOTIATIONS EXPLAINED

[8] https://ipccitalia.cmcc.it/net-zero-emissioni/ [28/09/2022]

1.4 LEVEL(S)

Level(s) is an assessment and reporting tool for sustainability performance of buildings, firmly based on circularity. Contrary to Green Building Rating System (GBRSs) (chapter2.4), Level(s) does not provide any certification to the building, in that it provides a common language and framework for the building transformation process in line with the EU sustainable initiatives. It helps understanding the full life cycle of a building and brings the circular economy into building design and use. Providing a universal basis, it enables to take actions at building level that can make a clear contribution to broader European environmental policy objectives. Level(s) involves gathering, handling, and processing a wide range of data relating. It is based on six macro-objectives which describe the strategic priorities. For each of these strategic priorities the contribution and performance of the individual building projects should be measurable. Sixteen indicators have therefore been developed that enable the measurement of performance and contribution of a building towards a specific macro-objective. The six macro-objectives address key sustainability aspects over the building life cycle. The sustainability indicators help to align the project with the strategic EU policy objectives in areas such as energy, material use and waste, water, indoor air quality and resilience to climate change. The six macro-objectives and the relative indicators are[9]:

1. Greenhouse gas emissions long building life cycle: evaluating greenhouse gas emissions throughout the building's life cycle. The main objectives are to reach net zero energy consumption in the in-use phase, minimizing greenhouse emissions.
   Indicators:
   1.1. Use stage energy performance (kWh/m^2/yr)
   1.2. Life cycle Global Warming Potential (CO_2 eq. /m^2/yr)
2. Resource efficient and circular material life cycles: analysing the life cycle of materials to extend their use and reduce waste.
   Indicators:
   2.1. Bill of quantities. Materials and lifespan
   2.2. Construction & Demolition waste and materials
   2.3. Design for adaptability and renovation
   2.4. Design for deconstruction, reuse, and recycling
3. Efficient use of water resources: improving water use efficiency.
   Indicator:
   3.1. Use stage water consumption (m^3/occupant/yr)
4. Healthy and comfortable spaces: create buildings that are comfortable, attractive and productive.
   Indicators:
   4.1. Indoor air quality
   4.2. Time outside of thermal comfort range
   4.3. Lighting and visual comfort
   4.4. Acoustics and protection against noise
5. Adaptation and resilience to climate change
   Indicators:
   5.1. Protection of occupier health and thermal comfort

[9] European Commission JRC TECHNICAL REPORTS, chapter 2.1. Level(s) – A common EU framework of core sustainability indicators for office and residential building, User Manual 1.

5.2. Increased risk of extreme weather
5.3. Sustainable drainage

6. Optimised life cycle cost and value: long term view of the whole life costs. Indicators:
   6.1. Life cycle cost (€/m^2/yr)
   6.2. Value creation and risk factors

A project team decides which objectives to focus on, which indicators to work with and finally, at what level. In fact, the common framework is organised into three different levels[9]:

- Level 1, Conceptual design: assessment on the concepts that the chosen indicators will cover, in early stage. It provides a simple structure that can be presented to clients to prioritize attention on sustainability aspects.
- Level 2, Detailed design and construction: quantitative assessment of the designed performance. Allowing comparison between different design options and monitoring of the construction according to standardized units and methods.
- Level 3, As-built and in-use: monitoring and surveying of activity both on the construction site and of the completed building and its first occupants. Level 3 helps the entire team understand actual building performance and identify lessons learned from the design to inform and improve future projects.

Each level is used for different scopes. An indicator can be easily integrated into each level of the building process to provide practical guidance. The aim is to let the indicator guide decisions and provide a foundation for comparing solutions and reflecting on how to increase the sustainability performance of a building.

One of the most important features of Level(s) is the fact that it embraces a life-cycle approach, looking at the performance of any building through its whole lifetime, ensuring sustainability from the cradle to the grave. By taking a life cycle approach, the full range of environmental impacts associated with a building can be analysed and the most significant impacts – so-called 'hot spots' – can be identified. Level(s) has been designed to encourage building professionals to, as far as possible to think about the whole life cycle and circularity of a building design from cradle to grave. It guides users from an initial focus on individual aspects of building performance towards a more holistic perspective, with the aim of wider European use of Life Cycle Assessment. LCA can be potentially used as tool to assess the core indicators of the macro-objectives 1,2 and 3. Linked LCA approach, Level(s) encourages circularity too, providing indicators that can help understand how to extend the utility of the building, not just in terms of its service life and value in the property market, but also in terms of the future potential for recovery, reuse, and recycling of the materials it is composed of.

▪ SETTING UP TO USE LEVEL(S)

According to User Manual 2[10] realised by the European Commission, to follow a Level(s) approach a project plan should be developed as first step. Which includes: definition of the macro-objectives considered, indicators considered, level at which the performance will be assess, planning of the resources will be needed to assess performance.

[10] European Commission JRC TECHNICAL REPORTS, chapter 2.1. Level(s) – A common EU framework of core sustainability indicators for office and residential building, User Manual 2

STEP 1 (macro-objectives and indicators):

Since the aim of the study is just to focus the attention on the footprint of the external walls the macro-objective and the indicator chosen are: 1. Green gas house emissions long building life cycle, indicator 1.2. the chosen indicator helps to reduce the building's carbon footprint by focusing the attention on the greenhouses gas (GHG) emissions associated with buildings at different life cycle stages. This indicator thus embraces the Life Cycle Assessment methodology monitoring the emissions resulting from the production, installation, maintenance, and disposal of building materials. It is the only European policy instrument that covers all life cycle stages at the building level when it comes to monitoring carbon emissions, and it plays an important part in supporting the European Commission roadmap to reduce whole life carbon[11]. The indicator is measured according to the Global Warming Potential (GWP) of the greenhouse gases emitted. The unit of measurement is kg CO2 equivalents per m2 useful internal floor area for a reference study period of 50 years. The results are to be reported for each life cycle stage, of which there are four – production (A), use (B), end of life (C) and additional benefits and loads (D). The system boundary is 'cradle to grave' as defined by EN 15978.[12]

STEP 2 (level):

Based on the purpose of the thesis Level 1 is the one adopted since there is no intention to calculate the life cycle GPW emissions of the building project. The intend of this study is, in accordance to level 1, to incorporate some important life cycle concepts in detailed design and to interpret and use the results. Level 1 entails early-stage qualitative assessments on the basis for the conceptual design and reporting on the concepts that have or are intended to be applied for reporting at level 1, it is necessary to specify which design concepts have been addressed.

STEP 3 (workflow requirement and building description):

Step 3 is about planning when and how Level(s) will be used and who will need to be involve. User Manual 2 provides different matrix that can help to enable an effective planning and integration into the project of Level(s) assessment. An important part of working at level 2 and 3 is the building description to provide a transparent basis for comparing the performance of different buildings. Once again user manual 2 provides different matric and guidelines to assess a complete building description.

[11] European commission, Indicator 1.2. LEVEL(S): Putting whole life carbon principles into practice.
[12] European commission JRC TECHINICAL REPORTS, Introductory briefing. Level(s) indicator 1.2: Life cycle Global Warming Potential (GWP)

2. LIFE CYCLE ASSESSMENT (LCA)

2.1 LCA HISTORY

LCA history is usually divided in decades:

- **1970-1990, decades of conception**

Life-cycle-oriented methods that were precursors of today's LCA were developed in the 1960s in collaboration between universities and industry. At the beginning the scope of these studies was initially limited to energy analyses in a comparative context ("Is product A better than product B?")[13]. Gradually, the importance of addressing the life cycle of a product, or of several alternative products, became an issue in the 1980s and 1990s, when it was recognized that, for many products, a large share of the environmental impacts is not in the use of the product but in its production, transportation or disposal.

Many of the early process-based LCA studies analysed packaging, which was a great consumer concern around the 1970s. Studies were typically commissioned by companies producing or using the packaging, such as Coca Cola Company that was one of the first (unfortunately unpublished) study quantifying the resource requirements, emission loadings, and waste flows of different beverage containers, the study was conducted by Midwest Research Institute (MRI) in 1969[13]. The results were mainly used for internal purposes, such as guiding reduction of life cycle impacts. A follow-up of this study conducted by the same institute for the U.S. Environmental Protection Agency in 1974 marked the beginning of the development of LCA as we know it today. The MRI used the term Resource and Environmental Profile Analysis (REPA) for this kind of study, we have to wait until 1990s for term LCA to become the norm. After a period of diminishing public interest in LCA and a number of unpublished studies, there has been rapidly growing interest in the subject from the early 1980s on. It is also in this period that a first impact assessment method based on critical volumes was introduced (1984).

Toward the end of 1980s and into 90s, the world became concerned about global environmental issues (such as ozone depletion and climate change). In particular, during the 1980s, in Europe started an interest in the impacts of milk packaging that inspired a number of large LCA studies performed in different European countries[14].

All studies compared alternative packaging systems for milk distribution. A comparison of the studies shows that although they aimed to answer the same question and although they compared more or less the same packaging technologies, they reached very different conclusions. That could be caused by the fact that, during this first decades LCAs were performed using different methods and without a common theoretical framework, therefore a lack of international scientific discussion and exchange platforms for LCA was clear. The obtained results differed greatly, even when the object of the study was the same. Rather than disqualify LCA as a serious decision support tool, these findings triggered an international collaboration among scientists and LCA practitioners on furthering LCA methodology

[13] Guinée, J.B.; Heijungs, R.; Huppes, G.; Zamagni, A.; Masoni, P.; Buonamici, R.; Ekvall, T.; Rydberg, T. Life cycle assessment: Past, present, and future

[14] Michael Z. Hauschild Ralph K. Rosenbaum Stig Irving Olsen, chapter 3. Lice Cycle Assessment, Theory and Practice

development and harmonisation, as shown by the strong international development work and standardisation in the 1990s.

▪ 1990-2000, decade of standardization

The application of LCA expanded to include numerous other types of products during this decade as reflected in the proliferation of LCA-based ecolabels. The first LCA-supported Nordic Ecolabel was initiated in 1989[14] to guide consumers towards products with the lowest environmental impacts, and the number of product categories covered by this and other ecolabels grew rapidly under. During the 1990s many impact assessment methods evolved, and the ambition has since then been to quantify all relevant environmental impacts. The first impact assessment methodology to cover a comprehensive set of midpoint impact categories, as we know them today, was CML92 released in 1992[14]. The Society of Environmental Toxicology and Chemistry (SETAC) started playing a leading and coordinating role in bringing LCA practitioners, users, and scientists together to collaborate on the continuous improvement and harmonization of LCA framework, terminology and methodology. The SETAC "Code of Practice" was one of the key results of this coordination process, and with it the publication of an international reference framework.

> *"Life-Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life-cycle of the product, process, or activity, encompassing extracting and processing raw materials; manufacturing; transportation and distribution; use, re-use, maintenance; recycling, and final disposal"*[15] (LCA definition according to SETAC 1993)

From the latter definition it is clear that, since the begging, the LCA assessment it has been always based on a single principle: a product must be followed and analysed at every stage of its life, from its manufacturing to its disposal (cradle-to-grave). Next to SETAC, the International Organization for Standardization (ISO) has been involved in LCA since 1994. Whereas SETAC working groups focused at development and harmonization of methods, ISO adopted the formal task of standardization of methods and procedures. It contributed with two international standards used until date:

- ISO 14040 (first released: 1997): 'Environmental management - Life cycle assessment - Principles and framework';
- ISO 14044 (first released: 1998): 'Environmental management - Life cycle assessment - Requirements and guidelines.

The main result of ISO's standardization work has been the definition of a universal methodological framework, which made it easier to compare different LCAs. It is important to keep in mind that even with the consensus on the framework, ISO never aimed at defining the exact methods by stating: "there is no single method for conducting LCA".

The early 1990s also saw the birth of a number of life cycle inventory databases managed by different institutes and organisations and covering different industrial sectors. Due to

[15] SETAC, chapter 3. Guidelines for Life-Cycle Assessment: A "Code of Practice"

differences in data standards and quality, the resource uses and emissions of a single industrial process could, however, differ substantially in the different databases, but at this point in the development, the focus was on expanding the coverage and for many processes, there were no data at all. This situation was improved in 2003 with the release of the first eco-invent database covering all industrial sectors and aiming for consistent data standards and quality.

- **2000 until nowadays, integration with building and construction (B/C) sector**

From the start of the 21st century, it has been recognised that the integration of LCA into daily practice could help achieve sustainable practices. This awareness has resulted in interest for LCA in many sectors of industry, including the building and construction (B/C) sector. Once again SETAC played an important role with the publication of a state-of-the-art-report on Life-Cycle-Assessment in building and construction in 2003. This study highlights the important issues that arise when LCAs are performed in the B/C sector and the main differences between the general approach of LCA and LCAs of buildings[16].

Such standardization continued, with two leading organizations, the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN). One of the first standard to be realised by CEN technical Committee 350 “Sustainability of construction works”, was EN 15978 in 2011used until date. EN 15978 was part of a much broader project to fully define how to measure the sustainability of buildings made of:

- Environmental performance,
- Social performance,
- Economic performance.

Therefore, the final objective was to cover the full suite of buildings’ sustainability under one set group of standards. The present buildings’ sustainability standards and LCA standards situation is explained in the Chapter 2.2.

Currently European environmental policies refer to LCA methodology. For example, as regarding Italy, both the D.Lgs 50/2016 about Green Public Procurement (GPP) and the minimum environmental criteria (CAM), defined by D.M. 6/11/2017 n.259, refer to LCA methodology.

This is also an indicator of how the cause which bring professionals to the use of LCA has changed during years. From a company driven situation, to an environmental response to a complete shift in which policies encourage and, in some case, impose the use of this methodology.

The introduction of more stringent regulations that require clear and actionable metrics and a market increasingly concerned with the future of the planet have led to a focus on the development of tools which can help and guide professionals. Today, there are many different LCA tools available, some are focused on specific industries, while others can be used in many different industries.

[16] SETAC. Life-cycle assessment in building and construction: a state-of-the-art report

2.2 LCA STANDARDS

At the international level, the LCA methodology has always been regulated by the ISO standards of the 14040's series according to which a life cycle assessment study required: the definition of the objective and scope of the analysis (ISO 14041), the compilation an inventory of the inputs and outputs of a given system (ISO 14041), the assessment of the potential environmental impact related to these inputs and outputs (ISO 14042) and finally the interpretation of the results (ISO 14043).

All of them have been replaced by ISO 14040 and ISO 14044 since 2006.

- ISO 14040 – Environmental management – Life cycle assessment - Principles and framework: synthetizes on a theoretical level what a correct LCA evaluation must include.
- ISO 14044 – Environmental management – Life cycle assessment – Requirements and guidelines: guides the operator in the execution of an LCA study.

▪ ISO 14040

The ISO14040[17] international standard covers LCA (Life Cycle Assessment) studies and LCI (Life Cycle Inventory) studies. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA.

Life cycle assessment addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. (In the standard, with life cycle it refers to consecutive and interlinked stages, from raw material acquisition or generation from natural sources to final disposal, cradle-to-grave).

LCA is an iterative technique of which depth of detail depends on the goal and scope definition.

According to the standard there are four phases in an LCA study:

a) The goal and scope definition phase
b) The inventory analysis phase (LCI)
c) The impact assessment phase (LCIA)
d) The interpretation phase

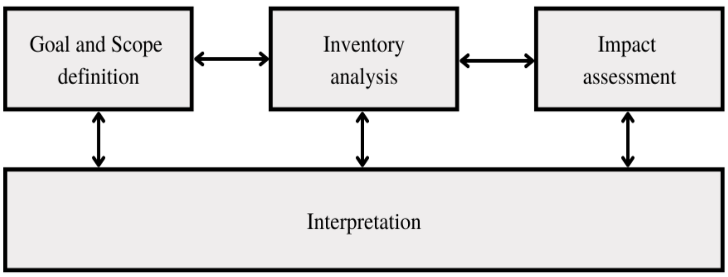

Figure 5: LCA Phases

[17] ISO/TC207. EN ISO:14040: 2006 +A1:2020

There are cases where the goal of an LCA can be satisfied by performing only an inventory analysis and interpretation. This is usually referred to as an LCI study. LCI studies are similar to LCA studies but exclude the LCIA phase.

LCI studies comprise three phases:

- The goal and scope definition
- Inventory analysis
- Interpretation

LCA models the life cycle of a product as its product system, which performs one or more functions. A product system is a model that describe the key element of physical system. It is characterized by its function and cannot be defined solely in terms of the final products. Product system are subdivided into set of unit processes. The unit process are the smallest elements considered for which input and output data are quantified. Unit processes are linked to:

- One another by flows of intermediate products and/or waste for treatment
- Other product systems by product flows
- The environment by elementary flow

Dividing a product system into its component unit processes facilitates identification of the inputs and outputs of the product system. Ideally product systems should be modelled in such a manner that inputs and outputs at its boundary are elementary flows (elementary flow: material or energy entering or leaving the system being studied without human transformation).

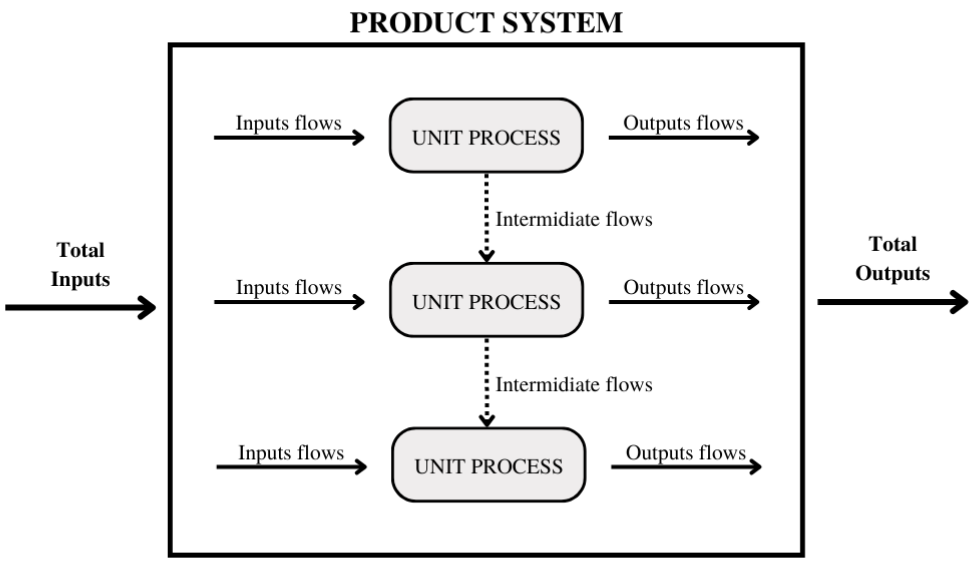

Figure 6: Example of a product system

LCA PHASES:

GOAL AND SCOPE DEFINITION (why and how the LCA is carried out):

The **GOAL** states:

- The intended application
- The reasons for carrying out the study
- To whom the results are intended to be communicated
- Whether the results are intended to be used in comparative assertations intended to be disclosed to the public

The **SCOPE** defines what is included in or excluded out from the analysis. Thanks to a correct assess of the scope it is possible to be sure that depth and detail of the study are sufficient to reach the stated goal. The scope should include:

- Product system to be studied
- Functions of the product system:

  "Comparisons between systems shall be made on the basis of the same function(s), quantified by the same functional unit(s) in the form of their reference flows".[18]

  A system may have a number of possible functions (purposes) and the ones(s) selected for a study depend(s) on the goal and scope of LCA. For each function a reference unit is settled, called functional unit. The primary purpose of the functional unit is to provide a unit to which the inputs and outputs are related and normalized (in a mathematical sense). The inputs and outputs of an LCA study are called reference flows, which are necessary to ensure comparability of LCA results.

- System boundary:

  The criteria used in setting the system boundary are important for the degree of confidence in the results of a study and the possibility of reaching its goal.

- Data quality requirements:

  Data quality requirements specify in general terms the characteristic of the data needed for the study

LIFE CYCLE INVENTORY ANALYSIS (LCI)

The inventory analysis are iterative processes that involve data collection and calculation procedures to quantify relevant inputs and outputs of a product system. (Collection procedures are adopted to meet the settled goal. Sometimes, issues may be identified be identified that require revisions to the goal or scope of the study).

- DATA COLLECTION: data collected for each unit process within the system boundary can be classified in the following macro-categories:
  - Energy inputs, raw material inputs, ancillary inputs other physical inputs
  - Products, co-products and waste

[18] ISO/TC 207, chapter 4.2.3.2. EN ISO 14044: 2006 + A2: 2020

- Emissions to air, discharge to water and soil
- Other environmental aspects

- DATA CALCULATION, calculations procedures include:
  - Validation of data collected
  - Relating of data to unit processes
  - Relating of data to the reference flow of the functional unit

(See ISO 14044 for the procedures explanations)

It is important to underline that just a few industrial processes are based on a linearity of raw material inputs and outputs. In fact, most of industrial processes yield more than one product, and they recycle intermediate or discarded products as raw material. For these reasons, considerations should be given to the need for allocation procedures when dealing with systems involving multiple products and recycling systems. (Allocation procedures are explained in details in the LCI chapter in ISO 14044)

LIFE CYCLE IMPACT ASSESSMENT (LCIA)

This process involves associating inventory data with specific environmental impact categories and category indicators. LCIA is aimed at evaluating the significance of potential environmental impacts using the LCI results. The impact assessment may include the iterative process of reviewing the goal and scope of the LCA study to determine if the objectives of the study have been met, or to modify the goal and the scope if the assessment indicates that they cannot be achieved. It is important to note that LCIA addresses only the environmental issues that are specified in the goal and scope. Therefor LCIA is not a complete assessment of all environmental issues of the product system under study. (See LCIA in the ISO 14044 for more detailed information)

LIFE CYCLE INTERPRETATION

Interpretation is the phase in which findings from the inventory analysis and impact assessment are considered together. This phase should deliver results that are consistent with the defined goal and scope. The finding of this interpretation may take the form of conclusions and recommendations to decision-makers, consistent with the goal and scope of the study. (See "life cycle interpretation in the ISO 14044 for more detailed information)

REPORTING

The results and conclusions of an LCA must be reported in an adequate form to the intendent audience. Data, methods, assumptions and limitations should be clearly stated.

- **ISO 14044**

The ISO14044[19] international standard specifies requirements and provides guidelines for life cycle assessments. It enhances and completes the standard ISO 14040 to which refers. Therefore, ISO 14044 explain in a more detailed way all the different LCA phases which also represent the main chapters of the standard. For this reason, some of the concept that were already deepened in the latter standard will not explained again.

LCA PHASES

GOAL AND SCOPE DEFINITION

While the goal is well explained in ISO 14040, the scope is defined IN ISO 14044 through the following items:

- The product system to be studied
- The function(s) of the product system and the functional unit used
- The system boundary
- Data quality requirements

While the first two were already explained (in chapter 2.2, subchapter: ISO 14040) the latter two are enhanced as follow:

- System boundary: it determines which unit process shall be included within the LCA and also the level of detail to which this unit processes shall be studied. Any decisions to omit life cycle stages, processes, inputs or outputs shall be clearly stated and explained. It is helpful to describe the system using a process flow diagram showing the unit processes and their inter-relationship. Ideally, the product system should be modelled in such a manner that inputs and output at its boundary are elementary and product flow. The cut-off criteria shall be clearly described. Cut-off criteria are used in LCA practice to decide which inputs are to be include in the assessment such as: mass, energy and environmental significance.
- Data quality requirements: it should address the following characteristics:
    a) Age of data and minimum span of time of the collection of data
    b) Geographical area from which collect data
    c) Technology coverage
    d) Precision (measure of the variability of the data)
    e) Completeness (percentage of the flow that is measured or estimated)
    f) Qualitative assessment of the degree to which the data set reflects the true population of interest
    g) Qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis
    h) Reproducibility
    i) Sources of data
    j) uncertainty of the information (e.g., assumptions).

Moreover, the ISO 14044 add three more items to define the scope of LCA study, which are:

[19] ISO/TC207. EN ISO:14044: 2006 +A2:2020

- Allocation procedures (that are well explained as a step of the LCI in the following paragraphs)
- LCIA methodology and type of impacts: It shall be determined which impact categories; category indicators and characterization models are included within the LCA study. (The selection of all of them shall be consistent with the goal of the study)
- Types and sources data (detailed in Annex A of ISO 14044): data selected depend on the goal and scope of the study. All data may include a mixture of measured (from the production site associated with the unit processes), calculated or estimated data.

LIFE CYCLE INVENTORY ANALYSIS (LCI)

According to ISO 14040 the LCI phase is made of two different steps. In turn, ISO 14044 other than recall these two steps, it also introduces a third one: the allocation, born to deal with systems involving multiple products and recycling systems. Therefore, an LCI study is made of:

- Collecting data: data shall be collected for each unit process. The collected data whether measured, calculated or estimated are utilized to quantify the inputs and outputs of a unit process. Sources shall be referenced. (See the chapter LCI of the official standard ISO 14040 for a more detailed explanation).
- Calculating data:
    - Validation of data: a check on data validity shall be conducted. Validation may involve establishing mass balance or energy balance, as each unit obeys the laws of conservation of mass and energy.
    - Relating data to unit process and functional unit: a flow with related quantitative input and output data shall be determined for each unit process. The flows of all unit processes are related to the reference flow (flow of a product system). Care should be taken when aggregating the inputs and outputs in the product system. Data should only be aggregated if they are related to equivalent substances and similar environmental impacts.
    - Refining the system boundary: the initial system boundary shall be revised.
- Allocation: the inputs and outputs shall be allocated to the different products. Many processes produce more than one product, in such cases it is necessary to divide the environmental impacts from the process between the products, even though it is not a straightforward procedure. The ISO 14040-series suggest using system expansion whenever possible and where it is not possible to use it, allocation can be used. Standards provide the following stepwise procedure:
    a) STEP 1
    Whenever possible allocation should be avoided by:
    1) Dividing the unit processes to be allocated into two or more sub-processes.

2) *Expanding the product system* (this step is studied in deep in annex D of the official Standard ISO 14044):

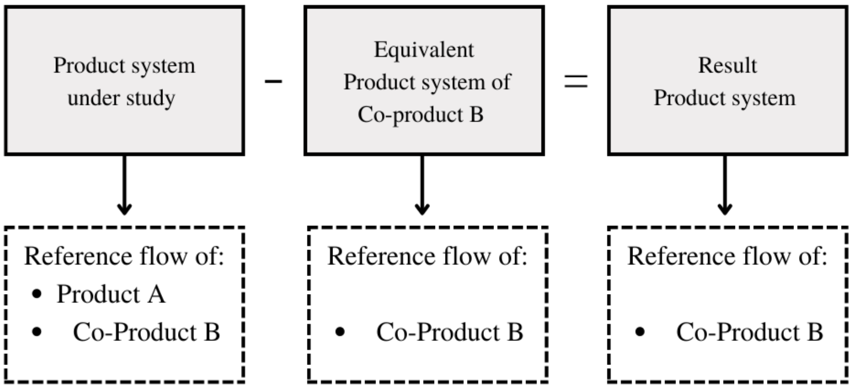

Figure 7: Schematic representation of the system expansion procedure

expanding the product system to include additional functions related to the co-products can be means of avoiding allocation. In practice, the co-products are compared to a functionally equivalent product system, that is assumed to be the substitute of the co-product. The inputs and outputs associated with the substituted product system are assumed to be avoided by the production of the co-product. So, in order to get inputs and outputs of the product, the input and output of the avoided co-product are subtracted to the product system under study (Figure 7). The application of system expansion involves an understanding of the market for the co-products. Decisions about system expansion can be improved through understanding the way co-products compete with other co-products.

It is important to underline that the system described above shows how to avoid allocation when the investigated product system has two products: product and co-product. Where system expansion models are complex, the data requirements can be onerous. It is not always straightforward to identify the products that are assumed to be substituted by co-products of the multifunctional process.

b) STEP 2 (physical)

When allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different functions. (They should reflect the way in which inputs and outputs are changed by quantitative changes in the functions).

c) STEP 3

Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them (ex: economic value).

Particular attention should be given in common case of when output are partly co-products and partly waste. In these cases, it is necessary to identify the ratio between co-products and waste since the allocation procedure should refer to just the co-product. While, in case of reuse and recycling the allocation procedure can be applied but additional elaboration is needed.

LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The LCIA consists of mandatory and optional elements.

Mandatory elements:

- Selection of impact categories, category indicators and characterization models

  Useful definitions:

Term	Definition	Example
Impact Category	Class representing environmental issues to which LCI results may be assigned	Climate change
Characterization model	Model referred to	Baseline model of 100 years
Impact Category Indicator	Quantifiable representation of an impact category	Infrared radiative forcing (W/m^2)

Table 2: Definitions of: Impact category, characterization model, impact category indicator

For most LCA studies, existing impact categories, category indicators or characterization model will be selected. However, in some cases the existing ones are not sufficient to fulfil the define goal and scope of the LCA and new ones have to be defined.

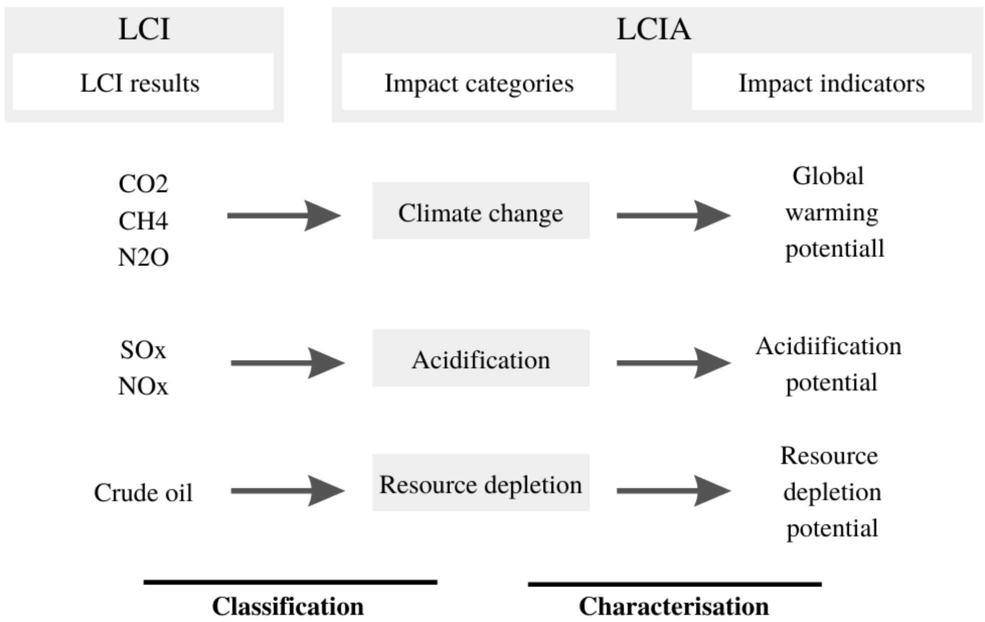

Figure 8: Schematic representation of Life Cycle Impact Assessment

- Assignment of LCI results to the selected categories (**classification**)
  1. Assignment of LCI results that are exclusive to an impact category
  2. Identification of LCI results that relate to more than one impact category. Which includes:
     - LCA results which contributes to different impact category
     - LCA results which refer to different characterization factor

- Calculation of category indicator results (**characterization**)
  This phase involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category. This conversion uses characterization factors. The outcome of the calculation is a numerical result. The usefulness of the indicator results for a given goal and scope depends on the accuracy, validity and characteristics of the characterization models and characterization factors.

Optional elements:

- Normalization: The aim of the normalization is to understand better the relative magnitude for each indicator result of the product system under study
- Grouping: sorting and possibly ranking of the impact categories. There are two different possible procedures:
    - sorting and possibly ranking of the impact categories on a normal basis
    - to rank the impact categories in a given hierarchy
- Weighting: Weighting is the process of converting indicator results of different impact categories by using numerical factors based on value-choices. Once again, two possible procedures can be followed:
    - to convert the indicator results or normalized results with selected weighting factors, or
    - to aggregate these converted indicator results or normalized results across impact categories

  It is important to state that, weighting steps are based on value-choices and are not scientifically based.
- Data quality analysis: additional techniques and information may be needed to understand better the significance, uncertainty and sensitivity of the LCIA results

LIFE CYCLE INTERPRETATION

The life cycle interpretation phase of an LCA or an LCI study comprises several elements:

- identification of the significant issues based on the results of the LCI and LCIA phases of LCA;
- an evaluation that considers completeness, sensitivity and consistency checks. The results of the evaluation should be presented in a manner that gives the commissioner or any other interested party a clear and understandable view of the outcome of the study.
    - Completeness check: ensure that all relevant information and data needed for the interpretation are available and complete. In case of missing data, based on they relevance could be necessary or to record their missing or to revisit and/or adjust the scope and goal of the study
    - Sensitivity check: The objective of the sensitivity check is to assess the reliability of the final results and conclusions by determining how they are affected by uncertainties in the data

- Consistency check: The objective of the consistency check is to determine whether the assumptions, methods and data are consistent with the goal and scope.

- conclusions, limitations, and recommendations: The objective of this part of the life cycle interpretation is to draw conclusions, identify limitations and make recommendations for the intended audience of the LCA. This should be done iteratively with the other elements in the life cycle interpretation phase.

REPORTING

The results and conclusions of the LCA shall be completely and accurately reported without bias to the intended audience. The results, data, methods, assumptions and limitations shall be transparent and presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA. The report shall also allow the results and interpretation to be used in a manner consistent with the goals of the study

2.3 LCA IN THE BUILDING SECTOR

In the building sector, the LCA methodology can be applied at several levels. Different field of application lead to different assumptions and different system boundaries, both of which adapt themselves to the object under study. Possible levels of application:

- Building product (e.g. brick, concrete, paint, etc.) or constructive solution (e.g. masonry technological system): LCA analyses the life cycle starting from the extraction of raw materials, then evaluates environmental impact due to: transport, production in the factory, installation on site, maintenance and/or replacement during use, demolition method and consequent disposal/recycling at the end of its life;
- Building: LCA analyses the environmental impact related to construction materials, but also the environmental impact associate to the use phase of the building by analysing the usage of energy and water made users during the life-span of the building under study;
- District: LCA takes into account the building from which it is composed but also the green areas, street furniture, roads and public utilities. With the same approach up to the analysis of the complex system of a city.

As regarding LCA standards in the building sector as shown in the figure below the general requirements for sustainability assessment of buildings are described from the EN 15643's series.

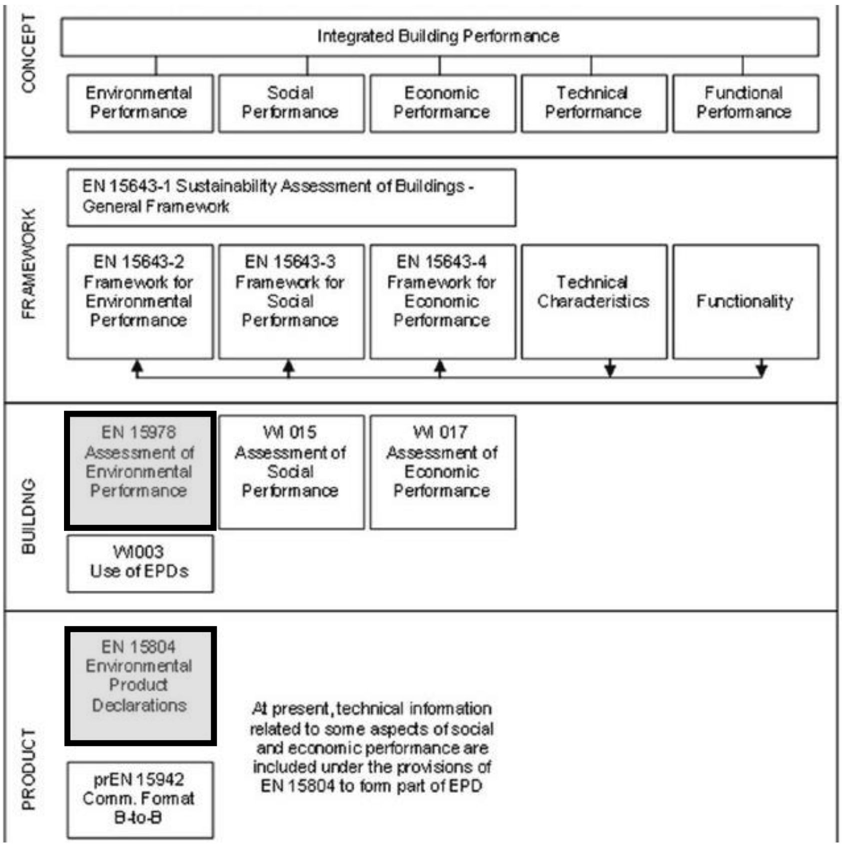

Figure 9: CEN/TC 350, chapter: Introduction. EN 15978

From the chart it is clear that the environmental performance of a building is only one aspect of its sustainability. The social and economic performance of the building are also aspects of sustainability that should be assessed as part of sustainability assessment. According to the aim of this thesis just the environmental performance will be analysed and with it the two main standards applicable in this field:

- Building scale: EN 15978 - Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method: specifies the calculation method, based on LCA, to assess the environmental performance of a building, and gives the means for the reporting and communication of the outcome of the assessment. The approach to the assessment covers all stages of the building life cycle and is based on data obtained from Environmental Product Declarations (EPD), their "information modules" (EN 15804).
- Product scale: EN 15804 - Sustainability of construction works – Environmental product declarations - Core rules for the product category of construction products: provides environmental products declaration (EPD) and other information for construction products and construction services necessary and relevant for carrying out the LCA assessment.

▪ EN 15978

the EN 15978[20] states a clear division of the different stages of the building assessment, as showed in the following table:

A 1-3			A 4-5		B 1-7							C 1-4				D
PRODUCT Stage			CONSTRUCTION PROCESS Stage		USE Stage							END OF LIFE Stage				Supplementary information beyond the building life cycle
					Building Fabric					Operational usage						
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw materials	Transport	Manufacturing	Transport	Construction-installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling Potential
Cradle-to-Gate			Gate-to-Grave													
Cradle-to-Grave																
Cradle-to-Cradle																

Table 3: Building assessment stages

The standard provides also steps to follow in order to carry out and complete the calculation necessary for the assessment of environmental performance (Figure 10).

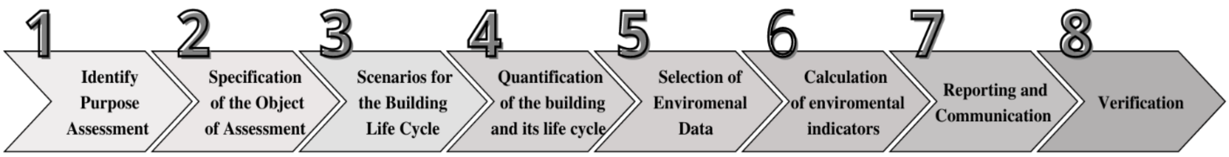

Figure 10: Flowchart of the process for the assessment of the environmental performance

[20] CEN/TC 350. EN 15978:2011

Except for steps which bring to unique results for all stages (A1-5, B1-7, C1-4, D), such as scope and goal, all the other steps should be determined for each stage separately.

1. IDENTIFY PURPOSE OF ASSESSMENT

The purpose of the assessment is defined by the:

- goal
- scope
- intended use of the assessment

This step is important because determining why and how an LCA is conducted will help the assessor to direct all the effort and ensure that all the work is meeting the goal. According to that the identification of the scope defines what is included in or excluded from the analysis.

2. SPECIFICATION OF THE OBJECT OF ASSESSMENT

The object of assessment is the building under analysis. The following items must be identified:

- Functional equivalent (describes the key function(s) of the object of assessment):
  the functional equivalent is a representation of the required technical characteristics and functionalities of the building. This is important because when making comparison in LCA, you must ensure that options are equivalent in terms of the broad range of performance characteristics throughout a building life cycle so you must ensure functional equivalence. Functional equivalent shall include but it is not limited to:
    - building type
    - relevant technical and functional requirements
    - pattern of use
    - required service life
- Reference Study Period (RSP):
  assessment is carried out on the basis of a chosen reference study period. The default value for the reference study period shall be the required service life (ReqSL) of the building, but it may also differ from it. If the ReqSL ≠ RSP:
    - if RSP is longer (>) than ReqSL, scenarios for refurbishment, or demolition and construction of an equivalent new building shall be developed
    - if RSP is shorter (<) than ReqSL, it is necessary to ensure that the analysis results are scaled to the RSP. Therefore, the quantified values of impacts are adjusted by a factor RSP/ReqSL (see standard EN 15978 for more details)
- system boundary:
  the system boundary determines the processes that are taken into account for the object of assessment. For a new building, the system boundary shall include the building life cycle as shown in Table 3. In this context, the object of assessment is the building and its site. This includes all the upstream and downstream processes needed to establish and maintain the function(s) of the building, from the acquisition of raw materials to their disposal or to the point where materials exit the system boundary either during or at the end of the building life cycle (see standard EN 15978 chapter 7.4 for the application of system boundary at each stage)
- building model - physical characteristics:

the purpose of building model is to enable the quantification of the mass and energy flows. This quantification should be organised in a structured way (see annex A of standard EN 15978for more details)

3. SCENARIOS FOR DEFINING THE BUILDING LIFE CYCLE

To provide the complete description of the object of assessment, geographic and time related characteristics need to be added to the physical description of the building. This requires the development and use of appropriate scenarios representing assumptions (or, where known, real information) that can be applied to models for product, construction, use, and end-of-life stages of the object of assessment. How scenarios work in different stages:

- Product stage (A1 to A3): for this stage the environmental information are defined in the product declaration (EPD, standard: EN 15804)
- Construction process stage (A4 to A5): this stage shall cover the period from the factory gate of different construction products to the practical completion of the construction work
- Use stage (B1 to B7): this stage shall describe all activities with a relevant environmental impact arising from the operation of the building
- End of life stage (C1 to C4): this stage shall describe the processes used during the end-of-life stage.

4. QUANTIFICATION OF THE BUILDING AND ITS LIFE CYCLE

This step consists on the quantification of all materials and products determined based upon the design description of the object of assessment.

- Specification net amount: net units of products, materials, components and elements that all together constitute the building.
- Accounting for the gross amount: gross amount of material and products used to form the object of assessment, taking into account the "losses" that occur as a result of a number of diverse factors. Particular attention must be taken for:
    - Components that will not be replaced, therefore Estimated Service Life (ESL) is greater than or equal to the Request Service Life (ReqSL)
    - Replaceable components and number of replacements, therefore ESL is minor than ReqSL
- Type of data for the assessment: the choice of data depends on the scope and the availability of the information. This information may be given in different forms:
    - Aggregated data, either as a whole or for major components
    - Product/material specific data for components

  As regarding quantification specific to operational energy use and water use are derived from the EPD.

5. SELECTION OF ENVIROMENTAL DATA AND OTHER INFORMATION (use of EPD)

At the building level, the data need to address the full life cycle of the product in the context of the building. However, the LCA-based information found in an EPD may represent one of the following:

a) The product stage alone: cradle to gate
b) The product stage and selected further life cycle stages: cradle to gate with options
c) The life cycle of a product: in this case the EPD covers information required for modules A1 to C4
d) Module D: provides information on the loads and benefits from reuse, recycling and recovery beyond the system boundary.

Regarding data quality, it is important to state that, if the environmental data used are in accordance with the requirements of EN 15804 then they have to meet the requirements of the latter standard. If the environmental data are from other sources than they should be as current as possible, the emission should be accounted for at least 100 years (see the official standard EN 15978 for more details).

6. CALCULATION OF THE ENVIROMENTAL INDICATORS

Indicators used in this clause represent the quantified environmental impacts and aspects caused by the object of assessment during its whole life cycle. (Note that the environmental indicator reported in the standard have been chosen on the basis that there are agreed calculation methods).

Type of indicators:

- Indicators describing environmental impacts
- Indicators describing resources use: they describe use of renewable and non-renewable primary energy and water resources
- Indicators describing additional environmental information: they describe waste categories and output flows derived from scenarios

Calculation methods: the values for each indicator are calculated for each module in the life cycle stages based on a matrix calculation routine. (Check standard EN 15978 for the mathematical procedure)

7. REPORTING

Transparency and traceability of information represent the basis of the assessment. Thus, results shall be traceable and transparent. Therefor information shall be reported in a clear and complete way which allows the reader to assess the quality of the study. Results are usually reported and presented as structured list, according to the scenario used. Standard EN 15978 in chapter 12.5 provides different example of useable table of results.

8. VERIFICATION

The transparency mentioned in the reporting section should allow all information used, options or decisions taken to be verifiable. If there is need for verification of the assessment, a verification procedure shall be applied.

- **EN 15804**

This European standard EN 15804 provides core product category rules (PCR) to elaborate environmental label Type III: environmental products declarations (EPD), for any construction product and construction service.

The core PCR:

- defines the indicators to be declared, information to be provided and the way in which they are collated and reported;
- describes which stages of a product's life cycle are considered in the EPD and which processes are to be included in the life cycle stages;
- defines rules for the development of scenarios;
- includes the rules for calculating the Life Cycle Inventory and the Life Cycle Impact Assessment underlying the EPD, including the specification of the data quality to be applied;
- includes the rules for reporting predetermined, environmental and health information, that is not covered by LCA for a product, construction process and construction service where necessary;
- defines the conditions under which construction products can be compared based on the information provided by EPD.

EPDs are labels that describe the life cycle environmental performance of products thanks to a LCA analysis. The objective of the core PCR is to provide a structure to ensure that all environmental product declaration (EPD) of construction products, construction services and construction processes are derived, verified and presented in a harmonised way.

ENVIROMENTAL PRODUCT DECLARATION (EPD)

The purpose of an EPD in the construction sector is to provide the basis for assessing buildings and other construction works, and identifying those, which cause less stress to the environment. According the standard all construction products and materials shall declare modules A1-A3, module C1-C4 and module D. Construction product and materials that are identified as exemptions may omit the declaration of module C1-C4 and module D. Any omission of modules C1-C4 and module D shall be justified. The EPD types could be classified with respect the "system boundary" which settled which life cycle stages are covered and which ones are omitted:

- <u>Cradle to gate with modules C1–C4 and module D</u>. Stages A1–A3, C and D are the minimum to be declared for the default type of EPD.
- <u>Cradle to gate with options, modules C1–C4, and module D</u>. A1–A3, C, D are the mandatory stages to which could be added additional modules. The additional modules may be A4 and/or A5 and/or B1–B7.
- <u>Cradle to grave and module D</u>. Stages A, B, C and D are all mandatory.
- <u>Cradle to gate</u>. Stages A1–A3 are the minimum to be declared for all construction products that are exempt from declaring modules C and D and shall be based on a declared unit. This type of EPD is not allowed for products containing biogenic carbon;

- Cradle to gate with options. Stages A1–A3 are mandatory to which additional modules can be added. The additional modules may be A4 and/or A5. This type of EPD is only possible for construction products that are exempt from declaring modules C and D. This type of EPD is not allowed for products containing biogenic carbon.

An EPD consists of two key documents[21]:

- The underlying LCA report, a systematic and comprehensive summary of the LCA project to support the third-party verifier when verifying the EPD. This report is not part of the public communication.
- Public EPD document that provides the LCA results and other EPD content

The public EPD document includes the following sections[22]:

- Cover page: it shall include the main information to characterize the EPD. Such as the product name and image, the name and logotype of the EPD owner, the EPD registration number, the date of publication and validity and a statement of conformity with standards.
- Programme information: which shall include the address of the programme operator, and information about verification and PCR (such as name and organization of the PCR reviewer)
- Product information: it comprehends the address and contact information of the EPD owner, the name and location of the product site, product identifications by name, a description of the product (including its application/intended use), the reference service life (RSL), a system diagram of the processes included in the LCA divided in the LCA stages, a description of the EPD system boundary and information on which life cycle stages are not considered (if any) with a justification for the omission.
- Content declaration: it shall declare the weight of one unit of the product, as purchased, and contain information about the content of the product in the form of a list of materials and chemical substances including information on their environmental and hazardous properties.
- Environmental performance: all the results of the environmental performance indicators shall be declared per functional unit and per included life-cycles stages. The values declared refers to three different categories:
    - Environmental impact
    - Resource use
    - Output flows and waste categories
- Additional environmental information: information not derived from the LCA-based calculations
- Additional social and economic information: This may be product information or a description of an organization's overall work on social or economic sustainability, such as activities related to supply chain management or social responsibility
- References: a list of all sources referred to in the EPD

[21] https://www.environdec.com/all-about-epds/the-epd [28/10/2022]
[22] The international EPD SYSTEM, Chapter 9. GENERAL PROGRAMME INSTRUCTIONS FOR THE INTERNATIONAL EPD® SYSTEM

Basically, an EPD does not say whether a particular building material is more or less sustainable. The strength of an EPD lies in the fact that it makes it possible for consultants or developers to assess the environmental impact of different building materials – and to make informed decisions based on the various EPD's data. After verification an EPD is valid for a five-year period from the date of issue, after which it shall be reviewed and verified. An EPD shall only be reassessed and updated as necessary to reflect changes in technology or other circumstances that could alter the content and accuracy of the declaration. An EPD does not have to be recalculated after five years, if the underlying data has not changed significantly.

2.4 LCA IN GBRS (Global Building Rating System)

Due to all the environmental problems linked to construction sector, building performance has become one of the major concern of professionals in the building industry. The old approach of using separate indicators and criteria, one topic at time, such as air quality and indoor comfort, needed to be replaced. In this context, GBRSs appeared as a comprehensive way to address buildings as whole.

Green building rating systems (GBRSs) support sustainable design processes by offering objective assessment tools that allow building sustainability solutions to be assessed in accordance with standardized guidelines. Hundreds of GBRSs are now available worldwide, varying in approaches, application processes, and evaluation metrics.

GBRSs measure buildings' sustainability level by multi-criteria assessment that takes into account both quantitative and qualitative indicators. All the indicators influence the finale score for the certification according to a weighting scale and when not explicitly, all criteria are given equal weights. Qualitative criterion points are assigned whether or not a specific environmental concern is applied, making this form of credit easier to evaluate. Quantitative criteria are those that are based on numerical data and are supported by scientific methodologies. These criteria can be more difficult to implement since they require particular calculating techniques and simulations. However, adding more quantitative indicators to the GBRS, such as LCA studies, can enhance the scientific validity of the credits while encouraging innovation in the design.

GBRSs have started including Life Cycle Assessment (LCA) into their credits system as a response to the building industry's demand for validity and transparency. Therefore, LCA can be used to score points in green building and construction rating systems, basing the assessment on empirical calculation methodologies.

According to the scope of this thesis the GBRS are going to be analysed only from the point of view of LCA and how it is involved and evaluated. It is important to underline that due to the weighting scale the number of points awarded for different assessed criteria does not help to reveal their potential impact on the environment[23].

[23] W.L. Lee, C.K. Chau ∗, F.W.H. Yik, J. Burnett, M.S. Tse, chapter 1. On the study of the credit-weighting scale in a building environmental assessment scheme

- **BREEAM (British Research Environmental Assessment Method)**

BREEAM was the first commercialized GBRS and was born in UK. It provides a holistic sustainability assessment framework, measuring sustainable value in a series of categories and validating this performance with third-party certification. There are ten categories[24]:

- management (Man),
- health and wellbeing (Hea),
- energy (Ene),
- transport (Tra),
- water (Wat),
- materials (Mat),
- waste (Wst),
- land use and ecology (LE),
- pollution (Pol)
- innovation (Inn).

Therefore, the performance of a project, as measured by BREEAM, is influenced by a variety of factors, each of which contributes to achieve a specific BREEAM rating[24]:

BREEAM rating		% Score
Outstanding	★★★★★	≥85
Excellent	★★★★	≥70
Very good	★★★	≥55
Good	★★	≥45
Pass	★	≥30
Unclassified	-	<30

Table 4: BREEAM rating system

The BREEAM rating benchmarks make it possible for a client and all stakeholder to compare a building's performance to those of the BREEAM-rated structures of the same type.

BREEAM has been introducing building LCA into their schemes since 2011 when two exemplary credits were included in BREEAM UK New Construction for building LCA. BREEAM International has included building LCA since 2013.

Although building LCA standards have been available since 2011, BREEAM UK New Construction has continued to use the Green Guide (with building LCA included as an exemplary level achievement) because, until recently, building LCA has been too specialist for most design teams. Now that building LCA is better understood and several suitable tools are available, BREEAM UK New Construction 2018 has fully embraced it and completely replaced the old green guide approach, with the aim of enabling and encouraging the construction industry to rise to the challenge of further reducing the environmental impact of buildings. The LCA is introduced in BREEAM through the section: "materials", in the criteria: "*Mat 01 Life cycle impacts*". There are up to five credits available (on a total of 150). The credits can be obtained by assessing the environmental impact of the building elements through a life cycle

[24] https://bregroup.com/products/breeam/how-breeam-works/ [04/09/2022]

assessment tool. There are some mandatory building elements to analyse that make the LCA methodology itself compulsory within the protocol.

The credits are calculated thanks to the BREEAM InternationalMat01 calculator. The latter gives a score in percentage based on the robustness of the LCA tool used and the scope of the assessment in terms of the elements considered. Then percentage is converted in credits. An addition credit can be earned if at least five products are covered with verified EPD[24].

- **LEED (Leadership in Energy and Environmental Design)**

Created by the US green building council (USGBC), is the most widely used green building rating system. It provides a framework for healthy, efficient, carbon and cost-saving green-buildings. It covers the following range:

- LEED for Building Design and Construction (BD+C), which includes residential design and construction
- LEED for Interior Design and Construction (ID+C)
- LEED for Building Operations and Maintenance (O+M)
- LEED for Neighbourhood Development (ND)
- LEED for Cities and Communities

In LEED rating systems the following elements are used in order to achieve the certification[25]:

- LEED PREREQUISITIES: set by the standard, they are mandatory elements necessary in order to achieve LEED certification
- LEED CREDITS: they can be picked and chosen by the project manager and they are what truly set a building apart from the rest. Through credits it is possible to earn points
- LEED POINTS: Projects go through a verification and review process by Green Building Certification Institute (GBCI) and are awarded points, the number of points a project earns determines the level of LEED certification it receives.

	Certified	**Silver**	**Gold**	**Platinum**
LEED certification				
Points earned	40-49 points	50-59 points	80+ points	80+ points

Table 5: LEED rating system

The credits are divided in the following categories:

- Integrative process
- Location and transportation
- Sustainability of the site

[25] https://www.usgbc.org/leed [02/09/2022]

- Efficient use of water
- Energy and atmosphere
- Materials and resources
- Indoor environmental quality
- Innovation
- Regional priority

LCA methodology is introduced in the category "materials and resources" as a credit called: "*Building life-cycle impact reduction*" which has the main goal to encourage the optimization of the environmental performance of products and materials. The credit mentioned above has five options[26] depending on the time of work under study and to each option are associated the maximum number of credits it is possible to achieve:

- Option 1: historic building reuse (5 points)
- Option 2: renovation of abandoned or blighted building (5 points)
- Option 3: building and material reuse (2-4 points)
- Option 4: whole-building life-cycle assessment (3 points)

Therefore, the LCA study appears just in the fourth option which referred to new construction (building or part of building). Therefore, LCA study is rewarded with a maximum of 3 points out of a total of 110, which represents a 4% of incidence in the protocol. Option 4 consists on the conduction of a life cycle assessment of the project's structure and enclosure that must results in a minimum of 10% reduction and a maximum of 5% increase, compared with a baseline building, in at least three of the six impact categories listed below, one of which must be global warming potential:

- global warming potential (greenhouse gases), in kg CO2e;
- depletion of the stratospheric ozone layer, in kg CFC-11;
- acidification of land and water sources, in moles H+ or kg SO2;
- eutrophication, in kg nitrogen or kg phosphate;
- formation of tropospheric ozone, in kg NOx, kg O3 eq, or kg ethene; and
- depletion of non-renewable energy resources, in MJ.

The baseline building should have a comparable size, function, orientation and operating energy performance with respect to the analysed building. As regarding the service life, it should be the same and at least 60 years for the baseline and the proposed building. LEED protocol rewards with an additional credit if at least twenty products used in the project, supplied by at least five different manufacturers, are certified with environmental product declaration (EPD). Data set must be compliant with ISO 14044 and the assessment has to be carried out with the same software tools for both the baseline and proposed building. For European projects, EN standard 15978 may be used as framework for the Life-Cycle-Assessment, but where implementation of EN 15978 conflicts with any of requirements of this credit, the credit requirements prevail. It is possible to notice that the LCA assessment in LEED protocol does not take into account the environmental impact during the use stage of the building, and it still has an ancillary role in establishing the certification level of the analysed building. For this

[26] https://www.usgbc.org/credits/healthcare/v4-draft/mrc1 [02/09/2022]

reason, it is possible to state that LCA assessment in LEED protocol still has some applicative shortcoming to be solved.

▪ DGNB (Deutsches Gutesiegel Nachaltiges Bauen)

The DGNB System was the first scoring system to contain within it, from the beginning, the Life Cycle Assessment. It evaluates the overall performance of a building based on criteria. If these criteria are fulfilled in an outstanding way, the building receives a certificate or pre-certificate in platinum, gold, silver or bronze for existing real estate. The certification method is organized as follow:

	Platinum	**Gold**	**Silver**	**Bronze**
DGNB certification				
Total performance index	80% and higher	65% and higher	50%and higher	35% and higher
Minimum performance index	65%	50%	35%	--%

Table 6: DGNB rating system

The protocol is made by six macro-categories:

- environmental quality
- economic quality
- sociocultural and functional quality
- technical quality
- process quality
- site quality

LCA methodology is taken in to account in the following criterion: "*Environment 1.1 – Life Cycle Impact Assessment*". The maximum points including bonuses that can be achieved in this criterion are 130 points with a total share of 9.5% on the global score[27] (considering a residential building). It is interesting to underline that a particular importance is given to the LCA methodology in the early planning process, during which the building variants included in the planning phase are compared with regard to their potential environmental impacts. As part of this, information from at least three different specialist planners is included in the assessment.

▪ GREEN-STAR

Green-Star was developed by Green Building Council of Australia and nowadays is used in South Africa too. The Green Star rating system assesses the sustainability of projects at all stages of the built: from architectural drawings and community development plans to the bricks and mortar of construction, from the chairs and paints of interior fitouts to the energy

[27] DGNB system – new buildings criteria set, Env1.1 building life cycle assessment.

monitoring and waste management of building operations. Thus, there are four Green Star rating tools, which provide a means of certification for building design and construction, operation, fitouts and communities[28]. These tools assess the sustainability of a building awarding points across nine holistic impact categories:

- Management
- Indoor Environmental Quality (IEQ)
- Energy
- Transport
- Water
- Materials
- Land use and ecology
- Emissions
- Innovation

Green Star – Design, As Built, Interiors and Communities projects can achieve a Green Star certification of 4 – 6 Star Green Star. Buildings assessed using the Green Star – Performance rating tool can achieve a Green Star rating from 1 – 6 Star Green Star28[28].

★	★★	★★★	★★★★	★★★★★	★★★★★★
Minimum Practice	**Average Practice**	**Good Practice**	**Best Practice**	**Australian Excellence**	**World Leaderships**
Performance					
			Design & As built		
			Interiors		
			Communities		

Table 7: Green Star rating system

LCA methodology is taken into account in the credit called: Life Cycle Impacts of the materials category. There are up to 7 points available for LCA[29] (out of 110 total points available) that represents 6.4% of all credits available.

▪ ITACA

ITACA it is an Italian multi-criteria system aimed to assess the environmental sustainability of buildings. It is made of five macro-themes:

- Area A: site quality
- Area B: resources exploitation
- Area C: environmental loads
- Area D: environmental indoor quality
- Area E: services quality

Each area consists of more than one category, each of which deals with a particular aspect of the main starting area. In turn each category is subdivided in criteria which deal with a particular

[28] Greenstar (Green building Council of Australia). Introducing Green Star
[29] https://gbca-web.s3.amazonaws.com/media/documents/dab-v1.3-credit-categories.pdf [26/09/2022]

aspect of the starting category. Thanks to the set of criteria, it is possible to calculate a final performance score representative of the building's sustainability level. The evaluation procedure to achieve the final performance is divided into the following phases:

- characterization: the performance of the building for each criterion is quantified through appropriate indicators
- normalization: the value of each indicator is made dimensionless and is "rescaled" in a normalization range
- aggregation: normalized scores are combined together to determine the final score

The final score of the building is influenced not only by the "quality" of the building but also by the "quality" of the location.

The reference standard of ITACA protocol never mentions the LCA. Despite areas such as B and C deals with concepts which are at the base of a Life cycle assessment, ITACA standard gives to the assessor all the indications to be able to conduct the necessary calculations without ever recall the LCA methodology.

Therefore, the credit: C.1.2. "Foreseen emission in an operative stage" can be considered the only integration between the LCA study and ITACA protocol. The mentioned credit, as suggested by the name, is part of the area C (environmental load) and category C.1. (CO_2 equivalent emissions). For this credit 5 points can be earned:

▪ PROTOCOLS COMPARISON

Excluding ITACA which does not include directly LCA methodology, all the remaining GBRSs refer to LCA but in none of them it really makes a remarkable difference. The following table supply a schematic view of the three protocols in order to offer an easier comparative view.

<table>
<tr><th>GBRSs</th><th colspan="2">BREEAM</th><th colspan="2">LEED</th><th colspan="2">DGNB</th><th colspan="2">GREEN-STAR</th></tr>
<tr><td rowspan="2">Points arned</td><td>LCA</td><td>5</td><td>LCA</td><td>3</td><td rowspan="2">LCA</td><td rowspan="2">130</td><td rowspan="2">LCA</td><td rowspan="2">7</td></tr>
<tr><td>EPD</td><td>1</td><td>EPD</td><td>1</td></tr>
<tr><td>Weight in percentage</td><td colspan="2">6%[30]</td><td colspan="2">3%</td><td colspan="2">9.5%</td><td colspan="2">6.4%</td></tr>
<tr><td>Mandatory requirement</td><td colspan="2">✓</td><td colspan="2">-</td><td colspan="2">✓</td><td colspan="2">-</td></tr>
<tr><td rowspan="2">Part of the building assessed</td><td>Required elements:</td><td>Envelope, structure, finishes, upper floors, internal walls</td><td rowspan="2">Required elements:</td><td rowspan="2">Structure and enclosure</td><td colspan="2" rowspan="2">Structure</td><td colspan="2" rowspan="2">Not specified</td></tr>
<tr><td>Extra credits:</td><td>Foundations, internal finishes, building services</td></tr>
</table>

Table 8: comparative table about LCA in different protocols

[30] Green Building Council Italia, chapter: 2.4. Life Cycle Assessment in edilizia.

2.5 LCA TOOLS

The increased interest in building sustainability and how to better achieve it has as a response the rise of Building LCA tools. The demand for a clear, objective way to measure the carbon footprint and other environmental impacts of buildings worldwide has led to increased adoption of scientific methodologies applied to the built environment, like Life Cycle Assessment and thus to an LCA tool equally clear and objective which could help professionals in their daily work life. As a result, many governmental bodies, academic institutions, and private bodies have invested in developing tools to calculate the environmental impacts of buildings. Life Cycle Assessment calculations rely on Life Cycle Inventory data. Whilst many tools offer their own databases. LCA database come to help in gathering the data of the complete supply-chain. As such, the LCA practitioner can focus on the main hotspots in their system and its supply chain, without having to spend extensive amounts of time uncovering details of the supply chain. Once data are available, thanks to database, the different software give the possibility to personalize the study setting parameters like: quantity of material, type and distance of the transportation, service life, end-of-life treatment, energy, and water consumption and so on. Making professionals' life easier, LCA tool are nowadays also recognize by GBRS that can be thus achieved thanks to them.

▪ ONE CLICK LCA

The tool used for the aim of this paper is One Click LCA, specifically designed for the construction industry and therefore made of functionalities specifically needed for the construction sector. One Click LCA software allows to calculate the carbon footprint and other environmental impacts of your buildings, thanks to automated data import. It is online and it is recognized by more than 30 GBRSs among which: BREEAM, LEED, DEGNB etc.

The One Click LCA platform provides the following types of market-based LCA data, covered by One Click LCA's Quality Policy (DQP) and usable for the calculation[31]:

- Public EPD data: any EPD published anywhere in the world that has suitable construction sector data
- Public LCA data: any LCA data published anywhere in the world that is suitable for construction uses
- One Click LCA generic data - Materials: generic LCA data for key materials, either country specific or global. All global data is automatically adapted to represent better local manufacturing
- One Click LCA generic data – Processes: generic data for energy and processes. Energy data are country specific; processes are global or regional.

[31] https://www.oneclicklca.com/how-we-work-with-data-at-one-click-lca/ [15/10/2022]

3. CASE STUDY

The project under study is a new residential building located in the intersection between via Venosta and via Martini. That area is in the South-West peri-urban area of Milan, in a context of a functional residential-tertiary-productive mix, under an ongoing requalification.

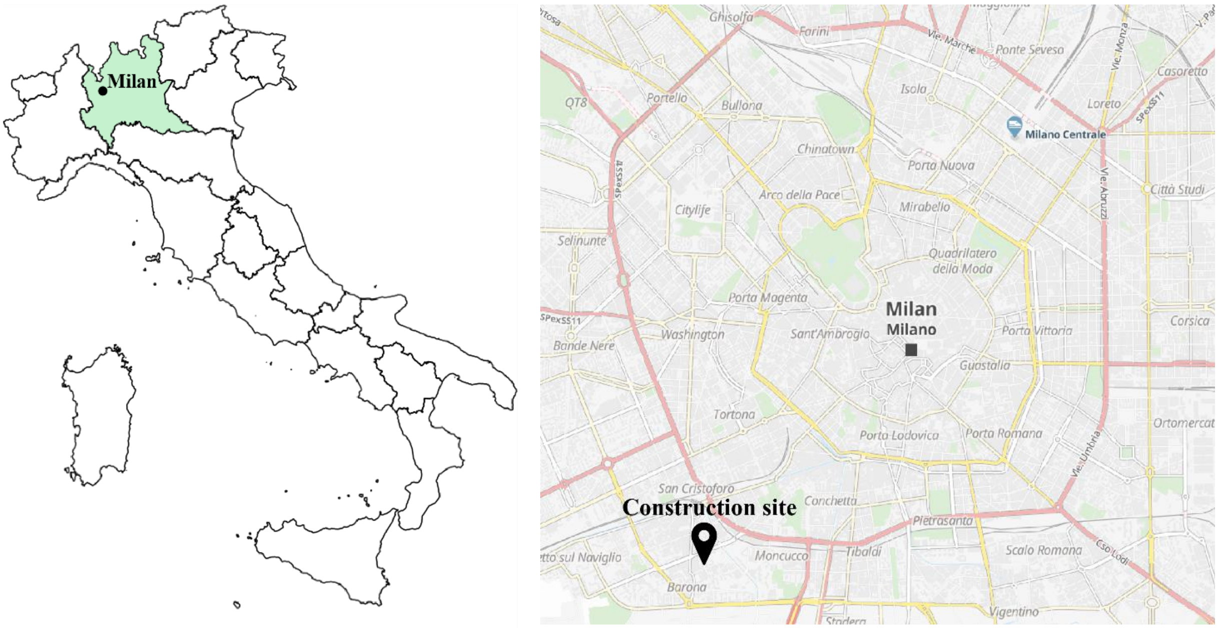

Figure 11: General framework

The construction site, has a total area of approximately 3,750 m2; it is bordered to the north and east by other properties, to the west by via Venosta and to the south by via Martini.

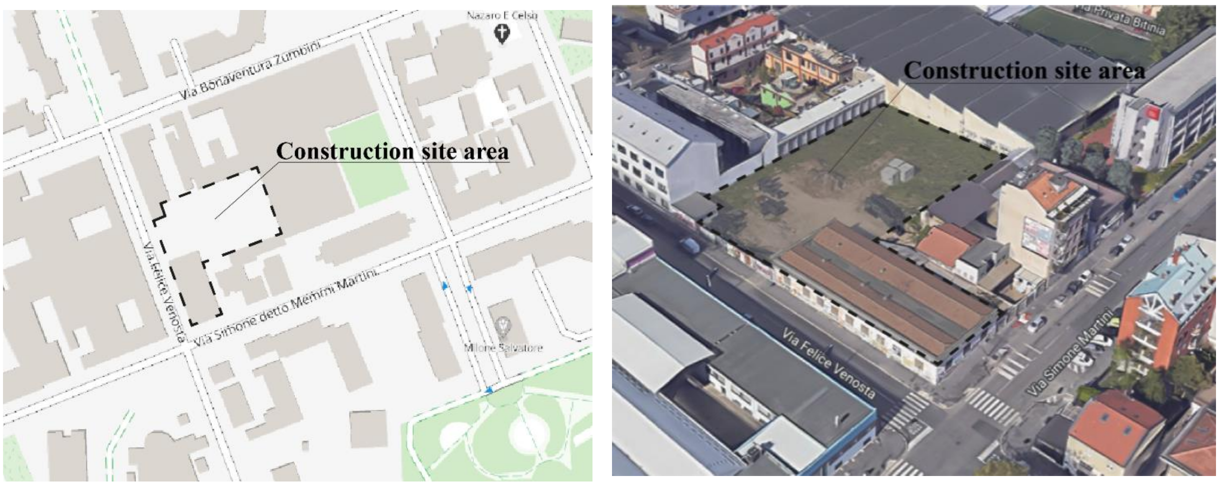

Figure 12: Construction area

The aim of the project is to continue the requalification of the area in which is localized. The key element of the project is the sustainability: starting from the choice of materials up to the choice of subcontractors with a certified green supply chain. Respect for the environment and the correct man-built relationship will be the main focuses of the project.

The project arises on a former industrial: it is a sinuous and harmonious 5-storey building, with over 65 apartments, for a total area of almost 7,000 m2, as well as a large internal garden and underground boxes. Plans, elevations and sections, supplied by Gruppo Boffa Petrone & Partners, are shown below.

Figure 13: Basement plant

Figure 14: 1st floor plant

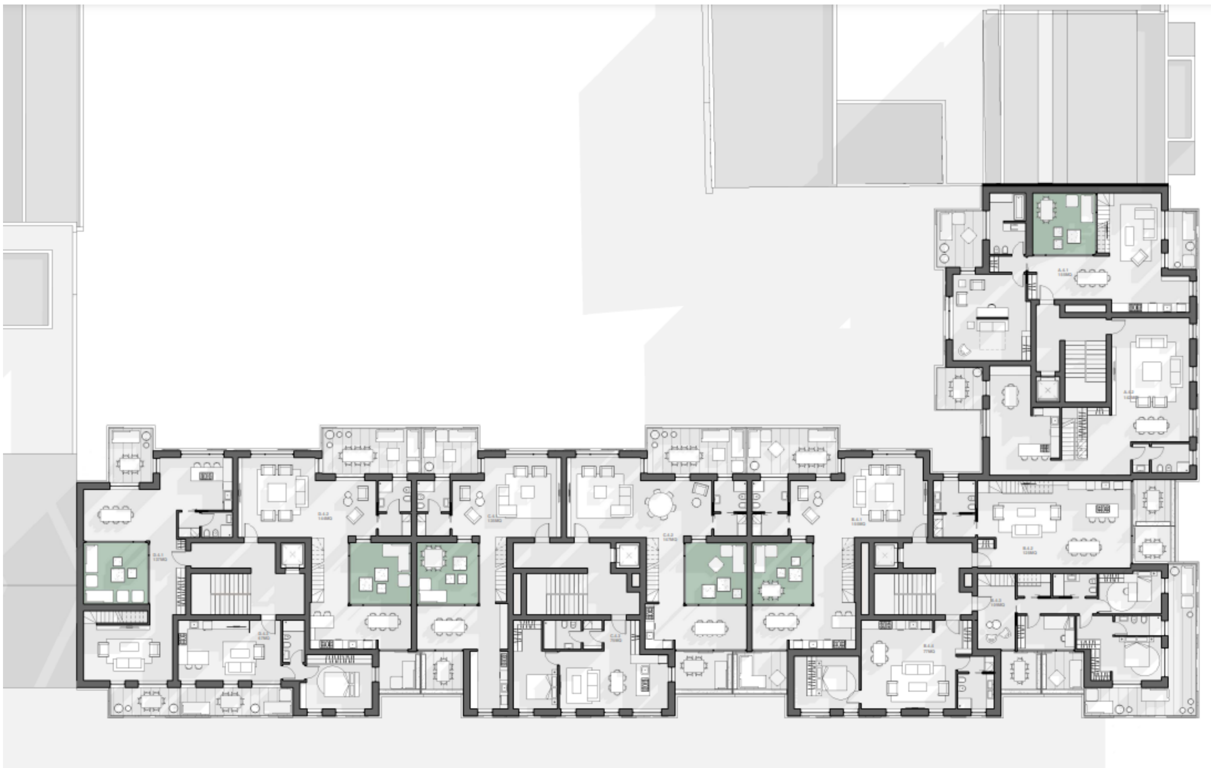

Figure 15: 2nd -4th floor example plan

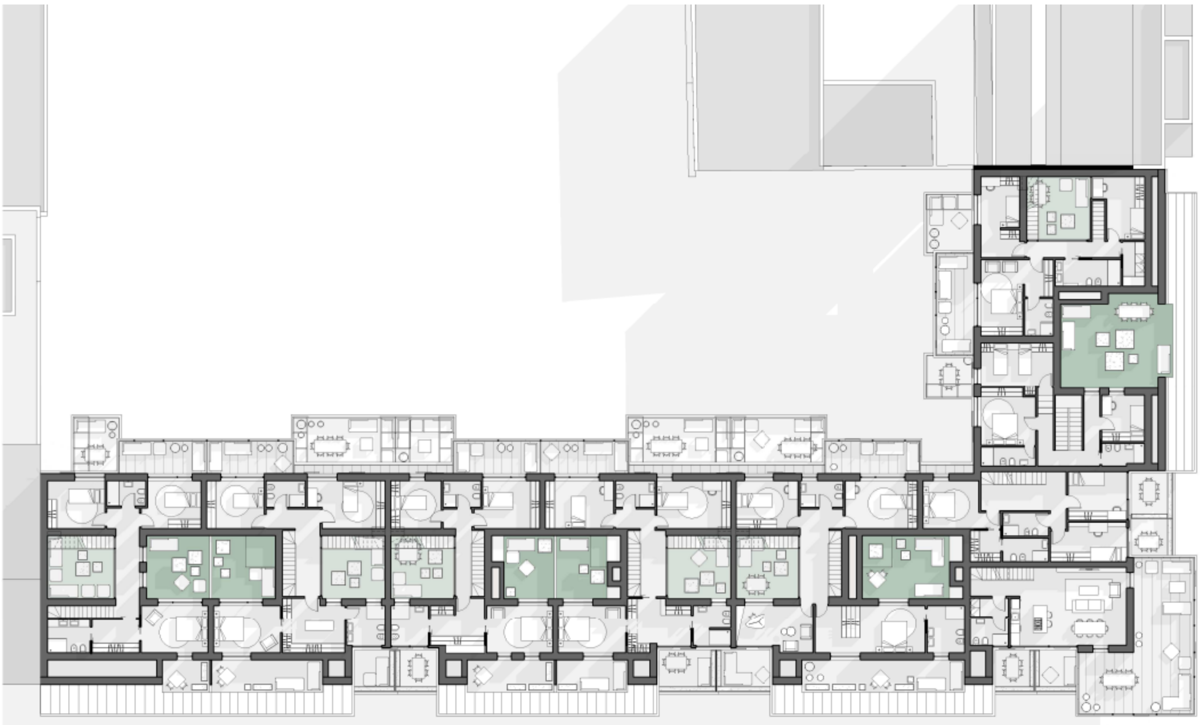

Figure 16: 5th floor plan

Figure 17: 6th floor plant

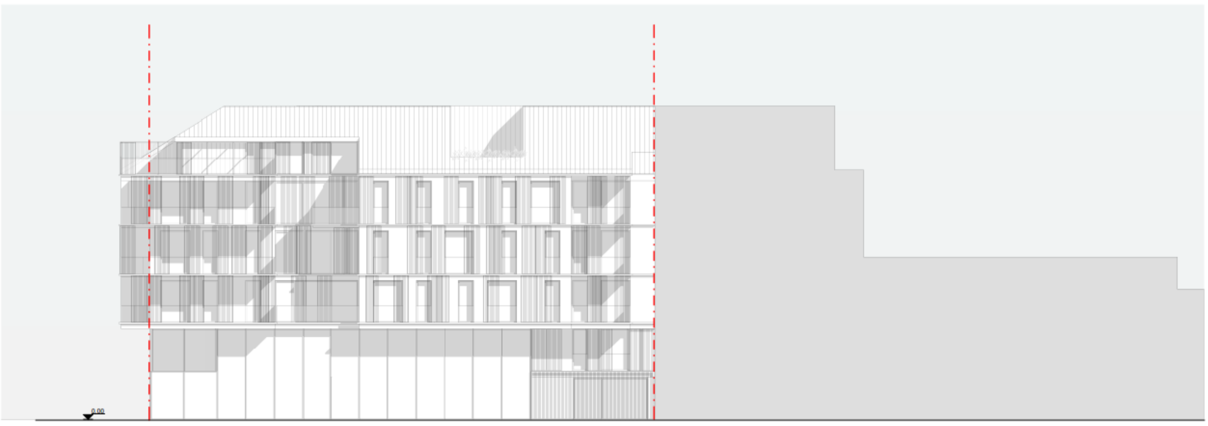

Figure 18: Elevation, South-Est

Figure 19: Elevation, South-West

Figure 21: Section A-A'. Elevation North-West

Figure 20: Section B-B'. Elevation North-Est

In complete agreement with the primary objective of sustainability, my thesis intends to research strategies and solutions to understand and reduce the foot print of the project. By acting in a preliminary phase, characterized by decisions and choices to be made, my goal is to demonstrate how more informed choices can make the difference. For the study, I chose to focus my attention on one of the building components that most contributes to its carbon emissions: the external opaque vertical envelope. Through the use of Revit, the main quantities regarding the external wall are settled. The most useful one is the total area in m^2. Through the area and the characteristic proprieties of each material (such us density) it was possible to calculate all the necessary data for the calculations.

<Abaco dei muri esterni>

A	B	C	D
Tipo	Area	Larghezza	Volume
Muro esterno - 45 cm	4061.26 m²	45.00	1811.40 m³

Figure 22: Abaco with quantities (extracted from Revit)

External wall

In order to carry out a study as complete as possible, I decided to analyse the globally most used solutions of external vertical opaque envelope in the residential building sector: a traditional masonry wall, a CLT wood wall and a drywall. The stratigraphy of all the proposal have been developed in order to ensure the same value of thermal transmittance, equal to: 0.185 W/m^{2}K. The thermal transmittance of each wall typology was calculated using the following formula:

$$U = \frac{1}{R} = \frac{1}{R_{si} + \frac{s_1}{\lambda_1} + \frac{s_2}{\lambda_2} + \frac{s_3}{\lambda_3} + \cdots + R_n + R_a + R_{se}}$$

Where:

U = thermal transmittance [W/m^{2}K]

R = thermal resistance [K m^2/W]

R_{si} = internal heat transfer resistance [K m^2/W]

s_i = thickness of the layer number i [m]

λ_i = specific thermal conductivity of the layer number i [W/(mK)]

R_n = thermal resistance of non-homogeneous materials [K m^2/W]

R_a = thermal resistance of air cavity [K m^2/W]

R_{se} = external heat transfer resistance [K m^2/W]

R_{si} and R_{se} are tabulated values, and for a horizontal heat flow are respectively equal to 0.13 and 0.04.

It is important to highlight that for the purpose of this thesis the materials composing the stratigraphy are changed more than once, but to have reliable results all the materials used will ensure a thermal transmittance of the walls equal to 0.185 W/m^{2}K with a range of variability.

In any case, considering all the substitutions, I treat values of thermal transmittance minor than the maximum value supplied by the reference standard. According to D.P.R 412/1993 to determine the heat requirement of a specific area of Italy, the national territory was divided into six climatic zones (from A to F) on the basis of the average daily temperatures. The construction site under analysis is located in Milano, therefore climatic zone E. For each climatic zone the standard (M.D. 26/06/2015, values from 2019/2021) provides a maximum value of thermal transmittance for all the constructive elements which composed a building. In our case, opaque vertical building envelope, in climatic zone E the maximum value of the thermal transmittance is 0.26 W/m^{2}K.

MASONRY WALL (MW)

MW is the identification code used for the masonry wall proposal. The figure and table bellows show all the characteristics of this type of external wall.

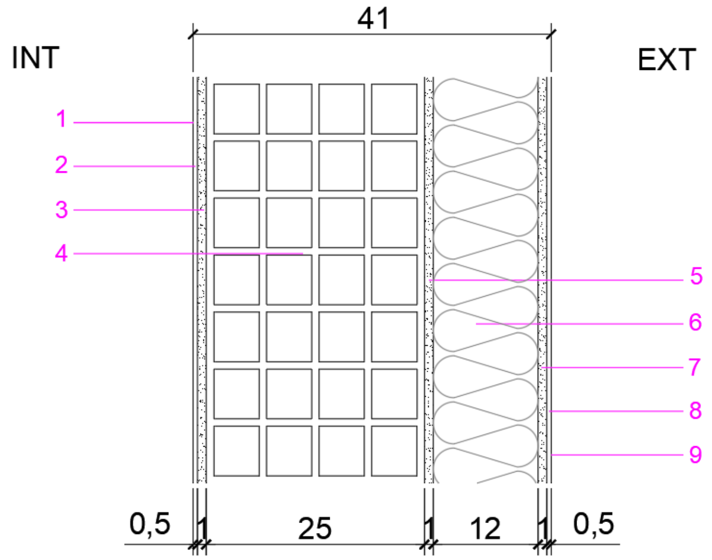

Figure 23: Masonry wall stratigraphy (starting point)

STARTING POINT						
MW Stratigraphy:	Reference number in the stratigraphy	Identification code	Typology	Total thickness [m]	λ [W/mK]	U [W/m²K]
Indoor coating paste	1	MW_CP00	acrylic-siloxane paint	-	-	
Levelling plaster	2	MW_LP00	natural lime mortars for levelling plaster	0,01	0,45	
Plaster	3	MW_P00	natural lime mortars for plaster	0,01	0,54	
Brick	4	MW_B00	clay-based holed brick	0,25	0,145	
Plaster	5	MW_P00	natural lime mortars for plaster	0,01	0,54	0,185
Insulation	6	MW_I00	sintered expanded polystyrene sheet (EPS)	0,12	0,035	
Plaster with grid	7	MW_P00	plaster with metal grid[1]	0,01	0,54	
Levelling plaster	8	MW_LP00	natural lime mortars for levelling plaster	0,01	0,45	
Outdoor coating paste	9	MW_CP00	acrylic-siloxane paint	-	-	

Table 9: Masonry wall stratigraphy, MW (starting point)

1. This layer will be considered as just a plaster layer for the calculation of the footprint.

CLT WOOD WALL (WW)

WW is the identification code used for the CLT wood wall proposal. The figure and table bellows show all the characteristics of this type of external wall.

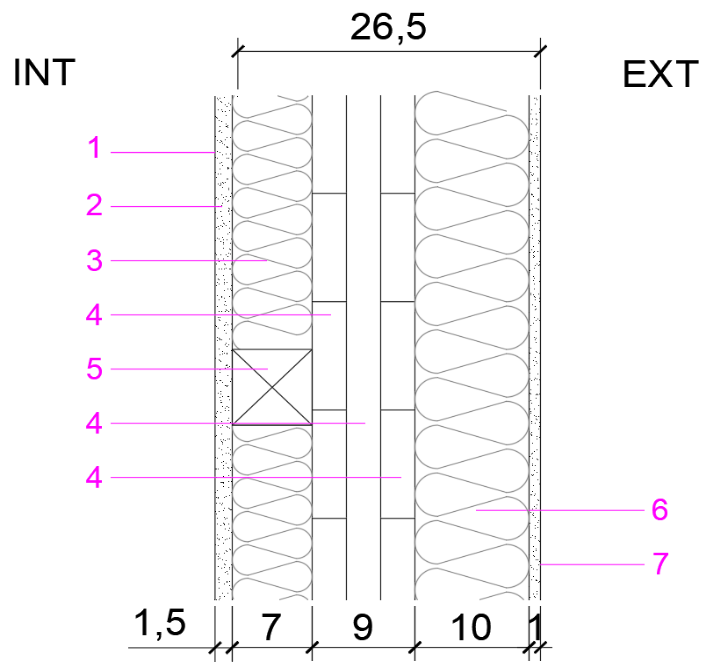

Figure 24: Wood wall stratigraphy (starting point)

STARTING POINT						
WW Stratigraphy:	Reference number in the stratigraphy	Identification code	Typology	Total thickness [m]	λ [W/mK]	U [W/m²K]
Indoor coating paste	1	WW_CP00	acrylic-siloxane paint	-	-	0,185
Plasterboard	2	WW_PB00	gypsum board	0,015	0,2	
Insulation	3	WW_MW00	Mineral Wool	0,07	0,04	
Timber	4	WW_T00	Cross Laminated Timber (CLT or X-LAM)	0,09	0,12	
Structural timber[1]	5	WW_ST00	Structural wood slats	0,07	-	
Insulation	6	WW_WF00	Wood Fibre	0,10	0,038	
Plaster	7	WW_P00	natural lime mortars for plaster	0,015	0,54	

Table 10: Wood wall stratigraphy, WW (starting point)

1. For the purpose of this thesis this layer is not considered in any of the calculations.

DRY-WALL (DW)

DW is the identification code used for the dry-wall proposal. The figure and table bellows show all the characteristics of this type of external wall.

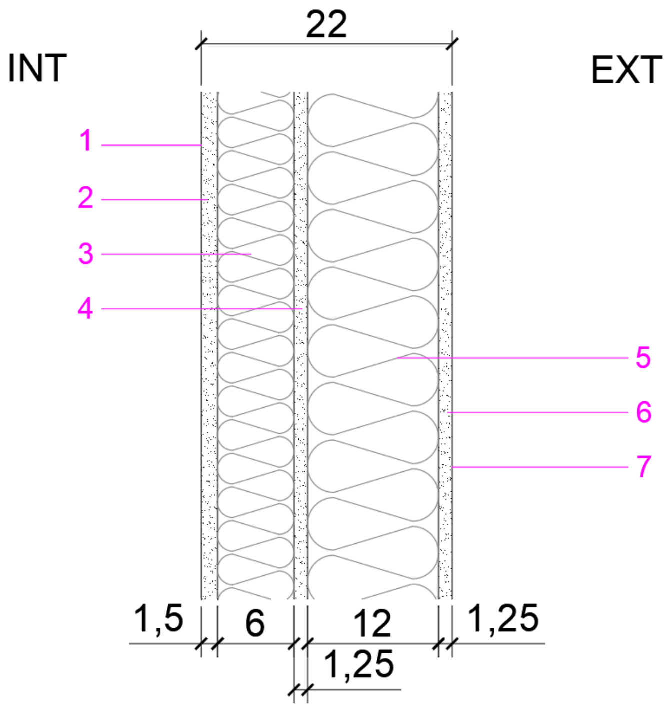

Figure 25: Dry Wall stratigraphy, DW (starting point)

STARTING POINT						
DW Stratigraphy:	Reference number in the stratigraphy	Identification code	Typology	Total thickness [m]	λ [W/mK]	U [W/m²K]
Indoor coating paste	1	DW_CP00	acrylic-siloxane paint	-	-	0,186
Plasterboard	2	DW_PB00	vapour resistant gypsum board	0,015	0,2	
Mineral Wool	3	DW_MW00	mineral wool	0,06	0,04	
Plasterboard	4	DW_P00	gypsum board	0,0125	0,2	
Insulation	5	DW_EPS00	sintered expanded polystyrene sheet (EPS)	0,12	0,034	
Outdoor cement-board	6	DW_CB00	cement-board (Aquapanel)	0,0125	0,35	
Outdoor coating paste	7	DW_CP00	acrylic-siloxane paint	-	-	

Table 11: Dry Wall stratigraphy, DW (starting point)

USEFUL QUANTITIES

In the tables below are reported some quantities used for the calculations. The technical data are data supplied from the producer in the technical sheet. (“nn” states for: “not necessary”).

MW_00	Reference number in the stratigraphy	Total thickness [m]	Technical characteristics			Total area [m²]	m³ TOT	kg TOT
			type of data	unit	data			
Levelling plaster	2	0,01	performance	kg/m² per cm	12	4061,26	20,31	24.367,56
Plaster	3	0,01	performance	kg/m² per cm	13	4061,26	40,61	52.796,38
Brick	4	0,25	density	kg/m3	520	4061,26	1015,32	527963,8
Plaster	5	0,01	performance	kg/m² per cm	13	4061,26	40,61	52.796,38
Insulation	6	0,12	nn	nn	nn	4061,26	487,35	nn
Plaster with grid	7	0,01	performance	kg/m² per cm	13	4061,26	40,61	52.796,38
Levelling plaster	8	0,01	performance	kg/m² per cm	12	4061,26	20,31	24.367,56

Table 12:: useful quantities masonry starting point stratigraphy

WW_00	Reference number in the stratigraphy	Total thickness [m]	Technical characteristics			Total area [m²]	m³ TOT	kg TOT
			type of data	unit	data			
Wood	4	0,09	nn	nn	nn	4061,26	365,51	nn
Wood Fibre	6	0,10	nn	nn	nn	4061,26	406,13	nn
Glass Wool	3	0,07	nn	nn	nn	4061,26	284,29	nn
Plaster-board	2	0,015	nn	nn	nn	4061,26	60,92	nn
Plaster	7	0,015	performance	kg/m² per cm	12	4061,26	60,92	73.102,68

Table 13: useful quantities wood starting point stratigraphy

DW_00	Reference number in the stratigraphy	Total thickness [m]	Technical characteristics			Total area [m²]	m³ TOT	kg TOT
			type of data	unit	data			
Plaster-board	2	0,015	nn	nn	nn	4061,26	60,92	nn
Mineral Wool	3	0,060	nn	nn	nn	4061,26	243,68	nn
Plaster-board	4	0,013	nn	nn	nn	4061,26	50,77	nn
Insulation	5	0,120	nn	nn	nn	4061,26	487,35	nn
Outdoor cement-board	6	0,013	nn	nn	nn	4061,26	50,77	nn

Table 14: useful quantities dry starting point stratigraphy

3.1 AIM OF THE ANALYSIS

The aim of the analysis is to show how to use the LCA methodology (and its outcomes such us: environmental product declaration) to minimize the total footprint of the most used opaque vertical envelope solutions of a residential building. In order to do that, generic stratigraphies were settled using materials which allow to reach the same value of transmittance. These stratigraphies, showed in the previous paragraph, represent a starting point to be improved thanks to the analysis. The analysis showed in the following paragraphs can be divided in three main phases:

- First phase - Materials contribution: in this first phase through OneClick LCA software it is possible to see the different contribution of each material to the external wall footprint in percentage. To have more reliable results, through excel sheet and EPDs the footprint of the materials of the starting point stratigraphies are settled. This phase allows to start all the analysis with more consciousness. Once all the contributions are settled it is possible to intervene in a targeted manner on the most determining materials.
- Second phase – Improvement: once the most determining materials are known, they have to be changed with more sustainable options in order to improve the carbon emissions due to the stages from A1 to A4. To do that, different proposals of materials are analysed and compared in terms of carbon emissions. Those comparison allows to identify the best materials for all the stratigraphies. At this point, the best material options are put together in order to compose new improved stratigraphies characterized by a lower footprint. The new improved stratigraphies are the object of analysis in the third and last phase.
- Third phase – Long-Term analysis: once the improved stratigraphies are settled and compared, they should be analysed also with a long-term perspective. Therefore, the aim of the third phase is to take into consideration all the life of the building until its disposal considering also the carbon emissions of its end-of-life treatments. So, stage from C1 to C4 and D are analysed in this phase.

At this point all the results of the study are enough to make a comparison based on the footprint of the three external wall typologies.

▪ MATERIALS CONTRIBUTION

All the three proposals were inserted inside of OneClick LCA software in order to calculate their footprint and to better understand the contributions of each material to the total carbon emissions. Once uploaded all the necessary data, OneClick LCA generates different results, such as: emissions of each stage, total emissions and emissions of each material. In the figure below it is possible to see an example of the results of the materials' carbon emissions in the masonry wall scenario.

I materiali più contribuenti (Il riscaldamento globale)

No.	Risorsa	Cradle to gate impacts (A1-A3)	Cradle to gate (A1-A3)
1.	Clay bricks, ?	118 tonnellate CO_2e	56.8 %
2.	Protective plasters, for indoor and outdoor application, ?	39 tonnellate CO_2e	18.9 %
3.	EPS insulation panel, L=0.035 W/mK, 17 kg/m3, Lambda=0.035 W/(m.K) ?	38 tonnellate CO_2e	18.2 %
4.	Protective plasters, for indoor and outdoor application, ?	12 tonnellate CO_2e	5.6 %
5.	Acrylic-siloxane coating, thick-layered, water-repellent, UV resistant, for indoor and outdoor use, 2.1 kg/m2, 1.2 mm ?	0,95 tonnellate CO_2e	0.5 %

Figure 27: Materials contribution (OneClick LCA extracted)

On the left it is possible to see the list of the materials composing the stratigraphy, represented by the same name used in the title of their EPD, a coloured cloud which indicates the level of sustainability of the material (there are five colours, in a crescent sustainability order: red, orange, light green, green, dark green) and a question mark through which it is possible to access to the material's EPD and main characteristics. On the right of the image the software gives the cradle-to-gate impacts for each material in tons of $kgCO_2e$ and in percentage.

As starting point the stratigraphy of each wall was uploaded in the software through the available EPDs supplied by OneClick LCA. All EPDs chosen at the start are Italian or refers to products that can be manufactured in Italy. Together with the materials also the distance from the manufacturer location to the construction site in km was inserted in order to calculate the carbon emissions also for the transportation stage (A4). The figure below shows where it is possible to insert the type and distance of the transports' mode on OneClick LCA.

Figure 28: Transport (OneClick LCA extracted)

It is important to highlight that, in this first phase of the study, only stage A1 -A4 are included, therefore the software outputs used do not take into consideration for example maintenance, possible replacements and the end-of-life treatments. The figure below shows how to avoid that OneClick LCA considers the end-of-life treatment contribution when a martial is inserted.

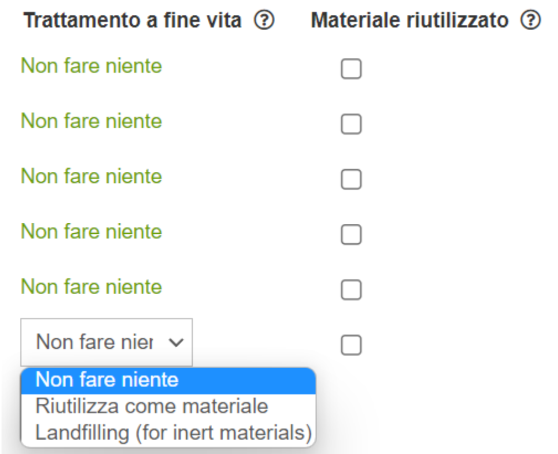

Figure 29: end of life treatment (OneClick LCA extracted)

For each material there are more than one options to choose. The "Not doing anything" option allow to not consider the end-of-life phase in the calculations.

The choice of considering just the product and transport stage is due to the fact that the first part of the study is aim to find the best solution in terms of materials in order to obtain an external wall proposal with a really low foot print. Moreover, the contributions of the other phases, such us the end-of-life treatment, will be taken into consideration and deepen later on the already improved stratigraphy.

Analysing OneClick LCA outputs, the following comments can be stated regarding the different proposals at a starting point

MASNORY WALL

In the traditional masonry wall, more than 50% of carbon emissions are related to the ceramic brick (57%). If on one hand the greater contribution from the brick was predictable, the remaining carbon emissions are divided in an unexpected way among the other materials. In fact, despite EPS has a thicker layer than plaster in the stratigraphy, their percentage are respectively: insulation (17,9%), plaster (24,7%). Therefore, plaster contributes more than insulation to the carbon emissions of a traditional masonry wall.

STARTING POINT	
MW_00 stratigraphy:	CARBON EMISSIONS %
Brick (MW_B00)	57,0
Insulation (MW_I00)	17,9
Levelling Plaster (MW_LP00)	6
Plaster (MW_P00)	18,7
Coating pastes (MW_CP00)	0,4
MASNORY WALL	100,0

Table 15: MW materials contributions [%]

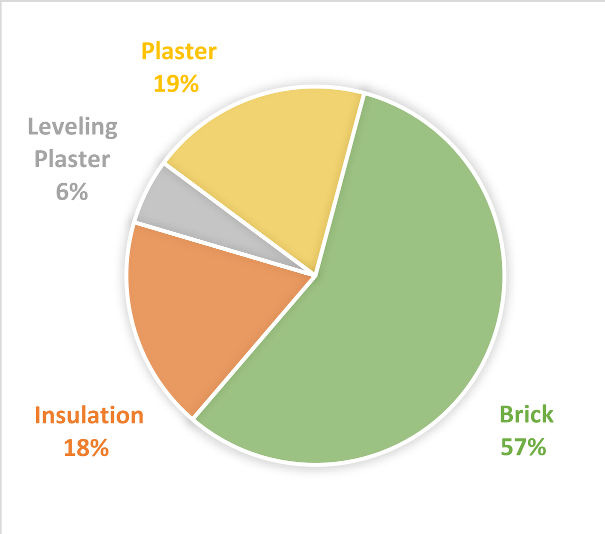

Figure 30: MW materials contributions [%]

WOOD WALL

For the wood wall, as predictable, the most influencing are the CLT wood panels (50.4%), followed by insulation. It is interesting to notice that, there are two different types of insulation which have two really different contribution: the glass wool insulation (9%) and the wood fibre insulation (22%).

STARTING POINT		
WW_00 stratigraphy:		CARBON EMISSIONS %
Wood (WW_T00)		50,4
Insulation	Wood fibre (WW_WF00)	21,6
	Glass wool (WW_MW00)	9,0
Gypsum	Plasterboard (WW_PB00)	9,8
	Plaster (WW_P00)	9,2
CLT WOOD WALL		100,0

Table 16: WW materials contribution [%]

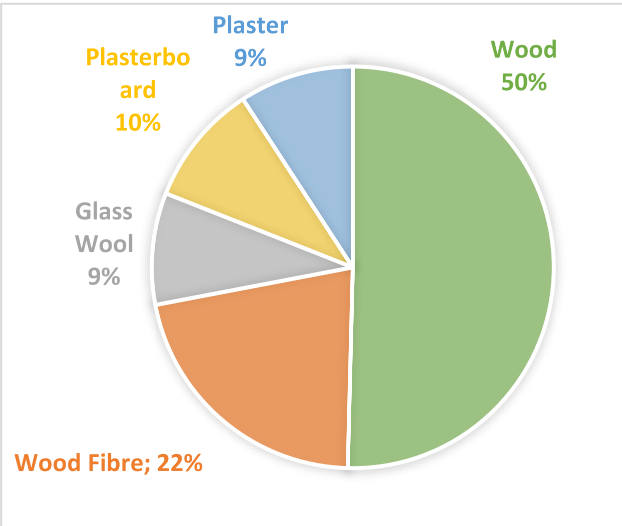

Figure 31: WW materials contributions [%]

As the quantities show, it is clear that the second type of insulation is the one responsible for the high percentage of insulation in the global contribution of each material composing the stratigraphy. In fact, it is possible to notice that both plaster (9,2%) and gypsum plasterboard (9,8 %) realise more carbon emissions than the glass wool insulation (9%).

DRYWALL

In the Dry wall solution, the major contribution to carbon emission is given by the outdoor cement board (56.7 %). Following the outdoor panel there is the insulation, divided between the two different typologies: EPS (23%) and mineral wool (7,3%). While the gypsum plasterboards are the minor contribution to the CO_2 emissions.

STARTING POINT		
DW_00 stratigraphy:		CARBON EMISSIONS
		%
Gypsum plasterboard	Vapour resistant (DW_PB00)	6,9
	Classic (DW_P00	5,7
Insulation	Mineral wool (DW_MW00)	7,3
	EPS (DW_EPS00)	23,5
Outdoor cement-board (Aquapanel) (DW_CB00)		56,7
DRYWALL		100,00

Table 17: DW materials contributions [%]

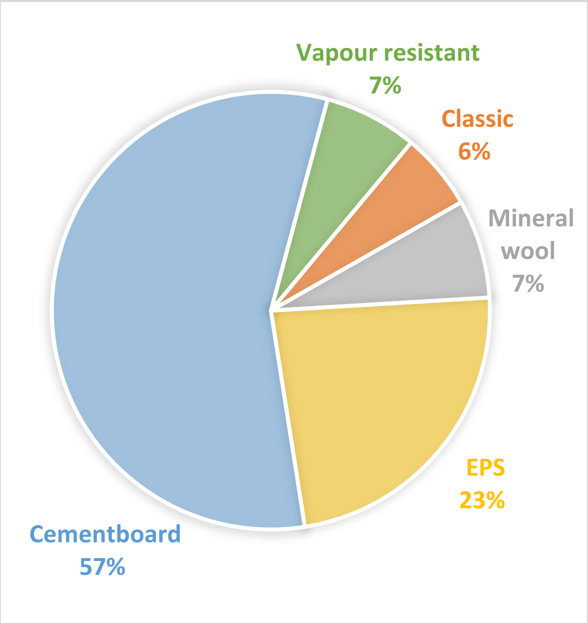

Figure 33: DW materials contributions

In order to proceed with the analysis, it is necessary to determine the carbon emission of stages A1-A3 of the starting point stratigraphy. The latter are calculated through excel sheet using materials' EPDs.

MASONRY WALL

MW_00	Identification code	EPD N°	Functional Unit (F.U.)	Quantities in the project	$kgCO_2$/F.U.	$kgCO_2$ TOT
					A1-A3	
Levelling plaster	MW_LP00	S-P-01642, rev. 2021	1 kg	24.367,56	2,38E-01	5,80E+03
Plaster	MW_P00	S-P-01642, rev. 2021	1 kg	52.796,38	2,48E-01	1,31E+04
Brick	MW_B00	EPDITALY0107	1 ton	527,96	2,24E+02	1,18E+05
Plaster	MW_P00	S-P-01642, rev. 2021	1 kg	52.796,38	2,48E-01	1,31E+04
Insulation	MW_EPS00	EPDITALY0164	1 m^3	487,35	7,79E+01	3,80E+04
Plaster with grid	MW_P00	S-P-01642, rev. 2021	1 kg	52.796,38	2,48E-01	1,31E+04
Levelling plaster	MW_LP00	S-P-01642, rev. 2021	1 kg	24.367,56	2,38E-01	5,80E+03
					Total carbon emissions:	**2,07E+05**

Table 18: MW_00 Carbon emissions (A1-A3)

WOOD WALL

WW_00	Identification code	EPD N°	Functional Unit (F.U.)	Quantities in the project	$kgCO_2$/F.U.	$kgCO_2$ TOT
					A1-A3	
Wood	WW_T00	EPD-RUB-20180060-IBB1-EN	1 m3	365,5134	-6,64E+02	-2,43E+05
Wood Fibre	WW_WF00	EPD-STE-20150327-IBD1-EN	1 m3	406,13	-1,73E+02	-7,03E+04
Glass Wool	WW_MW00	INIES_IFEU20180419_085405, 8175	1 m^2	4.061,26	5,50E-01	2,23E+03
Plaster-board	WW_PB00	S-P-01933	1 m^2	4.061,26	3,16E+00	1,28E+04
Plaster	WW_P00	S-P-01642, rev. 2021	1 kg	48.735,10	2,48E-01	1,21E+04
					Total carbon emissions:	**-2,86E+05**

Table 19: WW_00 Carbon emissions (A1-A3)

DRY WALL

DW_00	Identification code	EPD N°	Functional Unit (F.U.)	Quantities in the project	$kgCO_2$/F.U.	$kgCO_2$ TOT
					A1-A3	
Plasterboard	DW_PB00	INIES_IPLA20170615_155601, 26957	1 m^2	4.061,26	3,16E+00	1,28E+04
Mineral Wool	DW_MW00	INIES_IFEU20180419_085405, 8175	1 m^2	4.061,26	5,50E-01	2,23E+03
Plaster-board	DW_P00	S-P-01933	1 m^2	4.061,26	2,27E+00	9,22E+03
Insulation	DW_EPS0	EPDITALY0164	1 m^3	487,3512	7,79E+01	3,80E+04
Outdoor cement-board	DW_CB00	INIES_IPLA20170615_155601, 26957	1 m2	4.061,26	9,88E+00	4,01E+04
					Total carbon emissions:	**1,02E+05**

Table 20: DW_00 Carbon emissions (A1-A3)

▪ IMPROVEMENT

Once settled a general framework on the footprint of the most used external wall stratigraphy in the residential building it is possible to proceed and improve them in terms of CO_2, acting on the materials which influenced the global wall footprint the most. A1, A2, A3, and A4 of the construction phases settled in EN 15978 are analysed below for each stratigraphy and, different solutions are given in order to minimise as much as possible the carbon emissions for each stage and for each stratigraphy. It is important to highlight that all the materials options are chosen in order to guarantee a thermal transmittance as close as possible to the initial one.

PRODUCT STAGE: A1-A3

These modules, also called the product stage, refer to the carbon impact of a product from its production to its transport to the construction site (cradle-to-gate). All the information regarding these modules are provided by the EPDs released from the manufacturers. Depending on the type of analysis they conducted it is possible to find information about module A1 -A3 and, sometimes also about module C1-C3 (this would be a cradle-to-grave EPD). Using OneClick LCA it is possible to see that these stages are the major contributors to carbon emissions therefore improving them is a crucial step in order to minimize the external wall footprint.

Since these modules concern the single products, the only way to intervene and reduce their impact is to change the product itself. A possible improvement would be to find materials that are produced from recycled raw materials and which therefore have a lower impact in the module A1. Below there are some examples of product changes that have led to a decrease in the environmental impact of all the three starting proposals described above.

MASONRY WALL

In Masonry wall, as said before, the major quantities of CO_2 emissions come from bricks. The brick used as point of start is a holed clay-based block with horizontal holes (Brick 0). In order to reduce the carbon emissions other two proposal are taken into account. Both the alternative proposals are produced by Stabila in north of Italy. Brick 1, which the technical name is: Alveolater BIO, is a block lightened with wood flour. Brick 2 is a common brick not lightened, which despite being the same typology as Brick 0 releases less carbon emissions than it. The two alternative proposals are produced by the same company, showing how the same producer can create a big variety of products characterized by different environmental impact. The table below shows in a schematic way the main characteristics of the three proposals.

BRICKS' CHARACTERISTICS COMPARISON				
Proposals	**Identification Code**	**EPD N°**	**Producer**	**Typology**
BRICK 0	**MW_B00**	EPDITALY0107	Wienerberger (Vercelli, Italy)	Clay-based holed brick
BRICK 1	**MW_B01**	EPDITALY0053	Stabila Srl (Isola Vicentina, Italy)	Lightened blocks with wood flour
BRICK 2	**MW_B02**	EPDITALY0053	Stabila Srl (Isola Vicentina, Italy)	Clay-based holed brick

Table 21: Bricks characteristics comparison

The table below shows in a schematic way the main technical characteristics of the three proposals.

BRICKS' TECHNICAL CHARACTERISTICS COMPARISON							
Proposals	**Thickness [m]**	**Area [m²]**	**Volume [m³]**	**Density [kg/m³]**	**Mass [kg]**	**λ [W/mK]**	**U (of the total stratigraphy) [W/m2K]**
MW_B00	0,25	4.061,26	1.015,32	520,00	527.963,80	0,145	0,185
MW_B01	0,25	4.061,26	1.015,32	863,00	876.216,85	0,181	0,198
MW_B02	0,25	4.061,26	1.015,32	737,00	748.287,16	0,192	0,201

Table 22: Bricks technical characteristics comparison

The table below shows in a schematic way the carbon emissions of the three proposals. All the environmental impact declared below have as reference unit 1ton.According to the below calculation the brick lightened with wood flour (Brick 1) is the best option in terms of $kgCO_2e$.

BRICKS' CARBON EMISSIONS COMPARISON					
Proposals	**EPD N°**	**Functional Unit (F.U.)**	**Quantities in the project**	**PRODUCT STAGE (A1-A3)**	
				$kgCO_2$/F.U.	**$kgCO_2$ TOT**
MW_B00	EPDITALY0107	1 ton	527,964	2,24E+02	1,18E+05
MW_B01	EPDITALY0053	1 ton	876,217	4,10E+01	3,59E+04
MW_B02	EPDITALY0053	1 ton	748,287	5,24E+01	3,92E+04

Table 23: Bricks carbon emissions comparison

The second major contribution to the total carbon emissions is given by the plaster. Two options are compared below, Plaster 0 is the one used for the initial comments. Its technical name is Biocalce Intonco and it is a natural lime mortar for plaster produced by Kerakoll. The alternative option is Plaster 1 produced by HD system, its technical name is TD13M and it is a hydraulics lime mortar for plaster. The table below shows in a schematic way the main characteristics of the two proposals.

PLASTERS' CHARACTERISTICS COMPARISON				
Proposals	**Identification Code**	**EPD N°**	**Producer**	**Typology**
PLASTER 0	**MW_P00**	S-P-01642	Kerakoll (Sassuolo, Italy)	Natural lime mortars for plaster
PLASTER 1	**MW_P01**	Srl-91-EN	HD system (Trento, Italy)	Hydraulics lime mortar for plaster

Table 24: Plasters characteristics comparison

The table below shows in a schematic way the main technical characteristics of the two proposals.

PLASTERS' TECHNICAL CHARACTERISTICS COMPARISON							
Proposals	**Thickness [m]**	**Area [m²]**	**Volume [m³]**	**Density [kg/m³]**	**Mass [kg]**	**λ [W/mK]**	**U (of the total stratigraphy) [W/m2K]**
MW_P00	0,03	4.061,26	121,84	1.300,00	158.389,14	0,54	0,185
MW_P01	0,03	4.061,26	121,84	1.650,00	201.032,37	1,11	0,186

Table 25: Plasters technical characteristics comparison

The table below shows in a schematic way the carbon emissions of the three proposals. All the environmental impact declared below have as reference unit 1kg.

PLASTERS' CARBON EMISSIONS COMPARISON					
Proposals	EPD N°	Functional Unit (F.U.)	Quantities in the project	PRODUCT STAGE (A1-A3)	
				$kgCO_2$/F.U.	$kgCO_2$ TOT
MW_P00	S-P-01642	1 kg	158.389,14	2,48E-01	3,93E+04
MW_P01	Srl-91-EN	1kg	201.032,37	1,10E-01	2,21E+04

Table 26: Plasters carbon emissions comparison

According to the above table Plaster 1 is the best option in terms of kg CO_2e.

WOOD WALL

In the case of the wood wall stratigraphy the wood layer contributes the most to the total footprint of the external wall, for this reason three different solution are proposed and compered below. CLT 0 is the one composing the starting point stratigraphy, it consists of at least three layers made from kiln dried coniferous wood and it is produced in Bolzano. The alternative proposals CLT 1 and CLT 2 are both imported from out of Italy. CLT 1 produced in Austria consists of several bonded single-layer panels (3 cm each) arranged at right angles to each other. CLT 2 produced in Switzerland consists of at least two dried boards of coniferous solid wood glued together parallel to the grain. The table below shows in a schematic way the main characteristics of the three proposals.

CLTs' CHARACTERISTICS COMPARISON				
Proposals	Identification Code	EPD N°	Producer	Typology
CLT 0	**WW_T00**	ECO-00000725	Rubner Holding AG - S.p.A. (Bolzano, Italy)	At least three layers made from kiln dried coniferous wood
CLT 1	**WW_T01**	ECO-00001225	Stora Enso (Austria)	Several bonded single-layer panels (3cm each) arranged at right angles to each other
CLT 2	**WW_T02**	EPDSLH-20180066IBC1-EN	Schiliger Holz (Switzerland)	Dried boards of coniferous solid wood glued together parallel to the grain

Table 27: CLTs characteristics comparison

The table below shows in a schematic way the main technical characteristics of the three proposals.

CLTs' TECHNICAL CHARACTERISTICS COMPARISON							
Proposals	**Thickness [m]**	**Area [m²]**	**Volume [m³]**	**Density [kg/m³]**	**Mass [kg]**	**λ [W/mK]**	**U (of the total stratigraphy) [W/m2K]**
WW_T00	0,09	4.061,26	365,51	not necessary	not necessary	0,12	0,185
WW_T01	0,09	4.061,26	365,51	not necessary	not necessary	0,12	0,185
WW_T02	0,09	4.061,26	365,51	not necessary	not necessary	0,12	0,185

Table 28: CLTs technical characteristics comparison

The table below shows in a schematic way the carbon emissions of the three proposals. All the environmental impact declared below have as reference unit 1m³.

CLTs' CARBON EMISSIONS COMPARISON					
Proposals	**EPD N°**	**Functional Unit (F.U.)**	**Quantities in the project**	**PRODUCT STAGE (A1-A3)**	
				$kgCO_2$/F.U.	**$kgCO_2$ TOT**
WW_T00	ECO-00000725	1 m³	365,51	-6,64E+02	-2,43E+05
WW_T01	ECO-00001225	1 m³	365,51	-7,07E+02	-2,58E+05
WW_T02	EPDSLH-20180066IBC1-EN	1 m³	365,51	-6,15E+02	-2,25E+05

Table 29: CLTs carbon emissions comparison

It is interesting to notice that for all the option the content of biogenic CO_2 is accounted for as a negative input to the global warming potential, this is due to the fact that the wood itself is the raw material. According to the calculation CLT 2 is the best option in terms of kg CO_2e.

The material with the second highest values of carbon emissions in the external wood wall is the insulation in wood fibre. Wood Fibre 0 is the one composing the starting point stratigraphy, produced in Italy it consists of wood fibre insulation mats. The alternative options are imported from out of Italy, Wood Fibre 1 and Cellulose, respectively produced in France and Austria. Wood fibre 1 is flexible wood fibre insulation boards. The Cellulose is manufactured in Austria from mono-fraction paper from newspaper with additional additives to protect against fire and mould.

The table below shows in a schematic way the main characteristics of the three proposals.

ORGANIC INSULATIONS' CHARACTERISTICS COMPARISON				
Proposals	**Identification Code**	**EPD N°**	**Producer**	**Typology**
WOOD FIBRE 0	**WW_WF00**	EPD-STE-20150327-IBD1-EN	BetonWood Srl (Firenze, Italy)	wood fibre insulation mats
WOOD FIBRE 1	**WW_WF01**	EPD-STE-20200001-IBA1-DE	Steico (France)	flexible wood fiber insulation boards
CELLULOSE	**WW_C01**	EPD-PSG-20210030-IBA1-EN	Peter Seppele Gesellschaft m.b.H (Austria)	manufactured from mono-fraction paper from newspapers

Table 30: Organic Insulations characteristics comparison

The table below shows in a schematic way the main technical characteristics of the three proposals.

ORGANIC INSULATIONS' TECHNICAL CHARACTERISTICS COMPARISON							
Proposals	**Thickness [m]**	**Area [m²]**	**Volume [m³]**	**Density [kg/m³]**	**Mass [kg]**	**λ [W/mK]**	**U (of the total stratigraphy) [W/m2K]**
WW_WF00	0,10	4.061,26	406,13	not necessary	not necessary	0,038	0,185
WW_WF01	0,09	4.061,26	365,51	not necessary	not necessary	0,036	0,190
WW_C01	0,10	4.061,26	406,13	44,00	17.869,54	0,037	0,183

Table 31: Organic Insulations technical characteristics comparison

The table below shows in a schematic way the carbon emissions of the three proposals. Once again, since it is a natural raw material the content of biogenic CO_2 is accounted for as a negative input to the global warming potential. According to the calculation Cellulose is the best option in terms of kg CO_2e. Cellulose's really low value in the product stage is due to the fact that its raw material is recycled newspaper.

ORGANIC INSULATIONS' CARBON EMISSIONS COMPARISON					
Proposals	**EPD N°**	**Functional Unit (F.U.)**	**Quantities in the project**	**PRODUCT STAGE (A1-A3)**	
				kgCO_2/F.U.	**kgCO_2 TOT**
WW_WF00	EPD-STE-20150327-IBD1-EN	1 m^3	406,126	-1,73E+02	-7,03E+04
WW_WF01	EPD-STE-20200001-IBA1-DE	1 m^3	365,5134	-6,11E+01	-2,23E+04
WW_C01	EPD-PSG-20210030-IBA1-EN	1 kg	17869,544	-1,73E+02	-3,09E+06

Table 32: Organic Insulations carbon emissions comparison

DRY WALL

In the dry wall option, the external layer is composed by a cement board manufactured to be in the outdoor environment and it is the major contributor to the carbon emissions of the wall. The cement boards compared have all no-Italian EPD but, the one produced by Knauf (cement board 0) can be manufactured also in Italy since there is a KNAUF site of production in Pisa. Cement Board 0 consists of a plate reinforced on each side by a fiberglass mesh and is the one used for the initial comments in the previous paragraphs. The other two (cement board 1 and cement board 2) are imported from respectively France and Finland. Cement Board 1 is a sandwich panel composed of cement and aggregates and reinforced on both side by a alkali resistant fibre glass mesh. Cement Board 2 is an untreated fibre cement board. The table below shows in a schematic way the main characteristics of the three proposals.

CEMENT BOARDS' CHARACTERISTICS COMPARISON				
Proposals	**Identification Code**	**EPD N°**	**Producer**	**Typology**
CEMENT BOARD 0	**DW_CB00**	INIES_IPLA20170615_155601, 26957	KNAUF (Pisa, Italy)	Cement plate reinforced on each side by a fiberglass mesh
CEMENT BOARD 1	**DW_CB01**	27469692021	Fermacell (Nantes, France)	sandwich plate composed of cement and aggregates reinforced on both sides with a reinforced fibre glass mesh
CEMENT BOARD 2	**DW_CB02**	MD-16001-EN	Cembrit (Finland)	untreated fibre cement board

Table 33: Cement boards characteristics comparison

The table below shows in a schematic way the main technical characteristics of the three proposals.

CEMENT BOARDS' TECHNICAL CHARACTERISTICS COMPARISON							
Proposals	**Thickness [m]**	**Area [m²]**	**Volume [m³]**	**Density [kg/m³]**	**Mass [kg]**	**λ [W/mK]**	**U (of the total stratigraphy) [W/m2K]**
DW_CB00	0,0125	4.061,26	50,77	not necessary	not necessary	0,35	0,186
DW_CB01	0,0125	4.061,26	50,77	not necessary	not necessary	0,17	0,185
DW_CB02	0,08	4.061,26	324,90	not necessary	not necessary	0,48	0,182

Table 34: Cement boards technical characteristics comparison

The table below shows in a schematic way the carbon emissions of the three proposals. The three proposals have all nearly the same foot print. According to the below calculation Cement Board 0 is the best option in terms of kg CO_2e

CEMENT BOARDS' CARBON EMISSIONS COMPARISON					
Proposals	**EPD N°**	**Functional Unit (F.U.)**	**Quantities in the project**	**PRODUCT STAGE (A1-A3)**	
				kgCO_2/F.U.	**kgCO_2 TOT**
DW_CB00	-	1 m^2	4.061,26	9,88E+00	4,01E+04
DW_CB01	27469692021	1 m^2	4.061,26	1,44E+01	5,84E+04
DW_CB02	MD-16001-EN	1 m^2	4.061,26	1,15E+01	4,66E+04

Table 35: Cement boards carbon emissions comparison

The second highest contribution to carbon emissions in a dry wall is given by the external insulation, in particular the EPS typology. Two alternative proposals are taken into account. EPS 0, used for the starting point stratigraphy. Both options consist of sintered expanded polystyrene sheet. The table below shows in a schematic way the main characteristics of the two proposals.

EPSs' CHARACTERISTICS COMPARISON				
Proposals	**Identification Code**	**EPD N°**	**Producer**	**Typology**
EPS 0	**DW_EPS00**	EPDITALY0164	Polisette (Crremona, Italy)	sintered expanded polystyrene sheet
EPS 1	**DW_EPS01**	EPDITALY0029	IsolCofort (Alessandria, Italy)	sintered expanded polystyrene sheet

Table 36: EPSs characteristics comparison

The table below shows in a schematic way the main technical characteristics of the two proposals.

EPSs' TECHNICAL CHARACTERISTICS COMPARISON							
Proposals	**Thickness [m]**	**Area [m²]**	**Volume [m³]**	**Density [kg/m³]**	**Mass [kg]**	**λ [W/mK]**	**U (of the total stratigraphy) [W/m2K]**
DW_EPS00	0,12	4.061,26	487,35	not necessary	not necessary	0,035	0,190
DW_EPS01	0,12	4.061,26	487,35	not necessary	not necessary	0,036	0,193

Table 37: EPSs technical characteristics comparison

The table below shows in a schematic way the carbon emissions of the three proposals.

EPSs' CARBON EMISSIONS COMPARISON					
Proposals	**EPD N°**	**Functional Unit (F.U.)**	**Quantities in the project**	**PRODUCT STAGE (A1-A3)**	
				$kgCO_2$/F.U.	**$kgCO_2$ TOT**
DW_EPS00	EPDITALY0164	1 m^3	487,3512	7,79E+01	3,80E+04
DW_EPS01	EPDITALY0029	1 m^3	487,3512	5,38E+01	2,62E+04

Table 38: EPSs carbon emissions comparison

According to the above table EPS 1 is the best option in terms of kg CO_2e. Since this material is used also in other proposal (masonry wall) it will be used every time an EPS insulation in needed.

PRODUCT STAGE: A4

This module includes the transport of products along with the packaging from the manufacturer's production plant to the construction site. The carbon emissions value that will be compered and analysed are calculated through OneClick LCA software. In order to obtain them, the location of the installation sites and mode of transport needs to be identified. When setting up the project parameters, transport settings are included.

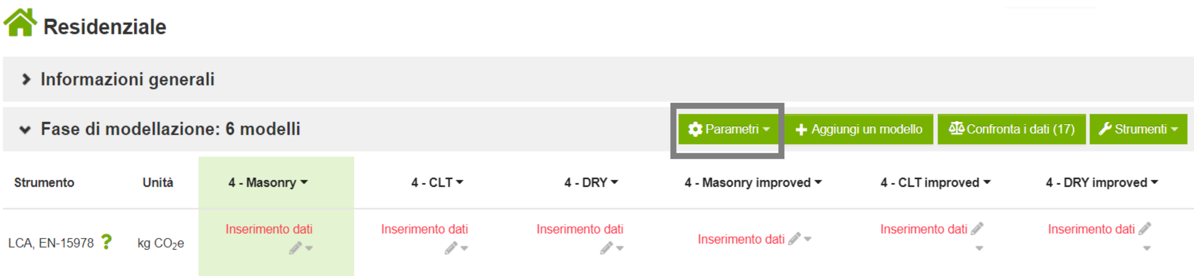

Table 39: Project parameters (OneClick LCA extracted)

Once a transport setting is selected it applies default settings to the entire project. These default settings regard: transportation and distances of the transportation of the product from the facility where it is made, to the construction site. These default settings are useful when the mode of transport or distance have not been defined yet, however they can be always adjusted and customized. In setting the transportation method the software allows to know the source and emissions of each transport method through their data cards, all the data are declared in kilograms of CO2 equivalent per ton of material transported per kilometre or mile. Unless transport is likely to be very significant, generic datasets for transport per 'kg + kilometre' can be used, therefore for the purpose of this thesis only the distance has been customized while the default transport method has been used for all the hypothesis. The default transport is a generic data supply by the software based on the consume of the European territory. It is a trailer combination with 40-ton capacity and with 100% fill rate. The software also gives the possibility to add an additional transport leg, but since it is not so decisive, for the purpose of this thesis all the transports are hypostasized with just one leg.

The aim of this paragraph is to investigate how total carbon emissions are influenced by the transportation and therefore by the distance between manufacturer and construction site.

MASNORY WALL

As regarding bricks' comparison, since all the proposals are manufactured in Italy, the transportation do not make any big difference on comparing the proposals' footprint. As expected, the best option is still Brick 1 (MW_B01). It is interesting to notice that the kg CO_2e of the transportation of Brick 1 and Brick 2 (MW_B02) is not the same despite they are manufactured in the same site. This is due to the fact that transport carbon emissions depend not only from the distance but from the type and quantity of transport that is transported.

BRICKS COMPARISON						
Proposals	**EPD N°**	**Producer**	**Distance producer - construction site [km]**	**$kgCO_2$**		**$kgCO_2$ TOT**
				Product stage	Construction Process Stage transport	
				A1-A3	**A4**	
MW_B00	EPD ITALY0107	Wienerberger (Vercelli, Italy)	99,6	1,18E+05	2,02E+03	1,20E+05
MW_B01	EPD ITALY0053	Stabila Srl (Isola Vicentina, Italy)	240	3,59E+04	8,05E+03	4,40E+04
MW_B02	EPD ITALY0053	Stabila Srl (Isola Vicentina, Italy)	240	3,92E+04	6,88E+03	4,61E+04

Table 40: Bricks comparison (stage A4)

As regarding the plaster options, once again the transport contribution does not change the previous results:

PLASTERS COMPARISON						
Proposals	EPD N°	Producer	Distance producer - construction site [km]	kgCO_2		kgCO_2 TOT
				Product stage	Construction Process Stage transport	
				A1-A3	A4	
MW_P00	S-P-01642	Kerakoll (Sassuolo, Italy)	185	3,93E+04	1,12E+03	4,04E+04
MW_P01	Srl-91-EN	HD system (Trento, Italy)	260	2,21E+04	2,00E+03	2,41E+04

Table 41: Plaster comparison (stage A4)

WOOD WALL

In the case of the wood wall, only one of the three CLT proposed is made in Italy, the remaining two are imported from Austria (CLT 1, WW_T01) and Switzerland (CLT 2, WW_T02).

CLTs COMPARISON						
Proposals	EPD N°	Producer	Distance producer - construction site [km]	kgCO_2		kgCO_2 TOT
				Product stage	Construction Process Stage transport	
				A1-A3	A4	
WW_T00	ECO-00000725	Rubner Holding AG - S.p.A. (Bolzano, Italy)	360	-2,43E+05	2,32E+03	-2,40E+05
WW_T01	ECO-00001225	Stora Enso (Austria)	645	-2,58E+05	4,24E+03	-2,54E+05
WW_T02	EPDSLH-20180066-IBC1EN	Schiliger Holz (Switzerland)	266	-2,25E+05	1,58E+03	-2,23E+05

Table 42: CLTs comparison (stage A4)

As shown by the table, although solution two (CLT 2, WW_T02) is the farthest one, the emissions due to its transport, even if almost double the ones of the other solutions, do not penalize this choice. Therefore, despite the distance, CLT 1 (WW_T01) is still the best in terms of CO2 emissions.

As regarding the transportation of the organic insulation, carbon emissions due to their transport do not change the results obtained at a product stage level:

ORGANIC INSULTAIONS COMPARISON						
Proposals	EPD N°	Producer	Distance producer - construction site [km]	$kgCO_2$		$kgCO_2$ TOT
				Product stage	Construction Process Stage transport	
				A1-A3	A4	
WW_WF00	EPD-STE-20150327-IBD1-EN	BetonWood Srl (Firenze, Italy)	300	-7,03E+04	7,35E+01	-7,02E+04
WW_WF01	EPD-STE-20200001-IBA1-DE	Steico (France)	530	-2,23E+04	3,84E+02	-2,20E+04
WW_C01	EPD-PSG-20210030-IBA1-EN	Peter Seppele Gesellschaft m.b.H (Austria)	580	-3,09E+06	3,97E+02	-3,09E+06

Table 43: Organic insulations comparison (stage A4)

DRY WALL

The most interesting and maybe unexpected results are given by the cement board proposals. The total carbon emissions seem to be not affected by the enormous gap of kms between the three options. It almost looks like it does not make any difference to use a local product (cement board 0, DW_CB00) or to take it from almost 3000 km away (cement board 2, DW_CB02). Carbon emissions realised by the three options are almost the same but the best option is Cement Board 0 (DW_CB00).

CEMENT BOARDS COMPARISON						
Proposals	EPD N°	Producer	Distance producer - construction site [km]	$kgCO_2$		$kgCO_2$ TOT
				Product stage	Construction Process Stage transport	
				A1-A3	A4	
DW_CB00	INIES_IPLA20170615_155601, 26957	KNAUF (Pisa, Italy)	340	4,01E+04	7,93E+02	4,09E+04
DW_CB01	27469692021	Fermacell (Nantes, France)	1000	5,84E+04	1,94E+03	6,03E+04
DW_CB02	MD-16001-EN	Cembrit (Finland)	2700	4,66E+04	4,34E+03	5,10E+04

Table 44: Cement boards comparison (stage A4)

As regarding the EPS transportation, since the producers of the two proposals are only a few kilometres apart from each other, the contribution of transport to carbon emissions is practically irrelevant, as the table below shows.

EPSs COMPARISON						
Proposals	**EPD N°**	**Producer**	**Distance producer - construction site [km]**	**$kgCO_2$**		**$kgCO_2$ TOT**
				Product stage	Construction Process Stage transport	
				A1-A3	**A4**	
DW_EPS00	EPDITALY0164	Polisette (Crremona, Italy)	85	3,80E+04	2,70E+01	3,80E+04
DW_EPS01	EPDITALY0029	IsolCofort (Alessandria, Italy)	81	2,62E+04	2,65E+01	2,62E+04

Table 45: EPSs comparison (stage A4)

Since considering the A4 stage do not change the product stage analysis result it is possible to say that in this case transport stage do not make any different in the materials choice. Now it is possible to put together the best materials options and to assess the improved stratigraphy.

▪ IMPROVED STRATIGRAPHIES

Now that different materials options were compered, it is possible to select the materials which allows to reach the minor footprint possible for the external wall proposals.

The aim of the following chapter is to highlight how, through a more conscious selection of the materials, it is possible to influence and minimize the footprint of a construction solution. The improved stratigraphies and their main characteristics are presented through schematic tables below. On the left of the tables the old stratigraphy, on the right of the tables the improved one with the changed materials highlighted in green.

MASONRY WALL

	OLD STRATIGRAPHY		IMPROVED STRATIGRAPHY				
MW_01 Stratigraphy	Typology	U [W/m²K]	Identification code	Typology	Total thickness [m]	λ [W/mK]	U [W/m²K]
Indoor coating paste	acrylic-siloxane paint	0,185	MW_CP00	acrylic-siloxane paint	-	-	0,199
Levelling plaster	natural lime mortars for levelling plaster		MW_LP00	natural lime mortars for levelling plaster	0,01	0,45	
Plaster	natural lime mortars for plaster		MW_P01	Hydraulics lime mortar for plaster	0,01	1,110	
Brick	clay-based holed brick		MW_B01	lightened blocks with wood flour	0,25	0,181	
Plaster	natural lime mortars for plaster		MW_P01	hydraulics lime mortar for plaster	0,01	1,110	
Insulation[1]	sintered expanded polystyrene sheet (EPS)		MW_EPS00	sintered expanded polystyrene sheet (EPS)	0,12	0,035	
Plaster with grid[2]	plaster with metal grid		MW_P01	Hydraulics lime mortar for plaster	0,01	1,110	
Levelling plaster	natural lime mortars for levelling plaster		MW_LP00	natural lime mortars for levelling plaster	0,01	0,45	
Outdoor coating paste	acrylic-siloxane paint		MW_CP00	acrylic-siloxane paint	-	-	

Table 46: Masonry wall improved stratigraphy, MW_01

1. EPS insulations was studied and improved for the dry wall, but the improved one would change the new stratigraphy thermal transmittance into a value too high with respect the standards. Therefore, I decided to leave the EPS used for the starting point stratigraphy.
2. This layer will be considered as just a plaster layer for the calculation of the footprint.

WOOD WALL

	OLD STRATIGRAPHY		IMPROVED STRATIGRAPHY				
WW_01 Stratigraphy	Typology	U [W/m²K]	Identification code	Typology	Total thickness [m]	λ [W/mK]	U [W/m²K]
Indoor coating paste	acrylic-siloxane paint		WW_CP00	acrylic-siloxane paint	-	-	
Plasterboard	gypsum board		WW_P00	gypsum board	0,015	0,2	
Insulation	mineral wool		WW_MW00	mineral wool	0,07	0,04	
Timber	At least three layers made from kiln dried coniferous wood	0,185	WW_T01	Several bonded single-layer panels (3cm each) arranged at right angles to each other	0,09	0,120	0,183
Structural timber1	structural wood slats		WW_ST00	structural wood slats	0,07	-	
Insulation	wood fibre		WW_C01	manufactured from mono-fraction paper from newspapers	0,10	0,037	
Plaster	natural lime mortars for plaster		WW_P00	natural lime mortars for plaster	0,015	1,110	

Table 47: Wood wall improved stratigraphy, WW_01

DRY WALL

	OLD STRATIGRAPHY		IMPROVED STRATIGRAPHY				
DW_01 Stratigraphy	Typology	U [W/m²K]	Identification code	Typology	Total thickness [m]	λ [W/mK]	U [W/m²K]
Indoor coating paste	acrylic-siloxane paint		DW_CP00	acrylic-siloxane paint	-	-	
Plasterboard	vapour resistant gypsum board		DW_PB00	vapour resistant gypsum board	0,015	0,2	
Mineral Wool	mineral wool		DW_MW00	mineral wool	0,06	0,04	
Plasterboard	gypsum board		DW_P00	gypsum board	0,0125	0,2	
Insulation	sintered expanded polystyrene sheet (EPS)	0,186	DW_EPS00	sintered expanded polystyrene sheet (EPS)	0,12	0,036	0,193
Outdoor cement-board[1]	cement-board (Aquapanel)		DW_CB00	cement-board (Aquapanel)	0,0125	0,35	
Outdoor coating paste	acrylic-siloxane paint		DW_CP00	acrylic-siloxane paint	-	-	

Table 48: Dry wall improved stratigraphy, DW_01

1. The outdoor cement-board was compared with other solutions but the one used in the starting stratigraphy was the best one in terms of carbon emissions

Once the improved stratigraphies are settled, it is possible to determine their product stage carbon emissions through the values supplied by materials' EPDs.

MASONRY WALL

MW_01	Identification code	Functional Unit (F.U.)	Quantities in the project	kgCO2/F.U. A1-A3	kgCO2/F.U. TOT
Levelling plaster	MW_LP00	1 kg	24.367,56	2,38E-01	5,80E+03
Plaster	MW_P01	1kg	201.032,37	1,10E-01	2,21E+04
Brick	MW_B01	1 ton	876,217	4,10E+01	3,59E+04
Plaster	MW_P01	1kg	201.032,37	1,10E-01	2,21E+04
Insulation	MW_EPS00	1 m^3	487,35	7,79E+01	3,80E+04
Plaster with grid	MW_P01	1kg	201.032,37	1,10E-01	2,21E+04
Levelling plaster	MW_LP00	1 kg	24.367,56	2,38E-01	5,80E+03
				Total carbon emissions:	**1,52E+05**

Table 49: MW_01 Carbon emissions (stages A1-A3)

WOOD WALL

WW_01	Identification code	Functional Unit (F.U.)	Quantities in the project	kgCO2/F.U. A1-A3	kgCO2 TOT
Wood	WW_T01	1 m3	365,5134	-7,07E+02	-2,58E+05
Cellulose	WW_C01	1 kg	11371,528	-1,73E+02	-1,97E+06
Glass Wool	WW_MW00	1 m^2	4.061,26	5,50E-01	2,23E+03
Plaster-board	WW_PB00	1 m^2	4.061,26	3,16E+00	1,28E+04
Plaster	WW_P01	1kg	48.735,10	2,48E-01	1,21E+04
				Total carbon emissions:	**-2,20E+06**

Table 50: WW_01 Carbon emissions (stages A1-A3)

DRY WALL

DW_01	Identification code	Functional Unit (F.U.)	Quantities in the project	kgCO2/F.U. A1-A3	kgCO2 TOT
Plasterboard	DW_PB00	1 m^2	4.061,26	3,16E+00	1,28E+04
Mineral Wool	DW_MW00	1 m^2	4.061,26	5,50E-01	2,23E+03
Plaster-board	DW_P00	1 m^2	4.061,26	2,27E+00	9,22E+03
Insulation	DW_EPS01	1 m^3	487,3512	5,38E+01	2,62E+04
Outdoor cement-board	DW_CB00	1 m^2	4.061,26	9,88E+00	4,01E+04
				Total carbon emissions:	**9,06E+04**

Table 51: DW_01 Carbon emissions (stages A1-A3)

In the following chapters the improved stratigraphy carbon emissions are compared with the starting point stratigraphy ones. in order to see how much changing materials can impact the reduction of kgCo2e.

MASONRY WALL

	STARTING POINT	IMPROVED SOLUTION	
MW stratigraphy:	CARBON EMISSIONS	CARBON EMISSIONS	REDUCTION [%]
	kgCO2e	kgCO2e	
Brick	118.263,89	35.924,89	-69,62
Insulation	37.964,66	37.964,66	-
Levelling Plaster	11.598,96	11.598,96	-
Plaster	39.280,51	66.340,68	-68,89
Total:	**kgCO2e**	**kgCO2e**	REDUCTION [%]
MASNORY WALL	**207.108,01**	**151.829,19**	-26,69

Table 52: Starting point vs Improved (masonry wall)

As shown from the above table the carbon emissions of the wood walls are minimized of almost the 30% thanks to just the use of different materials. The highest improvement is given by the use of a lightened brick with wood flour which clearly stress less the environment (-69,62%).

WOOD WALL

		STARTING POINT	IMPROVED SOLUTION	
WW Stratigraphy:		CARBON EMISSIONS	CARBON EMISSIONS	REDUCTION [%]
		kgCO2e	kgCO2e	
Wood		- 242.700,90	- 258.308,32	- 6,43
Insulation	Organic	- 70.313,81	- 1.968.786,76	- 2.700,00
	Glass Wool	2.233,69	2.233,69	-
Gypsum	Plasterboard	12.833,58	12.833,58	-
	Plaster	12.086,30	12.086,30	-
Total:		**kgCO2e**	**kgCO2e**	REDUCTION [%]
CLT WOOD WALL		**- 285.861,13**	**- 2.189.914,24**	- 666,08

Table 53: Starting point vs Improved (wood wall)

In the case of the wood the improvement is really high. The highest contribution to the improvement is given by the substitution of the organic insulation. In the starting stratigraphy the organic insulation consists of wood fibre while in the improved one, it is replaced with blown cellulose. Wood-fibre insulation and cellulose insulation are made from the same raw material, but cellulose is newspaper, whereas wood fibre comes from softwood chips. Since cellulose insulation is made mostly from recycled newspaper which is one of the largest components of our solid waste stream[32], there is no wonder it minimizes a lot the global

[32] https://www.greenbuildingadvisor.com/article/wood-fiber-insulation-products [13/11/2022]

footprint. The second highest contribution to the footprint improvement is given by the wood. In this case, the two materials do not differ a lot and therefore the improvement is not so much significant, especially compared to the cellulose one.

DRY WALL

		STARTING POINT	**IMPROVED SOLUTION**	REDUCTION [%]
DW Stratigraphy:		**CARBON EMISSIONS**	**CARBON EMISSIONS**	
		kgCO2e	**kgCO2e**	
Gypsum plaster-board	Vapour resistant	12.833,58	12.833,58	0,00
	Classic	9.219,06	9.219,06	0,00
Insulation	Mineral wool	2.233,69	2.233,69	0,00
	EPS	37.964,66	26.219,49	-30,94
Outdoor cement-board (Aquapanel)[1]		40.125,25	40.125,25	0,00
Total:		**kgCO2e**	**kgCO2e**	REDUCTION [%]
DRY WALL		**102.376,24**	**90.631,08**	-11,47

Table 54: Starting point vs Improved (dry wall)

1. Despite the comparison carried out for the cement board the starting option is the best one in terms of carbon emissions for this reason, therefore it is highlighted in green but it does not increase the reduction.

For the dry wall the only contribution to the optimization of the footprint is given by the EPS insulation, which allows alone to reach a total reduction of the almost 12%.

In the following page all the results of the comparison between the starting point stratigraphies and the improved ones are showed through a graph which has the main aim to make the comparation easier and more intuitive.

CONSIDERATIONS

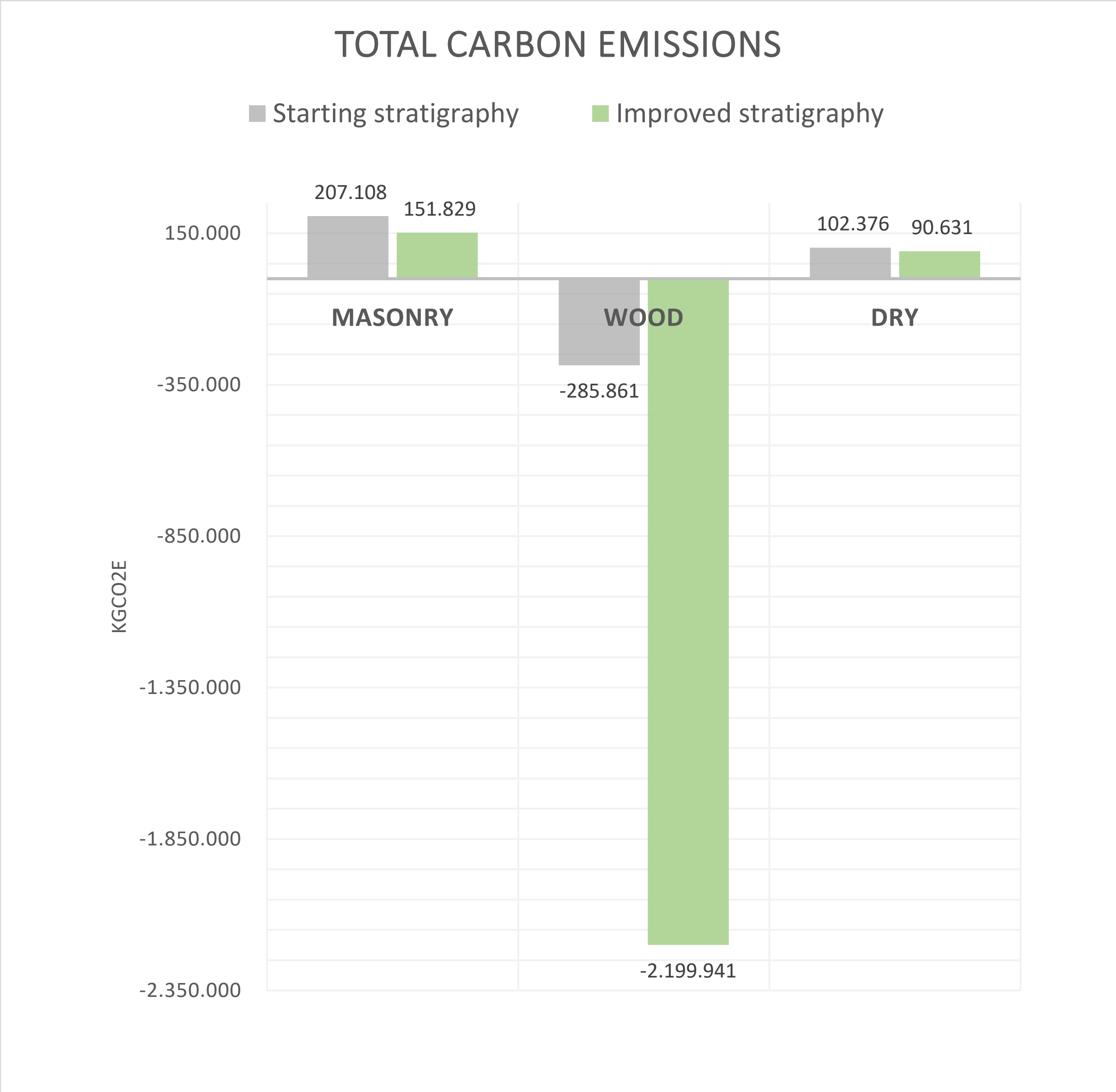

Figure 35: Graph of the comparison between starting point and improved stratigraphies

It is clear that, basing the assumption on only the product stage, the wood wall is the option with not only the lowest footprint but with a negative value of it. That means that this typology of external wall has an active positive role in climate change. Otherwise, the other two options contribute to global warming. The traditional solution is the one with the highest value of carbon emissions, while dry wall is in between the previous mentioned options but it anyway has a positive value of carbon emissions.

As shown by the graph all of the stratigraphies have been improved by the substitutions. On the other hands, none of the substitutions made such a difference in order to completely change the overall results. In other word, with the starting point the three stratigraphies stress the environmental in the following decrescent order: wood wall, dry wall and masonry wall. After the improvements that order of classification did not change. As shown by the tables the wood is the one with the highest reduction (-666.08%).

- ## LONG TERM ANALYSIS

Since now the three external wall typologies have been compared only on their early stages. In order to make a more complete comparison also long-term analysis should be taken into account. In other words, the carbon emissions found in the previous paragraphs need to be implemented with the carbon emissions released at the end of life of the walls. This means adding to the calculations carbon emissions values from stage C1, to stage C4 and stage D.

C1-C4; D

The end-of-life stages (C1-C4) take into account emissions released during decommissioning, stripping out, demolition, deconstruction, transportation of materials away from the site, waste processing and disposal of materials. The end-of-life stage includes:

- C1, de-construction, demolition: Deconstruction includes dismantling or demolition of the product from the construction.
- C2, transport to waste processing: considers how the product is uninstalled and the construction mixed waste is transported away from the construction site in accordance with the waste management adopted.
- C3, waste processing for reuse, recovery and/or recycling
- C4, disposal
- D, declares the potential charges and benefits related to the secondary material, secondary fuel or recovered energy leaving the product system (in stage C3)

In order to do that, each EPD assumes different scenarios with assumptions on the end-of-life treatment. All the scenario are well explained in the EPDs. The one used in my calculation, according to the declaration used, are showed in the next paragraphs.

For each external wall proposal, the carbon emissions supplied by the materials' EPD of stage C1-C4 are used to calculate the total carbon emissions of the wall. In some cases, can happen that the material's EPD is not a cradle to grave and, therefore do not supply any information about the end-of-life stages. In these latter cases EPD of other similar product are used as reference in order to complete the calculations and have a general idea of the total footprint of the opaque vertical envelope. When substitutes are used, it is important to highlight that from the substitutive EPDs only the environmental indicators are taken, the quantities of the materials are the ones of the improved stratigraphy.

MASONRY WALL

In the case of the masonry wall none of the EPD of the improved stratigraphy supplies information about the stage under analysis. Therefore, other substitutive materials' EPD are used for the calculation which are presented in the table below.

	IMPROVED STRATIGRAPHY MATERIALS			**MATERIALS USED FOR CALCULATIONS**		
	EPD N°	**Producer**	**Typology**	**EPD N°**	**Producer**	**Typology**
Levelling plaster	S-P-01642	Kerakoll (Sassuolo, Italy)	natural mortars for plaster	INIES_ISER20210707_084158, 26819	Optiroc Saint-Gobain (Francia)	Smoothing plaster
Plaster	Srl-91-EN	HD system (Trento, Italy)	Hydraulics lime mortar for plaster	INIES_ILUT20181212_164710, 9018	Placoplatre (Francia)	mortar for plaster
Brick	EPDITALY0053	Stabila Srl (Isola Vicentina, Italy)	Lightened blocks with wood flour	-	Bouyer Leroux (France)	brick traditional
Insulation	EPDITALY0164	Polisette (Cremona, Italy)	sintered expanded polystyrene sheet	-	Knauf Francia	sintered expanded polystyrene sheet

Table 55: Substitutive materials used for the end-of-life stage values (Masonry wall)

The table below shows the scenarios supplied by the EPD used for the calculations:

Material	**EPD N°**	**Scenario for C1-C4**	**Scenario for D**
Levelling plaster	INIES_ISER20210707_084158, 26819	The product is considered to be placed in a storage facility without reuse, recovery and/or recycling. The cladding must be buried in a storage centre for non-hazardous waste in its entirety (100%)	The producer does not foresee the recovery of the material
Plaster	INIES_ILUT20181212_ _64710, 9018	The product is considered to be placed in a storage facility without reuse, recovery and/or recycling. The plaster is supposed to be buried in a waste storage centre in its entirety (100%).	The producer does not foresee the recovery of the material
Brick		The product is deconstructed using demolition machinery, modelled by fuel consumption. The end-of-life distribution of product waste is as follows: - 94.7% of the product is considered reused (backfill, quarry filling, etc.)	The 94.7% of the mass of product recovered at the end-of-life stage is considered to be recovered as backfill or quarry filling.

		- 4.7% considered inert waste (landfill) - 0.6% considered non-hazardous waste (landfill). Traditional mortar is considered to be recovered with the bricks and disposed of in landfill.	
EPS (insulation)		Storage in a dumpster for burial in a Class II Waste Storage Facility: non-hazardous waste. This waste is transported by dump truck over a distance of 30 km.	The producer does not foresee the recovery of the material

Table 56: Materials' scenarios used for the end-of-life stage values (Masonry wall)

Thanks to the substitutive EPDs it is possible to proceed with the end-of-life carbon emissions calculations, which are reported in the tables below. From the table it is possible to notice that the coating paste are not considered in these calculations, since their contribution to the end-of-life carbon emissions is not decisive.

MW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**$kgCO^2$/F.U.**				**$kgCO^2$ TOT**
				C1	**C2**	**C3**	**C4**	
Indoor coating paste	MW_CP00	-	-	-	-	-	-	-
Levelling plaster	MW_LP00	1 m^2	4.061,26	0,00E+00	6,27E-03	0,00E+00	7,87E-03	5,74E+01
Plaster	MW_P01	1 m^2	4.061,26	0,00E+00	2,70E-02	0,00E+00	1,50E-01	7,19E+02
Brick	MW_B01	1 m^2	4,06E+03	4,57E-01	6,78E-01	5,09E-02	9,60E-02	5,21E+03
Plaster	MW_P01	1 m^2	4.061,26	0,00E+00	2,70E-02	0,00E+00	1,50E-01	7,19E+02
Insulation	MW_EPS00	1 m^2	4.061,26	0,00E+00	3,78E-03	0,00E+00	3,37E-03	2,90E+01
Plaster with grid	MW_P01	1 m^2	4.061,26	0,00E+00	2,70E-02	0,00E+00	1,50E-01	7,19E+02
Levelling plaster	MW_LP00	1 m^2	4.061,26	0,00E+00	6,27E-03	0,00E+00	7,87E-03	5,74E+01
Outdoor coating paste	MW_CP00	-	-	-	-	-	-	-
Total carbon emissions, C1-C4 stage of the masonry wall:								**7,51E+03**

Table 57: MW_01 carbon emissions (stage C1-C4)

Identification code	Functional Unit (F.U.)	Quantities in the project	$kgCO^2$/F.U.	$kgCO^2$ TOT
			D	
Indoor coating paste	-	-	-	-
Levelling plaster	-	-	-	-
Plaster	-	-	-	-
Brick	1 m^2	4,06E+03	-1,90E-01	-7,72E+02
Insulation	-	-	-	-
Total carbon emissions, D stage of the masonry wall:				**-7,72E+02**

Table 58: MW_01 carbon emissions (stage D)

As predictable from the scenarios, the only material which includes a waste processing at the end of life is brick. For this reason, it is the only one which contributes to stage C3 and D.

WOOD WALL

In the case of the wood wall all the materials' EPDs supply the carbon emissions for the end-of-life stage, with the exception of the plaster. Therefore, for plaster it is used the same substitutive material's EPD used for the masonry wall while the remain materials' EPDs of the improved stratigraphies are used in order to determine the total foot print of the wood wall proposal. The table below recall the plaster used in the masonry wall.

	IMPROVED STRATIGRAPHY MATERIALS			MATERIALS USED FOR CALCULATIONS		
	EPD N°	**Producer**	**Typology**	**EPD N°**	**Producer**	**Typology**
Plaster	Srl-91-EN	HD system (Trento, Italy)	Hydraulics lime mortar for plaster	INIES_ILUT20181212_164710, 9018	Placoplatre (Francia)	mortar for plaster

Table 59: Substitutive materials used for the end-of-life stage values (Wood wall)

The table below shows the scenarios supplied by the EPD used for the calculations:

Material	EPD N°	Scenario for C1-C4	Scenario for D
Wood	ECO-00001225	Four alternative scenarios have been developed: - Reuse -Recycling (used for the calculation)[1] -Incineration - Landfilling	- Reuse: reuse of product, substituting virgin material - Recycling: recovery of wood chips, substituting virgin material - Incineration: substitution of natural gas in heat production - Landfilling: the methane uptake from landfill partly substitutes natural gas in heat production
Cellulose	EPD-PSG-2021003 IBA1-EN	Contaminated insulation material is disposed of as residual waste and thermally recycled in a waste incineration plant	Thermal recycling
Glass Wool	INIES_IFEU20 180419_085405, 8175	Glass wool is assumed to be placed in a non-inert and non-inert waste disposal facility.	The producer does not foresee the recovery of the material
Plaster-board	S-P-01933	Once plasterboards Knauf GKI are installed, they are not suited for re-use in an unchanged way. Once the product is uninstalled, is transported to the landfill disposal.	The producer does not foresee the recovery of the material
Plaster	INIES_ ILUT201 81212_164710, 9018	The product is considered to be placed in a storage facility without reuse, recovery and/or recycling. The plaster is supposed to be buried in a waste storage centre in its entirety (100%).	The producer does not foresee the recovery of the material

Table 60: Materials' scenarios used for the end-of-life stage values (Wood wall)

1. The Wood's EPD supplies four different scenarios. The one with the total minor carbon emissions (C1-C4, D) is the one used for the calculations. The table below shows how the Recycling scenario is the best in terms of carbon emissions:

	kgCO²/F.U.					kgCO²/F.U. TOT
	C1	C2	C3	C4	D	
Reuse	5,42E-01	2,04E+00	7,62E+02	0,00E+00	-8,14E+02	-4,94E+01
Recycling	5,42E-01	2,04E+00	7,68E+02	0,00E+00	-8,21E+02	-5,04E+01
Inceniration	5,42E-01	2,04E+00	7,95E+02	0,00E+00	-3,65E+02	4,33E+02
Landfill	5,42E-01	2,04E+00	0,00E+00	1,05E+03	-3,93E+00	1,05E+03

Table 61: Alternative scenarios for CLTs panels provided by the EPD

It is possible now to proceed with the end-of-life carbon emissions calculations, which are reported in the tables below. Once again, the coating paste are not considered in these calculations, since their contribution to the end-of-life carbon emissions is not decisive.

WW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**kgCO^{2}/F.U.**				**kgCO^{2} TOT**
				C1	**C2**	**C3**	**C4**	
Wood	WW_T01	1 m^3	365,5134	5,42E-01	2,04E+00	7,68E+02	0,00E+00	2,82E+05
Cellulose	WW_C01	1 kg	17.869,544	1,87E-03	1,17E-02	1,62E+00	0,00E+00	2,92E+04
Glass Wool	WW_MW00	1 m^2	4.061,26	0,00E+00	3,40E-03	0,00E+00	3,80E-03	2,92E+01
Plaster-board	WW_PB00	1 m^2	4.062,26	2,15E-02	2,26E-02	0,00E+00	3,47E-02	3,20E+02
Plaster	WW_P01	1 m^2	4.061,26	0,00E+00	2,70E-02	0,00E+00	1,50E-01	7,19E+02
Coating pastes	WW_CP00	-	-	-	-	-	-	-
Total carbon emissions, end-of-life stage of the wood wall:								**3,12E+05**

Table 62: WW_01 carbon emissions (stage C1-C4)

Identification code	**Functional Unit (F.U.)**	**Quantities in the project**	**kgCO^{2}/F.U.**	**kgCO^{2} TOT**
			D	
WW_T01	1 m^3	365,5134	-8,21E+02	-3,00E+05
WW_C01	1 kg	17.869,544	-4,75E-01	-8,49E+03
WW_MW00	-	-	-	-
WW_PB00	-	-	-	-
WW_P01	-	-	-	-
WW_CP00	-	-	-	-
Total carbon emissions, D stage of the wood wall:				**-3,09E+05**

Table 63: WW_01 carbon emissions (stage D)

As predictable from the scenarios, the only materials which include a waste processing at the end of life are the CLT and the cellulose insulation. For this reason, they are the only ones which contribute to stage C3 and D.

DRY WALL

In the dry wall case, all the material's EPDs supply the necessary information about the ned of life stage. Therefore, it is not necessary to look for substitutive materials. All the data used for the calculations are taken from the EPDs of the materials of the improved stratigraphy. The table below shows the scenarios supplied by the EPD used for the calculations:

Material	EPD N°	Scenario for C1-C4	Scenario for D
Plaster-board	S-P-01933	Once plasterboards Knauf GKI are installed, they are not suited for re-use in an unchanged way. Once the product is uninstalled, is transported to the landfill disposal.	The producer does not foresee the recovery of the material
Mineral Wool	INIES_IFEU20180419 _085405, 8175	Glass wool is assumed to be placed in a non-inert and non-inert waste disposal facility.	The producer does not foresee the recovery of the material
Plaster-board	S-P-01934	Once plasterboards Knauf GKI are installed, they are not suited for re-use in an unchanged way. Once the product is uninstalled, is transported to the landfill disposal.	The producer does not foresee the recovery of the material
Insulation	EPD2017-02-03	Two different scenarios are proposed: - Scenario 1: 100% of the product is recycled[1] -Scenario 2: 100% of the product used for energy recovery	Depends on the scenario is used
Outdoor cement-board	INIES_IPLA20170615 _155601, 26957	Once plasterboards Knauf GKI are installed, they are not suited for re-use in an unchanged way. Once the product is uninstalled, is transported to the landfill disposal.	The producer does not foresee the recovery of the material

Table 64: Materials' scenarios used for the end-of-life stage values (Dry wall)

1. The EPS insulation's EPD supplies two different scenarios. The one with the total minor carbon emissions (C1-C4, D) is the one used for the calculations. The table below shows how the Scenario 1 is the best in terms of carbon emissions:

	kgCO²/F.U.					kgCO² TOT
	C1	C2	C3	C4	D	
Scenario 1	0,00E+00	1,02E-01	9,56E+00	0,00E+00	-3,10E+01	-2,13E+01
Scenario 2	0,00E+00	1,02E-01	5,94E+01	0,00E+00	-1,19E+00	5,83E+01

Table 65: Alternative scenarios for EPSs insulation provided by the EPD

It is possible now to proceed with the end-of-life carbon emissions calculations, which are reported in the next tables.

DW_01	Identification code	Functional Unit (F.U.)	Quantities in the project	kgCO²/F.U.				kgCO² TOT
				C1	C2	C3	C4	
Plaster-board	DW_PB00	1 m²	4.061,26	2,15E-02	2,26E-02	0,00E+00	3,47E-02	3,20E+02
Mineral wool	DW_MW00	1 m²	4.061,26	0,00E+00	2,40E-09	0,00E+00	1,50E-09	1,58E-05
Plaster-board	DW_P00	1 m²	4.061,26	2,82E-02	2,95E-02	0,00E+00	4,54E-02	4,19E+02
EPS	DW_EPS01	1 m³	487,3512	0,00E+00	1,02E-01	9,56E+00	0,00E+00	4,71E+03
Outdoor cement-board	DW_CB00	1 m²	4.061,26	0,00E+00	1,85E-02	0,00E+00	3,26E-02	2,08E+02
Total carbon emissions, end-of-life stage of the dry wall:								**5,66E+03**

Table 66: DW_01 carbon emissions (stage C1-C4)

Identification code	Functional Unit (F.U.)	Quantities in the project	kgCO²/F.U.	kgCO² TOT
			D	
DW_PB00	-	-	-	-
DW_MW00	-	-	-	-
DW_P00	-	-	-	-
DW_EPS01	1 m³	487,3512	-3,10E+01	-1,51E+04
DW_CB00	-	-	-	-
Total carbon emissions, D stage of the wood wall:				**-1,51E+04**

Table 67: DW_01 carbon emissions (stage D)

As predictable from the scenarios, the only material which includes a waste processing at the end of life is EPS insulation. For this reason, it is the only one which contributes to stage C3 and D.

3.2 FINAL RESULTS

		$kgCO^2e$			$kgCO^2$ TOT
		A1-A3	C1-C4	D	
Masonry Wall	**MW_01**	1,52E+05	7,51E+03	-7,72E+02	1,59E+05
Wood Wall	**WW_01**	-2,20E+06	3,12E+05	-3,09E+05	-2,20E+06
Dry Wall	**DW_01**	9,06E+04	5,66E+03	-1,51E+04	8,12E+04

Table 68: Total carbon emissions of the proposals

Even taking into account a long term prospective of the three proposals, the results do not change a lot. In fact, even considering the end-of-life treatment, wood wall remains the best option with still a positive active role in the fight against global warming. In the following figures the results are showed through charts with the main aim of make the comparation easier and more intuitive

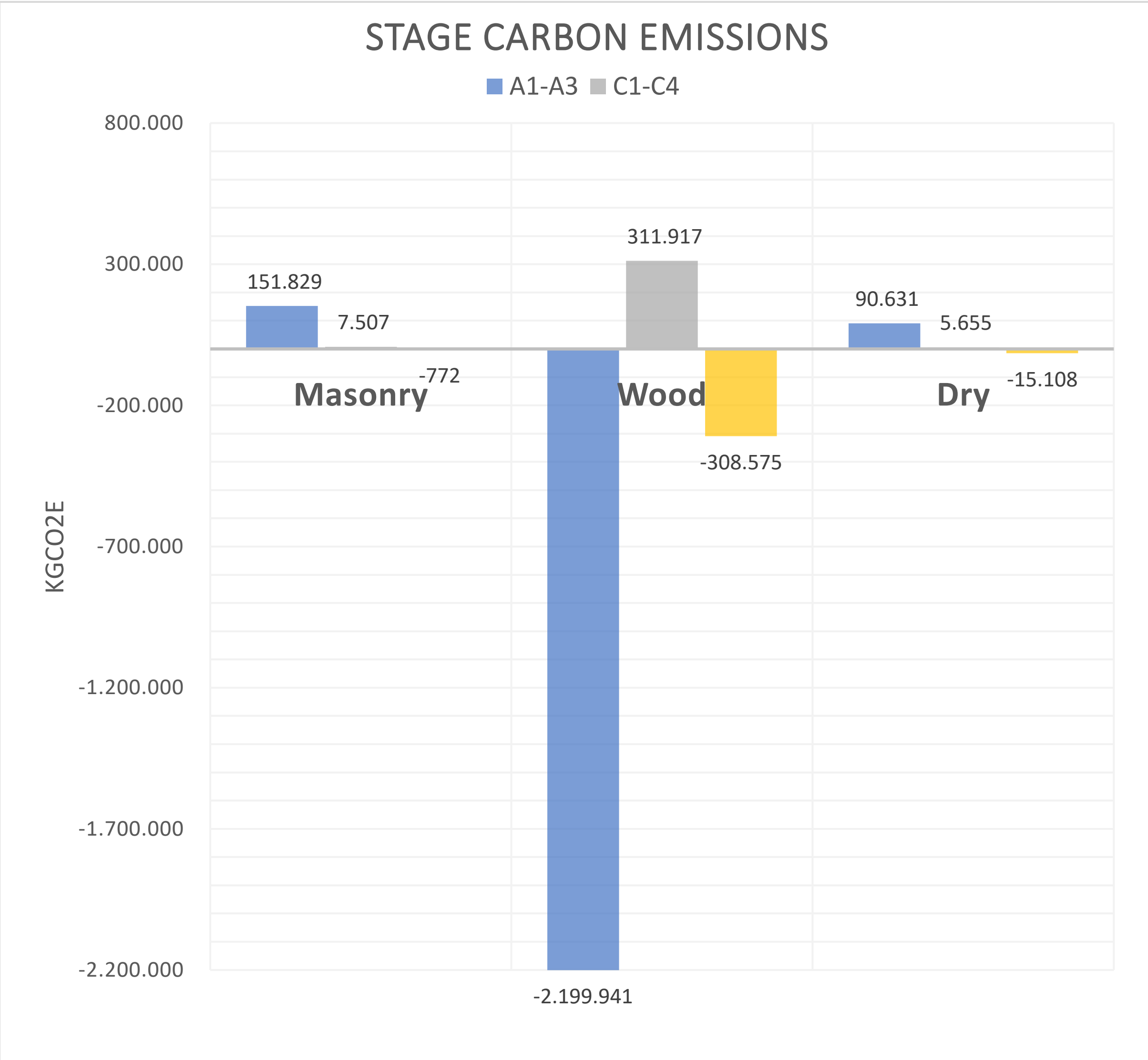

Figure 36: Chart of the carbon emissions in each stage for each wall typology

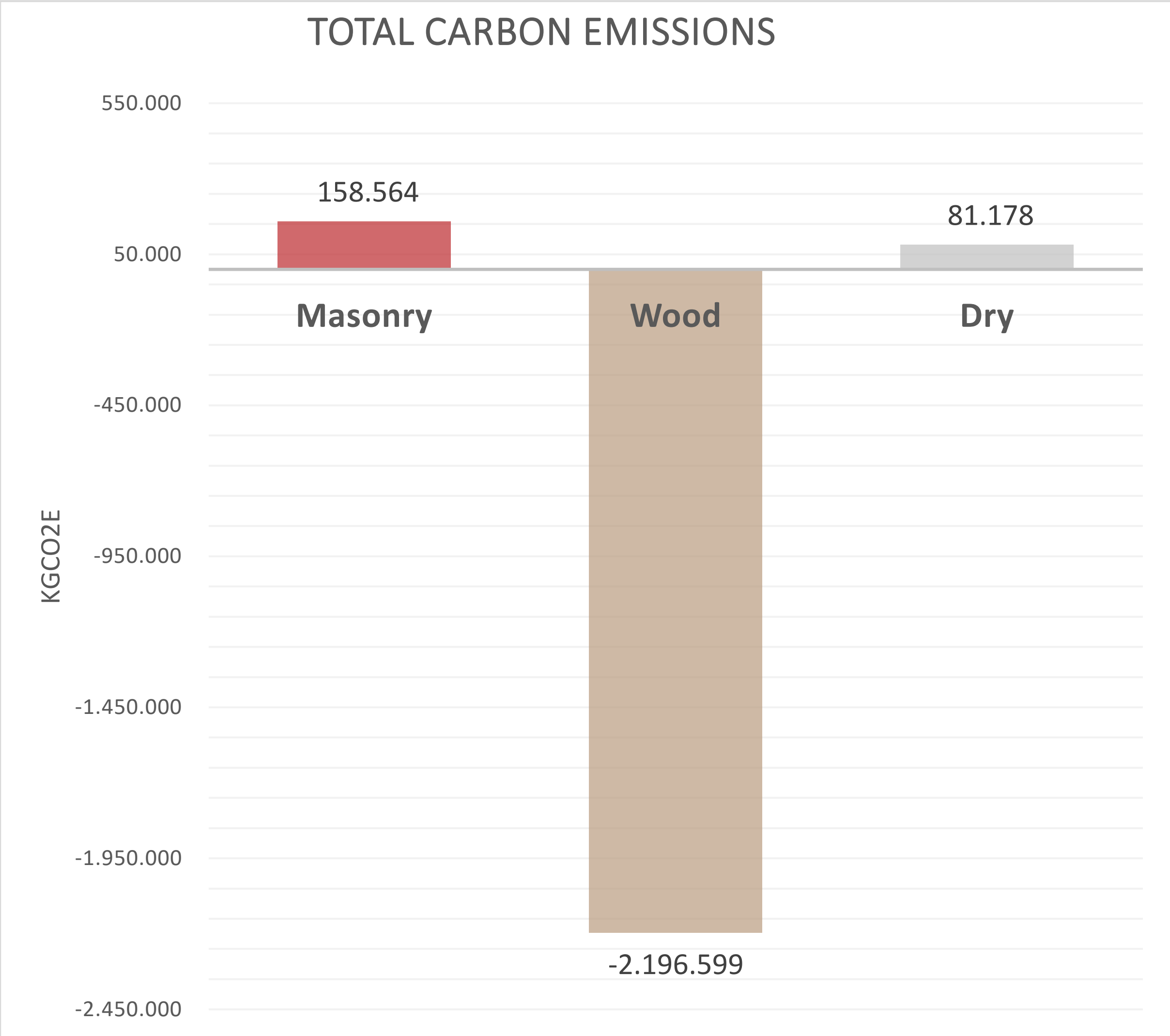

Figure 37: Chart of the total carbon emissions of the three walls

From the chart in figure 36 it is evident that despite wood is the best option its carbon emissions in the stages C1-C4 are two orders of magnitude higher than the others. That is possible only thanks to the enormous opposite difference in the other two stages, in which the values of the wood are clearly lower than those of the other two walls. From the diagram in figure 37 it is, once again, clear how wood wall other than be the best option it also acts positively on the environment by which is surrounded.

3.3 CONSIDERATIONS

This type of study allows to choose the best constructive option based only on its global warming potential. It is important to highlight that this indicator is fundamental but not the only one. In order to be sure to choose the choice which stress less the environment not only all the indicators but also resource use and waste production should be taken into account. All the letter data are delivered in the materials' EPD. In order to show how results can change by taking into account more environmental polluting aspects two more information are added to the study:

- ABIOTIC DEPLETION POTENTIAL FOR FOSSIL RESOURCES [MJ]: Abiotic depletion refers to the removal of abiotic resources from the earth, or the depletion of non-living natural resources. For materials it is generally measured as abiotic depletion potential (ADP). In general, it is separated out into two categories, one for non-fossil-based resources (minerals and metals) and a second for fossil resources. In both cases, it is recommended that assessment of ADP as an environmental impact indicator should be used with care as the uncertainties of the results are high and there is limited experience of its use as an indicator. For the aim of this thesis only the use of fossil resource is considered.
- WASTE PRODUCTION [KG]: Regarding the waste production three indicators are provided in an EPD, all measured in kg:
    - Hazardous waste disposed
    - Non-hazardous waste disposed
    - Radioactive waste disposed

  for non-radioactive waste, "waste disposed" means waste which is sent to landfill or to an incinerator.[33]

In the next pages all the calculations regarding these new factors are shown through the use of tables and graphs. It is important to state that all the EPD used for the following calculations are the same used in the section of the long-term analysis.

[33] https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en [14/11/2022]

ABIOTIC DEPLETION POTENTIAL FOR FOSSIL RESOURCES

MASONRY WALL								
MW_01	Identification code	Functional Unit (F.U.)	Quantities in the project	MJ/F.U.				MJ TOT
				A1-A3	A4	C1-C4	D	
Levelling plaster	MW_LP00	1 m^2	4.061,26	4,63E+00	9,09E-01	3,29E-01	-	2,38E+04
Plaster	MW_P01	1 m^2	4.061,26	2,00E+01	3,50E+00	3,15E+00	-	1,08E+05
Brick	MW_B01	1 m^2	4,06E+03	5,15E+01	2,92E+01	2,09E+01	-2,67E+00	4,02E+05
Plaster	MW_P01	1 m^2	4.061,26	2,00E+01	3,50E+00	3,15E+00	-	1,08E+05
Insulation	MW_EPS00	1 m^2	4.061,26	1,45E+02	8,61E-01	9,18E-02		5,93E+05
Plaster with grid	MW_P01	1 m^2	4.061,26	2,00E+01	3,50E+00	3,15E+00	-	1,08E+05
Levelling plaster	MW_LP00	1 m^2	4.061,26	4,63E+00	9,09E-01	3,29E-01	-	2,38E+04
Total abiotic depletion potential for fossil resources of the masonry wall:								**1,37E+06**
WOOD WALL								
WW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**MJ/F.U.**				**MJ TOT**
				A1-A3	**A4**	**C1-C4**	**D**	
Wood	WW_T01	1 m^3	365,5134	9,18E+02	6,25E+02	1,22E+02	-9,52E+02	2,61E+05
Cellulose	WW_C01	1 kg	17.869,54	2,23E+00	7,02E-01	5,52E-01	-6,80E+00	-5,93E+04
Glass Wool	WW_MW00	1 m^2	4.061,26	9,90E+00	8,00E-01	1,43E-01	-	4,40E+04
Plaster-board	WW_PB00	1 m^2	4.062,26	4,78E+01	1,35E+01	3,07E+00	-	2,61E+05
Plaster	WW_P01	1 m^2	4.061,26	2,00E+01	3,50E+00	3,15E+00	-	1,08E+05
Coating pastes	WW_CP00	-	-	-	-	-	-	-
Total abiotic depletion potential for fossil resources of the wood wall:								**6,15E+05**
DRY WALL								
DW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**MJ/F.U.**				**MJ TOT**
				A1-A3	**A4**	**C1-C4**	**D**	
Plasterboard	DW_PB00	1 m^2	4.061,26	4,78E+01	1,35E+01	3,07E+00	-	2,61E+05
Mineral Wool	DW_MW00	1 m^2	4.061,26	9,90E+00	8,00E-01	1,43E-01	-	4,40E+04
Plasterboard	DW_P00	1 m^2	4.061,26	3,36E+01	8,11E+00	2,15E+00	-	1,78E+05
Insulation	DW_EPS01	1 m^3	487,3512	1,46E+03	1,31E+01	1,12E+02	-1,00E+03	2,85E+05
Outdoor cement-board	DW_CB00	1 m^2	4.061,26	8,33E+01	5,30E+00	6,61E-01	-	3,63E+05
Total abiotic depletion potential for fossil resources of the dry wall:								**1,13E+06**

Table 69: abiotic depletion potential for fossil resources of the three walls (stages: A1-A3, A4, C1-C4, D)

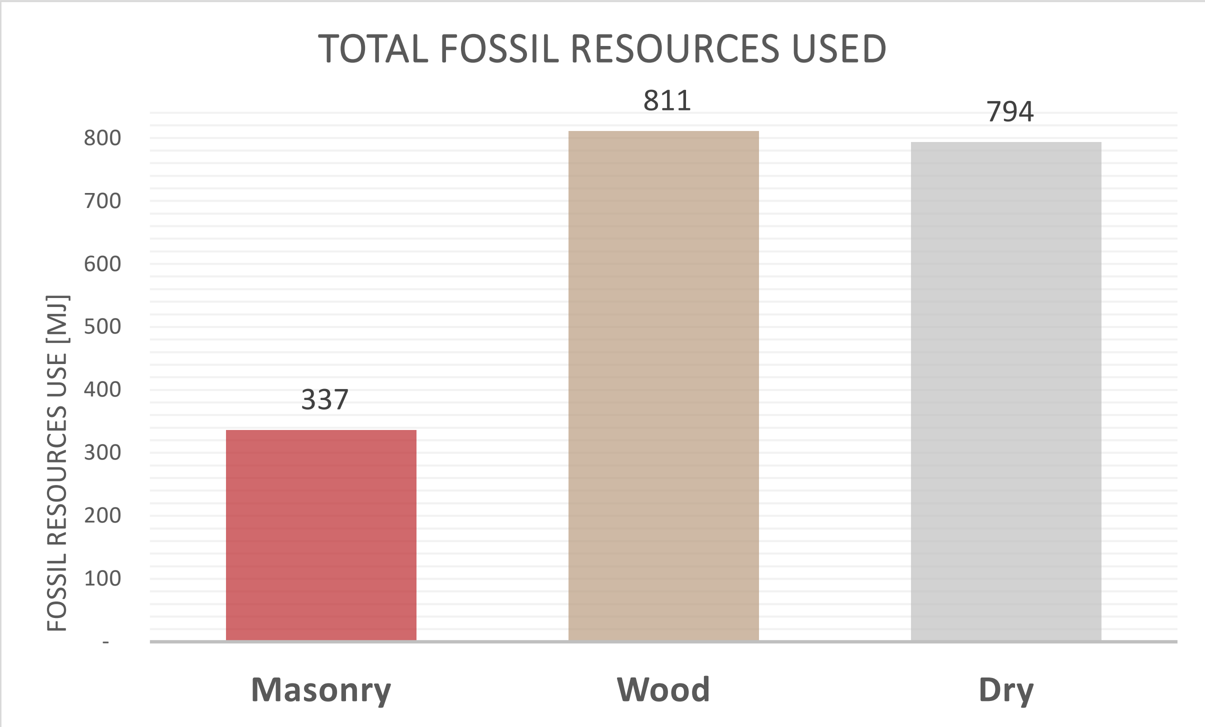

Figure 39: Chart of the total fossil resources used

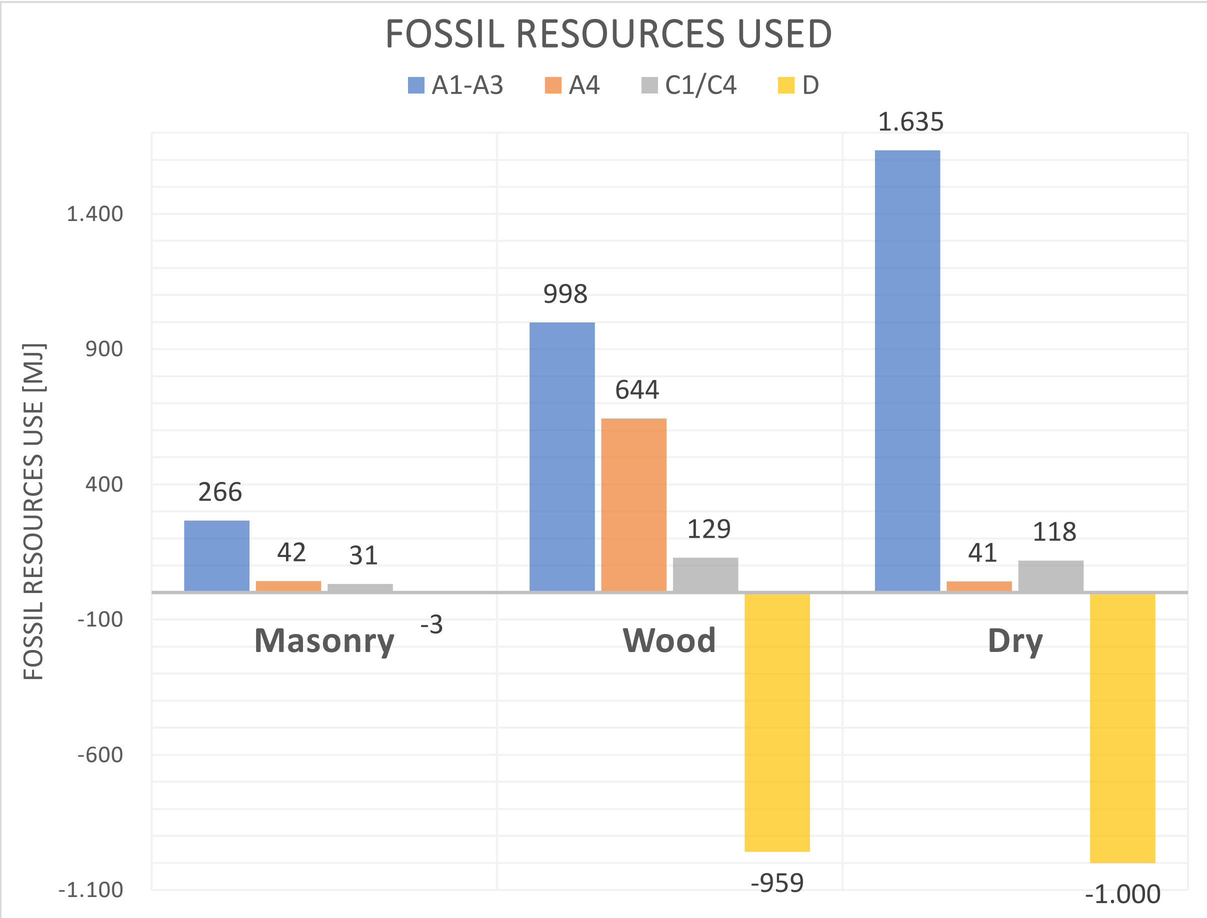

Figure 38: Chart of the fossil resources used in each stage for each wall typology

This new indicator analysed, after the $kgCO_2e$, perfectly represent what said before. From this new perspective the classification of the three wall is exactly symmetric to the one based on carbon emissions. The masonry option becomes the best solution for the environment while the wooden solution during its entire life needs almost three times the fossil resources used by the traditional masonry wall solution. Even if the dry wall is at the second position it is just slightly minor than the wood solution. More over if considering just the product stage of the dry wall, the number of fossil resources used are extremely high and higher than the other options. That latter aspect is quite unexpected and daunting since stage A1-A3 are the only stages improved during the analysis. This really high value in the product stage is compensated by a negative contribution of the D stage.

HAZARDOUSE WASTE PRODUCTION

MASONRY WALL								
MW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**kg/F.U.**				**kg TOT**
				A1-A3	**A4**	**C1-C4**	**D**	
Levelling plaster	MW_LP00	1 m^2	4.061,26	5,39E-03	2,67E-07	1,63E-05	-	2,20E+01
Plaster	MW_P01	1 m^2	4.061,26	6,20E-03	1,10E-04	4,80E-02	-	2,21E+02
Brick	MW_B01	1 m^2	4,06E+03	2,10E-02	1,22E-02	9,39E-03	-6,68E-03	1,46E+02
Plaster	MW_P01	1 m^2	4.061,26	6,20E-03	1,10E-04	4,80E-02	-	2,21E+02
Insulation	MW_EPS00	1 m^2	4.061,26	3,60E-03	2,67E-05	2,54E-06	-	1,47E+01
Plaster with grid	MW_P01	1 m^2	4.061,26	6,20E-03	1,10E-04	4,80E-02	-	2,21E+02
Levelling plaster	MW_LP00	1 m^2	4.061,26	6,20E-03	1,10E-04	4,80E-02	-	2,21E+02
Total hazardous waste production of the masonry wall:								**1,07E+03**

WOOD WALL								
WW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**kg/F.U.**				**kg TOT**
				A1-A3	**A4**	**C1-C4**	**D**	
Wood	WW_T01	1 m^3	365,5134	1,56E-01	0,00E+00	0,00E+00	0,00E+00	5,70E+01
Cellulose	WW_C01	1 kg	17.869,54	3,01E-08	5,29E-08	1,39E-08	-2,79E-09	1,68E-03
Glass Wool	WW_MW00	1 m^2	4.061,26	1,80E-02	2,40E-05	5,03E-05	-	7,34E+01
Plaster-board	WW_PB00	1 m^2	4.062,26	1,46E-04	8,08E-06	2,10E-06	-	6,34E-01
Plaster	WW_P01	1 m^2	4.061,26	6,20E-03	1,10E-04	4,80E-02	-	2,21E+02
Total hazardous waste production of the wood wall:								**3,52E+02**

DRY WALL								
DW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**kg/F.U.**				**kg TOT**
				A1-A3	**A4**	**C1-C4**	**D**	
Plasterboard	DW_PB00	1 m^2	4.061,26	1,46E-04	8,08E-06	2,10E-06	-	6,34E-01
Mineral Wool	DW_MW00	1 m^2	4.061,26	1,80E-02	2,40E-05	5,03E-05	-	7,34E+01
Plasterboard	DW_P00	1 m^2	4.061,26	1,25E-04	4,87E-06	1,34E-06	-	5,33E-01
Insulation	DW_EPS01	1 m^3	487,3512	5,31E-07	6,86E-07	1,89E-07	-1,64E-07	6,05E-04
Outdoor cement-board	DW_CB00	1 m^2	4.061,26	4,41E-02	1,62E-04	1,80E-05	-	1,80E+02
Total hazardous waste production of the dry wall:								**2,54E+02**

Table 70: Hazardous waste production of the three walls (stages: A1-A3, A4, C1-C4, D)

NON- HAZARDOUSE WASTE PRODUCTION

MASONRY WALL								
MW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**kg/F.U.**				**kg TOT**
				A1-A3	**A4**	**C1-C4**	**D**	
Levelling plaster	MW_LP00	1 m^2	4.061,26	4,98E-02	1,63E-03	1,50E+00	-	6,30E+03
Plaster	MW_P01	1 m^2	4.061,26	1,30E-01	2,90E-04	9,60E+00	-	3,95E+04
Brick	MW_B01	1 m^2	4,06E+03	7,78E-01	2,71E+00	2,30E+01	-5,27E-02	1,07E+05
Plaster	MW_P01	1 m^2	4.061,26	1,30E-01	2,90E-04	9,60E+00	-	3,95E+04
Insulation	MW_EPS00	1 m^2	4.061,26	2,90E-01	1,36E-05	1,56E+00	-	7,51E+03
Plaster with grid	MW_P01	1 m^2	4.061,26	1,30E-01	2,90E-04	9,60E+00	-	3,95E+04
Levelling plaster	MW_LP00	1 m^2	4.061,26	4,98E-02	1,63E-03	1,50E+00	-	6,30E+03
Total non-hazardous waste production of the masonry wall:								**2,46E+05**

WOOD WALL								
WW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**kg/F.U.**				**kg TOT**
				A1-A3	**A4**	**C1-C4**	**D**	
Wood	WW_T01	1 m^3	365,5134	1,22E+00	0,00E+00	0,00E+00	0,00E+00	4,46E+02
Cellulose	WW_C01	1 kg	17.869,54	1,58E-03	6,08E-05	1,17E-01	-2,79E-09	2,12E+03
Glass Wool	WW_MW00	1 m^2	4.061,26	3,10E-01	6,60E-05	6,60E-01	-	3,94E+03
Plaster-board	WW_PB00	1 m^2	4.062,26	1,51E-01	6,59E-01	1,34E+01	-	5,76E+04
Plaster	WW_P01	1 m^2	4.061,26	1,30E-01	2,90E-04	9,60E+00	-	3,95E+04
Total non-hazardous waste production of the wood wall:								**1,04E+05**

DRY WALL								
DW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**kg/F.U.**				**kg TOT**
				A1-A3	**A4**	**C1-C4**	**D**	
Plasterboard	DW_PB00	1 m^2	4.061,26	1,51E-01	6,59E-01	1,34E+01	-	5,76E+04
Mineral Wool	DW_MW00	1 m^2	4.061,26	3,10E-01	6,60E-05	6,60E-01	-	3,94E+03
Plasterboard	DW_P00	1 m^2	4.061,26	1,60E-01	3,95E-01	8,54E+00	-	3,69E+04
Insulation	DW_EPS01	1 m^3	487,3512	3,19E-01	1,04E-03	2,33E+00	-1,24E-01	1,23E+03
Outdoor cement-board	DW_CB00	1 m^2	4.061,26	1,04E+01	8,36E-05	1,07E-05	-	4,22E+04
Total non-hazardous waste production of the dry wall:								**1,42E+05**

Table 71: Non-hazardous waste production of the three walls (stages: A1-A3, A4, C1-C4, D)

RADIOACTIVE WASTE

MASONRY WALL								
MW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**kg/F.U.**				**kg TOT**
				A1-A3	**A4**	**C1-C4**	**D**	
Levelling plaster	MW_LP00	1 m^2	4.061,26	1,05E-05	6,67E-06	2,25E-06	-	7,89E-02
Plaster	MW_P01	1 m^2	4.061,26	2,90E-05	5,70E-05	1,00E-05	-	3,90E-01
Brick	MW_B01	1 m^2	4,06E+03	9,54E-04	2,17E-04	2,16E-04	-3,87E-05	5,48E+00
Plaster	MW_P01	1 m^2	4.061,26	2,90E-05	5,70E-05	1,00E-05	-	3,90E-01
Insulation	MW_EPS00	1 m^2	4.061,26	1,12E-03	1,39E-05	1,48E-06		4,61E+00
Plaster with grid	MW_P01	1 m^2	4.061,26	2,90E-05	5,70E-05	1,00E-05	-	3,90E-01
Levelling plaster	MW_LP00	1 m^2	4.061,26	1,05E-05	6,67E-06	2,25E-06	-	7,89E-02
Total waste production radioactive of the masonry wall:								**1,14E+01**

WOOD WALL								
WW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**kg/F.U.**				**kg TOT**
				A1-A3	**A4**	**C1-C4**	**D**	
Wood	WW_T01	1 m^3	365,5134	1,08E-02	1,08E-02	3,384E-07	-1,65E-06	7,89E+00
Cellulose	WW_C01	1 kg	17.869,54	0,00000152	0,00000151	2,98E-05	-4,90E-04	-8,17E+00
Glass Wool	WW_MW00	1 m^2	4.061,26	6,00E-05	1,30E-05	1,32E-06	-	3,02E-01
Plaster-board	WW_PB00	1 m^2	4.062,26	4,75E-05	9,46E-05	2,29E-06	-	5,87E-01
Plaster	WW_P01	1 m^2	4.061,26	2,90E-05	5,70E-05	1,00E-05	-	3,90E-01
Total waste production radioactive of the wood wall:								**1,00E+00**

DRY WALL								
DW_01	**Identification code**	**Functional Unit (F.U.)**	**Quantities in the project**	**kg/F.U.**				**kg TOT**
				A1-A3	**A4**	**C1-C4**	**D**	
Plasterboard	DW_PB00	1 m^2	4.061,26	4,75E-05	9,46E-05	2,29E-06	-	5,86E-01
Mineral Wool	DW_MW00	1 m^2	4.061,26	6,00E-05	1,30E-05	1,32E-06	-	3,02E-01
Plasterboard	DW_P00	1 m^2	4.061,26	4,54E-05	5,70E-05	1,47E-05	-	4,75E-01
Insulation	DW_EPS01	1 m^3	487,3512	1,19E-02	2,72E-05	7,47E-03	-7,50E-03	5,80E+00
Outdoor cement-board	DW_CB00	1 m^2	4.061,26	2,82E-04	8,55E-05	1,07E-05	-	1,54E+00
Total waste production radioactive of the dry wall:								**8,70E+00**

Table 72: Radioactive waste production of the three walls (stages: A1-A3, A4, C1-C4, D)

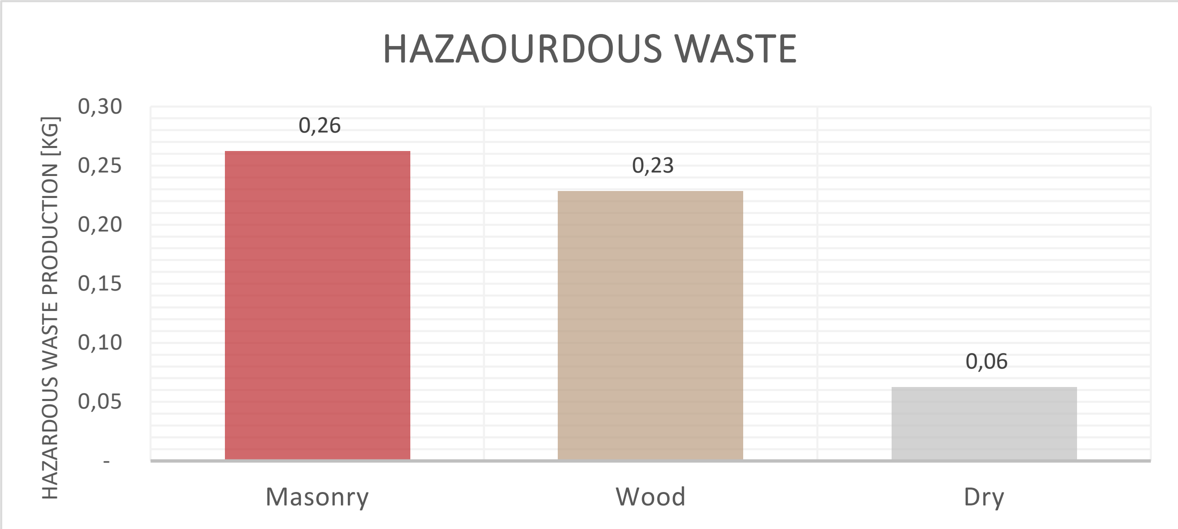

Figure 40: Chart of the hazardous waste of the three walls

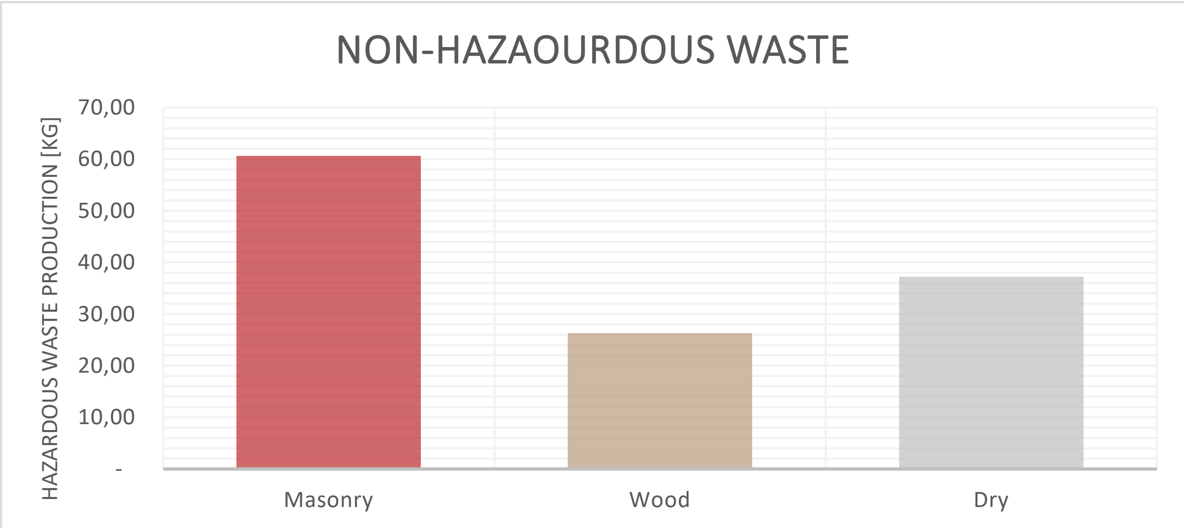

Figure 42: Chart of the non- hazardous waste of the three walls

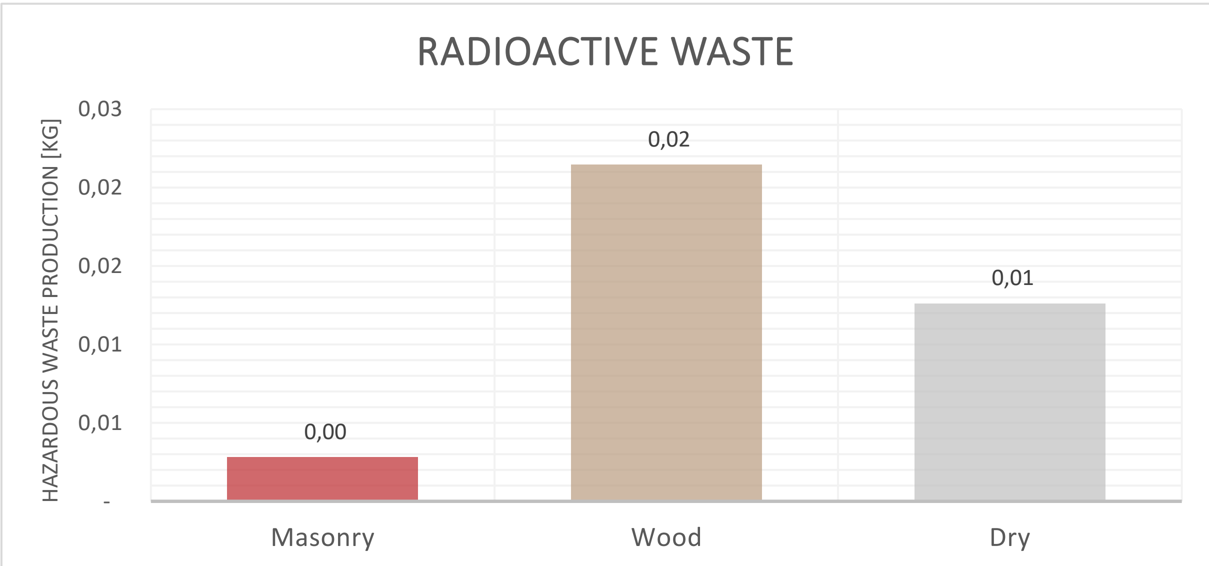

Figure 41: Chart of the radioactive waste of the three walls

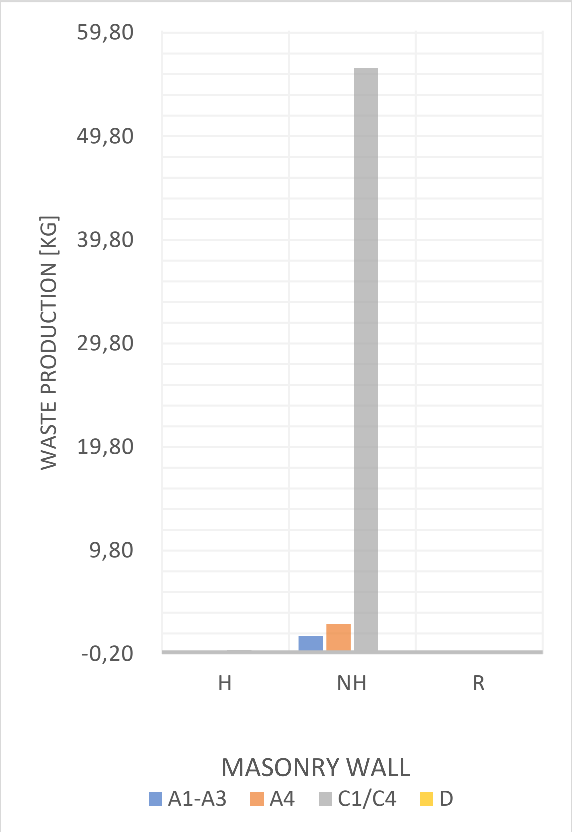

Figure 44: Chart of the waste production (masonry wall)

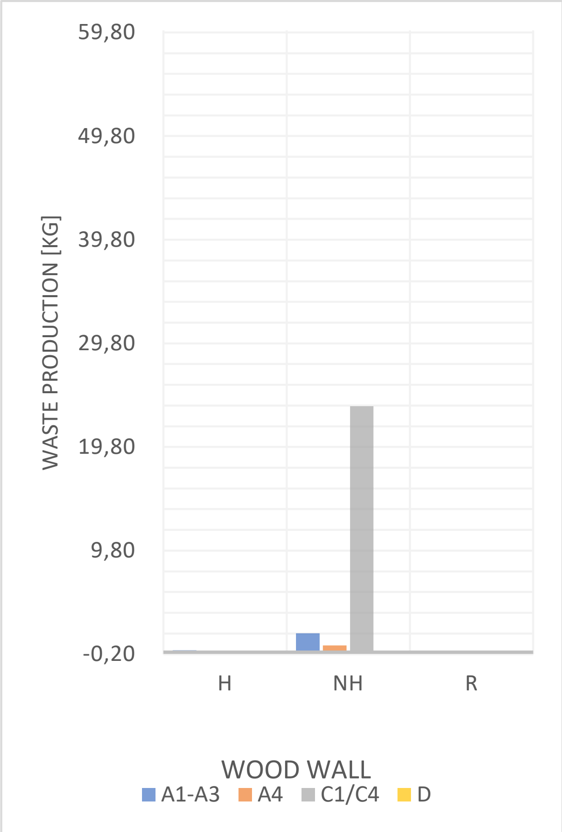

Figure 45: Chart of the waste production (wood wall)

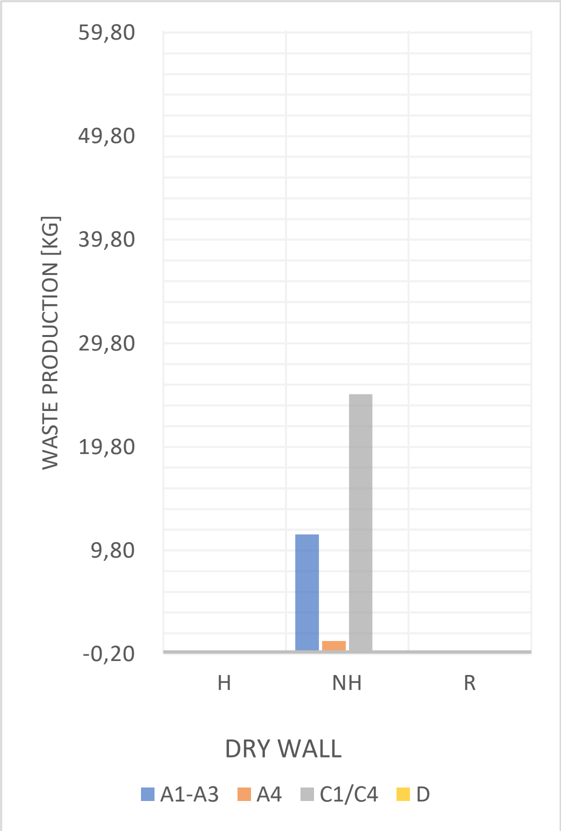

Figure 43:Chart of the waste production (dry wall)

As regarding the waste production, the stage which contributes the most is the end-of-life stage (C1-C4). While the type of waste which contributes the most are the non-hazardous waste. The latter are produced especially during the end-of-life stage. The only exception is represented by the dry wall, which produces a considerable quantity of non-hazardous waste even in the product stage.

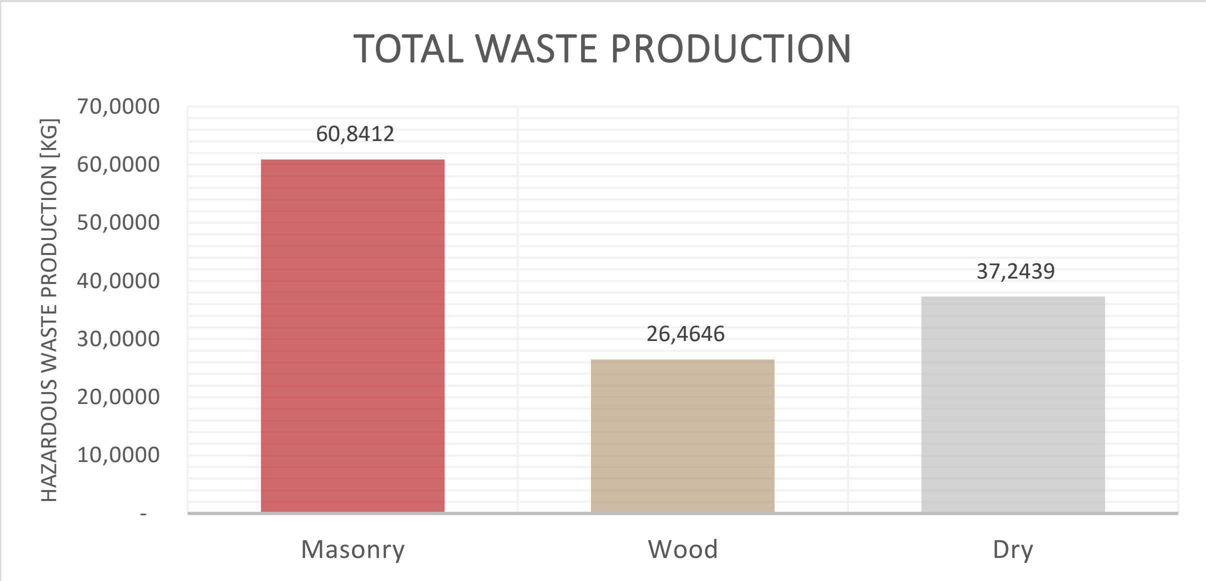

Figure 46:Total waste production of the three walls

As shown from the chart above, if analyses of fossil resources overturned the results obtained based on carbon emissions. These confirm them. According to the production of waste, the solution that least stresses the environment is the wooden one, followed by the dry one and the traditional one.

- **FINAL CONSIDERATIONS**

The study demonstrates how more conscious choices can make a difference on the level of stress that a building brings to the environment in which it is inserted. Conscious choices mean fully mastering concepts such as environmental product declarations, the life cycle methodology, the main stages of buildings' lives and above all the environmental impact indicators (all topics explained more or less thoroughly during the chapters of the thesis).

Therefore, I believe that one of the main steps towards a building industry that works aligned with global environmental goals is: experts' knowledge. Only by fully knowing the problem and the tools at our disposal is it possible to apply and improve them. As a second step towards the goal of a more sustainable building is the increase in the number and quality of the data currently available. The latter step is strictly connected with the experts' knowledge. In fact, the EPDs, declaring the LCA of a single product, represent a fundamental key for reaching the above-mentioned knowledge. Unfortunately, the currently existing EPD certifications concern a too small percentage of products and furthermore I do not always provide completely complete data.

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