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BUILDING EMISSIONS IN THE PRE-USE PHASE: THE CASE STUDY OF A MULTI-STORY RESIDENTIAL BUILDING IN TAMPERE

EMISSIONI DI EDIFICI NELLA FASE PRE-USO: IL CASO STUDIO DI UN EDIFICIO RESIDENZIALE MULTIPIANO A TAMPERE

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ABSTRACT

A causa del largo utilizzo di acciaio e calcestruzzo per la costruzione degli edifici, il settore delle costruzioni è responsabile di un terzo delle emissioni globali di gas serra in atmosfera.

Il presente lavoro di tesi mira a valutare le emissioni di anidride carbonica dovute alla costruzione di un edificio con materiali convenzionali e a confrontarle con le emissioni dello stesso edificio se fosse in legno laminato: in particolare vengono analizzati tre principali scenari: nel primo si analizza l'edificio costruito con materiali convenzionali, nel secondo vengono sostituiti da materiali convenzionali sostenibili, nel terzo viene eliminato il calcestruzzo e al suo posto vengono inseriti pannelli di legno laminato. Viene utilizzato il software One Click LCA prodotto dalla Bionova, che, valutando le fasi di estrazioni di materie prime, lavorazione, produzione, trasporto e messa in opera, permette di quantificare l'anidride carbonica immessa in atmosfera in seguito a tali processi.

Dai risultati emerge un netto miglioramento sin dal secondo scenario in cui le emissioni si riducono del 47%, al terzo scenario dove si abbassano del 75% rispetto al valore iniziale: per questo motivo, un'analisi LCA dovrebbe essere sempre effettuata durante la progettazione di un edificio.

INTRODUCTION

Since architecture and building have lost their connection with real housing needs and the needs of society, designing and building have become activities that too often merely respond to the laws of the market: supply-demand, cost-benefits.

Moreover, in recent decades, the use of cement and oil products has made us forget the typical materials of our ancient tradition and the basic rules of building. The quality of the design of a building, as well as the materials used to build it, affect the ecosystem and the well-being of those who will inhabit that space; these aspects are directly related to CO_2 emissions into the atmosphere, the production of waste to landfill, the quality of space and the air you breathe indoors.

It is necessary to make a distinction between conventional building and traditional building: the building of today and of the last decades cannot be considered as part of our tradition. Conventional building, i.e., the construction methods used in the last sixty years, are based on the use of materials such as cement, polystyrene, mineral wool, polyurethane foam, sealants and plastics of various kinds, all products that do not belong to traditional building, applied by humans through thousands of years using materials directly from nature and mainly found near the place of construction. We refer to clay, stone, lime, wood, hemp, straw, vegetable fibers. There are examples of centuries-old buildings still existing all over the world, made with various techniques from the materials listed above. Today, thanks to the current technological development, we can enhance the intrinsic technical characteristics of a natural material, to use it in countless applications and with excellent performance, equal and superior to the most common materials of petrochemical origin.

This thesis project was developed during a study period at the University of Iceland in Reykjavik, in collaboration with Professor Jukka Heinonen, an expert in sustainable built environment. The thesis aims to quantify the emissions due to the construction of a residential building in 5 chapters:

- The first chapter introduces climate change, its causes and mitigation methodologies;
- in the second chapter, carbon dioxide emissions due to the construction sector are presented, describing the main structural and non-structural materials and their sustainable alternatives;
- the third chapter defines the LCA methodology and the main software useful to quantify emissions in the building sector;
- in the fourth chapter the building under study is presented;
- in the fifth and last chapter an analysis of the data obtained is carried out and possible improvements are defined to reduce CO_2 emissions into the atmosphere.

1 CLIMATE CHANGE

The great challenge of the 21st century is to combat climate change: this term refers to the variation of the climate, due to an alteration in the composition of the atmosphere, directly or indirectly caused by human action.

In recent decades, the global temperature has been rising steadily and this phenomenon is accelerating. The main cause is the presence of a high concentration of greenhouse gases in the atmosphere: the most common greenhouse gas is carbon dioxide (or CO_2), followed by methane, nitrous oxide, sulphur hexafluoride and hydrocarbons. Unlike fluorinated gases, other greenhouse gases have always existed in nature, but with the development of industry their presence has increased exponentially.

As already mentioned, the consequence of climate change is an increase in temperature, which in turn causes other effects, such as the alteration of ecosystems (damaging and compromising the survival of plant and animal species, thus causing a loss of biodiversity), the acidification of the oceans, the melting of glaciers, and desertification. In addition, the warming of ocean waters causes the sea level to rise and increasingly frequently triggers extreme weather phenomena such as hurricanes and typhoons, heavy rainfall in a short period causing floods and landslides, long periods of drought, etc.

Since the industrial revolution, human activities have increasingly had the capacity to bring about changes in the natural biophysical processes of the planet and the atmosphere. With increasing pro-capita consumption of energy and materials and dependence on commerce, cities are expanding, using resources from different and very distant areas, moving further and further away from the concept of sustainability.

The term carrying capacity of an environment means the maximum sustainable load in a persistent way. In essence, carrying capacity defines whether the population of a certain species can sustain itself, not only based on the quantity of individuals but also based on pro capita consumption. Humanity will only be sustainable if we preserve a natural stock for the next generation: at the moment, however, this is a very difficult challenge, since the population and its consumption are increasing, reducing more and more the natural stock, causing loss of biodiversity, collapse of fisheries, air and water pollution, deforestation, and desertification.

To measure the human load, it would be enough to find the ecological footprint, which is a productive area large enough to meet the demands of a certain population. The ecological footprint is defined as a product of population, richness, and technology. The ecological footprint mechanism can also be used to estimate the impact of new alternative technologies.

When the ecological footprint is larger than the available land, an ecological deficit is created and it is necessary to reduce consumption to have long-term ecological sustainability. Most industrialised countries have a very high ecological deficit.

It is estimated that by 2040, a 90 per cent reduction in the materials and energy used today will be required to meet the needs of the growing population. One method of mitigation would be not to concentrate the population in cities, to have lower ecological impacts (although this urban structure can also bring considerable benefits, first and foremost reducing daily travel and thus sharply reducing emissions)[1].

Two documents known as the 'Kyoto Protocol' and the 'Paris Agreement' were issued to contrast and prevent global change. The Kyoto Protocol, created in 1997

[1] Source: W. Rees, M. Wackernagel, Urban ecological footprints: why cities cannot be sustainable, and why they are a key to sustainability, Environmental impact assessment review, Volume 16, Issue 4-6, 1996

and operational since 2002, was the first international agreement on climate, born from the collaboration of industrialised countries to combat climate change and safeguard the health of the planet: the objective was to reduce greenhouse gas emissions by at least 5,2% compared to 1990. Since 2015, it has been replaced by the Paris Agreement, whose main objectives are to limit the average temperature increase to below 2°C and to achieve zero emissions by 2050, i.e., to be able to absorb all the emissions produced.

To achieve this goal, all sectors must work together and not only move towards zero-emission processes but also capture emissions already present in the atmosphere. This is the reason why negative emission technologies NET (also called Carbon Dioxide Removal) have developed, which are able to permanently remove CO_2 from the earth's atmosphere, through biological or technical approaches, by storing it more or less permanently. At current rates of carbon dioxide in the atmosphere, if NETs were able to absorb 400-1000 Gt of CO_2, it would take 10 to 25 years. However, the problem with NETs is their high cost and the amount of land required, so they can cause very significant risks to food security and biodiversity conservation: therefore, some sort of cost-benefit analysis should always be carried out to assess the amount of CO_2 that can be absorbed, the costs and the risks involved in introducing NETs[2].

The main causes of anthropogenic greenhouse gas emissions include:

- the energy sector, as fossil fuels such as coal, oil and natural gas are burned for electricity and heating;
- the food sector, which involves both agriculture (i.e. land use and fertilisers) and intensive livestock farming. These two industries are the main causes of deforestation;

[2] Source: J. Minx, W. Lamb, M. Callaghan, L. Bornmann, S. Fuss, Fast growing research on negative emissions, Environmental research letters, Volume 12, Number 3, 2017

- the manufacturing industry, referring to the production of materials and waste disposal;
- the transport sector, relating to pollution caused by aircraft and land vehicles powered by petrol and diesel.

In detail, the construction sector creates around 40% of global emissions, of which 10% are from the construction process and the remaining 30% from the production of materials, their transport to the construction site and emissions from the use of the building during its life[3].

[3] Source: Saynajoki, Heinonen, Junilla, A scenario analysis of the life cycle greenhouse gas emission of a new residential area, 2012

2 BUILDING EMISSIONS

The construction sector contributes to climate change by causing one third of the entire planet's emissions.

Cities need to become sustainable and green, which requires the introduction of sustainable materials and low-energy construction processes. In general, attention must be paid to atmospheric CO_2 emissions, energy and water consumption and affordability, and 'green building' techniques such as recycling, reuse and the choice of renewable and local materials are of great importance.

Sustainable construction was created to ensure control of the impact of environmental loads (anthropogenic stress on natural resources), considering:

- polluting emissions in the atmosphere;
- liquid effluents;
- noise emissions;
- minimisation of construction and demolition waste in the decommissioning phase (considering the recycling potential of materials and the separability of components);
- management of construction and demolition waste during the construction phase;
- control of municipal waste fluxes;
- determination of environmental effects.

This study will focus particularly on carbon dioxide emissions into the atmosphere from construction materials, their production, transport, and installation.

The term 'green building' refers to a building that, from the design stages, through to the execution, construction, and maintenance phases, is designed to be both high-performing and sustainable, both from the point of view of the well-being of its inhabitants and based on its ecological footprint. Green buildings are designed to pollute less and provide a higher quality of life for their inhabitants.

The aim of sustainable construction is (both in the short and long term) to measure the ecological impact of a building and to significantly reduce it throughout its life cycle. For this reason, a green building is the result of careful design choices, a careful selection of materials and technologies and a detailed study of the energy absorption of buildings.

The construction of a building requires many resources, different types of construction equipment and transport, concentrating large amounts of carbon dioxide emissions in a very short time. The construction, operation, and demolition phases of a building produce 12.6 %, 85.4 % and 2 % of global emissions respectively[4]: while operation depends on the inhabitants and their habits, emissions from the construction phase can be significantly reduced by paying attention to specific materials and innovative technologies.

By paying attention to the choice of materials to be used in the construction of buildings, it is possible to significantly reduce total emissions; natural materials may also have a greater initial impact than conventional materials; however, they are able to reabsorb the CO_2 in the atmosphere during their useful life as an integral part of the building. They can therefore behave, simultaneously, as building materials and as emission sinks.

The carbon peak due to the construction phase, i.e., the large number of emissions related to the beginning of the building's life cycle (from a few months to a few years) can often be extremely high and one must question whether such a building

[4] Source: Peng, Calculation of a building's life cycle carbon emissions based on Ecotect and building information modelling, 2016

can contribute to meeting GHG reduction targets. In addition, the construction of energy-efficient buildings may produce more emissions than the construction of conventional buildings, whereas renovation of the current building stock for the purpose of energy efficiency improvements may result in a smaller peak in emissions while at the same time compensating through reduced energy consumption during the use phase. The payback time of carbon produced during the construction of a new residential area is several decades (a few years, in the case of energy-efficient housing), so increasing the energy efficiency of buildings is not a valid tool for climate change mitigation in the short to medium term: in other words, starting the construction of a significant number of energy-efficient buildings would cause emissions to rise exponentially in the short term, completely contradicting the climate change mitigation objective[5].

2.1 URBAN PLANNING

The increase in population and the migration from rural areas to the centres creates more and more pressure on natural resources, creating interlinked environmental problems:

- depletion of resources;
- deterioration of ecosystems;
- deterioration of human health;
- effects on the environment.

Urban planning plays a key role in the process of controlling and mitigating the growth of cities and its negative effects on the environment, particularly in the long term. There are two main city models:

[5] Source: A. Saynajoki, J. Heinonen, S. Junnila, A scenario analysis of the cycle greenhouse gas emissions of a new residential area, Environmental Research letters, Volume 7, Number 3, 2012

- dispersed city, characterised by a less dense and more self-sufficient approach. It is a model that counteracts the pressure on urban centres, tending to urbanise city boundaries and peripheral areas.
- compact city, tending towards greater urbanisation of city centres, although an extreme point could be reached where the benefits cancel out, losing its efficiency and its sustainability. This model encourages the construction of taller buildings, thus limiting land consumption, loss of biodiversity and changes to the land[6].

One solution could be to decentralise the centre, creating an "urban village", an urban structure that combines the positive aspects of the two city models analysed above, while enjoying the energy efficiency of the compact city and the better quality of life of the dispersed city.

The urban form is closely related to the energy demand of the inhabitants: in fact, the design and location of residential areas have important consequences on the consumption of housing and transport.

Seventy percent of global GHG emissions come from cities and are mainly due to energy supply[7]. For this reason, energy planning should be integrated within urban planning and urban development to reduce carbon emissions. Many cities have set the goal of achieving carbon neutrality, sometimes in more ambitious timeframes than their nation's standards (e.g. New York 2050, Stockholm 2040, Berlin 2050, Copenhagen 2025, Tampere 2030), aiming for certification as an A40, or zero-carbon city.

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[6] Source: Norland, Holden, Three challenges for the compact city as a sustainable urban form: household consumption of energy and transport in eight residential areas in the greater Oslo region, 2005

[7] Source: J. Laine, J. Heinonen, S. Junnila, Pathways to carbon-neutral cities prior to a national policy, Transforming built environments: towards carbon neutral and green-blue cities, 2020

2.2 IMPACT OF BUILDING MATERIALS

Natural, local, and sustainable materials are gaining increasing attention within the scientific community and building designers because they represent a method of optimising the construction of an indoor microclimate and having high energy efficiency with low environmental impact. In addition, green materials have the advantage that at the end of their useful life they are dispersed into the environment without causing damage to the ecosystem.

2.2.1 STRUCTURAL MATERIALS

The main conventional materials used to build a structure are concrete and steel. Each year, the steel and concrete industries are responsible for 16% of global greenhouse gas emissions. To reach the goal of carbon neutrality by 2050, we need to act on the production process and the use of materials in construction.

Concrete is the material that has the greatest impact on the environment in terms of CO_2 emissions in the atmosphere, due to the extraction of raw materials and its production, which requires high-energy processes. One ton of Portland cement creates one ton of carbon dioxide. However, during the carbonation phase, concrete can absorb CO_2, reducing its impact by up to 50%. One possible solution to reduce the concrete's impact on the environment would be to reduce the amount of clinker in it, replacing it with mineral materials with a much lower impact, such as fly ash and ground granulated blast-furnace slag. Other materials that can be used are recycled plastic and recycled glass: plastic can replace 50% of the cement in the concrete mix[8], while glass replaces 10-30% of the eventual cement[9]. Using these mitigation methods will result in net reductions in CO_2 emissions, conservation of natural resources, reduced energy use in the production process and contribute to effective waste disposal and management.

Steel production accounts for 7-9% of global CO_2 emissions: for each ton of steel produced, 1,85 ton of CO_2 is emitted[10]. Its production process is carried out in a blast furnace, which requires very high amounts of energy to melt the raw material from which the steel is made. The alternative of the electric blast furnace can be used in the case of recycled materials and have less impact on the environment. In addition, a way to cut emissions by 95% is being explored by substituting hydrogen for the metallurgical coal that is usually used during the production process for heating and in the chemical reactions to create iron (a key ingredient in the creation of steel)[11].

Replacing fossil fuels with renewable sources is not sufficient to counteract the amount of CO_2 generated by the concrete and steel production process because the chemical reactions that take place in them would produce unavoidable emissions. For this reason, natural alternatives to conventional building materials are becoming increasingly popular.

Wood

The most common natural material is wood, which can be compared structurally to steel. Wooden elements can function tensioned, compressed, and flexed, and can be produced in many sizes and shapes. In terms of emissions, being a natural material, there are no CO_2 emissions from its production and growth, but on the contrary, it can store carbon in the atmosphere throughout its life cycle. The

[8] Source: Siddique, Khatib, Kaur, Use of recycled plastic in concrete: a review, 2007
[9] Source: Shayan, Xu, Value-added utilisation of waste glass in concrete, 2003
[10] Source: Hoffmann, Van Hoey, Zeumer, Decarbonization challenge for steel, 2020
[11] Source: Kurrer, The potential of hydrogen for decarbonising steel production, 2020

absorption capacity of wood in a construction does not depend on the type of wood or the type of building and its size, but exclusively on the number and volume of wood elements used as structural and non-structural components in the construction. The only problem with using wood in construction would be that it would accelerate the deforestation process: the use of wood is only reasonable if the forests are managed efficiently, otherwise it would cause their disappearance. For this reason, the material must be used in accordance with sustainable silviculture, the science that deals with the conservation of forest land. To limit the deforestation process, the practice of planting two trees for every tree that is felled and used in construction has emerged: this also results in greater capture of emissions by the new plants, increased water retention, conservation of biodiversity and, of course, production of new wood. Generally, levels are defined to describe the CO_2 absorption capacity of a timber building[12]:

- low level, absorption of 100 $\frac{kg}{m^2}$;
- medium level, absorption of 200 $\frac{kg}{m^2}$;
- high level, absorption of 300 $\frac{kg}{m^2}$.

In conclusion, wooden structures can, in the long term, counteract the increase in the concentration of CO_2 in the atmosphere because:

- the CO_2 emission from production is lower than from conventional building materials such as concrete and steel;
- they are able to store carbon throughout the life of the building;
- wood waste and by-products can be recycled or burned to produce energy;
- the energy incorporated in wood products can be reused.

[12] Source: Amiri, Ottelin, Sorvari, Junnila, Cities as carbon sinks, classification of wooden buildings, 2020

Figure 1: wooden house [13]

The following picture shows the sequestration advantage of wood over conventional steel and concrete:

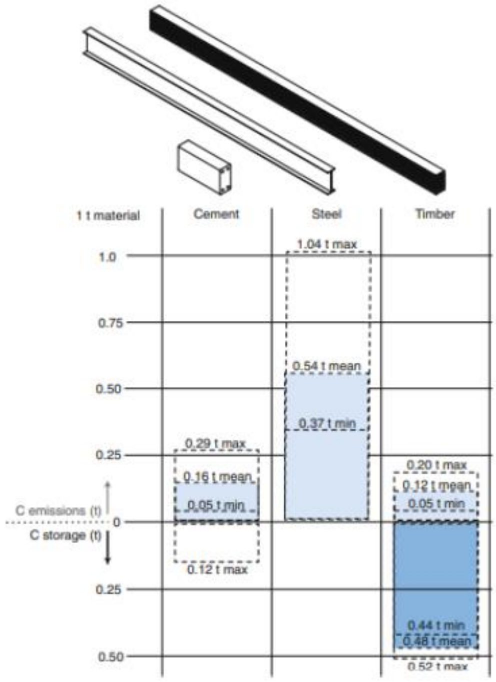

Table 1: physical dimensions, carbon emissions and carbon storage capacity of 1t of cement, steel, and timber materials[14]

[13] Source: Legno-2.jpg (960×640) (easyservicesolutions.com)
[14] Source: Churkina et al, Building as a global carbon sink, 2020

Bamboo

Another material suitable for renewable construction is bamboo, the demand for which is increasing to cope with the scarcity of wood; there is no extensive legislation on this material, especially in Europe, but its use in construction is growing, also due to its short growth cycle. While a wood forest grows in at least 25 to 30 years, a bamboo forest takes 3 to 5 years, and some species can reach a height of 20 or 30 metres in a few weeks, at which point they are suitable to be cut, treated (they are dried in the sun and processed with chemical treatments to have protection from insects and fungi) and used for the construction of buildings. During its useful life, bamboo absorbs CO_2 from the atmosphere which remains trapped in the steam until the material is discarded or burned. Due to its mechanical properties, it is called "green steel". It can be used for the construction of different components of a building such as:

- the roof structure;
- walls;
- flooring;
- foundations;

In addition, because of its elastic properties, it allows structures to resist earthquakes, reducing or eliminating the amount of damage caused. Among other advantages, bamboo is characterised by its lightness, robustness and versatility and its ease of repair and use[15].

[15] Source: Yadav, Mathur, Bamboo as a sustainable material in the construction industry: an overview, 2021
Akwada, Akinlabi, Bamboo use in construction industry: how sustainable is it?, 2015

Figure 2: bamboo building [16]

Cork

Cork originates from a special oak tree typical of southern Europe and northern Africa, which can remove its own cortex without killing it, so it can be harvested repeatedly, making it one of the most sustainable plant materials in the world: the first harvest takes place at 20 years of the plant's life and then every 9 years, calculating a life expectancy of the oak tree of about 200 years. Cork cortex that has just been stripped absorbs five times more carbon dioxide than other trees[17]. Cork has properties that make it suitable for use in structural and infrastructure applications, due to its insulation capacity, resistance to wear and tear and thus its durability. It is used as a construction material for floors, exterior finishes, ceilings, and acoustic coverings. It consists of closed cells containing air, suberin and ceroids, making it impermeable to gases and liquids, heat, and impact resistant,

[16] Source: edificio-bambù_740.jpg (740×416) (lifegate.com)
[17] Source: McCormick, Cork as a building material: a history, 2016

hypoallergenic, and lightweight. In addition, when the building is demolished, the natural recyclable material will be available[18].

Figure 3: Cork house [19]

2.2.2 NON-STRUCTURAL MATERIALS

Maintaining a comfortable indoor environment is one of the main reasons for energy consumption during the lifetime of buildings. This implies an increase in environmental pollution due to the fossil fuel used daily to maintain a certain ideal temperature inside the house.

Globally, 30-40% of all primary energy is used in buildings[20], much of it for insulation. Insulation materials play a very important role in reducing energy demand and achieving energy efficiency in buildings, helping the building to

[18] Source: Knapic, Oliveira, Machado, Pereira, Cork as a building material: a review, 2016
[19] Source: The Cork House in Berkshire is shortlisted for RIBA Stirling Prize 2019 (stirworld.com)
[20] Source: Asdrubali, D'Alessandro, Schiavoni, A review of inconventional sustainable building insulation materials, 2015

conserve its own energy and thus reduce the need and cost of cooling and heating and, consequently, environmental pollution.

Conventional buildings are thermally and acoustically insulated with materials from petrochemical products or energy-intensive processed natural sources (e.g., plastic, glass wool, rock wool), causing serious environmental damage during the production phase, where non-renewable sources are used, and during the disposal phase, as there are no effective recycling techniques.

The goal for the future is to reduce the demand for heating and cooling in homes, focusing not only on improving the efficiency of appliances or changing people's lifestyles, but also on improving the insulation properties of buildings. In addition, efficient insulation materials also reduce the impact of urban noise, which can have negative effects on human health.

Insulators used in traditional construction are: expanded polystyrene, expanded polyurethane, expanded polyethylene, expanded resins, cellular glass, expanded polyvinyl chloride, expanded clay, natural pumice, glass fibres, mineral fibres (rock wool), plasterboard. In the long term, the use of these materials can cause serious damage to human health and the environment due to the emission of toxic gases. Furthermore, their production requires a lot of energy and their disposal can be harmful to the environment. If managed effectively, renewable building insulation can produce a net reduction in CO_2 emissions during the life cycle of the structure and can be continuously renewed.

An alternative could be kenaf or wood fibre, which are currently uncommon but perform very similarly to synthetic materials.

Figure 4: Kenaf fibre [21]

The development of new insulating materials requires knowledge and study of the thermo-physical properties: the parameters to be analysed to examine the performance of an insulating material are thermal conductivity, specific heat and density for thermal insulators and sound absorption for acoustic insulators. In addition, fire and vapour resistance can also be considered.

Thermal insulation aims to reduce the transmission of heat flow. The performance of a thermal insulator is assessed primarily through thermal conductivity, which quantifies the steady-state heat flow through a unit area of a homogeneous material 1 m thick, with a difference of 1 K on its faces, in practice measuring the effectiveness of a material to conduct heat. A material is considered a thermal insulator if it has a conductivity of less than 0,07 $\frac{W}{mK}$, and the lower its value, the better. The thermal conductivity of a fibrous material varies with its density. The material density (also called specific gravity) influences the time lag, i.e., the

[21] Source: fibra-di.-kenaf.jpg (580×388) (guidaxcasa.it)

thermal inertia of a wall. Insulation with a high density (>130 $\frac{kg}{m^3}$) is usually preferred. This corresponds to a reduction in the volume of air bubbles within the material and therefore to a higher thermal conductivity. In any case, the relationship between density and thermal conductivity depends on the structure of the material.

Another important parameter is the specific heat, which indicates the ability of a material to store heat and is defined as the capacity of 1 kg of material to change its temperature by 1 K. Generally, values range from 900 $\frac{J}{kgK}$ to 2500 $\frac{J}{kgK}$.

Thermal conductivity, density, and specific heat, can be related by the following formula of diffusivity:

$$\alpha = \frac{\lambda}{\rho c_p}$$

which is an indicator of how quickly heat is conducted into a material.

Thermal effusivity:

$$B = 0{,}5(\lambda \rho c_p)$$

indicates the ability of a material to absorb and release heat.

Regarding sound insulation, attention is paid to the weighted sound reduction index Rw which defines the ability of a structure to prevent sound from passing through itself: a high Rw value means good sound insulation.

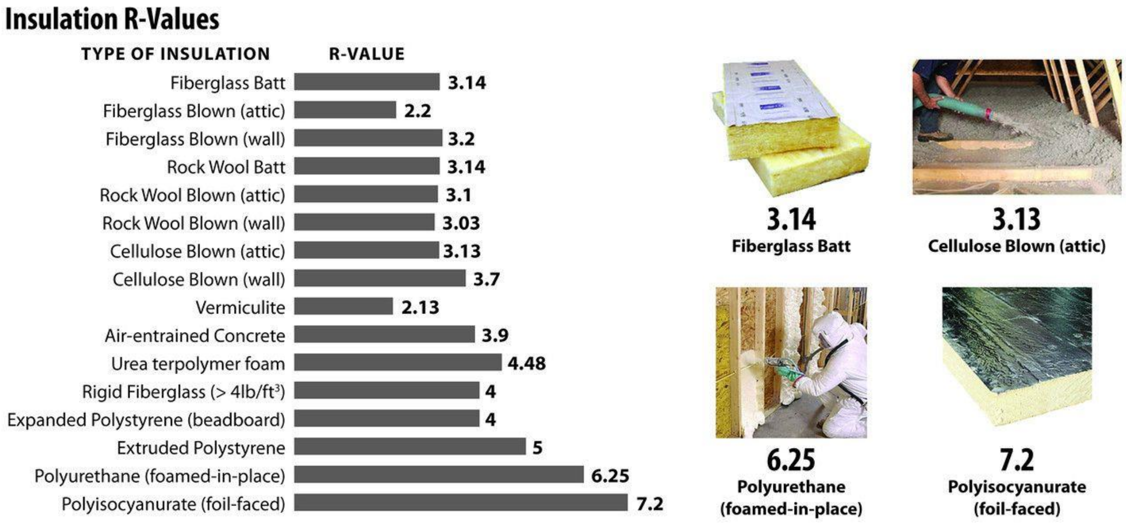

Figure 5: Weighted sound reduction index typical values [22]

Many materials derived from agricultural waste or natural materials in general can be used in the manufacture of panels for thermal insulation and sound absorption with a low environmental and economic impact. Below is a list of natural materials that could be used as a substitute for conventional insulation materials and that are completely degradable at the end of their life.

Reeds panels

The 'arundo donax' plant is widely available throughout the world, where it grows wild in wetlands, usually near water sources. Panels can be made from bundles of reeds tied together with wire or nylon, or the reeds can be cut, dried, and chopped into a loose granular material from which new panels are made. Properly designed panels are a sustainable and low-cost alternative and have good thermal insulation and sound absorption performance[23]. For this type of material, the thermal

[22] Source: fbb2ebe378caaef6f449eb1cf33c0a82.jpg (1280×599) (pinimg.com)
[23] Source: Asdrubali, D'Alessandro, Schiavoni, Mencarelli, Sounds absorption properties of reed, 2015

conductivity values are in the order of 0,045-0,056 $\frac{W}{mK}$, with a density of 130-190 $\frac{kg}{m^3}$.

Figure 6: Reeds panels [24]

Bagasse

Bagasse is an extraction residue from the crushing and pressing of sugar cane (Saccharum officinarum), consisting of the fibrous part and the bark of the cane. It is often used as fuel in sugar refineries, making them energy self-sufficient. In the construction industry it is used to create chipboard panels suitable for thermal and acoustic insulation: its high cellulose content saves on the use of synthetic binders[25]. In this case, conductivity is 0,046-0,055 $\frac{W}{mK}$, with a wide density range between 70 and 350 $\frac{kg}{m^3}$.

[24] Source: bild5_big.jpg (600×450) (hiss-reet.de)
[25] Source: Carvalho et al, Acustic characterization of sugarcane bagasse particleboard panels, 2015

Figure 7: Sugarcane bagasse [26]

Cattail

Cattails (Typha) are swamp plants and therefore very well suited to resist moisture. They have been used for wastewater treatment and other purposes, but lately they have been studied as an insulating material and plaster reinforcement. The material is characterised by its flexural rigidity and low weight. The panels are made from the leaves of the plant which act as a supporting fabric and are filled with a soft sponge fabric, so that they are stable and have excellent insulating properties: in fact, the panels are characterised by good fireproofing, soundproofing and thermal insulation. It can be used for the construction of walls, roofs, floors, and ceilings[27]. Cattail insulation panels have a thermal conductivity of 0,0438-0,0606 $\frac{W}{mK}$, with a density of 200-400 $\frac{kg}{m^3}$.

[26] Source: sugarcane_bagasse_cuba.jpg (1600×1200) (feedipedia.org)
[27] Source: Fraunhofer-Gesellschaft, Using cattail for insulation, 2013

Figure 8: Cattail [28]

Corn cob

Cobs are the waste product of corn processing. They were widely used as a wood-filling material in 'tabique' buildings typical of Portugal in the 18th and 19th centuries. Corn cob has the same microstructure as XPS extruded polystyrene, although the latter is obviously much more regular and uniform, and a comparable chemical composition, as they are composed of the same chemical elements but in different proportions.

Whereas in the past corn cob was used as a filling material for walls, nowadays real panels are made from chipboard material obtained from corn cobs and wood glue. The thermal conductivity is not the best but it has very good fire resistance compared to conventional thermal insulation[29]. For this panels, conductivity is about 0,058-0,101 $\frac{W}{mK}$, so in some cases not acceptable, and a density of 170-250 $\frac{kg}{m^3}$.

[28] Source: cattails-6.jpg (625×486) (survivallife.com)
[29] Source: Pinto et al, Corn's cob as a potential ecological thermal insulation material, 2011

Figure 9: Corn cob panel [30]

Cotton stalks

Cotton stalks are a residue of cotton production. They can be processed into fibres (without the use of chemical additives) which are glued together by hot pressing to create insulation boards. It has good thermal insulation characteristics: a less dense material will provide better insulation. Thanks to the presence of this material, which can be applied to walls and ceilings, clear energy savings are possible[31]. Thermal conductivity is 0,0585-0,0815 $\frac{W}{mK}$, again not always acceptable, if higher than 0,07 $\frac{W}{mK}$, with a density if 150-450 $\frac{kg}{m^3}$.

[30] Source: Possible Applications of Corncob as a Raw Insulation Material | IntechOpen

[31] Source: Zhou, Zheng, Li, Lu, An environment-friendly thermal insulation material from cotton stalk fibers, 2010

Figure 10: Cotton stalks [32]

Date palm

The leaves, stalks and branches of date palms are natural waste that can be processed into fibres, which are pressed and dried to make panels with good thermal insulation performance[33]. Thermal conductivity values are in the range of 0,0475-0,0697 $\frac{W}{mK}$, and a density in a range of 700-800 $\frac{kg}{m^3}$.

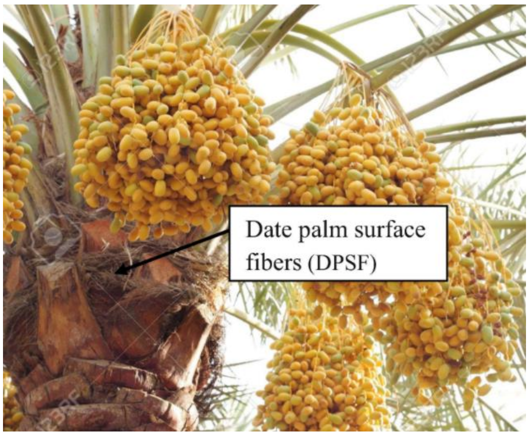

Figure 11: Date palm [34]

[32] Source: cotton-branches-with-raw-cotton-bolls-12x27-4.jpg (427×600) (d28xhcgddm1buq.cloudfront.net)
[33] Source: Ali, Alabdulkarem, On thermal characteristics and microstructure of a new insulation material extracted from date palm trees surface fibers, 2017
[34] Source: On thermal characteristics and microstructure of a new insulation material extracted from date palm trees surface fibers - ScienceDirect

Durian and coconut

Durian (durio zibethinus) together with coconut can be used to make insulating panels due to their low thermal conductivity. The peel of the durian is reduced to a small size, dried together with the coconut at 80°C and then hammered. Urea-formaldehyde and paraffin wax emulsion are added to the flakes; the mixture is then placed in a moulding box and pressed into panels. The optimum ratio between durian peel and coconut must be found: a high percentage of durian allows the panel to absorb more moisture, while a high percentage of coconut decreases the space between the fibres and makes the panel water resistant. Panels with a high coconut content have fewer voids than panels with a predominance of durian peel, so they have a higher density, which is directly proportional to the thermal conductivity: the best result is obtained for 90% coconut and 10% durian peel. Durian and coconut panels can be used for wall and ceiling insulation; they also provide a solution for agricultural waste management by creating a valuable product[35]. Based on material percentages, the thermal conductivity is equal to 0,064-0,185 $\frac{W}{mK}$, with a density of 357-907 $\frac{kg}{m^3}$.

Figure 12: Coconut fibre panel and durian peel [36]

[35] Source: Khedari, Nankongnab, Hirunlabh, Teekasap, New low cost insulation particleboards from mixture of durian peel and coconut coir, 2003
[36] Source: materiali-isolanti-fibra-di-cocco.jpg (650×488) (rifarecasa.com)

Oil palm fiber

Coconut palm fibre is a very critical agricultural waste for producers so it can be turned into a valuable product to be used in construction to create insulation panels. The fibres are air-dried for a month and then left at a temperature of 28°C in the laboratory, with a humidity of 60%, and then the fibres are twisted to create panels. As the density of the fibres used in the panels increases, the thermal conductivity decreases as there will be less air trapped in the fibres and the heat transfer modes will decrease their effectiveness[37]. For this type of material, the thermal conductivity values are in the order of 0,055-0,091$\frac{W}{mK}$, with a density of 20-120 $\frac{kg}{m^3}$.

Figure 13: Oil palm fiber insulation panel [38]

[37] Source: Manohar, Experimental investigation of building thermal insulation from agricultural by-products, 2012

[38] Source: Hassan, Al-Kayiem, Ghaffari, Development of thermal insulation from oil palm fiber for chimney of fire tube steam packaged boiler, 2014

Pineapple leaves

Pineapple leaves are a crop waste that is usually disposed of by burning, causing air and soil pollution. Especially in developing countries, pineapple leaves are of high engineering value for practical applications in a sustainable way. Panels made from pineapple fibres have good thermal conductivity, like conventional insulation materials on the commercial market[39]; In addition, it is possible to make panels from pineapple leaf fibre with natural rubber latex as a binder, manufactured by hot pressing (at 150°C). In this case, the thermal conductivity is higher (0,057 $\frac{W}{mK}$ but still acceptable)[40].

Figure 14: Pineapple leaf fiber [41]

Rice

Rice can be used in construction, both thermally and acoustically. The hulls resulting from its processing and refining are used to create chipboard panels with

[39] Source: Tangjuank, Thermal insulation and physical properties of particleboards from pineapple leaves, 2011

[40] Source: Kumfu, Jintakosol, Thermal insulation produced from pineapple leaf fiber and natural rubber latex, 2012

[41] Source: Nextevo-Social-Images-2-1.png (1080×1080)

an excellent thermal conductivity value, which, in addition, meet all the requirements of an insulating material for the construction sector (smoke developed, odour, critical radiant flux, moisture vapor sorption, flame spread, smoldering combustion, corrosiveness)[42]. As far as acoustic properties are concerned, panels can be made from rice straw and wood in different proportions: panels made from 10% rice straw have a better sound absorption coefficient than normal commercial panels[43]. Thermal conductivity is 0,0464-0,0566 $\frac{W}{mK}$.

Figure 15: Rice hulls [44]

Sunflower

Chipboard panels can be made from ground sunflower seeds from the residues of sunflower oil production. A good range of thermal conductivity values is obtained, varying according to the temperature considered, particle diameter and density[45] (an increase in particle size implies an increase in empty spaces and therefore a lower density). Conductivity is in a range of 0,0385-0,0501 $\frac{W}{mK}$ and a density of 36-152 $\frac{kg}{m^3}$.

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[42] Source: Yarbrough, Wilkes, Olivier, Vohra, Apparent thermal conductivity data and related information for rice hulls and crushed pecan shells

[43] Source: Yang, Kim, Kim, Rice straw-wood particle composite for sound absorbing wooden construction materials, 2002

[44] Source: Ricel_Hulls.JPG (2048×1362) (shopify.com)

[45] Source: Vandenbossche, Rigal, Saiah, Perrin, New agro-materials with thermal insulation properties, 2012

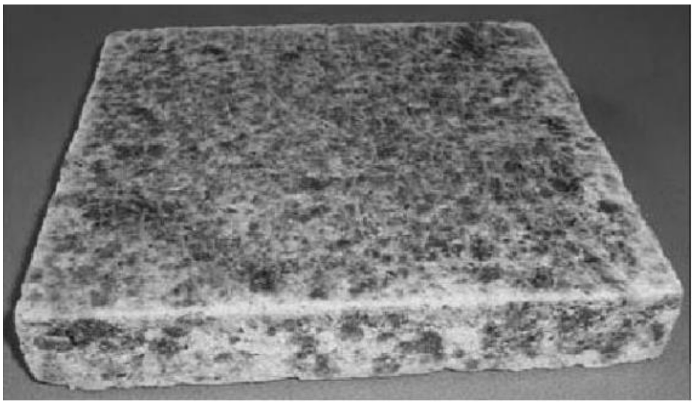

Figure 16: Sunflower panel [46]

Straw bale

Straw is a waste product of cereal processing. Panels made from straw bales have good thermal insulation characteristics[47], especially if the straw stalks are arranged perpendicular to the heat flow. It has been shown that the clay-straw mix does not perform as well. As it is composed mainly of cellulose and lignin (the same main components as wood), it is an excellent material for storing carbon. Finally, due to its specific density, it is also excellent for sound absorption[48]. In this case, conductivity is 0,038-0,067$\frac{W}{mK}$, with a wide density range between 50 and 150 $\frac{kg}{m^3}$.

Figure 17: Straw bale wall [49]

[46] Source: Vandenbossche, Rigal, Saiah, Perrin, New agro-materials with thermal insulation properties, 2012
[47] Source: Goodhew, Griffiths, Sustainable earth walls to meet the building regulations, 2005
[48] Source: Koh, Kraniotis, A review of material properties and performance of straw bale as building material, 2020
[49] Source: strawbale8.jpg (537×355) (inhabitat.com)

Recycled materials

The use of recycled materials in the production of building materials is an excellent way to limit the use of virgin material and the disposal of waste. They stand out:

- recycled glass foam and fibers, with a thermal conductivity between 0,031 and 0,050 $\frac{W}{mK}$[50];
- recycled plastic, with thermal conductivity between 0,034 and 0,039 $\frac{W}{mK}$ and a sound absorption coefficient of 0,6 (increasing to 0,75 if ofwaste sheepwool is added)[51];
- recycled cotton fibres, 0,039-0,044 $\frac{W}{mK}$;
- recycled textile fibres (polyester and polyurethane), 0,041-0,053 $\frac{W}{mK}$[52];
- fly ash residue and scrap tire fibers, 0,035 $\frac{W}{mK}$[53].

Most of the materials analysed meet building standards: some have properties comparable to (if not better than) commonly available materials in commerce.

Natural materials would seem to be the best choice, but it is very important to give new life to the used materials, through recycling processes, avoiding landfill, and thus curbing the risk of soil degradation or incineration, which causes harmful emissions.

The following tables summarise the thermal conductivity values for the analysed insulating materials and conventional building materials.

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[50] Source: Ayadi, Stiti, Boumchedda, Rennai, Lerari, Elaboration and characterization of porous granules based on waste glass, 2010

[51] Source: Intini, Kuhtz, Recycling in buildings: an LCA case study of a thermal insulation panel made of polyester fiber, recycled from post-consumer PET bottles, 2011

[52] Source: Valverde, Castilla, Nunez, Rodriguez-Senim, de la Mano Ferreira, Development of new insulation panels base don texile recycled fibers, 2013

[53] Source: Van de Lindt, Carraro, Heyliger, Choi, Application and feasibility of coal fly ash and scrap tire fiber as wood wall insulation supplements in residential buildings, 2008

Material	Thermal conductivity	Density	Specific heat	Diffusivity	Effusivity
	λ ($W \cdot m^{-1} \cdot K^{-1}$)	ρ ($kg \cdot m^{-3}$)	Cp, ($J \cdot kg^{-1} \cdot K^{-1}$)	α, ($m^2 \cdot s^{-1}$)	β, ($J \cdot m^{-2} K^{-1} s^{-0.5}$)
Brick (outer)	0.77	1,750	1,000	4.40E-07	1,161
Brick (inner)	0.56	1,750	1,000	3.20E-07	990
Concrete block (heavy)	1.75	2,300	1,000	7.61E-07	2,006
Concrete block (light)	0.20	600	1,000	3.33E-07	346
Mineral wool (quilt)	0.042	12	1,030	3.40E-06	23
Plaster (dense)	0.57	1,300	1,000	4.38E-07	861
Plaster (light)	0.18	600	1,000	3.00E-07	329
Plasterboard	0.21	700	1,000	3.00E-07	383
Steel	50	7,800	450	1.42E-05	13,248
Wood	0.13	500	1,000	2.60E-07	255

Table 2: Thermal properties of materials [54]

Remember that a material is considered a good insulator if it has a thermal conductivity λ of less than 0,07 $\frac{W}{mK}$, and is better the lower the value. For this reason, most of the materials listed in the above table can't be used as insulators, as they all have values well above the allowed threshold - in fact, bricks, concrete, steel, wood, are used in buildings otherwise. The only material with acceptable thermal conductivity is mineral wool, which is widely used in insulation, with a thermal conductivity of 0,042 $\frac{W}{mK}$.

Other popular materials are expanded polystyrene and extruded polystyrene, with values between 0,030 $\frac{W}{mK}$ and 0,040 $\frac{W}{mK}$. The potential insulators studied have very similar values, between 0,032 $\frac{W}{mK}$ and 0,067 $\frac{W}{mK}$, very comparable to conventional materials on the market.

[54] Source: Module 48: Simple thermal analysis for buildings – CIBSE Journal

Material	**Thermal conductivity** $\left(\frac{W}{mK}\right)$	**Density** $\left(\frac{kg}{m^3}\right)$
Expanded Polystyrene EPS	0,031-0,038	15-35
Estruded Polystyrene XPS	0,032-0,037	32-40
Cork	0,032-0,045	100
Glass wool	0,039	20-80
Rock wool	0,033-0,040	40-180
Kenaf	0,034-0,043	30-180
Reeds	0,045-0,056	130-190
Bagasse	0,046-0,055	70-350
Cattail	0,0438-0,0606	200-400
Corn cob	0,058-0,101	170-250
Cotton stalks	0,0585-0,0815	150-450
Date palm	0,0475-0,0697	700-800
Durian	0,064-0,185	357-907
Oil palm fiber	0,055-0,091	20-120
Pineapple leaves	0,035-0,042	178-232
Rice	0,0464-0,0566	154-168
Sunflower	0,0385-0,0501	36-152
Straw bale	0,038-0,067	50-150

Table 3: Summary of thermal conductivity and density

3 QUANTIFYING EMISSIONS: METHODOLOGIES

3.1 WHAT IS AN LCA?

The LCA (Life cycle Assessment) approach to quantify environmental burden is formalized by the International Organization for Standardization (ISO) 14040 series. LCA is defined as a method which allows the development of objective criteria and procedures for the assessment of the environmental impacts of products (e.g., emission), based on the total life cycle of the product (from cradle to grave). According to ISO 14040, LCA is defined as the "compilation and evaluation of the inputs and outputs and their potential environmental impacts of a product system during its lifetime." Thus, LCA is a tool for the analysis of the environmental burden of products at all stages in their life cycle – from the extraction of resources, through the production of materials, product parts and the product itself, and the use of the product to the management after it is discarded, either by reuse, recycling, or final disposal (in effect, therefore, 'from the cradle to the grave'). Notable documents in this series are ISO 14040:2006 – Principles and Framework and ISO 14044:2006 – Requirements and Guidelines (ISO 2006a; ISO 2006b), which together shape fundamental concepts relevant to developing and conducting an LCA study. The ISO standards break the LCA framework into four stages:

- definition of the objective and scope of the analysis;
- compilation of an inventory of the inputs and outputs of a given system;
- assessment of the potential environmental impact related to these inputs and outputs;
- interpretation of results.

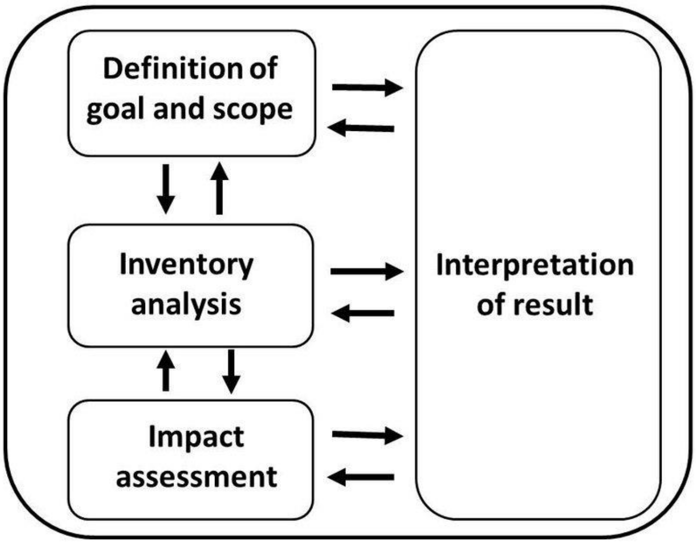

Figure 18: Stages of a life cycle assessment [55]

3.2 LCA TOOLS

A variety of software tools and databases provide standardized assessment models and inventory data at multiple scales. The scales range from industry-wide and sector-wide data down to product- and even brand-specific data. LCA tools can be categorized into three levels[56]:

- Level 1, product comparison tools such as Ganzheitliche Bilanzierung Integrated Assessment (GaBi), SimaPro, BEES, National Renewable Energy Laboratory's (NREL), U.S. Life-Cycle Inventory (LCI) Database, and Life Cycle Explorer.
- Level 2, whole-building decision support tools like Athena Eco-Calculator, Envest 2, and LCA in Sustainable Architecture.

[55] Source: V. Mikita, T. Madarasz, K. Szita, B. Kovacs, Cost and risk assessment of treatment facilities: chapter 4, Filtration materials for groundwater: a guide to good practice, 2016
[56] Source: W. Trusty, S. Horst, LCA tools around the world, Building design and construction, 2005

- Level 3, whole-building assessment systems and frameworks, such as Athena Impact Estimator, BRE environmental assessment method, and the LEED rating system.

In the following table the main environmental assessment tools developed for the building sector:

Tool	Developer
ATHENA™ Experimental Impact Estimator	ATHENA Sustainable Material Institute, Canada
BEAT 2002	Danish Building Research Institute (SBI), Denmark
BeCost (previously known as LCA-house)	VTT, Finland
BEES 4.0	U.S. National Institute of Standards and Technology (NIST), USA
BREEAM	Building Research Establishment (BRE), UK
EcoEffect	Royal Institute of Technology (KTH), Sweden
EcoProfile	Norwegian Building Research Institute (NBI); Norway
Eco-Quantum	IVAM, The Netherlands
Envest 2	Building Research Establishment (BRE), UK
Environmental Status Model (Miljöstatus)	Association of the Environmental Status of Buildings, Sweden
EQUER	École de Mines de Paris, Centre d'Énergétique et Procédés, France
ESCALE	CTSB and the University of Savoie, France
EXIOBASE	The Institute of Environmental Sciences (CML), Universiteit Leiden
GaBi	University of Stuttgart, Germany
LEED®	U.S. Green Building Council, USA
LEGEP® (previously known as Legoe)	University of Karlsruhe, Germany
PAPOOSE	TRIBU, France
SimaPro	PRé Consultants, The Netherlands
TEAM™	Ecobilan, France

Figure 19: Building environment assessment tools [57]

[57] Source: A. Haapio, P. Viitaniemi, A critical review of building environmental assessment tools, Environmental impact assessment review, Volume 28, Issue 7, 2008

An introduction to the most used software [58]:

- Athena EcoCalculator, developed by the Athena sustainable material institute in Canada, is able to consider whole-building assemblies and recognize the characteristics of building materials and their effects when combined with other materials (and compared with similar materials);
- BEES, born in the United States, provides an economic and environmental assessment of building materials in its portfolio. In addition, several categories of damage can be assessed;
- ECO-BAT, has information on about 100 generic materials and European energy sources, so it is possible to both choose materials and define the energy level of the building;
- Envest 2, is an LCA tool that evaluates the economic and financial impacts in the design process of a structure: by introducing the characteristics of the building, the program suggests the best materials at economic and environmental level;
- GaBi, developed by the University of Stuttgart and in accordance with ISO 14040, is a process-based model complete with economic costs. It uses a database of products obtained from industry reviews and technical literature. It does not assess the impact of the use phase of the building;
- MIET 2.0, developed by Leiden University, allows input-output analysis of hybrid LCAs;
- SimaPro, is one of the most widely used software tools in this field. It collects, analyses and monitors data on the environmental sustainability of building products and services, at all stages of the life cycle. It assesses sustainability, carbon and water footprints, product design, and the determination of performance indicators.

[58] Source: L. Cabeza, L. Rincon, V. Vilarino, G. Perez, A. Castell, Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review, Renewable and sustainable energy reviews, Volume 29, 2014

However, construction life cycle assessment tools are incomplete because they fail to consider certain boundary conditions, such as:

- construction site-specific impacts;
- model complexity, due to the presence of a large number of materials;
- scenario uncertainty, due to doubts about the long-term use phase;
- interior environments, regarding furniture elements used in the building's use phase;
- data on recycled materials, generally absent from LCA software databases.

3.3 ONE CLICK LCA: CASE SETTING

For the life cycle assessment of the case study, the One Click LCA software is used.

One Click LCA, developed by Panu Pasanen of the company Bionova, enables life cycle analysis, carbon management, carbon footprint and life cycle cost analysis. In addition, it can be used for BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (LCA certification of residential and commercial buildings) certifications, green architecture and infrastructure, and environmental product declarations.

The program has a large amount of building materials in its database, with information about the manufacturer, technical, environmental, and economic aspect. Let’s see below how to set up the case study.

First, the resources used in the construction of the building are enter, divided into categories:

- Foundations: foundation walls, columns, and ground beams, bearing ground slab, air raid shelter structures;
- Frame and roof structures: slab and beams, stairs, external walls, external terraces and balconies, elevator shaft;
- Complementary works: windows and doors, lightweight partition walls;
- Finishes: internal wall cladding and finishes, ceiling cladding and finishes, surface structure of floors.

Only the building (structure, shell, interior, and filling) is included in the analysis, omitting supplies for bathrooms and kitchens, air conditioners and cookers as these values are not useful for the study, and omitting values for the transport of materials from the production site to the construction site as these are not available within the software used (the data shows that all material was transported by truck).

When entering the materials used, it is necessary to provide the quantity and origin of each material: all materials were considered to come from Finland or Europe. In addition, it is necessary to enter the "service life" values, i.e., the life expectancy of the material before it is replaced; in the following table these values are shown for the main construction materials but for the purposes of this study the default values suggested by the software were used.

Element	Typical life expectancy (years)
Frame	
Concrete frame	81
Upper floors	
Reinforced concrete floor	71
Precast concrete slab	78
Roof	
Asphalt covering to flat roof	36
PVC covering to flat roof	27
EPDM covering to flat roof	25
Stairs	
Concrete stairs	74
Steel stairs	50
Aluminum stair nosings	21
Plastic stair nosings	15
External walls	
Aluminum curtain walling	43
Windows	
Aluminum windows	44
Internal doors	
Internal softwood door	42
Wall finishes	
Plasterboard to wall	39
Clay tiling to wall	37
Floor finishes	
Vinyl sheet floor covering	17
Vinyl tile to floor covering	18
Carpet floor covering	13
Ceiling finishes	
Suspended ceilings	24

Table 4: Typical life expectancy of building materials [59]

These values are necessary to know the replacement factor which quantifies the number of times it is necessary to introduce a resource into the system, over a period equal to the expected lifetime of the building. In this way, the impact of a certain material will be given by the impact of its first installation scaled up by the replacement factors. Assuming a building lifetime of 60 years, the value of the replacement factor is calculated using the following formula:

[59] Source: BCIS, Life expectancy of building components, 2006

$$Replacement\ factor = \frac{60}{expected\ lifespan\ (years)}$$

However, most materials have a life expectancy of at least 40 years, so they are replaced only once during the life of the building: this means that the result of the equation tends to be rounded down (but may depend on need)[60].

Moreover, the software suggests a percentage of material "waste" on site: this value varies according to the building construction and design process. The average value for all materials used is about 4-5%. In the following table the wastage values for the main building materials:

Types of materials	Wastage (in %)
Aluminum	5
Bricks and blocks	3
Cast iron	5
Concrete	3
Copper	5
Durasteel	3
Fibre glass	8
Galvanized steel	5
Glass	5
Precast concrete elements	2.5
Precast structural concrete element	2.5
Reinforcing bar	5
Special aggregates (Dynagrip, in non-skid finish)	10
Stainless steel	5
Structural steel	5
Stone	5

Table 5: Percentage of construction wastages for different types of building material[61]

Finally, it is possible to define if the material used has been recycled: for the purposes of this study, we assume that all the material used has been purchased

[60] Source: Chau, Hui, Ng, Powell, Assessment of CO2 emissions reduction in high-rise concrete office buildings using different material use options, 2012

[61] Source: Poon, Yu, Ng, On-site sorting of construction and demolition waste in Hong Kong, 2001

new (however, as stated in the EPDs - Environmental Product Declarations -, materials may have an intrinsic percentage of recycled component)

For the study - calculation of carbon dioxide emissions due to the construction of the building - it is necessary to specify that the CO_2 emissions associated with building materials depend on the type (oil, wind, solar, nuclear) and the amount of energy used in the production process[62]. The amount of CO_2 emitted by the individual materials is therefore obtained by multiplying the mass of the individual materials with the corresponding embodied energies and the CO_2 emission factor: in other words, for a given building, the amount of CO_2 emitted will be given by the sum of the CO_2 emitted by all its individual constituent materials, summarised in the following formula[63]:

$$Q = \sum_{1}^{n} e_n \beta_n m_n$$

where e_n represents the embodied energy intensity of the n-th building material (in $\frac{MJ}{kg}$), β_n is the emission factor of the n-th material (in $\frac{kg\ CO_2}{MJ}$) and m_n is the mass of the n-th building material (in kg).

The embodied energy of a material is the energy content of the resource fuel plus the energy expended during extraction, refining, production, and transport from the extraction site to the refinery: the embodied energy of a material is the sum of the energy of the raw materials and the energies of the process fuel. The intensity of embodied energy varies greatly even when considering the same type of material, as it considers its possible small variables. The following table shows the

[62] Source: Gaonzalez, Navarro, Assessment of the decrease of CO2 emissions in the construction filed through the selection of materials: practical case study of three houses of low environmental impact, 2006
[63] Source: Chau. Hui, Ng, Powell, Assessment of CO2 emissions reduction in high-rise concrete office buildings using different material use options, 2012

ranges of values usually used for the main construction materials (One click software intrinsically has these values):

Type of building material	Embodied energy intensities[a] (in MJ/kg)
Aluminum	166.0–312.7
Bitumen and asphalt	3.4–50.2
Bricks and blocks	0.5–3.3
Concrete	0.7–1.6
Galvanized steel	30.6–34.8
Glass	6.8–25.8
Stone, gravel and aggregate	0.1–0.8
Purified fly ash (PFA)	<0.1
Paint	60.2–144
Plaster, render and screed	0.1–2.0
Plastic, rubber and polymer	70.0–116.0
Plywood	3.1–18.9
Precast concrete element	2.0
Reinforcing bar and structural steel	6.2–42.0
Stainless steel	8.2–13.3
Thermal and acoustic insulation	1.2–17.6
Ceramic and tile	2.2–5.5

Table 6: Embodied energy intensities for different types of building materials [64]

The emission factors of the materials depend on the electricity production in the different countries: they are derived by multiplying the ratios of the fuel type used for electricity production in the individual countries with the emission factors of the corresponding fuel types. The following table provides a list of emission factor values β for the main countries in the world:

[64] Source: Gaonzalez, Navarro, Assessment of the decrease of CO2 emissions in the construction filed through the selection of materials: practical case study of three houses of low environmental impact, 2006
Scheuer, Keoleian, Reppe, Life cycle energy and environmental performance of a new university building: modelling challenges and design implications, 2003
Chen, Burnett, Chau, Analysis of embodied energy use in the residential building in Hong Kong, 2001
Huberman, Pearlmutter, A life-cycle energy analysis of building materials in the Negev desert, 2008
Kofoworola, Gheewala, Life cycle energy assessment of a typical office building in Thailand, 2009

Country	Emission factor[a], β (in kg CO_2/MJ)
Australia	0.02294
Belgium	0.00775
Brazil	0.00186
China	0.02176
France	0.00148
Germany	0.01253
Hong Kong	0.01655
India	0.02165
Indonesia	0.01911
Italy	0.01460
Japan	0.01261
Korea	0.01473
Malaysia	0.01781
Romania	0.01677
Russian	0.01658
Singapore	0.01755
South Africa	0.02358
Spain	0.01129
Taiwan	0.01479
Thailand	0.01641
UK	0.01453
US and Canada	0.01583
Vietnam	0.00817

Table 7: Average CO2 emission factor values for electricity generation in different countries [65]

A final data point that should not be overlooked is the impact of the calcination and carbonation processes due to the carbon emissions of concrete (included in One Click calculations). The calcination process involves emissions during the concrete production phase, due to the decomposition of limestone into calcium oxide CaO and carbon dioxide, a phenomenon that occurs at high temperatures. During the rest of their life, concrete products (concrete, cement, and mortar), give rise to the carbonation process through which they absorb a part of carbon dioxide, thanks to the calcium oxide CaO inside them binds with the CO_2 present in the atmosphere, to form carbonate[66], thus reducing the amount of carbon dioxide.

[65] Source: EMSD, Life cycle energy analysis if building construction, 2005
EPD, EMSD, Guidelines to account for and report on greenhouse gas emissions and removals for buildings (commercial, residential or institutional purpose) in Hong Kong, 2010
[66] Source: Dodoo, Gustavsson, Sathre, Carbon implication of end of life management of building materials, 2009

4 CASE STUDY OF RESIDENTIAL BUILDING IN TAMPERE

The building under study is the Pyry, located in the ex-industrial district, now a residential area of Härmälänranta a few kilometres from the centre of Tampere, Finland.

Figure 20: Number 4 is Pyry position in Härmälänranta [67]

Construction of the district began in 2007 and is planned for completion in 2026. Härmälänranta originates from the idea of the "20-minute neighbourhood", first developed in Portland (USA), and then spreading more and more rapidly in the city's strategic planning: it consists in the creation of zonal areas that ensure residents have all the goods and services they need to live, work, and play within a 20-minute walk from their homes, thus facilitating daily activities and reducing the use of transport.

[67] Source: Skanska, Koti järven rannalla hyvän olon Härmälänrannassa Tampereella, 2011

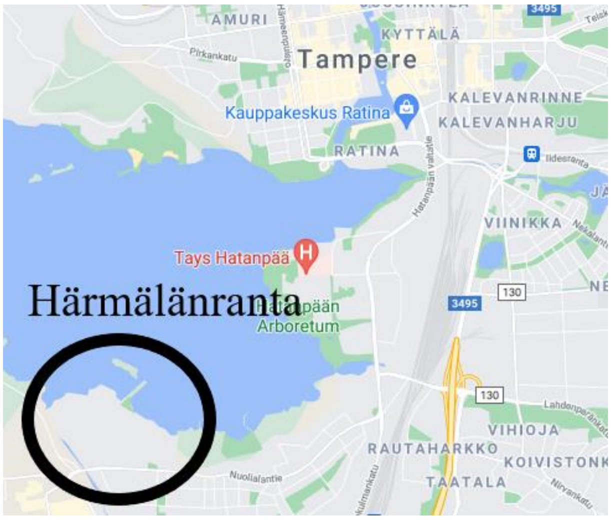

Figure 21: Härmälänranta position [68]

The neighbourhood aims at sustainability through green housing, a good public transport network and car and bike sharing, making the area eco-sufficient. All flats have low energy consumption: in particular, the Pyry building has an estimated energy demand for the use phase of 80 $\frac{KWh}{\frac{m^2}{y}}$ of heat and 14 $\frac{KWh}{\frac{m^2}{y}}$ of electricity, referring to the common areas. With these data, the building is in energy class A (for Finland).

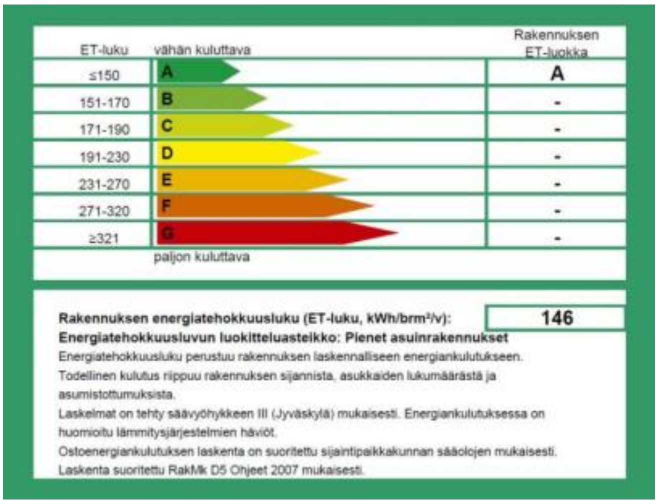

Figure 22: Energy audit in Finland [69]

[68] Source: Google Maps, 2021
[69] Source: Mikkonen, Energy audit in Finland, 2012

Pyry's balconies have a double facade to protect against the cold and reduce the problem of overheating, high quality windows and doors prevent heat loss, motion sensors and acoustic controls are installed to manage lighting in common areas, and counters are installed to measure the electricity and water used in each flat.

In addition, the shape of the building and the flats is optimised to reduce heat loss, there is a ventilation system that allows heat recovery, energy-efficient appliances, and sockets for recharging electric cars.

Furthermore, the materials used in the construction of the Pyry building meet the requirements of emission class M1, which promotes the development and use of low-emission building materials. This classification sets limit values for the release of volatile organic compounds (VOC), formaldehyde and ammonia in materials and furniture, as well as assessing the acceptability of the product's smell. The M1 mark therefore indicates that the product is odourless and has low emissions. For the design and construction of the interior areas of a building, bricks, natural stone, ceramics, glass, and metal are defined as M1 products. The following table summarises the criteria that must be met for a material to be awarded the M1 mark:

Features to be studied	**Category M1**	**Category M2**
Total emission of volatile organic compounds (TVOC) [mg/ m^2h]	< 0,2	< 0,4
Emission of a single organic compound (VOC) [µg/m^3]	≤ EU-LCI	≤ EU-LCI
Formaldehyde emission [mg/ m^2h]	< 0.05	< 0,125
Ammonia emission [mg/ m^2h]	< 0.03	< 0.06
Article 13 of Regulation No 1049/2001. The emission of CMR compounds in Classes 1A and 1B [mg/m^3] [1]	< 0,001	< 0,001
smell [2]	doesn't smell	doesn't smell

Table 8: M1 classification criteria [70]

[70] Source: M1-vaatimukset | Rakennustietosäätiö (rts.fi)

Figure 23: Pyry building [71]

The quantities of materials used for the construction of the entire building were extracted from the project documents, and are given below:

	Quantity	Unit
Foundations		
Reinforcing steel A 500HW	2555	kg
Balcony pillar bolts PM 24/L	11	kg
Balcony pillar bolts PM 24/L	2,2	kg
Concrete K 35-2	60	m3
EPS 120 50 mm	579	kg
EPS 120 50 mm	259,5	kg
Bitumen surface	214,5	kg
Foundation walls, columns and ground beams		
Reinforcing steel A 500HW	163	kg
Concrete K 35-2	4	m3
EPS 120 50 mm	40,5	kg

[71] Source: Heinonen, Saynajoki, Junnonen, Poyry, Junnila, Pre-use phase LCA of a multy-story residential building: can greenhouse gas emissions be used as a more general environmental performance indicator?, 2015

Water insulation	22,5	kg
Bearing ground slab		
Reinforcing steel A 500HW	2560	kg
Prefabricated reinforcing steel A 500HW	1501	kg
- Y 1 10-200/10-200-5000x2350 mm	171,14	kg
- R 1 8-200-2000/700	254	kg
Concrete C-4-30	85	m3
Filter fabric (0,11 kg/m2)	36,85	kg
Sand (2000 kg/m3, 30 cm)	16320	kg
EPS 100 floor 200 mm (30 kg/m3)	4050	kg
Air raid shelter structures		
Reinforcing steel A 500HW	1021	kg
Concrete mesh 3-50 B500K	20	kg
SBKLr 150x150+ 100x8-250 Rst	18	kg
Concrete K 30-2	18	m3
Air raid shelter roof	2369	kg
- EPS 60 S 50 mm	97,5	kg
- Concrete mesh 8-200 B500K	257	kg
- Concrete K 35-2	6	m3
Sand (2000 kg/m3, 160 mm)	16000	kg
Filter fabric (0,14 kg/m2)	5,5	kg
EPS 100 50 mm	166,5	kg
EPS 120 50 mm	30	kg
Polyurethane insulation 100 mm (30 kg/m3)	320	kg
Bitumen surface + K-MS 170/4000	142,5	kg
- Filter fabric (0,14 kg/m2)	5,32	kg
- Gravel 150 mm	1539	kg
- Crushed stone 200 mm	10640	kg
Transport	69910	tkm
Frame and roof structures		
Load bearing internal walls and columns		
- Pillar elements 320x480 mm,3460 mm	0,51	m3
- Reinforcing steel	40,09	kg
Partition wall elements B= 200 mm	0,20	m3
- Reinforcing steel	11466	kg
- 70 mm wool insulation B= 250 mm	6,3	kg
Roof elements	1	m3
- Reinforcing steel	50	kg
Slabs and beams		
Vault:	430	kg
- Concrete K 30-2	10	m3
- Reinforcing steel A 500HW	10	m3
Hollowcore slabs		

200 mm: (245 kg/m2)		
- L = < 7,5 m	6,34	m3
- Reinforcing steel	259,6	kg
265 mm: (360 kg/m2)		
- L = < 7,5 m	25	m3
- Reinforcing steel	933,8	kg
- L = 7,5-9 m	19,5	m3
- Reinforcing steel	719,2	kg
370 mm: (485 kg/m2)		
- L = < 7,5 m	237,9	m3
- Reinforcing steel	7092	kg
- L = > 9 m	197,2	m3
- Reinforcing steel	5880	kg
250 mm	36,0	m3
- Reinforcing steel	2058	kg
Hollowcore slab seam reinforcement and soldering	82,6	kg
- cement 0,8 jm/m2	0,16	m3
Stairs		
Cast-in concrete stairs:		
- Reinforcing steel A 500HW	86	kg
- Concrete K 30-2	2	m3
Steel stairs	72	kg
Concrete element stairs		
- Concrete K 30-2	7,06	m3
- Reinforcing steel A 500HW	400	kg
External walls		
Steel pillar 100x100x6 mm, 8,25 m	141	kg
Eaves' steel support, hot galvanized:		
- Steel	156	kg
- plastic membrane	1	kg
- Bolts PL-10-150x150 2M8 (2 kg/pc)	72	kg
Plaster	11628	kg
Sealant	1104	kg
External wall elements:		
- Concrete	11,25	m3
- EPS slab 102, 50 mm	225	kg
- Reinforcing steel	1800	kg
- Polyurethane insulation 200 mm (40 kg/m3)	1800	kg
Color concrete elements:		
- Concrete	19,3	m3
- Reinforcing Steel	3276	kg
- Mineral wool	2620,8	kg
- Concret+D102:D792e	36,1	m3

- Reinforcing Steel	3276	kg
Plastered concrete elements:		
- Plaster mesh	768	kg
- Cast plaster	11520	kg
- Mineral wool	3072	kg
- Polyurethane insulation 170 mm (40 kg/m3)	10368	kg
- Concrete	127,1	m3
- Reinforcing steel	11520	kg
Eaves		
- Concrete, fine-tinted	1,8	m3
- Reinforcing steel	312	kg
- Mineral wool	249,6	kg
Sealant	0,38	m3
Thermo wall elements:		
- Beams	0,49	m3
- Frame 150 mm, K 600	1,24	m3
- Mineral wool insulation	488	kg
- Exterior cladding panels	3,35	m3
- Vapor barrier	12,23	kg
- Gyproc board	736	kg
- EPS 120 50 mm	121,5	kg
External terraces and balconies		
Terraces:		
- Reinforcing steel	2580	kg
- SBKL 200/200 (4,9 kg/pc)	29,4	kg
- SBKL 100/100 (0,9 kg/p)	2,7	kg
- Concrete K 35-2	27	m3
- Bitumen	568	kg
- EPS 100 floor 100 mm	210	kg
- EPS 100 floor 70+70 mm	294	kg
- Concrete mesh	138	kg
- Concrete K 35-2	6	m3
- Tiles	510	kg
- Cast plaster (4 kg/m2)	240	kg
- Roof elements	1992	kg
Balcony rails and glasses:		
- Rails	298	kg
- Glass 6 mm	7087,5	kg
Balcony elements:		
- Concrete fine-tinted	674	kg
- Reinforcing steel	92,9	m3
- Mineral wool insulation	8424	kg
- Sealant		

Attic and roof structures		
- Vapor barrier, bitumen (1,4 kg/m2)	2152	kg
- EPS 80 S roof, 2x100 mm	1614	kg
- light gravel 450-650 mm (270kg/m3)	3995	kg
- Conrete surface (300 kg/m3)	3228	kg
- Polyethylen board	1,37	kg
- Eaves	138,6	kg
Elevator shaft:		
- Timber structure	0,075	m3
- pressure-impregnation	0,075	m3
- Mineral wool insulation 150 mm	864	kg
- Vapor barrier bitumen felt	432	kg
Eaves	7,2	kg
Truck	311987	tkm
Complementary works		
Wood-aluminium windows 355 m2:		
- Aluminium	66,5	kg
- Wood	18,3	m3
- Glass	7,992	kg
Window doors		
- Glass	1390,689	kg
- Wood	2,6298	m3
- Mineral wool insulation	540	kg
Sealant	113	kg
Seam tape	56,5	kg
Aluminium profile doors	3,6	m2
Steel doors:	23,55	kg
- Steel	8,9	kg
- Mineral wool insulation	98,91	kg
- Safety glass (4 mm)	40	kg
Internal doors:		
- Wood	57,3	m2
- Glass (4 mm)	68,4	kg
- Chip board	2,09664	kg
Lightweight partition walls		
Brick walls:		
- Bricks	11994	kg
- Plaster	1,36	m3
Partition walls		
- Steel frames	832	kg
- Mineral wool 50 mm	4080	kg
- Gyproc boards (9 kg/m2, 13 mm)	5054	kg
- Knauf Aquapanel 13,5 mm (11,7 kg/m2)	632	kg

Rails and bridges	27	kg
- Steel rails	30	kg
- Steel bridges	105	kg
Sewer concrete casting	9,01	m3
Elpo flue elements	49,7	m3
Truck	23469	tkm
Finishes		
Roofing		
Eaves	7,93	kg
Drainpipes	9,8	kg
Bitumen felt	8230	kg
Roof drains	7,5	kg
Internal wall claddings and finishes		
Wall tiles Pukkila Color (13,5 kg/m2)	1800	kg
Wall tiles Brancos 200x330 (18,1 kg/m2)	452,5	kg
Plaster	1496	kg
Water insulation	149,3	kg
Silicone seaming	80,1	kg
Wall preparation plaster	1122	kg
Ceiling claddings and finishes		
Panel ceilings	801	kg
Plywood	6,84	m3
Galvanized steel board	300	kg
Ecophon Fucus 600x600, AL2	142,5	kg
Seaming	1512	kg
Surface structures of floors		
Surface concrete 10 mm	205,2	kg
Floor tiles Pukkila Arcadia 100x100 (15,4 kg/m2)	123,2	kg
Water insulation	292	kg
Parquet (7,6 kg/m2)	24,78	m3
- Base mat	123,9	kg
- Base boards, plastic (120 g/m2)	0,79	m3
Paintings	1012	kg
Filler	560	kg
Truck	9228	tkm

Table 9: Materials used in the building construction

5 RESULTS

The total emissions due to the construction of the Pyry building, considering the extraction of raw materials, the production of materials and the installation is 986 tons of CO_2 with a corresponding social cost of € 49321: this value is obtained directly from the programme which has automatically set a cost of € 50 per ton of carbon dioxide for Finland. This value indicates the economic damage resulting from CO_2 emissions and is highly variable depending on the country and the type of company and is used as a means of mitigating the climate crisis by regulating the market with real carbon taxes.

Figure 24: Total carbon dioxide and social cost of carbon values

In detail, the following table shows the impact of each building element:

	Tons CO_2	**Percentage**
Foundations and substructure	102	10%
Loading bearing internal walls/lightweight partition walls	117	12%
Slabs and beams	249	25%
Sewer/elevator shaft/external terraces and balconies/stairs/windows and doors/finishes	333	34%
External walls	185	19%

Table 10: Categories emissions

The following table presents a division in section A, B, C, indicating respectively the emissions before, during and after the construction of the structure, obtaining, as already seen, a total of 986 tons of CO_2, from which 416 tons can be subtracted during its life, due to carbon storage, carbonisation of cement products and reuse and recycling, thus considerably reducing the impact of the entire building.

Section	Result category	Global warming kg CO2e/m2/a
A1-A5	Emission effects before use	782317,3
A1-A3	Manufacturing	744843,4
A4	Transport	
A5	Construction site - material wastage - materials	37473,83
A5-YM	New constuction site activities	
B3-B4,B6	Emission effects during operation	204109,6
B3-4	Energy consumption of repairs	
B4	Material replacement	204109,6
B6	Energy use	
C	Emission effects after use	
C1	Demolition site operations	
C2	Transport for further processing	
C3-4	Waste treatment and disposal	
A-C	Total carbon footprint (sum modules A-C)	986426,9
A-D	Total carbon handprint (sum modules A-D)	-416264
bio-CO2	Carbon storage, biogenic	-33500,4
B1	Carbonisation	-26939
D	Benefits of re-use and recycling	-355824
D-energy	Exported energy	

Table 11: Building carbon assessment

The One Click LCA software then presents a list, in ascending order, of the materials that have the greatest impact on the total emissions value.

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
1.	Ready-mix concrete, C30/37	385 tons CO_2e	51.7 %
2.	Reinforcement steel (rebar), generic	202 tons CO_2e	27.1 %

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
3.	Powder coating for steel	22 tons CO_2e	3.0 %
4.	EPS insulation panels	19 tons CO_2e	2.5 %
5.	Rock wool insulation panels, unfaced, generic	13 tons CO_2e	1.7 %
6.	Polyurethane (PUR) foam insulation	11 tons CO_2e	1.4 %
7.	ETICS with acrylic plasters and mineral wool insulation	8,7 tons CO_2e	1.2 %
8.	Acrylic solvent-free dispersion paint	8,9 tons CO_2e	1.2 %
9.	Bitumen cold adhesive	7,2 tons CO_2e	1.0 %
10.	Floor screed	7,8 tons CO_2e	1.0 %

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
11.	Hot rolled steel sheets and coils	5,9 tons CO_2e	0.8 %
12.	Plywood, birch, coated	6,3 tons CO_2e	0.8 %
13.	Polypropylene roofing membrane, French average	5 tons CO_2e	0.7 %
14.	Water-based acrylic paint for interior use	5 tons CO_2e	0.7 %
15.	EPS insulation panel, fireproof	4,2 tons CO_2e	0.6 %
16.	Clay bricks, perforated and unperforated	4,7 tons CO_2e	0.6 %
17.	Coated /uncoated flat glass	4,7 tons CO_2e	0.6 %
19.	GLT, Glued laminated timber	3,3 tons CO_2e	0.4 %
20.	Wooden interior door, per m2	2 tons CO_2e	0.3 %

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
21.	Polyurethane (PUR) foam insulation	1,7 tons CO_2e	0.2 %
22.	Gypsum plasterboard	1,6 tons CO_2e	0.2 %
23.	Concrete block, lightweight aggregates, insulated, U 0.17 W/m2K	1,7 tons CO_2e	0.2 %
24.	Glued laminated timber (Glulam) for indoor use	1,2 tons CO_2e	0.2 %
25.	Ceramic floor and wall tiles	1,4 tons CO_2e	0.2 %

Table 12: Material impact

As it turns out, the most impactful material is concrete, which alone causes 385 tons of CO_2 which is more than half of the total emissions related to the construction of the building, mainly due to its production process.

The following bar graphs show the results provided by the software regarding the emission levels for the different construction areas, the types of materials used and the work processes respectively.

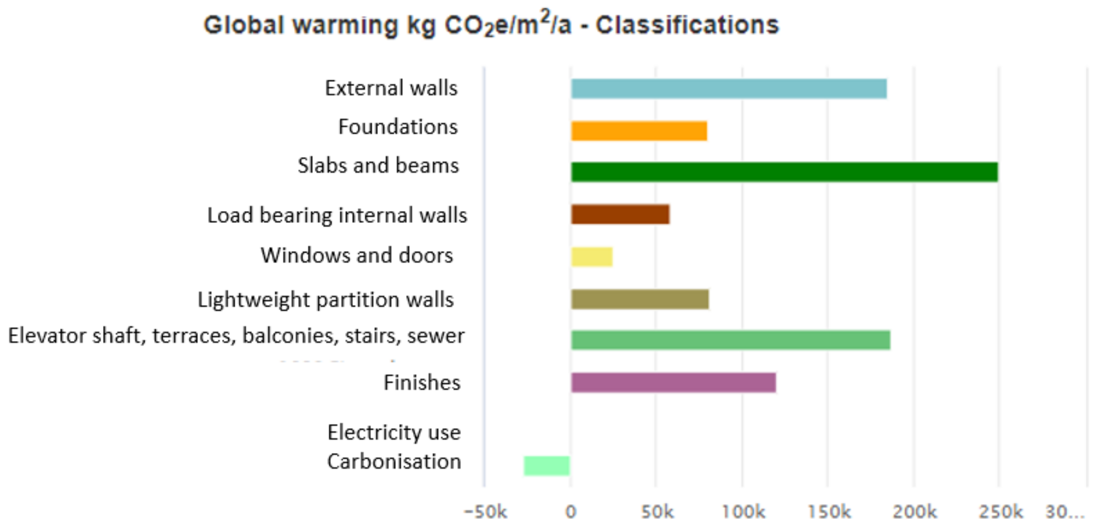

Figure 25: Impact of each section

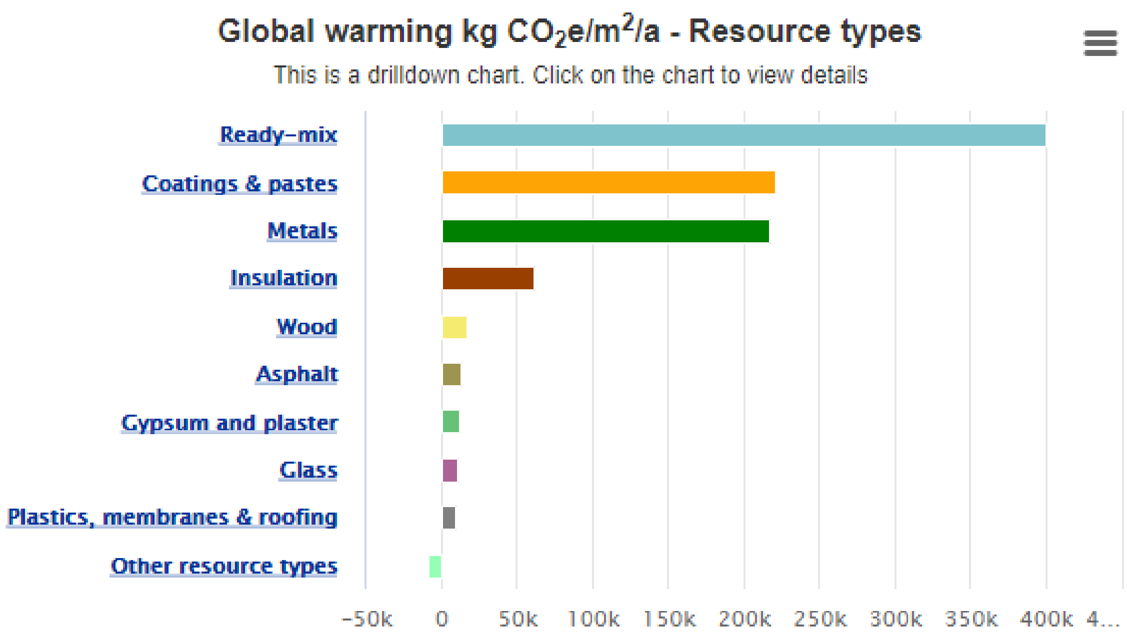

Figure 26: Impact of each material

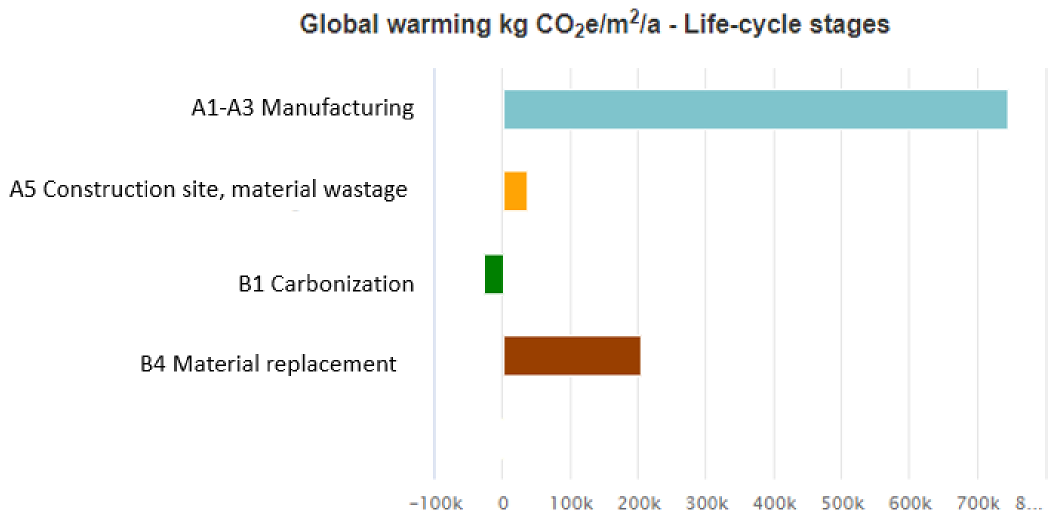

Figure 27: Impact of each process

5.1 SUSTAINABLE ALTERNATIVES

From results, it emerged that the concrete used is the cause of greater CO_2 emissions and therefore guilty of the greatest environmental pollution.

In detail, for the calculations was considered a concrete "Ready-mix concrete" with strength class C30/37 and density 2363 $\frac{kg}{m^3}$, produced in Finland. The manufacture of this product causes emissions of 0,14 kg of CO_2 for every kg of concrete produced.

The software suggests several more sustainable alternatives: in this case the best option provided by the program is the "Ready-mix concrete C35/45, low-carbon class extreme" produced by the Skedsmo Betong company in Norway, with density 2400 $\frac{kg}{m^3}$ and emission of 0,0377 kg of CO_2 per kg of concrete: by choosing this product, the total emissions due to concrete would drop considerably from 385 tons of CO_2 to about 100 tons of CO_2. This improvement is due to the resource use in the production process of the material: in fact, an analysis of the technical data sheets of the two types of concrete shows that much less energy was used in the production of "Ready-mix concrete C35/45, low-carbon class extreme", most of which came from renewable sources.

The second most impactful material is steel, "Reinforcement steel, generic, 0% recycled content (only virgin materials)" with a density of 7850 $\frac{kg}{m^3}$, which causes the emission of 202 tons of CO_2 into the atmosphere due to its production process: in detail, 2,89 kg of CO_2 are emitted per kg of steel. Again, the software proposes several alternatives, the best being "Steel, rebar products (concrete reinforcement), scrap 100%" produced by Norsk Stal, in Norway, characterized by the same density of 7850 $\frac{kg}{m^3}$ and an emission of just 0,33 kg of CO_2 produced per kg of steel created: this means a substantial reduction of total emissions in the steel category of almost 90%, which means a total of 23 total tons of CO_2 produced. In this case there is a clear reduction in emissions because the sustainable steel alternative chosen is derived from steel scrap, so all the material is recycled; in the first case only virgin material was used.

Replacing only these two products with those suggested by the program provides a total value of emissions of 520 tons of CO_2 with a respective social cost of € 26018, a 47% lower impact than previously achieved.

Figure 28: Total carbon dioxide and social cost of carbon values, case sustainable concrete and steel

The following table compares the results obtained above for the categories defined in terms of the amount of emissions produced:

	Before		After	
	Tons CO2	Percentage	Tons CO2	Percentage
Foundations and substructure	102	10%	52	10%
Loading bearing internal walls/lightweight partition walls	117	12%	85	16%
Slabs and beams	249	25%	56	11%
Sewer/elevator shaft/external terraces and balconies/stairs/windows and doors/finishes	333	34%	246	47%
External walls	185	19%	82	16%

Table 13: Comparison categories emissions

Section	Result category	Global warming kg CO2e/m2/a
A1-A5	Emission effects before use	**316246,6**
A1-A3	Manufacturing	**298164,21**
A4	Transport	
A5	Construction site - material wastage - materials	**18082,42**
A5-YM	New constuction site activities	
B3-B4,B6	Emission effects during operation	**204109,6**
B3-4	Energy consumption of repairs	
B4	Material replacement	**204109,6**
B6	Energy use	
C	Emission effects after use	
C1	Demolition site operations	
C2	Transport for further processing	
C3-4	Waste treatment and disposal	
A-C	Total carbon footprint (sum modules A-C)	**520356,23**
A-D	Total carbon handprint (sum modules A-D)	**-457826,69**
bio-CO2	Carbon storage, biogenic	**-33500,4**
B1	Carbonisation	**-26939**
D	Benefits of re-use and recycling	**-397387,27**
D-energy	Exported energy	

Table 14: Building carbon assessment, case sustainable concrete and steel

The total carbon footprint has been almost halved while the benefits due to carbon storage, carbonisation and possible reuse and recycling of materials do not change, so over its lifespan the building will be almost able to cancel the emissions due to its construction. This result is very positive and is achieved by paying attention to the choice of materials to be used during construction.

In the list of the most impactful materials, concrete and steel continue to occupy the top positions, but despite this, their impact is significantly reduced: in the case of concrete, emissions have decreased from 385 to 99 tons, and for steel, from 202 to 23 tons.

Before:

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
1.	Ready-mix concrete, C30/37	385 tons CO_2e	51.7 %
2.	Reinforcement steel (rebar), generic	202 tons CO_2e	27.1 %

After:

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
1.	Ready-mix concrete CO_2 ?	99 tons CO_2e	33.3 %
2.	EPS insulation panel, fireproof CO_2 ?	23 tons CO_2e	7.6 %
3.	Steel, rebar products (concrete reinforcement) CO_2 ?	23 tons CO_2e	7.6 %

Below are the new charts proposed by the software for construction area emission levels, material types, and different work processes.

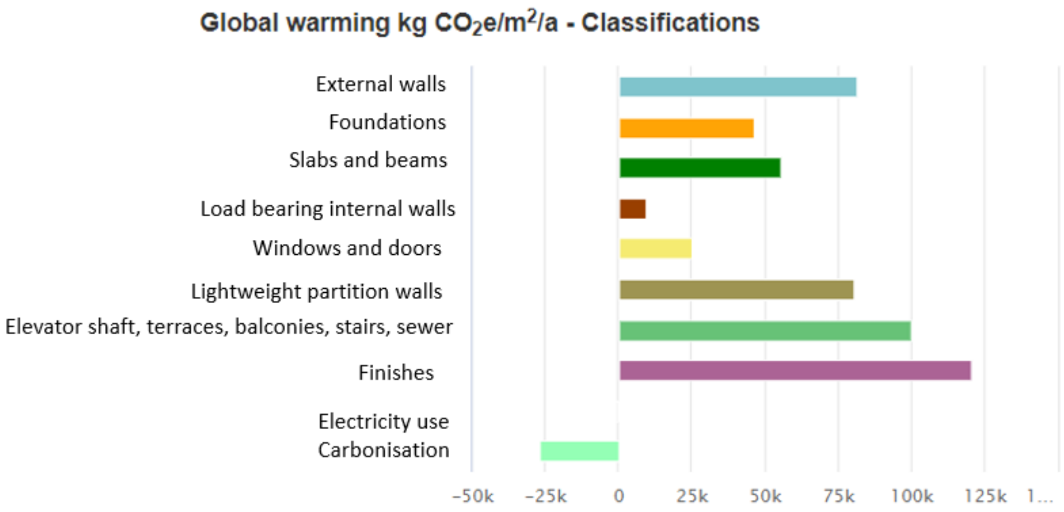

Figure 29: Impact of each section, case sustainable concrete and steel

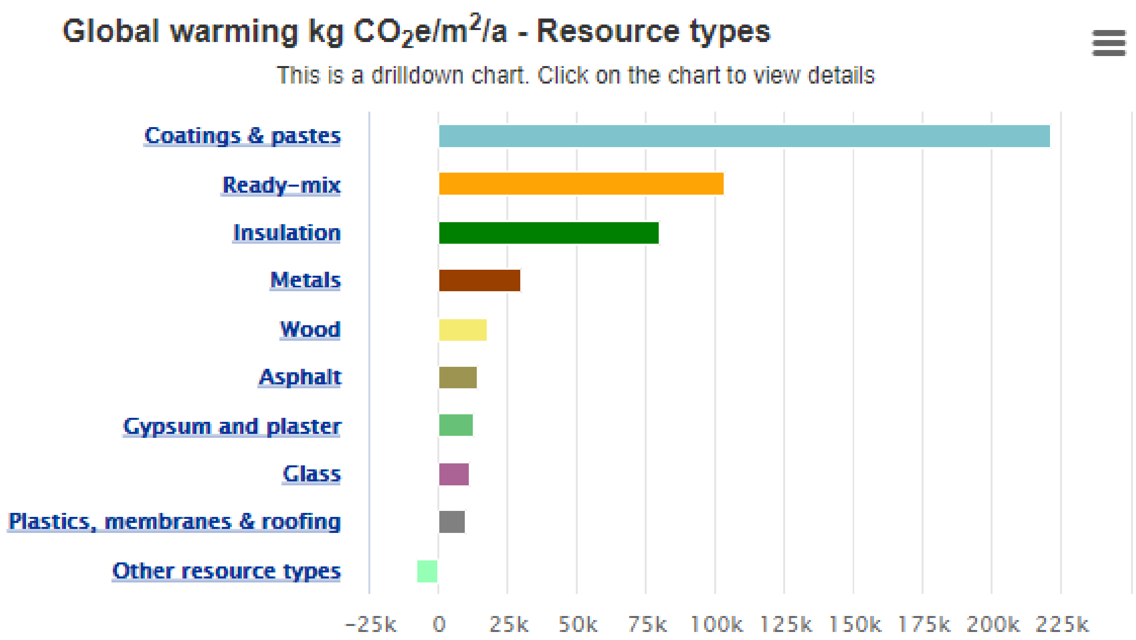

Figure 30: Impact of each material, case sustainable concrete and steel

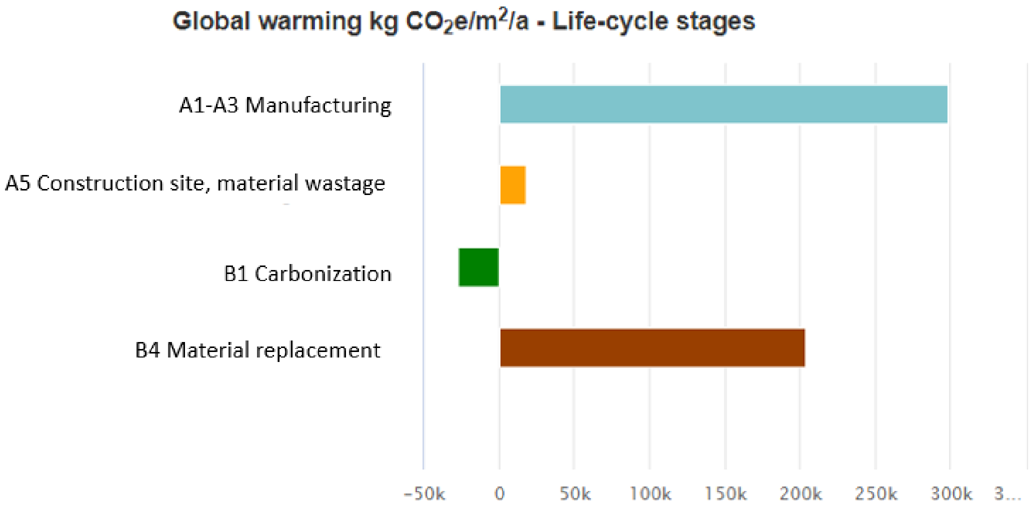

Figure 31: Impact of each process, case sustainable concrete and steel

And finally, using all the sustainable materials suggested by One Click LCA, make the following substitutions:

- "Powder coating for steel", originating from the Netherlands with an impact of 15,8 kg of CO_2 emitted per kg of product (a total of 22 tons of CO_2 in this study) is a typical coating for metals to achieve a harder finishing than conventional paints and has an anti-corrosive action. The program does not provide a more sustainable powder coating solution so this product is replaced with a "Waterborne alkyd primer paint" produced by Tikkurila in Sweden, with an impact of only 1,03 kg of CO_2 per kg of paint, a total of 5 tons of CO_2. This reduction in environmental impact is achieved through the use of renewable energy in the manufacturing of the material.
- "Floor screed, 34 $\frac{kg}{m^2}$, 20 mm, density 1700 $\frac{kg}{m^3}$" produced in Finland, with an impact of 9,38 kg of CO_2 per m^2 (a total of 7,8 tons of CO_2)" is replaced by "Leveling screed and render, 20 mm, 34 $\frac{kg}{m^2}$, 1700 $\frac{kg}{m^3}$" produced in Finland by Saint Gobain, with an impact of 5,24 kg of CO_2 per m^2, equal to

about half of the previous one. The improvement in emissions is due to the use of renewable energy in the production process.

- “Plywood, birch, coated, 680$\frac{kg}{m^3}$, moisture content 8%" produced in Finland, with an impact of 0,66 kg of CO_2 per kg (for a total of 6,3 tons of CO_2) is replaced with "Spruce plywood, uncoated" produced in Finland by UPM Plywood with an impact of 0,34 kg of CO_2 per kg of material, meaning 1,3 tons of CO_2 in the present case study. For this product there will be a CO_2 storage that will be subtracted from the A1-A3 production process of 814 kg CO_2 per m^3 of material used.

The remaining materials used are already considered the most sustainable in their field of application.

Thus, the emissions for each construction section are as follows:

	Tons CO_2	**Percentage**
Foundations and substructure	52	13%
Loading bearing internal walls/lightweight partition walls	27	7%
Slabs and beams	56	14%
Sewer/elevator shaft/external terraces and balconies/stairs/windows and doors/finishes	194	48%
External walls	73	18%

Table 15: Categories emissions, case sustainable materials

The total emissions obtained in this case is 403 tons of CO_2, with a corresponding social cost of € 20133, less than half of the initial result (-59%).

Figure 32: Total carbon dioxide and social cost of carbon values, case sustainable materials

Emissions at different stages of construction:

Section	Result category	Global warming kg CO2e/m2/a
A1-A5	Emission effects before use	**293893,2**
A1-A3	Manufacturing	**277988,82**
A4	Transport	
A5	Construction site - material wastage - materials	**15904,48**
A5-YM	New constuction site activities	
B3-B4,B6	Emission effects during operation	**108774,39**
B3-4	Energy consumption of repairs	
B4	Material replacement	**108774,39**
B6	Energy use	
C	Emission effects after use	
C1	Demolition site operations	
C2	Transport for further processing	
C3-4	Waste treatment and disposal	
A-C	Total carbon footprint (sum modules A-C)	**402667,69**
A-D	Total carbon handprint (sum modules A-D)	**-464682,65**
bio-CO2	Carbon storage, biogenic	**-39068,18**
B1	Carbonisation	**-26939**
D	Benefits of re-use and recycling	**-398675,47**
D-energy	Exported energy	

Table 16: Building carbon assessment, case sustainable materials

Based on the results obtained, throughout the life of the building the total carbon handprint will be greater than the total carbon footprint: this means that the emissions caused by the production phase of the materials and the construction will be compensated (obviously in case of recycling and/or reuse of the materials).

Finally, the new graphs for emission levels in the case of replacement with sustainable conventional materials:

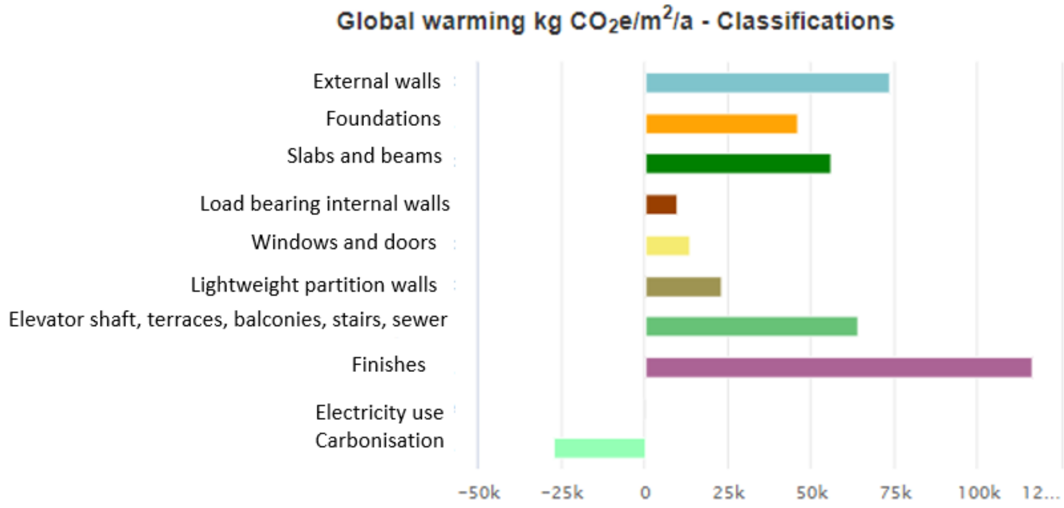

Figure 33: Impact of each section, case sustainable materials

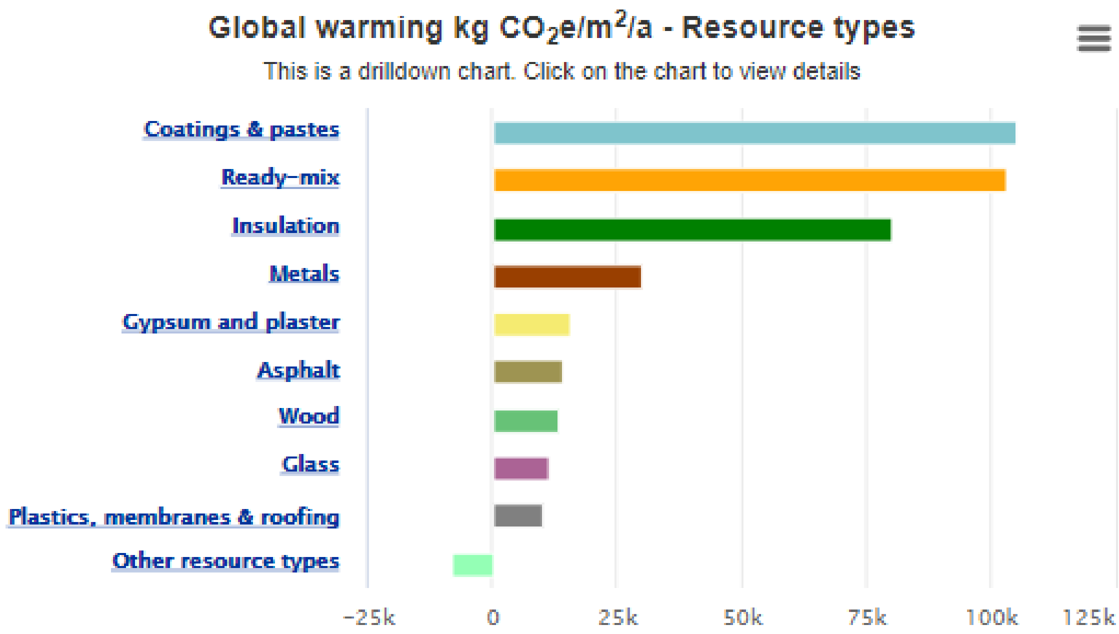

Figure 34: Impact of each material, case sustainable materials

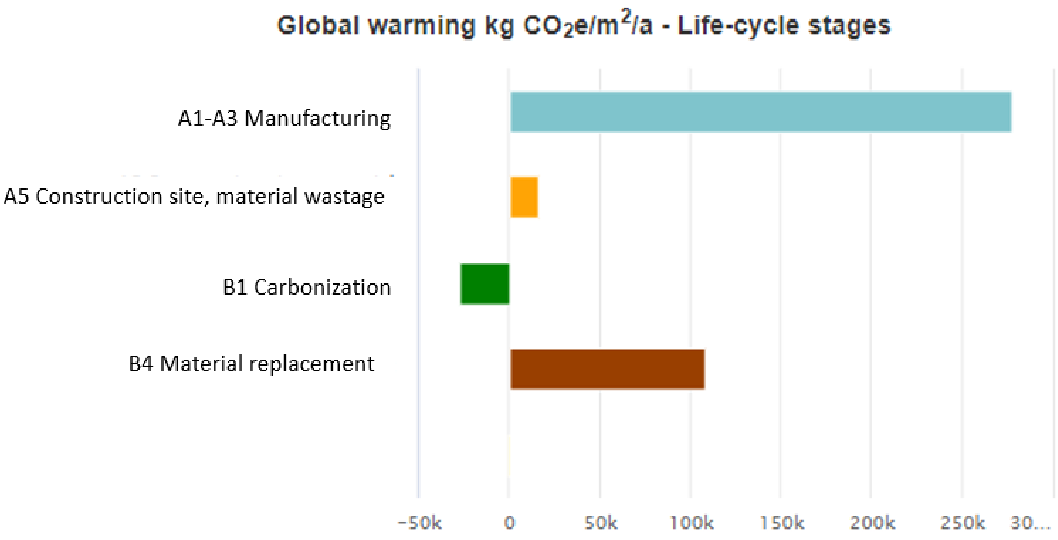

Figure 35: Impact of each process, case sustainable materials

5.2 NATURAL ALTERNATIVES

Regarding the use of natural materials, unfortunately it is not possible to perform a dimensioning and to obtain the real quantities of materials needed, due to the absence of structural schemes of the studied building.

However, a similar building studied by Alosio, Pasca, Tomasi and Frangiacomo was found in the literature in the scientific paper "Dynamic identification and model updating of an eight-storey CLT building", published by Engineering Structures in 2020: it is a building inside the campus of the Norwegian University of Life Science (NMBU) located in Ås, Norway, used as a residential building for students. The building has eight floors, a total height of 26,9 m and a rectangular floor plan (23,21 x 15,11 m), with a total area of the building of 2804,4 m^2, comparable to the area of the Pyry building, the subject of this thesis, which has a total area of 3085 m^2.

	Pyry	NMBU
Number of floors	6	8
Area (m^2)	3085	2804,4

Table 17: Buildings data

Figure 36: NMBU building

The NMBU building is built with Cross Laminated Timber (CLT), a material produced in the form of laminated timber panels that can be used for floors, walls, and roofing, in hybrid applications with materials such as concrete and steel, or as a component of prefabricated constructions to speed up construction times. Specifically, they are used:

- CLT wall panels, 3 or 5-layer, 90 - 180 mm;
- CLT floor panels, 5-layer, 180 - 220 mm;
- CLT roof panels, 5-layer, 200 mm;

for a total amount of used wood of 907,62 m^3. In addition, the quantity of connectors and other steel elements amounted to 8144,73 kg. The corresponding products used as input in One Click LCA are:

- "Cross laminated timber, rib panels 470 $\frac{kg}{m^3}$, 12% moisture content" produced by Stora Enso in Sweden, with an environmental impact of 51,9 kg of CO_2 emitted per m^3 of panel produced but a Biogenetic CO_2 storage of 211,58 kg of CO_2 per m^2 of material used in the structure;
- "Steel, rebar products (concrete reinforcement), scrap 100%" produced by Norsk Stal, in Norway (also used in the previous scenarios), with an emission of 0,33 kg of CO_2 produced per kg of steel used.

In this scenario, the results obtained are significantly better than the previous ones: the amount of CO_2 emissions due to the production and installation of materials for the construction of the building is 235 tonnes, with a corresponding social cost of €11771 (the best result so far was 403 tons). In this case there is a 76% reduction in emissions compared to the first value obtained.

Figure 37: Total carbon dioxide and social cost of carbon values, case natural materials

The table for the results of the different categories:

Section	Result category	Global warming kg CO2e/m2/a
A1-A5	Emission effects before use	**167060,6**
A1-A3	Manufacturing	**152380,73**
A4	Transport	
A5	Construction site - material wastage - materials	**14679,96**
A5-YM	New constuction site activities	
B3-B4,B6	Emission effects during operation	**68367,35**
B3-4	Energy consumption of repairs	
B4	Material replacement	**68367,35**
B6	Energy use	
C	Emission effects after use	
C1	Demolition site operations	
C2	Transport for further processing	
C3-4	Waste treatment and disposal	
A-C	Total carbon footprint (sum modules A-C)	**235428,04**
A-D	Total carbon handprint (sum modules A-D)	**-936420,17**
bio-CO2	Carbon storage, biogenic	**-361356,59**
B1	Carbonisation	
D	Benefits of re-use and recycling	**-575063,58**
D-energy	Exported energy	

Table 18: Building carbon assessment, case natural materials

In this scenario, the emissions due to the production, installation, and eventual replacement of materials during the life of the building are 235 tons of CO_2; however, over the years there will be a reabsorption of carbon dioxide equal to 936 tons, thanks to the properties of the natural materials used for the construction and the reuse of some products. Unlike the cases analysed previously, in this scenario there is no benefit due to carbonisation of cement products because they have not been used (except for foundations). Therefore, the result is very positive, as the building is able to absorb more CO_2 than was produced in the construction phase.

The materials that have the greatest impact are the laminated wood and the concrete used in the foundations, but their values are acceptable when compared to the previous cases.

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
1.	Cross laminated timber (CLT) rib panels ?	47 tons CO_2e	30.9 %
2.	Ready-mix concrete ?	16 tons CO_2e	10.3 %

Figure 38: Material impact, case natural materials

The following figure confirms that wood is the most impactful material due to the panel production process:

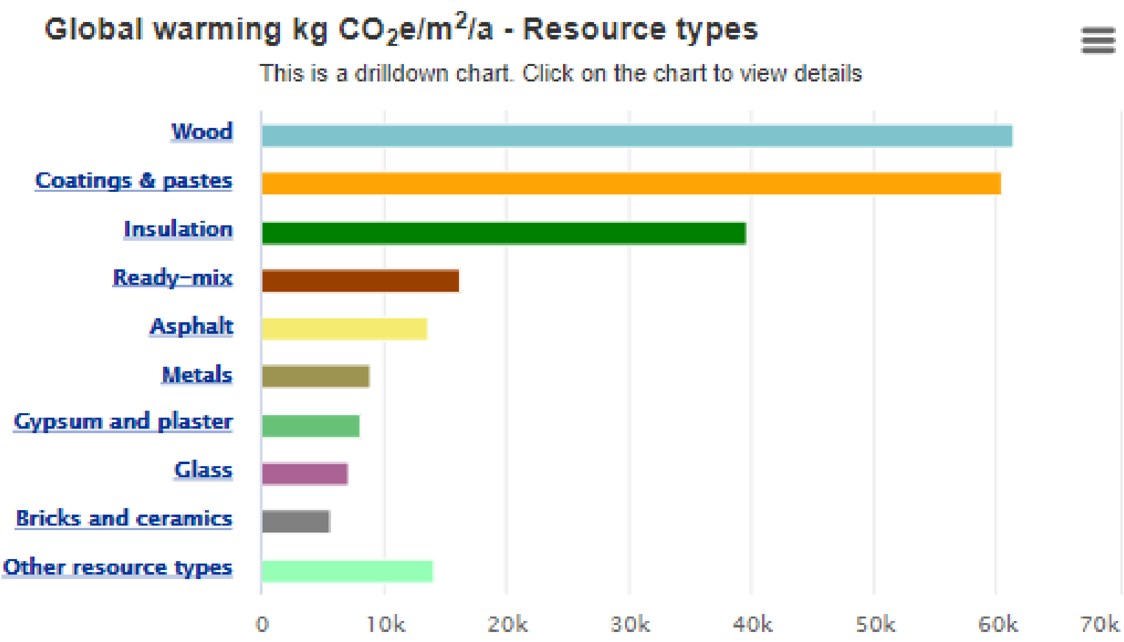

Figure 39: Impact of each material, case natural materials

A special note regarding insulation: mainly EPS panels produced by Finnfoam in Finland (L=0,031 $\frac{W}{mK}$, T: 85-800 mm, 17-20 $\frac{kg}{m^3}$) were used with a production impact of 5,19 kg of CO_2 per m^2 of material produced. A good substitute of natural origin is the "Rice straw insulation panel" (L=0,039 $\frac{W}{mK}$, 100 mm, 50 $\frac{kg}{m^3}$) produced by FBT Isolation in France, which provides a thermal resistance of 2,56 $\frac{m^2K}{W}$. This material has an impact due to its production process of 87 kg of CO_2 per m^2; however, thanks to biogenic CO_2 storage can reabsorb during its lifecycle 91,67 kg of CO_2 equivalent per m^2 of material used in the construction of the building. This substitution results in a total carbon dioxide emission of 276 tons (72% lower than the first case), slightly more than in the previous case, but with a reabsorption of 975 tons of CO_2 over the life of the building, which is similar to the previous positive value.

Below a summary table of the values obtained from the study:

Scenario	**Emissions (tons of CO_2)**	**Improvement (emissions savings)**
Materials from project	986	
Sustainable concrete and steel	520	-47%
All sustainable conventional materials	403	-59%
CLT	235	-76%
CLT + natural insulation	276	-72%

Table 19: Summary of values obtained and percentages of improvement

CONCLUSIONS

In this thesis work, a building was analysed, evaluating the carbon dioxide emissions released into the atmosphere due to the production and installation of its constituent materials, in order to make an optimal choice of materials to be used in construction in view of climate change mitigation.

The One Click LCA software was used which allows an immediate calculation of emissions and corresponding social cost, estimating a price of € 50 per ton of CO_2 produced.

Assuming a life expectancy of the building of 60 years, the input of the defined materials according to the project gives an amount of 986 tons of CO_2 produced, most of it coming from steel and concrete, key materials in modern construction.

Following the software's suggestions, steel and concrete were replaced with sustainable alternatives, resulting in 520 tons of CO_2 produced; then all other materials deemed too environmentally polluting were replaced, reducing the result to 403 tons of CO_2.

Finally, the concrete was replaced entirely by laminated timber panels (using the same amount of timber as in a similar building), resulting in 235 tons of CO_2 produced, due to the pre-use phase of the building, but 936 tons of CO_2 reabsorbed by the structure, thanks to the properties of the materials used, which trap carbon dioxide inside them.

The study showed that greater awareness and care in the choice of materials results in carbon dioxide emission savings of 47% to 76%, in the case of the building studied.

The One Click LCA software proved to be a good tool in this practice, simple and straightforward, allowing rapid changes even during the construction phase.

Buildings play a key role in society and have a huge impact on climate change, causing 40% of global emissions. By carrying out simple LCA analyses, paying attention to materials and construction techniques, it is possible to significantly lower the emissions produced by the construction sector.

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