BIO-BASED MATERIALS AND PREFABRICATED PRODUCTION PROCESSES:

GUIDELINES FOR THE EUROPEAN CONTEXT

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Master Thesis

Bio-Based materials and prefabricated production processes: Guidelines for the European context

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Abstract

English

Today's mainstream consumption and production patterns have led to a high quality of life in many parts of the world, but this has come at a high environmental price that is unsustainable and has led to climate change. In order to achieve a net-zero goal by 2050 a change in direction is essential.

The current construction sector is responsible for a large percentage of global energy consumption and energy-related CO_2 emissions; it presents a key opportunity for impactful change. While efforts to improve building efficiency have gained momentum, it is crucial to consider the whole-life-cycle emissions of buildings, and the concern over embodied energy and material efficiency will increasingly become a key aspect to address. Integrating bio-based solutions could have the potential of reducing embodied emissions as part of mitigation strategies. To fully leverage the potential of bio-based materials, mainstream prefabrication production processes must be integrated, enabling better choices on a larger scale.

The research methodology consists of conducting a comprehensive analysis and review of the scientific literature of the state-of-the-art in regards to the transition towards circularity and material efficiency and the use of bio-based materials within the European context. As a result, this thesis focuses on introducing guidelines with the primary objective of encouraging design-for-disassembly, waste reduction, and promoting reuse and recycling through the utilization of prefabricated bio-based elements and components.

The focus is to facilitate informed decision-making during construction and retrofit processes and provide a comprehensive understanding of the potential and contribution of bio-based solutions toward a transition to circularity and material efficiency, as well as efficiently performing envelopes. The specific objective of this research is to provide a set of guidelines that aid the use of bio-based building materials. By doing so, it aims to promote a more holistic approach as well as environmentally conscious decisions.

The work is divided into three parts. The first part explores the current environmental impacts of the building sector and its effects and contribution to climate change, with a specific focus on manufacturing processes of building materials and products. This first part identifies solutions and strategies that combine material substitution, bio-based alternatives, and prefabrication processes. It highlights potential liked to prefabrication at different degrees and identifies the gap within that is the material choice. The second part explores material substitution with bio-based materials, defining their potential and contribution towards envelope performance and comfort, circularity, waste reduction, and recycling potential. Subsequently, this develops in the guidelines that consist of the heart of the thesis and aim to guide and support all actors involved in construction and retrofit processes.

The third part is a result of an ongoing research project that sees the collaboration between the Politecnico di Torino, The Ne[s]t and the Club del Sole of the RE-TREE-T project: laboratory of innovative hospitality. This project chosen as a case study provides a possible application of the guidelines in order to assess material alternatives and optimization strategies.

In conclusion, this master's thesis highlights the urgent need for a change in consumption and production patterns to address the high environmental price tag associated with today's traditional practices in the building sector. This sector, with its significant energy consumption and CO_2 emissions, presents a crucial opportunity for transformative change.
Ultimately, the research presented in this thesis aims to provide information and facilitate the transition to circularity, material efficiency, and environmentally efficient envelopes of new and existing buildings in the context of the European Union.

Key words: Climate change mitigation, Embodied carbon, Circularity, Material efficiency, Material substitution, Bio-based building materials, prefabricated production processes.

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Abstract

Italian

Gli attuali modelli di consumo e produzione hanno determinato un notevole miglioramento della qualità della vita in molte parti del mondo. Tuttavia, questo progresso è stato raggiunto a un costo elevato e insostenibile per l'ambiente, con conseguenti cambiamenti climatici. Al fine di raggiungere l'ambizioso obiettivo di emissioni zero entro il 2050, è essenziale un drastico cambio di direzione.

L'attuale settore dell'edilizia è responsabile di una considerevole percentuale del consumo energetico globale e delle emissioni di CO_2 legate all'utilizzo dell'energia, e pertanto rappresenta un'opportunità chiave per un cambiamento di impatto. Nonostante gli sforzi volti a migliorare l'efficienza degli edifici abbiano guadagnato un *momentum*, è fondamentale considerare le emissioni nell'intero ciclo di vita degli edifici. La preoccupazione per l'energia incorporata e gli aspetti legati all'efficienza dei materiali diventeranno e stanno diventando sempre più cruciali e necessari da affrontare.

L'integrazione di soluzioni basate su materiali biologici potrebbe ridurre le emissioni incorporate come parte delle strategie di mitigazione. Per sfruttare il potenziale dei materiali biologici, è necessario rendere prodotti bio-based più reperibili e uniformi pertanto, integrare processi produttivi di prefabbricazione potrebbe favorire la loro adozione ad una scala più ampia.

La metodologia di ricerca si basa su un'analisi completa e una revisione della letteratura scientifica sullo stato dell'arte riguardante la transizione verso la circolarità e gli aspetti legati all'efficienza dei materiali, con un particolare focus sull'utilizzo dei materiali biologici nell'ambito europeo. Di conseguenza, questa tesi si concentra sulla formulazione di linee guida con l'obiettivo principale di promuovere la progettazione per il disassemblaggio, la riduzione dei rifiuti e la promozione del riuso e del riciclo attraverso l'impiego di elementi e componenti prefabbricati di origine biologica.

L'obiettivo è agevolare una presa di decisioni informata du-

rante i processi di costruzione e retrofitting, fornendo una comprensione esaustiva del potenziale e del contributo delle soluzioni biologiche contribuendo alla transizione verso la circolarità, l'efficienza dei materiali e l'ottimizzazione degli involucri edilizi. Lo scopo specifico di questa ricerca è quello di fornire una serie di linee guida per agevolare l'uso dei materiali da costruzione biologici, promuovendo così un approccio più olistico e decisioni consapevoli dal punto di vista ambientale.

Il lavoro è articolato in tre parti. La prima parte esamina gli attuali impatti ambientali del settore edilizio e il suo contributo ai cambiamenti climatici, con particolare attenzione ai processi produttivi dei materiali e dei prodotti da costruzione. Questa sezione identifica soluzioni e strategie che combinano la sostituzione dei materiali con alternative biologiche e l'utilizzo dei processi di prefabbricazione. Inoltre, mette in luce i vantaggi potenziali della prefabbricazione a vari livelli e individua la lacuna in cui si inserisce la scelta dei materiali.

La seconda parte esplora la sostituzione dei materiali convenzionali con quelli a base biologica, definendone il potenziale in termini di proprietà e comfort dell'involucro edilizio, di circolarità, di riduzione dei rifiuti e di opportunità di riciclo. Successivamente, queste considerazioni si sviluppano nelle linee guida, che costituiscono il cuore della tesi e si propongono di informare e supportare le scelte di tutti i diversi *stakeholders* coinvolti nei processi di costruzione e retrofitting.

La terza parte rappresenta il risultato di un progetto di ricerca in corso che coinvolge il Politecnico di Torino, The Ne[s]t e il Club del Sole del progetto RE-TREE-T: un laboratorio di ospitalità innovativa. Il caso studio scelto fornisce un'applicazione concreta delle linee guida, al fine di valutare alternative materiali e strategie di ottimizzazione.

In conclusione, questa tesi evidenzia l'urgente necessità di cambiare i modelli di consumo e produzione al fine di affrontare l'alto costo ambientale associato alle pratiche tradizionali nel settore edilizio. Questo settore, con il suo elevato consumo energetico e le emissioni di CO_2, rappresenta un'opportunità cruciale per un cambiamento trasformativo. In definitiva, la ricerca presentata in questa tesi mira a fornire informazioni e a agevolare la transizione verso la circolarità, l'efficienza dei materiali e gli involucri edilizi ecocompatibili per edifici nuovi ed esistenti all'interno dell'Unione Europea.

Parole chiave: Mitigazione dei cambiamenti climatici, Carbonio incorporato, circolarità, efficienza dei materiali, sostituzione dei materiali, materiali da costruzionebiogenici, processi di produzione prefabbricati.

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/ Introduction

"Precious natural materials can be over-farmed and excessively cultivated, resulting in extreme depletion of natural ecosystems and the increase of by-product pollutants. Designers are acknowledging that the Earth's natural assets are a shifting landscape and what is abundant today may not be in the future. In order to reap sustainably, designers need to be flexible and inventive, basing their practice on what is currently available".

Kate Franklin and Caroline Till
Radical Matter: Rethinking materials for a sustainable future

00.1 Thesis framework

Problem definition

Today's trends in consumption and production have resulted in improved quality of life worldwide. However, this progress has come at a significant environmental cost, leading to unsustainable conditions and contributing to the issue of climate change. To achieve the objective of reaching net-zero emissions by 2050, a change in direction is imperative.

The current construction sector is responsible for a large percentage of global energy consumption and energy-related CO_2 emissions; it presents a key opportunity for impactful change. While efforts to improve building efficiency have gained momentum, it is crucial to consider the whole-life-cycle emissions of buildings, and the concern over embodied energy and material efficiency is increasingly becoming a key aspect to address.

Research statements

Despite efforts to enhance building efficiency, the full environmental impact of construction processes, encompassing both operational and embodied energy. The integration of prefabrication practices presents a promising avenue for reducing embodied emissions and transitioning towards more environmentally sustainable practices. However, a possible gap in this

design strategy could be represented by material choice: prefabrication combined with materials substitution and specifically bio-based materials could further aid the transition.
This thesis seeks to investigate the incorporation of bio-based solutions and prefabrication strategies to encourage circularity and material efficiency in the European construction sector.

General objectives and questions

- Investigate the current environmental impacts of the construction sector and identify its contribution to climate change, with a focus on manufacturing processes of building materials and products.

-Explore the potential of bio-based materials as substitutes for traditional construction materials, examining their impact on material efficiency and circularity.

• What are the key environmental issues associated with traditional construction practices and materials manufacturing?

• What are the benefits and challenges associated with integrating bio-based materials into construction processes?

Specific objectives and questions

-Explore the potential of prefabrication as a mean to upscale the use of bio-based materials in the construction industry through understanding what is available on the market or is currently being studied and experimented as a future solution;

-Promote the use of bio-based building materials and develop comprehensive guidelines to support stakeholders in making informed decisions during construction and retrofit processes;

-Assess the potential environmental indicators and life cycle assessment related to bio-based materials and prefabricated components, aiding decision-making during the design phase.

• Can prefabrication processes be effectively integrated with bio-based materials to enable larger-scale adoption and better choices in sustainable construction and retrofitting?

• Are there bio-based alternatives that could be adopted?

• What are environmental benefits and concerns linked to bio-based building materials?

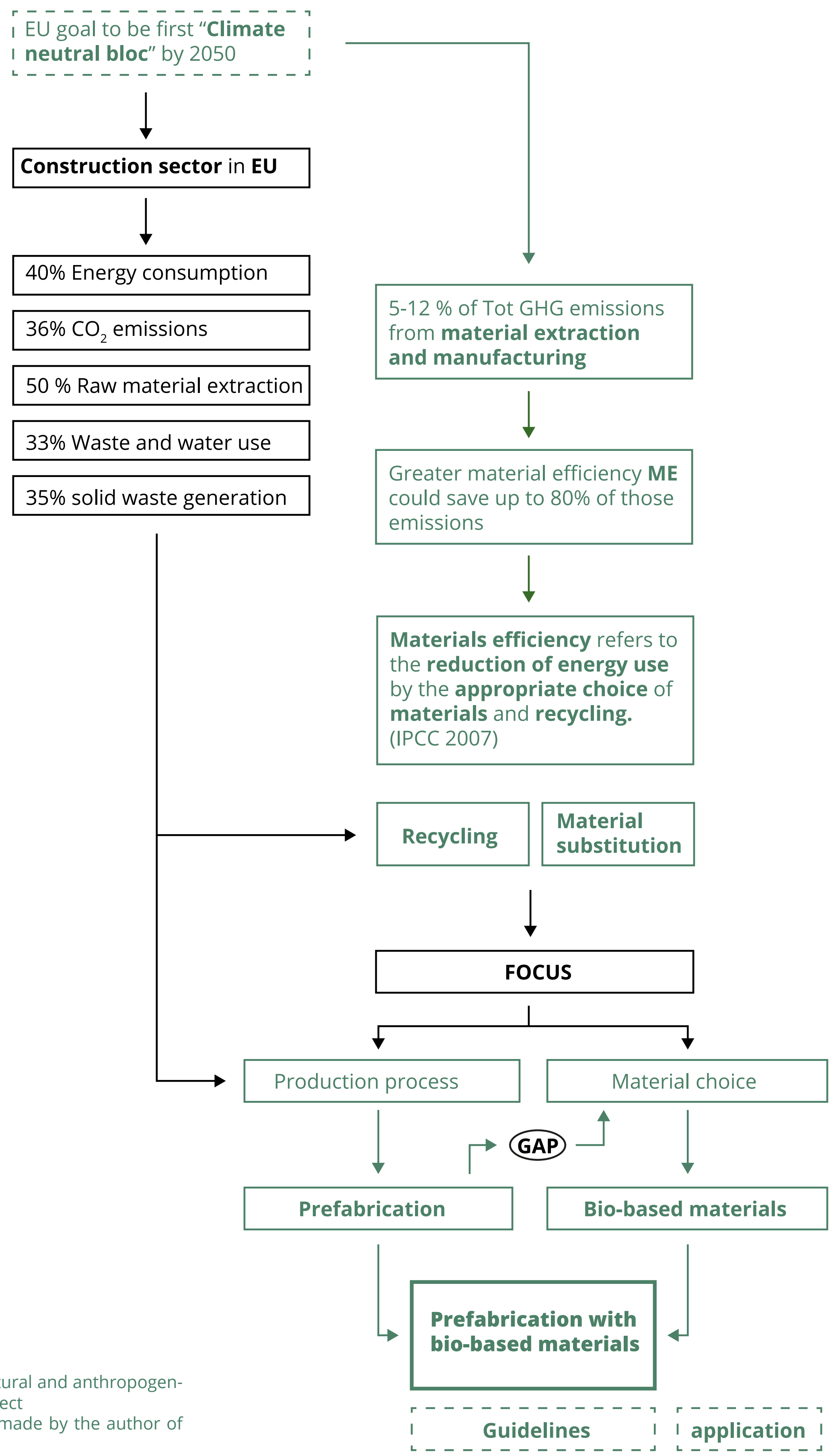

Figure 00.1.1: Natural and anthropogenic green-house effect
Source: Drawing made by the author of thesis

00.2 Methodological note

The methodology employed in this master's thesis entails a dual approach: a thorough analysis and review of scientific literature, books, articles, and publications, complemented by the practical application of the research through a case study. A detailed description of the tools utilized for information gathering can be found in the "Tool" section, located at the conclusion of this thesis.

In addition, at the end of each chapter, a "Reference and Resources" section is included to enhance the clarity and contextual understanding of the information presented.

Part One
To lay the foundation for the structure of this thesis, the initial section delved into the environmental impact of the building sector. It accomplished this by gathering information from a variety of sources, including reports primarily from the IPCC, BPIE, and EEA, alongside articles, papers, publications, and books. This comprehensive approach established the primary framework upon which the subsequent sections of the thesis were built.

Part Two
The research methodology for developing guidelines on bio-based materials and prefabrication employed a systematic approach. It included an extensive review of scientific papers, articles, books, and data sheets specific to relevant products.

The primary aim was to gather comprehensive and current information on bio-based building materials. This comprehensive review encompassed elements, components, projects, and best practices related to bio-based materials. Through this thorough literature review, the research aimed to establish a foundational knowledge base for understanding various aspects and potential applications of bio-based materials. Furthermore, the life cycle assessment of bio-based materials was conducted, relying on SimaPro software or referencing articles and papers.

At the end of the material "cards" is also provided a summary of qualitative and quantitative information regarding the materials.

Part Three
To gain insights into real-world implementations of bio-based materials and prefabrication practices, a careful selection of relevant case studies was conducted. The final case study chosen was the RE-TREE-T project, serving as a practical illustration of potential applications and guidelines' utilization while defining optimization strategies.

The site survey and construction activities for the chosen case study occurred from July 26th to July 30th, 2023, in Lido di Spina, Comacchio (FE) - Italy. During this period, on-site assembly procedures were meticulously observed and documented in a *Report di cantiere*. Additionally, as a vital component of the research project, a weather station was installed to collect micro-climatic data during the same time frame.

00.3 Abbreviations and Glossary

EU European Union

IPCC Intergovernmental Panel on Climate Change

EEA European Environment Agency

BPIE Buildings Performance Institute Europe

GHG greenhouse gas

GWP Global warming potential

EC Embodied Carbon

ME Material efficiency

LCA Life cycle assessment

LCIA Life cycle impact assessment

LCT Life cycle thinking

LCD Life cycle design

WLC Whole life carbon

DfMAD Design for manufacturing and assembly disassembly

GREEN HOUSE GASES: "A gas that contributes to the natural greenhouse effect. The Kyoto Protocol covers a basket of six greenhouse gases (GHGs) produced by human activities: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride. Annex I Parties' emissions of these gases taken together are to be measured in terms of carbon dioxide equivalents on the basis of the gases' global warming potential. An important natural GHG that is not covered by the protocol is water vapour." (EEA Glossary)

GLOBAL WARMING POTENTIAL: "Global Warming Potentials (GWP) are calculated as the ratio of the radiative forcing of one kilogramme greenhouse gas emitted to the atmosphere to that from one kilogramme CO2 over a period of time (e.g., 100 years)". (IPCC 2006)

WHOLE-LIFE CARBON: "Carbon emissions resulting from the materials, construction and use of a building over its entire life, including its demolition and disposal. Other terms used are life-cycle carbon or cradle-to-grave carbon." (BPIE 2021)

EMBODIED CARBON: "Emissions associated with energy consumption and chemical processes during the extraction, manufacture, transportation, assembly, replacement and deconstruction." (BPIE 2021)

CARBON FOOTPRINT: "Life cycle emissions of greenhouse gases (GHGs) of final consumption, expressed in tonnes of CO2 -equivalents. Hence, this includes non-CO 2 greenhouse gases, such as CH4 or N 2 O, but does not cover greenhouse gases related to land use change." (CREEA 2015)

CO_2 -eq.: "Measure to express the emission of different greenhouse gases in one single unit, i.e., the global warming potential of a tonne of CO_2." (CREEA 2015)

BIOGENIC CARBON: **"**Biogenic carbon. Carbon derived from biogenic (plant or animal) sources excluding fossil carbon." (IPCC, 2006).

EMBODIED ENERGY: "Energy used to manufacture products all through the process of mining or harvesting the raw materials, refining, processing, and various stages of transport, to the finished product at the factory gate." (Bjørn Berge 2009)

OPERATIONAL ENERGY: "Emissions associated with energy consumption while the building is occupied, e.g. heating, cooling, lighting and appliances." (BPIE 2021)

END-OF-LIFE CARBON: "Emissions associated with deconstruction/ demolition, transport from site, waste processing and disposal of a building or infrastructure." (BPIE 2021)

LIFE CYCLE: "Consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to the final disposal." (EEA Glossary)

LIFE CYCLE ASSESSMENT: "Life-cycle assessment (LCA) is a process of evaluating the effects that a product has on the environment over the entire period of its life thereby increasing resource-use efficiency and decreasing liabilities. It can be used to study the environmental impact of either a product or the function the product is designed to perform. LCA is commonly referred to as a "cradle-to-grave" analysis. LCA's key elements are: (1) identify and quantify the environmental loads involved; e.g. the energy and raw materials consumed, the emissions and wastes generated; (2) evaluate the potential environmental impacts of these loads; and (3) assess the options available for reducing these environmental impacts." (EEA Glossary)

LIFE CYCLE IMPACT ASSESSMENT: "A scientific technique for assessing the potential environmental impacts of industrial systems and their associated products. This technique is 'cradle-to-grave' in scope, meaning that it considers impacts at each stage of a product's life-cycle, from the time natural resources are extracted from the ground and processed through each subsequent stage of manufacturing, transportation, product use, and ultimately, disposal." (EEA Glossary) - ISO 14044 (2006).

MATERIAL EFFICIENCY: "Refers to the reduction of energy use by appropriate choice of materials and recycling." (IPCC 2007).

CARBON SEQUESTRATION: the long-term storage of carbon in plants, soils, geologic formations, and the ocean. Carbon sequestration occurs both naturally and as a result of anthropogenic activities and typically refers to the storage of carbon that has the immediate potential to become carbon dioxide gas. (Britannica,2023)

BY-PRODUCT: A by-product is defined as an incidental product deriving from a manufacturing process or chemical reaction, and not the primary product or service being produced. A by-product can be useful and marketable, or it can have negative ecological consequences. (European Commission, 2023).

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Part One

"Mitigation and adaptation can lead to synergies and trade-offs with sustainable development. Accelerated and equitable mitigation and adaptation bring benefits from avoiding damages from climate change and are critical to achieving sustainable development. Climate resilient development pathways are progressively constrained by every increment of further warming. There is a rapidly closing window of opportunity to secure a liveable and sustainable future for all."

IPCC, 2023
Climate Change 2023: Synthesis Report.
Contribution of Working Groups I, II and III to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

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Chapter One:

Climate change and the building sector, material efficiency and circularity

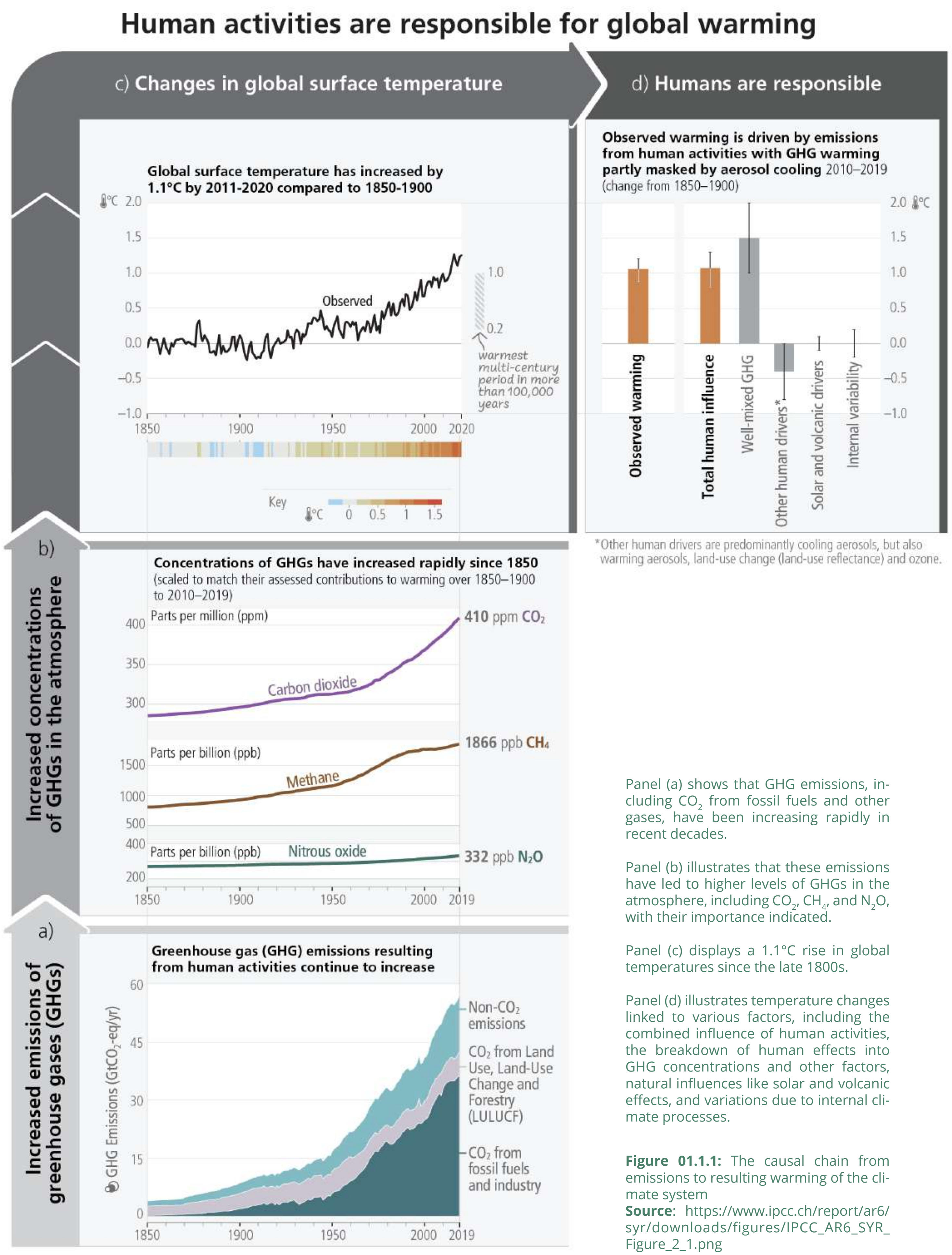
01.1 Climate change, future scenarios

Climate. Climate, as defined by the IPCC (Intergovernmental Panel on Climate Change), the main international organization for assessing the climate crisis, is "the average weather, or more precisely, the statistical description in terms of the mean and variability of relevant quantities such as temperature, precipitation, and wind, over a period of time" (IPCC 2007).

What individuals need to realize is that climate is not something intangible to us, "**Climate is everything**", it affects every aspect of our lives, from food to water security, agriculture, and ecosystems, from the economy, society and directly to human health.

Climate change as defined by the UN (United Nations) refers to shifts in temperatures and weather patterns that persist for an extended period. As a phenomenon, it can be both natural or anthropogenic factors.

"Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020. Global greenhouse gas emissions have continued to increase over 2010-2019, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles, and patterns of consumption and production across regions, between and within countries, and between individuals" (IPCC 2023).



Panel (a) shows that GHG emissions, including CO_2 from fossil fuels and other gases, have been increasing rapidly in recent decades.

Panel (b) illustrates that these emissions have led to higher levels of GHGs in the atmosphere, including CO_2, CH_4, and N_2O, with their importance indicated.

Panel (c) displays a 1.1°C rise in global temperatures since the late 1800s.

Panel (d) illustrates temperature changes linked to various factors, including the combined influence of human activities, the breakdown of human effects into GHG concentrations and other factors, natural influences like solar and volcanic effects, and variations due to internal climate processes.

Figure 01.1.1: The causal chain from emissions to resulting warming of the climate system
Source: https://www.ipcc.ch/report/ar6/syr/downloads/figures/IPCC_AR6_SYR_Figure_2_1.png

The opening lines and data outlined previously in the latest report on climate change from the IPCC state a worrying situation spread across the globe.

One important aspect of contrasting climate change is to make it more tangible and the key for that is understanding what are the main factors causing this phenomenon.

According to the IPCC, the main consequence of climate change and global warming is the greenhouse effect, and these phenomenons are linked to green-house-gasses emissions amongst other things. The greenhouse effect can be described as an increase in the average temperatures of the Earth's surface, atmosphere, and oceans. This happens because the Earth's energy, once radiated, transforms into heat. This heat is then absorbed and trapped by the greenhouse gases present in the atmosphere, leading to a reduction in the usual heat dissipation and consequently higher temperatures. (Calkins 2009). This effect is both natural and man-made but the IPCC concludes that “Most of the observed increase in mid-20th century is very likely due to the observed increase in anthropogenic green-house-gas concentration” (IPCC, 2007b). What are the gasses causing the green-house effect?

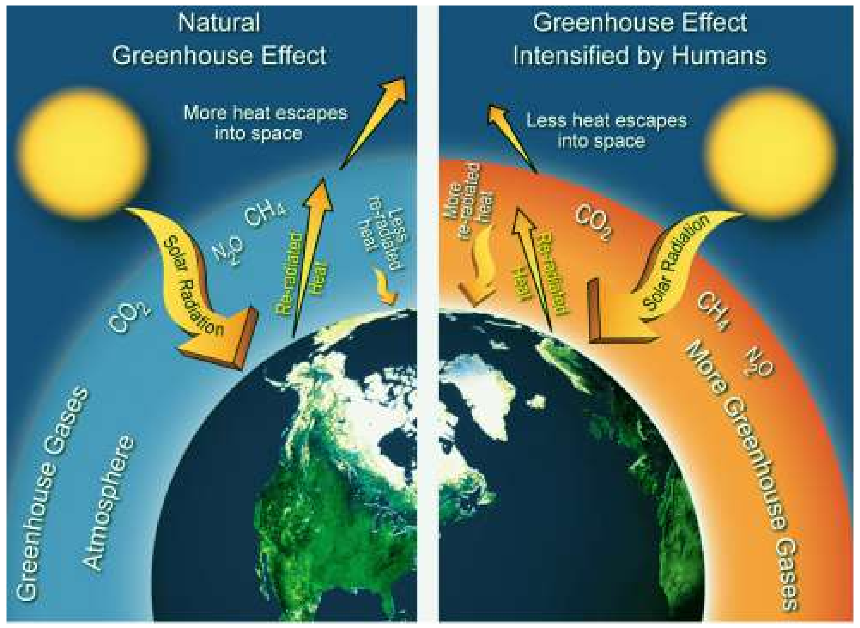


Figure 01.1.2: Natural and anthropogenic green-house effect
Source: https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/faq-1-3-figure-1.html

The Kyoto protocol[1] encompasses the six greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N2O), and the so-called F-gases (hydrofluorocarbons and perfluorocarbons) and sulphur hexafluoride (SF_6). Each gas is weighted by its global warming potential and aggregated to give total greenhouse gas emissions in CO_2 equivalents (Eurostat, 2023).

The effect of these GHGs on the environment is evaluated using the Global Warming Potential (GWP) [measured in Kg CO_2 eq.]. This index measures how much a gas can contribute to the greenhouse effect compared to an equivalent weight of carbon dioxide over a specific period, like 100 years.
The reason behind the reference to carbon dioxide (CO_2) is be-

[1] The Kyoto Protocol was an international treaty , published in 1992 in Kyoto Japan, that operationalized the United Nations Framework Convention on Climate Change by committing industrialized countries and economies in transition to limit and reduce greenhouse gases (GHG) emissions in accordance with agreed individual targets.

Full document at: https://unfccc.int/resource/docs/convkp/kpeng.pdf

cause it is the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance. (IPCC, 2018). It is a naturally occurring gas, but it polluting potential is usually referred for the resulting by-product of burning fossil fuels such as oil, gas and coal, or of burning biomass, and of industrial processes (e.g., cement production). Being the reference gas against which other GHGs are measured and therefore it has a global warming potential (GWP) of 1 (IPCC, 2018).
The concentration of these climate-altering gasses varies in percentage but it is mainly due to the six GHG reported in the table below [Figure 01.1.3].

Gas	Qualifying sources	Emission trends since the late 1980s	Lifetime (years)	% GHG 1990, GWP–100
Carbon dioxide (CO_2)	Fossil fuel burning, cement	EU static, increases other OECD, sharp decline EITs	Variable, with dominant component c. 100 years	1
Methane (CH_4)	Rice, cattle, biomass burning and decay, fossil fuel production	Decline in most countries (big increase only in Canada, USA, Norway)	12.2 ± 3	21
Nitrous oxide (N_2O)	Fertilizers, fossil fuel burning, land conversion to agriculture	Varies, small increases in many countries, decline expected before 2000, decline in EITs	120	310
Hydrofluorocarbons (HFCs)	Industry, refrigerants	Fast-rising emissions due to substitution for CFCs	1.5–264, HFC 134a (most common) is 14.6	140–11,700; HFC 134a (most common) is 1,300
Perfluorocarbons (PFCs)	Industry, aluminium, electronic and electrical industries, fire fighting, solvents	Static	2,600–50,000	Average about 6,770; CF_4 is 6,500; C_2F6 is 9,200
Sulphur hexafluoride (SF_6	Electronic and electrical industries, insulation	Increase in most countries, further rise expected	3,200	23,900

Figure 01.1.3: Green-house-gases Kyoto Protocol
Source: Grubb, Michael. (2003). The Economics of the Kyoto Protocol. World Economics. 4. 143-189. ; IPCC , SAR WG I, Table 2.9, p. 121

What are the main sources of anthropogenic emissions of GHG?

The three principal anthropogenic sources of these climate-altering-gases are energy production, chemical industry and waste cycles. Of these, the energy related sources are dominant because they stem mainly from fossil fuel combustion in power plants and the transport sector (Bjørn 2009).

"Human-caused climate change is already affecting many weather and climate extremes in every region across the globe." (IPCC 2023).

The main consequences result in increase in agricultural and ecological drought, increase in flooding and fire weather, increase in heavy precipitations, glacier retreat and global sea level rise. All these affect *us* on a day-to-day basis more than

we realise, the concept of widespread and substantial impacts and related losses and damages attributed to climate change is very well summarized by the IPCC in the figure below [Figure 01.1.4].

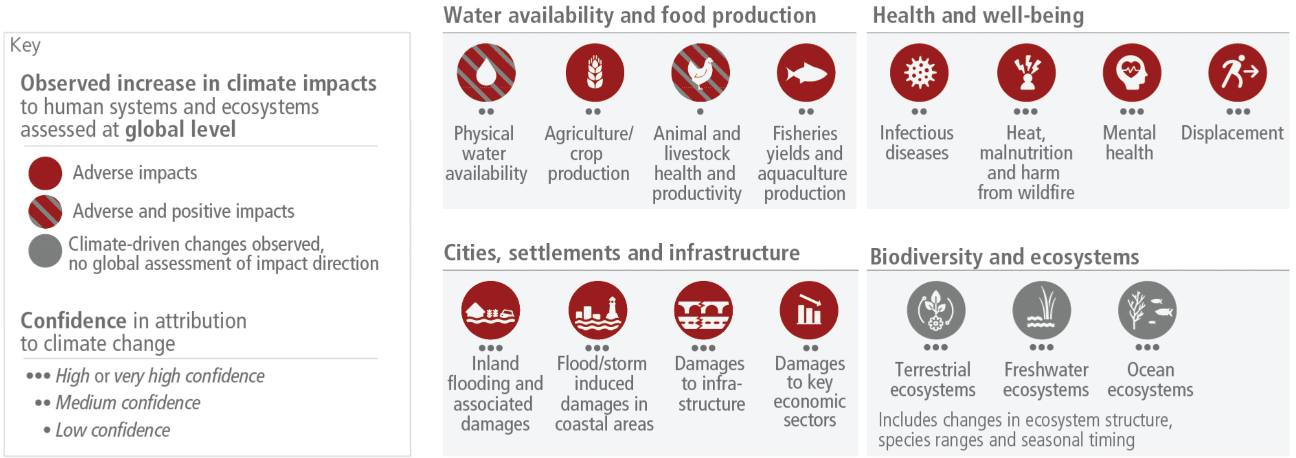


Figure 01.1.4: Observed widespread and substantial impacts and related losses and damages attributed to climate change
Source: IPCC (Intergovernmental Panel on Climate Change) AR6 Synthesis Report: Climate Change 2023.

"With every increment of global warming, regional changes in mean climate extremes become more widespread and pronounced" (IPCC 2023).

What are environmental concerns?

Environmental concerns can be evaluated by environmental impacts categories (midpoints), that could be grouped in three main typologies: **ecosystems, resources** and **human health (endpoints)**.

Ecosystems

Global warming
Green-house-gasses as mentioned above in the first paragraph are the main cause of the green-house effect resulting in one type of climate change which is global warming.
It is measured with the Global Warming Potential (GWP) [Kg CO^2 eq.]

The difference between CO_2 and CO_2eq. lies in the fact that CO^2 specifically refers to carbon dioxide emissions, whereas CO^2eq, or carbon dioxide equivalent, is a measurement that goes beyond just carbon dioxide (CO_2) emissions. It considers other greenhouse gases as well as their global warming potential (GWP). This approach offers a standardized way to compare how different green-house-gases contribute to warming in comparison to CO_2 and their overall impact on climate change.

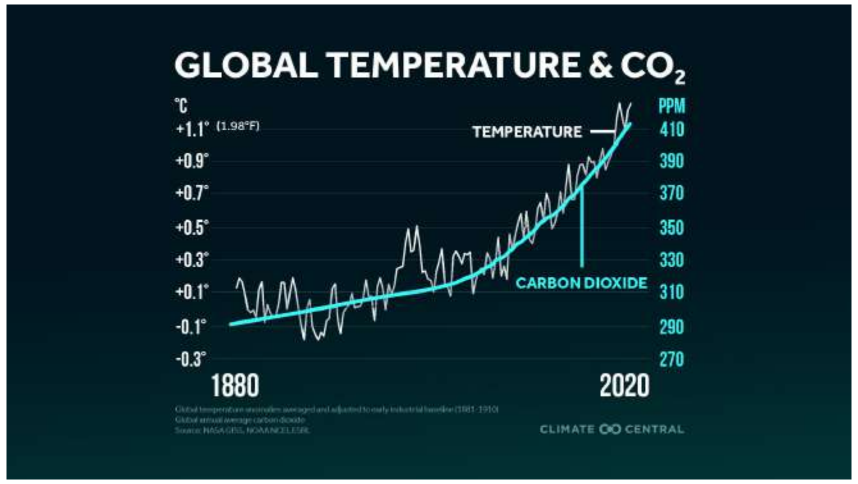


Figure 01.1.5: Global Temperature and CO_2 linkage
Source: https://www.climatecentral.org/climate-matters/yearly-carbon-dioxide-peak

Photochemical smog
Photochemical smog is a consequence of pollutants that emerge when nitrogen oxides and volatile organic compounds (VOCs) interact with sunlight. This reaction leads to the production of ozone and secondary pollutants, ultimately causing a brown haze known as brown photochemical smog that envelops urban areas. This phenomenon is more prevalent during the summer due to increased sunlight. Its assessment relies on the *Photochemical Ozone Creation Potential* (POCP) [expressed in Kg $C2H_4$ eq.], a metric designed to measure how much a human-made substance contributes to the development of photochemical smog compared to the effect caused by an equivalent weight of ethylene ($C2H_4$).

Ozone depletion
The Ozone is the barrier layer of the stratosphere that prevents harmful ultraviolet radiation to reach the earth. Ozone depletion refers to attenuation of this barrier caused by increase of substances, mainly chlorofluorocarbons (CFC), that consequently sees an increase of UV rays with harmful impact to human health, plants, water, soil and animals.
It is measured by the *Ozone Depletion Potential* (ODP) [Kg CFC-11 eq.], this can be defined as the potential contribution that a substance of anthropic origin has towards reduction of the ozone layer, compared to that caused by same weight of trichlorofluoromethane (CFC-11), fluid commonly used as a refrigerant fluid.

Acidification of soil and water
Acidification occurs in water and soils as acidifying gases, mainly sulphur oxide and nitrogen oxide compounds, dissolve in water or cling to soil particles. These polluting compounds reach ecosystems mainly through acid rain caused by emissions of sulphur and nitrogen deriving from fossil fuel combustion. Acid rain causes acidification of water bodies lowering pH and causing damage to aquatic ecosystems, and in soil by mobilizing toxins and leaching essentials nutrients and minerals with negative effects to vegetation, animals and humans.
It is measured by the *Acidification Potential* (AP) [Kg SO_2 eq.], this estimates the potential contribution that an atmospheric gas causes acidification, then that caused by the same weight of dioxide sulphur dioxide (SO_2), primarily caused by fossil fuel combustion.

Habitat alteration
Habitat alteration occurs when human activities change plants and animals in an area. This is connected to practices like mining raw materials (e.g., making construction products). It can also happen due to the release of waste into the environment—air, soil, or water—during different industrial processes. As a result, ecosystems experience shifts, and there's a potential decrease in biodiversity.

Loss of biodiversity
As a result of climate change, overexploitation of resources, waste cycles and air, soil, and water pollution ecosystems all over the world have suffered from a loss in the variability or biological diversity of living organisms. As a result, the stability of ecosystems has been compromised threatening their complex balance.

Eutrophication
Eutrophication, also known as Nitrification, is the phenomenon through which a water body or soil becomes enriched with nutrients like nitrogen and phosphorus, leading to excessive plant growth. While this process occurs naturally, human activities expedite its occurrence. The sources of these pollutants are primarily fertilizers employed in agriculture, sewage discharges, and industrial wastewater. In aquatic environments, eutrophication is evident through uncontrolled growth of algae and phytoplankton, often resulting in *blooms*.

It is measured by the *Eutrophication Potential* (EP) [Kg NO_3 eq.) which estimates the potential contribution that a substance of anthropic origin causes eutrophication, i.e. growth of biomass, compared to that caused by the same weight of nitrate or phosphate.

Ecological toxicity
Ecological toxicity refers to the release of toxic substances in water, air or soil that impact ecosystems, cause loss of biodiversity, and are harmful to humans, animals and plants. Toxic materials are mainly by-products of manufacturing processes, fossil fuel combustion, and toxic pesticides.

It is measured by the *Eco-Toxicity Potential* (ET) that estimates the potential effect on ecosystems of a substance as a volume in m3 of water, air or soil, in which the substance would have to be diluted in order to reach a level of concentration that does not lead to any kind of eco-toxic effect.

Resources

Abiotic Fossil Fuel Depletion
As of today, fossil fuels are considered to be the main source of energy in the world. They are considered non-renewable

resources because they are being extracted at a faster rate than the time they take to renew (which is considered to take millions of years). In the construction industry fossil fuels are often used to fuel vehicles for extraction, transportation, construction and maintenance; to produce heat in industrial processes; to power machinery; for electricity; lastly to produce plastic-based building materials (such as insulation).

This phenomenon can be assessed by the *Abiotic Depletion Potential* (ADP) [kg Sb eq.]

$$\text{abiotic depletion} = \sum_i ADP_i \times m_i$$

$$ADP_i = \frac{DR_i/(R_i)^2}{DR_{ref}/\left(R_{ref}\right)^2}$$

where,

ADP_i: abiotic depletion potential of resource i (kg antimony equivalents/kg of resource i);
m_i: quantity of resource i extracted (kg);
R_i: ultimate reserve of resource i (kg);
DR_i: extraction rate of resource i ($kg \cdot yr^{-1}$) (regeneration is assumed to be zero);
R_{ref}: ultimate reserve of the reference resource, antimony (kg);
DR_{ref}: extraction rate of the reference resource, Rref ($kg \cdot yr^{-1}$).

Figure 01.1.6: Abiotic Depletion Potential (ADP) [kg Sb eq.] calculation
Source: van Oers, L., & Guinée, J. (2016). The Abiotic Depletion Potential: Background, Updates, and Future. Resources, 5(1), 16. MDPI AG. Retrieved from http://dx.doi.org/10.3390/resources5010016

Deforestation, desertification and soil erosion
The world has lost one-third of its forest (Ritchie and Roser, 2021).
"Deforestation and forest degradation continue to take place at alarming rates, which contributes significantly to the ongoing loss of biodiversity" (UN, 2020). Forest account for a big share of terrestrial biodiversity (FAO, 2023). Forests are essential to mitigate climate change as they largely contribute to carbon dioxide sequestration, erosion control, and regulation of the hydrological cycle. Deforestation causes soil erosion, resulting in loss of topsoil and sedimentation in water bodies (Calkins, 2009). Deforestation and forest degradation are driven mainly by agricultural expansion, mining, new construction of buildings and roads, and when trees are harvested for timber and for fuel.

"Year-to-year data on forest change comes with several issues: either data at this resolution is not available, or year-to-year changes can be highly variable." Because of this, data outlets, such as the UN Food and Agriculture Organization (FAO), typically combine yearly losses into averages spanning five-year or ten-year intervals (Ritchie and Roser, 2021).

Water resource depletion
Water resource depletion refers to the overexploitation of water at a rate that exceeds groundwater reserves and prevents aquifer recharge. In the production process of construction materials water plays both as input and output in the form of effluent waste, and this reduces the water body because of pollution. Water depletion ultimately decreases availability for

water consumption as well as for plants and animals.

Human health

Human toxicity
When toxic materials are realised into air, water, and soil and exposed to humans they can have a negative effect on their health. During the whole-file-cycle of construction materials many toxic substances come as by-products, resulting in diseases and death.
It is measured by the *Human Toxicity Potential* (HTP) [Kg 1,4 DCB eq.] which estimates the potential effect on human health of a toxic substance present in the environment compared to that caused by the same weight of 1,4 dichlorobenzene (1,4 DCB).

Ultimately all environmental concerns are linked to human health, because as we are part of all different ecosystems, when these are threatened (e.g. the air we breathe and air pollution, the water we drink and water depletion or acidification etc.) we too suffer and have negative effects.

"The scientific evidence is unequivocal: climate change is a threat to human well-being and the health of the planet. Any further delay in concerted global action will miss a brief and rapidly closing window to secure a liveable future," Hans-Otto Pörtner[2].

The literature supports that climate change is one very much real, two human-caused, and three *our* biggest threat is very substantial, so finding solutions is of the utmost importance.

Strategies towards reducing the advancement of climate change have been at the centre of debate for many decades now. In 2015 with the COP21 and the **Paris Agreement**[3] the participants stated that climate change is inevitable but efforts to contrast it and achieve **sustainability goals**[4] in particular keep global temperature below 2° C compared to pre-industrial levels and continue efforts to limit it to 1.5° C, and reducing the peak of GHG as much as possible in order to achieve **carbon neutrality** are necessary.

Climate-actions are aimed towards two **pathways**:

Mitigation: "An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases" (IPCC, 2001a).

Adaptation: "Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities " (IPCC, 2001a).

Both approaches are essential in order to avert reaching the irreversible tipping point and to observe a significant reversal in patterns. Simultaneously, there needs to be a fundamental

[2] Prof. Dr. Hans-Otto Pörtner is a physiologist and marine biologist performing research at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven

[3] The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015. It entered into force on 4 November 2016. Full document at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[4] The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries - developed and developing - in a global partnership. Full document at: https://sdgs.un.org/2030agenda

shift in global consumption and production behaviours for international climate policies to be effectively put into practice. As indicated by the United Nations (UN) under the 12th sustainable development goal, unsustainable consumption and production practices are the fundamental drivers behind the threefold planetary challenges of climate change, biodiversity decline, and pollution. These challenges, along with the associated environmental deterioration, threaten human well-being and the achievement of the Sustainable Development Goals (UN 2015).

To acknowledge the troublesome situation, we face globally the Global Footprint Network[5] hosts and calculates the **Earth Overshoot Day.** "This day marks the date when humanity's demand for ecological resources and services in a given year exceeds what Earth can regenerate in that year" (Global Footprint Network, 2023). The deficit described in the figure 01.1.7 (and that of previous years) by liquidating stocks of ecological resources and accumulating waste, primarily carbon dioxide in the atmosphere (Global Footprint Network, 2023).

[5] The Global Footprint Network is an international research organization that provides decision-makers with a menu of tools to help the human economy operate within Earth's ecological limits. More information at: https://www.footprintnetwork.org/

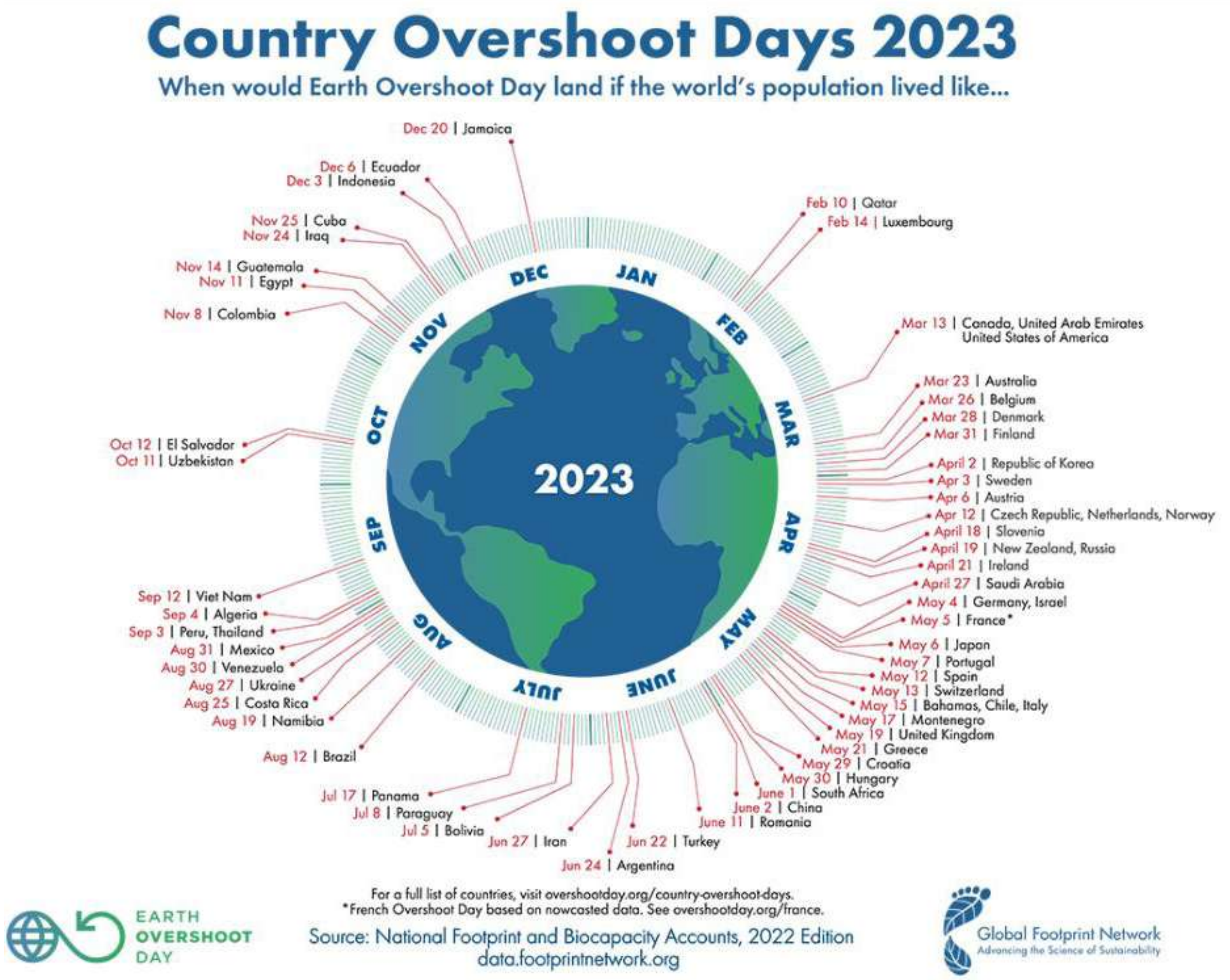


Figure 01.1.7: Overshoot day in the world in 2023
Source: https://www.overshootday.org/newsroom/country-overshoot-days/

While adaptation pathways can reduce impacts of climate change, they can present limits towards their effectiveness according to the possibility of greater magnitude and rates of climate change (IPCC, 2014). On a more long-term perspective, however, immediate adaptation actions will enhance the future options and preparedness of people worldwide. When talking about mitigation pathways, there are multiple actions that are likely to limit warming to below 2°C relative to pre-industrial levels, but these would require substantial emissions reductions over the next few decades and near zero emissions of CO_2 and other greenhouse gases by the end of the century. Implementing these reductions could comprise substantial technological, economic, and social challenges (IPCC, 2014).

“Climate change mitigation and adaptation, while simultaneously allowing for economic development, improving the well-being of all people and ensuring social justice and equality and protecting ecosystems, seems to be the largest challenge in the history of mankind. So far, the efforts to address growing environmental and human problems through technological solutions and policy measures have been largely outpaced by growing population and increasing consumption. It is becoming increasingly clear that consumption – the demand for goods and services – needs attention alongside the production of goods and services. The current patterns and levels of consumption at all levels, by states (public procurement), businesses (private purchasing) and households, are unsustainable” (Oksana Mont, 2014).

Emission reductions has to translated at the consumption level. The possibility of a change in direction could be proven, for example, by a reverse in trends of CO_2 emissions from energy combustion and industrial processes from 2019, 36.1 Gt CO_2 to 34.2 Gt CO_2 in 2020 (IEA 2023) caused by heavy restrictions in almost every industry during the global pandemic of COVID-19 and a total halt of daily lives of consumers word wide.

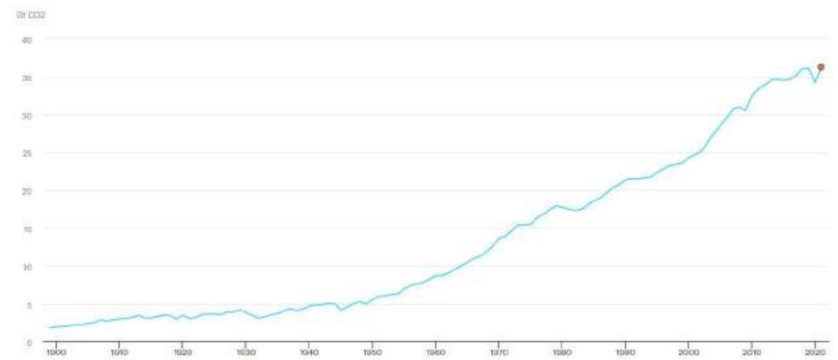


Figure 01.1.8: CO_2 emissions from energy combustion and industrial processes, 1900-2021
Source: IEA https://www.iea.org/data-and-statistics/charts/co2-emissions-from-energy-combustion-and-industrial-processes-1900-2021

This proves that if individuals, industries and governments, work as a collective in a synergic way changes can lead to effective results. So, at a global level the choices made from now onwards should aim towards climate actions because these will directly determine all future scenarios.

Adaptation and mitigation have to evolve as complementary strategies in order to reduce and manage risks linked to climate change. A substantial reduction in emissions over the next few decades could reduce climate risks and increase prospects of adaptation, while reducing the costs and challenges of mitigation on the long-term and also contributing to climate-resilient pathways for a more sustainable development (IPCC, 2014).

But what are **future scenarios**?
The IPCC describes scenarios as follows:

"In climate change research, scenarios describe plausible trajectories of different aspects of the future that are constructed to investigate the potential consequences of anthropogenic climate change. Scenarios represent many of the major driving forces - including processes, impacts (physical, ecological, and socioeconomic), and potential responses that are important for informing climate change policy. They are used to hand off information from one area of research to another (e.g., from research on energy systems and greenhouse gas emissions to climate modelling). They are also used to explore the implications of climate change for decision making (e.g., exploring whether plans to develop water management infrastructure are robust to a range of uncertain future climate conditions). The goal of working with scenarios is not to predict the future but to better understand uncertainties and alternative futures, in order to consider how robust different decisions or options may be under a wide range of possible futures" (IPCC, 2014)[7].

[7] IPCC Scenario Process for AR5, Full document at: https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf

To simplify scenarios can be described as alternative images of how the future might unfold. These consist of a valuable tool with which is possible to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties. Future scenarios are key to climate change analysis and the assessment of impacts, adaptation, and mitigation solutions.

There are many climate modelling teams in the world and in order to compare studies, in 1992 the IPCC published the first set of climate change scenarios, called IS92. Subsequently in the year 2000 they released a second generation of projections, referred to as the Special Report on Emissions Scenarios (SRES). Finally, in 2007, the same IPCC introduced the Representative Concentration Pathways (RCPs) and these are still in use today.

RCPs, to understand in simple words, determine how much anthropogenic green-house-gases concentration in the atmosphere could change according to **four different paths**. They include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5) (IPCC, 2014).

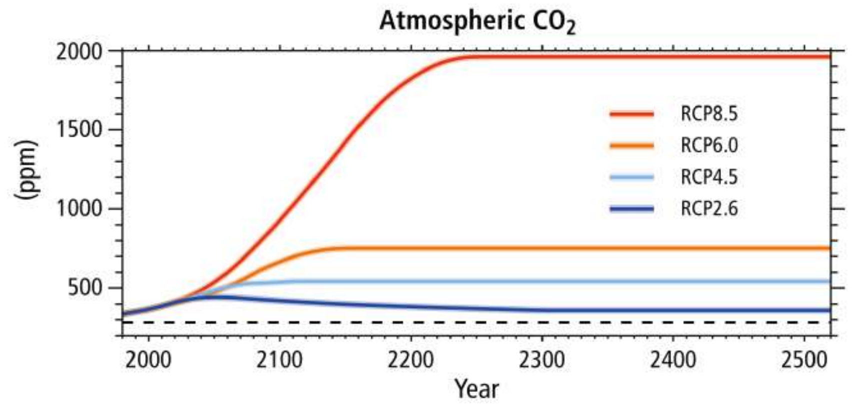


Figure 01.1.9: Atmospher CO_2 and future scenarios
Source: IPCC (2014), IPCC Scenario Process for AR5, Full document at: https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf

Key message: Climate change is a complex and dynamic system determined by many factors such as demographic development, socio-economic development and technological change. (IPCC, 2021). This suggests that climate actions have to be the result of a collective effort across all sectors that carefully take into consideration the future consequences of every decision, and very importantly require a rooted change in consumption and production patterns worldwide. There is no one fits all solution and changes require investment and efforts to ensure sustainability goals and stand clear from the worst-case future scenario.
Many countries in the world are committing to fulfilling goals set towards adaptation and mitigation of climate change, in particular Europe is aiming to become the first carbon-neutral continent by 2050.

The European Green Deal

To achieve this ambitious aim, the European Union (EU) gave the green light to **The European Green Deal**[8] in 2019. This blueprint strives to reshape the EU into a sustainable, climate-neutral economy, with a primary focus on cutting down green-house-gas emissions and safeguarding biodiversity (European Commission, 2023). The plan also involves endeavours to enhance air and water quality, preserve forests and oceans, support sustainable food systems, and transition to a circular economy that promotes responsible resource use and minimizes waste.

[8] Full document at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

The key objectives of the Green Deal are:

Climate neutrality: "Reducing greenhouse gas emissions by at least 55% by 2030. Achieving net-zero greenhouse gas emissions by 2050 through a range of measures, such as investing in renewable energy, energy efficiency, and cleaner transport".

Circular economy: "Promoting sustainable resource use and waste reduction, with a focus on reducing plastic waste, promoting sustainable agriculture and forestry, and creating a circular economy that minimizes waste".

Biodiversity: "Halting and reversing biodiversity loss, protecting and restoring natural ecosystems, improving air and water quality, and improving the health and well-being of citizens".

Clean energy: "Accelerating the transition to renewable energy sources, such as wind, solar, and hydro-power, and reducing energy consumption through energy efficiency measures".

Sustainable mobility: "Encouraging the use of public transport, cycling, and walking, and promoting the shift to low-emission vehicles".

Farm to Fork: "Promoting sustainable food systems and reducing food waste, improving food safety and quality, and supporting sustainable agriculture".

The plan outlines a route to accomplish sustainability objectives, encompassing various sectors like energy, transport, agriculture, industry, and **buildings.**

Figure 01.1.10: The European green deal main objectives
Source: Elements of the European Green Deal (European Commission, 2019a) https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

01.2 Environmental impact of building sector

The **building** sector accounts for a very substantial part of impacts related to climate change. These impacts evolve during the whole life cycle, they are mainly related to land use and habitat destruction, deforestation and loss of biodiversity, water use and water pollution, resource exploitation for material production, waste production, energy consumption and emission of green-house-gasses, in particular CO_2 emissions related to energy combustion, industrial processes and transportation. Energy consumption in the building sector covers the entire lifespan of energy use, including both operational and construction-related. The concept of "embodied energy" refers to the overall energy used for constructing, maintaining, and eventually demolishing a building, which includes both direct and indirect energy (Li et al., 2020). Direct energy refers to the energy needed for manufacturing, transporting, assembling, and constructing building components. Indirect energy includes the energy used for initial construction and eventual demolition (Li et al., 2020). Initial embodied energy accounts for the energy consumed in sourcing, manufacturing, and transporting materials and products to the construction site (Hu and Milner, 2020). Demolition embodied energy involves the energy required for demolishing a building at the end of its useful life, managing waste in landfills, and recycling or reusing salvaged materials (Marzouk and Elshaboury, 2022). Operational energy, on the other hand, refers to the energy necessary for everyday building operations, such as maintaining indoor conditions, lighting, and running building appliances.

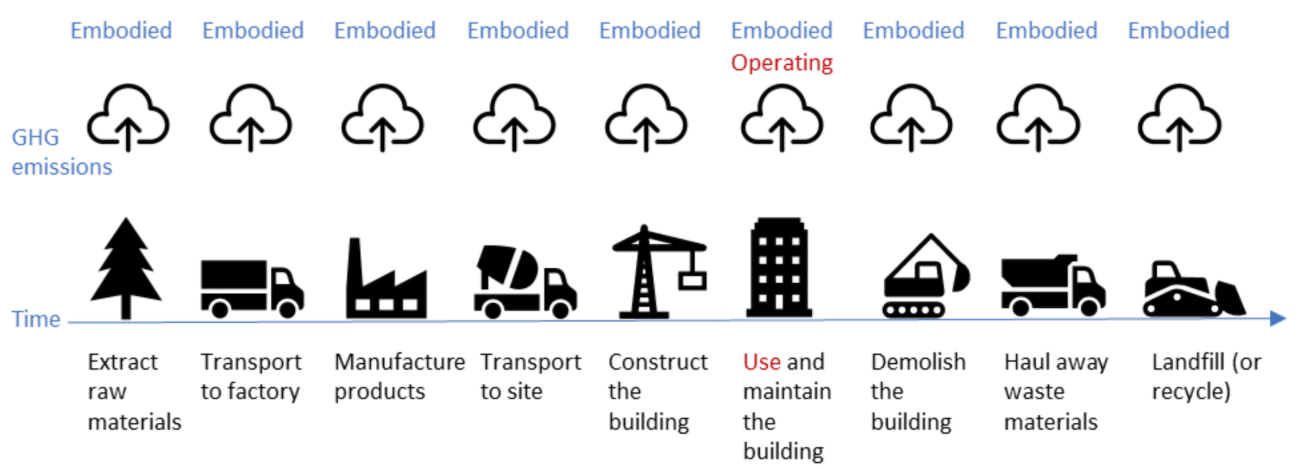


Figure 01.2.1: Embodied and operational energy

Source: One Click LCA Ltd (2018) The embodied carbon review, www.embodiedcarbonreview.com, image at: https://www.c40knowledgehub.org

Globally, the building sector consumes around 30 percent of worldwide energy, which comes from electricity, gases, liquids, solids, and energy for building-related purposes. It's also accountable for about 27 percent of the global CO_2 emissions stemming from operations (IEA, 2022).

In 2021, the production of common building materials like concrete, steel, and aluminium contributed to 4 percent of global energy usage and 6 percent of CO_2 emissions. Bricks and glass added another 2-4 percent to global emissions (IEA, 2022).

Collectively, emissions of CO_2 produced by constructed structures amount to about 40 percent of the global CO_2 emissions annually, which is approximately 14.5 billion tons of CO_2 (IEA, 2022).

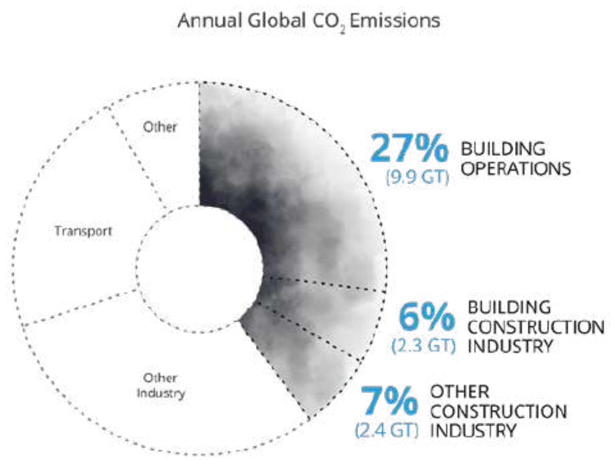


Figure 01.2.2: Annual Global CO2 Emissions divided by sector
Source: Architecture 2030, Data source IEA (2022), Buildings, IEA, Paris https://architecture2030.org/why-the-building-sector/

In Europe buildings and the construction industry account for 40% of energy consumption, 50% of raw materials extraction and 33% of waste and water use and 35% of the EU's total waste generation and 36% of CO_2 emissions (European Commission 2023).

The Global Alliance for Building and Construction (GlobalABC) stands as the primary worldwide platform uniting governments, private enterprises, civil society, research bodies, and intergovernmental organizations in their dedication to achieving a zero-emission, efficient, and robust buildings and construction sector. In 2021, they released a publication[9] outlining a series of 10 crucial steps designed to lower carbon emissions within the building sector. These steps are pivotal in guiding policymakers and decision-makers towards effective entry points for integrating building-related actions within their Nationally Determined Contributions as part of the Paris Agreement[10].

[9] Full document at: https://globalabc.org/sites/default/files/2021-07/Decarbonizing%20the%20building%20sector.pdf

[10] Nationally Determined Contributions or NDCs outline the post-2020 climate-actions that each party involved in the Paris Agreement are required to pursue in order to achieve long-term sustainability goals.

The 10 key measure as suggested in the document focus on:

- "Establishing and implementing an energy code for buildings both new and existing, this would allow to address future emissions growth related to both operational and embodied emissions";

- "Support the use of integrated design process from the early stages involving all disciplines concerning a project in order to adopt effective design measures such as low-cost solutions or life-cycle-assessment to minimize the whole life carbon emissions of buildings";

- "Promoting energy renovation working towards a zero-carbon society";
- "Leading by example by de-carbonizing public buildings to raise awareness within the population about net-zero building solutions";
- "Using energy information and behaviour change to drive energy efficiency and encouraging a reduction in energy use";
- "Promoting financing for energy efficiency";
- "Enabling easy access to information on the carbon footprint of materials in order to chose materials with less embodied energy and working towards a more circular economy to minimize waste cycles";
- "Develop public procurement policies that incentive materials with low carbon footprints";
- "Integrate nature-based solutions into urban planning, buildings and construction";
- "Develop integrated resilience strategies and plans for the built environment".

Understanding that life span of buildings is anywhere from thirty to fifty years to a hundred years effective actions to reduce their environmental impact could affect in the long run different possible scenarios of climate change.

As governments implement regulation and allocate funds towards climate actions in the building sector, a lot of them focus on energy efficiency towards operational energy, however as building become more and more efficient toward net zero, the concern over the initial energy will increasingly become an important point of research and practice (Smith, 2009).

01.3 Environmental impact of building materials production process

On a global scale, the construction and demolition of buildings accounts for about one-third of global material flows. In buildings with an average performance, embodied energy represents between 10 and 20 per cent of the life cycle carbon footprint (UNEP, 2021).

Materials extraction and processing of concrete alone is expected to contribute to 12 per cent of global greenhouse gas emissions in the year 2060 (OECD, 2019).

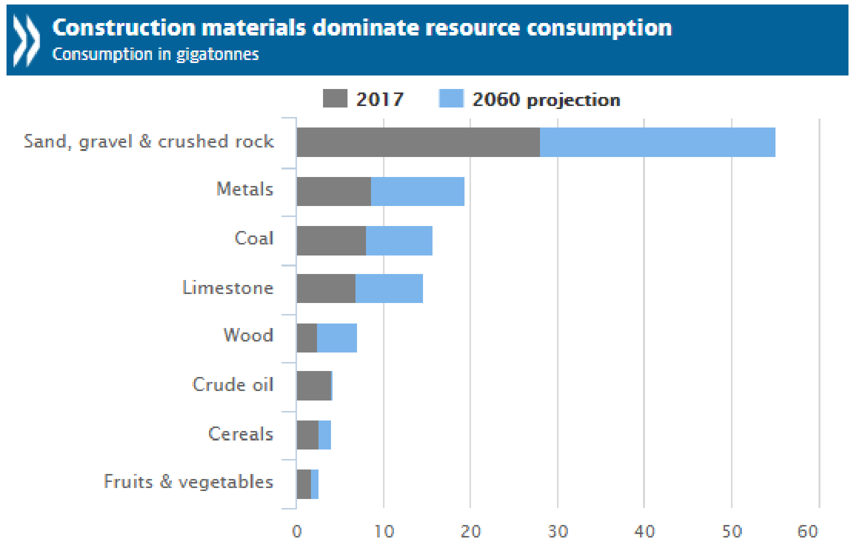


Figure 01.3.1: Construction materials and resource consumption
Source: OECD (2019) The Global Material Resources Outlook to 2060: Economic drivers and Environmental Consequences, OECD Publishing, Paris. https://doi.org/10.1787/9789264307454-en

"With expected population and economic growth over the coming decades, global demand for steel is expected to increase by approximately 30%, cement by 10% and aluminium by about 75% through to 2060 relative to 2017 levels. This is in the absence of significant changes in the way materials are consumed. The increasing material demand poses challenges for sustainability, including an increase of approximately 15% in CO_2 emissions compared to 2017 levels. Therefore, material production and consumption need to be managed." (IEA, 2019)

In the context of Europe, the emissions of greenhouse gases resulting from the extraction and manufacturing of construction materials, along with the construction and renovation of buildings, are approximated to contribute to 5-12% of the overall national greenhouse gas emissions (European Commission, 2023).
To have a better understanding of how exactly building materials are linked to climate change Meg Calkins[11] reports in her book *Materials for Sustainable Sites* from 2009 the following table of connections.

[11] Meg Calkins is an Associate Professor of Landscape Architecture at Ball State University. As an officer of ASLA's Sustainable Development Professional Practice Network. She is the Author of the book Materials for Sustainable Sites: A Complete Guide to the Evaluation, Selection, and Use of Sustainable Construction Materials, written in 2009 and published by John Wiley & Sons

Environmental Concerns	Connections to construction materials
Global climate change	Greenhouse gas (GHG) emissions from energy use, non-fossil fuel emissions from material manufacture (e.g. Cement production, iron and steel processing), transportation of materials, landfill gases
Fossil fuel depletion	Electricity and direct fossil fuel usage (e.g., power and heating requirements), feedstock for plastic, asphalt cement, and sealants, solvents, adhesives
Air pollution	Emissions of CFCs, HCFCs, halons, nitrous oxides (e.g., cooling requirements, cleaning methods, use of fluorine compaunds, aluminium production, steel production)
Smog	Fossil fuel combustion, mining, material processing, manufacturing processes, transport, construction and demolition
Acidification	Sulfur and NO_x emissions from fuel combustion, smelting, acid leaching, acid mine drainage and cleaning
Eutrophication	Manufacturing effluents, nutrients from nonpoint source runoff, fertilizers, waste disposal
Deforestation, desertification, and soil erosion	Commercial forestry and agriculture, resource extraction, mining, dredging
Habitat alteration	Land appropriated from mining, excavating, and harvesting materials. Growing of biomaterials, manufacturing, waste disposal
Loss of biodiversity	Resource extraction, water usage, acid deposition, thermal pollution
Water resource depletion	Water usage and effluent discharges of processing and manufacturing
Ecological toxicity	Solid waste and emissions from mining and manufacturing, use, maintenance and disposal of construction materials

Figure 01.3.2: Environmental concerns and linkage to manufacturing processes of construction materials
Source: Ayers 2002; Azapagic et al. 2004; Graedel and Allenby 1996; Gutuwski 2004; UNEP 1999, from Materials for Sustainable Sites, John Wiley & Sons, Inc., Hoboken, New Jersey by M. Calinkgs in 2009, p. 15

The built environment impacts different parts of the economy, job possibilities in local areas, and our general well-being. It uses up a lot of resources, making up around half of all the things we take from the Earth (European Commission, 2020). In the European Union, only the construction industry adds up to over 35% of all the waste created (Eurostat, 2016).

The release of greenhouse gases resulting from activities like material extraction, manufacturing construction products,

building construction, and renovations is believed to contribute to around 5-12% of a country's overall green-house-gas emissions (Boverket, 2023).
Enhanced material efficiency has the potential to cut down as much as 80% of these emissions (Hertwich et al., 2020).

As Meg Calkins states “In materials and product production, interaction with the environment occurs in two distinct ways. The earth is the source of all material resources and sink for emissions, effluents, and solid waste”.

As demonstrated by the linkages to manufacturing processes of building materials and their consequent environmental concerns, impacts vary widely. From resource depletion of raw materials and water, to emissions of air pollutants, and effluents that cause habitat alteration and pollute water sources, it becomes obvious how acting upon and halting the current *way of* producing according to the model “take, make, dispose” (Benachio et al. 2020) is destructive.
Considering that the built environment is responsible for the majority of material flows in *our* society and serve as the largest storage of materials, with more than 90% of human-made inventory stored in long-lasting goods within the built environment (Schiller et al., 2019), the potential for impactful change is very substantial.

A key factor toward an ecological transition in the manufacturing processes is understanding that not all building materials are equally harmful to the environment, in fact as stated by the OECD, “Global environmental impacts differ significantly across materials”. Commonly used materials such as concrete and metals are a massive contributor to environmental concerns linked to the manufacturing of building materials [Figure 01.3.3].

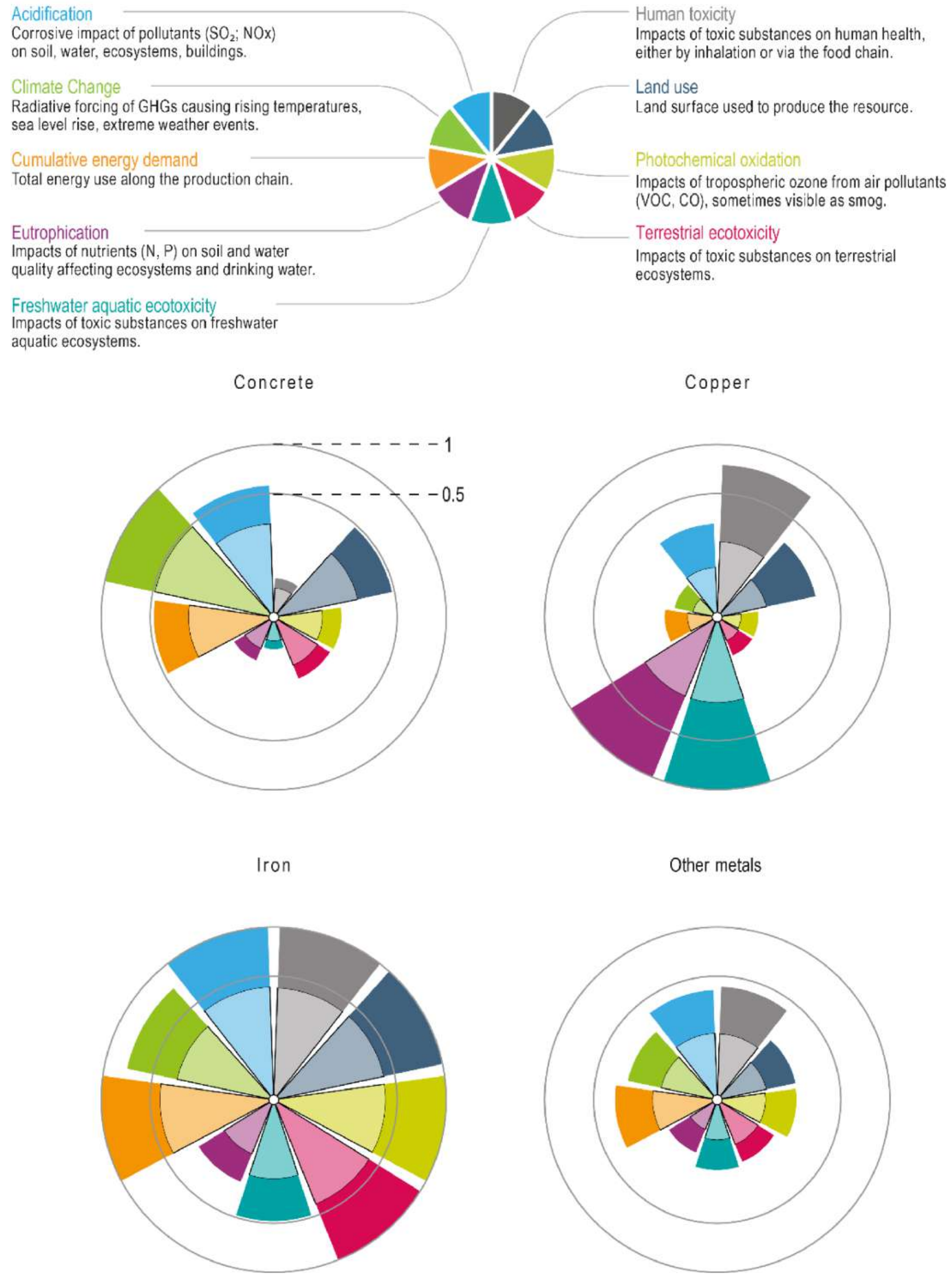


Figure 01.3.3: Environmental concerns linked to the manufacturing of common building materials
Source: OECD (2019) The Global Material Resources Outlook to 2060: Economic drivers and Environmental Consequences, OECD Publishing, Paris. https://www.oecd-ilibrary.org/environment/global-material-resources-outlook-to-2060_9789264307452-en

Key message: Material choice can play a crucial role in driving an ecological shift within the construction industry, as different building materials vary in their environmental impact as shown in the *Material pyramid* below.

Figure 01.3.4: Pyramid of environmental impact of building materials expressed in GWP
Source: Developed by the Royal Danish Academy Centre for Industrialized Architecture (Cinark) developed the Construction Material Pyramid

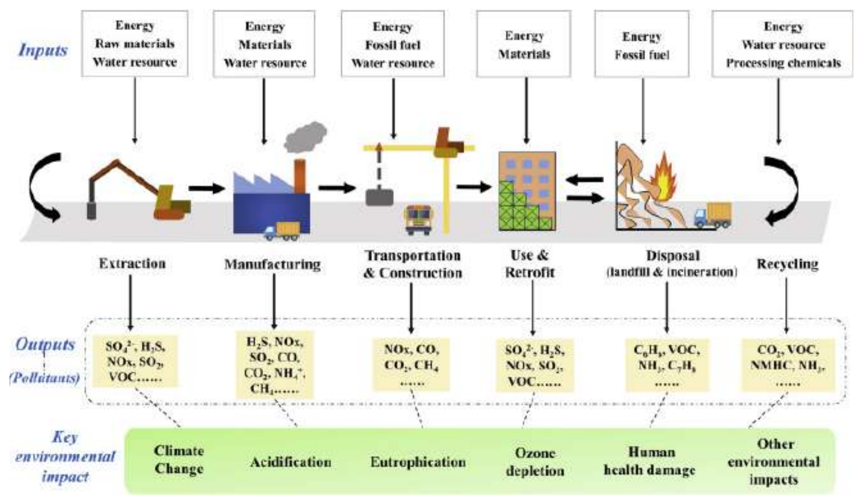
01.4 Product Life

The typical production process of building materials and products starts from the extraction of the raw material (through harvesting, drilling, dredging and mining) and ends with the disposal of waste or recycling into other materials. Most manufacturing process are characterized by a linear approach.

Building materials are made through a multitude of inputs, both from nature and industries, and result in outputs, in the form of waste and pollutants, and products.

Both inputs and outputs are linked to environmental concern [Figure 01.4.1].

Figure 01.4.1: Environmental Impacts during the Life Cycle of building materials
Source: Beijia Huang, Xiaofeng Gao, Xiaozhen Xu, Jialing Song, Yong Geng, Joseph Sarkis, Tomer Fishman, Harnwei Kua, Jun Nakatani, (2020). A Life Cycle Thinking Framework to Mitigate the Environmental Impact of Building Materials, One Earth, Volume 3, Issue 5, Pages 564-573, ISSN 2590-3322, https://doi.org/10.1016/j.oneear.2020.10.010



Inputs mainly include raw materials, water resources, and energy.

Inputs

Raw materials and water resources
As previously mentioned raw material extraction and water use are linked to significant environmental impacts. These include, among others, water contamination, soil erosion and contamination, air pollution, ecosystem destruction and habitat alteration and loss of biodiversity. (see 01.1 Climate change, future scenarios). For these reasons circularity, reuse and recycling are fundamental concepts towards a change in direction.

Energy
During 2021, the operation of buildings was responsible for 30% of the total global final energy consumption and contributed to 27% of the complete energy sector emissions. This includes emissions originating from both energy combustion and industrial processes, with 8% constituting direct emissions from buildings and 19% being indirect emissions resulting from the production of electricity and heat utilized in buildings. Furthermore, the industrial sector, encompassing not just the manufacturing of building materials but also other industries, stands as one of the foremost energy consumers on a global scale. Within the European Union (EU) for the year 2021, the industrial sector accounted for a notable 25.6% of the final energy consumption. This ranking positioned it as the third-largest consumer category, following only transport and households (Eurostat, 2023).

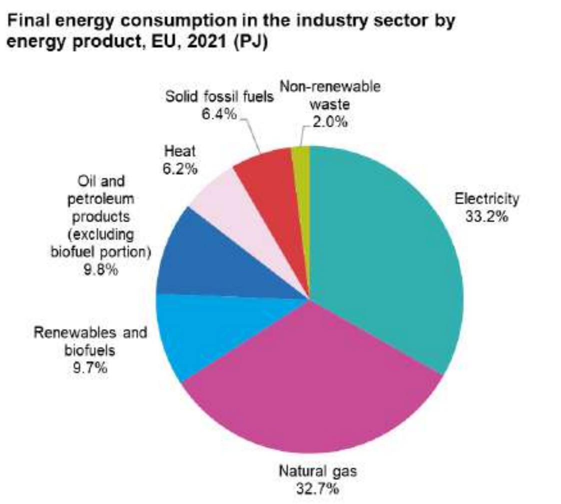


Figure 01.4.2: Final Energy consumption in the industry sector by energy product in the Eu in 2021.
Source: Eurostat (nrg_bal_s)

The industry sector operates through both non-renewable and renewable energy. Fuel type is a crucial aspect of environmental impact from energy use. Renewable energy sources come from solar power, wind energy, hydroelectric power, geothermal energy, biofuels and biomass.
Non-renewable fossil fuels are the primary fuel source, these include natural gas, coal, coal products, derived gas, crude oil, petroleum products and non-renewable wastes (Eurostat,2023).

The primary issue associated with the utilization of fossil fuels, namely coal, oil, and gas, lies in their significant contribution to climate change. These sources are responsible for more than 75% of worldwide green-house-gas emissions and close to 90% of all carbon dioxide emissions (UN, 2023). It is evident that the shift towards renewable energy sources holds paramount significance in the process of de-carbonizing the building and manufacturing sector.

What is the embodied energy of building materials?

An important concept that is part of energy inputs and fundamental towards evaluating environmental assessment of building products is the embodied energy. Emissions of green-house-gases associated with building materials are typically directly connected to embodied energy. This is frequently a result of the fossil fuel combustion necessary in the manufacturing procedures.(Calkins, 2009).

As previously mentioned the embodied energy is the sum of the energy requirements associated, directly and indirectly, to the whole-life-cycle of a product. The embodied energy accounts for the energy use in all life-cycle phases regardless of energy source, therefore it would be important to differentiate the amount coming from renewable sources and from that coming from non-renewable sources as they have different environmental impacts. In addition, it is important to understand that also bio-energy, sourced from the organic material known as biomass, is not unproblematic. In fact, also burning biomass releases carbon dioxide and green-house-gasses (output) and if it does not come from sustainable harvesting it can also contribute to other environmental impacts such as soil erosion, deforestation, flooding, loss of biodiversity and habitat alteration.

Outputs

Outputs mainly include the products and pollutants. Pollution linked to the construction industry and the manufacturing processes. When acknowledging pollutants all air, earth a water are to be considered, in the form of emissions, effluents and waste.

Air pollutants are usually linked to emissions of green-house-gasses directly deriving from fossil fuel combustion (carbon dioxide being the largest share) and indirectly from the generation of electricity that is consumed by the industry. Direct and indirect both depend on the scale of production and the volume of materials produced.

Water is impacted in all phases of the production process, primarily through wastewater (effluents) that are often contaminated with significant consequences to the environment and human health.

Solid waste does not just come from excessive consumption and demand. The whole manufacturing process also has a significant environmental cost because waste is present in every stage of its life cycle. Waste can be solid, liquid, or in gas form, and it ends up in the air, water, soil, or land. Waste can be managed properly or disposed of in a careless manner. Managing the solid waste from building construction and demolition is often complex and can lead to most of it going in landfills or incinerated, which can cause pollution, including toxic pollution, depending on what materials are involved. Construction and demolition waste makes up over a third of all the waste produced in the EU (European Commission, 2023).

How to evaluate the effects that a product has on the environment?

The Life-cycle-assessment (LCA) constitutes one of the main references for assessing the environmental eco-compatibility of construction products.

Life-cycle-assessment (LCA) is a methodology regulated by the ISO 14040/44, recognized at an international level, for evaluating the effects that a product has on the environment over the entire period of its life. LCA's key elements are: (1) identify and quantify the environmental loads involved; e.g. the energy and raw materials consumed, the emissions and wastes generated; (2) evaluate the potential environmental impacts of these loads; and (3) assess the options available for reducing these environmental impacts (EEA, 2023).

LCA represents a powerful tool for holistic decision-making based on comparisons among possible or competing systems. The structure of the LCA can be summarised in the scheme based on the ISO 14040 standard.

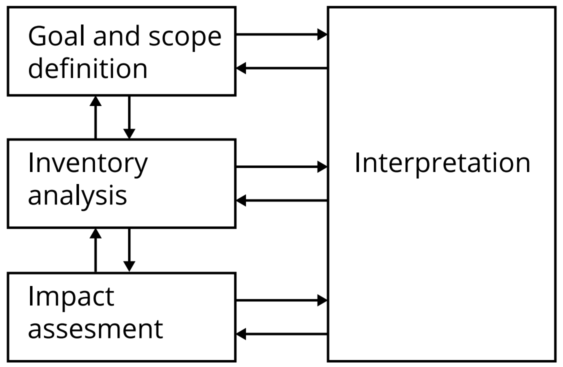


Figure 01.4.3: Diagram of LCA structure based on the ISO 14040 framework.
Source: Data from ISO 14040

Goal and scope definition

The first stage establishes and outlines the analysis's goals, sets up system boundaries, defines functional units, and identifies the data categories that form the foundation of the study.

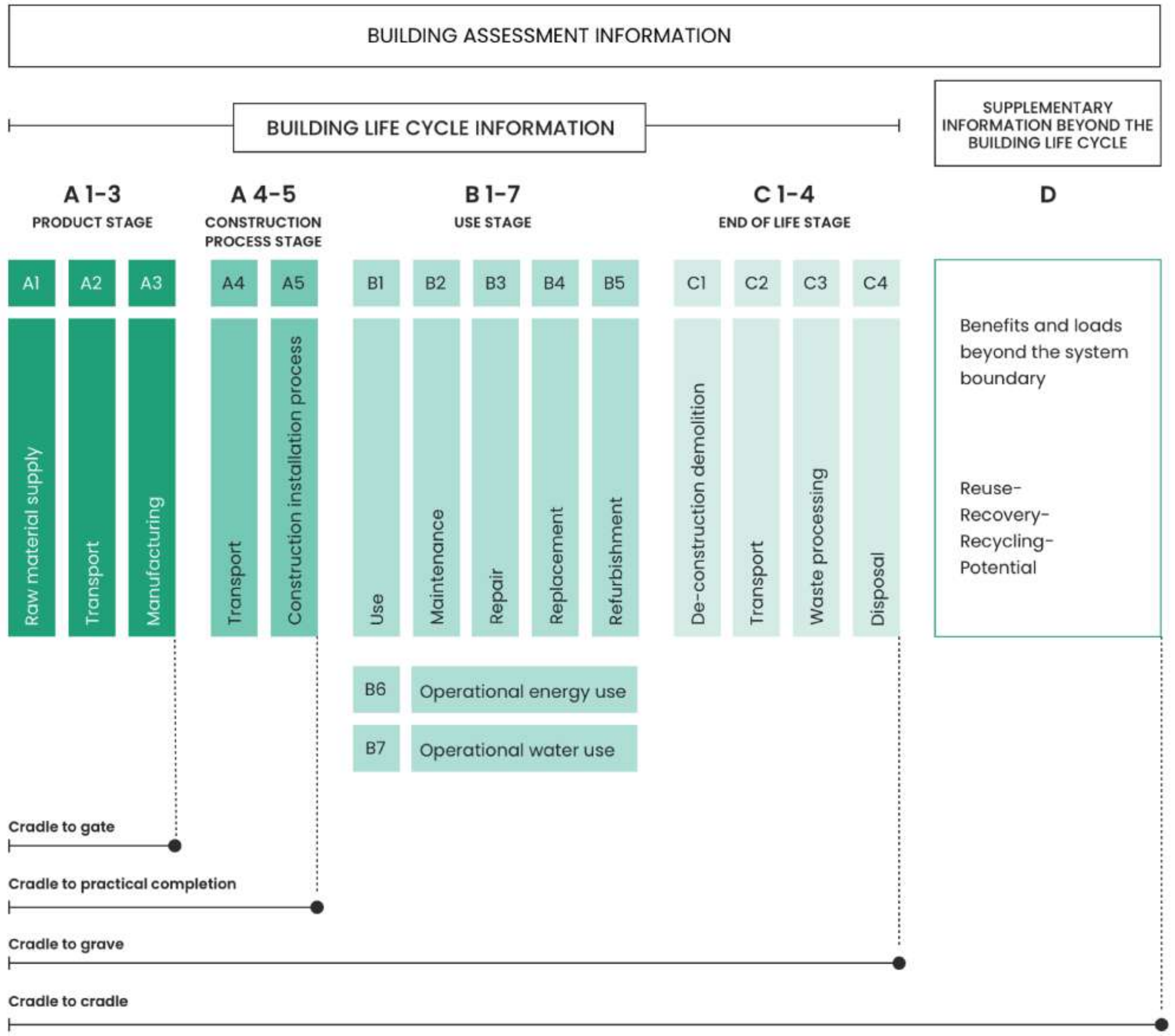


Figure 01.4.4: Scope and system boundaries of the LCA of buildings according to CEN TC350 standards
Source: One Click LCA (2021). LIFE CYCLE ASSESSMENT FOR BUILDINGS Why it matters and how to use it, Ebook, full document at: https://www.oneclicklca.com/wp-content/uploads/2021/10/Life-Cycle-Assessment-for-Buildings-2021.pdf?vgo_ee=fehcXac1DsDegY7uj7CtfN-26ziIX4g3Pmjy%2FVP4pVbs%3D

Inventory analysis – *Life Cycle Inventory Analysis*
The core of life cycle inventory analysis (LCI) involves creating flowcharts, gathering data, and using calculations to assess the inputs and outputs related to a product and system. These inputs and outputs cover resource usage and the release of substances into the air, land, and water. The analysis also includes building life cycle models and estimating emissions and resource usage throughout the product's life cycle. The main goal in this phase is to create a system model that matches the defined objectives and scope.

Impact assessment – *Life Cycle Impact Assessment*
Life cycle impact assessment (LCIA) involves both qualitative and quantitative evaluations of a product's environmental impact using resource and energy consumption data, as well as emission data obtained from the inventory analysis (LCI). LCIA converts the relevant materials and consumed energy into understandable impact indicators. These indicators express the significance of the impact categories and their contribution to the overall environmental harm.
Mandatory requirements are the selection of impact catego-

ries, definition of elementary flows from LCI that are then assigned to impact categories, and finally calculation of the impact of each emission or resource consumption (expressed as an impact score common to all contributions or characterisation factors within the impact category object of assessment). There are different types of indicator: the midpoint indicator, also defined as impact indicator, are expressed through the characterisation of the process, while endpoint indicators express the categories of damage and require a normalisation process (Thiebat, 2019).

Interpretation – *Life Cycle Interpretation*
Life cycle interpretation represents the final stage of the LCA study and focuses on analysing the outcomes of both the life cycle inventory analysis and life cycle impact assessment. During this phase, the results are carefully examined, conclusions are drawn, and limitations are identified to derive meaningful recommendations to reduce the environmental impact of the product or process at the base of the study. Therefore, this methodology overall allows for increasing resource-use efficiency and decreasing liabilities.

How are impacts referred to in a building material?

Being that the largest share of GHG is Carbon dioxide one important factor to evaluate impact of building materials and products a lot of the focus is towards the GWP (Global Warming Potential), that, as previously mentioned, is the ratio of radiative forcing impact resulting from emissions of one kilogramme of green-house-gas emitted to the atmosphere equivalent to one kilogram of CO_2 over a set period of time. The GWP is an indicator often used to assess the impact of building materials and processes during all stages of the life-cycle. It can be further discomposed depending on the origin of the emissions in:

GWP fossil - contribution of greenhouse gas emissions from burning fossil fuels;

GWP biogenic - greenhouse gas emissions from biological sources, such as plants, animals, and micro-organisms. Biogenic carbon refers to CO2 sequestered from the atmosphere during feedstock growth and then released during bio-fuel combustion;

GWP-GHGs – sum of non biogenic greenhouse gas emissions;

GWP land use and land use change (GWP luluc) - greenhouse gas emissions and removals associated with land use, including deforestation, afforestation, reforestation, and changes in carbon stocks in vegetation and soils.

In Europe, there are several standards and methodologies available for calculating the Global Warming Potential (GWP) of buildings. The most used standard is EN 15978:2011, which

provides a framework for assessing the environmental performance of buildings throughout their life cycle. This standard includes the calculation of GWP as one of the environmental indicators. EN 15978:2011 considers the emissions of greenhouse gases resulting from the construction, use, and end-of-life phases of a building. It includes both operational emissions, such as those from energy consumption for heating, cooling, and electricity use, as well as embodied emissions, which are associated with the extraction, production, transportation, and assembly of building materials. The GWP calculation in EN 15978:2011 is performed using life cycle assessment (LCA) methodology.

Other European standards, like the EN 15804:2012+A1:2013, focus on the environmental performance of construction products. These standards guide the calculation of environmental impacts of construction products, including the GWP, using LCA-based methods.

The total amount of green-house-gases produced throughout a building's life cycle is often called the Building carbon footprint or Product Environmental Footprint[12] (PEF). This indicator covers emissions of both energy use (operational carbon) and materials (embodied carbon).

[12] The Product Environmental Footprint is a multi-criteria measure of the environmental performance of a good or service throughout its life cycle. The objective of PEF information is to seek a reduction of the environmental impact of goods and services taking into consideration end-to-end Supply Chain activities. https://green-business.ec.europa.eu/environmental-footprint-methods_en

Another term to consider in regards to greenhouse gas emissions released during a product's life cycle is the whole-life-carbon. This can be divided into embodied carbon, upfront carbon, operational carbon, and emissions related to reuse or recycling beyond the building's life cycle.

These factors involve emissions at different stages of the life cycle, as illustrated in figure 01.4.5.

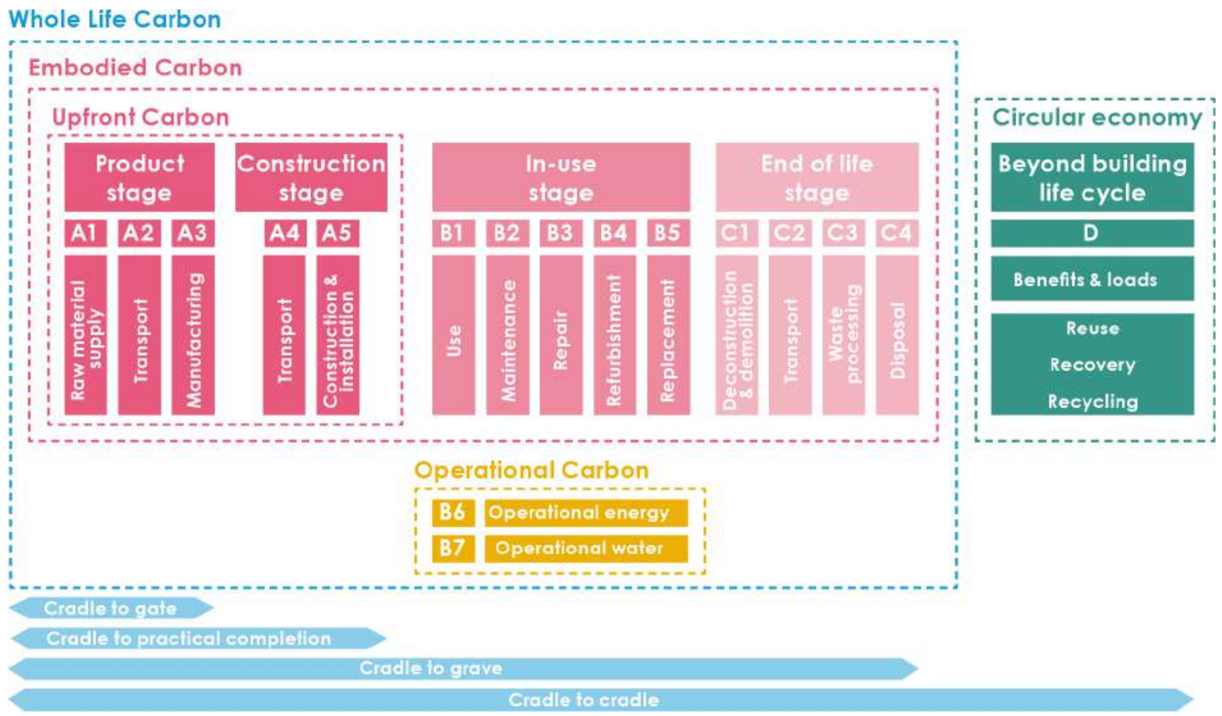


Figure 01.4.5: Whole-life-carbon breakdown
Source: LETI Low Embodied Carbon Specification and Procurement: Guide For Low and Net Zero Carbon Buildings https://www.leti.uk/_files/ugd/252d09_25883cf6c33547b48b367ec3c7d0319b.pdf

In Europe, the most relevant ones are: EN 15978 presents the general structure and definition of stages in the life cycle of buildings according to the European standard for the sustainability of construction works, assessment of the environmental performance of buildings. EN 15804 defines how companies should go about creating Environmental Product Declarations, which are a crucial component in enabling whole-life carbon reporting. EN 15643-5 outlines how to assess the sustainability of buildings and civil engineering works.

Another important aspect when considering environmental impact of building materials production process and evaluation is the sources of energy used during manufacturing as there is a difference between embodied energy deriving from renewable and non-renewable sources.

Renewable embodied energy refers to the energy required to produce building materials derived from renewable resources. These resources have the capacity to regenerate over time, such as timber from sustainably managed forests or bio-based materials.

Non-renewable embodied energy, on the other hand, refers to the energy required to produce building materials derived from finite resources like fossil fuels, these are associated with significant greenhouse gas emissions, depletion of natural resources, and environmental degradation.

Emission deriving from two different sources have different impacts. (see biogenic carbon in the following chapter 03.3 Environmental impact of bio-based building materials).

Key message: The environmental impact of materials depends on the impact per unit of material produced and the quantity of materials consumed. When focusing on carbon dioxide (CO_2) emissions, the emissions associated with each unit of material can be reduced by improving the production processes. These improvements may involve transitioning to lower-carbon fuels, enhancing energy efficiency, adopting innovative low-carbon production processes, or substituting materials with lower emissions during production. Additionally, the demand for materials can be reduced through the implementation of various material efficiency strategies. These strategies aim to decrease material consumption without compromising the quantity or quality of services provided.

01.5 Climate change mitigation: Material efficiency

Materials, as defined by the IEA, have historically aligned with economic development and are referred to as "the building blocks of society, constituting the structures, infrastructure, equipment, and goods that facilitate the daily activities of individuals and businesses."

As detailed thus far, the rising demand for materials has led to increased energy consumption and corresponding emissions. To effectively reduce emissions, it is imperative to incorporate material efficiency throughout the value chain. Often underestimated in its potential for emission reduction, material efficiency offers opportunities across all stages of a product's life cycle, from design and manufacturing to usage and end-of-life handling. By advocating for efficient strategies within practical yet achievable limits, significant cuts in the demand for resource-intensive materials become feasible.

Consequently, enhanced material efficiency can alleviate some of the requirements for other CO_2 emission mitigation measures while attaining equivalent emission reductions. This, in return, contributes to the transition towards cleaner energy sources (IEA, 2019).
In a broader sense, material efficiency refers to fulfilling human needs with minimal material production and processing (Allwood et al., 2011). Achieving this primarily entails altering, as previously noted in the first chapter, global consumption and production patterns across all sectors.

Furthermore, materials efficiency involves reducing energy consumption through appropriate material selection and recycling (IPCC 2007). At several stages in a product's life cycle, material efficiency can be improved through more effective design, material replacement, product and material recycling, as well as quality cascading (IPCC 2007).

Authors of the publication[13] "*Material efficiency: providing material services with less material production*" offer an additional interpretation, defining material efficiency as "the pursuit of technical strategies, business models, consumer preferences, and policy tools that would substantially decrease the production of high-volume, energy-intensive materials necessary to support human well-being."

[13] Allwood JM, Ashby MF, Gutowski TG, Worrell E. (2013) Material efficiency: providing material services with less material production. Phil Trans Soc A 371:20120496. http://dx.doi.org/10.1098/rsta.2012.0496

As seen from these different definitions, strategies for this mitigation approach might differ and should work together on various aspects. However, their main goal should be to reduce energy use and its emissions, ultimately resulting in less material consumption overall.

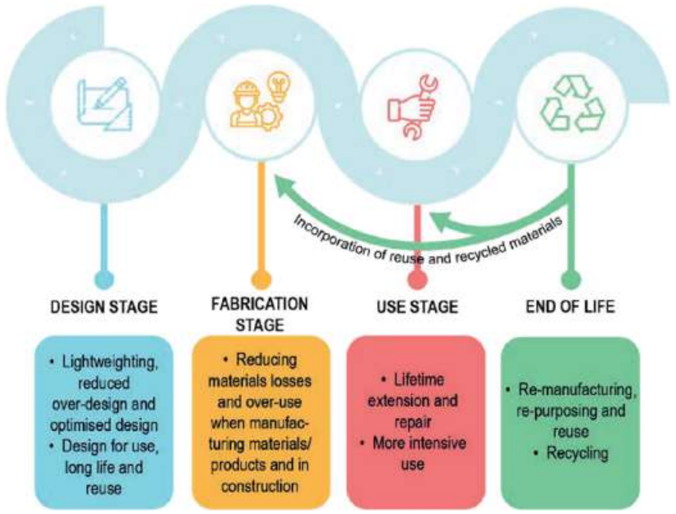
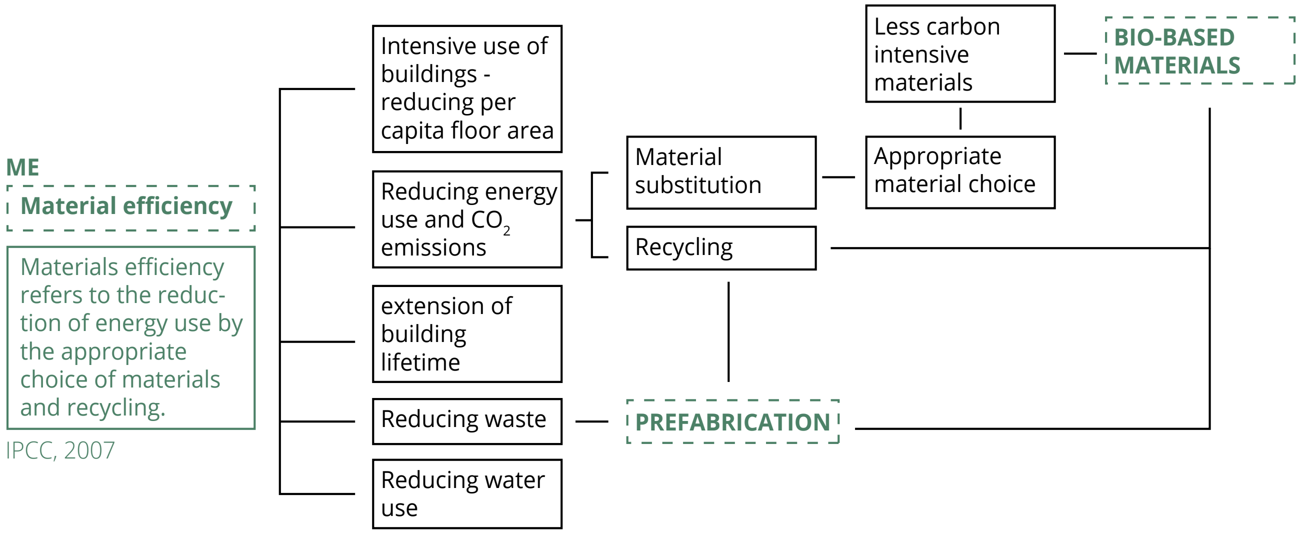


Figure 01.5.1: Material efficiency strategies across the value chain
Source: IEA (2019) Material efficiency in clean energy transitions.
Full document at: https://iea.blob.core.windows.net/assets/52cb5782-b6ed-4757-809f-928fd6c3384d/Material_Efficiency_in_Clean_Energy_Transitions.pdf

Similarly, within the construction industry an important part of material efficiency focuses on different aspects as described by the following scheme [Figure 01.5.2].

Figure 01.5.2: Material efficiency and circularity
Source: Drawing made by the author of the thesis



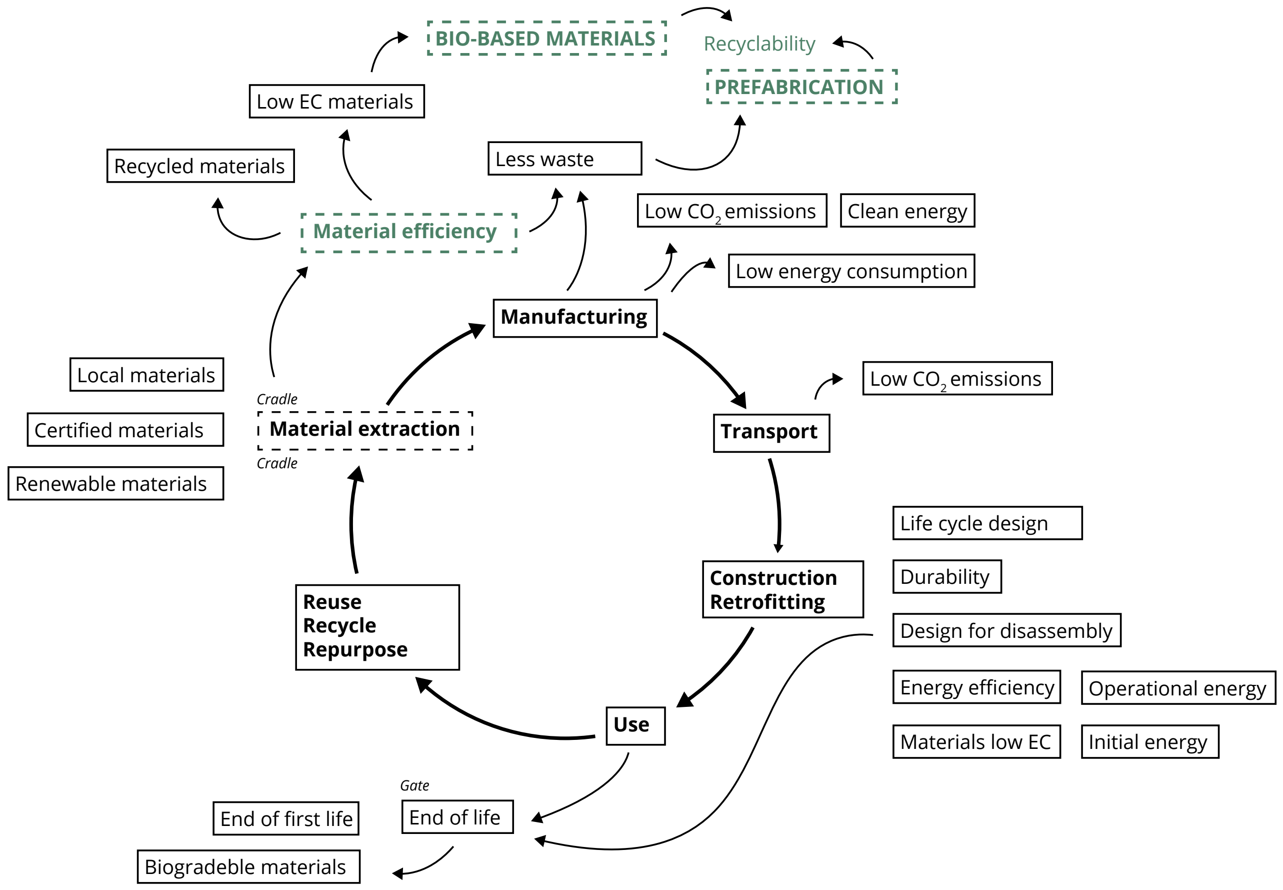


Figure 01.5.3 Circularity and Material efficiency: production processes and material substitution BRAINSTORMING
Source: Drawing made by the author of the thesis

Future building materials demand and related emissions can be reduced through more intensive use of buildings (reducing per capita floor area), building lifetime extensions, the use of lighter constructions and less carbon- intensive building materials and material substitution, within material substitution, the use of bio-based materials is a special case of material substitution (IPCC, 2007), reduction of construction waste, e.g. through prefabrication, the reuse of structural elements, and the recycling of building materials.

What does it mean to reduce per capita floor area?

When considering a more intensive use of buildings and thus reducing per capita floor area, it must be considered that urbanization continues and more people move into cities and urban areas, therefore, pressure on available land for new constructions will continue to increase. This situation results in an incentive to review more intensive use of buildings in order to create more "vibrant" cities without building on virgin land (Höjer and Mjörnell, 2018).

What are the main strategies to reduce embodied carbon of buildings products?

As reported by Gianluca Grazieschi[14] (Eurac Research) in the article Overview Article - *Circularity and Low-Carbon Building Materials in Construction*[15] written in November 2022 and posted on the European Commission website, the main strategies to reduce the embodied carbon of buildings are:

[14] Gianluca Graziesschi is a Post-Doc-Researcher at Institute for Renewable Energy at Eurac, which private research center based in Bolzano (South Tyrol) in Italy.

[15] Full document at: https://build-up.ec.europa.eu/en/resources-and-tools/articles/overview-article-circularity-and-low-carbon-building-materials

1. Design for durability;

2. Application of circular economy principles (reduction of waste generation, direct re-use of materials from waste or demolition, use of recycled materials) (using prefabrication);

3. Material substitution, use of materials with a low carbon footprint (such as bio-based materials) to replace high embodied carbon ones (such as concrete) without concessions on the durability;

4. Increase of the environmental performance of the production chains (energy efficiency,
renewable energy integration, technological development);

5. Use of local products;

6. Design for disassembly (using prefabrication) and separation at source.

When talking about the building industry an effective way that aims towards a more circular economy by reducing waste is through prefabrication processes, this allows for an easier design for disassembly and thus higher recyclability of building components. Furthermore, prefabrication can provide greater control over the size, shape and manufacturing of building components, and help to speed up construction processes.

When considering reduction of waste an important aspect is considering the amount that ends up at landfills and is therefore highly impactful. If we think about bio-based products, more specifically bio-based building materials, they are characterized by the fact that their disposal often is the return to nature, therefore their end-of-life impact is usually low.

Bio-based materials in principle could originate from harvesting or from manufacturing, for example, materials that come from waste and recycling (e.g. shells from agrifood waste that are converted into building materials). One important aspect of bio-based materials, like all materials, is production processes and specifically related emissions (embodied carbon) as this aspect could counteract the benefits deriving from the use of these materials if their impact during production is high.
Like for the use of all materials, these also need to take into consideration lifecycle thinking and design, as well as end-of-life of products and projects, following the waste hierarchy in order to minimize and optimize (figure 01.5.4).

A key point that includes many others is the move from a linear to a circular economy.

Figure 01.5.4: From linear to circular Waste hierarchy
Source: https://zerowasteeurope.eu-/2019/05/a-zero-waste-hierarchy-for-europe/

01.6 From linear to circular

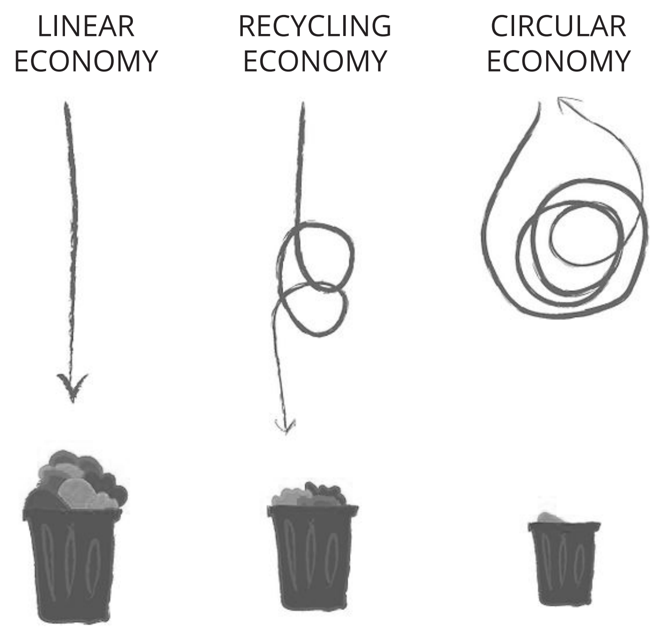
The circular economy, as defined by the European Parliament, revolves around production and consumption practices like sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products for extended periods. This approach extends the life cycle of products and reduces waste. When products reach their end-of-life, efforts are made to keep their materials within the economy through recycling and reuse. This minimizes dependence on raw material extraction and creates additional value, following the idea of cascading resource use.

Circularity in building sector

In the building sector, circularity is a crucial part of the broader shift towards climate neutrality and long-term competitiveness in industries. It can lead to significant material savings throughout value chains and production processes, opening up economic opportunities and adding value (European Commission, 2020).

Applying the circular economy principles to the built environment tackles global issues like resource scarcity and environmental degradation. Adhering to circular economy principles often reduces the carbon footprint, helping address the climate crisis (Leti, 2022).

Figure 01.6.1: From linear to circular
Source: https://www.regeneration2030.org/post/what-is-circular-economy-and-why-do-we-need-it



When discussing the building industry, there are two separate but connected life cycles: one for buildings and another for construction products (Seggewi(refer to figure 01.6.2).

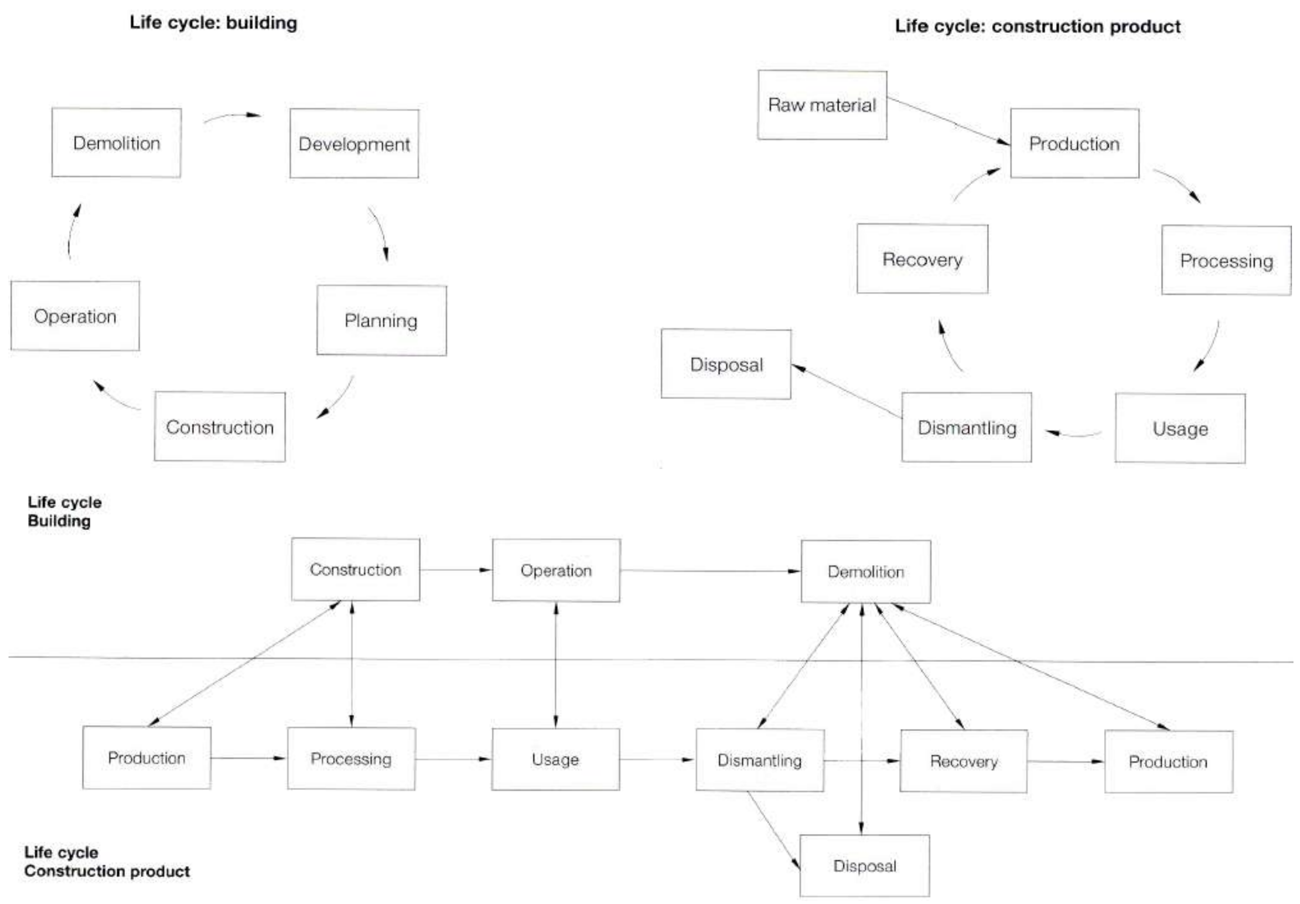


Figure 01.6.2: Building and construction product life cycle and their connection
Source: Seggewies, J., Riegler-Floors, P., Rosen, A., Hillebrandt, A., & Seggewies, J. (2019). Manual of Recycling. In DETAIL eBooks, p. 33. https://doi.org/10.11129/9783955534936

Circularity in buildings and construction products refers to two distinct but interconnected concepts.

Circularity in buildings focuses on the design, construction, operation, and end-of-life management of buildings. It encompasses strategies and principles aimed at maximizing resource efficiency, minimizing waste generation, and promoting the reuse, and recycling of materials within the building's life cycle. This translates into designing for adaptability, design for durability, efficient waste management systems, and promoting the reuse of elements and components and recycled materials.

Circularity in construction products refers specifically to the materials, elements and components used in the construction process. It involves designing products with a lifecycle thinking approach that considers their environmental impact during all stages of life. This translates into resource and material efficiency like selecting materials that come from renewable sources (e.g. bio-based materials), recyclable, or made from recycled content, as well as adopting product designs that facilitate disassembly, reuse, or recycling. Circular construction products are designed towards minimizing waste, extend their lifespan, and enable their recovery at the end of their use.

Both concepts are interrelated and complementary, as achieving circularity in buildings relies also on the availability of circular construction products and circularity in manufacturing construction products is driven by the demand for more holistic and sustainable building practices.

To implement circular strategies both new buildings and existing buildings must be considered.

When considering new construction design should focus on easy maintenance and renovation potential, flexibility and adaptation whilst avoiding overdesign, longer life, facilitating deconstruction for future reuse, recording accurate materials data for the future, and using low-carbon and biogenic materials.

When considering existing buildings interventions should focus on: understanding what resources are in existing buildings, reusing buildings, systems, components and materials rather than recycling, deconstructing not demolishing, and using low-carbon and biogenic materials.

01.7 Green transition in Europe towards material efficiency and circularity

Europe is currently undergoing a transitional phase towards ecology on many different fronts. Both strategies of circularity and material efficiency are essential to achieve sustainability goals.

As previously mentioned **The European Green Deal** is a plan that sets a roadmap towards carbon neutrality by 2050. It includes initiatives to promote circular economy principles, resource efficiency, and waste management. To connect the European Green Deal to our living spaces and experiences, in September 2020, the European Commission created an interdisciplinary initiative aimed at promoting sustainable and inclusive design and architecture all across Europe: **The New European Bauhaus**[16].

The New European Bauhaus sees the collaboration of architects, designers, artists, engineers, and other stakeholders to co-create and implement innovative solutions that promote sustainability, accessibility, and aesthetic appeal.
The initiative seeks to integrate principles of circularity, resource efficiency, and social inclusion into the design and construction of buildings, public spaces, and products.
The application of sustainable and inclusive design principles will see the launch of pilot projects in different EU countries starting in September 2021.

[16] Full document at: https://new-european-bauhaus.europa.eu/system/files/2021-09/COM(2021)_573_EN_ACT.pdf

Another building block of the European Green Deal is the **Circular Economy Action Plan (COM (2015) 614)**[17], first adopted by the European Commission in 2015, and reviewed in 2020 with **The New Circular Economy Action Plan (COM (2020) 98)**[18]. One of the main objectives of the plan is to reduce pressure on natural resources and produce less waste. The new action plan announces initiatives along the entire life cycle of products. It targets how products are designed, promotes circular economy processes, encourages sustainable consumption, and aims to ensure that waste is prevented and the resources used are kept in the EU economy for as long as possible (European Commission, 2023).
It introduces both legislative and non-legislative measures. The focus is on the sectors that use the most resources and where the potential for circularity could lead to impactful change: electronics and ICT (information and communication technologies), batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water and nutrients.
For further information, you can refer to **ISO/DIS 59004 - Circular Economy – Terminology, Principles, and Implementation Guidance**. This document outlines essential terminology, sets forth circular economy principles, and offers guidance on its implementation through a framework and action areas (also see ISO/DIS 59020 Circular economy — Measurement and Evaluation of Circularity).

In relation to the construction sector and the built environment, the primary objectives revolve around: extending the lifespan of buildings, decreasing the carbon footprint of materials, and establishing minimum criteria for renewable resources and energy efficiency.
During 2021, the United Nations Economic Commission for Europe (UNECE) endorsed a toolbox that encompasses policy recommendations for governments, guidelines for implementation, a traceability standard, and a call to action for industry stakeholders. The initiative's focus is on achieving traceability and transparency of information throughout the value chain, which aids circular business models in closing the loop. This includes aspects like eco-design, resource efficiency, recycling, repair, remanufacturing, waste management, and the assessment of impacts related to water, chemicals, and energy, as well as climate change mitigation and adaptation (UNECE, 2023).

In fact, transparency and traceability can be considered a key factor towards a systematic change. Actions to promote availability and access to reliable information are crucial and have been and are being implemented by governments to allow for an agreed classification system that facilitates and promotes circularity and material efficiency.
One important role in aiding better material choice and transparency regarding products and materials is played by environmental labels and declarations (ISO 14020:2000 - Environmental labels and declarations). Environmental labels provide information about a product or service interms of its overall

[17] Closing the loop - An EU action plan for the Circular Economy. Full document at: https://eur-lex.europa.eu/resource.html?uri=cellar:8a8ef5e8-99a0-11e5-b3b7-01aa75ed71a1.0012.02/DOC_1&format=PDF

[18] A new Circular Economy Action Plan For a cleaner and more competitive Europe. Full document: https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF

environmental benefits, such as the recyclability of its packaging, or the absence of noxious ingredients (ISO, 2019).

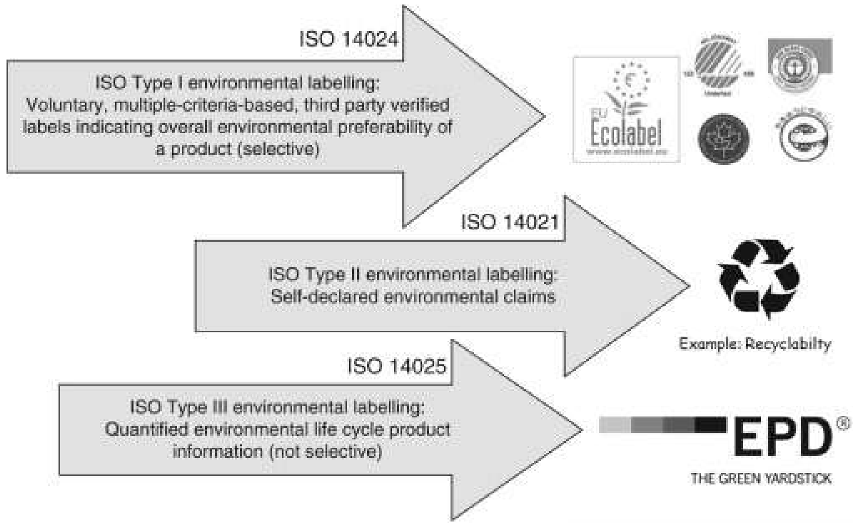


Figure 01.7.1: Environmental labels and declarations
Source: G.L. Baldo, G. Cesarei, S. Minestrini, L. Sordi (2014), 6 - The EU Ecolabel scheme and its application to construction and building materials, Editor(s): F. Pacheco-Torgal, L.F. Cabeza, J. Labrincha, A. de Magalhães, Eco-efficient Construction and Building Materials, Woodhead Publishing, Pages 98-124, https://doi.org/10.1533/9780857097729.1.98

There are three different types of environmental labels: **ISO type I, (ISO 14024), ISO type II (ISO 14021), and ISO type III (ISO 14025).**

ISO 14024, *Environmental labels and declarations – Type I environmental labelling* – Principles and procedures outlines the requirements for developing "Type I environmental labelling programmes", more commonly known as ecolabelling schemes. The marks or logos (e.g. **EU Ecolabel**[21] , **Nordic Ecolabel**[22] and **Blue Angel Ecolabel**[23]) of a product are awarded upon fulfilling a set criteria. ISO 14024 features the principles and procedures for selecting product categories, and product-environmental criteria, product-function characteristics and for assessing and demonstrating compliance (ISO, 2019). Global Ecolabelling Network (GEN), the international federation of ecolabelling bodies have adopted this standard.

ISO 14021, *Environmental labels and declarations – Self-declared environmental claims* (Type II environmental labelling), provides guidance and establishes principles and criteria for the use of environmental labels for organizations to make reliable and credible environmental claims.

ISO 14025, *Environmental labels and declarations* – Type III environmental declarations – Principles and procedures, provides guidelines for conducting and reporting environmental product declarations (EPD). Environmental Product Declaration consist of quantified environmental information concerning the cycle of the products (and services) in order to allow a comparison between products that perform the same function (Sala Lizarraga and Picallo-Perez, 2020). EPDs are comprehensive reports that communicate the environmental performance of a product or service based on a life cycle assessment (LCA).

[21] EU Ecolabel is an ecological quality mark that indicates and certifies (according to CE Regulation n. 66/2010) the low environmental impact of the companies' products. Certification can be requested on a voluntary basis. More information at: https://environment.ec.europa.eu/topics/circular-economy/eu-ecolabel-home_en

[22] Nordic Ecolabel is the official sustainability ecolabel of the Nordic countries in the EU, more information at: https://www.nordic-swan-ecolabel.org/

[23] Blue Angel Ecolabel is the ecolabel of the German Federal, more information at: https://www.blauer-engel.de/en

EPDs enable comparisons by following guidelines outlined in the **Product Category Rules (PCR) (UNE EN 15,804:201224)**. This document outlines the proper approach to conducting a life-cycle assessment (LCA). It offers insights into several key aspects:
- System boundaries, indicating the specific processes and stages of the product's life cycle to be considered.
- Declared/functional unit: specifying the quantity, weight, and expected lifespan of the product under assessment.
- Methods for defining elements like the utilization phase and available end-of-life choices.
- Identification of impact categories for assessment beyond those included in the standard set, as detailed in our General Program Instructions (GPI[25]).

[24] This European standard provides core product category rules (PCR) for Type III environmental declarations for any construction product and construction service.

[25] New version of the General Programme Instructions published at: https://environdec.com/news/new-version-of-the-general-programme-instructions-published

[26] Full document at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52008DC0400

The EU also introduced **Green Public Procurement (GPP)**, a process in which public authorities seek to obtain goods, services, and works with a reduced environmental impact across their life cycle compared to alternatives serving the same purpose (European Commission, 2023). GPP functions as a voluntary instrument, allowing Member States and Public Administrations to determine the extent of policy or criteria implementation. This aspect is integral to the EU's efforts to foster a more resource-efficient economy. The European Commission has been actively formulating voluntary GPP criteria for diverse product categories. As part of the 2020 Circular Economy Action Plan, the Commission proposes integrating minimum mandatory GPP criteria and targets into sectoral regulations. They also intend to introduce mandatory reporting to monitor GPP implementation. Labels can play a role in shaping technical specifications, award criteria, and validating compliance, thus simplifying the process for public buyers (European Commission, 2023).

In Italy, for example, with the context of the implementation of environmental policies, the **Minimum Environmental Criteria CAM (Criteri Minimi Ambientali)**[27] were introduced as specific environmental criteria within the context of the GPP. CAMs are the environmental requirements defined for the various stages of the purchasing process. It is aimed at identifying the best design solution, as well as product or service from an environmental perspective along the life cycle, and considering market availability. CAMs are defined within the framework of the Plan for the Environmental Sustainability of Consumption in the Public Administration Sector and are adopted by the Decree of the Ministry of Ecological Transition. Their systematic application enables the spreading of environmentally preferable environmental technologies and products and produces market leverage, inducing all economic operators to adapt to the new demands of government towards circularity (Ministero dell'Ambiente e della Sicurezza Energetica, 2023). CAMs are adopted for 18 categories, one of which is the building sector (edilizia in Italian).

[27] In Italy, the effectiveness of CAM was ensured thanks to Art. 18 of Law 221/2015 and, subsequently, Art. 34 bearing "Energy and Environmental Sustainability Criteria" of Legislative Decree 50/2016 "Procurement Code" (as amended by Legislative Decree 56/2017), which made its application mandatory for all contracting stations. More information at: https://gpp.mite.gov.it/Cosa-sono-i-CAM

In order to provide a reference for evaluation and monitoring framework to improve the sustainability of buildings that establishes indicators for the assessment of circularity, the European Commission has published, among other directives, **Level(s)**[28]. The main aim is to link building performance with European policy objectives. The scope of the publication is set to encourage the mainstream market to incorporate sustainability, as well as create greater awareness and demand for sustainable buildings on a wider scale. The idea is to target a variety of building types, particularly the residential market where sustainable practices are less widespread.

[28] Level(s) Full document at: file:///C:/Users/fiamma/Dropbox%20(Politecnico%20Di%20Torino%20Studenti)/TESI/RESOURCES/CHAPTER%201/REPORTS/Level_publication_EN.pdf

The actions undertaken by the European Union towards circularity and material efficiency are constantly evolving and increasing, so on a positive note it could be said that overall, *we* are heading in the right direction.

In fact, in March 2023, the European Parliament endorsed its position on the recast of the **Energy Performance of Buildings Directive (EPBD[29]).** Notably, this directive's updated version explicitly accounts for the emissions across the whole-life-cycle of buildings

[29] More information on the EPBD at: https://www.europarl.europa.eu/doceo/document/TA-9-2023-0068_EN.pdf

The directive aims to take into consideration and undertake actions for both operational and embodied energy for new constructions and renovations. Some important points for circularity, material and materials and resource efficiency of the document state:

"(7b) The introduction of requirements on whole life-cycle emissions will encourage industrial innovation and value creation, such as through an increase in the use of circular and natural materials."

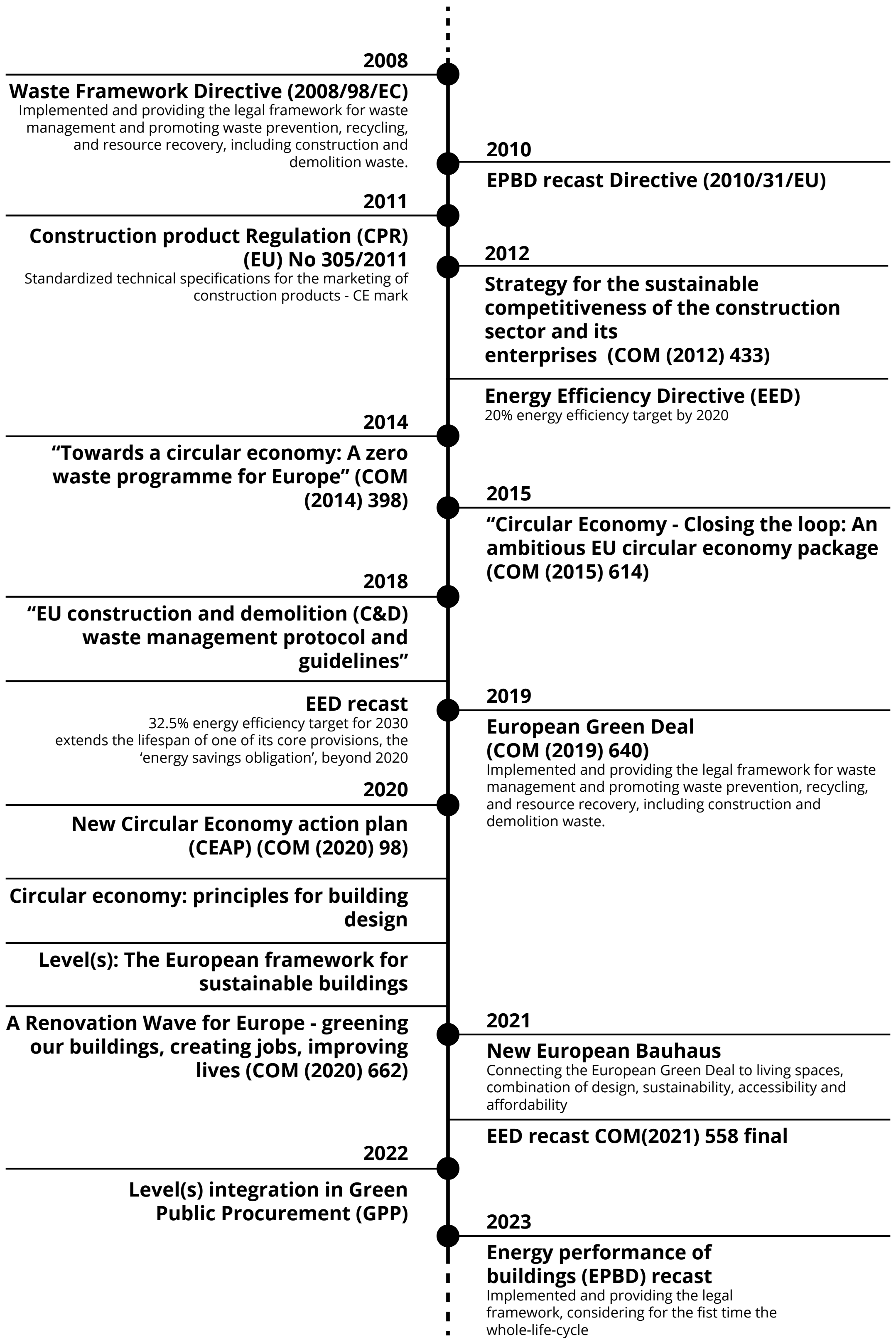
"(7c) It is crucial to promote and include the use of more sustainable construction materials, in particular bio- and geo-sourced materials, as well as simple passive low-tech and locally tested building techniques to support and promote the use of and research into material technologies that contribute to the best possible insulation and structural support of buildings. In view of the climate crisis and the increased probability of summer heat waves, special consideration should be given to heat protection for buildings."

"(8) Minimizing the whole life-cycle greenhouse gas emissions of buildings requires resource efficiency, sufficiency, circularity and turning parts of the building stock into a carbon sink."

"(9) The global warming potential (GWP) over the whole life-cycle indicates the building's overall contribution to emissions that lead to climate change. It brings together greenhouse gas emissions embodied in construction products with direct and indirect emissions from the use stage. A requirement to calculate the life-cycle GWP of new buildings therefore constitutes a first step towards increased consideration of the whole life-cycle performance of buildings and a circular economy. This calculation should be based on a harmonised framework at Union level. The Commission should provide a clear definition of the lifecycle approach. Member States should adopt a roadmap on a reduction of the life-cycle GWP of buildings."

This directive holds significance as it introduces new regulations and targets that encompass, for the first time, the whole life cycle.

Figure 01.7.2: TIMELINE of actions and directives Towards circularity and material efficiency in the EU - scheme
Source: made by the author or the thesis, data information from European Commission



When considering **energy efficiency** and **building standards** there are some tools and certifications to referrer to. For example, **PassiveHaus[30] (Germany)** and **CasaClima[31] (Italy)**. To obtain these certifications building must demonstrate exceptional energy efficiency and meet specific performance requirements that include limits on energy consumption for heating and cooling, airtightness of the building envelope, thermal comfort criteria, and ventilation standards (indoor air quality) and use of renewable resources.

[30] More information on Passivehaus certification at: https://passivehouse.com/

[31] More information on CasaClima certification at: https://www.agenziacasaclima.it/it/certificazione-edifici/certificato-energetico-casaclima-1281.html

When considering aspects linked to building materials and their impact on the environmenta and also indoor air quality and human health, other certifications can be taken into consideration. For example, **CasaClima Nature[32] (Italy)** and **Bio Safe[33] (Italy)**. CasaClima Nature introduces an objective assessment of the eco-compatibility of the materials and systems used in the construction and their water impact. To ensure the comfort and health of indoor environments, precise requirements are made for indoor air quality, natural lighting, acoustic comfort and protection from radon gas.

[32] More information on CasaClima Nature certification at: https://www.agenziacasaclima.it/it/certificazionesostenibilita/casaclimanature-1387.html

[33] More information of Bio Safe certification at: https://www.biosafe.it/

Figure 01.7.3: Passive House , Biosafe and CasaClima logos
Source: https://passivehouse.com/, https://www.biosafe.it/, https://www.agenziacasaclima.it

Other certifications that asses **o**verall environmental impacts are, among other, **Protocollo Itaca[34] (Italy), BREEAM[35] (United Kindom)** and non-EU **LEED[36] (U.S.A.)**. These certificates and protocol provide a tool to asses environmental impact of projects and buildings based on evaluation that focuses on different criteria such as energy efficiency, water conservation, indoor air quality, material selection, waste management, and overall sustainability.

[34] More information on Protocollo Itaca at: http://www.registroprotocolloitaca.org/

[35] More information on BREEAM at: https://bregroup.com/products/breeam/

[36] More information on LEED at: https://www.usgbc.org/leed

These certifications provide guidance and standards that promote environmentally responsible construction and operation. Each certification or protocol has its specific criteria and requirements, tailored to the region and priorities it serves, enabling stakeholders to make informed decisions and enhance overall sustainability performance of buildings and projects.

In conclusion, it is worth mentioning and referencing some distinctive projects and research that work towards sustainability goals, in particular the decarbonization of the built environment.

#BUILDINGLIFE

#BuildingLife

#BuildingLife[37] is an initiative that brings together ten European Green Building Councils to advance the objectives of the European Green Deal. These Green Building Councils are committed to driving climate action by means of national and

[37] More information on #BuildingLife at: https://worldgbc.org/buildinglife/

regional roadmaps for decarbonization. These roadmaps address the comprehensive environmental effects across the life cycle of the building and construction sector. Notably, this initiative offers comprehensive insights into building regulations, waste management, circular practices, and sustainable procurement and financing. The document titled "EU Policy Whole Life Carbon Roadmap #BuildingLife"[38], released in May 2022, elaborates on these aspects.

[38] Full document at: https://viewer.ipaper.io/worldgbc/eu-roadmap/

Leti (Uk)

Leti[39] is a Uk based voluntary network of environmental professionals working together on the path of a zero-carbon future. The vision is to understand and clarify actions needed to meet the climate change targets for the built environment, encouraging collaboration between different stakeholders. Through different publication of toolkits and guidelines Leti provides useful and effective information about circularity and low-embodied carbon materials and solutions for design and projects. In particular three interesting documents are: "*LETI Low Embodied Carbon Specification and Procurement Guide: For Low and Net Zero Carbon Buildings*"[40] published in March 2023, and "*Circular Economy for the built environment: a summary*"[41] published in April 2022, and also "*LETI Climate Emergency Design Guide: How new buildings can meet UK climate change targets*"[42] Published in January 2020. These, like their other publications, provide practical information that allow conscious decision-making for all the different actor involved in design prosses of different projects.

[39] More information about Leti at: https://www.leti.uk/ [40] Full document published on Leti website at: https://www.leti.uk/specification

[41] Full document published on Leti website at: https://www.leti.uk/_files/ugd/252d09_ecec993000bf4cf9acba953b845eb9af.pdf

[42] Full document published on Leti website at: https://www.leti.uk/_files/d/252d09_3b0f2acf2bb24c019f5ed9173fc5d9f4.pdf

RE2020 (Fr)

The RE2020[43] characterizes French national regulation for all new buildings that came into effect the 1st of January 2022. This practice is a great learning opportunity as it includes different scopes included in building energy efficiency, engaging all actors, and utilizing a whole-life-cycle approach. The guide to the RE2020 can be found in the document "*Guide RE2020 Réglementation Environnmentale: éco-costruire pour le confort de tous*" [44].

[43] Further information at: https://www.ecologie.gouv.fr/reglementation-environnementale-re2020

[44] Full document at: https://www.ecologie.gouv.fr/sites/default/files/guide_re2020.pdf

ANAB (It)

ANAB[45] (Associazione Nazionale Architettura Bioecologica) is an independent association dedicated to promoting and teaching sustainability practices. ANAB operates through consulting and training of designers and operators in the building cycle, through the certification of construction techniques and materials that respect living beings and their environment and by raising awareness about the dangers inherent in the traditional building model and the related need to change its methods.

[45] More information on ANAB at: https://www.anab.it/

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Chapter One

Resources

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Chapter Two:

Prefabrication processes and material choice

02.1 Prefabrication - Design for Manufacturing, Assembly and Disassembly

"Prefab has been a recurring idea in housing and construction culture for the nineteenth century to the present day. It has cast a cyclical 'spell' over many in the industry: each successive generation to rediscover prefab applies prodigious amounts of energy to it, only to encounter similar problems and mistakes. Protagonists have been lured to prefab by its transformative potential and core promises - these include better quality, shorter building times, lower cost and special solutions. Recently, these promises have been joined by the potential of more sustainable and individualized solutions." (Mathew Aitchison, 2018).

The word "prefabrication" is often used as a pervasive word that can have different meanings according to context. It is typically associated with the words "off-site", "assembly" or "fabrication" (Smith, 2009). The more common understanding of the word could define prefabrication as a manufacturing process, generally taking place at a specialised facility where various materials are joined to form an element or component that is part of the final installation (Tatum et al., 1986, CIRIA, 1999), or very simply as "made in sections that could be put together later" (OED, 2023). The advent of "prefab" technology has brought a significant revolution in contemporary construction all over the world. This revolution, marked by a reduction in the need for extensive and time-consuming on-site work, was and is all made possible through the effectiveness of off-site manufacturing techniques.

The fundamental concepts of prefabrication revolve around the principles and practices of construction approach. These concepts are centred primarily on efficiency and standardization. As prefabrication practices go hand in hand with the evolution of manufacturing, standardization, mass production and industrialization, some important concepts associated with this design and construction approach are Design for Manufacturing and Assembly (DfMA), and Design for Disassembly (DfD). Design for Manufacturing and Assembly (DfMA) constitutes a methodology that incorporates manufacturing and assembly considerations during the initial planning and design phases, its main aim is addressing potential challenges and intricacies that might arise during production, thereby optimizing factors like quality, time, and overall costs (Bayoumi, 2000). This approach presents similarities to the concept of assessing manufacturability, which evaluates a product's feasibility for effective manufacturing (Cao et al., 2022). Originally rooted in the manufacturing industry (Boothroyd, 1994), this approach has progressively extended its reach into various sectors and also has seen an application in architecture and prefabrication processes (Roxas et al., 2023). The focus when considering the end-of-life shifts towards the DfD allowing for reuse and re-purpose of components. The evolution in more recent years focuses on integration of strategies resulting in Design for Manufacturing, Assembly and Disassembly (DfMAD). This integration allows for optimization at production stage, construction stage and end-of-life stage in one singular design.

Applying these principles to buildings for better integration involves envisioning constructions as interconnected yet separable systems and layers. These systems are commonly categorized as *Site, Skin, Structure, Services,* and *Space* (Brand and Duffy, 1994; Smith, 2009). While prefabrication can be applied to all layers except the site (Smith, 2009), each layer has its distinct lifespan and can be further divided, especially when considering the structure and the skin. The structural layer encompasses the framework that supports the building's weight and load, including elements like columns, beams, foundations, and the overall structural system. The skin layer refers to the building envelope, which includes exterior walls, roof, windows, and doors. It offers protection from the elements, insulation, and contributes to the building's appearance and aesthetics.

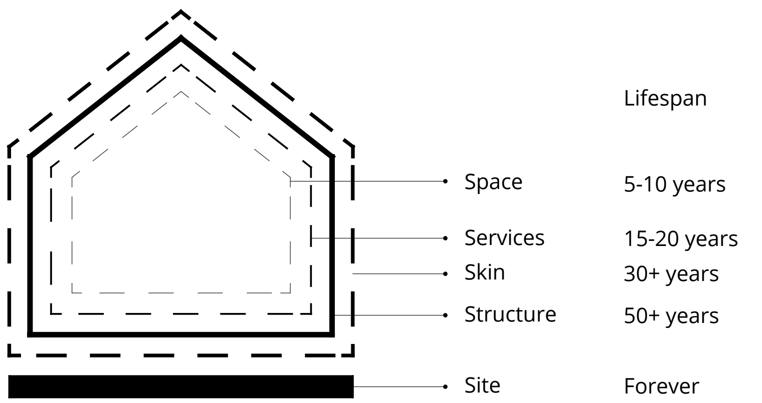


Figure 02.1.1: Building systems - lifespans
Source: made by the author or the thesis in reference to : Stewart Brand and Frank Duffy (1994) and Leti - Circular economy - 1 pager (2022)

02.2 Degrees and prefabrication processes

This thesis takes a specific focus on prefabrication within the context of manufacturing, standardization, and mass production, particularly pertaining to the manufacturing processes of building elements and components at a location separate from the site of assembly (off-site).

Depending on level of manufacturing and the extent of off-site assembling, there are four different categories of prefabrication in construction based on the level of integrability in the construction process and the component usage (Daniels, Bakliwal, Kostiz, Syal, 2020).

In the research paper *A Scientometric Review of Management of Prefabricated Construction from 2011-2021*[1], the authors define these four categories as materials, components, modules and units. These define the degrees of prefabrication and the corresponding work on-site for construction or assemblage (for the purpose of this thesis materials are interpreted as elements).

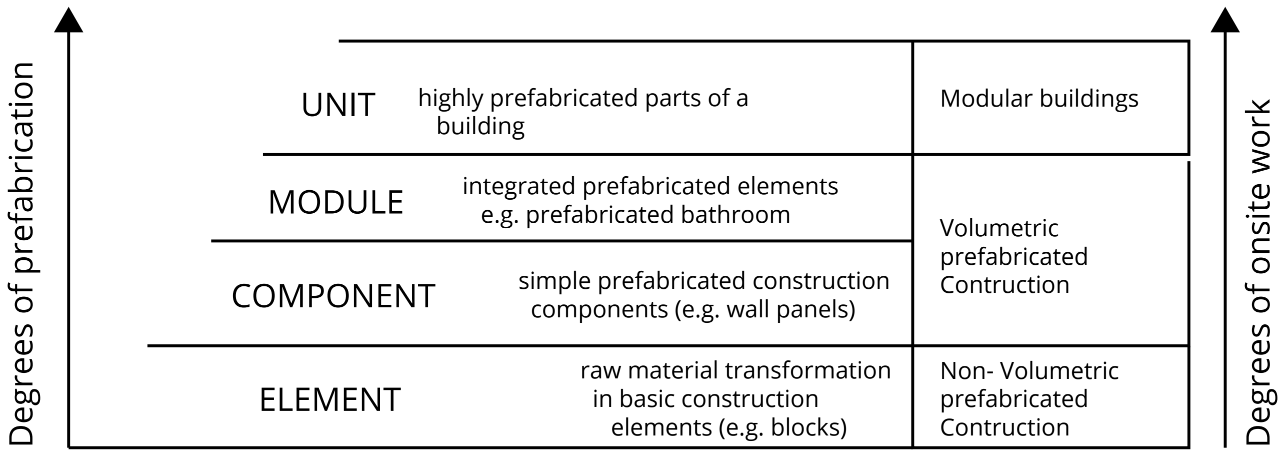
The first element category represents the lowest form of prefabrication. It describes the manufacturing of products from raw materials (e.g. bricks, tiles, plywood). These are considered to be prefabricated because they are pre-manufactured in the factory and then brought on the construction site ready for assembly. These consist of the basic elements of a building.

The second group pertains to components, which are individual parts of a building or other constructed asset created as standalone units, subsystems, or sub-assemblies. These components can be combined or integrated with other elements to form more complex structures (Designing Buildings Wiki, 2022). Examples of components include interior walls and prefabricated slabs.

[1] Li, C.Z.; Li, S.; Li, X.;Wu, H.; Xiao, B.; Tam, V.W.Y.; Asiedu-Kwakyewa, C. A Scientometric Review of Management of Prefabricated Construction from 2011–2021. Buildings 2022, 12, 1515. https://doi.org/10.3390/buildings12101515

The third category involves modules, which refer to rooms or sections of a building resulting from the integration of prefabricated elements and components (e.g., bathroom and kitchen modules).

The fourth and final group represents the highest level of prefabrication, where entire units are constructed in a factory as single or multiple modules. These units are then transported to the site for installation.
For the purposes of this thesis these four categories element,



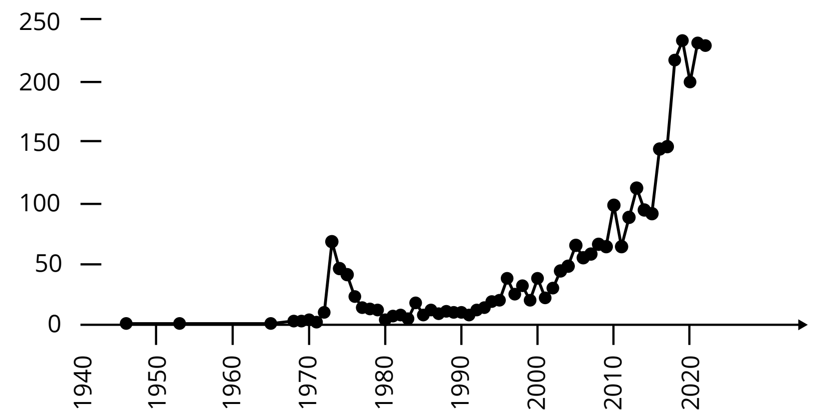
components, modules, units will be the ones referred to. In particular the focus will be on the lowest degree of prefabrication that is materials and components, building characterized by this design could be referred to as modular buildings.

Figure 02.2.1: Degrees of prefabrication
Source: made by the author or the thesis, data information from research paper: Li, C.Z.; Li, S.; Li, X.;Wu, H.; Xiao, B.; Tam, V.W.Y.; Asiedu-Kwakyewa, C. A Scientometric Review of Management of Prefabricated Construction from 2011–2021. Buildings 2022, 12, 1515. https://doi.org/10.3390/buildings12101515

An interesting aspect of componentized prefabrication, with elements and components, allows for the greatest degree of customization and flexibility within the design and execution phases (Smith, 2010).

The evolution of prefabrication in architecture has increasingly developed all over the world. When conducting a research on Scopus on this topic it is possible to notice the increase of publication (including papers, articles, conference papers, reviews, book chapters, short surveys, letters, books, notes, reports, data papers, conference reviews) by searching the key words "prefabrication" in regards of the architectural field, many results arise and when divided by year the growing interest becomes evident.

Figure 02.2.2: Timeline of Scopus publication when searching for "prefabrication" and selecting all topics regarding the architectural field. On the bottom line is the development in years, and on the left line the number of publications.
Source: schema by production of the thesis author, data resource Scopus https://www.scopus.com/search/form.uri?display=basic#basic



It is important to highlight that prefabrication has undergone a significant evolution in terms of sustainability. It is increasingly being recognized as a valuable approach for achieving environmentally conscious construction. Many architects, developers, and policymakers are actively exploring and implementing prefabrication methods to reduce the ecological footprint of buildings. The ongoing research, technological advancements, and a growing emphasis on sustainable practices, the future of prefabrication in architecture seems to be heading in the right direction.

02.3 Prefabrication and environmental impact

An important aspect of material efficiency and circularity is energy efficiency, carbon reduction, waste reduction and recycling or reuse. And although prefabrication is certainly not a synonym of sustainability, in many ways this process, or method, holds potential to contribute to these sustainable ends.

How could prefabrication processes participate in carbon reduction during the WLC?

In the BPIE report titled "Whole-life carbon: Challenges and solutions for highly efficient and climate-neutral buildings," the following diagram elucidates the connections between carbon reduction in the construction sector through the strategies of industrial prefabrication methods.

One of the fundamental potentials of prefabrication lies into delivering buildings that respond to time, change, reuse and recycle, and "this adaptability may be the greatest benefit toward total life-cycle sustainability for future-proofing projects" (Smith, 2010).
Buildings designed considering future adaptation include strategies that are focused on prefabrication as a process that allows: design for disassembly, design for reuse, design for temporality, and design for change. By building in a factory, materials are more easily reduced, reused, and recycled, thus decreasing the waste stream. Prefabrication is a more controlled process and therefore allows for more opportunities

for disassembly and reuse, whether in part or in whole (Smith, 2010).

One important aspect to consider within the “design-for-dis-assemble” assemblage method. In fact, dry construction systems (dry joints) should be preferred when working towards life-cycle thinking. Dry construction systems, as opposed to wet ones, are those construction methods that do not involve the use of water in the assembly process or the use of connection materials that need to consolidate after installation, such as adhesives and mortars. Therefore, make for an easier possibility of reuse a recycling of materials. A method that allows building themselves to become a source of materials throw means of reuse. Design for disassembly is also a very useful strategy as it allows to segregate waste materials directly at the demolition stage of buildings, facilitating appropriate disposal (Grazieschi, 2022).

Prefabrication today, if used mindfully, could be a method to further sustainability of construction from the perspective of the total life-cycle, especially regarding end-of-life, reuse and waste minimization, principles also characteristic to circularity.

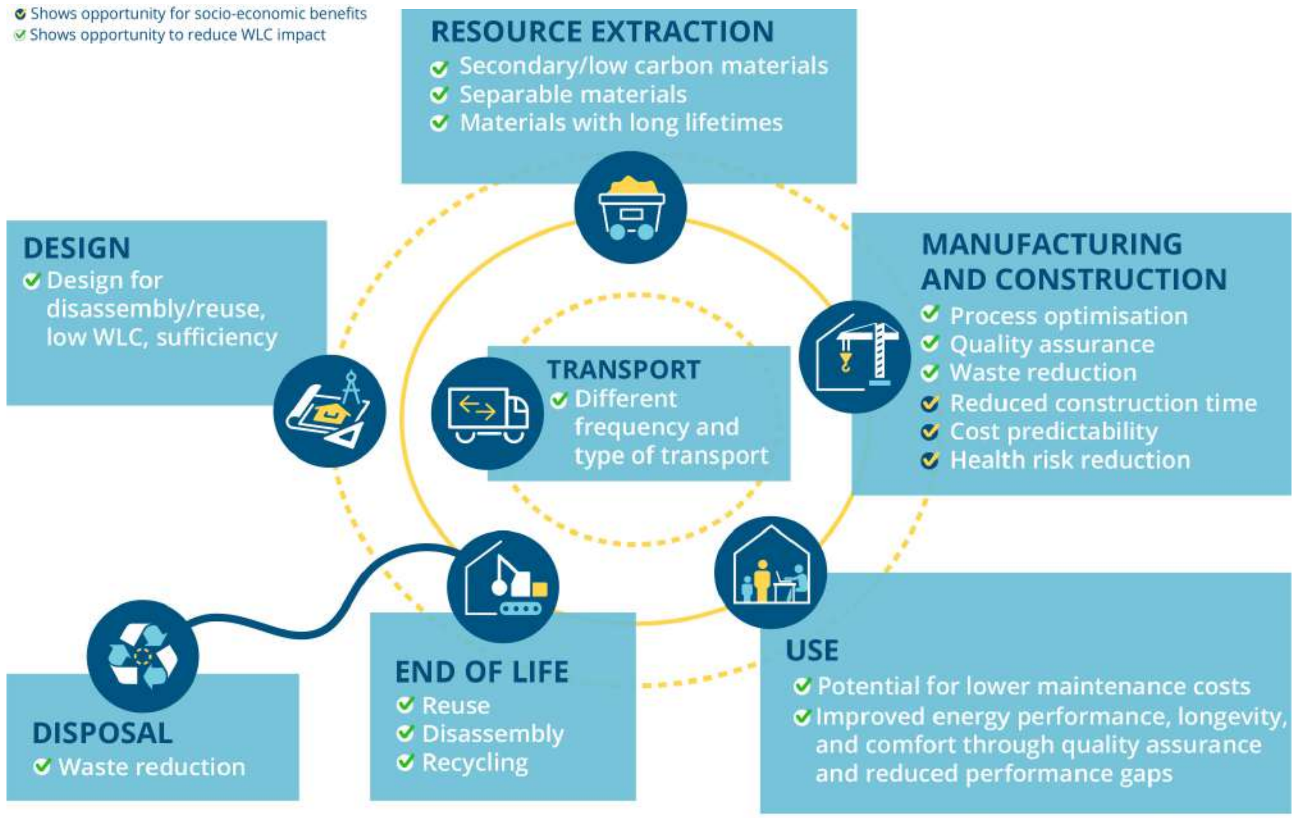


Figure 02.3.1: Links between carbon reduction within the construction sector trough the means of industrial prefabrication processes
Source: Buildings Performance Institute Europe (BPIE). 2021. Whole-life carbon and industrial renovation: Realising the opportunities to reduce the life-cycle carbon footprint of buildings. Full document at: https://www.bpie.eu/publication/whole-life-carbon-and-industrial-renovation/

As stated by R. E. Smith “Environmental impact in building requires a quantifiable measurement of impact in total life-cycle. [...] It stands to reason, therefore, that controlling the means and methods by which buildings are produced trough prefab, architects and construction professionals are able to ensure more sustainable materials and practices for construction as well as have a greater opportunity to predict future energy performance.” In this, the author, touches upon other important aspects as to why prefabrication could be a valuable method toward more sustainable design: providing quantifiable measurements as objective parameters, possibility for better material choices and predictions for future adaptability. Having more control over these aspects could allow for lower embodied (low embodied material choice) and operational energy (optimizing the need for energy and better predictions of consume).

All the professionals involved in the construction sector must understand that they have a huge responsibility towards making smart decisions that allow for less impactful buildings, not only the methodology but also the process.

"Architects are the primary actors in determining the material composition of our buildings and therefore assume the role of primary drivers in the extraction, recycling and processing of specific materials, the manufacture and assembly of components and the construction of our buildings" (John Fernandez[2]).

[2] John E. Fernández is an Associate Professor and Director of the Building Technology Program in the Department of Architecture at MIT and Director of MIT's International Design Centre. He is the author of the book Material Architecture.

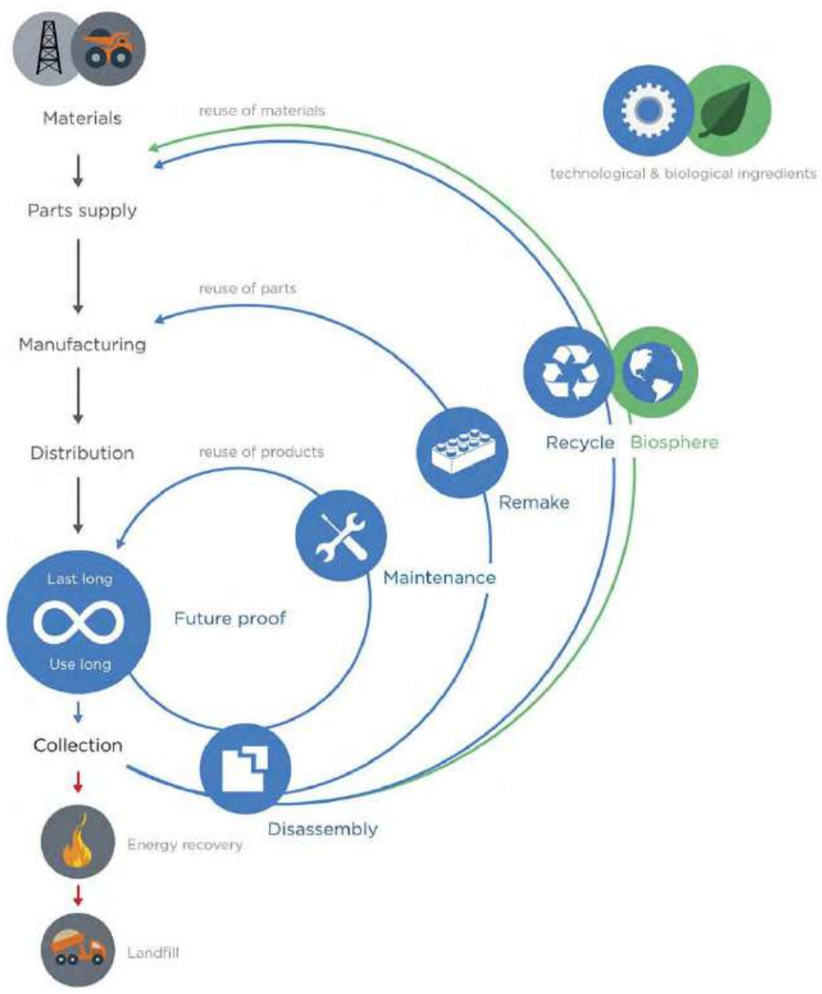


Figure 02.3.2: Prefabrication as a mean towards circularity
Source: Berg, M.V., & Bakker, C. (2015). A product design framework for a circular economy. https://www.semanticscholar.org/paper/A-product-design-framework-for-a-circular-economy-Berg-Bakker/999a66f2a10b8b4bf5435af72010d3c7a9f2ccb2

02.4 Prefabrication and material choice

Over the years, the notion of prefabricated construction has often been linked with images of residential housing and other different times of temporary structures. However, with advancing technology, both the concept of modular construction and the materials employed in its implementation have evolved. Another important consideration has to be made that the implementation of sustainability has seen applications of different strategies and materials. That being said the main building materials utilized in prefabrication can be considered as steel, concrete or cement and wood.

Steel

Figure 02.4.1: Steel modular construction
Source: https://www.steelconstruction.info/Modular_construction

Steel's strength and durability have established it as a prevalent material choice in prefabrication, in particular for constructing long-span and high-rise geometric designs (Smith, 2009). Its inherent ductility enables easy manipulation into intricate designs, offering flexibility in design. Because of its strength and resilience to withstand heavy loads and varying weather conditions, steel finds relevance across a spectrum of applications in residential construction as well as commercial buildings and bridge construction. Steel's enduring structural integrity and adaptability underline its enduring popularity in prefabrication and in architectural projects in general. That being said steel is a highly impactful material from the point of view of production processes and manufacturing of elements and components. Environmental concerns linked to steel production include resource depletion, soil erosion, deforestation (wood for charcoal), and disruption of ecosystems due to raw material extraction (primarily iron). Moreover, the manufacturing process is very energy-intensive. Conventional methods, like blast furnaces, require high temperatures, typically fuelled by coal or other fossil fuels. The combustion of these fuels releases significant amounts of CO_2, contributing to greenhouse gas emissions and air pollution. The steel production process can result in different waste and pollutants, that if not disposed of correctly can lead to environmental contamination of air, soil and water. It is important to consider that steel choice can also involve more sustainable practices. For example, ones that consider mitigation of the environmental impact of steel production such as: Implementing technologies to reduce energy consumption and emissions during production as well as transitioning to cleaner and renewable energy sources to power steel production resulting in a decrease of GHG emissions. Another important implementation is recycling and therefore encouraging the use of recycled steel in order to reduce the need for resource-intensive mining and energy-intensive production.

Concrete

Prefabricated concrete components are characterised by stability, fire resistance, and design adaptability. The mouldable nature of concrete allows for flexible and tailored solutions to comply with different applications and project requisites. As concrete is a brittle material it is reinforced with steel and it can be pre-cast into panels, beams, columns frames and modules. Even though concrete is one of the most used building materials in the sector, it is a very impactful material for both large utilization and requests but also for linked environmental concerns. The production of concrete is associated with resource extraction and depletion (aggregated comprises sand, gravel and limestone). Cement manufacturing involves high heat, therefore consumes a lot of energy and results in GHG emissions. Compounds released from cement kilns result in air pollution. High water usage strains local water resources, and waste generation poses disposal challenges. To address these concerns, exploring alternative materials, integrating with recycled materials, improving efficiency as well as utilizing clean energy sources, and responsible sourcing of raw materials are key aspects to lower environmental impact.


Figure 02.4.2: Concrete modular construction
Source: https://megaprefab.com/

Wood

Wood is the most know and utilized bio-based building material. It has been part of building traditions worldwide for many centuries. The utilization of wood is to this day very established and suited for many different applications. Wood can be processed into beams, columns, panels frames and modules. Furthermore, engineered wood products, such as cross-laminated timber (CLT) and Glulam beams, provide high strength-to-weight ratios, making them suitable for various structural


Figure 02.4.3: Wood modular construction
Source: https://www.sipeurope.eu/en/se-sip-construction-system/using-sip-system/modular-buildings/

applications. Wood has been prefabricated ever since it was first harvested, the process of taking tree logs for staking and processing them into timber frames and construction is by no mean a thing of recent history (Smith, 2009). Incorporating timber components into a project presents a chance to decrease the overall embodied carbon impact of new and renovated constructions. In comparison to steel and concrete, timber is associated with lower carbon emissions, and it possesses the added value of capturing carbon during its growth phase (carbon sink). However, it is crucial to pay significant attention to timber sourcing and its complete life cycle to ensure the material's low carbon and general environmental advantages are effectively achieved (Leti, 2023). It is recommended to source timber from forests managed sustainably, following certified schemes like FSC or PEFC. This guarantees that any forests used for building timber production are derived from sustainable sources or recycled materials. When choosing timber, it is essential to consider the material's durability and lifespan. Factors like weather resistance, susceptibility to insects, and temperature/humidity regulation as these can influence the integrity of paints, finishes, external coatings, and the overall service life (Leti, 2023).

As with other building materials, it is recommended to use local raw materials and supply chains. However, considering that opting for local suppliers does not always ensure the lowest carbon emissions, as alternative suppliers might employ more efficient production methods powered by renewable energy sources these could be the favourable choice. Moreover, considering the different typologies of wood worldwide that are suited for different applications, the importation and exportation of wood products are very well established. Although estimating emissions and environmental impact linked to transportation at the design phase might be difficult, ensuring that this aspect does not counteract the benefits of using said material is very important. Therefore, preferring low-carbon transportation and raw materials from a sustainable forest could also allow for the importation exportation to be part of good practices, but this has to be carefully considered. It is not easy to ensure eco-compatibility, however, regulations and certifications can help make a conscious and better decision.

As of today, there are different entities that are embracing and integrating product declarations and sustainability for tropical or foreign wood, for example, ATIBIT[3] which is a trade association that promotes the development of a sustainable, ethical and legal industry of tropical timber, or An Amazon Initiative[4] which promotes sustainable forestry in the Amazon, HelpDesk[5] which promotes the use of sustainably produced wood by making more knowledge available to suppliers. These associations or entities provide data such as LCAs and EPDs of wood that comes from foreign and tropical places (Not only in the EU).

[3] More infromation at: www.atibt.org

[4] More information at: https://www.amazoninitiative.org/

[5] More information at: https://www.vvnh.nl/Milieu-Helpdesk

"Prefabrication as a production method in itself is not sufficient to ensure lower embodied and operational emissions of (new) buildings, as it is possible to prefabricate highly inefficient buildings with high embodied carbon materials. Therefore, it is important to identify and incorporate emissions reduction potential during the whole-life of a prefabricated building or renovation (i.e., whole-life carbon)" (BPIE, 2022)[6].

[6] Buildings Performance Institute Europe) (2022). Whole-life-carbon and industrial renovation. Full document at: https://www.bpie.eu/publication/whole-life-carbon-andindustrial-renovation/

The author R. E. Smith writes that "prefabrication can be accomplished in virtually any material", furthermore he states that "the primary material compilation determines the flow of the material through its lifecycle from who harvests the materials, manufactures, fabricates, and finally installs it", and he also points out a very essential aspect of prefabrication:

"Although prefabrication may save on material waste, **it does not say anything about the environmental impact of materials used in construction** other than the distance of transportation from shop to construction site".

Today's mainstream industrialized production is mostly limited to handle certain types of materials, this stems from the market request and also the "tradition" set in stone in a slow changing industry. Therefore an effective use of prefabrication processes requires rethinking the initial stages of the design process. Moreover, implementing material substitution, as material efficiency strategy, could help further the sustainability of the prefabrication processes.

The architect Michelle Kaufmann[7] was one of the first to talk about prefabrication and sustainability as an integrated concept. In her book Prefab Green, she deepens this concept through the "5 Eco-principles". These are: smart design, eco-materials, energy efficiency, water conservation, and healthy environment.

When we think of eco-materials what do we mean?

As defined in her book Michelle Kaufmann refers to ECO MATERIALS as: renewable and long-lasting materials, sustainably harvested and recycled materials, and also that take into consideration waste reduction, and design that primarily uses less and allows for reusing elements.

[7] The architect Michelle kaufmann is the founder of the studio Michelle Kaufmanns designs where she successfully designed and built single-family and multi-family green homes using prefabricated modular technology. She also is leading sustainable architect working on scalable innovations to deliver on Google's 2030 Carbon aspirations and the hybrid future workplace.

She states that "it takes more than using recycled products to create an eco-friendly material. We must consider the entire life cycle of a product or material before deeming it sustainable. The life cycle of a product includes how the original raw material was obtained, the refinements made to the material, its shipping and installation, the material's use, and finally its disposal and recycling capabilities. Very similar eco-friendly products can have widely different environmental impacts."

So, what is an ECO MATERIAL? A material is eco-compatible if it requires a reduced energy content in the different phases

of its life cycle and in particular during the off-site production process (Giordano, 2010).

Therefore, a category of eco materials could be the one of natural and bio-based materials (e.g. rammed earth, wood and hemp), as these are often characterized by a production process of products that results in lower emissions of carbon and at times overall pollutants if compared to other commonly used building materials (e.g. concrete and steel). Therefore, material substitution could reduce the demand for impactful materials. If the substituted material has lower production emissions, then substitution also reduces emissions per unit of material used.

When considering prefabrication processes, as pointed out by R. E. Smith in his book *Prefab Architecture: A guide to modular design and construction*, the use of the "pre" in prefabrication implies that fabrication was in fact happening onsite.

Often elements made with natural materials are still being manufactured onsite. An example of this are rammed earth walls.

How are rammed earth walls usually constructed?

Figure 02.3.4: Building process of rammed earth walls
Source: https://madeinearth.in/topics/techniques/rammed-earth/

With the premise that there are many techniques for building an earth wall; one example of onsite construction can refer to rammed earth walls [Figure 02.3.1].

Rammed earth walls are constructed by ramming a mixture of selected aggregates, including gravel, sand, silt, and a small amount of clay and cement for stabilization, into place between a wooden formwork of two flat panels and then compressing this mixture with a wooden pole repeatedly.

The end product of the rammed earth wall has great advantages such as thermal inertia (when built with high thermal mass), good fire resistance, load-bearing structure, reduced use of water needed for construction, and very importantly earth can be recycled or composted (when there are no polluting additives). However, it also has disadvantages such as a time-consuming build, labour-intensive build that requires skills and makes the process relatively expensive, need for onsite storage space for the mixture while constructing, lack of regulation and certification, and also the use of this technique is limited to material availability onsite (or near the site).

To overcome these limits but still take advantage of the use of this building material a valuable solution could see prefabrication processes involved in the construction.

The architect Anna Heringer[4] in her book Upscaling earth: material process catalyst states referring to insitu construction,

"such an approach is not realistic for many industrialized parts of the world, where labour is expensive. In such contexts, prefabrication is more appropriate, representing the opposite end of the gradient between labour and technology: the ability to deliver component rammed earth elements."

She believes that the prefabrication process optimizes production and construction but also importantly allows for material consistency and higher-quality outputs, which are very important for achieving industrialized norms and standards, that ultimately are fundamental to "*upscale earth*".

[4] The architect Anna Heringer is the founder of Anna Heringer Architecture, she is one of the leading architects in sustainable architecture and the use of natural materials.

Figure 02.3.2: Robotic ramming system by ERNE
Source: Mohamed Gomaa, Sascha Schade, Ding Wen Bao, Yi Min Xie, Automation in rammed earth construction for industry 4.0: Precedent work, current progress and future prospect, Journal of Cleaner Production, Volume 398, 2023, 136569, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2023.136569

Figure 02.3.3: The Ricola Kräuterzentrum in Laufen Swizerland built with prefabricated rammed earth panels. Project by the architects Herzog & de Meuron and Martin Rauch.
Source: https://www.archdaily.com/634724/ricola-krauterzentrum-herzog-and-de-meuron

The project for the Ricola Kräuterzentrum in Laufen Swizerland by the architects Herzog & de Meuron[8] in collaboration with Martin Rauch[9] is a valuable example that showcases the innovative use of rammed earth walls as a result of prefabricated construction processes.

Over the years the topic of prefabrication processes and natural materials has characterised an ongoing debate.

The argument in regards to the sustainability and ethical perspective of industrializing the use of natural and bio-based materials sees two contrasting opinions. While supporters argue that industrializing production of natural building materials can enhance their production efficiency, time efficiency in the building process, reduction of waste Furthermore, by utilizing advanced manufacturing processes, it becomes possible to optimize the use of resources, reduce energy consumption, and decrease carbon emissions associated with transportation while lowering environmental impacts when substituting other more impactful material in commonly used in the sector (e.g. concrete and steel), and allowing for consistency and quality control. However, critics argue that industrialization may still involve energy-intensive processes and the use of potentially harmful chemicals, which can undermine the environmental benefits of natural materials when constructed with more traditional and craft building techniques. Additionally, advocates of the latter point of view, argue that promoting locally sourced and handcrafted materials can support local economies, preserve cultural heritage, and foster community engagement. Prefabrication, especially when centralized in large-scale factories, may undermine these local economies and traditional craftsmanship.

Although this debate is very complex, both perspectives must be taken into consideration: the key is and should be a balance of sustainability principles, ethical sourcing, responsible man-

[8] Herzog & de Meuron is an international architectural practice based in Basel, Switzerland, more information at: https://www.herzogdemeuron.com/

[9] Martin Rauch is the principal and founder architect of Lehm Ton Erde architectural studio in Austria. He is known in the field for construction in rammed earth.

ufacturing practices, local economies and crafts, and maintaining the intrinsic qualities of natural materials as crucial factors in determining the overall impact and appropriateness of prefabrication in the context of bio-based and natural construction materials.

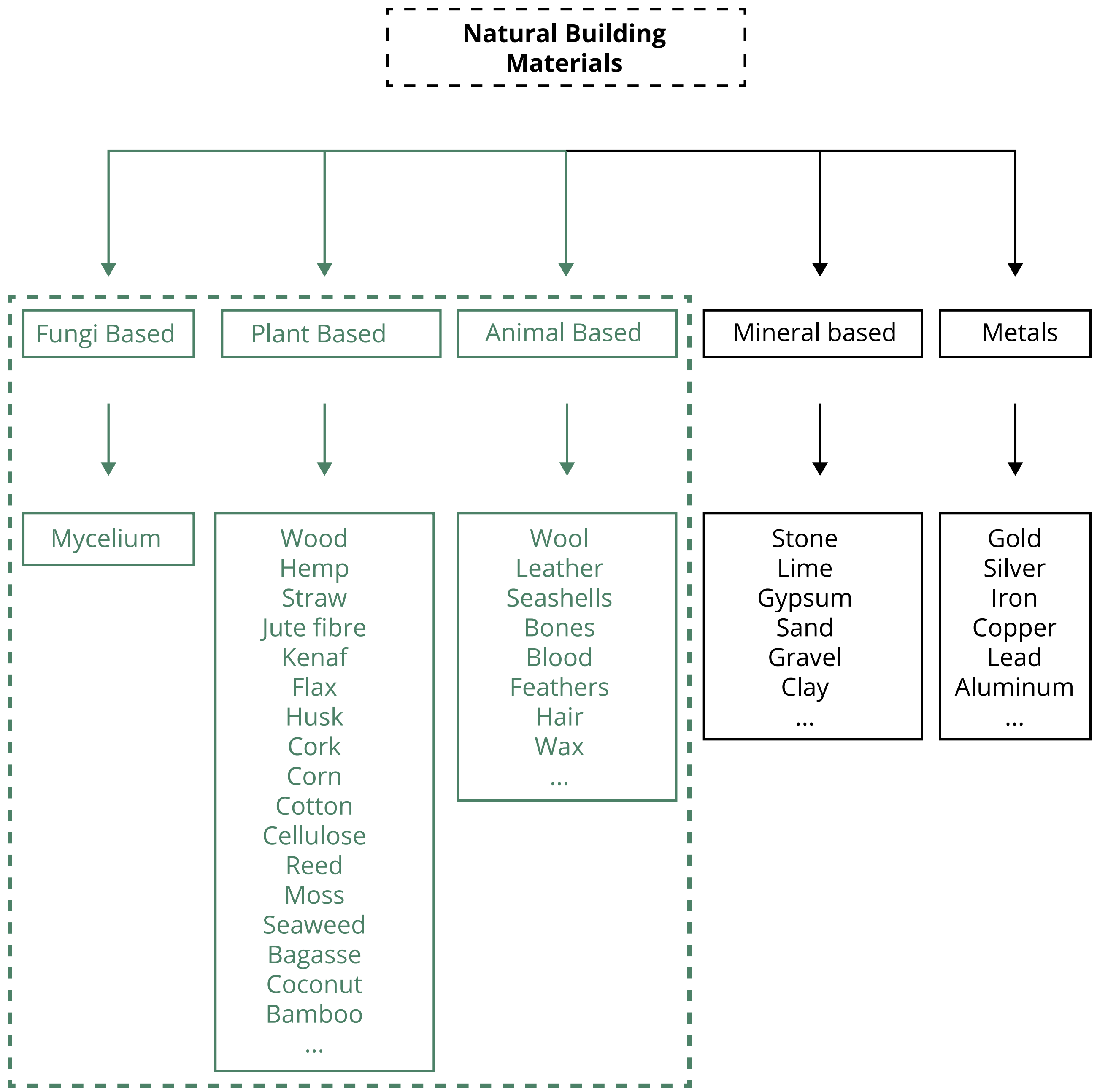
The central theme of this thesis revolves around the synergy between prefabricated processes and the utilization of natural materials, particularly bio-based materials, as substitutes. It examines the potential of this integration to expand the adoption of such materials and significantly reduce the environmental impact of the overall building industry

What are bio-based materials?

A bio-based product (from the Greek term βίο meaning life), is made partly or entirely from materials sourced from plants, animals, or other living organisms – collectively known as biological material. These products can undergo physical, chemical, or biological processing (Nordic Ecolabeling, 2023), and if left untreated, they are referred to as biotic material.
Although the use of bio-based materials, like other natural materials, in the construction industry is a valuable option it could still be considered a niche and developing sector limited to: material availability, lack of regulation, cost, skills and craftsmanship knowledge and at times inefficiency in the production process. Very often these materials are linked to tradition and vernacular architecture, the use in new buildings is relatively limited and is usually not considered at a large scale.

As some material efficiency strategies contribute not only to reducing material demand and waste generation but also reducing the environmental footprint of materials manufacturing, the question becomes: Can the integration of prefabricate processes of different parts of buildings and the strategy of material efficiency as material substitution, specifically the use of bio-based materials, result in an upscale of use of these materials, allowing for systematic change and possibly a positive and reduced impact on the environment of the overall building sector? How can prefabrication help the upscale of the use of bio-based materials?

Key message: Prefabrication, as a design and construction approach, can aid and implement sustainability practices but at the same time when considering the use of bio-based materials it can improve quality control, physical-mechanical properties, cost-effective and efficient manufacturing processes that could result in upscaled production (even mass production) and broadening adoption of bio-based material, therefore making them a feasible choice, in terms of availability, cost and time efficiency as well as standardized solutions.



Bio-based

A **bio-based** (from ancient greek βίο meaning life) product is wholly or partly made of material from plants and animals or other living organisms, so-called biological material. The product can be processed and treated physically, chemically or biologically (Nordic Ecolabeling, 2023). Can also be referred to as **biogenic**: produced by living organisms (EU, 2023)

Figure 02.3.4: Natural building materials and bio-based materials
Source: Drawing made by the author or the thesis

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Resources

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Part two

"We are beginning to use by-products of living systems as materials for design. The quest for sustainability and an ecological approach for design for design models is leading us towards a scenario where biological manufacture replaces industrial manufacture and living entities are engineered to grow materials and products. Designers and material innovators are mimicking the close-loop, circular systems found in the natural world to enable the production of biodegradable material..."

Kate Franklin and Caroline Till
Radical Matter: Rethinking materials for a sustainable future

/

Bio-based materials and prefabrication **guidelines**

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Chapter three:

Bio-based definition and introduction

03.1 Material substitution: Bio-based building materials

As previously mentioned, **bio-based materials** are products that derive from biological matter of plants or animals. These organic constitutes can be defined as renewable sources as they can both be replenished and replace the portion depleted by usage and consumption within a short period of time.

The use of bio-based materials ultimately constitutes to a new model of industry and economy: the **bio-based economy.**

Professor D. Jones[1] in the paper "Performance of bio-based materials – Products meeting expectations" states that Europe will lead the transition to climate neutrality by investing in realistic technical solutions, and one of the strategic building blocks identified to reach net-zero emissions is to utilize the benefits of the bio-economy, where improved utilization of the bio-based resources is essential.

As defined by the Bio-economy Council "The bio-economy is the knowledge-based production and use of biological resources to provide products, processes and services in all economic sectors within the frame of a sustainable economic system."

In many ways the bio-based sector or bio-economy, could be a catalyst for systemic change because it opens new ways of producing and consuming resources while respecting our planetary boundaries. So, it should contribute directly to achieving the economic, social and environmental goals of the European

[1] Dennis Jones is an Associate Professor at Luleå University of Technology, based in Skellefteå, Sweden. He has worked in areas related to wood science and technology and bio-based materials for nearly 25 years, having worked for research institutes and universities in the UK, Sweden, Denmark and The Netherlands. He was the Chair of COST Action FP1303 (Performance of Bio-based Building Materials) which concluded in 2017, and is also Vice-Chair of COST Action FP1407 (Understanding wood modification through an integrated scientific and environmental impact approach (ModWoodLife)) which will conclude in 2019.

Union's Green Deal (Pacevicius, 2022).

"Moving from a current reliance on the non-renewable materials of the geosphere, to the renewable and fundamentally cyclical materials of the biosphere can establish alternate foundations for thinking alternative sustainable building practices." (Thomsen and Tamke, 2022).

Shifting from fossil fuels to a bio-based economy has the potential to contribute to indipendance from fossil fuels whilst advancing sustainability and playing a substantial role in climate and environmental preservation. This approach places emphasis on the significance of biogenic material flows.

Where do bio-based materials come from?

The origin and resources of raw bio-based materials vary significantly.
Bio-based materials can be **harvested** from renewable sources, materials like wood, bamboo and cork, and can be used in the form they grow in or subsequently the primary raw material undergoes production processes to be transformed into building materials (1st generation).

These production manufacturing processes result in primary elements and components but also waste outputs. This waste is defined as **by-product** as it is often recovered and reused as a base of more building materials (for example wood scraps are combined with additives and transformed into particleboards) within the process to manufacture building materials. A by-product is defined by the European Commission glossary as: "an incidental product deriving from a manufacturing process or chemical reaction, and not the primary product or service being produced. A by-product can be useful and marketable, or it can have negative ecological consequences".

When considering circularity perspectives, reuse, recovery and recycling are essential. Bio-based materials in the building industry largely derive from by-products resulting from the waste of other industries and production processes (2nd generation).
A large quantity of bio-based building materials derives from crop cultivation for the agro-food industry waste as a by-product of production processes of food and feedstock, for example, straw, flax fibre, rice husk, seashells, wool and hemp fibres. Another set of bio-based materials is a by-product of the textile industry, plants like cotton, hemp, kenaf, and wool.

Ultimately, there are other materials like algae and mycelium that grow spontaneously or are purposely cultivated. These materials hold the potential to be transformed into bio-based building materials and find applications across various industries as substitutes for conventional materials.
Considering the diverse origins of these bio-based materials and the fact that they all originate from renewable resources,

they offer a substantial contribution to the principles of circularity and decreasing dependence on non-renewable resources significantly favouring the transition towards a bio-economy.

In the paper *Performance of bio-based building materials*[2] – products meeting expectations written by the Professor Dennis Jones he states that "the use of bio-based materials provides the capability to mimic and exploit properties that have evolved in nature to provide certain performance characteristics."
D. Jones also states that "among the advantages of these bio-based materials are that they are renewable, almost globally distributed in a variety of forms, easily sourced, readily adapted to needs of use, hydroscopic, recyclable, versatile, porous and non-abrasive". Furthermore, he offers an understanding on the potentials of bio-based materials within the construction sector and the linked benefits:

[2] Full document at: https://journal.augc.asso.fr/index.php/ajce/article/download/1101/655/

• Capturing and storing carbon drawn from atmospheric CO_2 during recent photosynthesis.
• Sustainable production from crops grown annually or through longer harvest-cycle foresting, including secondary products derived from food growth.
• Biodegradability upon reaching the end of its service life.
• Exceptionally low or nearly zero linear coefficients of thermal expansion, often comparable to or superior to many synthetic products.
• The ability to regulate temperature and humidity within enclosed spaces due to phase changes of water and moisture within cell walls.
• High vapour diffusivity and effective vapour dispersal.
• Relatively high specific heat capacity.
• Low thermal diffusivity.
• Outstanding performance-to-weight ratios.
• Generally lower embodied energy compared to synthetic or man-made materials.

These are general benefits of bio-based materials, but more specific performance information of these materials depends upon the chemical constituents within their structure (Jones and Popescu, 2017).
Being as building materials affect the indoor environment, there seems to be a link between the use of bio-based materials and indoor air quality as they affect indoor climate (i.e. thermal comfort, acoustics, moisture regulation) (Jones, 2019).
Consequently, as stated by the European Commission, Europeans spend 90% of their time indoors and therefore the use of bio-based materials could have the potential or contribution, not only to positive environmental impact, but also to positive human health impacts within the built environment (S.L. Bardage, 2017).

03.2 Closed and short loop of biotic materials

“We need to build differently, and use local, bio-based and recycled materials to create local jobs. We need to move towards circularity.” (Inger Andersen, 2021)

Terms such as circular economy are often associated with bio-based materials for the reason that fundamentally, bio-based materials are about closing and creating short loops (Material District, 2014). In fact, using biotic materials contributes to conserving resources and also producing less waste, as these compounds are usually biodegradable and can therefore be composted and return to nature. Consequently, the untreated biotic materials cycles are closed.

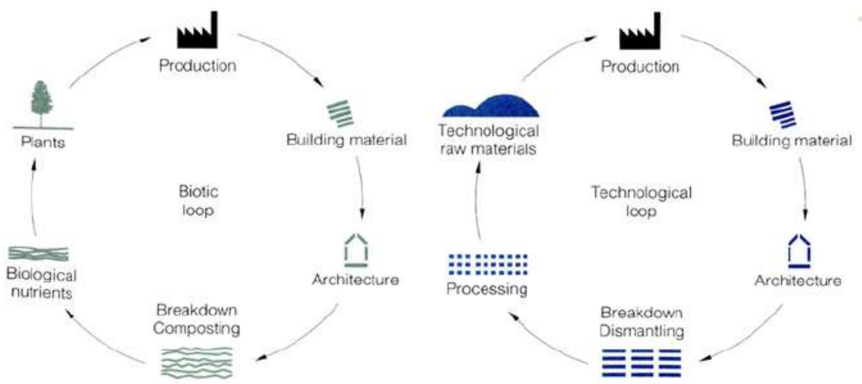

Figure 03.2.1: Recycling potential of biotic materials and technical recycling cycles, following the cradle-to-cradle strategy of Braungart and McDonough
Source: Hillebrandt A., Riegler-Floors P., Rosen A., Seggewies J., (2019). Manual of Recycling: Building as Sources of Materials, Edition Detail, Detail Buisiness Information GmbH, Munich, p. 60

When considering biotic materials, it could be said that it is borrowing from nature and the natural cycle of the sources, as bio-based products (when made of biotic materials) at end-of-life are to be returned to nature. However, even when considering benefits it also has to be considered a risk that cultivating certain plants or animals in an intensive because of profits and use way may lead to displacement of other species from habitats. This could ultimately lead to a biodiversity decline and deforestation, habitat alteration and soil erosion, and overall damage to ecosystems. Therefore, the cycles of materials deriving from plants and animals are only closed when the sources are harvested sustainably and in a controlled manner that sees resource regeneration and regrowth.

In order to prevent risks and contribute to using products whose materials come from sustainably harvested sources there are environmental declarations and certifications to refer to (see Chapter 03.4 Labels and standards related to bio-based products).

Figure 03.1.2: Philip Ross Molds Fast-Growing Fungi Into Mushroom Building Bricks, these bricks are biodegradable
Source: https://inhabitat.com

Figure 03.1.3: Ross grew the fungus Ganoderma lucidum (or Reishi) into bricks at the Far West Fungi mushroom farm in Monterey, California
Source: https://inhabitat.com

03.3 Environmental impact of bio-based building materials

As previously discussed, bio-based products, including bio-based materials, bio-energy or bio-fuels, and bio-based chemicals, have the potential to serve as substitutes for fossil-based chemicals. This substitution could play a role in moving towards a low-carbon economy, offering the opportunity to address global issues such as the depletion of abiotic resources. (Shikha, Ranaprathap, Seeram, Mohan, 2020).
The use of bio-based materials in building construction is perceived as a good alternative to GHG intensive ones (Grazieschi, 2021; Peñaloza, 2016) when considering their carbon capture capabilities. Materials such as wood, soil, clay, cellulose, sheep wool and hemp are expected to play an increasing role in the building sector (Grazieschi, 2022).

Why are bio-based materials considered to be a better choice?

Bio-based materials constitute a potential strategy to reduce the embodied impacts of buildings and substitute conventional, fossil fuel-based construction materials (UNEP,2021).
Despite the fact that manufacturing processes are different for distinct bio-based building materials, many of them are characterized by a lower use of energy (and CO_2 dispersal) than conventional materials. In fact, Bio-based building material products have the advantage of a significantly lower carbon footprint than steel, glass, or concrete (Tellnes et al. 2017).

Bio-based building materials not only usually require lower energy consumption during manufacturing and operational life of the building (when considering their thermo-hygrometric behaviour that contributes to an energy-efficient building), but also can contribute to carbon sequestration.

What is carbon sequestration?

Carbon sequestration is the long-term storage of carbon in plants, soils, geologic formations, and the ocean. Carbon sequestration occurs both naturally and as a result of anthropogenic activities and typically refers to the storage of carbon that has the immediate potential to become carbon dioxide gas (Selin, 2023). Reservoirs that retain CO_2 are know as carbon sinks. Carbon is transferred naturally from the atmosphere to terrestrial carbon sinks through photosynthesis; it may be stored in aboveground biomass as well as in the soil (Selin, 2023). Plants (as a form of biomass) are carbon sinks because as they grow the carbon is stored in the plants themselves, this is referred to as biogenic carbon.

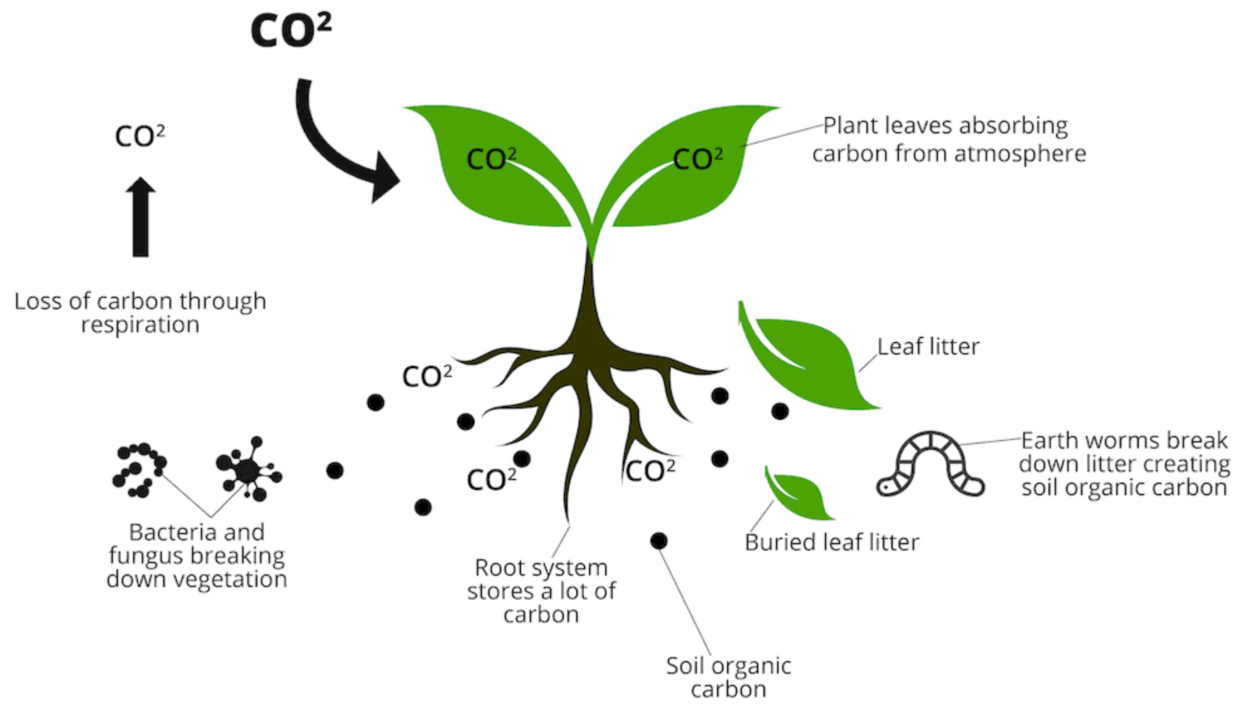

Figure 03.3.1: Infographic of photosynthesis
Source: https://www.greenelement.co.uk/blog/soil-carbon-sequestration/

Consequently, many bio-based building materials, as they are made of plant fibres, are considered to be "carbon sequestering materials", meaning they store biogenic carbon. Within building products, the presence of biogenic carbon can be seen as a "negative emission," as it involves the storage of carbon within the material during its growth stage.
As previously mentioned even considering the many advantages of bio-based materials, they still have some impact (Stafford, 2009), in fact, these contribute to many environmental concerns like deforestation, desertification and soil erosion, habitat alteration and loss of biodiversity (see Chapter 01.1 Climate change, future scenarios, under environmental indicators). Some of these consequences can be attributed to indus-

trial cultivation of biomass in regards to the intensity of land use and but also linked to other factors like the use of fertilizers and pesticides.
When assessing the environmental impact of bio-based materials and more specifically biomass feedstock, defined as any renewable, and biological material that can be used directly as a fuel, or can be converted to another form of fuel or energy product from raw material to supply for a machine or industrial process, it is important to consider that the combustion of these materials at the end of life does result in emissions of CO_2.

So, what is the difference between emissions related to fossil fuel combustion compared to one linked to biogenic carbon combustion?

As previously mentioned, biogenic carbon represents carbon that is stored within biological materials, including plants and soil, accumulated through the process of photosynthesis. It specifically refers to carbon derived from renewable or organic sources, such as plants or biomass, that are integral to the natural carbon cycle. When this biogenic carbon is released into the atmosphere through activities like combustion or decomposition, it has the potential to contribute to the overall greenhouse gas emissions. The conversion factor used to calculate the equivalent amount of carbon dioxide (CO_2) emissions from biogenic carbon indicates that for every kilogram of biogenic carbon released, it is considered equivalent to 44/12 kilograms of CO_2 in terms of its impact on the climate. The conversion factor allows for a standardized comparison of the emissions from biogenic carbon with those from CO_2.The ratio 44/12 corresponds to the molecular weight ratio of CO_2 to carbon. CO_2 has a molecular weight of 44, while carbon has a molecular weight of 12. By multiplying the mass of biogenic carbon by this conversion factor, it provides an estimate of the emissions in terms of CO_2 equivalents (CO_2eq.), facilitating comparisons and calculations in greenhouse gas inventories and environmental assessments (refer also to standard EN 15804).

It's important to underline that biogenic carbon has a different carbon footprint compared to fossil carbon (figure 03.3.2). While burning fossil fuels releases carbon that has been sequestered over millions of years, burning bio-based materials only releases the carbon that was absorbed from the atmosphere during the plant's growth cycle. Therefore, bio-based products and bioenergy derived from sustainable resources can play a role in reducing carbon emissions and contribute towards transitioning to a low-carbon economy (IEA Bioenergy, 2023).

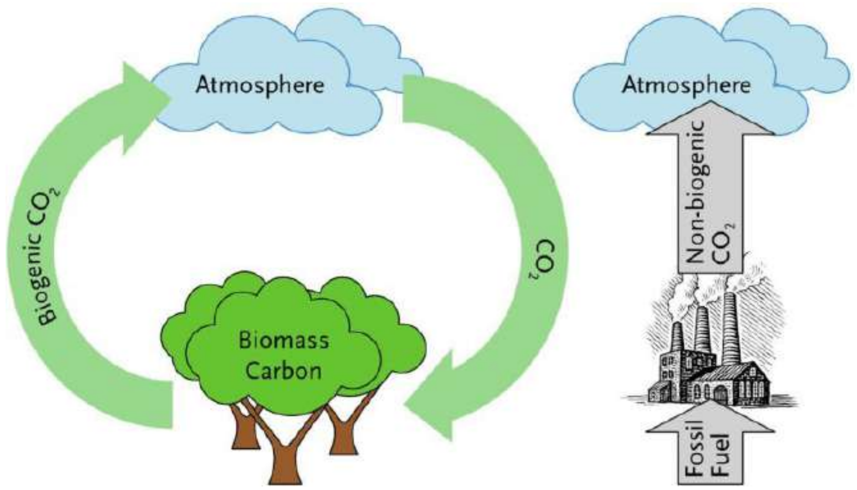

Figure 03.3.2: Fossil vs Biogenic CO2 emissions
Source: https://www.ieabioenergy.com/iea-publications/faq/woodybiomass/biogenic-co2/

[3] P. Pawelzik, M. Carus, J. Hotchkiss, R. Narayan, S. Selke, M. Wellisch, M. Weiss, B. Wicke, M.K. Patel (2013),
Critical aspects in the life cycle assessment (LCA) of bio-based materials – Reviewing methodologies and deriving recommendations, Resources, Conservation and Recycling, Volume 73, Pages 211-228, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2013.02.006

[4] Diego Peñaloza, Martin Erlandsson, Andreas Falk (2016), Exploring the climate impact effects of increased use of bio-based materials in buildings, Construction and Building Materials, Volume 125, Pages 219-226, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2016.08.041

Referenced in the research paper titled *Critical elements in the assessment throughout the life cycle of bio-based materials – A review of methodologies and establishment of recommendations* (2013), and subsequently discussed in the research titled *Investigating the climate effects of increased utilization of bio-based materials in buildings* (2016), the proper management of biogenic carbon is of utmost importance in conducting life cycle assessments (LCAs). This management aids in quantifying the emissions of greenhouse gases related to bio-based materials and facilitates their comparison with products derived from petrochemical sources. In the latter study, the authors contend that in using Life Cycle Assessment (LCA) to evaluate the climate impact of buildings, those incorporating a higher proportion of bio-based materials demonstrate a reduced impact. Traditional LCA approaches tend to neglect considerations such as biogenic carbon exchanges, their patterns over time, and the consequences of carbon storage (Peñaloza et al., 2016).

This underlines an important aspect to consider when assessing bio-based materials: yes, they could initially be considered carbon negative, but at their end-of-life if disposed throw combustion the biogenic carbon once stored in the biomass is again released and therefore must be contemplated.

In conclusion, there are many positive aspects of using and up-scaling bio-based materials in the building sector, but like everything this has to be certified and controlled to avoid and prevent environmental indicator always remembering that a strategy can have positive impact when consciously applied.

03.4 Labels and standards related to bio-based products

In 2013 IEA Bio-energy conducted a report of standardisation and certification for bio-energy and bio-fuels ("Monitoring Sustainability Certification of Bio-energy" by Task 40).

Subsequently, a focus on standards and certification on bio-based products was provided in 2018 by the report *Standards and Labels related to Bio-based Products: Developments in the 2016-2018 triennium*[5] published by EIA Bioenergy task 42. The aim of this report was to provide some useful information about existing standardisation approaches for bio-based products and policies that have been put in place to drive the transformation of the worldwide economy towards a bio-economy.

[5] Full documenta t: https://www.ieabioenergy.com/wp-content/uploads/2018/10/Standards-and-Labels-related-to-Biobased-Products-2016-to-2018.pdf

More information on bio-based content certification can be found at: https://biobasedcontent.eu/en/certification/testing-laboratories/

Standardization is an important tool for establishing requirements for products, services, or procedures. It is used to define benchmarks and criteria to promote consistency across industries and enabling systematic change. Standards serve as valuable resources by outlining specifications and technical details for a wide range of products, materials, services, and processes. They provide a basis for mutual understanding among individuals, businesses, public authorities, and other organizations. Moreover, standards facilitate effective communication, commerce, reliable measurement and testing, as well as efficient manufacturing processes (IEA Bioenergy, 2018). All these are key aspects for up-scaling and transitioning to the use of bio-based material and more in general to the bio-economy.

Bio-based content

The European standard EN 16785-1:2015 "Bio-based products - Bio-based content - Part 1: Determination of the bio-based content using the radiocarbon analysis and elemental analysis" describes the requirements for the determination of the biological content of a given product.

In the context of EN 16785, the designation "biologic" signifies "originating from biomass." A bio-based item comprises, either entirely or partially, of substances sourced from biomass. This criterion is relevant to all solid, liquid, or gaseous products that encompass carbon, thereby encompassing a diverse array of items.

Under this guideline, the biological content of a product is measured using EN 16640[6]: Bio-based products - Carbon content of biological origin - Determination of carbon content of biological origin using a method based on radiocarbon 14C6 (also see standard EN 15804).

[6] More information on bio-based content certification can be found at: https://biobasedcontent.eu/en/certification/testing-laboratories/

EN 16785-1 was drafted by the CEN[7] Technical Committee/TC 411 and was published in December 2015. Subsequently, in 2016 a certification scheme based on this standard was validated. Through the biologic certificate, companies can report the biological content of their products on the label.

[7] CEN is the European Committee for Standardization, more information at: https://www.cencenelec.eu/about-cen/

Figure 03.4.1: Bio-based content certification
Source: https://www.biobasedconsultancy.com/en/about-biobased/certification-and-ecolabels

Sustainable feedstock

The cultivation of renewable resources (usually from forestry and agriculture, sometimes from marine aquaculture) has a huge impact on the sustainability of the final bio-based products. Due to the EU's renewable energy policy, several certifiers have developed certification schemes for agricultural biomass that adhere to the conditions laid down in the EU's 2009 Renewable Energy Directive (RED). Some of them have by now adapted their schemes in a way that they can be applicable also to materials, not only to energy. For wood, sustainability certification schemes were developed before the renewable energy policy due to concerns about unsustainable forestry practices in many parts of the world.

The cultivation of renewable resources (often sourced from forestry and agriculture, and from marine aquaculture), plays a significant role in the overall sustainability and impact of bio-based products. In line with the European Union's renewable energy policy, certifiers have created certification programs for agricultural biomass that comply with the criteria outlined in the EU's Renewable Energy Directive 2018/2001/EU[8] (RED).

[8] Full document at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001

These programs have been modified to extend their applicability beyond energy to cover materials as well because of concerns linked to environmental indicators.

Figure 03.4.2: Certifications of sustainable feedstock
Source: https://www.biobasedconsultancy.com/en/about-biobased/certification-and-ecolabels

When considering unsustainable forestry, which is leading to deforestation and directly linked to wood-based products and biomass, the FSC (Forest Stewardship Council) logo and PEFC (Programme for the Endorsement of Forest Certification) is an assurance that all products are made with, or contain, materials from FSC- certified forests. This also means that the products have not contributed to deforestation and other environmental concerns.

Figure 03.2.3: Sustainable feedstock, FSC (Forest Stewardship Council) and PEFC (Programme for the Endorsement of Forest Certification)
Source: https://www.biobasedconsultancy.com/en/about-biobased/certification-and-ecolabels

End-of-life options

To highlight the end-of-life options of bio-based products there are certifications and labels such as compostability, biodegradability in soil, biodegradability in seawater, etc.

Figure 03.4.4: End-of-life options of bio-based products
Source: https://www.biobasedconsultancy.com/en/about-biobased/certification-and-ecolabels

Biodegradability is a relevant aspect in the life cycle of specific products, particularly those made of bio-based materials, as it is one of the potentials of products made of biotic materials and allows for close cycles (see chapter 03.2 Closed and short loop of biotic materials).

Most of these labels are type II (refer to Chapter 01.7 Green transition in Europe towards material efficiency and circularity).

Unfortunately most bio-based building products, elements and components are not certified or have environmental declaration. This void could be attributed to the fact that most of

them are a result of ongoing exploration, discovery, and study. Most databases today do not present information on bio-based materials, when it is provided it is very limited and is mainly about wood.

Recognizing these existing limitations should set the foundation for future practices where these materials can be integrated into sustainable construction as primary choices. However, embracing the challenges posed by the limited information and certification for bio-based building products presents an opportunity for collaboration and innovation between industries, researchers, policymakers, and practitioners to drive the exploration and adoption of these alternatives.

That being said, there are some distinctive projects and researches worth mentioning that work towards transitioning towards a bio-economy and regulating and providing useful information on bio-based materials and products.

InnProBio

In Europe, the InnProBio[9] forum focuses on fostering innovation in public procurement for bio-based products. It offers insights into bio-based products and their manufacturers across nine distinct product categories. One of these categories is specifically dedicated to "Construction, materials, and infrastructure," offering a comprehensive database of practical details about bio-based building products and their producers.

[9] InnProBio, the Forum for Bio-Based Innovation in Public Procurement, aimed to build a community of public procurement practitioners interested in Public Procurement of Innovation (PPI) of Bio-Based Products and Services More information and database can be found at: https://www.biobasedconsultancy.com/en/database

Agrodome (UK)

Agrodome[10] is an innovation and knowledge centre for ecological and bio-based building. Agrodome work as a network organization and focuses on the mission to stimulate and facilitate the transition to a bio-based economy. It is divided in two independent organizations both active in the field of bio-based circular building concepts, materials and products. The first is the **Stitching Agrodome**[11] for demonstration and knowledge exchange projects. And the **Agrodome B.V.**[12] for consultancy and development, and projects like product development, LCA and EPD-projects, renovation and development of bio-based circular houses.

[10] More information on Agrodome can be found at: https://www.agrodome.nl/uk/
[11] More information on Stichting Agrodome can be found at: https://stichting.agrodome.nl/
[12] More information on Agrodome B.V. can be found at: https://www.agrodome.nl/

Bio-based Bouwen

Bio-based Bouwen[13] is a knowledge base that contains information about the availability and application possibilities of bio-based materials, products, construction concepts and projects that aim to circularity in the construction and manufacturing industry.

[13] More information on Biobased Bouwen can be found at: https://www.biobasedbouwen.nl/

Wageningen University

Wageningen University based in the Netherlands that oversees many different research projects in regards of bio-based products and more in general the transition towards a bio-economy. One interesting study focuses on bio-based building materials and has resulted in the published catalogue *Catalogus biobased bouwmaterialen 2019: Het groene en circulaire bouwen*[14]. This document offers a general overview of different building construction materials that are bio-based.

[14] Full document at: https://www.wur.nl/en/article/catalogue-offers-complete-overview-of-bio-based-building-materials.htm

Baubook

Baubook[15] is a database for building products. It simplifies the process of ecologically sound and health-conscious construction while also facilitating verification within the realms of ecological tenders, building certifications, and funding systems. By offering validated and organized data on building materials, Baubook is an essential resource for accurately calculating energy and ecological indicators.

[15] https://www.baubook.info/de/oekoprogramme/wohngsund

Biobased materials

Bio-based materials[16] is an online source by Bio-based Creations[17], Company of New Heroes[18], which is a creative studio focused on installations, initiatives, and narratives centred around the shift towards regenerative and circular solutions. Their approach encompasses all facets of this transformation, spanning from sustainable energy to bio-based construction, and from emerging economies to social inventive solutions. Their collective comprises designers, researchers, artists, and storytellers, all dedicated to cultivating an innovative ecosystem that prioritizes equity and sustainability for both humanity and the natural world.

[16] https://biobasedmaterials.org/

[17] https://biobasedcreations.com/

[18] https://companynewheroes.com/

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Chapter Three

Resources

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Resources and References

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Chapter four:

Material guidelines

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Foreword

"Bio-based architecture is still mainly made of wood, but there are other materials such as hemp, seaweed, mycelium, straw and cattail, each with their own properties and challenges" (Hester van Dijk, 2023).

In the realm of sustainable and biogenic materials, wood has stood as a symbol of eco-friendliness and biodegradability. Its versatility and long history of use have made it a staple in the world of sustainable design and construction. However, today it represents the most used and studied of all bio-based materials. Therefore, the focus shifts from the well-known path of wood-based solutions towards other lesser-known alternatives that as of today still represent untapped potential.

Why not wood?

This is not a disregard for wood's merits or its pioneering role in sustainable practices. Instead, it's a testament to exploring the diverse tapestry of bio-based alternatives.

"Nature does not only inspire new materials, but it can also be part of materials' components. The 'bio-based' and 'living building materials' in architecture are rising as green alternatives to their petroleum-based counterparts" (Natasha Chayaamor-Heil et al., 2023).

At the same time, the realm of bio-based material is very vast and comprises many different resources, therefore the materials that are going to be presented do not represent all the different varieties, however they represent some of the most explored and studied current options.

04.1 Material resources

Raw material resources can differ and be categorised as natural resources, virgin or primary resources, recoverable resource, recovered or secondary resources and waste. These categories provide a structured framework to assess the origin, potential reuse, and sustainable management of resources throughout their lifecycle. By understanding and categorizing raw material resources within these parameters, industries can make more informed decisions to minimize waste and maximize resource efficiency.
As referenced in the standard ISO/DIS 59004 - ISO/TC 323 - Circular Economy – Terminology, Principles and Guidance for Implementation these categories comprise as follows:

Natural resource: "raw material occurring in nature";

Virgin resource - primary resource: *natural resource** or "energy that is used as a resource for the first time as input in a process or for creating a product";

* Virgin resources can be either a renewable resource or non-renewable resource.

Recoverable resource: *resource* "that can potentially be recovered and used again after it has already been processed or used";

Recovered resource - secondary resource: *resource* "that is obtained from a resource that has already been processed or used";

Waste: *resource* "that is considered to no longer be an asset as it, at the time, provides no *value* to the holder - *Value* can be assigned to waste as a result of a need from other interested parties, at which point the *resource* is no longer considered waste".

The guidance on resource management reported in the ISO/DIS 59004 - ISO/TC 323 - Circular Economy – Terminology, Principles and Guidance for Implementation, aims to assist organizations in prioritizing steps to enhance circularity. The organization should utilize a life cycle perspective and emphasize sustainability when pinpointing the optimal actions within their value creation model.

Many different bio-based materials can come from natural resources, by-products and waste of different production chains. They can come from industries such as: Agriculture and forestry, for example, straw and husk; the Food industry, for fruit peel; Textile industry, for example, hemp and flax fibre or cotton; Aquaculture and seafood processing, for example, seashells and algae; Paper industry, for example, cellulose from waste newspaper.

Bio-based products typically follow a design for circularity approach, meaning that they comply with circular economy principles and ecodesign therefore they are based on life cycle thinking. This ensures that they align with sustainable practices, promoting the efficient use of resources and contributing to a more environmentally conscious approach to production and consumption.

Resource management

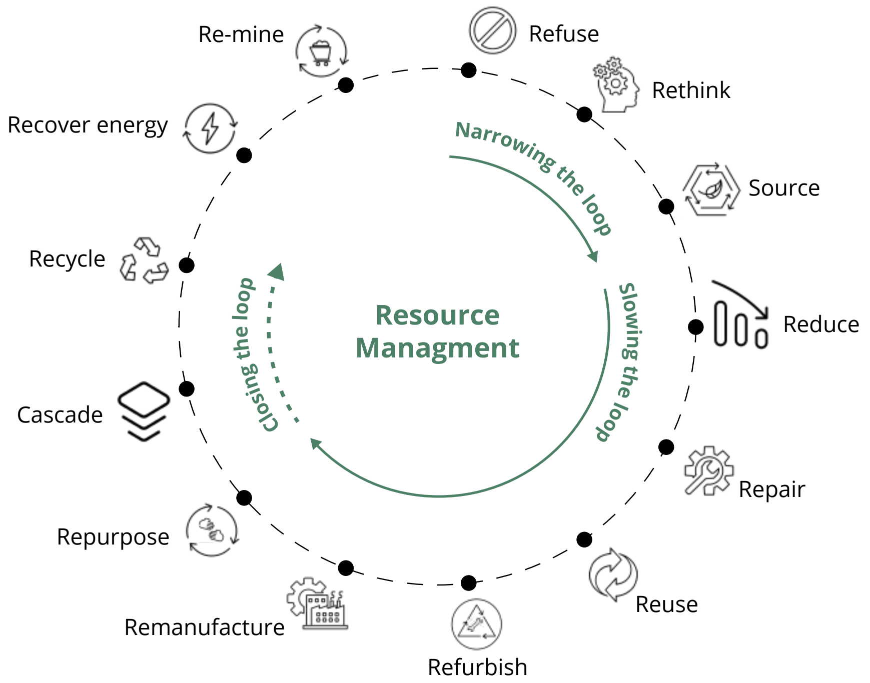


Figure 04.2.01: Guidance for Resource Management Actions (adapted from "Narrowing, Slowing and Closing the Loop", Bocken et al., 2016) - ISO/DIS 59004 - ISO/TC 323
Source: made from the author of the thesisi data from ISO/DIS 59004 - ISO/TC 323 - Circular Economy – Terminology, Principles and Guidance for Implementation

Refuse – "Make solutions redundant by abandoning its function or by offering the same function with radically different solution".
Rethink – "Reconsider design, and manufacturing decisions. Make service use more intensive".
Source – "Substitute virgin material with recovered or renewable resources; select recovered or renewable, sustainably-sourced or produced, use resources that can be easily recycled or returned to the biosphere, reconsider formulations".
Reduce – "Increase efficiency in product manufacture or use by consuming fewer natural resources and material".
Repair – "Restoration of defective of damaged product so that it can be used in its original function".
Reuse – "Reuse by another consumer of discarded product which is still in good condition and fulfils its original function".
Refurbish – "Largely aesthetic improvement of a product that may involve making it look new with limited functionality improvements".
Remanufacture – "A comprehensive process to return a product to like new conditions by fully disassembling and reconstructing for resale, recertifying its conditions".
Repurpose – "Adapt a product or its parts for use in a different function that it was originally intended without making major modifications to its physical or chemical structure".
Cascade – "Shift recovered materials from one loop to another to optimize feedstock flows through additional cycles. Often with decreasing quality and quantity. When adopting for bio-based material, cascading implies repeated use of renewable resources at decreasing quality, with final treatments like composting, energy recovery or biodegradation and safe return of the material to the environment".
Recycle – "Recover and process material to obtain he same (high grade) or lower (low grade) quality through collection and mechanical, physical or chemical recycling or cycling through other pathways".
Recover energy – "Incineration of material with heat or energy recovery".
Re-mine – "Mining or extracting from landfills and waste plants may be possible in some cases if mining or extraction activities are sustainably managed".

04.2 Guide to the guidelines

Why?

The **Bio-based Material and Prefabrication Guidelines** have been developed with a specific purpose in mind - to provide a comprehensive resource for anyone interested in understanding, utilizing, or advocating for bio-based materials and their applications. These guidelines aim to address different questions and serve a diverse range of users.

?

The key questions these guidelines seek to answer include:

- What essential information is needed to make informed decisions about possible application of bio-based materials?
- What are the main characteristics of these materials?
- What solutions are currently on the market or are being researched and explored?
- What are environmental impacts linked to bio-based materials?
- What are some real-life examples and utilization of these materials?
- What are limits that need to be overcome to allow for an upscaling of these materials?

Ultimately the main aim is to promote the adoption of sustainable practices and the reduction of environmental impacts within the built environment through the use of bio-based materials.

Who?

In the realm of sustainable materials, it has become increasingly important to make informed decisions and embrace innovative solutions. Designers, researchers, industry professionals, policymakers, and environmentally conscious consumers are all stakeholders in this evolving landscape. These guidelines are intended to help bridge the knowledge gap by offering valuable insights into bio-based materials, whether they are already in use or under exploration

How?

The information is categorized by material type, with each material further divided into 11 indicators, which include:

A Watch points
This section highlights considerations and potential concerns related to the use of bio-based alternatives.

B Life cycle
The life cycle section is a visual overview of the material's journey from its initial production to its eventual disposal. It includes stages such as raw material extraction, processing, manufacturing, distribution, use, and end-of-life.

C Key point
This category showcases the most essential aspects of the bio-based alternative. It provides a concise summary of the material and its various applications. It is divided in:
- Raw material origin
- Availability of raw material
- Degree of skill required for resourcing the raw material
- Degree of prefabrication
- Awareness

D Raw material
In this segment, the sources of the raw bio-based materials (in terms of resources) are discussed. This could include information on agricultural feedstocks, waste products, or other renewable resources

E Cultivation and Harvesting
Here, the methods and practices employed to cultivate and harvest the raw materials are detailed.

F Physical-mechanical properties
The section outlines general physical, chemical, and mechanical characteristics of the bio-based material. This includes aspects like strength, flexibility, thermal conductivity, and any unique features that make it suitable for specific applications.

Durability

G

This part assesses the material's longevity and resilience under various conditions. It explores how well the material holds up over time, especially in comparison to conventional alternatives.

End-of-life and recycling

H

The end-of-life considerations delve into how the material can be disposed of or recycled once it has served its purpose. This includes discussions about compostability, biodegradability, or recycling methods.

Life cycle assessment

I

Life cycle assessment reports data on the environmental impact of the material related to different stages of life cycle. This section analyses factors such as energy consumption, greenhouse gas emissions, and other midpoints. The data was obtained with the SimaPro software (when material was present in the databases - also see Tool section), or from research papers. The system boundaries are different for each materials and they are declared through the infographic that follows that provides the reference to what stages are included in the LCA of the material in question.

Prefabricated production processes

J

The focus is on innovative manufacturing techniques that involve prefabrication, modular construction, or streamlined production processes, contributing to more efficient and sustainable material utilization.

Case studies / Good practices

K

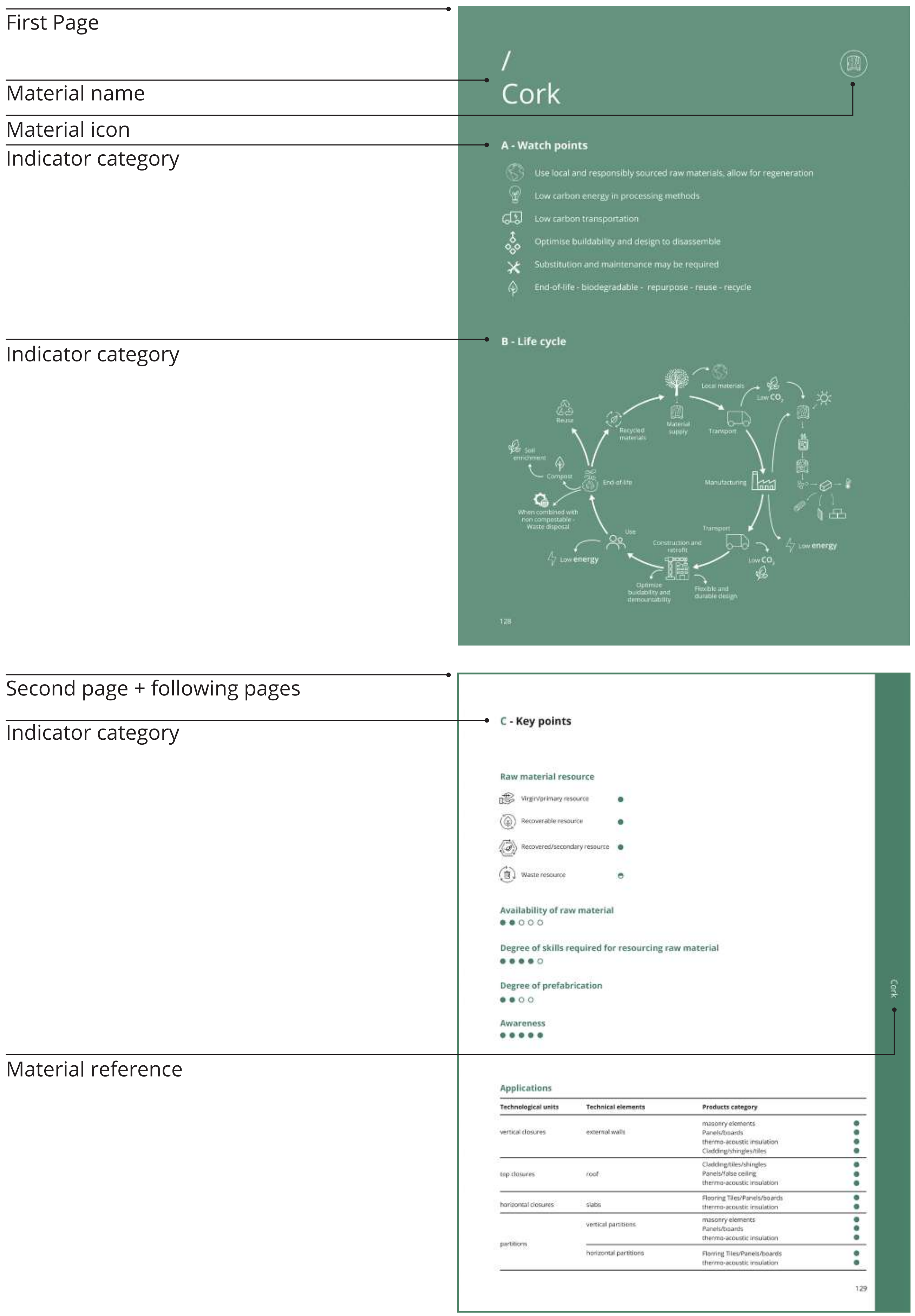
This category presents real-world examples of successful applications and projects that have effectively utilized bio-based solutions. It offers insights into best practices and innovative uses.

Limits to overcome

L

This section addresses the challenges associated with the adoption of the bio-based material. This could encompass technological hurdles, market barriers, regulatory constraints, or any other factors hindering broader implementation and up-scaling.

How to read the material "cards"



Icon caption

Raw material origin

- Virgin/primary resource
- Recoverable resource
- Recovered/secondary resource
- Waste resource

- Yes
- No
- At times

Availability of raw material

- Very low
- Low
- Moderate
- High
- Very high

Degree of skill required for resourcing the raw material

- Very low
- Low
- Moderate
- High
- Very high

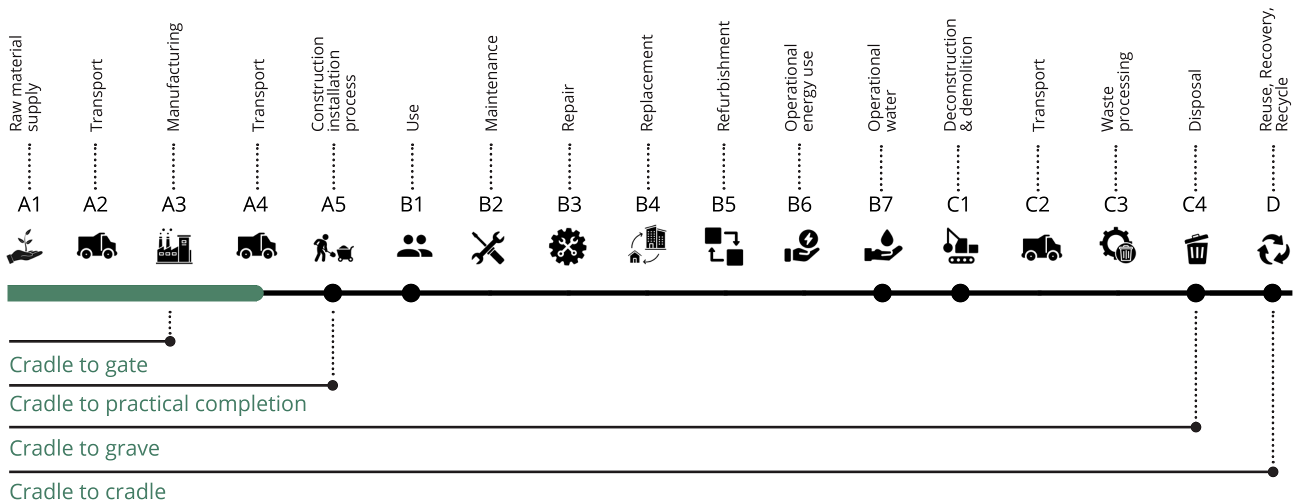
Degree of prefabrication

- Elements
- Components
- Moduls
- Units

Awareness

- Very low
- Low
- Moderate
- High
- Very high

Life cycle assessment



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Bio-based materials

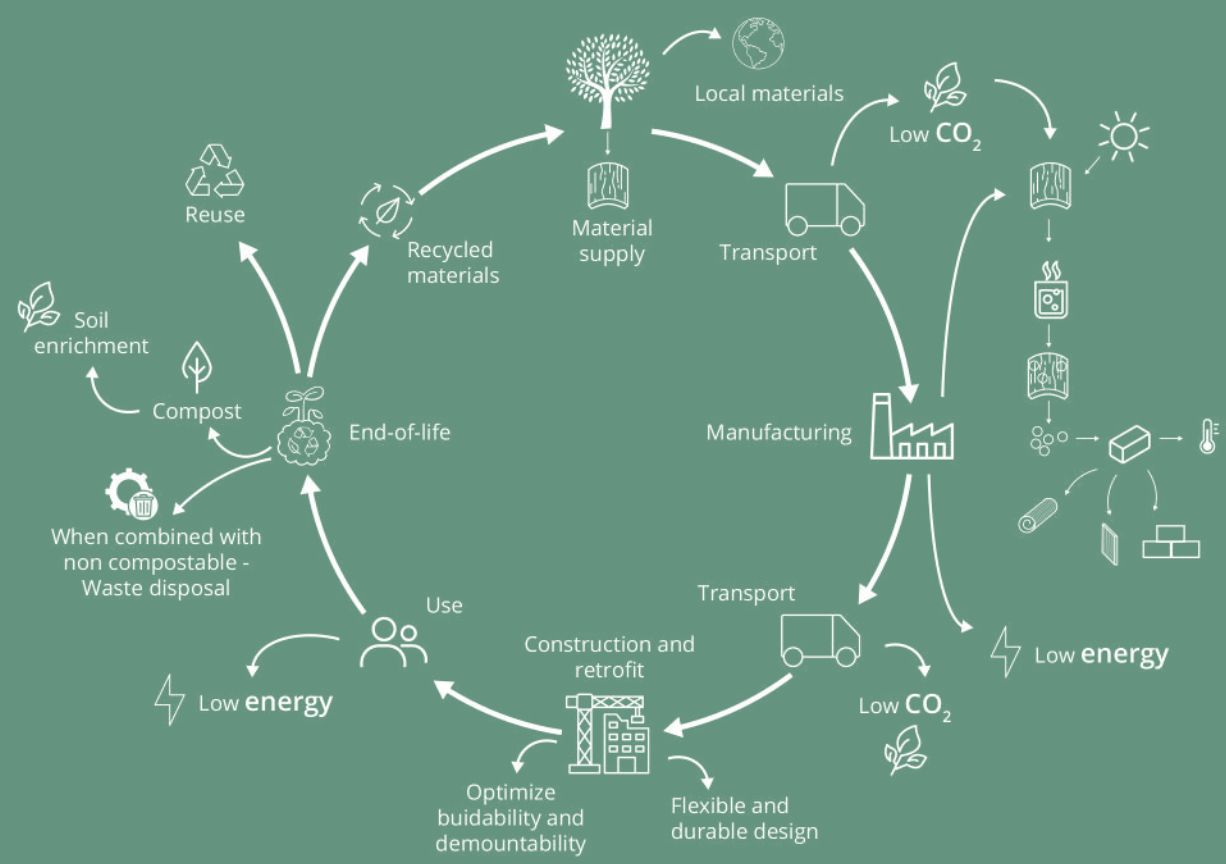
The information about the last three materials has been analysed more in general and it provides a shorter summary.

/
Cork

A - Watch points

- Use local and responsibly sourced raw materials, allow for regeneration
- Low carbon energy in processing methods
- Low carbon transportation
- Optimise buildability and design to disassemble
- Substitution and maintenance may be required
- End-of-life - biodegradable - repurpose - reuse - recycle

B - Life cycle



C - Key points

Raw material resource

Virgin/primary resource	●
Recoverable resource	●
Recovered/secondary resource	●
Waste resource	◐

Availability of raw material

●●○○○

Degree of skills required for resourcing raw material

●●●●○

Degree of prefabrication

●●○○

Awareness

●●●●●

Applications

Technological units	Technical elements	Products category	
vertical closures	external walls	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
		Cladding/shingles/tiles	●
top closures	roof	Cladding/tiles/shingles	●
		Panels/false ceiling	●
		thermo-acoustic insulation	●
horizontal closures	slabs	Flooring Tiles/Panels/boards	●
		thermo-acoustic insulation	●
partitions	vertical partitions	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
	horizontal partitions	Florring Tiles/Panels/boards	●
		thermo-acoustic insulation	●

D - Raw material

Cork, derived from the outer protective bark of the cork oak tree (*Quercus suber*), which is an evergreen oak native to the Mediterranean region, is characterized by its cells possessing thin walls, an irregular shape, and a wax coating. These distinctive cells are responsible for the unique peeling bark observed in various tree species, although, in the context of commercial use, only the bark from the cork oak is officially recognized as cork. The primary regions where cork oak thrives include Portugal, Spain, certain areas of southern France and Italy, and North Africa. These trees typically attain a height of approximately 18 meters (60 feet), showcasing a broad, rounded crown and glossy green leaves that resemble the leaves of holly (Britannica, 2023).

Figure Ck01: Cork bark
Source: https://www.jelinek.pt/cork-forest-raw-materials

Cork is globally known as a bottle sealant; however, its use is suited for different requirements within the construction industry. The combined characteristics of lightness, elasticity, resilience, impermeability, insulation, wear resistance, fire retardance, hypoallergenic traits, and lasting endurance sets it apart from conventional materials like wood or stone (Pereira 2007; Fortes et al. 2004).

Cork oak forests covers around 2.1 million hectares in total, with about a third located in Portugal. Every year, roughly 201 thousand tons of cork are produced, mainly from cork oaks in Portugal and Spain. These two countries contribute 49.6% and 30.5% of the overall raw material, respectively (Knapic, 2016).
Cork as a building material is mainly utilized as insulation, flooring and wall cladding that derive from: raw cork planks acquired by extracting them from tree trunks, cork in granulated form, cork agglomerates, which consist of cork granules combined with resin, including rubber-cork composites and expanded cork agglomerates without resin (Knapic, 2016).

E - Cultivation and Harvesting

The life cycle of cork as a raw material bigins with the extraction of the bark from the cork oak. Harvesting typically takes place from May-June to August, which is the most active period of cork growth. A cork oak takes around 25 years to produce cork, each tree has to reach a circumference of around 70 cm and 1.3 m above ground level to be harvested. Harvesting is for an average of 150 years (APCOR, 2023). The first harvest produces a very irregular bark structure that is hard to handle, this is referred to as “virgin cork”, and it is not used to manufacture cork-building materials. After around 9 years, the second harvest takes place as the tree produces cork with a regular structure, less hard but still not suitable as a building material, this is referred to as “secondary cork”. From the third harvest the cork has the best properties that are suitable for the production of “quality cork” used as a building material. From this harvest onwards, the cork oak supplies quality cork with a regular structure and a smooth inside and outside every 9 years for about 100 years resulting in about 15 bark harvests during its life span (APCOR, 2023).

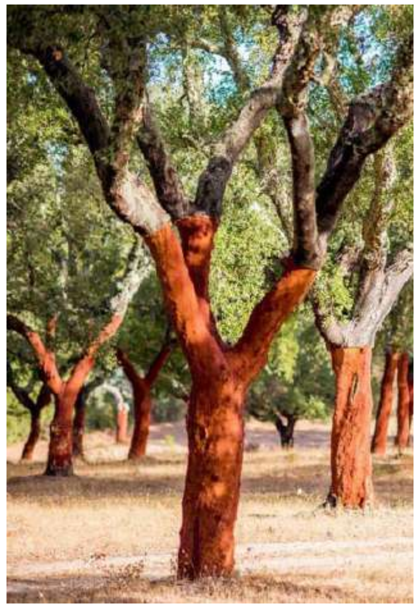


Figure Ck02: Cork oak tree
Source: https://alma-da-comporta.com/cork-oak-comporta/

Figure Ck03: Cork separation
Source: https://www.bbc.com

[1] Those who harvest cork in Portugal

[2] The stacks must be placed on materials that avoid cork contamination and keep it away from the ground. Wood, for instance, is strictly avoided due to its potential for fungal transmission.

Cork harvesting, an age-old practice that demands skill and expertise, unfolds through six distinct stages. The initial phase, known as "opening," involves a vertical axe cut into the deepest crevice of the cork. The second step, termed "dividing," entails a horizontal cut to delineate the dimensions of the cork bark to be extracted. This process can often result in markings on the inner bark, potentially impacting the trunk's shape. The third stage, "separation," involves prying the bark away from the tree by inserting the axe edge between the strip and the inner bark. During the fourth stage, "extraction," the bark is meticulously taken off the tree to prevent tearing. The larger the planks obtained, the higher their commercial worth. Once the initial bark is stripped, this procedure is replicated across the entire trunk. "Removal," the fifth phase, deals with eliminating residual cork fragments attached to the trunk's base after stripping. These remnants are tapped away using the axe's edge by the "descortiçador" to ensure complete detachment. The concluding and sixth step, "marking," involves inscribing the tree with the last digit of the year when the harvest took place (APCOR, 2023).

Figure Ck04: Cork bark stacking
Source: https://42birds.com/pages/why-cork

Following the harvest is a rest period in which the cork bark that has been removed is stacked in piles in the forest or in the yards of the factories where it is exposed to the elements. All the piles are stacked following the ICCSMP (International Code of Cork Stopper Manufacturing Practices) to allow the cork to stabilize[2]. Throughout this curing phase, the raw material matures and the cork achieves stability. According to the ICCSMP guidelines, the seasoning duration for the planks should never be below six months.

Figure Ck05: Cork bark boiling
Source: https://www.sommeliers-international.com/en/World/the-saga-of-the-cork.aspx

The production process continues with the boiling of the bark for around 1-2 hours with the objective of cleaning the cork, extracting water-soluble substances, increasing the thickness and reducing density, and finally making the cork softer therefore more elastic. The boiling ensures that the microflora is significantly reduced and the internal structure is improved. Following this stage there is stabilization for around 2-3 weeks. After this there is selection and division of the planks by quality categories. The selected planks are then "punched" by manual, semi-automatic or automatic process, this is the perforating of the cork with a cylindrical drill, the waste from this process is used as granulate. After the punching, there is rectification to obtain final dimensions and washing.

F - Physical-mechanical properties

Cork cells have pentagonal and sometimes hexagonal prism shape. The chemical composition is characterized by various components in average values of: suberin (45%), lighin (27%), polysaccharides (12%), ceroids (6%), tannins (6%) (APCOR, 2023). Cork possesses an unusual set of properties: it is anisotropic, it exhibits low density, impermeability to liquids and gases, minimal conductivity, chemical stability, durability, and high compressibility, elasticity and flexability. Cork is a light material, with density values ranging from 120 to 200 Kg m-3 (Knapic, 2016). Cork is non-toxic and hypoallergenic and absorbs water slowly and typically floats on water. Cork has very low heat transfer properties due to its large air content and small cell size, making it a good material for thermal and acoustic insulation (Knapic, 2016). In regards to the reaction to fire, the classification of natural cork according to the euroclass classification (EN 13501-1) is not well established and data is missing (Knapic, 2016).

G - Durability

Cork is highly durable. Thanks to its natural qualities like resilience, chemical stability, and resistance to wear and tear, cork can endure extended use and exposure to different environmental conditions without significant damage. It also maintains stability over time and stands up to insects and rodents (Fassi and Maina, 2006). However, it's worth noting that cork can be sensitive to certain chemicals and solvents, which might result in discolouration or damage.

H - End-of life and recyclability

Natural cork when not combined with non-natural binders is biodegradable and compostable and recyclable. Recycling involves grinding or granulating old cork items to create new materials like agglomerated cork or cork composites, thus extending the life cycle and lowering demand for new resources. The products with synthetic resins and binder have to be treated and disposed as special waste.

I - Life cycle assessment

Cork is considered to be a eco-friendly material with a very favourable ecological footprint since its production is carried out along tree's life time (Knapic, 2016).

In addition to their economic and societal value, cork oak stands, and consequently cork, assume an important role in ecological preservation, water retention, and soil conservation. They serve as crucial reservoirs of biodiversity for both flora and fauna (Pereira 2007).

Some aspects need to be considered in the production process, like sustainable resourcing from certified forestry that allow for regeneration in order to maintain the long-term viability of cork oak trees and don't harm the flora and fauna of the oak forests. Another important aspect is to use local materials and take into consideration low impact transport methods of both the raw material and finished product during distribution.
LCA was obtained for raw cork from the SimaPro software.

Cork, raw {RoW}| market for cork, raw | Cut-off, U - Kg Wood
Ecoinvent 3 - allocation, cut-off by classification - unit Material
Wood\Extraction\Market - Unit: 1 Kg

GWP

GWP - IPCC 2013 GWP 100a (incl. CO2 uptake) V1.00 - Characterisation

Impact category	Unit	Total
Total	kg CO_2 eq.	**-10.778**
Climate change - fossil	kg CO_2 eq.	0.013
Climate change - biogenic	kg CO_2 eq.	0.004
Climate change - CO2 uptake	kg CO_2 eq.	-10.80
Climate change - land use and transformation	kg CO_2 eq.	0.002

Embodied energy

EE - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation

Impact category	Unit	Total
Total	MJ	**117.0212**
Non renewable, fossil	MJ	0.2018
Non renewable, nuclear	MJ	0.0011
Non renewable, biomass	MJ	0.0024
Renewable, biomass	MJ	116.8153
Renewable, wind, solar, geothermic	MJ	0.002
Renewable, water	MJ	0.005

Impact category	Unit	Total
Climate change	kg CO2 eq	0.0163
Ozone depletion	kg CFC11 eq	0.0000
Ionising radiation	kBq U-235 eq	0.0009
Photochemical ozone formation	kg NMVOC eq	0.0005
Particulate matter	disease inc.	0.0000
Human toxicity, non-cancer	CTUh	0.0000
Human toxicity, cancer	CTUh	0.0000
Acidification	mol H+ eq	0.0001
Eutrophication, freshwater	kg P eq	0.0000
Eutrophication, marine	kg N eq	0.0001
Eutrophication, terrestrial	mol N eq	0.0005
Ecotoxicity, freshwater	CTUe	0.1880
Land use	Pt	285.5000
Water use	m3 depriv.	0.0053
Resource use, fossils	MJ	0.1910
Resource use, minerals and metals	kg Sb eq	0.0000
Climate change - Fossil	kg CO2 eq	0.0143
Climate change - Biogenic	kg CO2 eq	0.0002
Climate change - Land use and LU change	kg CO2 eq	0.0017
Human toxicity, non-cancer - organics	CTUh	0.0000
Human toxicity, non-cancer - inorganics	CTUh	0.0000
Human toxicity, non-cancer - metals	CTUh	0.0000
Human toxicity, cancer - organics	CTUh	0.0000
Human toxicity, cancer - inorganics	CTUh	0.0000
Human toxicity, cancer - metals	CTUh	0.0000
Ecotoxicity, freshwater - organics	CTUe	0.0400
Ecotoxicity, freshwater - inorganics	CTUe	0.0751
Ecotoxicity, freshwater - metals	CTUe	0.0728

EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation

J - Prefabricated production processes

Cork used as a building material can compose elements such as panels, flooring tiles, wall tiles and facade cladding.

Elements

Figure Ck06: Corkpan - by Technosugheri - (IT)
Source: https://www.tecnosugheri.it/

Panels

Depending on the production process, different types of panels can be obtained. Panels of brown, self-glued agglomerated cork are obtained by baking the granules in pressure furnaces (autoclaves) at approximately 350-400° C. The pressure and temperature cause the suberin contained in the granules to melt and migrate to the surface, realising the natural process of agglomeration and welding between the individual granules, without the addition of further adhesives. This results in blocks that are subsequently cooled and cut into panels of different thicknesses. The expansion process, also known as "toasting", determines the characteristic brown colour, and sees an expansion of the granules resulting in lightening of the product and lower compressive strength.

Application: the use mainly is as insulation panels, but can also be used as floor boards and ceiling boards.

Some EU producers

Lis - (IT) - EPD - Slim and Lisoflex insulation panels
Tecnosugheri - (IT)
Granorte - (PT)
Correia cork - (PT) raw cork

Figure Ck07: Cork roll - Portugal Cork Co. - (PT)
Source: https://portugalcork.com.au/products/country-cork-roll-1-220-x-006

Roll

A cork roll is a continuous sheet of cork material that is manufactured in a roll format. It consists of a thin layer of cork granules that have been compressed and bonded together.

Application: the main application is sound and acoustic insulation, which can also be used in slabs for flooring insulations and impact soundproofing mats. It can also be used as a decorative covering.

Some EU producers

Portugal Cork Co. - (PT)
Biosughero - (IT)

Blocks

The Biopan block is formed by thermally expanding cork granules with steam, enhancing their insulation, strength, and stability. The process melts the suberine, that acts as adhesive for granule aggregation. This yields a solid, water-resistant block with steam-permeable protection that is free from synthetic additives. The method preserves cork's properties, producing an elastic, thermally-insulating, and durable product.

Application: Cork blocks can be stacked to create exterior and interior walls.

Some EU producers

Biosughero - (IT)

Figure Ck08: Cork block Biopan - Biosughero - (IT)
Source: https://biosughero.it/

Cork Brick Europe - (PT)

The Cork Brick, as outlined by its creators, is a practical modular solution akin to the concept of Lego blocks. They have devised a system that is both modular and easy to assemble, consisting of seven different Lego-like block varieties. These blocks can be mixed and matched seamlessly without the necessity of adhesives or mortars. The blocks' geometric shapes facilitate their assembly. The "Base block" comes in the form of a 20 cm cube. Then there is the "Double block," which stands twice as tall as the Base block. To create interlocking connections, they offer four directional blocks: "1D," "2D," "3D," and "4D." Additionally, there's the "T block," which functions as a filler.

Figure Ck09: Cork brick base block - 20 cmcube
Source: https://corkbrick.com/

Figure Ck10: Cork bricks modules
Source: https://corkbrick.com/

The systems allows for a flexible, versitile and adaptable design. The seven 'brocks' mount and dismount without tools, screws, or glues.

Application: Cork blocks can be stacked to create interior walls as well as indor and outdoor furniture.

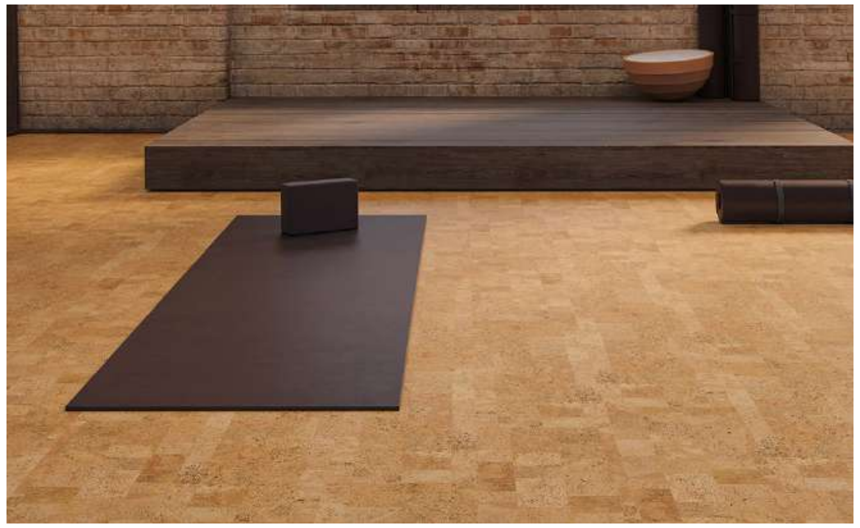
Producers

corkbrick.com

Floor tiles

Cork floor tiles are produced by compressing and bonding layers of cork granules together, which are then cut into tile-sized pieces and often coated with protective finishes.

Figure Ck11: Cork floor tiles -Primus - Line Naturalis - by Granorte - (PT)
Source: https://www.granorte.pt/it/prodotti/naturals/primus



Application: finishing floor layer - for interior use

Some EU producers

Granorte - (PT)
Biosughero - (IT)

Cladding tiles

Cork cladding tiles, similarly to floor tiles, are typically produced by compressing layers of cork material into a tile shape, which are then often combined with backing materials for stability and ease of installation. The tiles can undergo various finishing processes, such as sealing or coloring, before being ready for use.

Applications: facade cladding - indor wall cladding

Some EU producers

Portugal Cork Co. - (PT)
Tecnosugheri - (IT)
Granorte - (PT)

Figure Ck12: Cork cladding tiles - by Tecnosugheri - (IT)
Source: https://www.tecnosugheri.it/

K - Case studies / Good practices

Cork House - Matthew Barnett Howland with Dido Milne and Oliver Wilton - (UK)

Figure Ck13-14: Cork house - by Matthew Barnett Howland with Dido Milne and Oliver Wilton.
Source: https://www.matthewbarnetthowland.com/cork-house

The project of the Cork house by the architects Matthew Bernett Howland, Dido Milne and Oliver Wilton is an innovative construction that features solid cork walls and pyramid-like roofs made mainly from solid and load-bearing cork.

Projects that involve cork usually sees its use as cladding, this project showcases its potential as a possible structural material.

The house uses an improved version of a building technique developed by MPH Architects, The Bartlett School of Architecture UCL, University of Bath, Amorim UK, and Ty-Mawr. The research received funding from Innovate UK and EPSRC through the 2015 Building Whole Life Performance funding competition. The process included detailed lab tests for structural strength, rain resistance, and fire safety. Two prototype structures were built to see how well the technique worked in real-life situations.

The research project also developed a method of off-site prefabrication, with blocks for the house machined on a large-scale CNC (Computer Numerical Control) milling machine. The project of the Cork House embodies a whole life approach to design, from resource through the end-of-life. Expanded cork is a plant-based material made with a by-product of cork forestry.

Unlike typical and conventional building envelopes made of various materials, Cork House showcases an innovative approach. It aims to simplify the building envelope using only cork and timber. It is created as a prefab kit with parts, composed of large expanded cork blocks that are joined by hand, like a giant organic Lego® set, without needing glue or mortar.

This innovative form of plant-based construction has resulted in a building that is carbon negative at completion of construction with extremely low whole-life carbon of 619kgCO2e/m^2 as stated by the architects and as assessed by Sturgis Carbon Profiling to British Standard BS EN 15978.
This ecological origin of expanded cork shows benefits also when mirrored at the opposite end of the building's lifecycle. The construction system is dry-jointed, so that all the blocks can be reclaimed at end-of-building-life for re-use, recycling, or returning to the soil.

Figure Ck15: Cork house - by Matthew Barnett Howland with Dido Milne and Oliver Wilton.
Source: https://www.matthewbarnetthowland.com/cork-house

Figure Ck16: Cork house - by Matthew Barnett Howland with Dido Milne and Oliver Wilton - cork blocks
Source: https://www.archdaily.com

Figure Ck17: Cork house - by Matthew Barnett Howland with Dido Milne and Oliver Wilton - cork roof components
Source: https://www.matthewbarnetthowland.com/cork-house

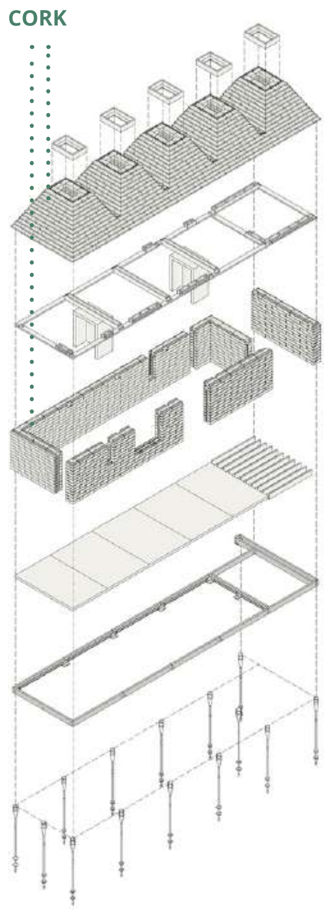


Figure Ck18: Cork house - by Matthew Barnett Howland with Dido Milne and Oliver Wilton - construction system axonometry
Source: https://www.archdaily.com

This mix of architectural and ecological objectives results in structural form that learn from the experience of simple construction principles of ancient stone structures such as Celtic beehive houses.

The project was a result of research testing and building prototypes, the contruction system allowed for developing and off-site production process that resulted in a construction kit.

Cork Construction Kit[3]

Figure Ck19: (top) Cabin roof assembled to check fit at The Bartlett then disassembled for transport to site; (bottom) Cabin assembly on site, # Oliver Wilton and Matthew Barnett Howland
Source: : Oliver Wilton & Matthew Barnett Howland (2020) Cork Construction Kit, TheJournal of Architecture, 25:2, 138-165, DOI: 10.1080/13602365.2020.1733812

[3] More information at: : Oliver Wilton & Matthew Barnett Howland (2020) Cork Construction Kit, The Journal of Architecture, 25:2, 138-165, DOI: 10.1080/13602365.2020.1733812

Poplar Grove - BLDUS - (U.S.A.)

Figure Ck20: Poplar grove - In the alleys - by BLDUS Architects
Source: https://www.archdaily.com/995031/poplar-grove-bldus

Poplar Grove is an alley residence located in Capitol Hill and designed by BLDUS Architects. The project draws inspiration from indigenous structures' natural materials, the spatial set-up of Roman domus, and the history of wooden alley structures in DC. The exterior facade is covered in tulip poplar bark layered over cork which is attached to bamboo panels with hollow walls filled with sheep wool. On the inside, four tulip poplar posts mark corners of a nine-square grid, featuring a central cluster of nine skylights.

The project showcases use and combination of natural and bio-based material results in a modern design. The cork cladding conveys a materiality that is carachterized by the natural pattern of the bark.

Figure Ck21: Poplar grove - In the alleys - by BLDUS Architects - bark cladding
Source: https://www.archdaily.com/995031/poplar-grove-bldus

L - Limits to overcome

Cork as a material combines physical, chemical, and biological stability while offering thermal insulation and energy absorption properties. Furthermore, cork stands as a natural and renewable resource with an eco-friendly production process, and for that reason, products derived from cork, such as agglomerates and composites, exhibit good environmental profiles. However, when considering the utilization of cork as a building material, some challenges must be addressed.

Due to its labour-intensive production process that is limited to some areas and a slow process the cost of cork is high when compared to over conventional building materials. This depends on thickness, density, and location of the material.

In order to maintain its eco-compatible properties cork must come from sustainable harvesting that protects the flora and fauna and does not harm the tree or the forest it comes from. At the same time, the distance must be considered when choosing cork as it grows in specific parts of the world and it might not be sustainable to import it from far locations resulting in impactful and long transportation routes.

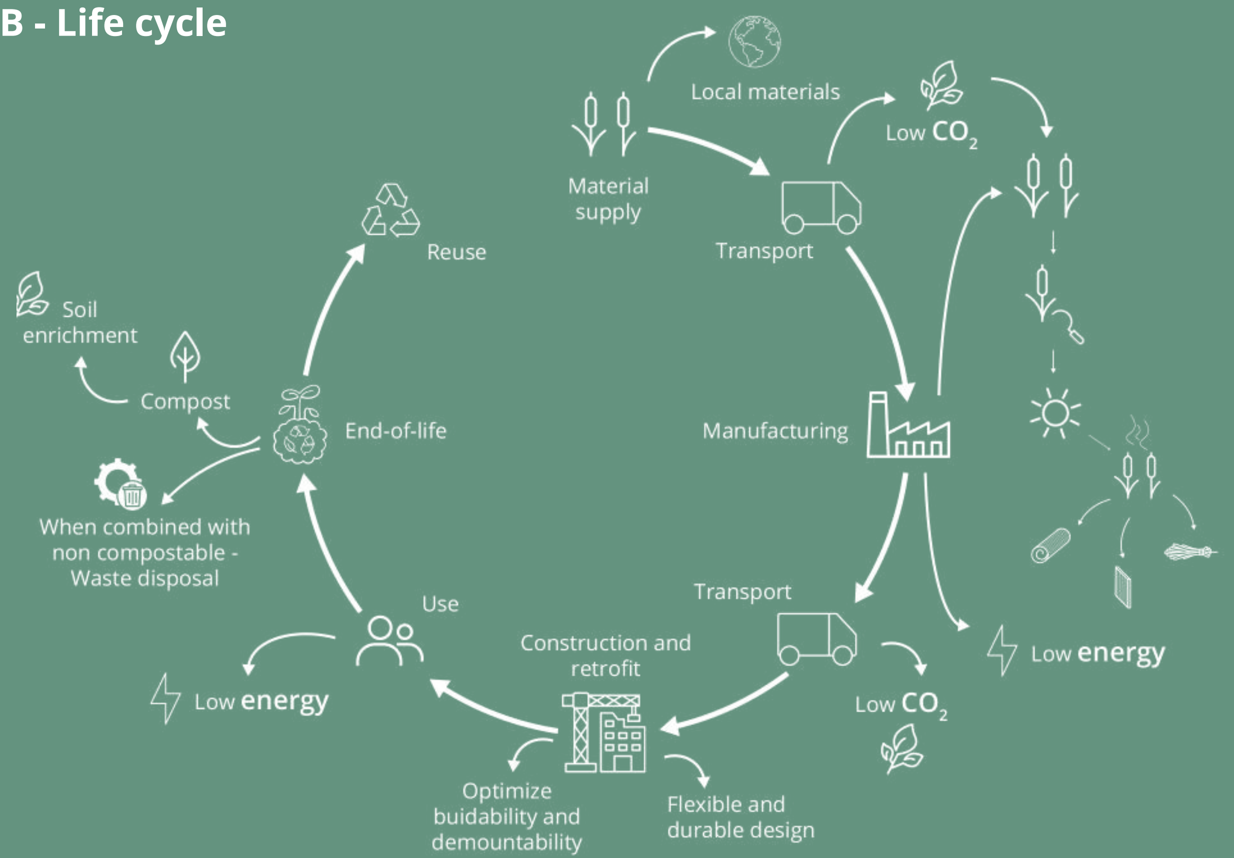
When considering some applications and uses, such as installing cork flooring, it requires skills and expertise.

/
Reed

A - Watch points

- Use local and responsibly sourced raw materials, allow for regeneration
- Low carbon energy in processing methods
- Low carbon transportation
- Optimise buildability and design to disassemble
- Substitution and maintenance may be required
- End-of-life - biodegradable - re-purpose - can also be used as biomass for energy

B - Life cycle



C - Key points

Raw material resource

Virgin/primary resource	●
Recoverable resource	●
Recovered/secondary resource	○
Waste resource	○

Availability of raw material

●●●●●

Degree of skills required for resourcing raw material

●○○○○

Degree of prefabrication

●○○○

Awareness

●●●●○

Applications

Technological units	Technical elements	Products category	
vertical closures	external walls	masonry elements	○
		Panels/boards	●
		thermo-acoustic insulation	●
		Cladding/shingles/tiles	●
top closures	roof	Cladding/tiles/shingles	●
		Panels/false ceiling	○
		thermo-acoustic insulation	●
horizontal closures	slabs	Flooring Tiles/Panels/boards	○
		thermo-acoustic insulation	○
partitions	vertical partitions	masonry elements	○
		Panels/boards	●
		thermo-acoustic insulation	●
	horizontal partitions	Florring Tiles/Panels/boards	○
		thermo-acoustic insulation	○

D - Raw material

In the field of botany, the term "reed" is used for various kinds of large aquatic grasses, particularly referring to the four species found in the *Phragmites genus* within the *Poaceae* grass family. One of these species is the common reed (*Phragmites australis*), which thrives along the edges of lakes, fens, marshes, and streams across regions from the Arctic to the tropics. This grass has wide leaves and can grow anywhere from 1.5 to 5 meters tall. It features airy flower clusters and sturdy, smooth stems. Other plants within the *Poaceae* family that are also called reeds include the giant reed (*Arundo donax*), sea reed (Ammophila arenaria), reed canary grass (*Phalaris*), and reedgrass (*Calamagrostis*). There are also plants like bur-reed (*Sparganium*) and reed-mace (*Typha*) that belong to different plant families (Britannica, 2023). Reed plants are abundant and grow naturally all over Europe.

Figure Rd01: Reed plant
Source: https://www.britannica.com/plant/reed-plant

Reed has been used for different purposes by many cultures over thousands of years (Allirand et al., 1995 and Barreca et al., 2012). Reed has been used as a construction material since ancient times, it has been used for creating baskets, fences, windbreaks, building walls, roofs, floors, shading barriers, and temporary shelters for people and animals. Additionally, it has played a role in producing paper, crafting musical instruments, and even as a source of bio-fuel (Malheiro et al., 2021).

E - Cultivation and Harvesting

The plant grows spontaneously along the shores of lakes, fens, marshes, and streams. It reproduces each year through rhizome shoots that grow into flexible stems, reaching heights of up to 5 meters and sporting pointed, lance-shaped leaves. It spreads rapidly, often becoming a bothersome weed. Moreover, the submerged stems contribute to the buildup of sediment in lakes. Hence, it's essential to trim these plants annually (Fassi and Maina, 2006).

Reed plants can also be grown in marsh farming that is considered to be an innovative approach for the exploitation of organic soils, as opposed to traditional land reclamation for agricultural purposes (Wichtmann and Joosten, 2007). Marsh farming, also known as" wetland farming" or "marshland agriculture", refers to the practice of cultivating crops in wetland or marshy areas. It involves utilizing the unique ecological conditions of wetlands for agricultural purposes. Marsh farming often involves adapting traditional agricultural techniques to the specific conditions of wetlands, such as managing water levels, soil composition, and the types of crops that can thrive in such environments, such as reed. Wetland farming requires careful management to avoid negative impacts on the wetland ecosystem, including water quality and wildlife habitat consideration.

The stalks are typically harvested with specialized machinery in winter, when the water has turned into ice. In winter, the plant contains less sap, making it drier and allowing for quicker regeneration. The cut stems have lower moisture levels, leading to faster drying and reduced vulnerability to biological agents (Malheiro et al., 2021).
Each hectare of reed is approximately equivalent to 26 m3 of finished product. the drying process is not necessary as only dry reeds are harvested (Fassi and Maina,2006).
In the construction industry reed can be used as roof thatching, plaster "mesh", wall partitions and insulation.

F - Physical-mechanical properties

Reed is characterized by proprieties such as a wide availability, lightweight stems, and moderate mechanical strength along with high flexibility (due to its tubular stem structure), allow for different applications as a construction material (Speck and Spatz, 2004 and Köbbing et al., 2013). However, due to its limited mechanical strength and susceptibility to catching fire, using reed for building structures more difficult. It is often employed for ceilings or supports under roofing, as well as wall paneling to enhance thermal efficiency (Barreca et al., 2012).
Reed has natural insulating properties, providing thermal and sound insulation (Fassi and Maina,2006). Reed has a hygroscopic nature, it adjusts its moisture content based on the air relative humidity. It expands when humidity rises and contracts as it decreases. Consequently, reed's dimensional stability is an important aspect to consider when used in construction applications (Malheiro et al., 2021). The water resistance property makes it ideal for applications such as roof thatching or construction in more damp environments.

G - Durability

When properly harvested and maintained, reed can have good durability. Reed is resistant to rodent attack, mould growth and rot (Fassi and Maina,2006) also depending on its moisture content. Drier reed results in less intense and slower mould growth (Malheiro et al., 2021). Therefore, it might be more susceptible to deterioration in wet and humid environments. Generally, reed's durability can be improved through appropriate harvesting techniques, protective coatings, and periodic maintenance.
When considering its use as roof thatching, water reed stands out for its remarkable longevity, it can last up to 40 years or more. However, combed wheat reed provides a lighter alternative but lacks the same level of durability as water reed, thatched roofs made from wheat reed typically last up to 35 years (National Society of Master Thatchers, 2023).

H - End-of life and recyclability

When left untreated reed can be composted at the end of its life as it is biodegradable. When considering reed panels tied with wire, the wire must be removed and the remaining reed can be composted. If reed is utilized as a plaster "mesh" it has to be disposed at an aggregates landfill.

I - Life cycle assessment

As of today, a life cycle assessment of reed has been conducted for its use as biofuel or pellet production. In the study by Jasinskas et al. in 2020, E*nergy Evaluation and Greenhouse Gas Emissions of Reed Plant Pelletizing and Utilization as Solid Biofuel*[1], three reed herbaceous energy plants were studied: reed (*Phragmites australis*), bulrush (*Typha*) and reed canary grass (*Phalaris arundinacea L.*) for the production of biomass pellet to be used as biofuel. The first part of harvesting, transporting, cutting, milling and drying could rappresent similar stages of production when used as a building material.

[1] Wenjuan Shuai, Ning Chen, Bin Li, Dongmei Zhou, Juan Gao, (2016). Life cycle assessment of common reed (Phragmites australis (Cav) Trin. ex Steud) cellulosic bioethanol in Jiangsu Province, China, Biomass and Bioenergy, Volume 92, Pages 40-47, ISSN 0961-9534, https://doi.org/10.1016/j.biombioe.2016.06.002.

Technological Operations	Energy Consumption	
	MJ ha⁻¹	MJ kg⁻¹
Energy consumption of reed plant pellet production:		
Energy consumed for reed harvesting, loading into vehicle trailers and transportation to storage facilities	5740	0.7
Plant chopping	2870	0.35
Milling and drying, in order to reduce moisture content by 10%	16,400	2.0
Biomass pellet production in low power granulator	1230	0.15
Pellet transportation and combustion equipment	570	0.07
Total energy consumption:	26,810	3.27

Figure Rd02: Energy consumption of reed biomass pellet production
Source: Wenjuan Shuai, Ning Chen, Bin Li, Dongmei Zhou, Juan Gao, (2016). Life cycle assessment of common reed (Phragmites australis (Cav) Trin. ex Steud) cellulosic bioethanol in Jiangsu Province, China, Biomass and Bioenergy, Volume 92, Pages 40-47, ISSN 0961-9534, https://doi.org/10.1016/j.biombioe.2016.06.002.

Being that reed is not a very common building materials, especially when considering products that have been regulated and assessed, the information on its environmental costs are limited. It is a material that is still linked to auto construction and mainly used as loose material, making it harder to find reliable information.
Nonetheless, it generally seems to have a low environmental cost. Fassi and Maina2 (2006) reported its energy consumption when used as an insulation building material during phases A1 to A3 of life cycle as:

[2] Source of data: Beck k. (1999); Koning H., Muller p. (2000); Motzl H., Zelger T. (2000)

Raw material sourcing: 0.15 MJ/Kg
Transportation: 0.12 MJ/Kg
Manufacturing process: 0.20 MJ/Kg
Packaging: 0.07 MJ/Kg

For a total of **0.54 MJ/Kg**

As reported by Fassi and Maina (2006) reed has a very low embodied energy when compared to both natural and synthetic materials (e.g. cork panels 7.05 MJ/Kg, hemp fibre 15 MJ/Kg, glass fibre 34.60 MJ/Kg, rock wool 22.12 MJ/Kg).

J - Prefabricated production processes

The use of reed in contemporary architecture involves its application in the realisation of technological solutions in new buildings, in restoration work and in contexts that require particular attention to environmental aspects. More specifically, this material is currently used mainly for the production of semi-finished products, such as mats and panels made of pressed reeds.

Elements

Reed mat

The reed mat involves the production of mats composed of reed stems placed side by side and tied together with a wire, their main use is as support of plaster finishing layers. Mats are supplied in rolls with a height that varies between 1 and 3 metres and length is between 3 and 5 metres long.

Figure Rd03: Reed Mat - by Lacep - (IT)
Source: https://www.lacep.it

Applications: support of plaster finishing layers, It can also be used as pergolas or screens for shade, and it can also be used for erosion control in landscaping projects.

Some EU producers

Lacep - (IT)
Terragena - (IT)
Leobodner - (IT)
UKU - (EE)
Canaplex - (GR)

Reed panel

Figure Rd04: Reed Panel- by Hiss Reet - (DE)
Source: https://www.archiexpo.com/

Pressed reed panels are used to create thermal and acoustic insulation layers and are generally finished with a layer of plaster. They are usually sold in modular sections characterised by a thickness ranging from 3 centimetres up to 8 centimetres and more, a height of generally 2 metres and a length that can vary from 1 metre to 2 metres. These panels are composed of reed stems entwined with a steel wire or a nylon wire.

Applications: thermal and acoustic insulation panels, plaster baseboard, decorative board

Some EU producers

Lacep - (IT)
Terragena - (IT)
Leobodner - (IT)
UKU - (EE)
ReedTech - (EE)
Hiss Reet - (DE)

Reed thatched roof tiles

The Lapa Company based in Kent - UK, produces thatched roof tiles for both straight and circular applications.
The tiles dimension and weight varies, the standard is 800mm x 450mm x 25mm and weighs approximately 4.4kg. The standard cape reed thatch tiles are designed for a Do-It-Yourself construction and can be clipped onto an 8mm diameter steel rod, rope or nailed onto a wooden batten.

Figure Rd05: Reed thatched roof tiles
Source: https://www.thelapacompany.co.uk/

The Lapa company - (UK)

Reed composite panel

100% of raw materials used at the company Circular Matters and utilized in the Panels is plant-based, (e.g. brewers' grains and reed). All feedstock comes from the Netherlands and Belgium. The material is comparable to HPL and hardwood in terms of technical and processing properties. It is hard and sturdy but can be processed with standard woodworking machines. The panels at the end-of-life are completely compostable and biodegradable.

Applications: internal walls, interior finishings, furniture

Circular matters - (FR)

Figure Rd06-07: Circular matters - Reed composite panelsl
Source: https://theexplodedview.com/materialbb/circular-matters-panel/

K - Case studies / Good practices

ecoSuites, A Reed-Clad Hotel / Alex A. Tsolakis Architecture

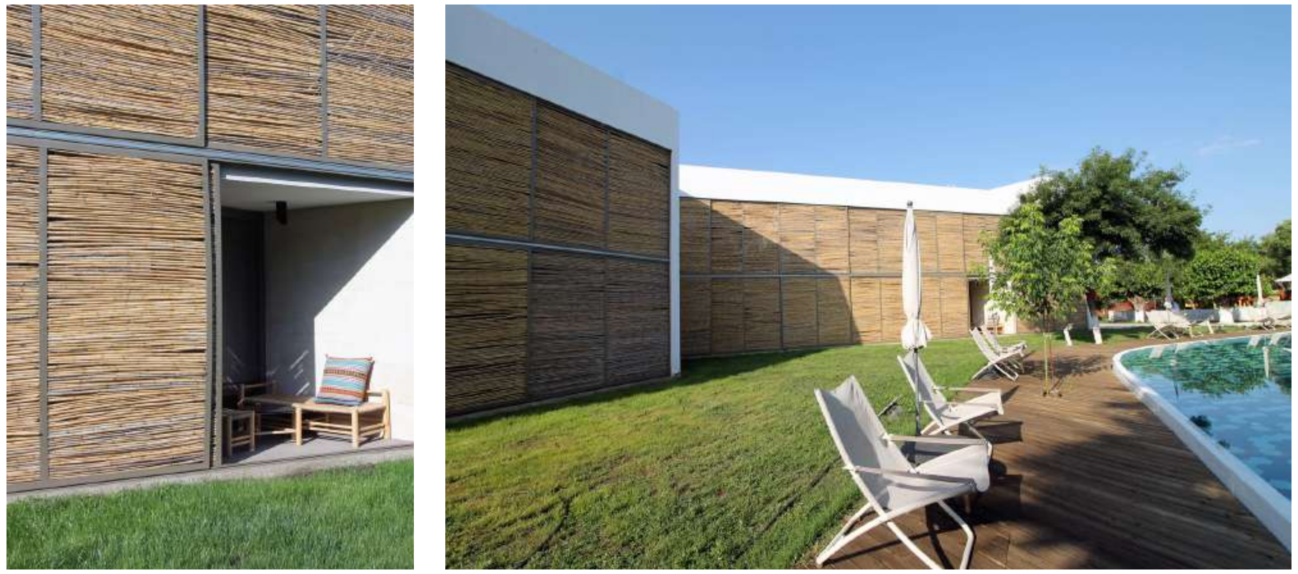


Figure Rd08-09: Reed cladding Panels - ecoSuites
Source: https://www.archdaily.com

Figure Rd10: Reed cladding Panels - ecoSuites - construction with local reeds
Source: https://www.archdaily.com

The project consists of a hotel extension of ecoSuites, in Tristinika Beach, Greece. The architect Alex A. Tsolakis Architecture designed a series of suites composed of prefabricated wall components. The side of the hotel facing the swimming pool (NE-NW) is entirely covered using sliding panels covered in locally sourced reed of the hotel surroundings. These reed panels cover the full-length glass windows, creating a blend with the natural surroundings and a softer appearance. Additionally, these movable reed panels offer both privacy and protection from the sun.

This solution showcases a more aesthetic way of reeds use in architecture as cladding whilst using local and bio-based materials.

Mudhif - Reed vernacular houses - Iraq

Figure Rd11: Mudhif house - Iraq
Source: https://www.atlasobscura.com/places/mudhif-houses

Mudhif houses are vernacular structures found in Iraq's marshlands. They utilize local materials such as reeds, mud, and wood in their construction. These houses are elevated above marsh terrain with a wooden framework from which raises a tightly woven set of reed bundles shaped in arches that compose the roof and wall structure providing insulation, protection from the elements and stabilizing the interior climate.

Mudhif houses offer several valuable lessons in terms of construction techniques, environmental adaptation, and community-centred design. Mudhif houses showcase resilience against environmental challenges and contribute to the preservation of cultural heritage.

There are a lot of lessons to be learnt from these architectures and that could be applicable to modern practices today, like the use of local and biogenic materials as well as their integration of passive strategies.

Although careful consideration should be given to balancing modern techniques with the traditional and environmental context, the potential of the arches to become a building element or component could allow for a modern use of this material in structures of different projects where reed is abundantly available.

Figure Rd12: Mudhif house arch construction
Source: https://www.texasmonthly.com/style/mudhif-houston-rice-university-iraqi-marsh-arabs/

Figure Rd13: Mudhif house arch construction
Source: https://www.atlasobscura.com/places/mudhif-houses

L - Limits to overcome

While reed has been used historically as a building material all over the world, there are certain limitations that need to be addressed when considering its contemporary use in construction. The first consideration is about the fact that reed's availability is region-specific, posing challenges in areas where it is not naturally abundant for the use of locally sourced materials. Moreover, while reed offers insulation properties, its effectiveness might vary in comparison to more conventional building materials.

The composition and properties of reed can vary depending on factors such as species, growth conditions, and harvesting methods. Ensuring consistent material properties and minimizing variability are critical challenges for the manufacturing and upscaling ofreed as a building material.

One very important aspect is also the fact that addressing fire resistance concerns and meeting modern building codes can be complex as its resistance is poor.

Even though reed is part of construction traditions worldwide, like many other bio-based materials, overcoming perception barriers, building codes and regulations, and establishing market acceptance for reed as a building material is an important factor for its successful integration into the construction industry.

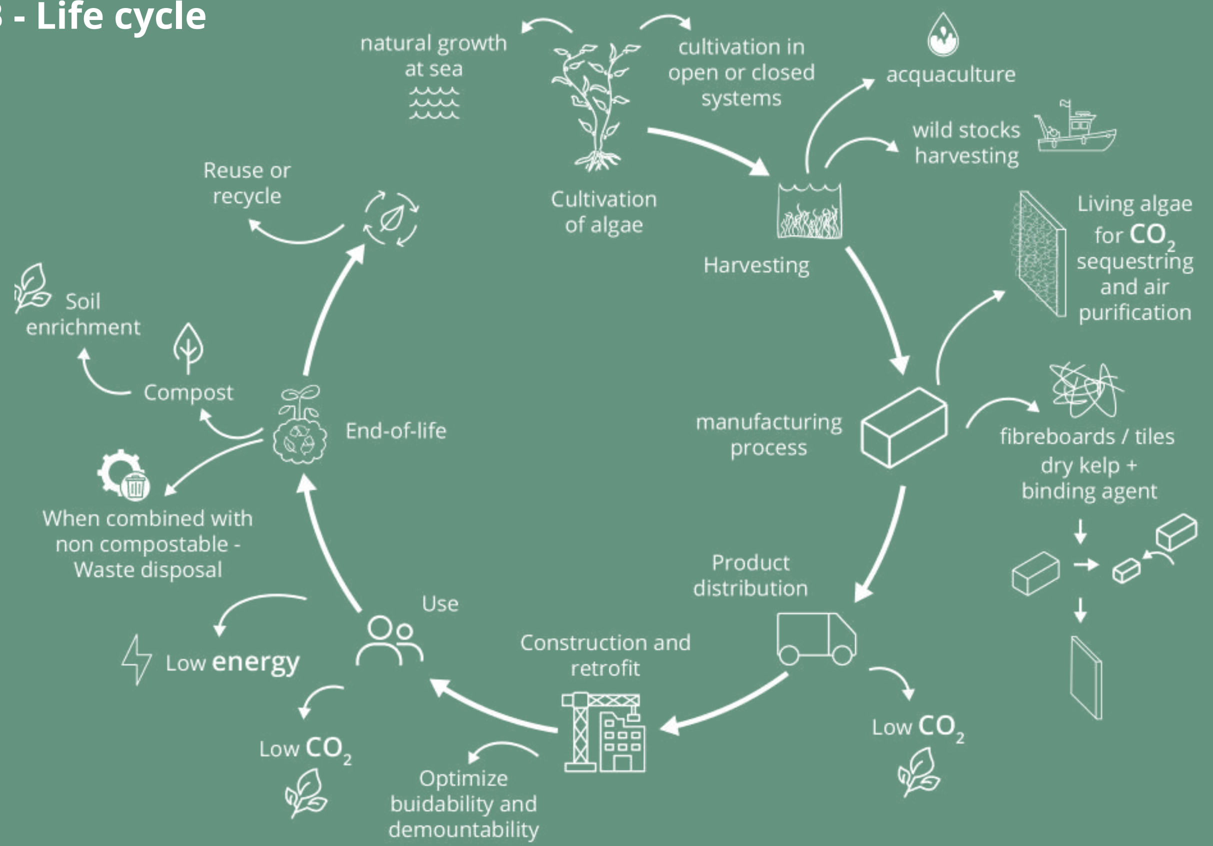
Overcoming these limitations has to involve research into potential treatment methods, engineering techniques, and strategic design approaches to showcase Reed's benefits.

/
Seaweed

A - Watch points

- Use local and responsibly sourced raw materials, allow for regeneration
- Need for specific skills and controlled environment for production process
- Low carbon energy in processing methods
- Low carbon transportation
- Optimise buildability and design to disassemble
- End-of-life - biodegradable - re-purpose - reuse

B - Life cycle



C - Key points

Raw material resource

Virgin/primary resource	●
Recoverable resource	●
Recovered/secondary resource	○
Waste resource	●

Availability of raw material

● ● ● ○ ○

Degree of skills required for resourcing raw material

● ● ● ● ●

Degree of prefabrication

● ● ○ ○ ○

Awareness

● ● ○ ○ ○

Applications

Technological units	Technical elements	Products category	
vertical closures	external walls	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
		Cladding/shingles/tiles	●
top closures	roof	Cladding/tiles/shingles	●
		Panels/false ceiling	○
		thermo-acoustic insulation	●
horizontal closures	slabs	Flooring Tiles/Panels/boards	●
		thermo-acoustic insulation	○
partitions	vertical partitions	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
	horizontal partitions	Florring Tiles/Panels/boards	●
		thermo-acoustic insulation	○

D - Raw material

The term algae is used to indicate a polyphyletic[1] wide range of photosynthetic organisms that comprise more than 72 500 estimated species. Algae and plants produce the same storage compounds as well as use similar defence strategies against predators and parasites, however they are different for as plants exhibit a high degree of structural complexity with specialized organs such as roots, stems, and leaves, while algae lack these distinct organs. Algae can range from microscopic single cells to macroscopic forms, but they do not possess well-defined vascular tissues like plants (Barsanti and Gualtieri, 2014).
Approximately 80% of algae species are composed of single cells and are referred to as microalgae, while the remaining 20% are made up of multiple cells and are known as macroalgae or seaweeds. Macroalgae are macroscopic organisms that vary in size from millimetres to lengths of up to 70 m (Araújo, 2019).
Algae are structuring organisms in coastal ecosystems as they provide habitat, food, reproductive areas, and shelter for various species within the food web (Bertocci et al., 2015; Reisewitz et al. 2006). They also contribute to significant ecosystem services along the coast, including carbon sequestration, nutrient removal, and coastal protection (Araújo, 2019).

For centuries, coastal communities have been utilizing algae biomass as a fertilizer, cattle feed, and human food source. Today, it is primarily employed by the food and chemical industries. However, in recent decades, the emergence of new applications based on algae biomass, such as feed and food supplements, pharmaceuticals, third-generation bio-fuels and bio-materials has led to a growing and diversified market for these resources (Barbier et al., 2019).
Algae has been traditionally used in vernacular architecture in various regions worldwide. In Europe examples of seaweed use can be seen in traditional construction techniques in coastal areas of countries such as Ireland, Scotland, and Norway. In these regions, seaweed was employed as a thatch material for roofing, providing insulation and protection against the elements.

Figure Sw01: Sargassum algae
Source: https://www.bbc.co.uk/

[1] "Polyphyletic" is a term used in taxonomy to describe a group that includes multiple organisms or species that do not share a common ancestor

E - Cultivation and Harvesting

Macroalgae biomass used for commercial purposes is obtained either through harvesting from wild stocks or through aquaculture. Collection of wild macroalgae involves techniques such as hand harvesting from the shore during low tide or mechanical harvesting using boats and specialized devices (Mac Monagail et al., 2017). In Europe, the commercially harvested species primarily include *Laminaria hyperborea* and *Ascophyllum nodosum* (Mac Monagail et al., 2017). Cultivation of macroalgae can be carried out in land-based tanks or ponds, as well as in sea-based structures like long-lines or rafts (Buschman et al., 2017). It can be done as monoculture or as part of integrated multi-trophic aquaculture (which is a farming approach that involves the cultivation of multiple species in close proximity to create a symbiotic relationship and optimize resource utilization), and a strategy promoted to minimize potential negative impacts of marine aquaculture (Ellis et al., 2019; Nardelli et al., 2019). Examples of cultivated species in European waters include *Alaria esculenta, Palmaria palmata*, *Saccharina latissima*, and *Ulva* (Barbier et al., 2019).
Microalgae exhibit rapid growth under favourable conditions, with certain strains capable of doubling their mass in a single day, offering the potential to produce significantly larger amounts of biomass compared to other more traditional crops (Schenk et al., 2008).
Microalgae can be cultivated in either open or closed systems. Open systems, which are more cost-effective, involve the growth via being exposed to direct contact with the atmosphere and can take the form of rectangular or circular ponds that are mechanically stirred by a paddle wheel (Enzing et al., 2014).
Closed systems, on the other hand, include photobioreactors (PBRs) or fermenters. PBRs, though more expensive, offer higher productivity and better control over cultivation conditions, preventing contamination and minimizing water use and CO_2 losses. PBRs can be designed with horizontally or vertically arranged tubes or panels (Enzing et al., 2014).
Fermenters are another type of closed system that takes advantage of the ability of microalgae to grow in the dark using sugars, making them a cost-effective method for large-scale production of certain microalgae species (Xiong et al., 2008; Doucha and Lívanský, 2012).

Figure Sw02: Traditional harvesting of algae on the foreshore of Pleubian - Brittany (FR)
Source: https://www.nuwen.com/en/nutraceutical/algae-from-brittany-and-their-effects-in-the-slimming-sphere/

Figure Sw03: Integrated farm - fish ponds, macroalgae tanks and supporting buildings, © ALGAplus
Source: https://www.sme-enterprize.com/sustainability-stories/environment/algaplus/ - Image by Alfonso Ré Lau

Figure Sw04: Photobioreactor microalgae production © Necton SA, 2019
Source: European Union (2019) Brief on algae biomass production1 doi:10.2760/402819 ISBN 978-92-76-12270-8 JRC 118214, pp. 3

Even though accelerated growth rate enables more frequent harvesting cycles, ensuring a steady supply for batch-wise harvesting requirements must be coherent with sustainable harvesting as for allowing for regeneration is essential.
Commercially exploited macroalgae species in Europe are facing challenges due to various stressors, including global warming, herbivory, water quality decline, and non-native species introductions. Sustainable management plans are in place in some countries, but guidelines are lacking in others, emphasizing the need for robust scientific knowledge and ecosystem-based management models (Williams and Smith, 2007; Lorentsen et al., 2010; Wernberg et al., 2010; Moy and Christie, 2012; Delebecq et al., 2013). Macroalgae aquaculture, such as integrated multi-trophic aquaculture (IMTA), offers environmental benefits but requires further evaluation to assess potential impacts on sedimentation rates, introduction of alien species, and community structure (Barbier et al., 2019).
Ensuring the environmental sustainability of microalgae production necessitates considering water, energy, land use, pollution, and invasive species risks, and implementing best practices throughout the production cycle (Brugère et al., 2018).

F - Physical-mechanical properties

Algae exhibit properties that make for promising building materials. Properties include renewability as their growth is rapid, lightweight nature, thermal and acoustic insulation capabilities, biodegradability, recyclability, and aesthetic versatility and overall low environmental impact.
Seaweed distinguishes itself from conventional building materials by being non-toxic and possessing fireproof characteristics. With its compact cellular composition, seaweed exhibits a long lifespan and incorporates antibacterial compounds, while aiding regulation of moisture levels and contributing to a healthy indoor environment (Building centre,2017).

G - Durability

Research on the durability of algae as a building material is still limited and more studies are needed to understand its long-term performance.
Factors such as environmental exposure, moisture resistance, and resistance to decay and degradation need to be thoroughly examined to assess the long-term durability of algae-based building materials and to enhance their durability.

H - End-of life and recyclability

The end-of-life and recyclability of algae-based materials are important considerations for their sustainable use, and while specific studies on algae's end-of-life and recyclability are limited, the biodegradable nature of algae suggests their potential for environmentally friendly disposal. Algae-based materials can undergo decomposition and return to the environment without causing long-term pollution, when left untreated, or treated and combined with other bio-based materials.

I - Life cycle assessment

As of today, Life cycle assessment analysis have not been carried out on the use of seaweed as a building material. There are some studies that assess the environmental impact when algae is used as bio-diesel. Arguably the first stages of the process, cultivation, harvesting and biomass filtering can constitute the same process as when used as bio-building materials.

In the study *A critical review on life cycle analysis of algae biodiesel: current challenges and future prospects*[2], the authors propose an overview on different stages of the production process, including cultivation, harvesting and biomass filtering.
The cultivation of algae can take different forms: an open pond, a photobioreactor, or a hybrid system. It needs light, CO_2, water, and nutrients to support algae growth. In commercial applications, the algae strains are initially cultured in a photobioreactor until they reach a desired density of biomass. To harvest the algae, methods like coagulation, flocculation (process that involves dosing a coagulant and then allowing collisions to occur), floatation, sedimentation, filtration, or centrifugation are used. The harvested algae contain a high-water content, typically 85-95%, which is reduced further through processes like dewatering, filtering, thickening, and drying in a biomass processing unit.

[2] Full article at: https://www.sciencedirect.com/science/article/pii/S1364032120304342#bib14

Large-scale algae cultivation and production requires significant land and water resources. If not managed properly, this could lead to habitat destruction, loss of biodiversity, and competition with other land uses, such as agriculture or natural ecosystems. Furthermore, algae cultivation at times utilizes and requires the addition of nutrients, such as nitrogen and phosphorus, to promote growth. If these nutrients are not properly controlled and managed, excess amounts can leach into surrounding water bodies, leading to nutrient pollution and potentially causing harmful algal blooms, also known as nitrification. The large-scale cultivation of algae involves energy-intensive processes such as harvesting and drying. If the energy used is not derived from renewable sources, the overall carbon footprint of algae-based products may be higher than anticipated, potentially offsetting some of its environmental benefits promoted by the use of this material.

Ultimately, not only artificial cultivation and harvesting processes need to be sustainable, also ones that harvest seaweed from sea need to consider low carbon methods and allow for regeneration in order to preserve and not disrupt ecosystems.

J - Prefabricated production processes

Elements

Seaweed fibreboards

SeaWood / BlueBlock - (NL)

Figure Sw05: SeaWood fibreboards - BlueBlocks
Source: https://www.blueblocks.nl

SeaWood represents a collection of fibreboard materials are a result of the project Maasplant (CityLab010[3]) by the company BlueBlocks[4] , in Rotterdam (NL), and crafted entirely from pressed seaweed and waste cellulose, ensuring a 100% natural, recyclable, and chemical-free composition. The challenge of the company is to develop a manufacturing process employing an innovative bio-tech approach that is both environmentally friendly and scalable, while eliminating the need for additional binding agents, enabling the material to be easily recycled after use as compost.

Applications: These materials possess wood-like properties and sound dampening qualities, making them suitable for a range of applications including interior walls, acoustic panels, and design products. Moreover, SeaWood Materials offers an aesthetic finishing layer for interior spaces.

Figure Sw06: SeaWood fibreboards - BlueBlocks - indoor wall
Source: https://www.blueblocks.nl

[3] More information at: https://www.citylab010.nl/

[4] More information at: https://www.blueblocks.nl/portfolio/seawood/

BlueBlock NL

BlueBlocks develops new bio-materials and circular products, complying with principles of the blue economy, which is an economic system based on sustainable use of ocean resources for economic growth (as defined by the United Nations).
BlueBlock focuses on bio-material research and development, zero-waste systems, circular design, and future food systems. It is a result of co-creation and was founded by Marjanne Cuypers, who is an industrial design engineer.

www.blueblocks.nl

Figure Sw07: Marjanne Cuypers elaborating SeaWood fibreboards
Source: https://www.blueblocks.nl

Seaweed thatched panels

Figure Sw08: Prefabricated thatched seaweed panels by Kathryn Larsen
Source: https://kathrynlarsen.com/

Kathryn Larsen, an architectural technologist based in Denmark and born in the United States, has drawn upon the Danish tradition of seaweed thatching from the island of Læsø to develop modern seaweed thatch prefabricated panels for the building industry.

Through her research, Larsen has discovered that eelgrass possesses inherent qualities such as natural fire resistance, resistance to decay, negative carbon footprint, and waterproofing within approximately a year.
Furthermore, it provides insulation while allowing for the growth of plants, creating the effect of a green roof.

Figure Sw09: Test panel with different bio-based binders
Source: https://kathrynlarsen.com/

In order to preserve the inherent characteristics of eelgrass, Larsen employed minimal quantities of binders. Through the utilization of eight natural, non-toxic binders derived from plants or animals, such as casein and bone glue, alongside water, she produced a series of test panels. These natural binders also enhanced the seaweed's waterproof properties.

Leveraging the properties of eelgrass, Larsen has created prefabricated seaweed thatch panels that can be installed on roofs or facades to enhance insulation. To assess their efficacy, she constructed an installation on the roof of the Copenhagen School of Design and Technology (KEA).

These panels are intentionally designed for disassembly. At the conclusion of the installation, all materials involved can be reused or recycled. After enduring approximately eight months outdoors, the panels remain almost entirely intact, with moss beginning to grow on the seaweed (Sofia Lekka Angelopoulou, 2020).

kathrynlarsen.com

Figure Sw10-11: Seaweed prefabricated panel - Pavillion
Source: https://www.designboom.com/design/kathryn-larsen-seaweed-prefab-thatch-panels-03-04-2020/

Algae tiles

Algae tiles are an alternative solution to conventional tiles, made from seaweed.

In particular, Algal Tiles, by the company Ecolurian[4] in Delfzijl (NL), are an environmentally-friendly tile solution for interior design. These tiles are crafted using hand-picked kelp algae sourced from the Pacific Ocean. The natural colours and patterns found in the kelp algae lend a unique aesthetic to each tile. Moreover, they offer a line of an uncoated variant that preserves the natural capabilities of the kelp tiles to absorb moisture from indoor spaces.

www.ecolurian.com

Figure Sw12: Algal Tiles - Collection Life - Ecolurian
Source: www.ecolurian.com

INDUS Algae purifying tiles - (UK)

The Bio-Integrated Design Lab[5] students at the Bartlett School of Architecture have developed a novel system for filtering pollutants found in rainwater. This innovation involves a combination of modular tiles infused with algae. Indus, the champion of the A/D/O Mini Water Future Design Challenge[6], showcases how design can take cues from nature while safeguarding it. These tiles, designed with patterns reminiscent of leaf structures to imitate water distribution, blend micro-algae with a seaweed-based hydrogel. This mixture not only sustains the micro-algae but is also environmentally conscious, being both recyclable and biodegradable. Indus applies bioremediation principles[7], utilizing microorganisms like algae to break down environmental pollutants, specifically for rainwater purification. The primary objective of the Bio-ID Lab is to empower rural artisan communities in revitalizing and repurposing water for their manufacturing processes.

Indus tiles are designed for easy on-site construction in areas with contaminated water sources. Using inexpensive local materials like clay, the fan-shaped moulds are filled, and the leaf-inspired channels are then filled with algae hydrogel mixed with water. The modular nature of Indus allows it to be assembled into a wall system where water is poured in from the top, flowing through the channels and collecting at the bottom. The saturated algae can be replaced, enabling continuous reuse and refilling of the tiles.
Each modular tile unit can be individually removed without dismantling the entire system, thanks to a half-lap joint. This feature facilitates simple maintenance and adaptation to local building constraints, as the size of the tiles can be easily customized to fit the available space (Greta Aldeghi, 2019).

https://www.dezeen.com/2019/09/21/bio-id-lab-indus-algae-tiles-water/

Figure Sw13: INDUS - Purifying clay-algae tiles
Source: https://www.dezeen.com

[5] More information at: https://www.ucl.ac.uk/bartlett/architecture/programmes/postgraduate/bio-integrated-design-bio-id-marchmsc

[6] More information at: https://www.dezeen.com/2018/03/22/ado-water-futures-design-challenge-call-for-entries/

[7] Bioremediation principles refer to the use of biological processes or organisms to mitigate or eliminate environmental pollutants. It is an approach that harnesses the natural abilities of certain microorganisms, plants, or other living organisms to break down, transform, or remove contaminants from soil, water, or air.

Figure Sw14: INDUS - Purifying clay-algae tiles - wall system
Source: https://www.dezeen.com

K - Case studies / Good practices

ecoLogicStudio - (UK)

Figure Sw15: ecoLogicStudio's installation at 2021 Biennale di Venezia - Bit.Bio.Bot
Source: https://www.ecologicstudio.com/projects/bitbiobot

Established in 2005 by Claudia Pasquero and Marco Poletto, ecoLogicStudio stands as an architectural and urban design studio situated in London, UK. Their reputation is rooted in a pioneering and multidisciplinary method towards architecture, placing notable emphasis on eco-friendly and sustainable design resolutions.
The studio harmonizes architectural expertise with scientific exploration and digital crafting methods to confront environmental issues and mold enduring urban landscapes. Their endeavors delve into the convergence of living systems, bio-digital strategies, and cutting-edge technologies, with a primary focus on *algae* integration.

Their work often involves the use of biomimicry, parametric design, and bio-digital fabrication methods to create projects architectural installations.
In 2018, ecoLogicStudio joined the Synthetic Landscape Lab and the Urban Morphogenesis Lab to establish the PhotoSynthetica venture[8].
Collectively, they are dedicated to creating scalable design solutions rooted in nature to address the pressing challenges of climate change and the ongoing pursuit of carbon neutrality.
ecoLogicalStudio's endeavours have given birth to a range of inventive design solutions that revolve around the theme of urban microbiology. Through their projects, they aim to seamlessly weave together bio-digital processes, living systems, and state-of-the-art technologies. For example:

Bio.Bolla - (UK)

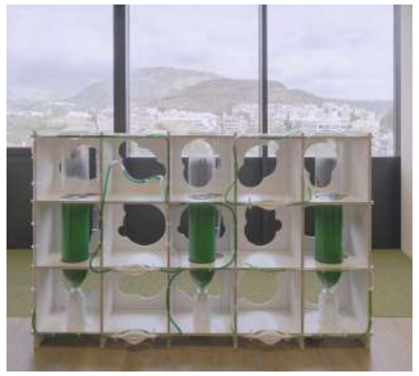


Figure Sw16: Bio.Bolla Project - ecoLogicalStudio - (UK)
Source: https://www.ecologicstudio.com/projects/biobolla

The BioBolla consists of an assembly of components designed for complete disassembly and reversibility. Each part can be recycled or composted at the end of its lifespan.

This project offers advantages for the health and well-being of both employees and visitors on the Arona Italian Embassy, where it is placed. It provides oxygenation, a soothing background bubbling sound, as well as air purification. As declared by ecoLogicStudio, "Bio.Bolla captures CO_2 equivalent to ONE mature tree with the power of photosynthetic microalgae".

www.ecologicstudio.com

TEDx Talks - Bucharest
Urban Microbiology is the Key to Building the Future of our Cities - Marco Poletto

https://www.youtube.com/watch?v=azD7YrIBUsQ&t=55s

Sargablock - Mexico

Sargassum is a type of brown seaweed that has been washing up on the shores of Mexico and other Caribbean countries in large quantities. To address this environmental challenge, innovative solutions have been developed.

Figure Sw17: Riviera Maya - (MX), Sargassum on the shore
Source: https://www.oceanbreezeakumal.com/en/1782592/sargassum-seaweed-in-the-riviera-maya

In particular, Omar Vazquez in Mexico has explored the use of Sargassum, harvested from the shores of Riviera Maya, as a raw material for manufacturing blocks: Sargablock.

Figure Sw18: Sargablock before being sun dried
Source: https://undplac.exposure.co/sea-change

These consist of a mix of 40% sargassum and 60% other organic materials, such as clay, and manufactured through adjusting a machine designed to make adobe blocks. The Sargablock, once they have been formed, are then “baked” in the sun and dried.
The Sargablock has thermal and acoustic insulation properties and is organic.

The concept brought on by the creator is to provide a cost-effective building material to construct homes for people in need. As of today, is prototype home Casa Angelita, has been reconstructed numerous times and donated to families in need. The project is part of the United Nations Development Program (UNDP) in Latin America and the Caribbean[9].

Figure Sw19: Machine designed to make adobe blocks and adjusted to make Sargablock
Source: https://undplac.exposure.co/sea-change

Figure Sw20: Casa Angelita - (MX) first home built with Sargablocks
Source: https://sargablock.com.mx/

L - Limits to overcome

It is worth noting that while algae-based building materials show promise, further research is needed. In order to exploit their full potential and further optimize their properties, as well as enhance durability, developing suitable production techniques, and ensuring compliance with building regulations and standards as well as sustainable harvesting practices are essential to meet quantities needed for an upscale in the building sector. Furthermore skill-sharing is a key aspect for the manufacturing processes, integration and application of algae in this sector.

The composition and properties of seaweed can vary depending on factors such as species, growth conditions, and harvesting methods. Ensuring consistent material properties and minimizing variability are critical challenges for the manufacturing and upscaling of algae-based building materials.

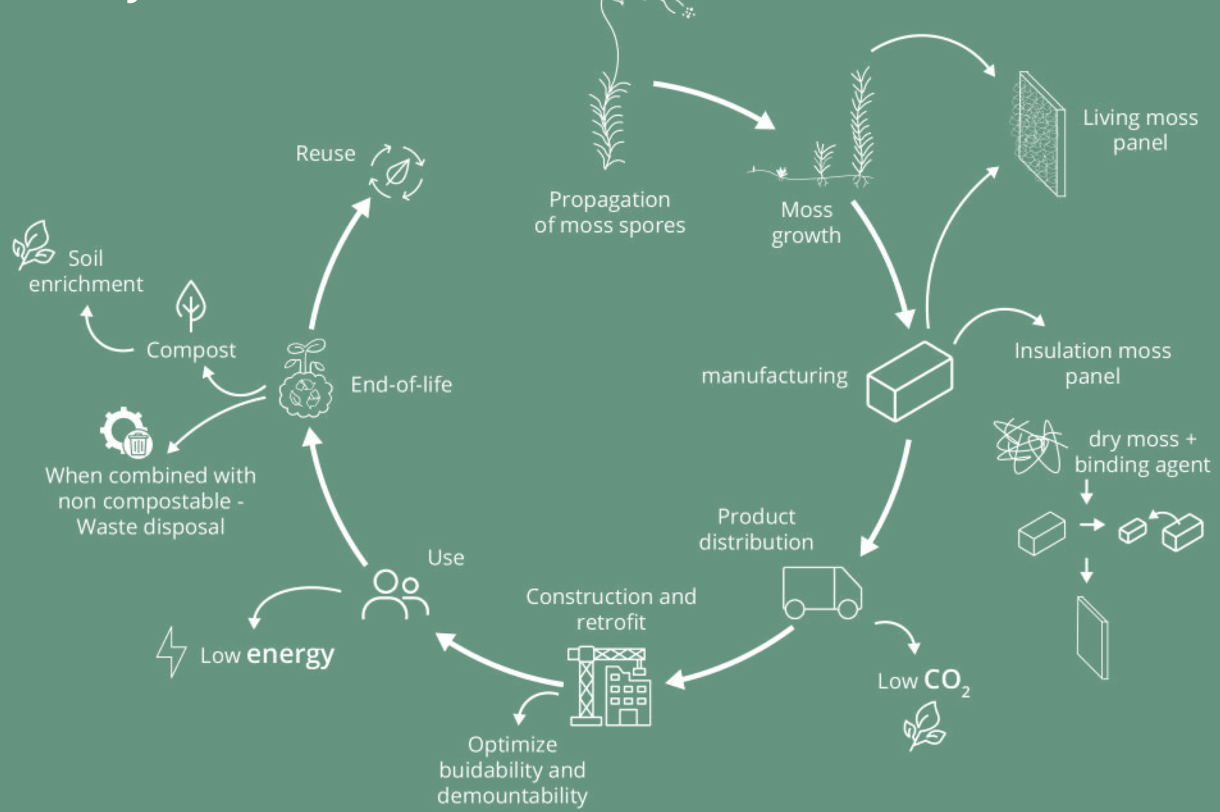
Like many other bio-based materials, overcoming perception barriers, building codes and regulations, and establishing market acceptance for seaweed-based materials are important factors for their successful integration into the construction industry.

/
Moss

A - Watch points

- Use local and responsibly sourced raw materials, allow for regeneration
- Need for specific skills and controlled environment for production process
- Low carbon energy in processing methods
- Low carbon transportation
- Optimise buildability and design to disassemble
- Maintain appropriate humidity levels when considering indoor use living moss
- End-of-life - biodegradable - composting

B - Life cycle



C - Key points

Raw material resource

Virgin/primary resource	●
Recoverable resource	●
Recovered/secondary resource	○
Waste resource	○

Availability of raw material
●●●●○

Degree of skills required for resourcing raw material
●●●○○

Degree of prefabrication
●●○○

Awareness
●●○○○

Applications

Technological units	Technical elements	Products category	
vertical closures	external walls	masonry elements	○
		Panels/boards	○
		thermo-acoustic insulation	●
		Cladding/shingles/tiles	●
top closures	roof	Cladding/tiles/shingles	○
		Panels/false ceiling	○
		thermo-acoustic insulation	●
horizontal closures	slabs	Flooring Tiles/Panels/boards	○
		thermo-acoustic insulation	○
partitions	vertical partitions	masonry elements	○
		Panels/boards	●
		thermo-acoustic insulation	●
	horizontal partitions	Florring Tiles/Panels/boards	●
		thermo-acoustic insulation	●

D - Raw material

Figure Ms01: Moss plant
Source: https://phys.org/news/2019-06-start-up-maintenance-free-evergreen-moss-faades.html

Mosses stand out as one of the most prevalent and widespread life forms across the globe (Turetsky et al., 2012). They make up a significant portion of plant biomass within diverse ecosystems, spanning deserts to boreal and arctic areas (Shaw et al., 2005). Mosses comprise around 12,000 species of diminutive, spore-bearing land plants. They are found distributed globally, frequently in damp and shaded environments. Notably, species within the *Sphagnum genus*, which forms peat, hold particular significance (Britannica, 2023).

Currently there still is limited knowledge regarding the impact of moss traits on terrestrial ecosystem biodiversity and function. As a result, the understanding of the contribution of mosses and their characteristics to soil biogeochemistry, biodiversity, and ecosystem services remains to be further explored and studied. This lack of understanding persists even when considering diverse climates, vegetation types, and land uses around the world (Eldridge et al., 2023).

A recent global study titled *The global contribution of soil mosses to ecosystem services*[1] delved into the role of mosses in ecosystems, highlighting their significant support in regions with sparse vascular plant[2] cover. Mosses serve important functions in various aspects of ecosystems, including nitrogen cycling, hydrology, carbon sequestration[3], as well as absorbing fine dust particles, air purification, and cooling. The research also revealed that soil mosses have the potential to store around 6.43 Gt more carbon in global soil layers compared to bare soils. These findings emphasize the essential role of mosses in soil health and functions, emphasizing the need to conserve these organisms for maintaining robust soils.

[1] Full article at: https://www.nature.com/articles/s41561-023-01170-x

[2] Vascular- plants are plants with vascular tissues, particularly, xylem and phloem for conducting water and integrating food, respectively (e.g. ferns and seed plant). Mosses are non-vascular plants.

[3] Jonsson, M. et al. (2015) Direct and indirect drivers of moss community structure, function, and associated microfauna across a successional gradient. Ecosystems 18, 154–169.
Delgado-Baquerizo, M. et al. (2018). Biocrust forming mosses mitigate the impact of aridity on soil microbial communities in drylands: observational evidence from three continents. New Phytol. 220, 824–835.
Eldridge, D. J. et al. (2020) The pervasive and multifaceted influence of biocrusts on water in the world's drylands. Glob. Change Biol. 26, 6003–6014.
Kasimir, Å., He, H., Jansson, P.-E., Lohila, A. & Minkkinen, K. (2021). Mosses are important for soil carbon sequestration in forested peatlands. Front. Environ. Sci. 9, 680430.

E - Cultivation and harvesting

Moss grows, as mentioned above, naturally throughout the globe, commonly in shady and moist locations. When considering peat moss, it comes only from peatlands, which are finite in nature and of significant importance to climate change action and carbon fixation (McKeon-Bennett et al., 2021)., thus removing them for other purposes, such as uses in architecture, could harm the ecosystems they grow in.

Cultivating moss usually starts with collecting samples of existing plants and propagating them. Water level control is a crucial element of successful Sphagnum farming (Gilbert, 2019).

The study Optimising Artificial Moss Growth for Environmental Studies in the Mediterranean Area, explored moss growth in a controlled environment. This study has found and demonstrated that it is possible to artificially grow moss in plastic containers with organic gardening substrate without fertilizers and achieving an average cover of the culture area of more that 60% within 5-8 weeks. The growth of most species is sus-

tained at around 15 °C, when temperatures are from 20-25 °C growth stops and the moss dies after some weeks. This cultivation process would allow for moss to be used in different projects, and furthermore preserve other native moss species in degraded areas.

F - Physical-mechanical properties

When considering the properties of the Sphagnum moss these include: ecological compatibility (Verhoeven and Liefveld, 1997), medicinal (bactericidal) properties (Podterob and Zubets, 2002) nonsusceptibility to decay and low thermal conductivity (Drobnik and Stebel, 2017).

When examining the application of moss in architectural contexts, particularly for indoor purposes such as wall, ceiling, and floor installations, moss exhibits commendable qualities such as effective insulation and sound absorption, reliable fire resistance, antibacterial properties, and an unfavourable environment for insects. Ensuring proper maintenance requires maintaining a relative moisture content of at least 40-50%, which coincides with the humidity levels conducive to human well-being (MOSSwall®, 2023).
The use of peat moss in insulation panels with bio-based adhesives in the study *Physical-Mechanical Properties of Peat Moss (Sphagnum) Insulation Panels with Bio-Based Adhesives*[4], has found that the peat moss samples have a low thermal conductivity that is comparable to that of other lightweight insulation materials. The lower-density boards have low mechanical stability. This limits their application to non-structural situations. Their moisture absorption and water absorption properties limit their application to interior spaces or shaded areas (Morandini et al., 2022).

[4] Full document at: https://www.mdpi.com/1996-1944/15/9/3299

G - Durability

Moss's lifespan varies and it ranges from a few months to several years for individual plants. Moss species complete their life cycle within a year or multiple years under favourable conditions, namely moisture conditions, sunlight exposure, temperature variations, soil conditions.
Mosses can regenerate and colonize new areas, allowing them to persist over time. They can enter a dormant state during unfavourable conditions and resume growth when conditions improve. While individual moss plants have short lives, moss populations can thrive through reproduction and adaptability.

When considering the lifespan of a preserved moss wall, can range anywhere from two to eight years before it needs professional maintenance. The longevity depends on the type of moss used, the ambient moisture of the environment, and sunlight exposure. Lastly, moss walls can be damaged by constant handling over time, therefore are best when out-of-reach.

Moss

H - End-of life and recyclability

Moss is biodegradable and compostable. When considering composite elements, such as insulating panel with moss and other materials, their composability potential can be compromised by the latter, therefore moss must be combined with other bio-based and biodegradable materials in order to *return to the soil.*

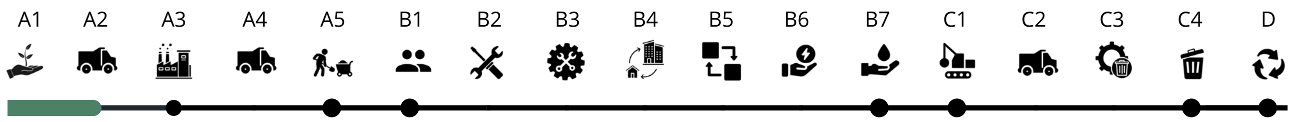
I - Life cycle assessment

As of today, a life cycle assessment of the use of moss as building material is yet to be conducted.

As previously mentioned moss contributes to the health and support of ecosystems, as well as carbon sequestration and significantly supports ecosystem services where vascular-plants cover is low.

Moss *Sphagnum* can be sustainably harvested every 4 years (Krebs et al., 2015), and about 3–6 tons of peat moss can be harvested per hectare per year. This value is related to the dry mass of the raw material (Gaudig et al., 2018). In order to exploit the full potential of carbon uptake, it is important to ensure a high water level in the cultivated areas of moss (Morandini et al., 2022).

LCA was conducted on moss used in horticulture, and data was obtained from the SimaPro software. The reference follows Peat moss {RoW} peat moss production, horticulture use|Cut-off, U (Ecoinvent) and refers to 1 m^3 of dry peat moss in loose form. A density of 100 Kg/m^3 is considered for dry peat moss in loose form. Therefore, to understand impact in terms of 1 Kg (functional unit also used for other materials), the results have to be converted - mass (kg) = volume (m^3) x density (kg/m^3) - and therefore have to be divided by 100.



GWP

Impact category	Unit	Total
Total	kg CO_2 eq.	**129.155**
Climate change - fossil	kg CO_2 eq.	129.082
Climate change - biogenic	kg CO_2 eq.	0.126
Climate change - CO2 uptake	kg CO_2 eq.	-0.062
Climate change - land use and transformation	kg CO_2 eq.	0.009

GWP - IPCC 2013 GWP 100a (incl. CO2 uptake) V1.00 - Characterisation

Embodied energy

EE - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation

Impact category	Unit	Total
Total	MJ	**1431.387**
Non renewable, fossil	MJ	1415.091
Non renewable, nuclear	MJ	9.689
Non renewable, biomass	MJ	0.002
Renewable, biomass	MJ	0.658
Renewable, wind, solar, geothermic	MJ	1.772
Renewable, water	MJ	4.175

EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation

Impact category	Unit	Total
Climate change	kg CO2 eq	126.960
Ozone depletion	kg CFC11 eq	0.000
Ionising radiation	kBq U-235 eq	0.715
Photochemical ozone formation	kg NMVOC eq	0.023
Particulate matter	disease inc.	0.000
Human toxicity, non-cancer	CTUh	0.000
Human toxicity, cancer	CTUh	0.000
Acidification	mol H+ eq	0.033
Eutrophication, freshwater	kg P eq	0.002
Eutrophication, marine	kg N eq	0.009
Eutrophication, terrestrial	mol N eq	0.098
Ecotoxicity, freshwater	CTUe	78.683
Land use	Pt	5158.694
Water use	m3 depriv.	0.660
Resource use, fossils	MJ	1554.387
Resource use, minerals and metals	kg Sb eq	0.000
Climate change - Fossil	kg CO2 eq	126.938
Climate change - Biogenic	kg CO2 eq	0.013
Climate change - Land use and LU change	kg CO2 eq	0.008
Human toxicity, non-cancer - organics	CTUh	0.000
Human toxicity, non-cancer - inorganics	CTUh	0.000
Human toxicity, non-cancer - metals	CTUh	0.000
Human toxicity, cancer - organics	CTUh	0.000
Human toxicity, cancer - inorganics	CTUh	0.000
Human toxicity, cancer - metals	CTUh	0.000
Ecotoxicity, freshwater - organics	CTUe	1.457
Ecotoxicity, freshwater - inorganics	CTUe	8.409
Ecotoxicity, freshwater - metals	CTUe	68.817

J - Prefabricated production processes

Elements

Insulating panels

In some experimental applications, moss has been explored as a natural insulation material combined with other bio-based materials it can characterize insulating panels.
The thermal conductivity determining factors for moss panels include the moisture content, the density and the dimensions of the panel (Gaudig et al., 2018). The cell structure of moss enables the plant's high water storage capacity (Krisai, 1999).

If peat moss is compared with other systems or insulation materials available in the market, moss can be placed in the range of mineral wool (Abdou and Budaiwi, 2005).

The experimental study *Physical-Mechanical Properties of Peat Moss (Sphagnum) Insulation Panels with Bio-Based Adhesives*[5] investigates the potential of insulating panels manufactured from moss and bio-based adhesives, drawing a comparison between those bonded with tannin[5] and animal glue, particularly derived from fish skins. The study examined the application of biodegradable adhesives to enhance the overall ecological sustainability of these products, aiming for an improved environmental impact (Morandini et al., 2022).

Figure Ms02: Peat moss panel bound with tannin-based adhesive
Source: Morandini, M. C., Kain, G., Eckardt, J., Petutschnigg, A., & Tippner, J. (2022). Physical-Mechanical Properties of Peat Moss (Sphagnum) Insulation Panels with Bio-Based Adhesives. Materials, 15(9), 3299. MDPI AG. Retrieved from http://dx.doi.org/10.3390/ma15093299

[5] Tannins are a class of astringent, polyphenolic biomolecules that bind to and precipitate proteins and various other organic compounds, they are typically found in wood, bark, leaves and fruits.

Concrete moss panels

Respyre, a company based in the Netherlands, has come up with an innovative bio-receptive concrete solution that is currently pending a patent. Once it hardens, the surface of this concrete is conducive to moss growth due to its porosity, ability to retain water, micro-pore texture, as well as its acidity and nutrient content. These features collectively create a favourable environment for moss to thrive, enabling the creation of green façades.

In facts Moss is well suited for green façades as moss has rhizoids instead of roots. Rhizoids are non-destructive mainly function as an adhesive, leaving the facade in good condition after removal. Their technology creates a substrate (bio-receptive concrete) that is suitable for the rhizoids and thus moss growth.

Producer

Respyre - (NL)

Figure Ms03: Bio-receptive Respyre - Netherlands
Source: https://2021.design-united.nl/

Figure Ms04: Bio-receptive Respyre sample - after growth
Source: https://gorespyre.com/our-technology/

Moss wall panel

Figure Ms05: MOSSwall® panel
Source: https://mosswallitalia.verdeprofilo.com/

MOSSwall® stands as a pre-assembled wall panel featuring preserved moss, structured using a 60x40cm galvanized steel sheet framework enveloped with PVC film. The stabilized lichen walls hold a patent from *Verde Profilo*, boasting complete natural composition and antibacterial properties, ensuring a lifespan of 5 years. Notably, MOSSwall® holds certifications for both fire resistance and acoustic absorption. It can be installed directly onto walls or via an upright system, allowing for the creation of partitions or self-supporting walls with dual sides.

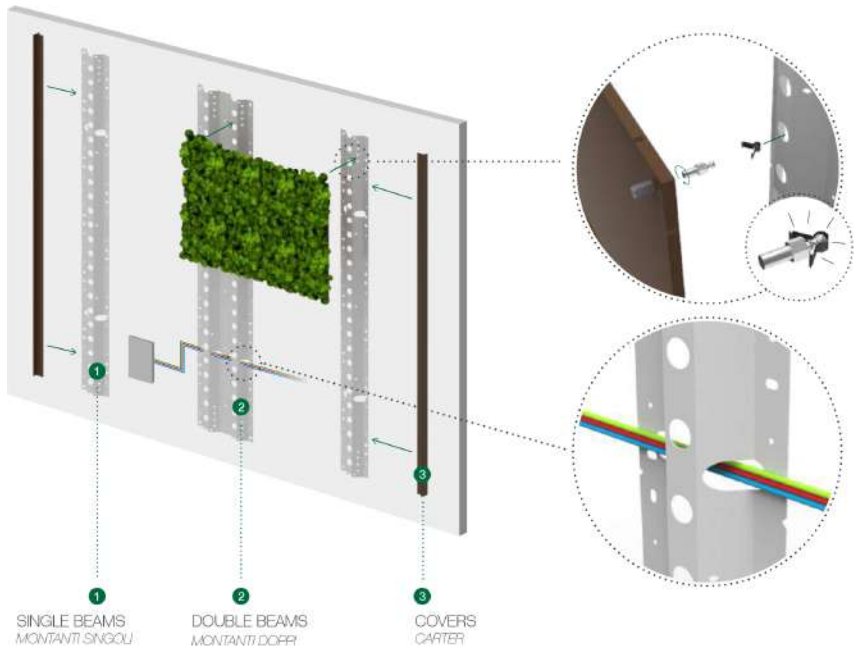


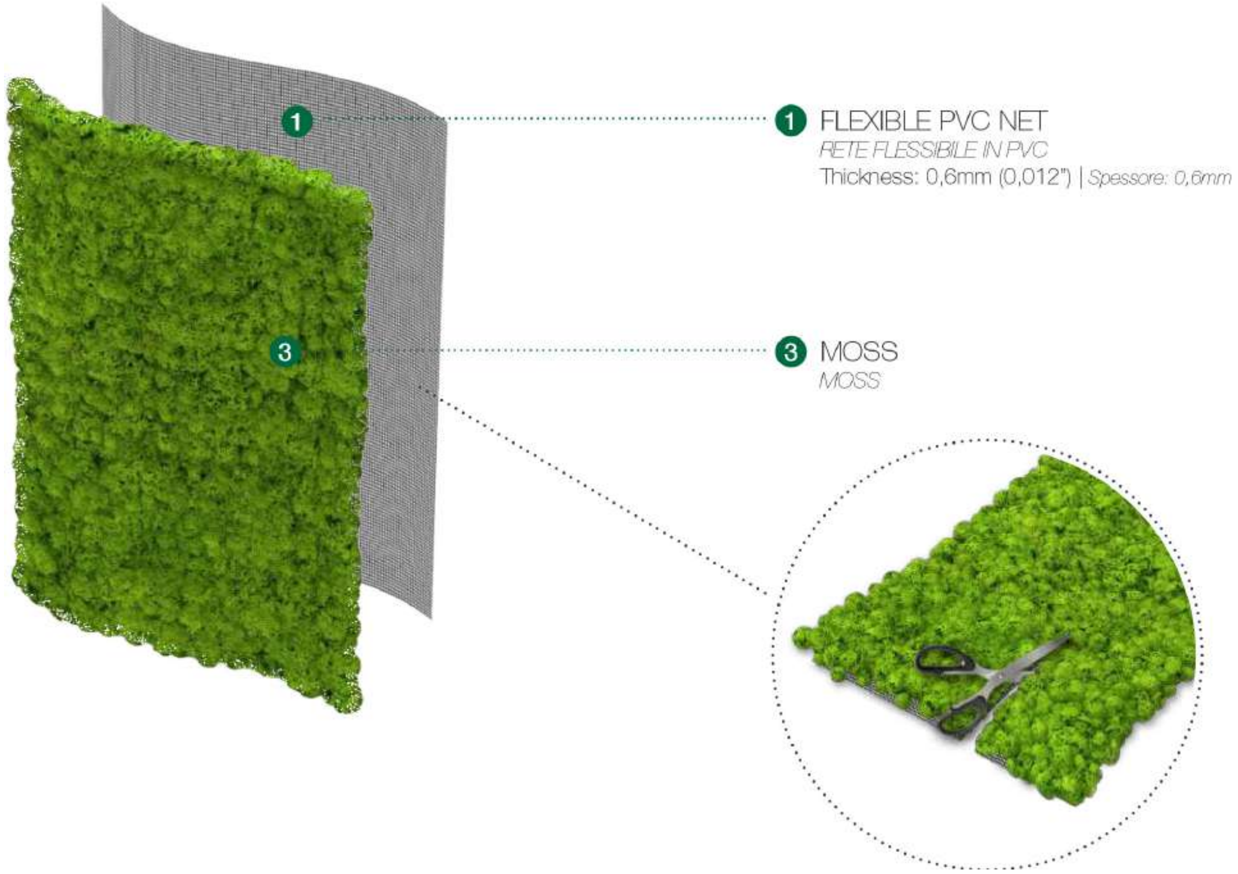
Figure Ms06: MOSSwall® panel installation
Source: https://mosswallitalia.verdeprofilo.com/

Application: Interior wall

Some EU producers

MOSSwall® - (IT)
Freund GmbH - (DE)

Moss mats



A more flexible solution provides preserved moss mats that can be applied on walls, ceiling, flooring and roof.

In the case of MOSSwall® for example the MOSSwall® Flexi provides moss on a PVC net and allows full flexibility for different types of indoor surfaces applications, it can be cut to size and either glued or stapled into place for easy installation.

Figure Ms07: MOSSwall® Flexi
Source: https://mosswallitalia.verdeprofilo.com/

MOSSwall® - (IT)

ECOLVE - Scape Agency

Ecolve serves as a bio-receptive substitute for concrete, and is composed of re-purposed components from conventional concrete production. These elements are joined using a binding agent that encourages the proliferation of mosses capable of absorbing CO2.

Aggregates are gathered from existing buildings through urban mining partners, and a bio-receptive binder is created from raw materials. This mixture is then poured into specialized 3D-printed moulds made of recycled plastic. Both the material and moulds are being analysed for potential recycling and reuse purposes.

Figure Ms08: MOSSwall® Flexi
Source: https://mosswallitalia.verdeprofilo.com/

Scape Agency - (NL)

K - Case studies / Good practices

Moss - voltaics

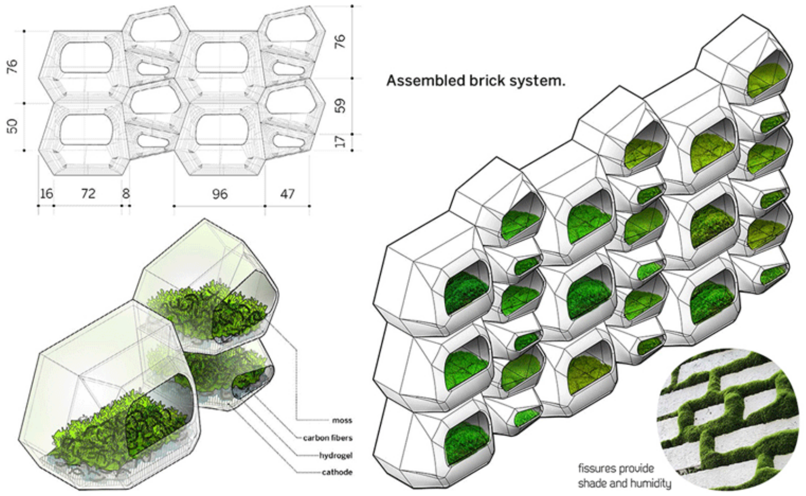


Figure Ms09: by Elena Mitrofanova - Modular Green Wall System that generates electricity from moss
Source: https://www.archdaily.com/782664/this-modular-green-wall-system-generates-electricity-from-moss

Elena Mitrofanova IaaC (Institute for Advanced Architecture of Catalonia) student and biochemist Paolo Bombelli (Department of Biochemistry, University of Cambridge) have proposed a new facade system that harnesses the electricity-generating abilities of plants. Their system uses hollow clay bricks filled with moss, taking advantage of advances in bio-photovoltaics to create an alternative to standard photovoltaics.

The system works by leveraging a symbiotic relationship between the moss and certain bacteria. When the moss undergoes photosynthesis, it releases organic compounds through its roots into the soil. The bacteria feed on these compounds and produce byproducts, including free electrons. The moss is planted in a hydrogel and carbon fibre soil that acts as an anode, attracting and harvesting these electrons to generate electricity.

The clay bricks are designed to support the growth of moss, with deep voids providing shade from direct sunlight. The bricks interlock without the need for mortar, allowing for easy assembly and electrical connections between modules. The clay components are mostly unglazed, enabling the absorption of rainwater to keep the air around the facade damp. The bottom of the bricks is glazed to prevent water damage.

Moss is chosen for its lightweight nature, high drought tolerance, low maintenance requirements, and resilience to urban conditions. While moss is the primary plant used, other plant types could potentially be utilized.

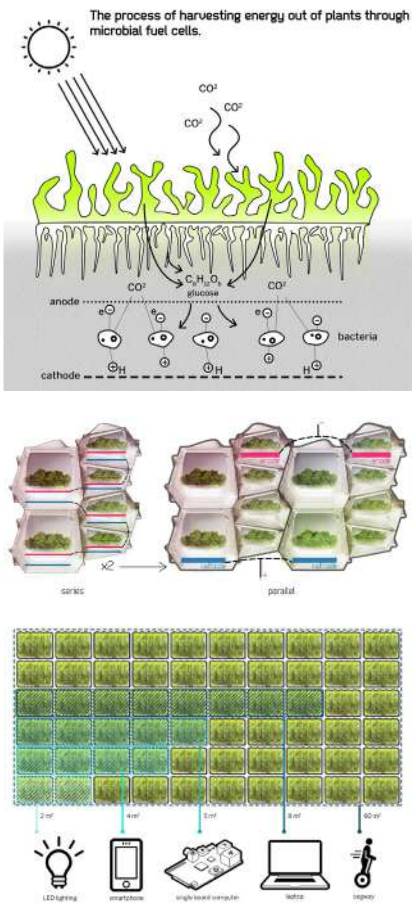


Figure Ms10-11-12: by Elena Mitrofanova - Modular Green Wall System that generates electricity from moss
Source: https://www.archdaily.com/782664/this-modular-green-wall-system-generates-electricity-from-moss

More information at:

elenamitro.com
vimeo.com/119702162

Green cities solutions

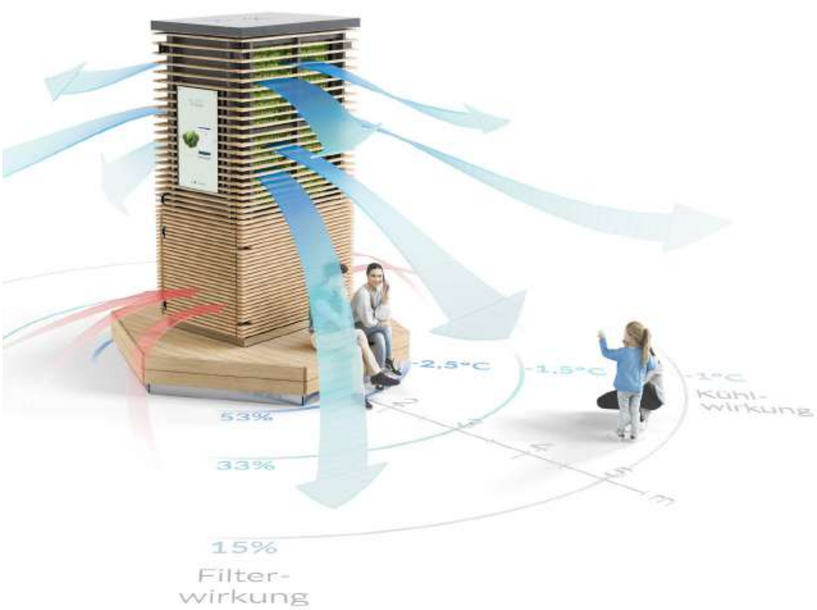


Figure Ms13: CITY TREE by Green Cities Solutions - cooling system
Source: https://nr21.com/greencitysolutions-citytree-2020-en/

Green City Solutions, founded by Peter Sänger and Liang Wu, has developed innovative biotech air filters and cooling products that utilize the power of moss and IoT technology[6] (Internet of Things). By combining different moss species that thrive in European climates, the company has created products with filtering capabilities. The moss filters up to 82% of fine dust particles through electrostatic binding and converts absorbed dust into biomass (Eureka 2021). Moss also has the ability to absorb carbon dioxide and store water, providing efficient natural cooling. Green City Solutions' products incorporate IoT technology to monitor environmental conditions and optimize the moss's performance through irrigation and ventilation. Green City Solutions' current products include the CityTree, a bench-shaped air filter, and the CityBreeze, which features a screen for displaying advertisements and can be integrated into various structures.

They are also developing a modular moss block system called WallBreeze for greening façades and inner-city tunnels. The focus is on air pollution hotspots in urban areas, the company aims to make a significant impact on reducing fine dust and improving air quality.

More information at:

greencitysolutions.de

eurekanetwork.org/blog/green-city-solutions-refresh-air-pollution-s-primeval-enemy-moss

[6] An IoT ecosystem consists of web-enabled smart devices that use embedded systems, such as processors, sensors and communication hardware, to collect, send and act on data they acquire from their environments

Figure Ms14-15-16: WALL BREEZE by Green Cities Solutions - Greening facades
Source: https://greencitysolutions.de/en/citytree/

L - Limits to overcome

Moss's use in architecture is still limited, and for many products still at an experimental phase (see moss-based insulating panels). In order for this material to make its way on the market, not only as indoor accent walls, it needs further exploration and analysis.

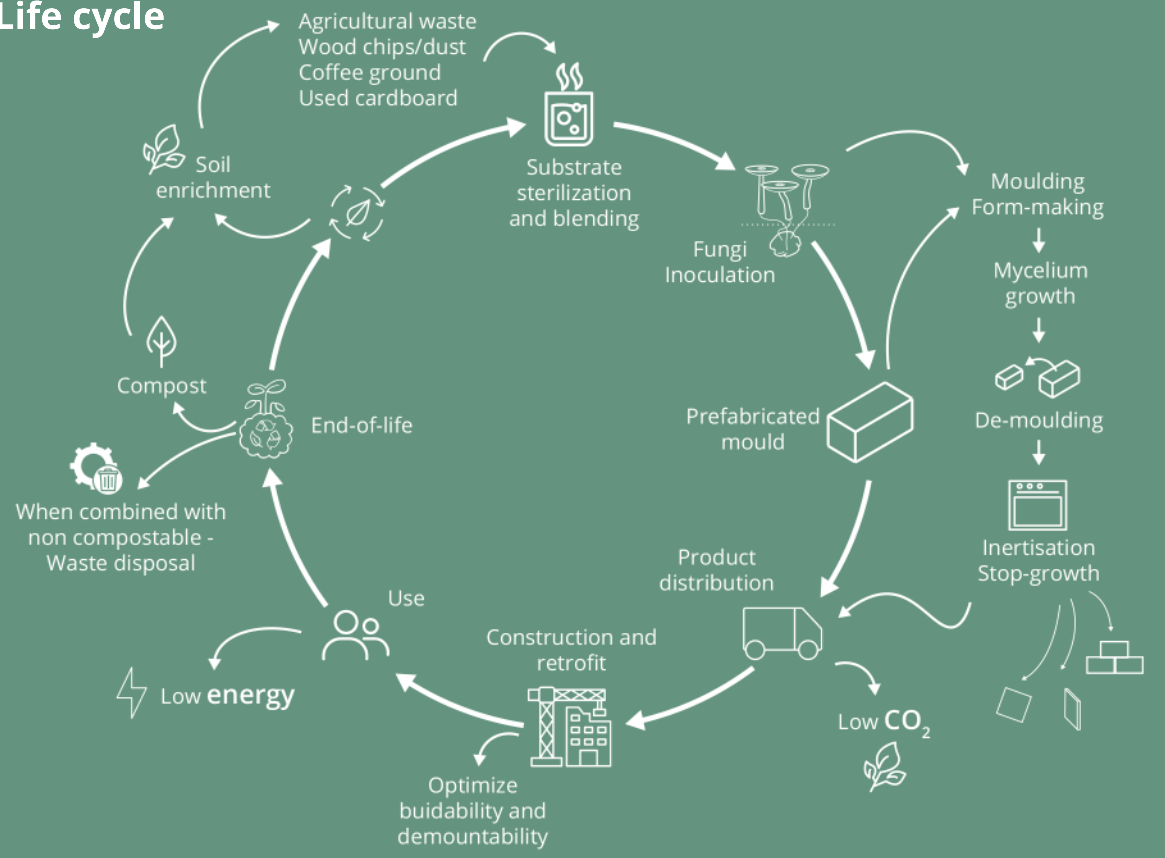
Furthermore, the perception of moss and lichen growth from the point of view of an architect is usually negative, as for when moos appears on a surface, it can mean problems in the design and technological structure. In fact, generally, building materials are designed specifically to withstand and resist its growth, and throughout the years there has been research on how to prevent its development, and of course when unwanted it is a sign of bad design. Yet when intentional, the use of moss holds potential as a valid alternative of more impactful building materials. As it grows and regenerates easily it could set its place in the realm of biogenic building materials.

/
Mycelium

A - Watch points

- Use local and responsibly sourced raw material for substrate
- Need for specific skills and controlled environment for production process
- Low carbon energy in processing methods
- Low carbon transportation
- Optimise buildability and design to disassemble
- Susceptible to insect attacks
- End-of-life - biodegradable - composting

B - Life cycle



C - Key points

Raw material resource

Virgin/primary resource	●
Recoverable resource	○
Recovered/secondary resource	●
Waste resource	●

Availability of raw material

●●○○○

Degree of skills required for resourcing raw material

●●●●●

Degree of prefabrication

●○○○

Awareness

●○○○○

Applications

Technological units	Technical elements	Products category	
vertical closures	external walls	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
		Cladding/shingles/tiles	●
top closures	roof	Cladding/tiles/shingles	○
		Panels/false ceiling	○
		thermo-acoustic insulation	○
horizontal closures	slabs	Flooring Tiles/Panels/boards	○
		thermo-acoustic insulation	○
partitions	vertical partitions	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
	horizontal partitions	Florring Tiles/Panels/boards	○
		thermo-acoustic insulation	○

D - Raw material

Fungi are ubiquitous micro-organisms that hold significant importance in both natural ecosystems and for mankind (Baxi et al., 2016). The fungal kingdom is characterized by 120.000 identified species and an estimated total number of up to 3.8 million species (Hawksworth & Lücking, 2017).
In order to obtain energy and carbon, fungi rely on organic compounds. To this end, they degrade deceased organic matter or by forming pathogenic, neutral or mutual symbiotic relationships with plants, animals, or other micro-organisms (Freek Apples, 2020).
The fungal kingdom includes both unicellular and multicellular organisms. Unicellular fungi, known as yeasts, reproduce through budding or fission. On the other hand, multicellular fungi colonize substrates using filamentous structures known as hyphae. These *hyphae*, which can range from millimetres to centimetres in length, typically have a width between 1-10 µm. By growing at the tips and branching just below, these *hyphae* form an intricate three-dimensional network. The diameter can vary greatly, spanning from millimetres to kilometres in size (Freek Apples, 2020).

Mycelium refers to the hidden network of fine, root-like fibres of mushrooms found beneath the soil or within trees. It constitutes of an intricate mesh of thread-like cells with diverse appearances and textures. Typically thriving on agricultural waste, fungal mycelium possesses little practical value or utility. When provided with ample nutrients, mycelium grows rapidly and without constraints. Its cellular composition comprises a chitin-based skeleton composed of polysaccharides, distinguishing fungi from plant matter which relies on cellulose and rigid lignin for rigidity. The significance of mycelium extends to our ecosystem as it plays a crucial role in recycling minerals, carbon, and participating in the nitrogen-fixing cycle. Cultivated edible fungi serve a multitude of purposes, including human consumption, as well as acting as biological control agents against pests, capturing and safely removing heavy metal contaminants, and even finds applications in the medical field. Through testing, cultivated building materials derived from fungal mycelium and grown on agricultural waste have shown favourable comparisons to certain petroleum-based resins and glues, as well as other composites, showcasing their potential (Philp Ross, 2017).

Mycelium-based materials can be made either from pure mycelium or through a combination of mycelium with other materials such as fibre. Pure mycelium finds application as an alternative to leather or textile materials. Composite materials have been innovatively developed for various purposes including alternative packaging, insulation, and construction materials. These composite materials can be obtained By neutralizing the fungus prior to complete consumption of its substrate, its growth can be arrested. The progression of fungal growth can be halted through a combination of drying and subjecting

Figure My01: Mycelium root-like structure
Source: https://www.cdrecycler.com/

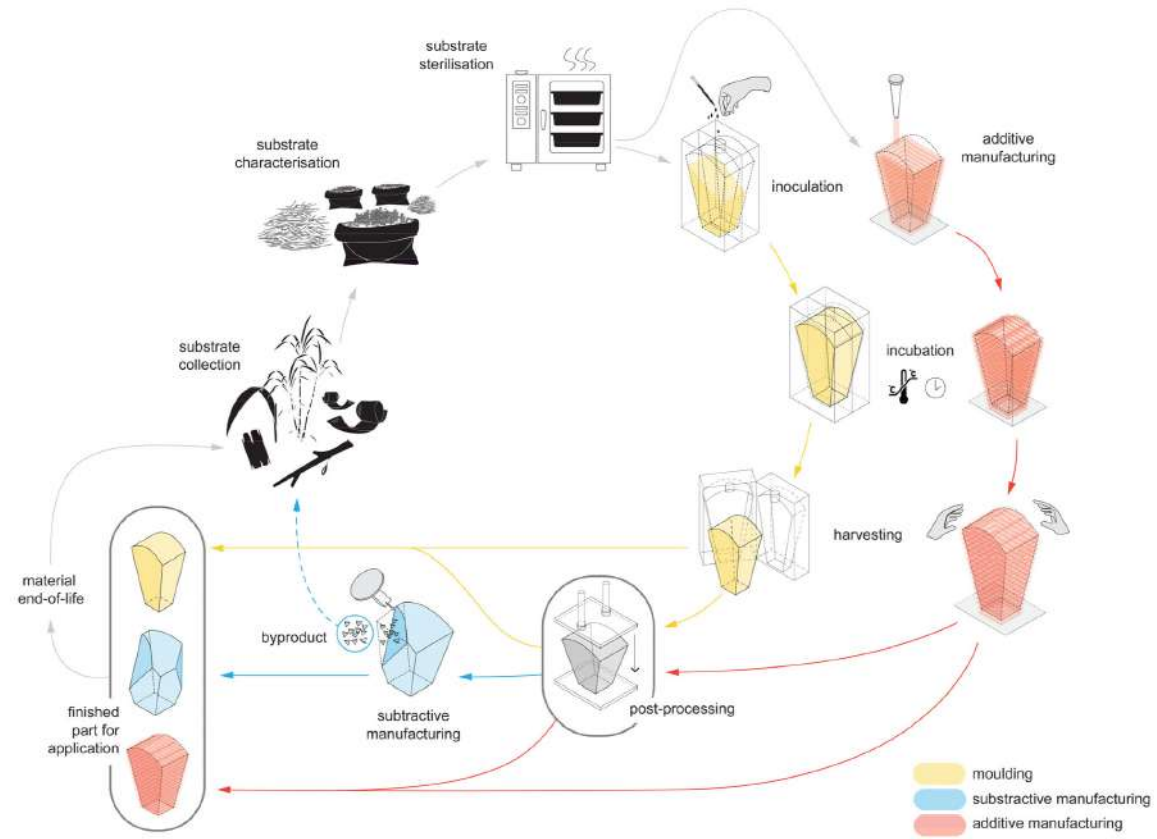
Figure My02: Fungi parts
Source: https://www.cdrecycler.com/

the colonized substrate to heat, as the elevated temperature eradicates the fungus and the drying process preserves it in a dormant state. However, if the substrate is rehydrated, the growth process can recommence (Freek Apples, 2020).

E - Cultivation and Harvesting

Two main techniques are employed in the fabrication of engineered materials using mycelium: pure mycelium materials and mycelium-bound composites. In the former approach, a mycological bio-polymer is generated by cultivating pure mycelium in liquid culture. The latter method involves a bio-composite formation, where the hyphal network of mycelium binds with lignocellulosic substrates. Notably, the latter technique is predominantly utilized for producing construction components like bricks and panels (Bitting et al., 2022). The procedure commences with the cultivation of mycelium within controlled laboratory environments, involving the deliberate choice of substrates that offer diverse nutrients to support mycelium growth. These substrates are primarily derived from lignocellulosic materials sourced from agricultural residues, including but not limited to cotton, corn, flax, hemp, and wheat (Bitting et al., 2022). This selection is aimed at optimizing mycelium growth. The mycelium culture or fungal spores are then inoculated in the various substrates following an incubation period and initiating (Initiation is the link between mycelial growth and mushroom formation) the growth of mycelium, the rate at which this happens will vary based on the density of the substrate and species of mushroom, most specialities on sawdust take about 21 days (Cornell Small Farms, 2022).

Figure My03: Circularity and workflow of current manufacturing processes applied to mycelium-based materials, adapted from
Source: Bitting, S.; Derme, T.; Lee, J.; Van Mele, T.; Dillenburger, B.; Block, P. (2022). Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication. Biomimetics, 7, 44. https://doi.org/10.3390/biomimetics7020044



Throughout the growth phase, mycelium breaks down the nutrients present in the substrate, infiltrating the fibres and creating a dense network of hyphae, effectively binding the substrate particles together. To attain the intended shape, various shaping techniques are employed, with the majority of mycelium-based components undergoing compression through methods primarily involving moulds.
After a growing phase (through a mould), the mycelium composite is harvested, this involves cutting and removing from the mould. Following there is a drying process to reduce moisture content and stop the growing, this helps enhance its structural integrity, durability, and resistance to moisture.
The harvested mycelium can characterize different building materials for various construction purposes. It can be used as panels, bricks, insulation, binding agents and adhesives or furniture. According to the desired end product, the production process varies.

F - Physical-mechanical properties

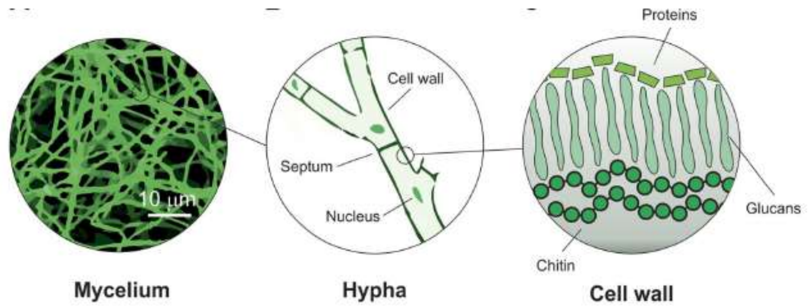


Figure My04: Mycelium structure
Source: https://www.nature.com/articles/srep41292#ref-CR36

Cell walls of fungi play an essential role in interactions of fungi with their (a)biotic environment and are important for morphogenesis and mechanical strength of hyphae (Gow, Latge, & Munro, 2017). The latter implies that the hyphal cell wall also plays an important role in determining the properties of mycelium materials (Freek Apples, 2020).
Mycelium utilizes both organic and synthetic waste as nourishment to develop into desired forms. By incorporating various waste streams within the product or substrate (such as straw, sawdust, or cotton), mycelium can achieve an array of thermal and mechanical material characteristics.
Mycelium-based materials, despite their lightweight nature, have the ability to showcase both strength (mainly to compression) and durability, depending on the specific formulation and manufacturing method used. This unique combination allows them to effectively withstand structural loads and deliver consistent performance over extended periods, given the appropriate treatment and care.

When considering thermal and acoustic insulation mycelium displays a highly effective performance, outperforming other natural and petrochemical/plastic alternatives currently available on the market (e.g. Biohm's mycelium insulation has achieved thermal conductivity as low as 0.03W/mK[1]).

Mycelium is non-toxic (VOCs free) and does not contain the synthetic resin-based materials that cause the harmful toxic smoke and quick spread of flames during a fire. In fact, mycelium releases significantly less heat and smoke during burning, with lower average and peak heat release rates and longer time to flash over synthetic materials owing to its charring behaviour, inhibiting spread when exposed to fire, thus demonstrating a **good fire resistance** (e.g. mogu acoustic panels[2] are characterized by the B-s1-d0 fire rating).

Adapting mycelium-derived materials to match specific design requirements is attainable owing to their innate design flexibility. This characteristic arises from the production methods that facilitate the moulding of mycelium into a variety of shapes.

G - Durability

Mycelium is still taking its place in the building sector as a valid alternative, most products or construction are still part of experimental studies and therefore need further testing to prove durability and other general proprieties of this materials, still the lifespan of mycelium bricks in set to be around 50 years (Abrams M (2014) Construction materials made from 'Shrooms'). To enhance the durability of mycelium-based building materials, researchers and manufacturers may employ techniques such as surface treatments, coatings, additives, and substrate modifications. These approaches aim to improve the resistance of the material to chemical and biodegradable degradation, as well as enhance its overall decomposition stability, ultimately extending its useful lifespan. That being the case, it holds real potential to make its way on the market.

H - End-of life and recyclability

Overall, the **biodegradable** nature of mycelium offers significant potential for sustainable waste management practices. Mycelium and mycelium-based products (if not processed with non-biodegradable compounds or additives) are compostable, organic and are biodegradable. Their ability to decompose as compost aligns well with the principles of the circular economy, minimizing environmental impact, minimizing waste and promoting resource efficiency.

[1] More information at: https://www.biohm.co.uk/mycelium

[2] More information at: https://mogu.bio/pannelli-acustici/

Mycelium

I - Life cycle assessment

These innovative bio-materials offer a hopeful substitute for product design and manufacturing, encompassing sustainable production procedures and a circular lifecycle (Freek Apples, 2020). Given the novelty of mycelium-based applications in the construction field, there is a scarcity of Life Cycle Assessment (LCA) studies.

The first LCA model of fungal mycelium bio-composites was published recently by Stelzer et al. in 2021.[3] This study refers to the fungal-based brick from the fungal mycelium tinder sponge *Fomes fomentarius* grown on hemp shives.

[3] Full publication at: Stelzer, L., Hoberg, F., Bach, V., Schmidt, B., Pfeiffer, S., Meyer, V., & Finkbeiner, M. (2021). Life Cycle Assessment of Fungal-Based Composite Bricks. Sustainability, 13(21), 11573. MDPI AG. Retrieved from http://dx.doi.org/10.3390/su132111573

The brick was produced within a cultivation system conducted in four steps:
1. pre-culture, 2. grain culture, 3. substrate culture, and 4. moulding.

In Step 1, the mycelium of *Fomes fomentarius* strain was cultivated on a nutrient-rich agar medium in a petri dish. A small amount of mycelium was transferred and incubated for seven days until it colonized the plate. Directly inoculating larger quantities of substrates from agar plates led to poor growth.

In Step 2, the mycelia were used to inoculate a rye grain culture. Rye grains were autoclaved with water and gypsum to maintain their integrity, and the culture induced the secretion of enzymes that degraded cellulosic components.

Step 3 involved transferring the mycelium to different plant substrates in cultivation bags, with water and wheat flour added to promote enzyme secretion. The substrate culture was mixed after seven days of incubation.

In Step 4, the mycelium-covered substrate was moulded into brick moulds made of coated plywood, following specific measurements. 3D-printed inlays were used for surface variations. After a final cultivation phase, the moulds were removed, and the mycelial growth was inactivated through pasteurization in a drying oven at 70 °C.

Figure My05: Resulting quantities of one hemp shive composite brick for the impact assessment categories of acidification,
eutrophication, climate change, land use, water scarcity, and smog for all four production steps and in total.
Source: Stelzer, L., Hoberg, F., Bach, V., Schmidt, B., Pfeiffer, S., Meyer, V., & Finkbeiner, M. (2021). Life Cycle Assessment of Fungal-Based Composite Bricks. Sustainability, 13(21), 11573. MDPI AG. Retrieved from http://dx.doi.org/10.3390/su132111573

Characterization Factor	Pre-Culture	Grain Culture	Substrate Culture	Moulding	Total
Acidification (kg SO_2 eq.)	2.41×10^{-5}	2.72×10^{-4}	3.63×10^{-4}	2.80×10^{-4}	9.39×10^{-4}
Eutrophication (kg PO_4^{3-} eq.)	4.13×10^{-6}	2.45×10^{-4}	3.04×10^{-4}	4.98×10^{-5}	6.02×10^{-4}
Climate change (kg CO_2 eq.)	1.81×10^{-2}	5.68×10^{-2}	2.10×10^{-1}	2.09×10^{-1}	4.94×10^{-1}
Land use (kg Pt eq.)	8.10×10^{-2}	5.76×10^{-1}	$1.74 \times 10^{+1}$	1.29×10^{0}	$1.93 \times 10^{+1}$
Water scarcity (m^3 world eq.)	1.10×10^{-3}	6.59×10^{-3}	9.42×10^{-3}	4.98×10^{-3}	2.21×10^{-2}
Smog (kg NOx eq.)	1.91×10^{-5}	1.02×10^{-4}	2.46×10^{-4}	2.16×10^{-4}	5.83×10^{-4}

Pre-culture (Step 1) has the lowest overall environmental impact, primarily influenced by the sterilization of the petri dish and medium. The energy required for sterilization is low due to the small amount of starting material.

Grain culture (Step 2) impacts vary across categories, with rye grain production playing a significant role. Rye and hemp shives have high impacts in eutrophication and water scarcity, but rye has lower land use impacts. Electricity usage in autoclaving affects climate change, acidification, and smog.

Moulding (Step 4) is mainly influenced by electricity used for drying the fungi bricks. Transportation has minimal impact as the distances are short, assuming substrates are produced nearby. Alternative substrates (rapeseed straw and poplar wood chips) can be used, resulting in changes primarily in **Step 3 (substrate culture)**. Differences are observed in acidification, eutrophication, water scarcity, and land use categories. The biggest changes are seen in acidification, eutrophication, and land use categories when comparing rapeseed straw and poplar wood chips to hemp shive composite bricks. Smog, water scarcity, and climate change categories show smaller differences.

On a more general assessment, mycelium is biodegradable in nature, the substrate requires easily available waste materials resulting in a cost-effective alternative. The impactful stages of mycelium-based products are linked to drying, forming and cutting (Jiang et al., 2016).

One other important thing to consider is the fact that the production process of mycelium-based products requires a high degree of expertise and controlled environments for manufacturing. (Sharma and Sumbria, 2022).
When considering mycelium bricks for example, eco-costs (meaning environmental impact) show potential as they require organic waste materials for their production (Sharma and Sumbria, 2022). Mycelium is considered to be 80 times more sustainable than concrete (van Empelen, 2018).

Figure My06: The eco-costs in relation to the lifespan of different concrete alternatives
Source: Empelen, J.C. (2018). A study into more sustainable, alternative building materials as a substitute for concrete in tropical climates.

	Life span	Eco-costs	Eco-costs in 500 years
Concrete	80 – 150	792	2640
Loam (rammed earth)	>500	36	36
Mycelium	<50	16	160
CoRncrete	50	168	1680
Hempcrete	>500	78	78
BioBricks	200	245	612,5

In conclusion, the evolving realm of mycelium-based biomaterials offers a prospect of sustainable manufacturing within the construction industry. Despite the existing scarcity of comprehensive Life Cycle Assessment (LCA) studies, the potential for a viable alternative remains substantial.

Mycelium

J - Prefabricated production processes

Elements

Mycelim-brick

Mycelium bricks, as previously mentioned, are created by growing mycelium in a controlled environment and allowing it to bind together organic matter, such as agricultural waste or wood chips. The mycelium acts as a natural adhesive, forming a dense network of fibres that hold the organic material together. Mycelium bricks are lightweight and provide thermal and acoustic insulation properties. Mycelium bricks exhibit good ductile properties, thermal insulation and flexural strength but lack in compressive strength (Sharma and Sumbria, 2022).

Figure My07: Mycelium brick - Grow Bio
Source: https://www.grown.bio/

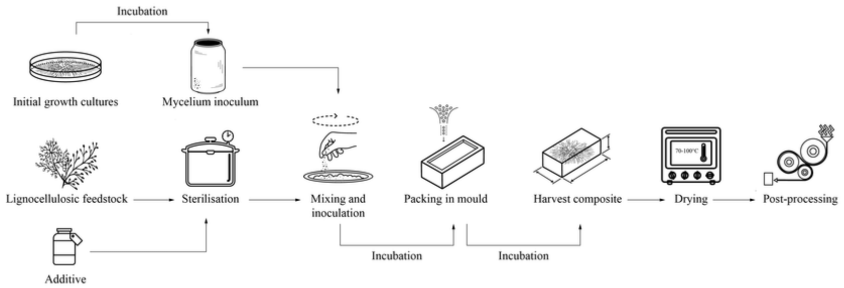


Figure My08: Mycelium brick manufacturing process
Source: Elsacker, Elise & Vandelook, Simon & Van Wylick, Aurélie & Ruytinx, Joske & De Laet, Lars & Peeters, Eveline. (2020). A comprehensive framework for the production of mycelium-based lignocellulosic composites. Science of The Total Environment. 725. 138431. 10.1016/j.scitotenv.2020.138431.

Although the mycelium brick is developing (Xing et al 2017), it is still a long way from becoming a viable and widely used building material as its compressive strength is limited to variation in performance material potential attributed to as yet unexplored biological variables (Attias et al 2019).

Application: Non/structural wall construction infill, insulation

Some EU producers

Grown.bio (NL)

Mycelim-flooring

Mycelium can be processed and moulded into resilient flooring tiles for indoor use. They are made from selected fungal mycelium, low-value biomasses, such as corn crops, rice straw, cotton residues spent coffee grounds, discarded seaweed and clam shells.

Figure My09: Mogu Srl – Florring tiles
Source: https://theexplodedview.com/the-exploded-view-beyond-building/materials/

Application: Indoor flooring tiles

Some EU producers

Mogu Srl – (IT)

Mycelim-panels

Figure My10: Mycelium panels
Source: https://www.researchgate.net/figure/Various-mycelium-based-panel-product-samples-Image-supplied-by-Phil-Ross_fig2_361056782

Compressed mycelium panels represent a category of products that are still awaiting introduction to the consumer market. Nevertheless, they stand as a well-studied iteration within the spectrum of mycelium composite building materials. These panels are achieved through cold or heat-pressing techniques (Javadian et al., 2020). Cold-pressing results in higher tensile strength elasticity and density. Heat-pressing further enhances tensile strength and elasticity, with a density increase of over 3 times, it results in panel-like properties and comparable compressive strength to timber products like oriented strand board (OSB) or medium density fibreboard (MDF). This is due to the softening of the lignin, which reacts to form new cross-links that increase the material strength (Bouajila et al., 2005).

Applications: Mycelium based panels can be used for rigid insulation, interior partitions and exterior and interior cladding and finishing layer.

Some EU producers

Grown.bio (NL)
Biohm – (UK)

Acoustic sound absorbing panels

Figure My11: Mogu – Sound absorbing panels
Source: https://mogu.bio/acoustic-collection/

Sound absorbing panels are made from soft, foam-like mycelium materials, they can have be shaped into different forms (reference to Mogu sound absorbing panels).

Applications: Sound absorbing panel for wall or ceiling installation - interior use

Some Eu producers

Mogu Srl – (IT)
Grown.bio (NL)

Mycelium

K - Case studies / Good practices

Mycotecture (2009) - U.S.A.

Mycotecture (2009) is a project designed by Philip Ross, a pioneer for the utilization of mycelium in architecture, and is considered to be the origin of combining prefabrication methods with mycelium-based materials.

The mycelium bricks constitute an arc shape to form a small construction that had the purpose of exposing people to the potential of fungi in architecture. Mycotecture was grown out of Ganoderma lucidum (or Reishi) cultures that were formed into bricks and stacked into an arch, the fungi that grew from the bricks were used to brew tea that was served to enrich the visitors experience.



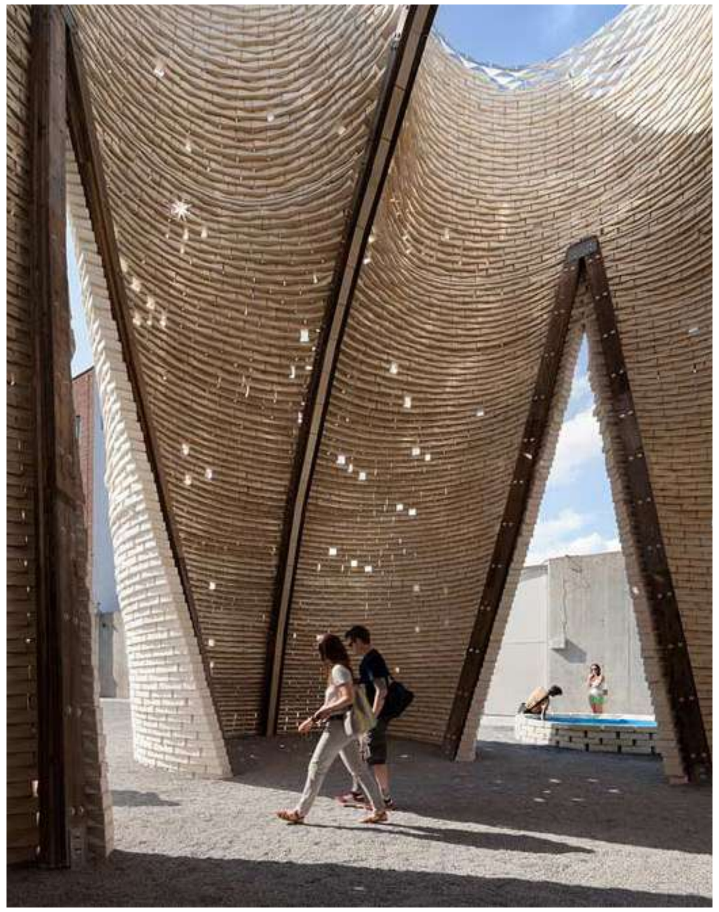
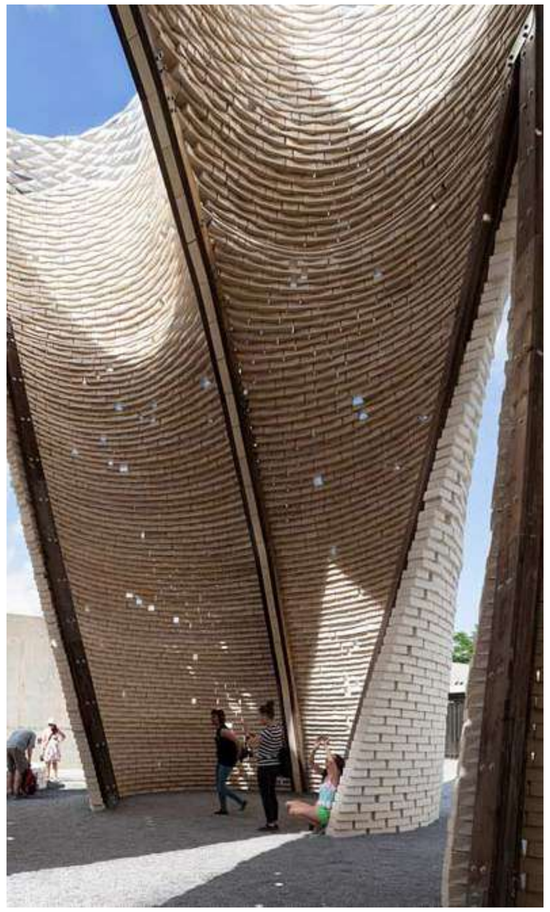


Figure My12-13-14-15-16: Philip Ross - Mycotecture 2009
Source: https://www.treehugger.com/mycotecture-mushroom-bricks-philip-ross-4857225

HI-FY (2014) - Museum of Modern Art and MoMA PS1, New York

The Hy-Fi pavilion (2017), a project by The Living, stood as a towering 12-meter structure constructed from 10,000 mycelium bricks stacked together and fortified with a wooden framework to ensure stability. The production of these bricks involved a restrained number of moulds, as the computational process was harnessed to generate the form, thereby minimizing the requirement for distinct moulds (Bitting et al., 2022). The pavilion stood for three months, and showcased the potential of mycelium as a construction material. At the end of its lifespan, all 10,000 bricks were composted and distributed to local gardens. Hy-Fi, however, represented the first large-scale experimental structure to employ mushroom bricks.

My17-18-19-20-21: The Living - HI-FY 2014
Source: https://urbannext.net/hy-fi/

MycoTree (2017) - Seul Biennale of architecture and urbanism

Initiated in 2017, the MycoTree initiative is the result of a collaboration involving the Karlsruhe Institute of Technology (KIT), Swiss Federal Institute of Technology (ETH) Zurich, Future Cities Laboratory in Singapore, and Mycotech based in Indonesia.

This endeavor involves combining Mycelium-Based Composite cultivated in molds with laminated bamboo connections to construct a load-bearing structure (Javadian, 2020). The molds were digitally fabricated, and the overall design derives from the application of 3D graphic statics, where the structure depends on the geometrical arrangement of elements for a compression-only spatial structure (Heisel, 2018). Instead of relying on material strength alone, the structure's robustness and stability arise from its geometry. The MycoTree project offers a distinctive illustration of mycelium's integration within a structural framework and underscores the benefits of incorporating suitable digital fabrication techniques with computationally-informed design approaches (Bitting et al., 2022).

Figure My22-23-24: Mycotree 2017 - Images by Carlina Teteris
Source: https://www.dezeen.com

Growing Pavilion (2019) - Dutch Design week and Floriade Expo (2022)

The Growing Pavilion is a collaborative project between Luca De Man CEO of the Company New Heroes, designer and artist Pascal Leboucq and Erik Klarenbeek's studio, Krown Design, located at Bio-based Creations in Amsterdam, and in collaboration with many other associations and actors in the field.

Figure My25-26-27: Growing Pavilion - 2019 - Images by Oscar Vinck
Source: https://www.dezeen.com

This innovative pavilion serves as a showcase for various bio-based materials utilization, including wood for the structure, hemp for the substrate, mycelium panels for the cladding, cattail for the flooring, and cotton for the roof and other agricultural waste for the furnishings such as the circular external seat on the perimeter of the pavilion. The façade is embracing the concept of growing structures as it is made of 88 mycelium panels and 125 sqm of external cladding, the fungal strain is Ganoderma. The substrate for these panels is a blend of aspen wood and hemp sourced from local farmers' residual flows in the Netherlands.

"The Growing pavilion is an attempt to inspire the construction world, the design world, and the broader audience to envision a building process with only bio-based materials or with more bio-based materials that ever before."
Luca De Man CEO Company New Heroes

thegrowingpavilion.com

L - Limits to overcome

From the literature present today it seems that the compressive strength of mycelium-based materials is currently limited. Improvements are required to ensure that mycelium structures can withstand the loads and stresses typically encountered in architectural applications. While mycelium naturally binds and reinforces materials, further research is needed to enhance its binding capacity and mechanical properties. Strengthening the mycelial network to improve load-bearing capabilities is crucial for constructing durable and long-lasting mycelium-based architectural elements.

When considering the current manufacturing process of mycelium-based elements, one important aspect for upscaling their use is achieving consistent and reproducibility as for variability in the growth and performance of mycelium can hinder the mass production and standardization of these materials. Furthermore, scaling up the production of mycelium-based materials to meet the demands of the construction industry could still be viewed as significant challenge. Large-scale industrialization requires efficient and cost-effective manufacturing processes that can produce mycelium materials in larger quantities while maintaining quality and consistency, and as for now the manufacturing process in a sterile controlled environment or laboratory limits the quantities of production. Therefore, developing techniques to minimize contamination and ensure reliable production is necessary to upscale production.

Mycelium and mycelium products are particularly susceptible to insect attack. This is an important aspect and challenge that needs to be further explored and solved.

Ultimately there is a need for regulation and standard certifications, as well as introducing courses to allow formation of more skilled professionals. Developing regulations, standards, teachings and testing methods that ensure the safety, durability, and performance of these materials will contribute to their acceptance and integration into mainstream construction practices.

Addressing these challenges will require further research, development, and innovation in the field of mycelium-based materials, but this can be achieved only by a collaboration between scientists, architects, engineers, and manufacturers in order to overcome these limits and unlock the full potential of mycelium in architecture.

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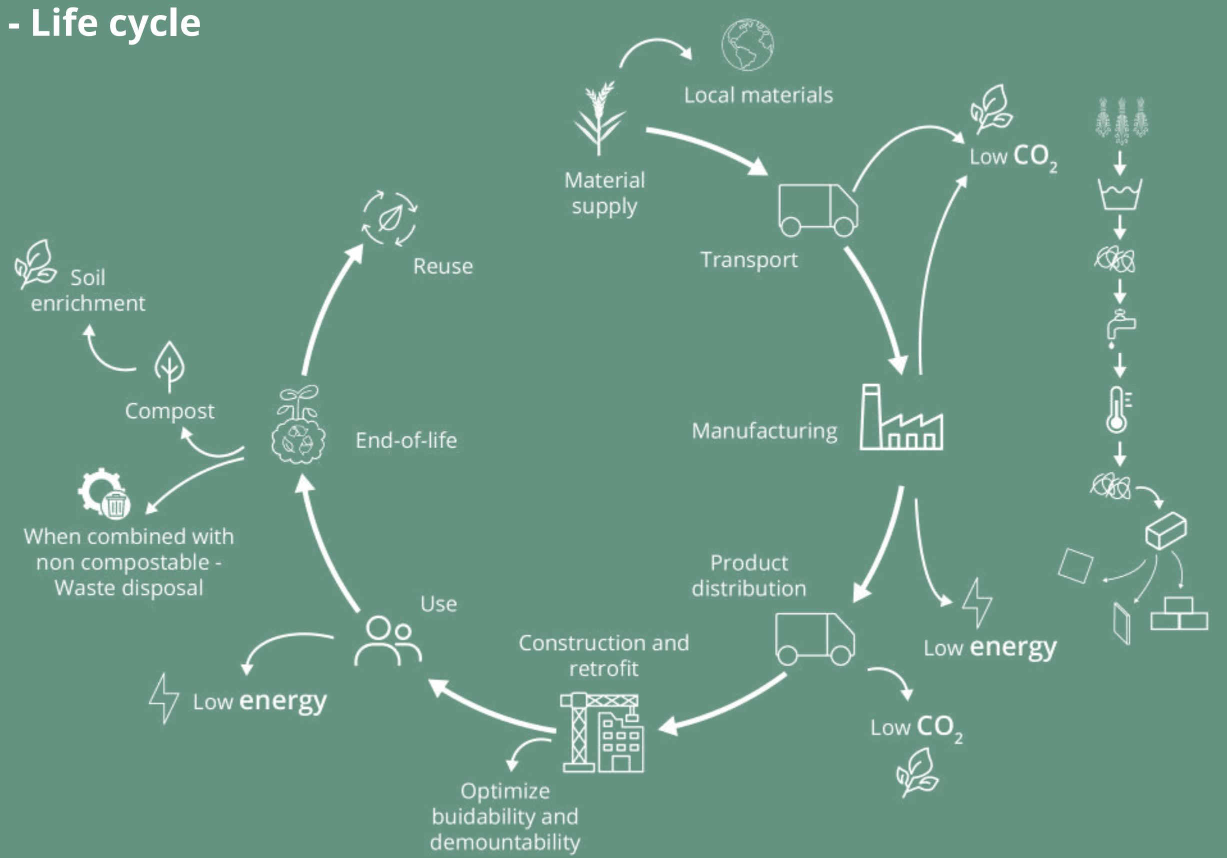
Plant fibres

A - Watch points

- Use local and responsibly sourced raw material, allow for regeneration
- Low carbon energy in processing methods
- Low carbon transportation
- Optimise buildability and design to disassemble
- Re-use, Recycle and Re-purpose
- End-of-life (biodegradable) can also be used as biomass for energy production

B - Life cycle



C - Key points

Raw material resource

Virgin/primary resource	●
Recoverable resource	●
Recovered/secondary resource	●
Waste resource	○

Availability of raw material

●●●●●

Degree of skills required for resourcing raw material

●●○○○

Degree of prefabrication

●●○○

Awareness

●●●○○

Applications

Technological units	Technical elements	Products category	
vertical closures	external walls	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
		Cladding/shingles/tiles	●
top closures	roof	Cladding/tiles/shingles	●
		Panels/false ceiling	●
		thermo-acoustic insulation	●
horizontal closures	slabs	Flooring Tiles/Panels/boards	○
		thermo-acoustic insulation	●
partitions	vertical partitions	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
	horizontal partitions	Florring Tiles/Panels/boards	●
		thermo-acoustic insulation	●

D - Raw material

Fibers are thin, filamentous materials with versatile applications. Natural fibres, also known as bio-fibres, can stem from both plants and animals (Svennerstedt, 2007). Among the array of these natural fibres, those derived from plants are notably in high demand within the market due to their widespread use across various applications and their availability across different regions globally (Svennerstedt, 2007).
Bio-fibres are classified based on their origins: leaves (such as abaca and sisal), seed hairs (like coir and cotton), bast fibres (including flax, hemp, jute, and ramie), and wood. Particularly noteworthy is the European focus on flax and industrial hemp, both extensively cultivated for their fibres and oil (Svennerstedt, 2007).

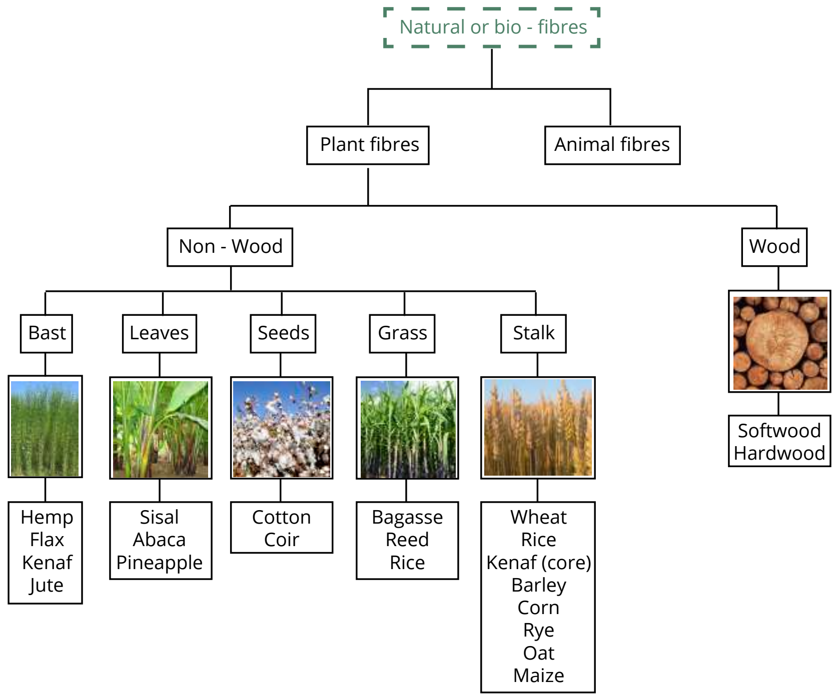


Figure Pf01: Natural plant categories
Source: Categorization from paper by S.R. Djafari Petroudy,(2017) 3 - Physical and mechanical properties of natural fibers, Editor(s): Mizi Fan, Feng Fu, Advanced High Strength Natural Fibre Composites in Construction, Woodhead Publishing, Pages 59-83, ISBN 9780081004111, https://doi.org/10.1016/B978-0-08-100411-1.00003-0

All plant species are composed of cells. A cell is designated as a fibre when its length greatly surpasses its width. This elongated cell, resembling a microscopic tube, is primarily comprised of cellulose, hemicelluloses, and lignin. Cellulose constitutes the fundamental structural element of all plant fibres, with its molecules being constructed from interconnected glucose units forming lengthy chains. Hemicelluloses, also present in all plant varieties, are polysaccharides connected in branching configurations. Lignin, a compound responsible for imparting rigidity to plants, forms a three-dimensional polymer characterized by an amorphous structure (Olesen & Plackett, 1999).

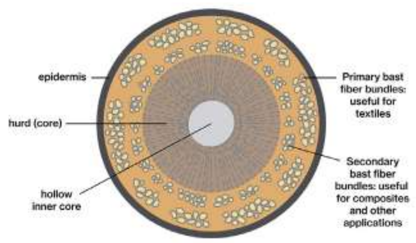


Figure Pf02: Cross section of hemp fibre
Source: https://mogu.bio/acoustic-collection/

Fibre	Cellulose %	Hemicellulose %	Lignin %
Flax	72–75	5–14	2–4
Hemp	57–77	14–17	9–13
Jute	41–48	18–22	21–24
Kenaf	44–57	22–23	15–19
Coir	32–45	27–29	40–45
Abaca	65–63	15–17	7–9

Figure Pf03: Chemical composition of some common plant fibres
Source: Data from the research paper by Labib WA. Plant-based fibres in cement composites: A conceptual framework. Journal of Engineered Fibers and Fabrics. 2022;17. doi:10.1177/15589250221078922

Brief description of most common EU plant fibres - Bast and seed fibres

Hemp - Pf1

Hemp, scientifically identified as Cannabis sativa Linn and a member of the *Cannabaceae* family, is classified as an herbaceous plant. Its versatility lies primarily in its industrial applications, which span a wide spectrum of sectors. The textile industry, food production, construction, paper manufacturing, cosmetics, and energy generation all find valuable uses for hemp. Notably, within the European Union, hemp cultivation has experienced a remarkable upswing, witnessing a 75% increase in cultivation area and a 62.4% surge in production from 2015 to 2019 (European Commission, 2023).
The remarkable adaptability of hemp fibres extends across a multitude of industries. These fibres undergo processing to yield bio-plastic products and contribute to paper production. Moreover, they play a vital role in creating insulating panels for construction, functioning as biodegradable geotextiles, and are integral to various textile applications, including carpets and upholstery. Additionally, the robust woody core of hemp significantly influences the construction domain by facilitating the formation of lime-based bio-composites, panels, and plasters, and offering valuable thermal and acoustic insulation properties. The seeds of hemp find diverse applications in the food industry, bakery goods, seasoning oil, cosmetics, animal feed, and specialized industrial oils containing gamma-linolenic acid. Furthermore, hemp's complete plant composition serves as a potent source for biofuel generation and contributes to silage production.

Figure Pf04: Hemp plant
Source: https://manitobaharvest.ca/blogs/hemp-resource-hub/organic-vs-natural

Kenaf - Pf2

Kenaf, scientifically referred to as *Hibiscus cannabinus*, is a rapidly growing plant within the hibiscus or mallow flowering family (*Malvaceae*). Its fibres also belong to the bast fibre category (Majid Ali, 2012; Britannica, 2023). This herbaceous plant is an annual plant that develops stalks reaching approximately 5.5 meters in height, with the fibre predominantly concentrated in the lower section. Its leaves are comprised of five lance-shaped lobes, mostly clustered near the upper part of the stalk. The flowers, characterized by pale yellow hues and central purple centres, emerge on short stalks sprouting from the upper intersections between leaf stalks and stems.
Kenaf uses mainly comprise paper products, building materials, absorbents and animal feeds (Ishak, 2012).

Figure Pf05: Kenaf plant
Source: https://shop3202.itinerarymasters.com/category?name=kenaf%20plant%20images

Jute - Pf3

Jute fibre originates from the Corchorus genus, belonging to the Tiliaceae family. It is a lengthy, smooth, and lustrous plant fibre with a colour spectrum ranging from off-white to brown. Elevated tensile strength and minimal extensibility stand out as fundamental characteristics of jute fibres (Majid Ali, 2012).

Figure Pf06: Jute plant
Source: https://stock.adobe.com/it/search?k=jute+plant

The jute plant is an herbaceous annual plant that typically reaches a height of around 3 to 3.6 meters. Its cylindrical stalk is approximately as thick as a finger. There are over 30 *Corchorus* species but only two have gained commercial importance, they are the *Corchorus capsularis* or white jute and *Corchorus olitorius tossa* jute (Yekta Karaduman, 2023).
Jute fibres are mainly used to produce sacks that are used as a packaging material for numerous products and goods. Over 80% of jute fibres produced worldwide are being used as packaging. Other uses of jute fibres comprise composite reinforcement, carpet backing, felts, cordage, and decorative materials (Krishnan et al., 2005)

Figure Pf07: Flax plant
Source: https://www.istockphoto.com/it/immagine/flax-plant

Flax - Pf4

The flax plant , *Linum usitatissimum*, of the family *Linaceae*, is cultivated both for its fibre, and for its seeds, called flaxseed. Flax is an herbaceous annual plant. When grown closely together for fibre production, these plants typically reach an average height of 0.9 to 1.2 meters, featuring slender stalks with a diameter of 2.5 to 4 mm and concentrating their branches at the upper end. In the case of plants cultivated for their seeds, they tend to be shorter and exhibit numerous branches. The leaves, alternating along the stem, possess a lance-like shape and are of medium size. The flowers, emerging from stems that grow from the tips of branches, consist of five petals, typically of blue colour, although white or pink petals are occasionally seen. The fruits, grow as small dry capsules, and they are composed of five lobes (Britannica, 2023).
The Flax plant is been known and used from ancient times from people of Flax finds diverse applications in food, personal care products, animal feeds, and industrial uses. In industry, it's valued for sustainable alternatives to chemical-based products, used for linoleum flooring, oilcloth, resins, inks, biofuels, and more. Flaxseed oil is utilized in personal care products. Flax straw is employed in paper manufacturing and industrial fibre products. Additionally, flax is embraced in functional foods due to its health-promoting attributes. In animal feeds, flax contributes to improved performance and health. The growing trend towards environmentally friendly products has boosted flax's role in insulation, specialty pulp and paper, geotextiles, building materials, textiles, and plastic composites. Shive, the leftover straw component after fibre extraction, holds potential as a co-product for various applications (Saskflax, 2023).
Linen fibre has been known since ancient times. The Egyptians (as early as the 5th millennium BC), the Phoenicians, the Babylonians and other Middle Eastern peoples spread its use to the Greeks and Romans. Its use as an insulating building material dates back to Roman times and, from the Middle Ages onwards, the cultivation of flax spread throughout Europe (Fassi and Maina, 2006).

Cotton - Pf5

Cotton originates from seed-hair fibre of several species of plants of the genus Gossypium, of the hibiscus, or mallow, family (Malvaceae). Cotton is a major agricultural crop that is grown globally and is abundant and economically cultivated, leading to affordable and different cotton products. Cotton fibres can be broadly categorized into three main groups based on staple length and appearance. The first group is composed of fine, lustrous fibres with staple lengths spanning approximately 2.5 to 6.5 cm. This group includes premium varieties like Sea Island, Egyptian, and pima cottons. Although less abundant and more challenging to cultivate, long-staple cottons are valued for their quality, primarily finding use in fabrics and yarns. The second category comprises standard medium-staple cotton featuring staple lengths of approximately 1.3 to 3.3 cm. Lastly, the third group encompasses short-staple cottons, with lengths ranging from about 1 to 2.5 cm. These varieties are employed in the production of carpets and blankets, as well as fabrics, often blended with other fibres (Britannica, 2023).

Figure Pf08: Cotton plant
Source: https://barnhardtcotton.net/blog/the-story-of-cotton-how-cotton-is-grown-processed-and-used/

E - Cultivation and Harvesting

Hemp - Pf1

Hemp is an annual plant with a spring-summer cycle. It is a fast-growing plant, in a short period of time it can reach heights that vary from 1.5 to 4.5m and a diameter from 0.5 to 2.0 cm. The cultivation of this plant is both indoor and outdoor. The cultivation in the EU is regulated by the European Commission, and the varieties allowed are listed in the Plant variety database[1] . The successful harvesting of hemp for construction purposes depends on different factors, such as species cultivated and very importantly the layout of the field. In order to grow strong stems (and therefore more fibre) plants have to be spaced out, this also allows for a more rapid growth.

The harvesting is in the flowering stage of the plant (this allows for more fibre use in building materials). Plant are oven dried and then macerated, preferably through the use of enzymes, to start fermentation processes and allow for the “adhesive substances” of the plant be separated from the fibre and facilitate their use. The fibres can be subsequently used for the production of different building materials. For example, to produce hemp acoustic panels the fibres, or hemp shives in 80-90% often treated with soda or boron salts, and bended with polystyrene fibre or corn-starch in 10/15%, and then subjected to heat treatment to allow for the binder to melt and stick to the fibres to make these prefabricated panel more resistant.

Kenaf - Pf2

The kenaf plants are left to dry in the field; the stalks, now devoid of sap, are cut at a height of 15/25 cm with the same machine used for maize. They are then harvested and transported to the primary processing plant, located within a radius of 40-50 km. As with hemp, in the past, harvesting and the first part of processing took place outdoors and manually. Today,

[1] Database link: https://ec.europa.eu/food/plant-variety-portal/

to obtain the fibre, specially designed machines are used to defibrate the plant, which constitute raw materials for different uses and processing (Fassi e Maina, 2006).

Jute - Pf3

Jute seeds are scattered by the farmers on cultivated soil to grow jute plants, jute plants are harvested after four months when they flower but before the flowers seed. The long stems of the mature jute plant are cut and placed in water to macerate, a process that removes putrescible organic parts from the fibres by mineralising them and making them more resistant to moisture and water. This process is called retting. Retting can be mechanical retting (hammering), chemical retting (boiling and applying chemicals), steam/vapor/dew retting, and water retting. When macerated in water, after about three weeks, the processors separate the fibrous bark from the woody inside of the stem. The fibres are washed and dried, beaten and piled into bales. Processing then takes place, which involves the mechanical process of carding the fibres and needle punching, resulting in soft felts that are particularly compact without the addition of binders. There is a large resource from recycled jute (jute sacks used in the food industry) (Fassi e Maina, 2006).

Flax - Pf4

The cultivation of flax plants normally takes about 100 days from the planting of the seeds up to the harvesting stage. Initially, the land is plowed during the spring season, followed by the conversion of the soil into a suitable seedbed through procedures like discing, harrowing, and rolling. Proper planting of flax seeds involves shallow burial and soil coverage. The distribution of seeds can be done manually or utilizing machinery for row planting. Once the growth period is finished, the seeds are initially harvested from the plants, and subsequently, the rest of the plants.
Uprooting the plants is done to ensure the preservation of optimal fibre length. Typically, fibre harvesting occurs after the lower segment of the stalk transitions to a yellow hue, yet prior to the complete maturation of the fruit. After the plant's robust stems are stripped of leaves and dried, they are gathered into bundles and subjected to water soaking (a process known as retting). This soaking aids in separating the fibres from the adhesive substances that bind them together. Scutching is carried out with specialised machines, separate the fibres from the woody residues; at this stage, the long fibres, destined for spinning for the textile industry, are separated from the short fibres, destined for other uses such as building insulation materials (Fassi e Maina, 2006).

Cotton - Pf5

The process of cotton fibre harvesting and processing involves several steps. It all begins with the harvesting phase. Timing of harvesting is crucial, as harvesting too early or too late can impact fibre quality and yield. Cotton pickers are employed, utilizing rotating spindles to remove seed cotton from bolls, leaving behind dried locules. An alternative method involves cotton strippers, which remove entire bolls from the plant using counter-rotating stripper rolls. The harvested seed cotton is then packed into modules by module builders, often covered with a protective film. This process is followed by ginning, where the cotton fibres are separated from the seed and cleaned to create saleable commodities. The resulting cotton commodities serve diverse industries, from agriculture to manufacturing, with the cotton fibre being the world's most widely used material for textile production due to its quality, efficiency, and profitability (Cotton Works, 2023).

F - Physical-mechanical properties

Plant fibres like hemp, kenaf, jute, flax, and cotton offer unique qualities when used as building materials. Properties vary in the time of fibre but they exhibit some common features. Hemp, for instance, excels in thermal conductivity and insulation, keeping indoor temperatures stable and absorbing sound effectively. When combined with lime binders to create hemp-crete, it becomes strong yet lightweight, capable of handling loads and resisting fire. Its ability to manage moisture adds to its appeal. Similarly, kenaf, jute, flax, and cotton are characterized for their properties of insulation and moisture control thus contribution to indoor air quality when used as building materials.
Natural plant fibres exhibit high strength and stiffness due to the cellulose fibrils they contain, typically measuring 10–30 nm in diameter and composed of 30–100 cellulose molecules in an extended chain form, which contribute to the fibre's mechanical integrity (Djafari Petroudy, 2017). The fibre's properties are influenced by factors like structure, micro-fibrillar angle, cell dimensions, defects, and chemical composition (Mohanty et al., 2005a,b). Generally, higher cellulose content results in increased tensile strength and Young's modulus. These fibres, as mentioned above, resemble composite materials, as they consist of cellulose, hemicelluloses, pectin, lignin, and waxes. Reinforcement in natural fibres comes from cellulose micro-fibrils surrounded by hemicelluloses and lignin. Under stress, micro-fibrils align with the fibre axis. Fibre failure occurs when matrix elements lose their bond with reinforcing fibrils, breaking hydrogen bonding in cellulose microfibrils. Thus, lower cellulose content leads to reduced tensile strength (Komuraiah et al., 2014). A higher hemicellulose content diminishes tensile strength due to their amorphous and nonhomogeneous nature (Park et al., 2006). Stiffness is determined by the orientation of cellulose fibrils relative to the fibre axis. A spiral orientation results in ductility, while parallel orientation creates inflexible, rigid, high-tensile-strength fibres. These fibres reinforce the matrix structure. Natural plant fibres like kenaf, hemp, flax, jute, and sisal have lower tensile strengths and Young's moduli compared to glass fibres, but their lower density makes them attractive for weight-sensitive applications. Regional origin and climate influence the physical-mechanical properties. Researchers aim to produce cellulose-rich bio-fibres for broad industrial use, given the significant role of natural plant fibres in composite industries (Mohanty et al., 2005a,b). Tensile and Young's modulus follow the order: bast fibre > leaf fibre > seed fibre, with only bast fibres comparable to inorganic fibres like glass and carbon. It's noteworthy that natural fibres with weaker mechanical properties might find suitability in non-structural applications (Djafari Petroudy, 2017).

G - Durability

The durability of plant fibres varies depending on factors such as the type of plant, processing methods, and the intended use of the fibre. In general, many plant fibres exhibit decent durability due to their inherent strength and resilience. For example, fibres like flax, hemp, and jute possess good tensile strength (Djafari Petroudy, 2017) and are suitable for various applications, including textiles, ropes, and even structural components in construction. However, the durability of plant fibres can be influenced by environmental conditions, such as exposure to moisture, and UV radiation. Natural plant fibres can be susceptible to degradation when exposed to prolonged moisture, and also tarmac and insect attack (Fassi and Maina, 2006).

H - End-of life and recyclability

The end-of-file of plant fibres varies between plant and their use. Hemp is reusable and recyclable. Hemp is suitable for cascading use: the fibrous part for textile uses. the textile residues for insulation and the paper industry, the recycled paper for coarser papers and cardboard, all of which can be recycled again and finally used as fuel. Composting is only possible for pure hemp, without synthetic fibre and other non-compostable materials. Otherwise, the material must be disposed of in landfills (Fassi and Maina,2006). Kenaf is reusable and recyclable. Composting is only possible if it is pure, and) therefore biodegradable, otherwise like hemp it must be disposed of in landfills (Fassi and Maina,2006). Jute fibre is reusable, recyclable and compostable in soil or composting sites if pure. Resources can be derived from regenerated and recycled jute from bags used in the food industry (Fassi and Maina, 2006). Flax fibre is reusable, recyclable and compostable in soil or composting sites if pure (and containing low percentages of boron salts – treatment for flax when used as insulation material as a fireproofing and anti-tarmac treatment) (Fassi and Maina, 2006).
Untreated cotton fibre, in its natural state, is both compostable and recyclable. Predominantly, cotton finds its primary utilization within the textile industry. Unfortunately, the prevalent "buy – use – dispose" culture of fast fashion has given rise to a highly impactful industry where waste has emerged as a substantial global concern. Shockingly, less than half of used clothing items are gathered for reuse or recycling, and merely 1% of used garments undergo recycling to be transformed

into new apparel. This is due to the emergence of technologies that enable the conversion of used clothes into virgin fibres, a development still in its nascent stages (European Parliament, 2020).Not all of waste is cotton, in fact a lot of textile fabrics are combine with plastic and synthetic material, however this waste holds a lot of potential to be transformed and reused.

I - Life cycle assessment

Hemp - Pf1

Hemp fibre cultivation is considered sustainable for different reasons: due to hemps resilience the requirements for pesticides and herbicides are minimal. Hemp cultivation does not typically lead to soil depletion unlike other industrial crops. As the plants grow they enrich the soil by shedding their leaves onto the ground throughout the growing season, creating compost in the process as retention of soil moisture, also because hemp requires about 50% of water used by other agricultural corps. At the same time the deep roots of the plant help with soil structure and prevent runoff. Hemp like other plants acts as a carbon sink as it absorbs and stores CO_2 as it grows (Rana et al., 2014). LCA data in the SimaPro software with the specific settings (as mentioned in the tool section at the beginning of the chapter) was not found. Therefore the data references to the paper by Hayo van der Werf - Life Cycle Analysis of field production of fibre hemp, the effect of production practices on environmental impacts[2] - the data references to the field production of 1 hectare of hemp to environmental impacts in western Europe for six impact categories. Different studies have reported the GWP value of hemp cultivation. Due to different methodologies, functional units chosen and different factors in cultivation practices, the value can differ.

[2] Van der Werf, H.M.G. Life Cycle Analysis of field production of fibre hemp, the effect of production practices on environmental impacts. Euphytica 140, 13–23 (2004). https://doi.org/10.1007/s10681-004-4750-2

Figure Pf09: the data referes to the field production of 1 hectar of hemp to environmental impacts in western Europe for six impact categories
Source: Van der Werf, H.M.G. Life Cycle Analysis of field production of fibre hemp, the effect of production practices on environmental impacts. Euphytica 140, 13–23 (2004). https://doi.org/10.1007/s10681-004-4750-2

Impact category	Unit	Annual per capita impacts	Reference for annual per capita impacts
Eutrophication	kg PO_4-eq.	38.4	Huijbregts et al., 2001
Climate change	kg CO_2-eq.	14,600	Huijbregts et al., 2001
Acidification	kg SO_2-eq.	84.2	Huijbregts et al., 2001
Terrestrial ecotoxicity	kg 1,4-DCB-eq.	146	Huijbregts et al., 2001
Energy use	MJ	154,000	PRé Consultants, 1997
Land use	m^2.year	10,100	Huijbregts et al., 2001

Authors such as Gonzales-Garcia (2010)[3] and Van der Werf (2004)[4] conducted life cycle assessments of hemp cultivation and other crops in European nations like Italy, Spain and France, which share climatic similarities. However, the outcomes they obtained showed differences. In the study by Gonzales-Garcia, the carbon footprint assessed using the global warming potential 100 (GWP100) was found to be 1600 kg CO_2 eq/ton of hemp fibre, ready for processing in a pulp mill. This assessment took into account cultivation, production, and supply processes. On the other hand, the study by Van der Werf reported a GWP100 value of 2330 kg CO_2 eq/ha for hemp cultivation in a field of 1 hectare. This calculation considered processes up to the point of harvest and transport to the farm, using the functional unit of field production per hectare.

[3] Gonzalez-Garcia, S.; Hospido, A.; Feijoo, G.; Moreira, M. T. Life cycle assessment of raw materials for non-wood pulp mills: Hemp and flax. Resour. Conserv. Recycl. 2010, 54 (11), 923−930

[4] van der Werf, H. M. G. Life cycle analysis of field production of fibre hemp, the effect of production practices on environmental impacts. Euphytica 2004, 140 (1−2), 13−23.

When considering the use of hemp as a building material, different studies of hemp based products were conducted. These products entail the combination with other materials, for example with lime in hemp-crete blocks by Tecnocanapa (IT) - Blocco ambiente with an EPD[5].

[5] Full EPD can be found at: https://www.epditaly.it/epd/prodotti-biocompositi-per-ledilizia-in-canapa-e-calce/

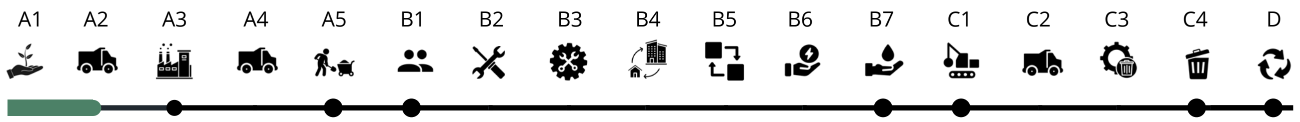
Figure Pf10: the data referes to the contributions (in %) to different impact categories of the processes (production of crop inputs, production and use of diesel, field emissions) making up the field production of hemp
Source: Van der Werf, H.M.G. Life Cycle Analysis of field production of fibre hemp, the effect of production practices on environmental impacts. Euphytica 140, 13–23 (2004). https://doi.org/10.1007/s10681-004-4750-2

Impact category (unit)	Processes	Hemp
Eutrophication	N fertiliser production	1.0
	P fertiliser production	1.1
	K fertiliser production	0.1
	CaO production	0.2
	Pesticide production	0
	Machinery production	0.2
	Diesel production and use	2.7
	Field emissions[1]	94.7
Climate change	N fertiliser production	24.6
	P fertiliser production	2.8
	K fertiliser production	2.6
	CaO production	13.1
	Pesticide production	0
	Machinery production	5.3
	Diesel production and use	10.5
	Field emissions[1]	41.1
Acidification (kg SO_2-eq.)	N fertiliser production	11.8
	P fertiliser production	10.7
	K fertiliser production	2.2
	CaO production	3.3
	Pesticide production	0
	Machinery production	12.5
	Diesel production and use	26.2
	Field emissions[1]	33.3
Energy use (MJ)	N fertiliser production	28.1
	P fertiliser production	5.6
	K fertiliser production	9.8
	CaO production	8.5
	Pesticide production	0
	Machinery production	19.3
	Diesel production and use	28.7

Kenaf - Pf2

Biomass production of kenaf, while offering potential benefits, can also lead to concerns of soil and groundwater pollution through the use of fertilizers and pesticides. Crop management practices and characteristics also impact soil quality, influencing nutrient levels, organic matter, structure, acidity, and erosion risk. However, the cultivation of crops, particularly perennials, can enhance soil quality by reducing erosion, compaction, and fostering carbon sequestration (Fernando et al., 2010c; Boléo 2011). The kenaf crop exemplifies these effects, with potential for extensive techniques requiring minimal technical inputs, resulting in positive environmental outcomes such as reduced emissions (Fernando, 2013).

LCA data was obtained by the SimaPro software, in reference to KENAF - stalk {RoW}| fibre production, kenaf, retting | Cut-off, U 1 kg 100 not defined - Textiles\Transformation the by-product of the process, is here approximated by stalk. Included activities start: The activity starts with the immersion of the plant bundles into the water. Included activities end: The activity ends with the extraction of the kenaf fibres from the retted plants. It is done manually by hand. The kenaf Fibre is then gets dried in the sun.



GWP

Impact category	Unit	Total
Total	kg CO_2 eq.	**-0.359**
Climate change - fossil	kg CO_2 eq.	0.025
Climate change - biogenic	kg CO_2 eq.	0.053
Climate change - CO2 uptake	kg CO_2 eq.	-0.438
Climate change - land use and transformation	kg CO_2 eq.	0.000

GWP - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 - Characterisation

Embodied energy

Impact category	Unit	Total
Total	MJ	**5.318**
Non renewable, fossil	MJ	0.209
Non renewable, nuclear	MJ	0.014
Non renewable, biomass	MJ	0.00
Renewable, biomass	MJ	5.088
Renewable, wind, solar, geothermic	MJ	0.002
Renewable, water	MJ	0.006

EE - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation

Impact category	Unit	Total
Climate change	kg CO2 eq	0.0414
Ozone depletion	kg CFC11 eq	0.0000
Ionising radiation	kBq U-235 eq	0.0012
Photochemical ozone formation	kg NMVOC eq	0.0002
Particulate matter	disease inc.	0.0000
Human toxicity, non-cancer	CTUh	0.0000
Human toxicity, cancer	CTUh	0.0000
Acidification	mol H+ eq	0.0009
Eutrophication, freshwater	kg P eq	0.0000
Eutrophication, marine	kg N eq	0.0006
Eutrophication, terrestrial	mol N eq	0.0041
Ecotoxicity, freshwater	CTUe	2.1730
Land use	Pt	3.8474
Water use	m3 depriv.	0.5852
Resource use, fossils	MJ	0.2070
Resource use, minerals and metals	kg Sb eq	0.0000
Climate change - Fossil	kg CO2 eq	0.0269
Climate change - Biogenic	kg CO2 eq	0.0144
Climate change - Land use and LU change	kg CO2 eq	0.0000
Human toxicity, non-cancer - organics	CTUh	0.0000
Human toxicity, non-cancer - inorganics	CTUh	0.0000
Human toxicity, non-cancer - metals	CTUh	0.0000
Human toxicity, cancer - organics	CTUh	0.0000
Human toxicity, cancer - inorganics	CTUh	0.0000
Human toxicity, cancer - metals	CTUh	0.0000
Ecotoxicity, freshwater - organics	CTUe	0.0167
Ecotoxicity, freshwater - inorganics	CTUe	0.4128
Ecotoxicity, freshwater - metals	CTUe	1.7436

Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation

Jute - Pf3

Some important aspects of jute fibre production related to sustainability are to be considered.

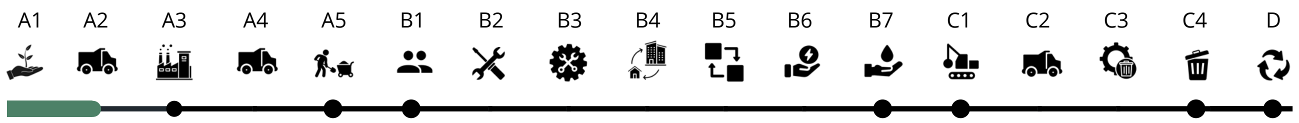
Jute fibres are derived from annual renewable resources. The cultivation process results in significant biomass production per unit of land. Jute can be harvested in just 4–6 months, producing a large quantity (40 tonnes of dry stem per hectare) when compared to wood. The higher biological efficiency of jute plants compared to wood as a substitution have the potential to lowers the cost of paper production but also mitigates deforestation by minimizing the need to cut down trees. Jute cultivation does not rely on chemical fertilizers, natural processes like shedding jute leaves and crop waste convert into organic matter, enriching the soil with nutrients.

The production of jute fibres generates organic chemicals and gases, including acetone, ethyl alcohol, butyl alcohol, methane, carbon dioxide, and hydrogen sulphide. Methane, released during the retting process of jute. Adopting techniques like ribbon retting and humidified retting can significantly decrease methane emissions, enhancing the sustainability of jute fibre production. (Rana et al., 2014).

Growing jute in rotation with other crops has shown the potential to enhance the health of these other crops, while also lowering the susceptibility to pest attacks and disease infestations (Islam et al., 2012).

LCA data was obtained by the SimaPro software, in reference to JUTE - fibre, jute {RoW}| fibre production, jute, retting | Cut-off, U 1 kg 100 Compost - Textiles\Transformation

Included activities start: The activity starts with the immersion of the jute plant bundles into the water. Included activities end: The activity ends with the extraction of the jute fibres from the retted plants. It is done manually by hand. The Jute Fibre is then gets dried in the sun.



GWP

Impact category	Unit	Total
Total	kg CO_2 eq.	**-2.720**
Climate change - fossil	kg CO_2 eq.	1.561
Climate change - biogenic	kg CO_2 eq.	0.169
Climate change - CO2 uptake	kg CO_2 eq.	-4.790
Climate change - land use and transformation	kg CO_2 eq.	0.340

GWP - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 - Characterisation

Embodied energy

Impact category	Unit	Total
Total	MJ	**68.251**
Non renewable, fossil	MJ	12.046
Non renewable, nuclear	MJ	0.309
Non renewable, biomass	MJ	0.001
Renewable, biomass	MJ	55.639
Renewable, wind, solar, geothermic	MJ	0.059
Renewable, water	MJ	0.196

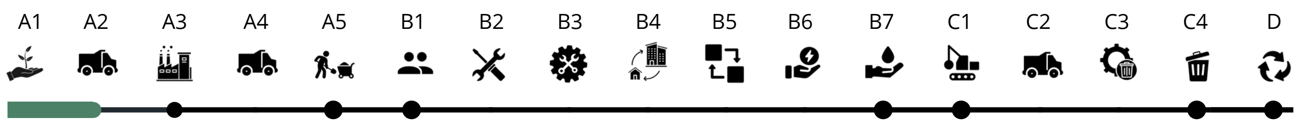
EE - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation

Impact category	Unit	Total
Climate change	kg CO2 eq	2.035
Ozone depletion	kg CFC11 eq	0.000
Ionising radiation	kBq U-235 eq	0.038
Photochemical ozone formation	kg NMVOC eq	0.008
Particulate matter	disease inc.	0.000
Human toxicity, non-cancer	CTUh	0.000
Human toxicity, cancer	CTUh	0.000
Acidification	mol H+ eq	0.076
Eutrophication, freshwater	kg P eq	0.021
Eutrophication, marine	kg N eq	0.037
Eutrophication, terrestrial	mol N eq	0.335
Ecotoxicity, freshwater	CTUe	279.626
Land use	Pt	176.857
Water use	m3 depriv.	5.084
Resource use, fossils	MJ	11.478
Resource use, minerals and metals	kg Sb eq	0.000
Climate change - Fossil	kg CO2 eq	1.652
Climate change - Biogenic	kg CO2 eq	0.042
Climate change - Land use and LU change	kg CO2 eq	0.340
Human toxicity, non-cancer - organics	CTUh	0.000
Human toxicity, non-cancer - inorganics	CTUh	0.000
Human toxicity, non-cancer - metals	CTUh	0.000
Human toxicity, cancer - organics	CTUh	0.000
Human toxicity, cancer - inorganics	CTUh	0.000
Human toxicity, cancer - metals	CTUh	0.000
Ecotoxicity, freshwater - organics	CTUe	32.739
Ecotoxicity, freshwater - inorganics	CTUe	40.543
Ecotoxicity, freshwater - metals	CTUe	206.344

Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation

Flax - Pf4

In order to improve sustainability aspects for production and cultivation of flax some aspects can be taken into consideration. Utilizing minimal or shallow ploughing techniques,that require less energy, can offer benefits, especially on sloping terrain, by minimizing soil erosion and runoff of sediment. The use of no-till and water retting results in lower environmental impact and energy requirements (Rana et al., 2014). Good practices involve also utilizing by-products like short fibres and shives as animal bedding or in paper production, and gathering and compacting the dust generated from scutching and hackling as biomass fuel (Dissanayake et al., 2009). LCA data was obtained by the SimaPro software, in reference to Flax - fibre, flax {RoW}| fibre production, flax, retting | Cut-off, U 1 kg 100 Compost - Textiles\Transformation. Flax retting activity involves immersion of the plant bundles in fresh water tanks in cultivation field. In the scenario of a stagnant water body, the minimal plant material-to-water ratio is 1:22. Following the retting process, the fibre is separated from the stalk. Subsequently, after three days, the bundles are subjected to thorough washing with clean water and set out on the ground for sun drying. The extraction of flax fibre takes place from the bast of the flax plant's stem. The more tender upper sections of the retted plants are trimmed to remove capsules from the plants. This prepares the flax fibre for the scutching process.



GWP

Impact category	Unit	Total
Total	kg CO_2 eq.	**-9.655**
Climate change - fossil	kg CO_2 eq.	0.913
Climate change - biogenic	kg CO_2 eq.	0.473
Climate change - CO2 uptake	kg CO_2 eq.	-11.043
Climate change - land use and transformation	kg CO_2 eq.	0.002

GWP - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 - Characterisation

Embodied energy

Impact category	Unit	Total
Total	MJ	**134.478**
Non renewable, fossil	MJ	7.642
Non renewable, nuclear	MJ	0.844
Non renewable, biomass	MJ	0.001
Renewable, biomass	MJ	125.516
Renewable, wind, solar, geothermic	MJ	0.139
Renewable, water	MJ	0.336

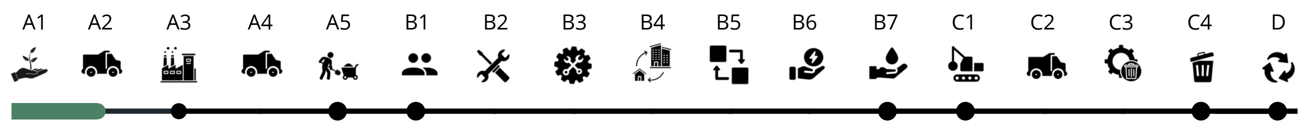
EE - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation

Impact category	Unit	Total
Climate change	kg CO2 eq	1.091
Ozone depletion	kg CFC11 eq	0.000
Ionising radiation	kBq U-235 eq	0.064
Photochemical ozone formation	kg NMVOC eq	0.006
Particulate matter	disease inc.	0.000
Human toxicity, non-cancer	CTUh	0.000
Human toxicity, cancer	CTUh	0.000
Acidification	mol H+ eq	0.031
Eutrophication, freshwater	kg P eq	0.000
Eutrophication, marine	kg N eq	0.019
Eutrophication, terrestrial	mol N eq	0.135
Ecotoxicity, freshwater	CTUe	81.501
Land use	Pt	16.220
Water use	m3 depriv.	18.134
Resource use, fossils	MJ	7.918
Resource use, minerals and metals	kg Sb eq	0.000
Climate change - Fossil	kg CO2 eq	0.963
Climate change - Biogenic	kg CO2 eq	0.126
Climate change - Land use and LU change	kg CO2 eq	0.002
Human toxicity, non-cancer - organics	CTUh	0.000
Human toxicity, non-cancer - inorganics	CTUh	0.000
Human toxicity, non-cancer - metals	CTUh	0.000
Human toxicity, cancer - organics	CTUh	0.000
Human toxicity, cancer - inorganics	CTUh	0.000
Human toxicity, cancer - metals	CTUh	0.000
Ecotoxicity, freshwater - organics	CTUe	4.709
Ecotoxicity, freshwater - inorganics	CTUe	14.154
Ecotoxicity, freshwater - metals	CTUe	62.638

Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation

Cotton - Pf5

Cotton fibre is deemed sustainable due aspects like its renewability and biodegradability. Key aspects of sustainability in cotton fibre production encompass soil, water, land, energy, and air quality. The cultivation of cotton fibre can impact soil quality through practices like land preparation causing soil erosion and the application of chemicals like insecticides and pesticides. However, modern methods of cotton cultivation, such as conservation tillage, minimize soil disruption and mixing, reducing soil erosion and promoting soil development through the planting of winter or cover crops (Rana et al., 2014). Cotton plants exhibit robustness in the face of arid and hot conditions, necessitating minimal water. In numerous regions worldwide, the cultivation of cotton relies on natural resources such as rainfall, contributing to a diminished environmental footprint. The quality of air is a notable consideration in the process of cotton fiber production and ginning. The adoption of modern techniques, such as reduced tillage, has contributed to the decline in dust emissions originating from the fields. Moreover, measures ensuring quality control have been implemented to mitigate dust emissions during the ginning phase. These contemporary approaches not only reduce dust emissions but also lead to a substantial decrease in CO_2 emissions. Additionally, the energy demands of cotton production can be offset through the creation of bio-fuel derived from cotton seeds (Cotton Incorporated, 2023).
LCA data was obtained by the SimaPro software, in reference to Cotton - fibre, cotton, organic {RoW}| fibre production, cotton, organic, ginning | Cut-off, U 1 kg 100 not defined - Textiles\Transformation. Included activities start: Ginning process starts with the input of seed-cotton, organic into the ginning machine where the lint is separated from the seeds and the lint is collected as a continuous loose sheet. The machinery and infrastructure are not included in the process. Included activities end: The loose continuous sheet of lint is then put into a hydraulic press machine to press the lint into bales. The seed is collected separately and are stored for future use in farming or are sent to allied industries for further processing. The ginning process culminates with the output of bales of cotton and separated cotton seeds.



GWP

Impact category	Unit	Total
Total	kg CO_2 eq.	**-2.414**
Climate change - fossil	kg CO_2 eq.	0.559
Climate change - biogenic	kg CO_2 eq.	0.000
Climate change - CO2 uptake	kg CO_2 eq.	-2.974
Climate change - land use and transformation	kg CO_2 eq.	0.000

GWP - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 - Characterisation

Embodied energy

Impact category	Unit	Total
Total	MJ	**34.816**
Non renewable, fossil	MJ	0.432
Non renewable, nuclear	MJ	0.005
Non renewable, biomass	MJ	0.000
Renewable, biomass	MJ	34.377
Renewable, wind, solar, geothermic	MJ	0.001
Renewable, water	MJ	0.002

EE - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation

Impact category	Unit	Total
Climate change	kg CO2 eq	0.626
Ozone depletion	kg CFC11 eq	0.000
Ionising radiation	kBq U-235 eq	0.002
Photochemical ozone formation	kg NMVOC eq	0.004
Particulate matter	disease inc.	0.000
Human toxicity, non-cancer	CTUh	0.000
Human toxicity, cancer	CTUh	0.000
Acidification	mol H+ eq	0.030
Eutrophication, freshwater	kg P eq	0.012
Eutrophication, marine	kg N eq	0.081
Eutrophication, terrestrial	mol N eq	0.138
Ecotoxicity, freshwater	CTUe	13.217
Land use	Pt	695.417
Water use	m3 depriv.	0.014
Resource use, fossils	MJ	0.411
Resource use, minerals and metals	kg Sb eq	0.000
Climate change - Fossil	kg CO2 eq	0.625
Climate change - Biogenic	kg CO2 eq	0.000
Climate change - Land use and LU change	kg CO2 eq	0.000
Human toxicity, non-cancer - organics	CTUh	0.000
Human toxicity, non-cancer - inorganics	CTUh	0.000
Human toxicity, non-cancer - metals	CTUh	0.000
Human toxicity, cancer - organics	CTUh	0.000
Human toxicity, cancer - inorganics	CTUh	0.000
Human toxicity, cancer - metals	CTUh	0.000
Ecotoxicity, freshwater - organics	CTUe	0.145
Ecotoxicity, freshwater - inorganics	CTUe	1.149
Ecotoxicity, freshwater - metals	CTUe	11.923

Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation

J - Prefabricated production processes

Natural-fibre-based composites are changing how materials are being used across different fields, spanning from aerospace to concrete applications (Ravindran et al., 2023). Alongside this trend, sustainable materials that are both environmentally friendly and strong are rapidly substituting traditional materials.
In recent years, numerous dedicated researchers have been actively exploring this area, resulting in the development of various materials for diverse uses. However, the transition from laboratory experimentation to real-world implementation and widespread utilization of these findings faces challenges and is yet to be implemented (Ravindran et al., 2023).

The world is rich in biological fibres from both agriculture and forestry, offering several advantages for their utilization. The most notable benefit lies in their strength and stiffness, which is especially evident in the long fibres of jute, flax, and hemp. When it comes to developing building materials from these bio-fibres, the goal should be to craft entirely "green" products that rely solely on biological raw materials. This objective should be cantered on introducing more environmentally friendly products to the market (Svennerstedt, 2007).

Elements

Figure Pf11: Blocco Ambiente® – Hemp Block - TECNOCANAPA
Source: https://tecnocanapa-bioedilizia.it/

Hemp-crete block

Hemp-crete stands as an eco-friendly construction material crafted from hemp fibres, lime, and water, renowned for its remarkable thermal insulation and positive ecological attributes. In its typical application, this material is utilized in loose form, amalgamated with lime, and compacted within formwork, akin to the process for constructing rammed earth walls. Alternatively, it can take the shape of blocks. Hemp-crete blocks, formed from compressed hemp shives, water, hydrated lime, and at times additional additives (depending on the specific product), serve as insulation and contributors to thermal mass.

Applications: Construction of insulating and breathable masonry walls or internal partitions, external wall insulation system, solid floor insulation. The installation takes place by laying the blocks with a thin layer of mortar of lime and hemp shives (to avoid thermal bridges), the blocks can be cut by manual or electric saw.

Some EU producers

Isohemp - (BE)
Hanfstein - (IT) - Gervasi - (IT)
Tecno Canapa Senini - (IT) - **Banca della calce - (IT)**
Batinfo - (FR)

Insulation panels

Insulation panels made from processing of plant fibres can come in various forms and can be used for different application depending on their composition and combination with other materials and binders. Insulating panel can come in soft and rigid form. Often in panels, different fibres are combined together.

The production process rigid panels begins with the mixing of plant fibres (already cleaned, and sorted) with a binding agent, such as polystyrene or corn-starch (and often flame inhibitors such as ammonium salts). The mixture is shaped into panels using moulds or presses, followed by compression and curing. Finally, the cured panels are trimmed, finished, and also often coated for protection. On the other hand, the creation of soft panels retains the natural flexibility of the fibres. After material preparation and cleaning, the fibres are intertwined through mechanical processes. Additional filling materials can be added to enhance insulation. The layers of prepared fibres and fillings are compressed between fabric or netting, creating a flexible, insulating panel.

The choice between rigid and soft panels depends on the specific insulation requirements and desired characteristics for a given application.

Applications: Plant fibre insulating panels have a variety of practical uses in construction, effectively providing thermal insulation for flooring, roofs and ceilings, thus contributing to maintain indoor comfort and minimize heat transfers while offering noise reduction.

Some Eu producers:

Hemp
Ton-Gruppe - (IT)
Tecno Canapa Senini - (IT)
Ekolution - (SE) - EPD
Kobe - cz s.r.o - (CZ) - EPD
Hgmatthews - (UK)

Hemp - Kenaf
Artemestieri - (IT)
Euchora - (IT) - ANAB cert.

Kenaf
K.E.F.I. s.p.a. - (IT)
Masacustic - (IT)

Hemp - Jute
Ton-Gruppe - (IT)

Jute
Ton-Gruppe - (IT)
QBat - (CH)

Flax
Isolina - (IT)

Figure Pf12:: Hemp fibre insulation panels
Source: https://store.artimestieri.com/

Figure Pf13: Hemp jute fibre insulation panels - Combi Jute - by HempFlax (NL)
Source: https://www.ecological-buildingsystems.com/product/thermo-hemp-combi-jute#product-overview

Figure Pf14: THERMO JUTE 100 PANNEAU - QBat (CH)
Source: https://www.qbat.fr/it/isolants-naturels/356-isolant-souple-fibre-naturelle-thermo-jute-100.html

Figure Pf15: Isolina - Flax fibre insulating panel
Source: https://www.bauhaus.fi/eristelevy-pellava-isolina-100-mm.html

Figure Pf16: Hemp panels by Jory Swart
Source: https://theexplodedview.com/materialbb/hemp-panels/

Figure Pf17: Canna Grove - by Hemp Traders - (U.S.A.)
Source: https://www.hemptraders.com/Hemp-Board-s/1937.htm

Fibre-boards / Particle-boards

Fibreboards and particleboards made from plant fibres represent innovative materials with diverse applications. In their production, plant fibres, such as those from hemp, flax, and jute, are combined with binding agents and compressed under high pressure to form dense and durable boards. Fibreboards are often created by blending these fibres with natural resins or adhesives and shaping them into sheets through pressing and curing.

Particleboards, on the other hand, involve mixing small shives and particles of plant fibres with adhesives, forming a mixture that is compressed into boards through heat and pressure.

Applications: Fibreboards are commonly employed in furniture and cabinetry, where their smooth surface and strength make them ideal for shaping into different designs. They are also utilized in construction for under-layment, interior walls, sub-flooring and components such as doors.

The utilization of plant-fibre to make composite fibre-boards or particle-boards is still being explored and researched, therefore products on the market are still limited. Hemp seems to be more researched than other plant fibres.

Some EU producers an Non-EU

Jory Swart - (NL)
Hemp Traders - Canna Grove - (U.S.A.)

Mats / Felt

Figure Pf18: Hemp felt - Hemp flax mat
Source: https://www.hempflax.com/en/

Figure Pf19: Flax and sheep wool felt
Source: http://www.lamasiera.it/it/materiali/isolanti08.html

Plant-fibres can be processed in felt mats that can have different applications. In their production, plant fibres like hemp, flax, and jute, similarly as the soft panels, they are mechanically intertwined and compressed to form dense, cohesive mats. This process normally involves minimal or no chemical additives. Felt mats, owing to their inherent insulation properties and moisture resistance, find a range of applications in the construction sector.

Applications: they are often employed as insulation materials typically for roofs. usually they are used in dry construction systems. Additionally, felt mats can serve as soundproofing elements, optimizing acoustic conditions within buildings.

Some EU producers

HempFlax - (NL)
KOBE -cz s.r.o. - (CZ) EPD
Thermo Hanf - (DE)
La Masiera - (IT) - Flax and sheep wool
Masacustic - (IT)

Acoustic panels

Figure Pf20: SAPPA Hemp acoustic panels - by Hanfstein - (IT)
Source: https://www.hanfstein.eu/home-english/hemp-acoustic-panel/

Acoustic panels can be crafted from plant fibres, representing a eco-friendly approach to sound management in various indoor spaces. These panels are made similarly to particleboards as they involve compressing a mix of plant-based shives with adhesives and binders.

Applications: acoustic absorbing panels for interior spaces applicable to walls and ceilings. They can come in different colours, designs and shapes.

One innovative acoustic panel has been developed by **EcoVerb™** in the U.S.A.**,** it utilizes recycled cotton fibre from the fashion industry waste.

Some EU producers

Hanfstein - (IT)
Silent Fibre - (DE)
EcoVerb™ Cotton Fiber Acoustic Panels - (U.S.A.)

Plant fibre composites - concrete

Plant fibre concrete are materials created by combining natural plant fibres with a matrix material, often a polymer or a cementitious substance to make bio-based concrete, in order to produce a composite material with enhanced properties. The plant fibres act as reinforcement, adding strength, stiffness, and other beneficial characteristics to the composite. These composites are commonly used in various industries, including construction, automotive, and even aerospace industry (Zhongsen, 2020), due to their lightweight nature, biodegradability, and sustainable sourcing. The types of plant fibres used in these composites vary and can include materials like hemp, flax, jute, sisal, and kenaf. These fibres are integrated into the matrix material through various methods, such as weaving, knitting, or being dispersed randomly, to create a homogeneous mixture. The resulting composite can exhibit improved mechanical properties, such as tensile strength, impact resistance, and thermal stability, compared to the matrix material alone (Svennerstedt, 2007).

Ongoing research in this field is focusing on optimizing the combination of plant fibres and matrix materials, understanding the effects of fibre orientation, developing efficient manufacturing processes, and investigating the long-term durability and performance of these composites. Currently there seems to be a gap between the research and products on the market. In regards to prefabricated elements and components the research is still exploring different possibilities.

K - Case studies / Good practices

Flax bridge - Almere (NL)

Figure Pf21-22: Smart circular bridge - (NL) - handrail made of robot-wound flax composite filament
Source: https://www.dezeen.com/2022/05/05/smart-circular-bridge-flax-completed-the-netherlands-architecture/

The Eindhoven University of Technology has taken the lead in a project to construct a bridge partially using flax in the Netherlands. The aim is to showcase how this material could potentially replace steel in construction. Situated in Almere, the bridge is crafted from a mix of flax fibres, bio-resin, and polyurethane foam blocks. This innovative combination results in a composite material that is both lightweight and stable, providing an alternative to aluminium or steel.
This Almere-based bridge is the first of a trio of bridges designed for pedestrians and cyclists under the "Smart Circular Bridge "project. The next two bridges are planned for Ulm, Germany, and Bergen Op Zoom in the Netherlands.
The project involves a total of 15 collaborators in the European Union (five universities, among them the Eindhoven University of Technology (TU/e) and the University of Stuttgart, along with seven companies and three municipalities). The primary objective is to gather essential data about the long-term stability and endurance of flax composite materials.

In Almere, the bridge consists of two different types of flax composite material. The deck utilizes flax fibre mats combined with foam blocks, while the handrails are formed using a flax filament wound by a robot. The foam blocks that compose the core of the bridge were bonded through a vacuum-infusion process, resulting in a unified structure. The robot-wound filament is arranged in interlinked triangular patterns. This choice was made to leverage the technique's ability to evoke a sense of "lightness and delicacy," showcasing the aesthetic and technical potentials of bio-composites and natural fibres.

Overall, the bridge incorporates approximately 3.2 tonnes of flax. This material is of particular interest to the researchers of the project due to its rapid growth compared to wood and its greater availability compared to hemp.

Figure Pf23: Composite blocks that compose the main structure of the bridge made from foam core wrapped with flax fibre
Source: https://www.dezeen.com/2022/05/05/smart-circular-bridge-flax-completed-the-netherlands-architecture/

FITNESs Hemp and sheep-wool panels - (IT) - Politecnico di Torino

Figure Pf24: FITNESs panels - Hemp fibre - washed wool fleece
Source: R. Pennacchio, L. Savio, D. Bosia, F. Thiebat, G. Piccablotto, A. Patrucco, S. Fantucci, (2017) Fitness: Sheep-wool and Hemp Sustainable Insulation Panels, Energy Procedia, Volume 111, Pages 287-297, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2017.03.030.

Building upon the prior research in regards to the Certonlana insulating panels[6], the team has investigated an innovative, eco-friendly system of semi-rigid panels for thermal and acoustic insulation. These panels are produced by incorporating recycled sheep's wool from the Piemont region alongside hemp technical fibre.

Hemp, which is utilized in panel production, undergoes a maceration process by being cut and left in the field for approximately four months, typically from October to February. Following maceration, it takes on a grayish hue and retains a minimal amount of shives residue, approximately equivalent to 1.25% of its weight. The shives in hemp are held together by fibres and can vary in size, ranging from 0.2 to 5 cm in length and 0.05 to 1 cm in thickness. In contrast, hemp fibres exhibit lengths between 10 and 70 cm, with the majority falling within the 10 to 20 cm range. The wool used in the production comes from sheep breeding in the Piemonte region. This wool is not suitable for the textile industry due to its dark colour and lower quality, characterized by thick fibres and irregular lengths. Despite being washed and dried, sheep wool may still contain plant debris entangled among the fibres. Similar to hemp, minimal treatments are applied to the raw wool to reduce energy consumption during panel production.

The production process consists of three primary phases:
-Blending of sheep's wool and hemp fibres,
-Subjecting the mixture to a soda solution treatment, which prompts the wool fibres to release a portion of their keratin protein, serving as a natural adhesive to bond the wool and hemp fibres,
-Eliminating the soda solution and subsequently drying the panel in an oven.

The ideal formula for creating FITNESs panels was determined by selecting from various samples. The end product of this process is a semi-rigid panel measuring 0.468 m² (90.00 cm x 52.00 cm) with a thickness of 4.50 cm and a weight of 3 kg. It is crafted from an equal weight of both wool and hemp.

[6] Bosia, Daniela & Savio, Lorenzo & Thiebat, Francesca & Patrucco, Alessia & Fantucci, Stefano & Piccablotto, Gabriele & Marino, Donatella. (2015). Sheep Wool for Sustainable Architecture. Energy Procedia. 78. 315-320. 10.1016/j.egypro.2015.11.650.

Tonin, C., Patrucco, A., Ramella Pollone, F., Bosia, D., Savio, L., & Giordano, R. Processo di lavorazione della lana, materiali di lana prodotti con detto processo e articoli comprendenti detti materiali di lana (2011). Italian Patent, 1410156.

[7] R. Pennacchio, L. Savio, D. Bosia, F. Thiebat, G. Piccablotto, A. Patrucco, S. Fantucci, (2017) Fitness: Sheep-wool and Hemp Sustainable Insulation Panels, Energy Procedia, Volume 111, Pages 287-297, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2017.03.030.

Figure Pf25: FITNESs panels
Source: R. Pennacchio, L. Savio, D. Bosia, F. Thiebat, G. Piccablotto, A. Patrucco, S. Fantucci, (2017) Fitness: Sheep-wool and Hemp Sustainable Insulation Panels, Energy Procedia, Volume 111, Pages 287-297, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2017.03.030.

Just BioFiber - (CA)

Figure Pf26: Just BioFibre building block
Source: https://justbiofiber.com/projects/

In 2014, Just Bio-fibre Structural Solutions, Corp. (JBF), from Calgary Alberta - Canada, was established with the goal of introducing a sustainable building system that enhances quality of life, reduces costs, minimizes waste, is time-efficient and simplifies construction processes. Utilizing patented structural blocks, JBF has developed an alternative and innovative building system. The building blocks are made with a hemp-crete mix with industrial hemp and lime without Portland cement, and are designed as interlocking block that do not need the use of mortar and can be dry assembled.

The blocks measurements are: length 542mm x width 272mm x height 203mm, blocks can be cut to size using standard power or hand saws.

Figure Pf27-28: Just BioFibre - Harmless Home project - building blocks - construction process
Source: https://justbiofiber.com/projects/

Figure Pf29: Just BioFibre - Serenity Home project - building blocks - construction process
Source: https://justbiofiber.com/projects/

L - Limits to overcome

When considering the use of plant fibres in structural applications, the main challenges revolve around the need for these materials to gain acceptance and comply with building codes and regulations at local, national, and international levels. Often, existing building codes do not account for the use of plant fibres, making it difficult to secure the necessary permits and approvals. However, for other functional purposes, meeting existing standards is typically sufficient. The primary issue arises when dealing with evolving regulations that may not readily accommodate these products, especially considering their typically higher production costs compared to petrochemical-based materials. This issue, as is often the case, centres on the economic aspects of industrial production.

Engaging with local authorities, building professionals, and organizations can help navigate these challenges and establish a framework for compliance.

At the same time, in recent years, numerous dedicated researchers have been actively exploring this area, resulting in the development of various materials with the use of plant-fibres for diverse uses. However, the transition from laboratory experimentation to real-world implementation and widespread utilization of these findings faces challenges and is yet to be implemented (Ravindran et al., 2023).

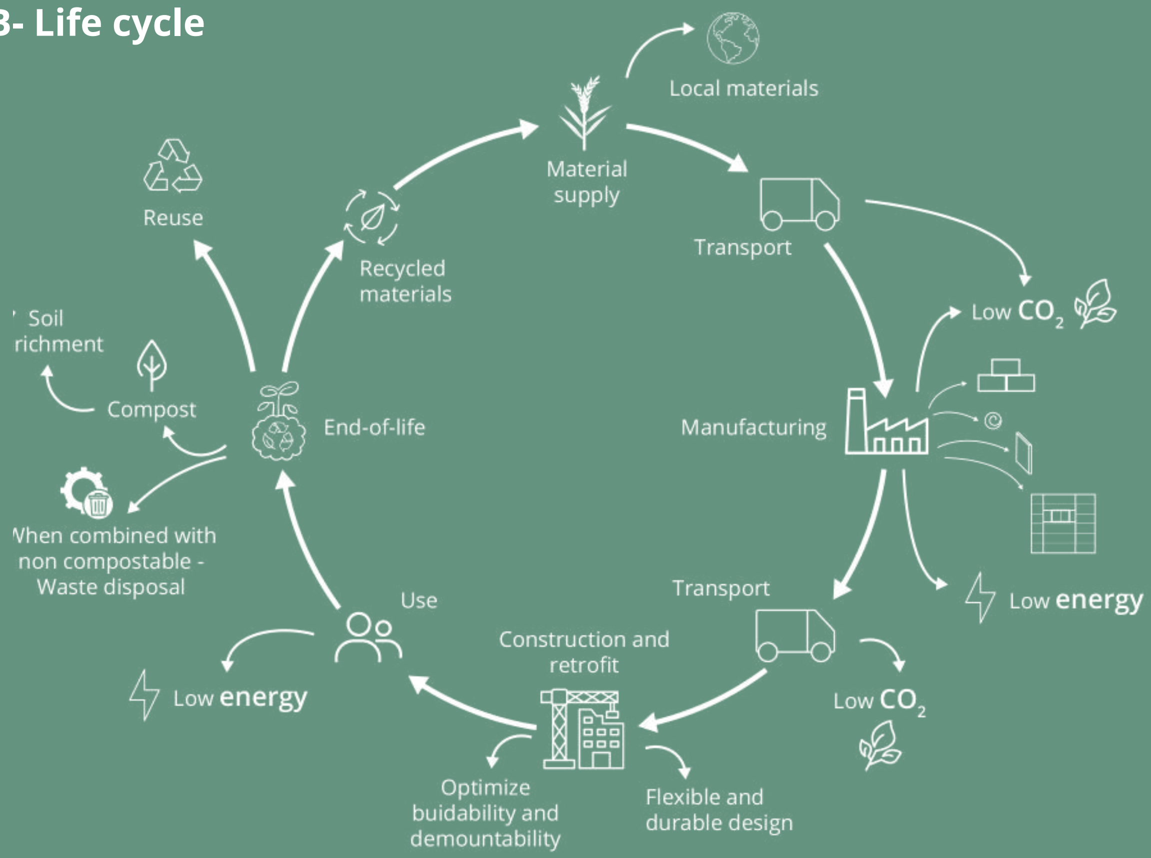
Additionally, another limitation that needs to be considered is the variable quality and consistency of raw sources, which can impact the performance and uniformity materials and products.

/
Straw

A - Watch points

- Use local and responsibly sourced raw material, allow for regeneration
- Low carbon energy in processing methods
- Low carbon transportation
- Optimise buildability and design to disassemble
- Re-use, Recycle and Re-purpose minimise raw material, maximise recycled content
- End-of-life - biodegradable - composting - re-purpose

B- Life cycle



C - Key points

Raw material resource

- Virgin/primary resource ●
- Recoverable resource ●
- Recovered/secondary resource ●
- Waste resource ◐

Availability of raw material

●●●●●

Degree of skills required for resourcing raw material

●○○○○

Degree of prefabrication

●●●○

Awareness

●●●●○

Applications

Technological units	Technical elements	Products category	
vertical closures	external walls	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
		Cladding/shingles/tiles	●
top closures	roof	Cladding/tiles/shingles	●
		Panels/false ceiling	●
		thermo-acoustic insulation	●
horizontal closures	slabs	Flooring Tiles/Panels/boards	○
		thermo-acoustic insulation	●
partitions	vertical partitions	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
	horizontal partitions	Florring Tiles/Panels/boards	○
		thermo-acoustic insulation	●

Figure St01: Straw stalks
Source: https://unsplash.com/s/photos/straw

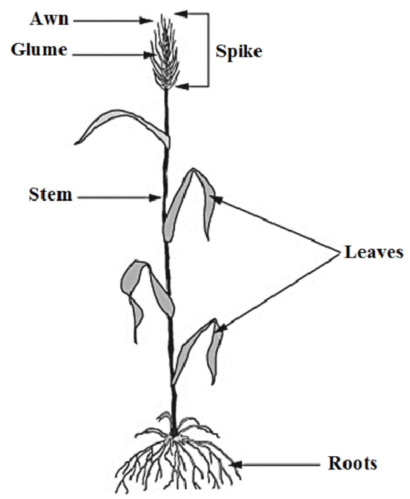


Figure St02: Straw parts
Source: https://unsplash.com/s/photos/straw

D - Raw material

Straw is the general term that refers to the dry stalks or stems of threshed grain, such as wheat, barley, oats, rye, maize and millet, or fibrous plants, such as flax, hemp, and rice. Straw is a regenerative resource that develops from photosynthesis processes using solar energy, water and minerals contained in the soil. Chemically it is made of cellulose, lignin, same as wood composition, and silica, the presence of silica is a major difference between the chemical content of straw and wood (Carbone, 2003). Straw is characterized by a water-repellent waxy layer on the epidermal layer of the stem. Due to the high content of silica, straw decomposes very slowly. The most suitable straw for production of building materials comes from plants of wheat, spelt and rye. Straw as a building material is strongly present in European (and non-European) tradition. It was used, among other, to thatch roofs, especially rye straw, and as an aggregate to the building material clay to increase thermal insulation and very importantly reduce the potential crack formation during drying phases of production. One of the most common uses for it was and is used for livestock bedding, incorporation into soil through ploughing, and as animals feed (Chuen Hon et al., 2020). Straw can also be utilized as biomass energy generation as a renewable energy source (Camia et al., 2018).

E - Cultivation and harvesting

The growing period of straw varies depending on the specific environmental conditions and crop. However, on average, it takes approximately three to six months for straw to grow. Factors such as the type of plant, climate, soil conditions, and agricultural practices can influence the exact duration.
The production process of straw as a building material, depends on the element or component but typically consists of harvesting crop of mature straw stalks, following there is a drying phase, usually the cut stalks are left in the field to dry naturally and then, once the straw has sufficiently dried, it is gathered and compressed into rectangular bales (these are the most common straw-based building product). Large balers are commonly used for this purpose. The bales are tied with twine or wire to hold them together.

F - Physical-mechanical properties

Proprieties of straw depend on different elements and components, as well as thickness, moisture content, climate conditions, density and also type of straw used and construction technique. Generally, for optimal performance as a construction material, straw bales have to be dry and should have a moisture content below 20%, calculated as a percentage of the bale's total weight (Cascone et al., 2019). One of the main advantages of straw is thermal insulation. It has excellent insulating properties, helping to regulate indoor temperatures by reducing heat transfer (thermal conductivity λ values range from 0.05 to 0.08 W/m·K). Due to its fibrous nature, the alternation of the stems and the voids created between them, as well as at the microscopic level the presence of cavities and micro-pores in the internal structure of the stems themselves, ensures good sound insulation performance. Straw allows for the passage of moisture vapour, resulting in a more breathable envelope that contributes to regulation of indoor humidity levels (the vapour resistance factor μ was calculated to be 2) (Minke and Mahlke, 2005). This also depends on final wall layer, for example earth plasters are optimal to contribute to moisture regulation. Many different studies have proven that, on the contrary of loose straw that has a low fire resistance, straw bale wall systems have a high fire resistance. The fire resistance class for a wall made of straw bales plastered on both sides is F90 (in case of fire, the load-bearing capacity of the wall is guaranteed for 90 minutes).

Finally, when properly compacted and supported, straw bales possess structural strength and good load-bearing capacity, making them suitable for load-bearing walls in some construction techniques. In load-bearing straw bale walls, the presence of framed timber structures with exposed woodwork can result in gaps between the timber and the render. It is crucial to seal all gaps meticulously, including those between the actual bales and between the bales and the primary structure to ensure air tightness and also avoid thermal bridges. This can be achieved by tightly packing the bales and using additional stuffing to fill any remaining cavities and by choosing appropriate render.

G - Durability

Some chemicals or prolonged exposure to moisture can lead to deterioration or discolouration of straw fibres. Straw, when left untreated, is a biodegradable material, and under certain conditions, like moisture and high humidity, it can be susceptible to biodegradation by micro-organisms such as fungi and bacteria. However, when properly protected from excessive moisture and kept dry, biodegradable degradation can be prevented to a certain extent. The decomposition stability of straw as a building material can vary depending on environmental conditions and exposure to moisture and sunlight (Minke and Mahlke, 2005). If exposed to consistent moisture over an extended period, straw can decompose and lose its structural integrity. To maintain stability, it is crucial to protect straw from excessive moisture and ensure proper ventilation to prevent prolonged dampness.

H - End-of life and recyclability

The end-of-life and recyclability of straw building materials can vary depending on the specific application, production processes and presence of additives. When left untreated (biotic material) straw can be composted as it is biodegradable. Straw bales or straw-based panels can be disassembled and reused in other construction projects. As mentioned above it can serve as source of biomass for energy production or as cattle bedding (also a traditional use).

I - Life cycle assessment

As stated by Dr. Arnaud Evrard[1] , when conducting LCA analysis on agricultural products utilized as building materials, a decision must be made between two primary assumptions.

The first considers straw as a by-product from grain cultivation; therefore, in calculating the environmental impacts it also considers a percentage of the tillage, the sowing of cereals and the eventual irrigation of plant protection products (like pesticides). The second sees straw as a waste produc; therefore, all energy and carbon inputs are not taken into consideration. Only the environmental impacts due to the baler machine are counted.

Dr. Evrard proposes an intermediate combination between the two. This one takes into consideration that, if not used as a building material, the straw would be partly remixed to the soil of the fields to help preserve the soil structure and its original organic content. In this case it is considered that more fertilizer would have to be spread at the next planting to make up for this deficiency (this approach has not been tested in the scope of this research but is currently being investigated in France as Evrard states).Taking all this into account, production process linked to straw is usually characterized by low embodied energy when considering other common building materials. Compared to other thermal insulating materials, straw bale has a significantly lower environmental impact when considering correspondence to thermal conductivity. As a load-bearing material, it has a lower carbon footprint than structural systems.

According to the ICE database version 2, developed by the University of Bath in 2011, straw has an embodied energy EE of 0.24 MJ/kg and a net emission of carbon dioxide EC of 0.01 $kgCO_2/kg$, when considering production stage A1 throw A3 (from cradle to gate).

One important aspect towards evaluating environmental impact of straw as a building material, is the origin of the raw materials that needs to take into consideration sustainable harvesting and regeneration, and also take into consideration transportation and linked emissions, local sources are the favourable option.
Unfortunately, the machinery utilized for harvesting is fossil fuelled and therefore increases environmental impact. Another aspect that has to be taken into consideration is the twine utilized in baling process as this is commonly made of plastic.

[1] Dr. Arnaud Evrard is a senior scientific at the Chair of Sustainable Construction of ETH Zürich in charge of the program coordination of the CAS Regenerative Materials.

LCA data was obtained from the SimaPro software. The reference follows Straw, stand-alone production {RoW}| production | Cut-off, U - 1 kg 100 Compost Agricultural\Plant production\Roughage\Transformation (Ecoinvent 3). Data refers to 1 kg dry matter of fresh straw from straw areas with 1.66 kg CO_2 and 17.6 MJ per kg dry matter. The dry matter content of fresh straw is about 15% the density about 120 kg/m^3.

Included activities end: The inventories include the cultivation of straw on a straw area. Included steps are harvest and loading for transport.

GWP

Impact category	Unit	Total
Total	kg CO_2 eq.	**-1.577**
Climate change - fossil	kg CO_2 eq.	0.073
Climate change - biogenic	kg CO_2 eq.	0.000
Climate change - CO2 uptake	kg CO_2 eq.	-1.650
Climate change - land use and transformation	kg CO_2 eq.	0.000

GWP - IPCC 2013 GWP 100a (incl. CO2 uptake) V1.00 - Characterisation

Embodied energy

Impact category	Unit	Total
Total	MJ	**18.040**
Non renewable, fossil	MJ	0.437
Non renewable, nuclear	MJ	0.001
Non renewable, biomass	MJ	0.000
Renewable, biomass	MJ	17.600
Renewable, wind, solar, geothermic	MJ	0.000
Renewable, water	MJ	0.001

EE - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation

Impact category	Unit	Total
Climate change	kg CO2 eq	0.079
Ozone depletion	kg CFC11 eq	0.000
Ionising radiation	kBq U-235 eq	0.002
Photochemical ozone formation	kg NMVOC eq	0.000
Particulate matter	disease inc.	0.000
Human toxicity, non-cancer	CTUh	0.000
Human toxicity, cancer	CTUh	0.000
Acidification	mol H+ eq	0.000
Eutrophication, freshwater	kg P eq	0.000
Eutrophication, marine	kg N eq	0.000
Eutrophication, terrestrial	mol N eq	0.002
Ecotoxicity, freshwater	CTUe	-0.379
Land use	Pt	290.587
Water use	m3 depriv.	0.059
Resource use, fossils	MJ	0.413
Resource use, minerals and metals	kg Sb eq	0.000
Climate change - Fossil	kg CO2 eq	0.079
Climate change - Biogenic	kg CO2 eq	0.000
Climate change - Land use and LU change	kg CO2 eq	0.000
Human toxicity, non-cancer - organics	CTUh	0.000
Human toxicity, non-cancer - inorganics	CTUh	0.000
Human toxicity, non-cancer - metals	CTUh	0.000
Human toxicity, cancer - organics	CTUh	0.000
Human toxicity, cancer - inorganics	CTUh	0.000
Human toxicity, cancer - metals	CTUh	0.000
Ecotoxicity, freshwater - organics	CTUe	0.026
Ecotoxicity, freshwater - inorganics	CTUe	0.068
Ecotoxicity, freshwater - metals	CTUe	-0.473

EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation

J - Prefabricated production processes

Elements

Prefabricated elements, components and construction systems made of straw offer the advantages of traditional straw construction, such as high performance and minimal environmental impact, while also providing reduced labour requirements and ensuring more consistent outcomes.

Straw Bales

Straw-bales are produced in various formats: small bales are usually 32 to 35 cm x 50 cm x 50 cm to 120 cm, with a density that varies from 80 to 120 Kg/m3 as lower density would make them unsuitable for construction (Minke, 2005b). Medium bales have dimensions of 50 cm x 80 cm x 70 to 240 cm. Jumbo bales are around 70 cm x 120 cm x 100 to 300 cm or more (large wall thickness).
To enhance its performance, additives can be incorporated into the straw bale structure, such as harmless biocides to reduce the risk of mould growth or additional fibrous materials to improve thermal performance (Chuen Hon et al., 2020).

Figure St03: Straw bales
Source: https://www.permaculturenews.org/2017/07/24/straw-bale-homes-passive-solar-design/

Applications: The use of straw-bales as a building material is varied. Straw-bales can be utilized as infill material (insulation) of a structure (best made of wood for compatibility of proprieties) consisting of beams and columns, they can also be attached to an existing structure and act as a thermal envelope in retrofitting interventions. Bales can form the load-bearing structure, Currently, straw bales with a load-bearing function-both large and small-are used almost exclusively to construct the perimeter walls of buildings; however, architect Werner Schmidt[2] in his project for a Swiss gardening company, Gartist GmbH, also used jumbo bales to make the roof structure, the principle of the false dome is reinterpreted by Schmidt by replacing stone with straw and stacking the overhanging bales toward the centre until they meet. When considering load-bearing straw bales, loads are transferred from the roof to the foundation directly from the straw bales, when considering them as infill it is the structural frame (usually wood) that carries the loads. Lastly, they can constitute, with a wood frame (structural), prefabricated wall, slabs and roof (flat or sloped) components (see following straw components).

[2] Architect Werner Schmidt founder of Atelier Werner Schmidt in Switzerland, is know for sustainable building construction specifically for utilization of straw-bales.

Figure St04: Atelier Werner Schmidt - Gartist GmbH - straw bale roof structure
Source: https://www.atelierschmidt.ch/gartist-bubikon

Full map of EU producers at:

https://strawbuilding.eu/map-of-straw-bale-producers/

Figure St05: Concluto compressed straw panel
Source: https://www.lehm-laden.de/

Panels

The fabrication of strawboards involves the compression of straw fibres combined with an adhesive binder, such as resin or cement. This process results in the production of panels that find utility across a range of applications.

Application: Such panels find versatility in applications such as wall sheathing, subflooring, or roofing, offering not only insulation but also essential structural reinforcement (OSSB straw panels). These panels can be tailored to fit specific dimensions using common tools like a circular saw or jigsaw. Their installation is hassle-free, as they can be securely affixed using screws or staples.

Some Eu producers

Lehm-laden - (DE)
NovoFibre - (DE)
Kodukuubis - (EE)

Figure St06: Straw matting rolls
Source: https://sandbaggy.com/products/straw-matting-rolls-erosion-control?variant=40544016040041

Mats

Straw can be woven or bound together to create mats or rolls.

Application and installation: These can be used for insulation, erosion control,thatching (traditional roofing technique where straw is used to create a waterproof and insulating layer).

Some Eu producers

TeMa Technologies & Materials S.r.l. - (IT)
SOILTEC - Greenfix - (DE)

Figure St07: Non-structural straw-clay bocks
Source: https://www.hgmatthews.com/lime-and-cob/natural-building-blocks/

Straw-Clay blocks

This material combines straw with a clay or soil mixture. The clay acts as a binding agent, creating a durable and insulating material that can be used for wall construction and as infill.

Applications: infill or wall construction

Some Eu producers

Claytec GmbH - (DE)
BCB - Beton Clay Blocks - (NL)
De Kleipot - (NL)

Straw

Lego Straw blocks

Inventors Ben Korman and partner Jay Ruskey at their company, Oryzatech, in Goleta (Santa Barbara County), have created **Stak Block**, an experimental Lego-like 12-by-12-by-24-inch building block made of dried rice straw. The straw is mixed with formaldehyde-free glue and tightly compressed in metal molds at temperatures around 300 degrees.
The blocks, mortised together without cement, are clamped together by a grid of threaded rebar inserted through their holes and bolted to the foundation and a top plate of wood.

Figure St08: Lego blocks from straw
Source: https://buildwellsource.org/materials/materials-natural-rural/straw-1/straw-blocks

Components

Prefabricate systems of components allow for a faster construction, cost efficiency and also design for assembly and disassembly (dry system). The continuous development of these techniques proves that straw bale systems are competitive in terms of price and performance (Evrard, 2012).

For components straw is usually combined with wood structures (because of their compatible proprieties). Their production process generally sees the construction of a structural wooden frame with a straw-bale infill, this can also have an additional reinforcement of vertical or horizontal rebar elements or mesh wiring to enhance structural strength. Subsequently, excess straw protruding from the wall is trimmed to create a smother surface on which finishing layer can be applied.
Exterior and interior finishes can utilize wood-based panel, renders and plasters to provide protection from exterior elements. One important aspect to consider is to guarantee consistency and energy efficiency, therefore these systems may require additional loose straw packed in wall cavities and/or applied into finishing layers to properly seal and prevent air leaks and also thermal bridges.

Wall component

Prefabricated wall components made with straw typically consist of compressed straw panels or blocks that are designed to be assembled into walls with a wooden structure. These panels or blocks are created by tightly compressing straw fibers and at times these are mixed with binder materials such as clay to form a solid and sturdy structure.
The resulting prefabricated components can be easily transported and quickly assembled on-site.

Some EU producers

EcoCocoon - (SK)
Paille-tech - (FR)
ModCell - (UK)
Okambuva.coop - (ES)
Strawtec Group - (DE)
Strawbuild Ltd - (UK)

Figure St09: Ecocoon prefabricated wall system. 01 6-10 cm fire board, 02 Airtight membrane 03 Timber straw prefabricated panel
Source: https://ecococon.eu/the-panel-system

EcoCocon

(Bratislava, Slovakia) – Prefabricated wall component

WALL component
INSULATION COEFFICIENT: U = 0.12 W/m²K
FIRE RESISTANCE: 120 min
DENSITY OF PRESSED STRAW: 110 kg/m³
AIRBORNE SOUND INSULATION: 54 dB
Exterior: The incorporation of a wood fiber layer contributes to meeting the Passive House standard in colder climates. An airtight, diffusion-open membrane effectively hampers heat loss while facilitating humidity transfer.
Panel: The insulation consists of straw, manufactured through multidirectional press technology, supported by a load-bearing twin stud frame sourced sustainably from forests. The dimensions are customizable to seamlessly integrate with any architectural design, featuring a uniform, level surface. The standard thickness is 40 cm.
Interior: The interior is certified and equipped with a humidity-regulating interior clay plaster. It harmonizes well with a range of standard interior finishes, ensuring adaptability and compatibility.

ecococon.eu

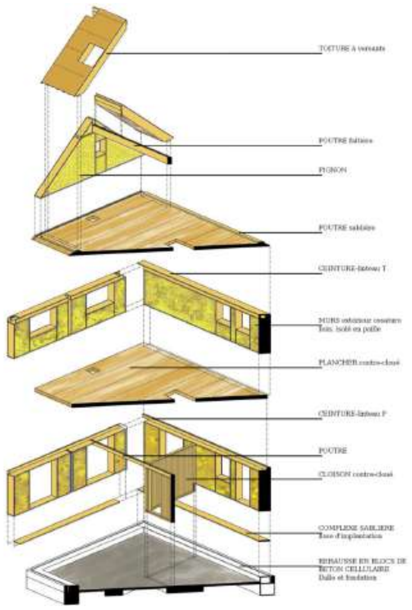


Figure St10-11: Baille tech - systems
Source: https://www.pailletech.be/systeme-constructif/elements-constructifs/

Paille-Tech

Paille-Tech is a Belgium based company that provides prefabricated components of exterior walls, slabs and roof, both flat and thatched.

Exterior wall: The wooden frame in Douglas fir (untreated class III) is insulated with straw bales and braced by an “agepan” type panel, which also serves as a rain barrier (protection against water from the construction site) and which is open to steam (μ 11). On the inside, the 4 cm raw clay coating allows the integration of techniques (blocks and wire-pulling sheaths), provides fire protection (RF 90'), great inertia (heavy or semi-heavy building) and excellent hygrometric (even hygrothermal) regulation.
Floors - Solid wood tiles: With a span of up to 5.5m, Paille-Tech floor slabs accept heavy loads. It is notably possible to finish them with a raw earth screed in order to increase the inertia of the building. The low or high face, of a raw visual quality, can remain visible in order to reduce the costs linked to the finishes.
Roof component: The roof elements (flat or sloped) are made up of load-bearing rafters 46 cm high, insulated with straw bales. Assembled in the workshop, the boxes can reach dimensions of up to 2.6 m by 13 m. The exterior face is protected by a rainproof panel, open to steam (μ 11), in compressed wood fibre. The inner face is closed by a panel used as finishing layer.

pailletech.be

K - Case studies – good practices

Eco46 - Losanne - (CH)

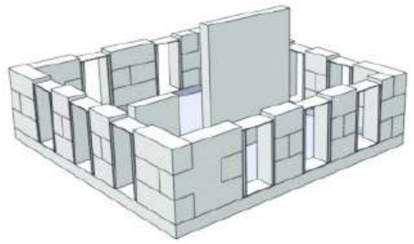


Figure St12-13-14: Eco46 - Lousanne (CH)
Source: https://www.researchgate.net/publication/289998552_Straw_bale_A_Waste_from_Agriculture_a_New_Construction_Material_for_Sustainable_Buildings

Adrien Chaussinand et al.'s work published in Energy Procedia 78 (2015)[3] provides a detailed description of the case study. The Eco46 is the first building in Europe that showcased the use of load baring structural straw bale (Nebraska technique - load-bearing straw-bale was selected to achieve the label performances required, with a straw wall of 80 cm).

The project concept originated from the "Strawd'laBalle" collectives drive to utilize straw as an innovative building material. Following the removal of the previous structure due to legal issues, the city of Lausanne initiated a feasibility study on straw in 2009. Encouraged by the favourable outcomes of this study, the municipal authorities proceeded with the construction of the straw bale building, with the intention of it serving as a new administrative facility for the Parks and Areas department. In line with the project specifications, the building was meticulously planned to accommodate seven workstations, two conference rooms (with seating for 16 and 6 individuals, respectively), a small restaurant area, and a kitchen. The primary objective was to adhere to the requirements of the Minergie-P-ECO® Swiss label[4].

The construction of the Eco46 building primarily utilized soil-based materials (including an adobe central wall layered with ground, lime and mud coating, and a vegetated roof), alongside wood sourced from the Lausanne vicinity (employed for the intermediate floor, beams, and structural components). Additionally, wheat straw was used for insulation in both the walls and roof.

https://www.lausanne.ch/ressources/diapos/nature/eco46/index.html

[3] Chaussinand, Adrien & Scartezzini, Jean-Louis & Nik, Vahid. (2015). Straw bale: A Waste from Agriculture, a New Construction Material for Sustainable Buildings. Energy Procedia. 78. 297-302. 10.1016/j.egypro.2015.11.646.

[4] https://www.minergie.com/

ViVihouse

Figure St15: Image of the Vivihouse project and the wall straw prefabricated wall panels
Source: https://www.vivihouse.cc/

The Vivihouse project, designed by architects Nikolas Kichler, Paul Adrian Schulz, Mikka Fürst, and Karina Stieldorf, was initiated in 2018 and successfully completed in 2022. It is situated in Vienna, Austria.

New European Bauhaus Prizes 2021, Award Finalist – category: Techniques, materials, and processes for construction and design

The Vivihouse is an innovative multi-storey construction system designed for mixed-use houses. It utilizes a modular timber frame structure and ecological materials like straw bales, timber frames, and lime and clay plasters for insulation. This approach emphasizes healthy living, low energy consumption, cost efficiency, and sustainability. The design's durability and adaptability allow for customization, disassembly, and relocation. The project encourages collaboration through workshops, combining traditional craftsmanship, digital production, and open-source principles. It started in Lower Austria in 2018 and has expanded to a three-story prototype in Vienna. The team plans to develop larger units, seeking input from ecological experts and users. Ongoing workshops will foster participation, aligning with the Vivihouse's commitment to sustainable building practices.

vivihouse.cc

Casa Quattro - (IT) - LCA Architects

Casa 4 project by LCA Achitects in the year 2020, is known as "the house of wood, cork, and straw". It is a sustainable private dwelling that embodies simplicity and connection with nature.

With its basic structure built from wood, insulation provided by rice straw and cork cladding panels printed in 3D by Technosugheri , and interior finishes featuring stone and oak wood, the house integrates harmoniously into the surrounding landscape of a small town of Magnano near Milan.

The design prioritizes a direct dialogue with nature, offering panoramic views of the sky, countryside, and adjacent acacia forest. Passive and active solar energy systems ensure self-sufficiency and minimal carbon emissions. By using simple materials and embracing a bio-ecological approach, Casa 4 showcases life-cycle thinking and efficiency.

Figure St19: Wall cork cladding - tiles
Source: http://www.lcarchitetti.com/proj/residential/casa-quattro-bioarchitettura-architetto-varese-milano-ticino-prefabbricata-in-legno-bioedilizia

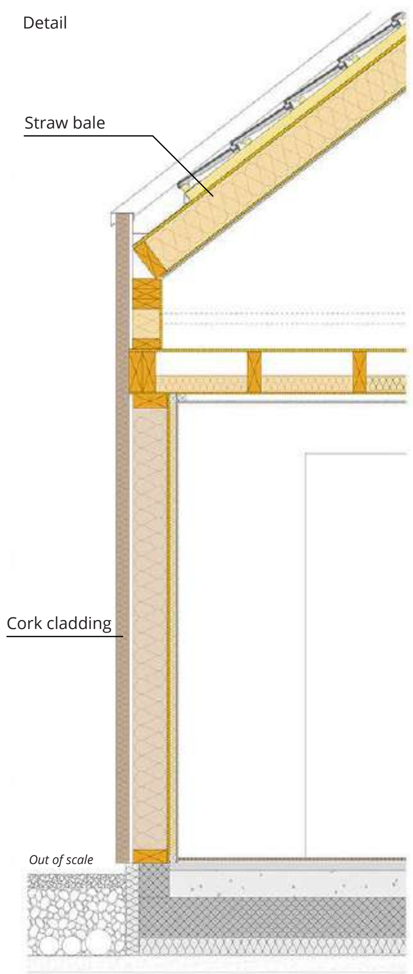


Figure St20-21-22: *Images by LCA Architetti - Casa Quattro*
Source: http://www.lcarchitetti.com/proj/residential/casa-quattro-bioarchitettura-architetto-varese-milano-ticino-prefabbricata-in-legno-bioedilizia

L - Limits to overcome

Based on the "STRAW CONSTRUCTION IN THE UK: Technical Guide First Edition 2022" report[5] specific barriers to the development of straw construction that remain are:

- Lack of resources was reported for promotion of the benefits and capabilities of straw construction.

- All the countries in the programme reported poor perception of straw construction, and an absence of confidence, knowledge, experience and training amongst clients, developers, planners, designers, inspectors, constructors and building users/ managers.

- Belgium, Netherlands and UK noted the need to develop similar regulatory support and professional guidance as that in France and Germany.

- The UK noted that scope for farmers and the agricultural sector to be engaged in the supply chain has not yet been realised, particularly in the context of farming diversity and the potential for circularity in construction and farming. Moreover, farmers prefer harvesting and shaping the straw in round bales, because handling is faster and more practical. Obviously, round bales, due to their shape, are not easily used in construction
- In the UK there is a lack of natural building content in the university course curricula, regional/local college skills training and in professional CPD training.

The limits to overcome in terms of both use and upscale of straw as a building material greatly rely on the need for code compliance and acceptance at a local, national and international level.

Building codes and regulations may not always explicitly cover straw as a construction material, making it challenging to obtain necessary permits and approvals. Engaging with local authorities, building professionals, and organizations specializing in straw construction can help navigate these challenges and establish a framework for compliance and thus elevating straw to its full potential.

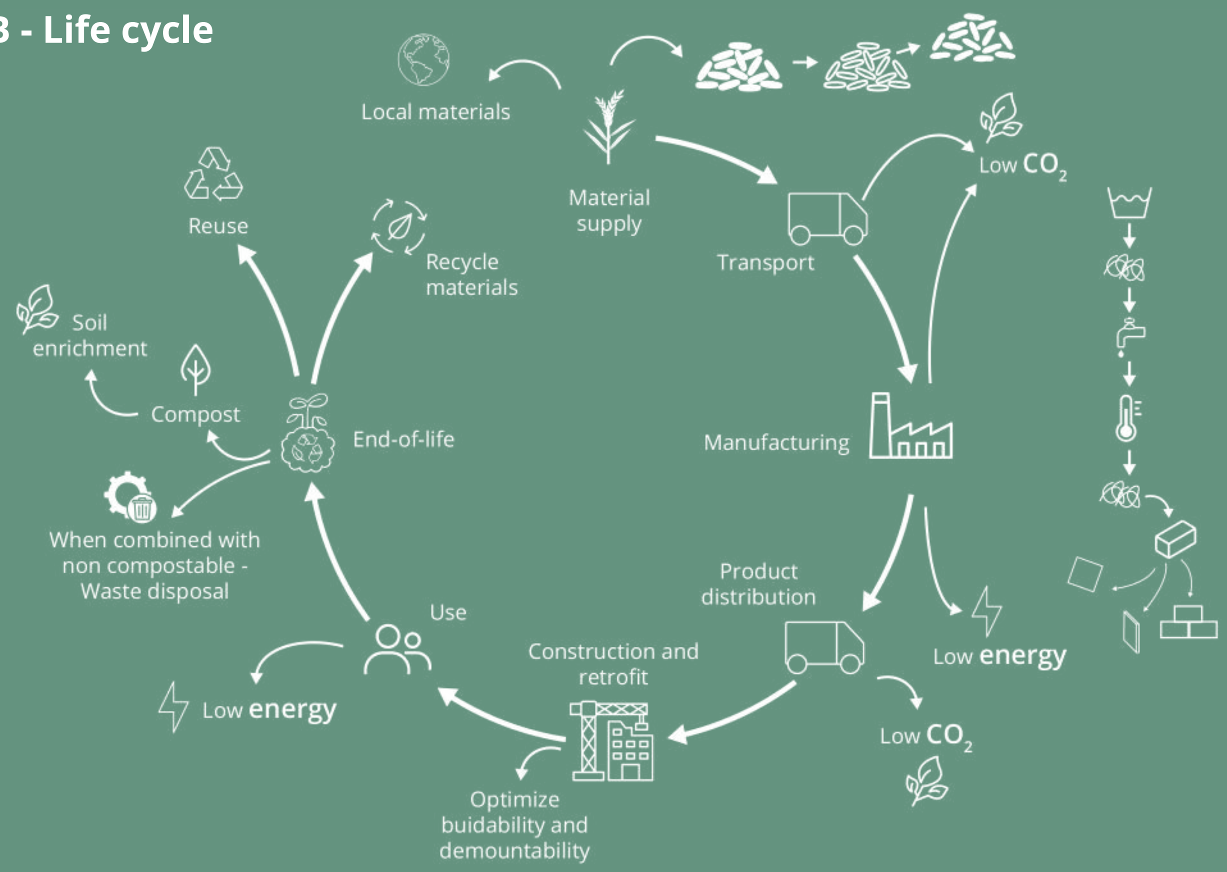
[5] Full document at: http://schoolofnaturalbuilding.co.uk/wp-content/uploads/2022/03/Technical-Guide-UK-Feb-2022-1.pdf

/
Husk

A - Watch points

- Use local and responsibly sourced raw material, allow for regeneration
- Low carbon energy in processing methods
- Low carbon transportation
- Optimise buildability and design to disassemble
- Re-use, Recycle and Re-purpose minimise raw material, maximise recycled content
- End-of-life - biodegradable - composting - re-purpose

B - Life cycle



C - Key points

Raw material resource

Virgin/primary resource	○
Recoverable resource	●
Recovered/secondary resource	●
Waste resource	●

Availability of raw material

●●●●●

Degree of skills required for resourcing raw material

●●●○○

Degree of prefabrication

●○○○

Awareness

●●○○○

Applications

Technological units	Technical elements	Products category	
vertical closures	external walls	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
		Cladding/shingles/tiles	●
top closures	roof	Cladding/tiles/shingles	●
		Panels/false ceiling	●
		thermo-acoustic insulation	●
horizontal closures	slabs	Flooring Tiles/Panels/boards	○
		thermo-acoustic insulation	●
partitions	vertical partitions	masonry elements	●
		Panels/boards	●
		thermo-acoustic insulation	●
	horizontal partitions	Florring Tiles/Panels/boards	○
		thermo-acoustic insulation	●

D - Raw material

Husk referrers to the outer protective layer of certain seeds or fruits. It is a rigid and often dry covering that surrounds the edible part of a seed or fruit. Husks serve as a form of protection for the seed, shielding it from environmental factors, pests, and other potential threats. Husks can vary in texture, thickness, and composition depending on the plant species. Example of husk can be rice husk, cotton seed hull, coconut husk, corn husk, coffee bean husk, hemp husk, wheat husk, cocoa been husk and many more.

Husk is typically deriving from processes of husking or de-hulling, which consists of separating the seed or fruit from the outer layer, therefore is considered to be a by-product of the food industry. When considering rice as a food resource, it is the third most produced commodity in the world with more than 769.9 million tons per year (FAO, 2018). The abundancy all over the world of this by-product hold a lot of potential for reuse and recycling that in recent years as gained a lot of interest. Husk find different applications: it can be processed into building materials, it can be used in horticulture or agriculture practices, it can be processed into animal feed and it can become biofuel (Babaso and Sharanagouda, 2017).

One of the most common types of husk that is being reused is rice husk. The rice husk constitutes the most superficial layer of the paddy rice, husk that encloses the caryopsis. It is obtained through the husking process of the rice and is light and voluminous, yellowish (when still attached to the grain) or brown (after husking) (Giaccone, 2020). The percentage of rice husk over paddy rice varies depending on the variety of rice, and can be between the 17–23% range by weight. The husk has a length of about 9 mm and a width of 1 mm. Rice husk is composed of 75–90% organic matter such as cellulose, lignin and mineral components, such as silica, alkalis, and trace elements (Kumar et al., 2012; Buratti et al., 2018). The content depends on rice variety, soil chemistry, climatic conditions, and also geographic localization of cultivation (Sarangi et al., 2009).

E - Cultivation and Harvesting

Cultivation and harvesting processes vary depending on the different origin of the husk. The raw material derives as mentioned above from the husking or dehulling, this separation is referred to as threshing, which is the process of removing the grains from the husks, often done using machines that mechanically separate the two. Following threshing, winnowing is carried out to separate the lighter husks from the heavier rice grains. This is typically done by tossing the mixture into the air, allowing the wind to blow away the lighter husk fragments. The separated rice husks are collected and usually stacked for further processing, depending on the intended use, the husks might undergo additional steps.

Figure Hk01: Rice husk
Source: https://www.eiriindia.org/blog/rice-husk-rice-agricultural-waste-how-to-prepare-project-report

Figure Hk02: Hemp husk
Source: https://www.designboom.com/

Figure Hk03: Corn husk
Source: https://www.carvedculture.com/blogs/articles/all-about-corn-husk

Figure Hk04: Coconut husk
Source: https://cocoutopia.com/2022/09/15/design-decision-with-bea-feitler-unstoppable/

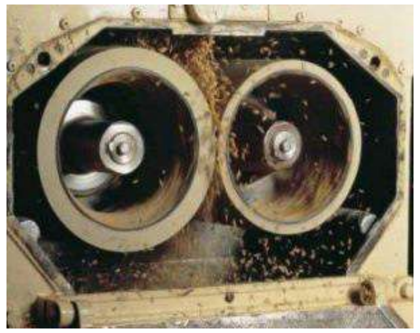


Figure Hk05: Rice dehusking
Source: www.wordpress.com, Ricehouse

F - Physical-mechanical properties

Properties vary based on type of seed or fruit, and their chemical composition. One of the most common uses of Husk is as building material is for insulation as it presents good thermal acoustic insulating properties due to its porous structure (Chiang et al., 2009). Some husks have the ability to absorb and release water (Chindaprasirt et al., 2007; Mansaray & Ghaly, 1998), which can make them useful for applications like moisture regulation. Considering that they consist of the hard and protective layer of seeds, they are typically a resistant material. When considering the chemical composition of rice husk, for example, it is a cellulose-based fibre that contains approximately 20% silica in amorphous form (Hu et al., 2008; Mansaray & Ghaly, 1998; Nair et al., 2008; Ndazi et al., 2007), making it suitable for application such as ash in blended cements rice husk ash.

G - Durability

Durability of husk depends on type and variety, as well as environmental conditions. Overall, considering its natural function of protection of the seed from pests and external environmental conditions, husk is typically resistant and durable. Yet, the longevity of husk materials could be impacted by elements like moisture, sunlight, temperature fluctuations, and microorganisms in the environment. As a result, husks that exhibit greater resistance to these factors might enjoy an extended lifespan.

H - End-of life and recyclability

Husk when left untreated is biodegradable and furthermore when considering for example rice husk and its composition of 75–90% organic matter (Kumar et al., 2012) when used as fertilizer it provides nutrients for the soil to improve not only productivity but also water use efficiency (Govindarao1980; Ebaid, et al., 2007; Badar and Qureshi, 2014).
When considering husk-based products, if not combined with non-compostable materials and binders, it is biodegradable and compostable.

I - Life cycle assessment

The utilization of husk in different applications can be considered as a good practice as the primary resource is considered a waste by-product and therefore reuse and recycling can create value and create a cascading utilization of the resource.

Considering that husk derives from agriculture processes, some consideration have to be made to the sustainability of cultivation practices, for example, land and water use, as well as use of fertilizes that can lead to soil and water pollution. Furthermore, the processing of husks into usable materials may involve energy-intensive processes, that could potentially offset some of the environmental benefits gained from using a renewable resource. Developing energy-efficient processing methods is essential to mitigate this concern. Another important aspect could be linked to carbon emissions of transportation and end-of-life disposal.

Another aspect to consider when using different types of husks, is the origin of the material. Some fruits and plants are specific to set locations and therefore the by-products should come from local supply chains in order not to increase environmental impact. For example, coconut is generally not cultivated in Europe, therefore the husk and products that derive from it should be evaluated when they consist of imported products. Types of husk that can be abundantly found in Europe can be among others, rice husk, hemp husk, corn husk, barley husk and wheat husk due to extensive cultivations in many different countries.

Most LCA studies have explored environmental impact resulting in processing of rice husk.

LCA data was obtained from the SimaPro software and references Rice husk – Rice husk meal, consumption mix, at feed compound plant/NL Economic 1 ton - 100 Compost - 1 kg Rice husk meal, consumption mix, at feed compound plant/NL Economic (of project Agri-footprint 5 - economic allocation).

This process describes the average consumption mix of rice husk meal in the Netherlands. Included activities are inputs of rice husk meal, a co-product of rice dry milling, and transport to a feed compound plant in the Netherlands. The Dutch average consumption mix of products has been estimated using trade information (import, export and production) from FAO statistics (FAOStat FAO, 2010).

GWP

Impact category	Unit	Total
Total	kg CO_2 eq.	**0.201**
Climate change - fossil	kg CO_2 eq.	0.055
Climate change - biogenic	kg CO_2 eq.	0.000
Climate change - CO2 uptake	kg CO_2 eq.	0.000
Climate change - land use and transformation	kg CO_2 eq.	0.146

GWP - IPCC 2013 GWP 100a (incl. CO2 uptake) V1.00 - Characterisation

Embodied energy

Impact category	Unit	Total
Total	MJ	**1.832**
Non renewable, fossil	MJ	1.809
Non renewable, nuclear	MJ	0.012
Non renewable, biomass	MJ	0.000
Renewable, biomass	MJ	0.000
Renewable, wind, solar, geothermic	MJ	0.000
Renewable, water	MJ	0.012

EE - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation

Impact category	Unit	Total
Climate change	kg CO2 eq	0.210
Ozone depletion	kg CFC11 eq	0.000
Ionising radiation	kBq U-235 eq	0.000
Photochemical ozone formation	kg NMVOC eq	0.002
Particulate matter	disease inc.	0.000
Human toxicity, non-cancer	CTUh	0.000
Human toxicity, cancer	CTUh	0.000
Acidification	mol H+ eq	0.003
Eutrophication, freshwater	kg P eq	0.000
Eutrophication, marine	kg N eq	0.001
Eutrophication, terrestrial	mol N eq	0.012
Ecotoxicity, freshwater	CTUe	13.127
Land use	Pt	3.037
Water use	m3 depriv.	0.729
Resource use, fossils	MJ	1.712
Resource use, minerals and metals	kg Sb eq	0.000
Climate change - Fossil	kg CO2 eq	0.149
Climate change - Biogenic	kg CO2 eq	0.061
Climate change - Land use and LU change	kg CO2 eq	0.000
Human toxicity, non-cancer - organics	CTUh	0.000
Human toxicity, non-cancer - inorganics	CTUh	0.000
Human toxicity, non-cancer - metals	CTUh	0.000
Human toxicity, cancer - organics	CTUh	0.000
Human toxicity, cancer - inorganics	CTUh	0.000
Human toxicity, cancer - metals	CTUh	0.000
Ecotoxicity, freshwater - organics	CTUe	12.968
Ecotoxicity, freshwater - inorganics	CTUe	0.088
Ecotoxicity, freshwater - metals	CTUe	0.072

EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation

J - Prefabricated production processes

Husk-s main application in the building sector are for insulation, in loose form or moulded into panel. Similarly to plant fibres and wool, husk can be combined or mixed within a matrix material to form composite material. For example, as an aggregate for bricks, like clay bricks, and also due to its composition, it can be added to high-performance concrete preparations as aggregate, making for a sustainable alternative while reducing its emissions into the atmosphere and improving it strength of the material. As husk is rich in silica, it is essential for the initiation of pozzolanic activity in concrete (Giaccone, 2020). Husks can also be used for interior design elements, such as wall coverings, decorative panels, and furniture.
In terms of prefabricated elements the ongoing research has resulted in different solutions and alternatives. One of the most explored uses of husk comprises rice husk.

Elements

Acoustic and Sound absorbing Panels

Husk can be processed and compressed with other binding agents into sound absorbing panels.

Figure Hk06: Hemp husk acoustic panels
Source: https://www.designboom.com/design/aotta-sound-absorbing-hemp-husks-panels-10-01-2018/

Applications: sound absorbing panels for wall and ceiling applications

Some EU and anon-EU producers

Aotta studio - (RU) - hemp husk
HexBix - (UK) - Wood and cocoa husk

Figure HK07: // Cornspan Corn husk panels - by Apilada Vorachart
Source: https://materialdistrict.com/material/cornspan/

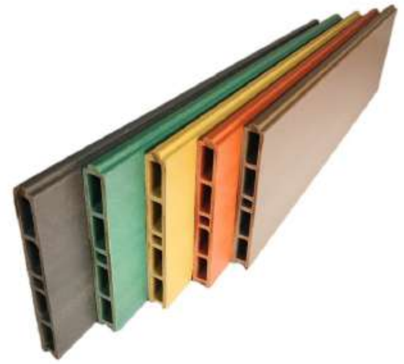


Figure Hk08: Coffee bean husk panels - by Woodpecker
Source: https://www.fastcompany.com/90604018/now-your-coffee-habit-can-help-build-houses

Panels

Husk panels are crafted from processed agricultural husks, such as rice, coconut husks, coffee husk, corn husk, which are combined other material and with binding agents, and subsequently moulded into different shapes, and dried to create lightweight alternative panels. The ongoing research is producing advancements and many different alternatives and solutions, considering the amount of waste all over the world, the potential for developing different products is very high and is gaining a lot of interest.

Applications: Husk panels find applications in various building components such as wall, roof, and ceiling panels, as well as in furniture, insulation boards, sound-absorbing panels, and decorative elements, offering sustainable and eco-friendly solutions for construction and interior design.

Figure Hk09: Rice husk, salt, mineral oils, panels - by Resysta (DE)
Source: https://materialdistrict.com

Some EU and anon-EU producers

Rice House - (IT) - Rice husk
Resysta -(DE) - Rice Husk -
Apilada Vorachart - (TH) - Corn husk (Cornspan)
NaturLoop AG - (CH) - Coconut husk - Cocoboard ©
Kedroplast - (RU) - Pine husk
Woodpecker - (CO) - Coffee husk panels

Figure Hk10: Coconut husk board - by NaturLoop AG
Source: https://materialdistrict.com

BIO-SIPs - (AU)

Julee Herdt and Kellen Schauermann have secured a patent for a pioneering construction system named BioSIPS (Bio-Structural Insulated Panels). These panels, also referred to as Bio-Structural Insulated Panels, possess structural capabilities and incorporate a blend of materials like wheat straw, rice husk, flax, hemp, bamboo, cork, palm kernel tree, straw bale, reeds, sheep's wool, wood chip, or pellets. These materials are combined with bio-based binders, resulting in robust panels suitable for diverse applications, including wall and ceiling panels.

Figure Hk11: Peanut shell panel
Source: https://materialdistrict.com

Bricks

Husk bricks are a notable innovation in sustainable construction, where agricultural by-products like rice husks are harnessed to create building materials. These bricks are manufactured through a process where husks are compressed and combined with other substances such as binding agents or clay, resulting in a malleable mixture that can be shaped into bricks.

There are different studies[1] that explore the properties of clay bricks mixed with husks. Another study by Damanhuri et al.[2] in 2020 explored the possibility of using rice husk ash as a partial substitution and has assessed the feasibility.

The ongoing research in this field holds a lot of potential but does not mirror the market, products are still limited.

Applications:

Some EU producers

Rice House - (IT) - Rice husk

Figure Hk12: Rice husk brick - by Rice House
Source: https://materialdistrict.com/article/a-house-made-of-rice/

[1] M.A. Rahman (1987), Properties of clay-sand-rice husk ash mixed bricks, International Journal of Cement Composites and Lightweight Concrete, Volume 9, Issue 2, Pages 105-108, ISSN0262-5075, https://doi.org/10.1016/0262-5075(87)90026-1

Gökhan Görhan, Osman Şimşek, (2013), Porous clay bricks manufactured with rice husks, Construction and Building Materials, Volume 40, Pages 390-396, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2012.09.110.

Kukuh Kurniawan D. Sungkono (2018). Characteristics Of Clay Tile With Rice Husk Ash On Absorption And Flexural Strength. Tunas Pembangunan University Kudus, Indonesia DOI 10.4108/eai.24-10-2018.2280589

[2] A.A.M. Damanhuri et al (2020) MECHANICAL PROPERTIES OF RICE HUSK ASH (RHA) BRICK AS PARTIAL REPLACEMENT OF CLAY, J. Phys.: Conf. Ser. 1529 042034, DOI: 10.1088/1742-6596/1529/4/042034/

Other composite elements

RIWOOD - (NL)

RIWOOD offers bio-based facade profiles and decking made from rice husk composite. While it possesses the inviting aesthetic of wood, this innovative solution does not present wood content. RIWOOD's rice husk composite terrace and facade cladding possesses heightened resistance to moisture, decay, and various forms of fungi and micro-organisms. It consists of 15% rice husk (from the food industry), 26% calcite (by-product of drinking water purification). 52% post-production recycling plastic (production waste window frame factory) and 7% process additives.

More information and other similar companies and products can be found at:

fiberplastbiobased.nl

Figure Hk13-14: Facade panel and flooring - by RIWOOD - (NL)
Source: https://www.fiberplastbiobased.nl/riwood/

K - Case studies / Good practices

Rice House - (IT)

The Italian start-up Rice House has explored the use of different bio-based architectural products by using waste generated from rice processing. The start-up was born in 2016 by the CEO Tiziana Monterisi and COO Alessio colombo in Biella - Italy, a natural context surrounded by rice fields.

Their ideas and products create a value chain for by-products of rice processing. Their offerings include insulation materials, panels, plasters, paint, cladding for ventilated façades, bricks, and even materials suitable for 3D printing made with rice straw and rice husk, among other natural materials. In fact, all their products are entirely natural, free from formaldehyde, and manufactured in Italy. These products deliver remarkable attributes such as efficient thermal insulation, fire resistance, durability, and effective acoustic insulation. Moreover, they demonstrate resilience against biological agents and mould. In addition to these benefits, these materials enhance indoor comfort, regulate humidity, and promote wall breathability.

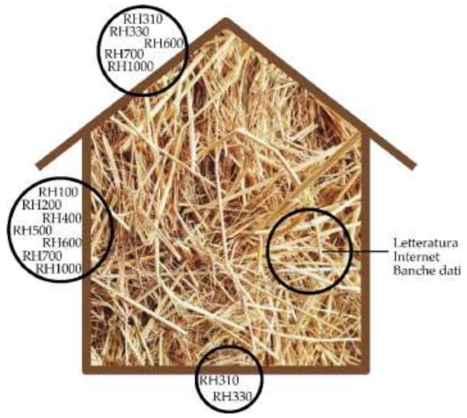


Figure Hk15: Ricehouse RH products are indicated for each part of the envelope that can be used.
Source: Giaccone. (2020). Da scarti agroalimentari a prodotti per l'architettura e il design: sviluppo di un pannello con lolla di riso = From agricultural wastes to products for architecture and design: the develop of a board with rice husk. Politecnico di Torino - p. 44

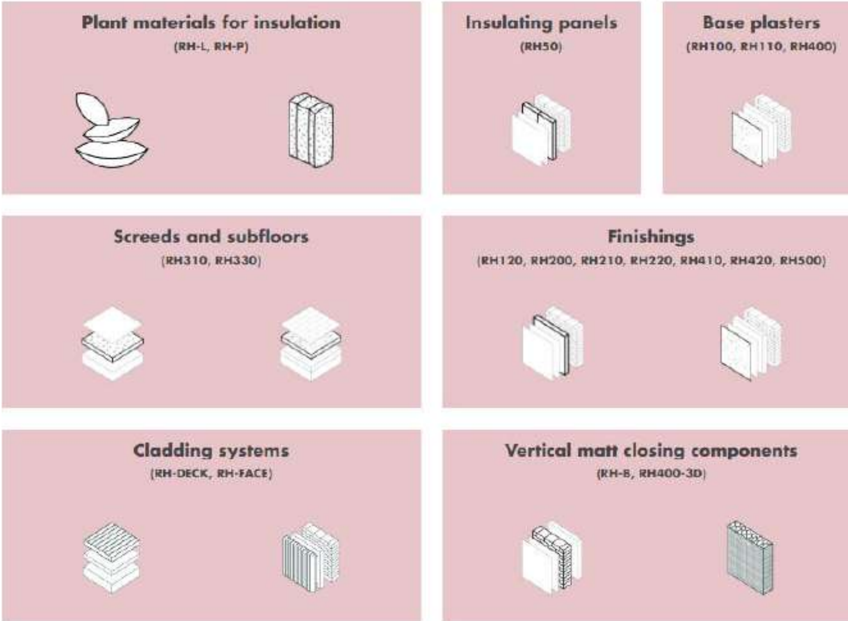


Figure Hk16: Ricehouse RH products
Source: https://www.ricehouse.it/

Rice House - (IT) - GAIA

Figure Hk17-18: Gaia project and 3D printing construction process - by Rice House
Source: https://www.ricehouse.it/

GAIA introduces a novel eco-sustainable architectural model. The project was developed in collaboration with WASP, it utilizes the 3D Crane WASP printer and natural materials sourced from the local landscape. The blend made of clay, ground sand, rice straw, and rice husk composes the RH400-3D product that build the walls. The concrete result is an energy-efficient dwelling that maintains a comfortable temperature throughout the year without the need for heating or air conditioning, offering a balanced living experience during both winter and summer. The project seamlessly integrates into an environmentally sustainable context, with the construction process taking just a few weeks due to the 45 cm-thick masonry. Within the wall there is rice husk insulation that further enhances the insulating properties of the 3D printed wall system.

Figure Hk019-20: Wall 3D printing construction process and rice husk infill - by Rice House
Source: https://www.ricehouse.it/

ricehouse.it

L - Limits to overcome

While husk-based building materials offer numerous benefits, there are challenges to overcome in their effective utilization.

One limitation that needs to be considered is the variable quality and consistency of husk sources, which can impact the material's performance and uniformity. Processing and binding husks into durable products require careful testing and optimization to ensure structural integrity and longevity, as of today the ongoing research does not mirror the market.

Additionally, regulations and certification standards might not yet be well-established for husk-based materials, this poses a limitation to up-scaling and widespread adoption.

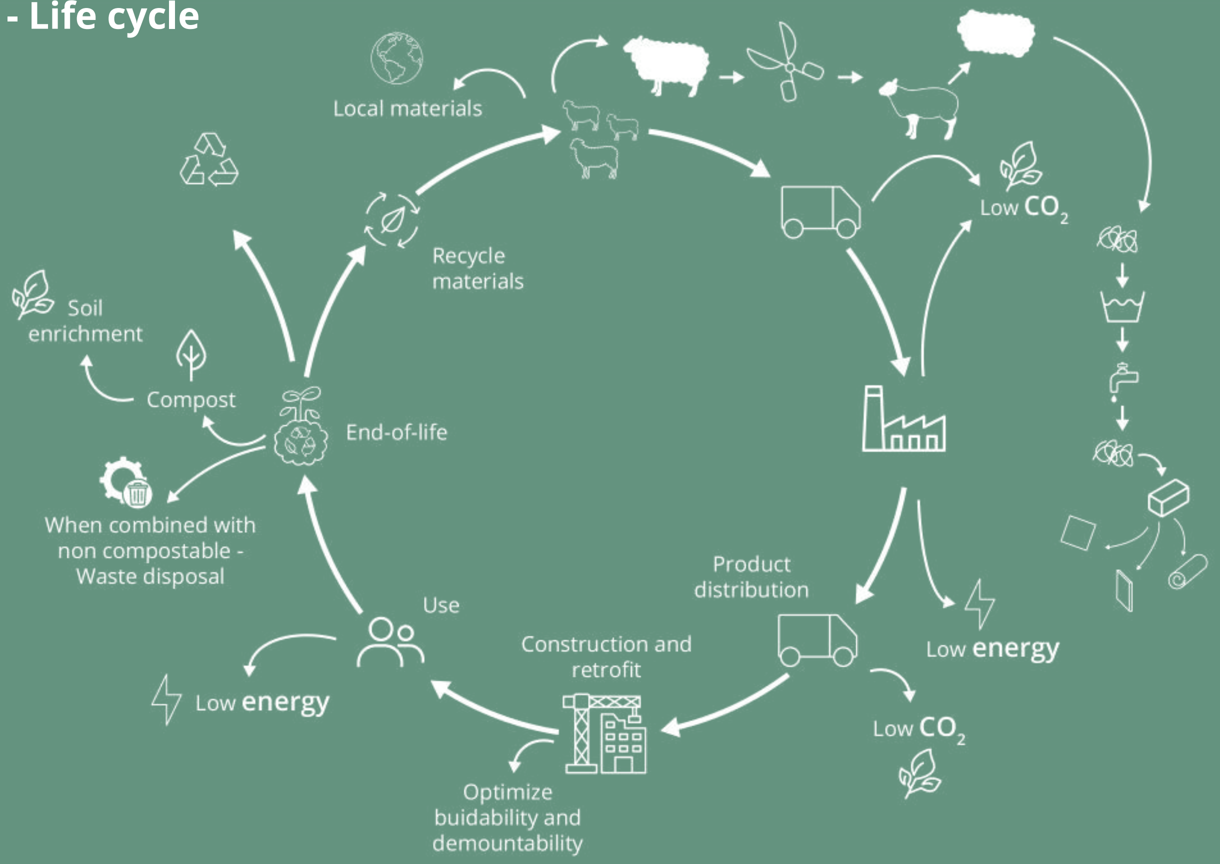
The availability of appropriate processing technologies and the need for skilled labour for specialized applications can also pose challenges. To overcome these limitations, extensive research, technological advancements, and collaboration between industries, researchers, and regulatory processes are essential to establish husk-based materials as a reliable and sustainable option in construction.

/
Wool

A - Watch points

- Use local and responsibly sourced raw material
- Low carbon energy in processing methods
- Low carbon transportation
- Optimise buildability and design to disassemble
- Re-use, Recycle and Re-purpose minimise raw material, maximise recycled content
- End-of-life - biodegradable - composting - re-purpose
- Use wool from animal cruelty free husbandry practices

B - Life cycle



C - Key points

Raw material resource

Virgin/primary resource	○
Recoverable resource	●
Recovered/secondary resource	●
Waste resource	●

Availability of raw material

●●●●○

Degree of skills required for resourcing raw material

●●●○○

Degree of prefabrication

●○○○

Awareness

●●●●○

Applications

Technological units	Technical elements	Products category	
vertical closures	external walls	masonry elements	○
		Panels/boards	○
		thermo-acoustic insulation	●
		Cladding/shingles/tiles	○
top closures	roof	Cladding/tiles/shingles	○
		Panels/false ceiling	○
		thermo-acoustic insulation	●
horizontal closures	slabs	Flooring Tiles/Panels/boards	○
		thermo-acoustic insulation	●
partitions	vertical partitions	masonry elements	○
		Panels/boards	○
		thermo-acoustic insulation	●
	horizontal partitions	Florring Tiles/Panels/boards	○
		thermo-acoustic insulation	●

D - Raw material

Sheep wool constitutes a natural fibre obtained through the shearing process of a sheep's fleece. The primary constituents of sheep wool consist of keratin protein fibres (approximately 60%), with moisture comprising about 15%, and fat accounting for 10%. Additionally, there is a presence of about 10% sheep sweat and approximately 5% impurities (Parlato et al., 2022).
Since ancient times, sheep's wool has been an excellent material for protection against the cold and damp weather, its use ranged from clothing to insulation for dwellings (Fassi and Maina, 2006). It can be considered a renewable raw material. Sheep wool is typically a by-product of the food industry, sheep for meat and milk production (Thiebat et al., 2015), or the textile industry, where the wool that does not meet quality requirements or is waste of the production process can be reused in other sectors. Traditionally, wool has played a substantial role in contributing to the economies of various producer and manufacturing countries (Umit Halis et al., 2020). The abundant supply of wool sheep leads to an oversupply on the world market: surplus wool is usually burnt or buried as fertiliser (Fassi and Maina, 2006; Thiebat et al., 2015). Wool generally comes from foreign countries outside the EU, Australia annually generates around 345 million kilograms of wool – roughly a quarter of the global wool production (The Woolmark Company, 2023). The European Union-28 countries hold the second-largest sheep population worldwide. In 2018, there were about 84 million sheep in this population (with some data gaps for smaller countries). The majority of these sheep were concentrated in the United Kingdom (26.8%), followed by Spain (18.6%), Romania (11.4%), Greece (10.3%), Italy (8.3%), France (8.2%), and smaller percentages in other countries (Eurostat, 2019).

Figure Wo01: Sheep animal
Source: https://www.agriwebb.com/blog/scanning-for-lambing-success/

E - Shearing and Harvesting

Wool's life cycle starts with the shearing processes, these consist of removing the fleece from the sheep. It's typically done using electric or manual shears, and it's important to ensure that the sheep is handled gently and safely during the process. Shearing is usually carried out by skilled individuals known as shearers. The goal is to remove the wool without harming the sheep and to gather high-quality, intact wool fibres (The Woolmark Company, 2023). During shearing, the fleece is removed in one piece from the sheep's body, including the wool from the back, sides, belly, and legs. The fleece is then rolled or folded and set aside for further processing. The next phases involve harvesting that comprise a series of steps to prepare the wool for various uses. After collecting the fleece, it is sorted to separate wool based on factors like fibre length, quality, and colour. Then, the wool goes through a washing process to remove dirt, grease, and other impurities with natural soaps or sodium carbonate, this process is referred to as scouring. In this stage lanolin by-product is collected and redirected for the cosmetic industry.

Figure Wo02: Shearing of sheep
Source: https://www.scienceabc.com/nature/animals/how-do-we-get-wool-from-sheep-and-how-it-is-converted-into-clothes.html

In order to protect the raw material from moths and other parasites, it can be processed with a pesticide treatment (Fassi and Maina, 2006). The initial phase concludes with a drying step, yielding untreated wool that can be processed further based on its intended final purpose. For textile applications, the untreated wool undergoes carding and combing to align the fibres and create a uniform texture. Once carded and combed, the wool is spun into yarn, which serves as the foundation for weaving or knitting fabrics employed in garments and various goods. This yarn can undergo additional treatment through dyeing, introducing colour and distinctiveness to the textiles.

In the context of producing insulation panels and felts, wool is carded to achieve thin layers that are layered, pressed, and then subjected to mechanical needling processes.

F - Physical-mechanical properties

Sheep wool stands out among natural fibres for its distinctive chemical and physical properties and proves to be well-suited for regulating micro-climatic conditions inside buildings (Zach et al., 2014; Rajabinejad, 2019). The indoor air quality (IAQ) and the well-being of humans and animals can be improved through the utilization of sheep wool as an insulation material (Parlato et al., 2022). Wool possesses the capability to counteract noxious substances (such as nitrogen dioxide, sulphur dioxide, toluene, and formaldehydes) through a chemical process called chemisorption (Parlato et al., 2022). Wool can effectively counteract harmful compounds, enhancing its environmental purification potential. Wool fibres have notable attributes like thermal and acoustic insulation. Being breathable, they can absorb and release moisture without compromising thermal efficiency, making them an ideal insulation choice (Korjenic, 2015). Comparative studies have evaluated the thermal and acoustic performance of sheep wool alongside other conventional insulation materials like polystyrene foam and glass wool. The findings indicated similar outcomes for all three materials, with a notable exception in the case of sheep wool, which demonstrated a considerable reduction in embodied energy (Zach et al., 2014; Parlato et al., 2022). The characteristics such as fineness, as well as the physical, mechanical, and chemical properties, can vary based on factors such as sheep variety (including age and location of breeding) and the specific part of the sheep from which the fibres were derived (Umit Halis et al., 2020).
Wool fibres show a stronger resistance to flames, particularly more than cellulosic fibres and comparable with synthetic fibres. If wool fibres come into contact with fire, they tend to char easily. But once the charred part is removed, the fibres look undamaged (Umit Halis et al., 2020).
Wool seams to have lower tensile strength but higher elongation at break when compared to other natural fibres making it more ductile and suited also for reinforcement for composite materials (Parlato et al., 2022).

G - Durability

Wool presents good natural resistance against microbial deterioration due to its keratin structure. Yet, in hydrophilic conditions, microorganisms can gradually degrade wool, leading to a weight loss of up to 33% over three months (Arshad and Mujahid, 2014). Enzymes such as proteases, esterases, and lipases are attracted to wool's keratin structure. They contribute in breaking down peptide linkages in the fibres (Cardamone, 2001). Therefore, when conditions are favourable, microbial growth on wool can cause biodegradation (Gochel et al., 1992). When considering waste wool, microbial attack is facilitated by broken fibres, exposing inner structural elements to enzymatic digestion. (Gupta et al., 2012).

H - End-of life and recyclability

Eco-friendly microbial degradation methods for wool waste offer an encouraging avenue for waste management (Sharma et al., 2019). Unfortunately, despite its features of biodegradability, wool waste is increasingly becoming a problem as it is considered a solid waste with a complex and difficult disposal management (Parlato et al., 2022). At the European level, the management of wool waste is governed by EC Regulation 1069 (2009) and EU Regulation 142 (2011). These regulations categorize wool as a low-risk waste, falling under category 3 of animal by-products (ABPs). Specific protocols are outlined within these regulations for the handling, treatment, disposal, and transportation of category 3 ABPs. In instances where raw wool has not been washed or disinfected, it is prohibited from burial or burning without a permit. Instead, it must be promptly disposed of through specialized incineration or landfilling facilities (Parlato, 2022) [Thiebat, 2014]. However, wool, in most cases is improperly disposed, it is buried and burned resulting in pollution on soil and air (Thiebat et al., 2015).
Among other livestock waste, sheep wool because of its mechanical and physical properties, is gaining attention in the building sector (Parlato, 2020). The advantages of an unconventional possible use of wool waste as natural, renewable, and biodegradable fibre in building sector, also results in reduction of CO_2 emissions and environmental pollution when considered as an alternative to more impactful materials. That being said, a sustainable reuse process of wastes or by-products has to start with accurate disposal management (Parlato 2022).

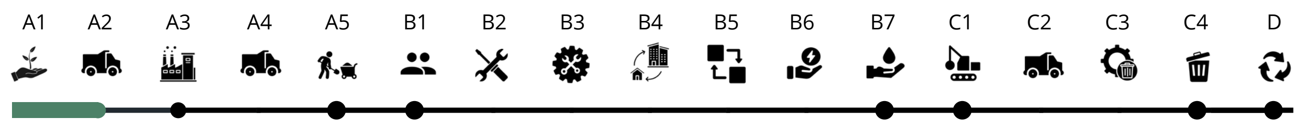
I - Life cycle assessment

Considering that wool production is inseparable from sheep breeding, the environmental impact of the production process has to consider several aspects (e.g land use for grazing or methane emissions). Therefore breeding has to be controlled and regulated to allow for a sustainable supply chain of the raw material. The use of wool as a building material has been assessed in different studies (Bosia et al., 2011; Giordano et al., 2011; Zach et al., 2010; Bosia et al., 2015; Rubino et al., 2021) and its overall environmental impact has demonstrated to be low. However, in order to ensure its eco-compatibility during its whole life cycle the stages of material supply, transport, end of life must be carefully considered (Thiebat et al., 2015).

Considering that most of the raw wool used in the building industry derives from waste of the sheep husbandry, LCA data was obtained from the software SimaPro and references to Sheep for slaughtering, live weight {RoW}| sheep production, for wool | Cut-off, U 1 kg 100 Compost Agricultural\Animal production\Ovine\Transformation.

Included activities start: This activity represents the expenditures and emissions of the husbandry of 1 sheep during 1 year. It includes the processes and inputs of sheep husbandry on pasture land (20% intensive and 80% extensive pasture land). Inputs of fertilisers, feedstuffs, pesticides and irrigation are considered.

Included activities end: Machine infrastructure and a shed for machine sheltering and shearing is included. The direct emissions on the field are also included. The system boundary is at the farm gate. The products of sheep husbandry are wool and sheep live weight. All further processes after the farm gate like transport to the slaughterhouse, slaughtering, cooling, etc. are excluded.



GWP

Impact category	Unit	Total
Total	kg CO_2 eq.	**22.760**
Climate change - fossil	kg CO_2 eq.	7.279
Climate change - biogenic	kg CO_2 eq.	18.841
Climate change - CO_2 uptake	kg CO_2 eq.	-6.656
Climate change - land use and transformation	kg CO_2 eq.	3.295

GWP - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 - Characterisation

Embodied energy

Impact category	Unit	Total
Total	MJ	**126.181**
Non renewable, fossil	MJ	19.636
Non renewable, nuclear	MJ	0.687
Non renewable, biomass	MJ	23.776
Renewable, biomass	MJ	81.384
Renewable, wind, solar, geothermic	MJ	0.121
Renewable, water	MJ	0.578

EE - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation

Impact category	Unit	Total
Climate change	kg CO2 eq	32.197
Ozone depletion	kg CFC11 eq	0.000
Ionising radiation	kBq U-235 eq	0.075
Photochemical ozone formation	kg NMVOC eq	0.023
Particulate matter	disease inc.	0.000
Human toxicity, non-cancer	CTUh	0.000
Human toxicity, cancer	CTUh	0.000
Acidification	mol H+ eq	0.776
Eutrophication, freshwater	kg P eq	0.008
Eutrophication, marine	kg N eq	0.132
Eutrophication, terrestrial	mol N eq	3.450
Ecotoxicity, freshwater	CTUe	487.406
Land use	Pt	3475.442
Water use	m3 depriv.	5.819
Resource use, fossils	MJ	18.873
Resource use, minerals and metals	kg Sb eq	0.000
Climate change - Fossil	kg CO2 eq	8.018
Climate change - Biogenic	kg CO2 eq	20.793
Climate change - Land use and LU change	kg CO2 eq	3.385
Human toxicity, non-cancer - organics	CTUh	0.000
Human toxicity, non-cancer - inorganics	CTUh	0.000
Human toxicity, non-cancer - metals	CTUh	0.000
Human toxicity, cancer - organics	CTUh	0.000
Human toxicity, cancer - inorganics	CTUh	0.000
Human toxicity, cancer - metals	CTUh	0.000
Ecotoxicity, freshwater - organics	CTUe	154.256
Ecotoxicity, freshwater - inorganics	CTUe	80.614
Ecotoxicity, freshwater - metals	CTUe	252.536

Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation

J - Prefabricated production processes

Wool's natural insulating properties make it a suitable choice for thermal and acoustic insulation in buildings. It helps regulate indoor temperatures. Wool fibres can also be combined with other natural materials to create bio-composite panels used for various applications in construction (similar concept of composite material reinforced with plant fibres).Prefabricated elements made of wool are mainly limited to insulation. There are panels, felts and acoustic sound absorbing panel.

Elements

Batts / Panels

Figure Wo03: Sheep wool batt by Thermafleece - (UK)
Source: https://thermafleece.com/

Wool bats for insulation are made from wool fibres that provide thermal and acoustic insulation in buildings and promoting indoor air quality. The production process involves the resource of sheep's wool, which is washed and treated with pesticides and then carded (combed) to obtain thin plies which, once overlapped to obtain the desired thicknesse, they are pressed and needled with a mechanical process that uses a large number of needles to dose the amount of fibre per surface area in order to obtain the panels. Subsequently, some products undergo a special process that consists of arranging the fibres vertically and attaching them to a thin grid of propylene that allows for greater dimensional stability and acts as a support (Fassi and Maina, 2006).

In order to provide more stiff panels and to lower environmental impact, some studies have experimented with the possibility of combination with other natural materials. For example in 2015 Thiebat et al[1]., developed the Cartonlana stiff panel that combined hemp and waste wool fibres (waste of local low quality wools) to obtain insulation stiff panels. The outcomes of the experimental analysis demonstrated that Cartonlana exhibited competitiveness in thermal conductivity and acoustic absorption, comparable to other insulation materials. Its practical implementation within a dry-constructed external wall reveals favourable workability and thermal insulation efficacy. Furthermore, Cartonlana proves suitable for indoor use in formaldehyde absorption. A key challenge for scaling up to industrial production, however, lies in the lack of resourcing regional wool collection.

[1] Bosia, Daniela & Savio, Lorenzo & Thiebat, Francesca & Patrucco, Alessia & Fantucci, Stefano & Piccablotto, Gabriele & Marino, Donatella. (2015). Sheep Wool for Sustainable Architecture. Energy Procedia. 78. 315-320. 10.1016/j.egypro.2015.11.650.

Figure Wo04: Cartonlana - hemp and waste wool insulation panel - by Thiebat et al. (2015)
Source: Bosia, Daniela & Savio, Lorenzo & Thiebat, Francesca & Patrucco, Alessia & Fantucci, Stefano & Piccablotto, Gabriele & Marino, Donatella. (2015). Sheep Wool for Sustainable Architecture. Energy Procedia. 78. 315-320. 10.1016/j.egypro.2015.11.650.

Applications: bats and panels can be utilized as various building applications for insulation, such as walls, ceilings, or roofs.

Some EU producers

Thermafleece - (UK) - EPD
Round Tower Lime - (IE)
Bausep - (DE)

Sound absorbing acoustic panels

Wool fibres can be used to create panels for wall and ceiling applications. Wool panels offer thermal and acoustic insulation properties while adding texture and visual interest to interior spaces. They can be used for decorative purposes and to improve the indoor environment. Typically the wool fibres are processes similarly to bats and they are combined with other material such as polyester to provide more support.

Applications: indoor wall and ceiling applications

Some Eu and non EU producers

Slalom ECOwool - (IT)
Tante Lotte - (UK)
Wollyshepherd - (UK)
Feltstudio - (U.S.A.)

Figure Wo05: ECOwall- acoustic wool panels
Source: https://materialdistrict.com/material/ecowall-wool/

Sheep wool as reinforced fibre for building components

Different studies have explored the potential use of wool fibre as reinforcement of building components. Similarly to plant fibres, the possible use of sheep wool inside different composite matrixe, such as unfired clay adobe or cement mortar.

For example in 2018 Mobili et al.[2], explored the production of masonry system based on unfired clay sandwich panels. Prefabricated panels combined the use of clay soil, water, calcium alginate and sheep wool fibres. The inclusion of sheep wool aimed to enhance the panel's ability to withstand compression, bending, and shearing forces, while also mitigating shrinkage. Additionally, sheep wool played a role in absorbing water vapor.

Another study by Fantilli et al.[3] examined the use of wool as mortar fibre-reinforcement. In detail, they tested small cement beams reinforced by untreated wool.

Statuto et al.[4] explored and performed compression tests on two different types of reinforced adobe clay, one mixed with 3% by weight of sheep wool and one with 3% by weight of wheat straw. Analysis confirmed that he compressive strength of adobe bricks reinforced by sheep wool fibre was considerably higher than of those with wheat straw.

Unfortunately, the research that is being carried through does not reflect what is available on the market.

[2] Mobili, S., Galán-Marín, C., & Rivera-Gómez, C. (2018). A New Affordable Masonry System Based on Unfired Clay Sandwich Panel. The Economy, Sustainable Development, and Energy International Conference. MDPI. Retrieved from http://dx.doi.org/10.3390/proceedings2221378

[3] Fantilli, A.P.; Sicardi, S.; Dotti, F. The use of wool as fiber-reinforcement in cement-based mortar. Constr. Build. Mater. 2017, 139, 562–569.

[4] Statuto, D.; Sica, C.; Picuno, P. Experimental Development of Clay Bricks Reinforced with Agricultural by-Products. Sustainable Farming-SFARM View Project Mediterranean Technology Led Incubator Co-Operation-MEDI-CUBE View Project. 2018. Available online: http://atae.agr.hr/46th_ATAE_proceedings.pdf

K - Case studies / Good practices

Architecture workshop with AIT and IWTO - (NZ)

Figure Wo06: Book cover - "Architecture workshop with AIT and IWTO in New Zealand: Wool in architecture and Interio Design"
Source: Academia.edu

In May 2010, the IWTO (International Wool Textile Organization) executive met with a number of prominent architects in New Zealand and organized a workshop with a group of worldwide leading architects to demonstrate at grassroots level the benefits and potential of the use of wool in architecture.
The group was taught about different uses and properties of wool in architecture and interior design and was left to experiment and brainstorm to show new approaches for the use of this natural material. The ideas had be directed towards sustainability and market-ready ideas. The theme chosen involved the project of an hotel, because it comprises a large number of subtopics (housing, public areas, temporary working...). The 12 architects had to focus on one of five themes: wool on the exterior facade, on the interior facade, in guest rooms, in the shop area, and lastly in the office and dining area.

The results showcased different creative possibilities for this natural material and most importantly taught the architects of the variety of uses it can have. While this workshop was organized many years ago, it still represents a good practice as it involved mainly teaching and changing perspective of how this material is perceived in order to showcase and possible convince how much value and potential it has also in modern architecture. The results of the workshop can be found in the book publication "Architecture workshop with AIT and IWTO in New Zealand: Wool in architecture and Interior design".

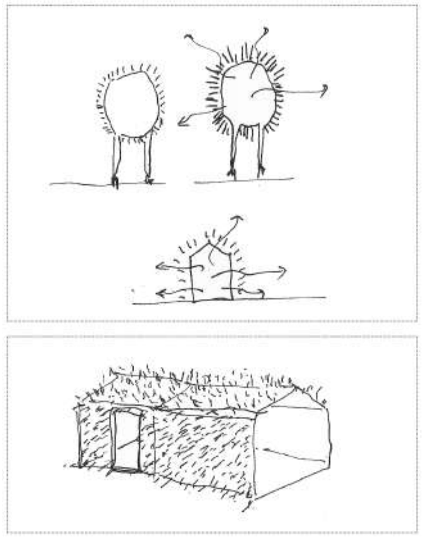


Figure Wo07: Solution by Manuel Bailo Esteve - (ES)
Source: Architecture workshop with AIT and IWTO in New Zealand: Wool in architecture and Interio Design (2011), pp. 64

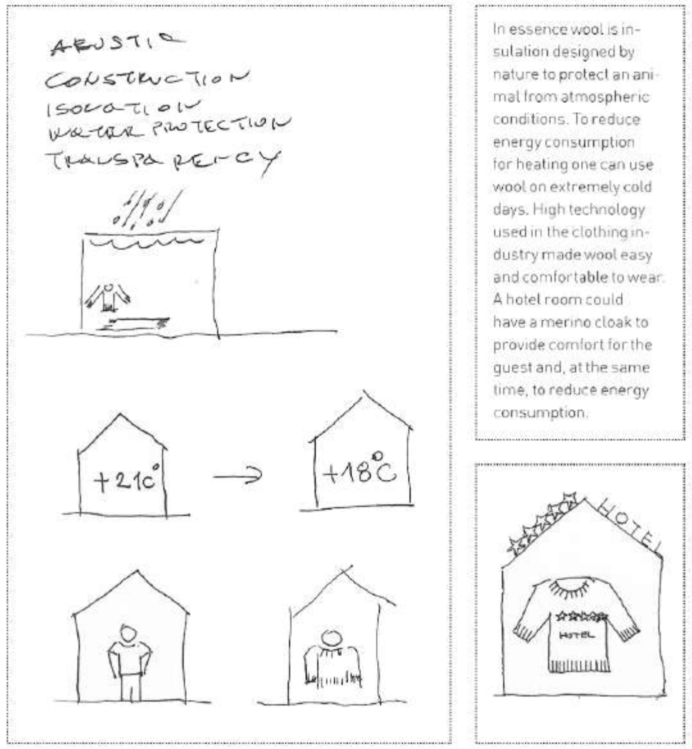


Figure Wo08: Solution by Arch. Branimir Medic - (NL)
Source: Architecture workshop with AIT and IWTO in New Zealand: Wool in architecture and Interio Design (2011), pp. 101.

The wool House Pavilion - AUW - architectural festival Hello wood (2018)

Figure Wo09-10: Wool House Pavilion by AUW
Source: https://www.dezeen.com/2018/08/23/auw-wool-house-architecture-uncomfortable-workshop-hungary/

The Wool House pavilion was constructed by Architecture Uncomfortable Workshop (AUW) for the annual architectural festival, Hello Wood, situated close to Lake Balaton in Hungary. Drawn to spaces intended for solitary occupancy, the architects based in Budapest opted to develop a construction that would offer individual festival attendees a brief respite from the commotion and gatherings. The project is characterized by the use different materials, the wooden foundation, tin roof, and fleece-covered exterior. The space is intended to encourage a "therapy session with themselves".

The pavilion's wooden frame has been densely packed with wool bundles, providing insulation against external sounds. The tin roof was prefabricated and manually positioned on top of the structure.

The choice of the wool cladding is both for insulation purposes, but also to bring warmth to the space. The project presents a sensory experience bringing a already known and comforting material as the main character.

Figure Wo11: Wool House Pavilion by AUW - inside space
Source: https://www.dezeen.com/2018/08/23/auw-wool-house-architecture-uncomfortable-workshop-hungary/

L - Limits to overcome

The use and recycling of wool for uses in the building industry holds a lot of potential however, some considerations have to be made.

A lot of products, specifically insulation felt and panels, are often combined with other materials such as propylene increase environmental impact, and if not separable make the products no longer compostable and biodegradable. In order to prevent this, solutions that combine different bio/based and natural material should be preferred.

Furthermore, the management of wool waste, and disposal seem to be an important issue that needs to be assessed. The waste wool from the food industry and the textile industry hold a lot of potential to be recycled but, a sustainable reuse process of wastes or by-products has to start with accurate disposal management and as of today disposal seams to occur in a lot of cases it is buried or burned, and improperly disposed causing impact on soil and air pollution.

Another issue concerns the cleaning, treatment and drying of wool so that it can be used for the production of building components. This is usually done through specific plants and machinery, usually used on a large scale in territories where there is a production of high quality wool, oriented towards the textile market. Where this production chain is missing, the treatment and drying process can be difficult and costly, both in economic terms and in terms of environmental impact (Savio et al., 2018).

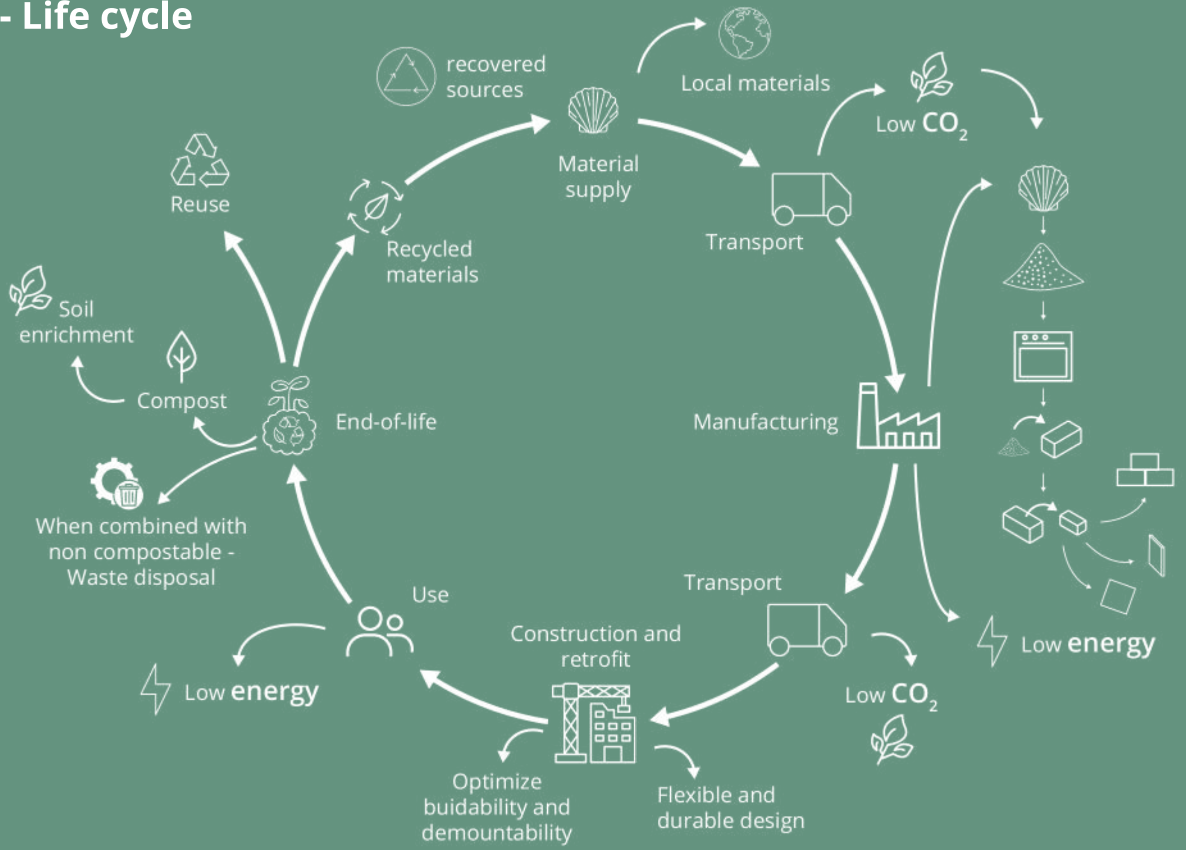
As for wool elements and products, further attention and solutions need to be explored to lower environmental impact during the whole-life-cycle, specifically the sourcing of the raw wool, the transportation and the end-of-life.

/
Seashells

A - Watch points

- Use local and recycled raw materials
- Low carbon energy in processing methods
- Low carbon transportation
- Optimise buildability and design to disassemble
- End-of-life - biodegradable - re-purpose - reuse

B - Life cycle



C - Key points

Raw material resource

Resource	
Virgin/primary resource	○
Recoverable resource	●
Recovered/secondary resource	●
Waste resource	●

Availability of raw material

●●●●○

Degree of skills required for resourcing raw material

●●●●○

Degree of prefabrication

●○○○○

Awareness

●●○○○

Applications

Technological units	Technical elements	Products category	
vertical closures	external walls	masonry elements	●
		Panels/boards	○
		thermo-acoustic insulation	○
		Cladding/shingles/tiles	●
top closures	roof	Cladding/tiles/shingles	●
		Panels/false ceiling	○
		thermo-acoustic insulation	○
horizontal closures	slabs	Flooring Tiles/Panels/boards	●
		thermo-acoustic insulation	○
partitions	vertical partitions	masonry elements	○
		Panels/boards	●
		thermo-acoustic insulation	○
	horizontal partitions	Florring Tiles/Panels/boards	●
		thermo-acoustic insulation	○

D - Raw material

Figure Ss01: Oyster collection from acquaculter and food industries waste
Source: https://www.dezeen.com/2020/08/28/sea-stone-newtab-22-design-shells-materials/

The term "seashell" refers to the hard outer covering of marine molluscs like snails, bivalves, and chitons. These shells provide protection and support to the creatures. Molluscs belong to a large group of invertebrate animals that includes clams, snails, mussels, and oysters. These shells are mainly made of calcium carbonate produced by the mollusc's mantle, a skin-like tissue on its body. Seashells are typically composed of multiple layers with distinct micro-structures, each having different mechanical properties. While various parts of the mantle create different shell layers, growth happens gradually only at the edge of the shell. Some shells, like those of bivalves, and cephalopods such as *Nautilus* and *Spirula*, feature a unique inner layer called nacre or mother-of-pearl (Britannica, 2023).

Seashell waste has been found by different studies to possess a chemical composition comparable to that of limestone, a crucial component used in the production of Portland limestone cement (Ong and Kassim, 2019). With a calcium carbonate ($CaCO_3$) content exceeding 90%, seashells can be considered as a potential source of calcium oxide when calcined and finely ground. Hence, seashells can be used as potential replacements for limestone in cement production (Ong and Kassim, 2019; Wang et al., 2019; Soltanzadeh et al., 2018).
Seashells have been historically utilized in architecture as a source of lime for mortar production, as decorative elements in shell mosaics and inlay, as ornamental features in architectural designs, and as roofing materials, showcasing their functional significance in coastal and maritime cultures particularly in regions where limestone deposits are scarce (Local Works Studio, 2019).

E - Cultivation and Harvesting

Seashells are not typically cultivated like crops, rather, they are naturally formed by marine molluscs as a part of their life processes. However, today the process of collecting seashells, or harvesting them, involves different methods and practices such as capture production and aquaculture production. Aquaculture pertains to the cultivation of aquatic organisms like fish, molluscs, crustaceans, and aquatic plants. Capture production, on the other hand, encompasses the quantity of wild fish and crustaceans caught, covering all catches gathered for commercial, industrial, recreational, and subsistence purposes (WDI, 2022). Today resources depend primarily from aquaculture. From 2000 to 2019, the overall production of fisheries and aquaculture around the world grew by 41%, reaching 178 million tons in 2019. This represents an expansion of 52 million tons compared to the initial figures in 2000 (FAO, 2021).
Mussel cultivation in aquaculture combines traditional methods with modern techniques (Tamburini et al., 2020). The shift towards efficiency began in the 1980s with suspended long-line systems (Maffei et al., 2011).

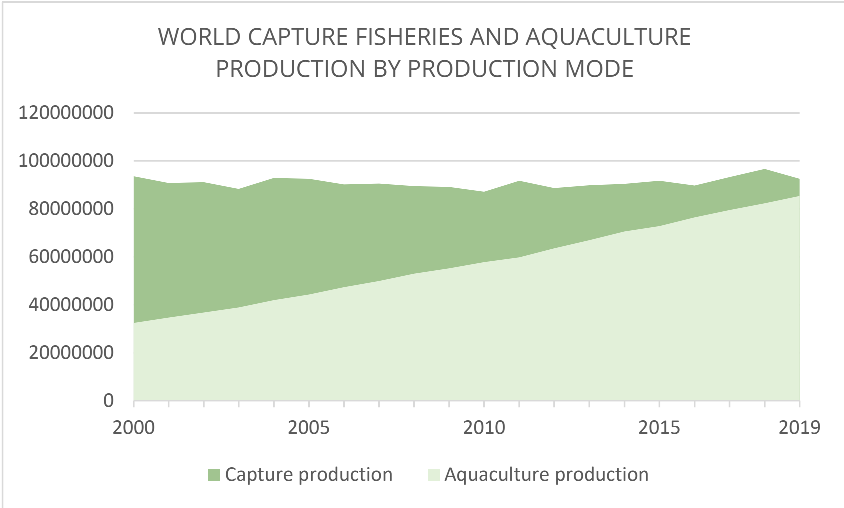


Figure Ss02: World capture fisheries and aquaculture production by production mode
Source: FishStat Note: Excludes aquatic mammals, crocodiles, alligators and caimans, pearls and shells, corals, sponges, seaweeds and other aquatic plants. Percentages on the figure indicate the shares in the total; they may not tally due to rounding https://doi.org/10.4060/cb4477en-fig31

Figure Ss03: Mussel aquaculture
Source: https://www.greatitalianfood-trade.it/en/progress/mussels-and-other-mussels-aquaculture-that-sequester-carbon/

Figure Ss04: Capture production
Source: https://www.ecomagazine.com/

The process starts by collecting wild mussel seeds in autumn, attaching them to infrastructure using strong threads (Buck et al., 2010). Seeds are then placed in plastic mesh socks on working boats, which are hung on long-lines at sea depths of 2–3 meters. These long-lines consist of ropes and cables anchored with concrete blocks on the seabed. As mussels grow, they are periodically moved to optimize conditions. Harvesting occurs in late spring to early summer, followed by sorting and cleaning on barges. Mussels meeting size criteria are packaged for sale in respect to food regulation. Harvested mussels are sold directly or processed, packaged in bags.

F - Physical-mechanical properties

In the construction sector seashells present similar proprieties to those of limestone because of their compositions, in fact, as previously mentioned the chemical composition of seashells of calcium carbonate ($CaCO_3$) content exceeding 90% (Ong and Kassim, 2019; Wang et al., 2019; Soltanzadeh et al., 2018), making them a potential replacement in cement production. To this end crushed and heat-treated mollusc shells can serve as additives in cement as filling material. Similarly, these shells can be employed as substitutes for traditional aggregates in concrete, like river sand (Topić Popović et al., 2023).
Exploring the utilization of discarded mollusc shells as substitutes for traditional concrete and mortar components has garnered interest as a promising alternative (El Biriane et al., 2020

and Mo at al., 2018). To assess the feasibility of using bivalves' shells for calcitic lime production, Ferraz et al. conducted a study in 2018 characterizing shells from eight distinct bivalve species based on their mineralogical, chemical, and thermal attributes, comparing them to commercial limestone as a benchmark. Their findings revealed that scallop and oyster shells are primarily composed of calcite, akin to the reference limestone, while mussel shells predominantly contain calcite.

In the study *Mechanical properties of seashell concrete*[1] Monita et al. through experimentation seashells (ground cockle) were utilized in concrete production as cement substitution. The study found that when cement was replaced with ground seashells, the strength of the resulting seashell concrete was lower in compression compared to regular concrete. However, the seashell concrete showed higher strength in tension and bending than the regular concrete. As the concrete aged, the Young's Modulus of Elasticity in seashell concrete increased. In summary, concrete with ground seashells had better tensile properties but lower compressive strength and elasticity compared to regular concrete. This utilization of seashells is still to be further studied and analysed in order to see an upscaled use.

[1] Full article at: https://doi.org/10.1016/j.proeng.2015.11.127

G - Durability

Seashell are very durable and exhibit strength and a capacity to withstand fractures due to the combination of calcium carbonate with proteins. These proteins function as binding agents, similar to bricks in a wall, reinforcing the material's strength and occasionally even its toughness (Eichhorn, 2010). In the study Durability and mechanical properties of seashell partially-replaced cement Bassman et al. found that, because seashells primarily originate from marine environments, when utilized in concrete production, they suggest a potential to exhibit greater resilience to the salt content of seawater compared to conventional concrete. This prompts an exploration into the durability of concrete formulated with seashell cement, which is assessed under conditions of sulphate attack and alkali attack. The study found that concrete's durability when utilizing a 5% seashell replacement for cement remains nearly equivalent to the standard in terms of resistance against sulphate and alkaline attacks. Consequently, concrete incorporating a 5% seashell content could potentially provide durability comparable to regular concrete in constructions exposed to these specific types of assaults.

H - End-of life and recyclability

Shells consist predominantly of chemically stable calcium carbonate ($CaCO_3$) and therefore, the decomposition does not occur naturally. Their thermal decomposition demands extremely high temperatures exceeding 1000°C, leading to substantial energy consumption and frequent greenhouse gas emissions

(Kobatake, 2019). As a result, the management and disposal of waste shells can emerge as significant operational and financial challenges.

Within the realm of fisheries and aquaculture, it is estimated that around 30–35% of the global harvest is lost or wasted annually (Summa et al., 2022). This is particularly prevalent during the consumption stage in high-income countries, whereas in low to middle-income countries, losses occur across the entire supply chain due to inadequate preservation infrastructure (Ishangulyyev et al., 2019). These losses can come from capture and harvest to post-production processes like landing, handling, storage, and distribution (Kruijssen et al., 2020).
Concerning molluscs, a substantial volume of pre- and post-consumer residues is generated, predominantly in the form of shells. These shells typically constitute approximately 65–90% of the live weight, depending on the species. Notably, for bivalves alone, more than 10 million tonnes of shells are produced annually, most of which are often disposed of in open areas or landfills (Khan et al., 2020) or at sea causing environmental concerns and alter marine ecosystems (Summa et al., 2022).

Given the significant waste generated in mollusc farming, seashells, which are by-products of this process, hold considerable untapped potential for diverse applications across various fields. However, their current utilization is still relatively limited.
According to the research paper *Trends and Opportunities of Bivalve Shells' Waste Valorisation in a Prospect of Circular Blue Bio-economy*[2] the literature present since 2000 in regards to valorisation of this by-product has highlighted various areas of value creation, which can be grouped into different categories based on the specific utilization sector:

[2] Full article at: https://doi.org/10.3390/resources11050048

-In agriculture as livestock feed supplements;
-In soils, water, and wastewater remediation;
-In substitution of mined $CaCO_3$ in mortar and concrete;
-In heterogeneous catalysis for biodiesel production;
-As biofilters

I - Life cycle assessment

When alive, mollusc cultivation can have various ecosystem benefits, such as controlling anthropogenic CO_2, natural coastal protection, and biodiversity conservation, the primary obstacle to its sustainable development lies in the management of shell waste at various stages, including harvesting, depuration, and post-consumption phases (Morris et al., 2019).
The disposal of shell waste presents a significant concern for those involved in shellfish production, distribution, and consumption, both in terms of practical implications and economic impact. The accumulation of discarded shells in various locations worldwide is a result of inadequate disposal practices, leading to environmental consequences such as unwanted

smells, area contamination from decomposing organic matter, and visual pollution caused by these shell piles (Jung et al., 2012).
As mollusc aquaculture is acknowledged for its environmentally friendly food production, enhancing the sustainability of the aquaculture sector through waste reduction or value extraction could have a substantial impact on ensuring food security in the coming decades (Morris et al., 2019).

As of today, Life cycle assessment has been done in regards to aquaculture bivalve shellfish production in different studies following various methods. In the paper *Life cycle assessment of aquaculture bivalve shellfish production — a critical review of methodological trends*[3] proposes an overview of all studies conducted, it takes into consideration 13 documents (85% of the studies were conducted in Europe). Regarding the type of species, mussels were the most studied (71% of the total sample of which 60% considered the Mediterranean mussel Mytilus galloprovincialis, and the remaining 40% the Blue mussel Mytilus edulis). Three documents studied oysters (Crassostrea gigas) and one studied clams (Ruditapes philippinarum) (Vélez-Henao, 2021). According to this paper the most recent study has been conducted in 2020 by Tamburini et al. and the results have been published in the paper *Sustainability of Mussel (Mytilus Galloprovincialis) Farming in the Po River Delta, Northern Italy, Based on a Life Cycle Assessment Approach*[4].

The LCA considers the relevance of Italian Mediterranean mussel (Mytilus galloprovincialis) aquaculture, from a cradle-to-gate perspective. The data about electricity, materials, infrastructure, and transportation were taken from the EcoinventTM v.3.6 database[5]. Mussel seeds are considered as not having much impact since they naturally grow on long-line ropes. The only significant impact for the seeds was in their procurement. For evaluating the environmental impact, the CML-IA method baseline 2000 v.3.01 was used. To create the complete assessment, the Open-LCA® 1.8.0[6] software developed by GreenDelta (Berlin, Germany) was used.

Mean impacts from Life Cycle Impact Assessment refers to of 1 kg of fresh mussels packed to be sold in Italy.

[3] Full article at: https://doi.org/10.1007/s11367-021-01978-y

[4] Full article at: https://doi.org/10.3390/su12093814

[5] Ecoinvent Database®. Available online: https://www.ecoinvent.org/database/database.html (accessed on 15th January 2020)

[6] https://www.openlca.org/

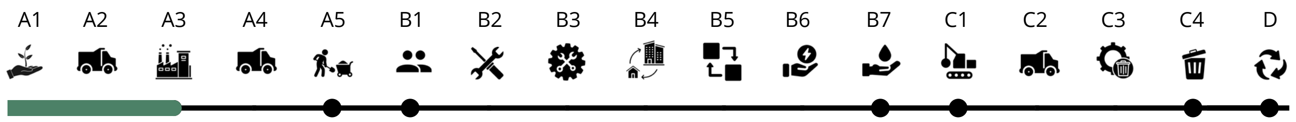


Figure Ss05: LCA by Tamburini et al., Impact category
Source: Tamburini, E., Turolla, E., Fano, E. A., & Castaldelli, G. (2020). Sustainability of Mussel (Mytilus Galloprovincialis) Farming in the Po River Delta, Northern Italy, Based on a Life Cycle Assessment Approach. Sustainability, 12(9), 3814. MDPI AG. Retrieved from http://dx.doi.org/10.3390/su12093814 - figure refers to Table 4.

Impact Category	Value	Unit
Climate change—GWP100 *	0.137	kg CO_2 eq.
Acidification potential (AP)	7.1×10^{-4}	kg SO_2 eq.
Eutrophication potential (EP)	1.7×10^{-4}	kg PO_4 eq.
Depletion of abiotic resources (ADP)—elements, ultimate reserves	4.4×10^{-7}	kg Sb eq.
Depletion of abiotic resources (ADP)—fossil fuel	2.55	MJ
Ozone layer depletion potential (ODP)	8.67×10^{-9}	kg CFC-11 eq.
Photochemical oxidant formation potential (POFP)	5.12×10^{-5}	kg ethylene eq.
Human toxicity potential (HTP)	0.13	kg 1,4-DCB eq. **
Marine water aquatic ecotoxicity potential (MAETP)	130.34	kg 1,4-DCB eq.

** GWP100, global warming potential for 100 years time horizon; * 1,4-DCB, 1,4 dinitrobenzene eq.

Tamburini et al. have found that the main driver behind the environmental impact categories is primarily attributed to assets like boats and long-lines. Specifically, the construction of boats significantly contributes to the overall environmental impact associated with mussel farming, surpassing their contributions from operational aspects such as diesel and engine oil consumption, as well as maintenance. Additionally, the non-recyclable nylon ropes used in long-lines make a substantial contribution to their environmental impact in various categories. The calculation for diesel and engine oil impact covers both the production of diesel and its subsequent combustion during boat operations. The considerable impact of boats and equipment, including onboard mussel processing machinery, is attributed to the production of materials like steel and glass fiber, with subsequent contributions from the production of copper, aluminum, and iron at the manufacturing plant (Tamburini et al., 2020).

It would be interesting including in the sistem boundries and in the impact categories also the positive aspect of mussel aquaculture such as filtering and uptake of nutrients, (e.g., carbon, nitrogen, and phosphorus) that occur during the whole-life-cycle.

Another aspect that could be interesting for future LCA studies is to consider the possibility of reuse of the by-product.

J - Prefabricated production processes

The use of seashells in architecture is part of traditions all over the world, it's main utilization in the construction industry include decorations, mosaics, shingles or cladding and even roof tiles for bigger shells (e.g. scallop shells).

So far as prefabricated elements and component present on the market, their use is still very limited. In recent years seashells as waste by-product, primarily of the food industry, has seen an increase in interest and are starting to see different applications. The main exploration in regards of ground shells is as **bio-concrete** in substitution of limestone.

Elements

Shellcrete

Researchers at the University of Brighton's School of Architecture and Design, in collaboration with specialized material consultants Local Works Studio, are involved in an EU-funded INTERREG SB&WRC (Sustainable bio & Waste Resources for Construction) research project. The project focuses on investigating the possibilities of using waste materials found near construction sites to create insulation and rain screen cladding for social housing developments.

This project involves the University of Brighton team partnering with restaurants to repurpose oyster shells into decorative tiles suitable for adorning the exteriors of buildings. For instance, 'English's of Brighton,' a restaurant that discards over 50,000 oyster shells annually, has contributed these shells to the initiative. Local Works Studio processes some of these shells at temperatures of 900°C, producing 'quick lime,' which is then combined with unfired crushed oyster shells to form an aggregate mixture. This mixture is compacted into silicone molds, triggering a natural chemical reaction when water is introduced, resulting in heat generation similar to the curing process observed in concrete. After approximately three weeks of curing, the tiles achieve the required level of hardness for mounting on buildings. Local Works Studio underscores that their approach utilizes 50kg of oyster shells per square meter of the installed tile, in contrast to traditional clay tiles weighing 78kg/m^2. This method not only makes use of waste materials but also demonstrates greater manufacturing efficiency.

localworksstudio.com

construction21.org

Another interesting projects that involves tiles is currently been explored by Brigitte Kock and Irene Roca Moracia. They produce tiles made from incinerated knotweed and crayfish shells. **irenerocamoracia.com**

Figure Ss06: Prototypes oyster shell tiles
Source: https://localworksstudio.com/projects/shellcrete-transforming-sea-shells-into-low-carbon-materials/

Figure Ss07: Oyster tiles
Source: https://localworksstudio.com/projects/shellcrete-transforming-sea-shells-into-low-carbon-materials/

Figure Ss08: Oyster hanging tiles
Source: https://localworksstudio.com/projects/shellcrete-transforming-sea-shells-into-low-carbon-materials/

Sea Stone - Newtab-22

Figure Ss09: Sea Stone tiles by Newtab-22
Source: https://www.dezeen.com/2020/08/28/sea-stone-newtab-22-design-shells-materials/

Newtab-22 created an eco-friendly substance resemble concrete by collecting waste seashells c from the seafood and aquaculture industries. The "Sea Stone," is an innovative material that involves the pulverization of shells originally destined for disposal. These crushed shells are then mixed with natural and non-toxic binders such as sugar and agar and added to a mould and left to solidify into concrete-like pices. This design is thought for a small-scale production and is hand-made as of today.

newtab-22.com

Figure Ss10-11: Sea Stone prototypes and production by Newtab-22
Source: https://www.newtab-22.com/

Thamed glass cladding tiles

Figure Ss12: Themed Glass Tiles made from ground mussels - by Artist Lulu Harrison
Source: https://luluharrisonstudio.com

Bureau de Change, an architecture studio based in London, has produced a series of tiles crafted from Thames Glass, a bio-material created by artist Lulu Harrison using mussel shells. Harrison, a Central Saint Martins graduate, created this bio-glass by blending finely crushed quagga mussel shells with locally sourced sand and residual wood ash.

Collaborating with Harrison, Bureau de Change's co-founders, Katerina Dionysopoulou and Billy Mavropoulos, explored the potential of utilizing this material as building cladding.

luluharrisonstudio.com

b-de-c.com

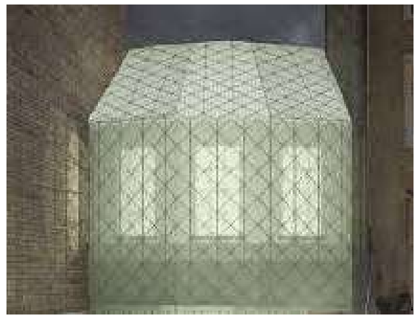


Figure Ss13: Rendering of use of thamed glass tiles as cladding
Source: https://surfacesreporter.com/

K - Case studies / Good practices

Coquina (shell block) quarry - WE (AU)

Figure Ss14: Coquina quarry - WE (AU)
Source: https://www.flickr.com/

This is an intresting case of natural shell blocks.

In Shark Bay (part of World Heritage Area) in Gascoyne - Western Australia, there is a coquina barrier[7] that is home to a cockle mollusc, specifically the *fragum erugatum,* it is so prolific that it has compacted in time and cemented into solid masses known as coquina, and resulting in what are coquina quarries.

In the past buildings in the surrounding of Shark Bay were constructed from these shell blocks.

sharkbay.org

[7] More information about the Coquina Barrier evolution in the paper: Jahnert, Ricardo & Paula, Osni & Collins, Lindsay & Strobach, Elmar & Pevzner, Roman. (2016). JAHNERT Evolution of a Coquina Barrier in Shark Bay, Australia.

Figure Ss15-16: Cutting coquina blocks from a quarry Coquina shell blocks
Source: https://www.sharkbay.org/

Oyster-tecture Brooklin, NY -Kate Orff / SCAPE

This case study by Kate Orff from SCAPE landscape and architectural studio proposes the use of oystern not as a building material but as a building block for regeneration of the New York Harbor and urban environment.

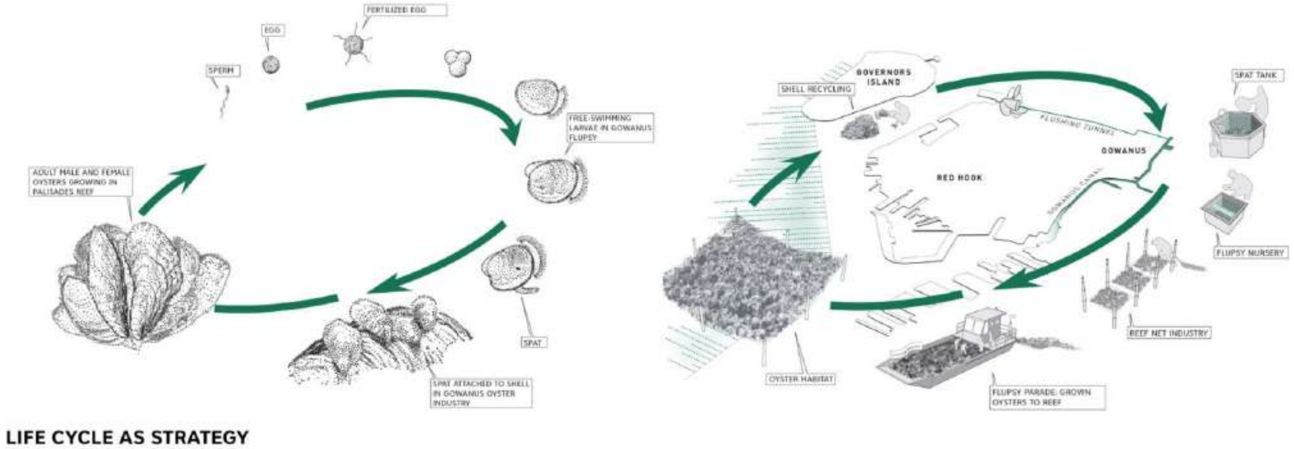


Figure Ss17: Life cycle as a strategy for regeneration - by SCAPE studio
Source: https://www.scapestudio.com/

The project Oyster-tecture proposes and envisions an active oyster reef that enhances marine life diversity and recreational potentials within the New York Harbor. The project was initiated by the Museum of Modern Art in 2009 as part of the Rising Currents exhibition, aimed at developing adaptation strategies for New York City to the challenges of climate change and rising sea levels. Oyster-tecture presents the concept of a living reef constructed from an interwoven matrix of 'fuzzy rope,' providing a foundation for marine growth. This arrangement generates a three-dimensional mosaic landscape that diminishes wave impact and purifies harbor water, utilizing the natural filtration capabilities of oysters, mussels, and eelgrass.
The resulting cleaner and calmer water facilitates the development of new waterways inland from the Gowanus Canal, forming a water-based regional park. This concept anticipates the city's sustainable reconnection with its waterfront for the forthcoming century. The primary goal of Oyster-tecture is to enhance habitats, improve water quality, revive biodiversity in tidal marshes, and foster new interactions between the city's residents and its harbor.

scapestudio.com

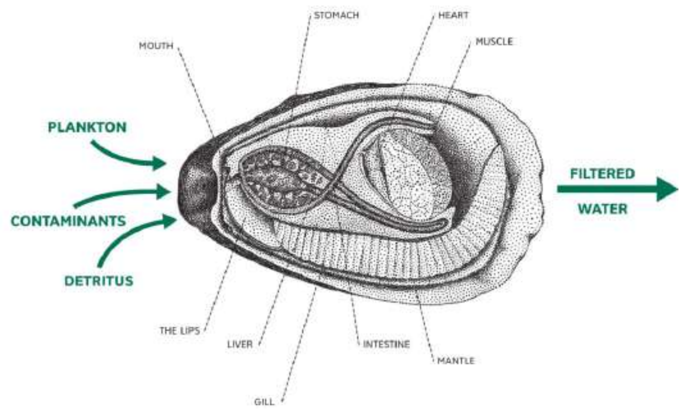


Figure Ss18: Concept of Oyster filtration of water - by SCAPE studio
Source: https://www.scapestudio.com/

L - Limits to overcome

The use of shells in architecture holds a lot of potential, but is still underdeveloped and requires further exploration and in-depth study.

When considering shells as a possible substitution and use in concrete, their performance, resistance and structural strenght needs to be further analysed for an upscaled used. Furthermore , as architectural materials need to adhere to safety and building codes, the use of shells may require approval and testing to ensure they meet the required standards.

Converting shells into usable architectural materials often requires specific processing methods, which can be energy-intensive (e.g. heating processes). Developing efficient and sustainable processing techniques is important.

One key aspetc is that extracting shells away from a beach changes the physical attributes of its sediment, therefore disrupting the natural ecosystem and resulting in the erosion of the shoreline.
The use of seashells should therefore consider the recyclin and use of waste materials from the food and aquaculture industries in order to not damage costs and marine ecosystems.

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Cellulose Paper

Figure Cp01: From wood to cellulose fibre
Source: https://materialdistrict.com/material/wood-fiber-textiles/wood-fiber-ona538-6/

Figure Cp02: Cellulose based insulation panels
Source: https://www.eci.com.tr/productdetail/cellulose-fiber-insulation-batt-blanket

Cellulose, an intricate carbohydrate or polysaccharide, functions as a structural element within plant cell walls, representing one of the most prevalent natural compounds in existence. Wood pulp primarily consists of cellulose, comprising a range of 60% to 85% (Ming et al., 2022).Paper production is primarily reliant on cellulose, a substance found in plant cell walls. While various plants like hemp, flax, cotton, jute, and straw can be sources of cellulose for paper, trees are the predominant choice. Unfortunately, traditional paper production has contributed to issues like deforestation, pollution, and excessive energy and water consumption. As a consequence, paper constitutes a significant portion, around 26%, of landfill waste (The World Counts, 2023). To address these challenges, responsible practices such as mindful consumption, reduction, and recycling have gained importance. According to The World Counts, recycling one tonne of paper can conserve approximately 1400 liters of oil, 26,500 liters of water, and save 17 trees. However, beyond these measures, the overlooked potential of waste materials should also be acknowledged as part of the solution. Paper can be recycled only a certain number of times before the cellulose fibres become too short to be bound together by conventional means. When this occurs, the leftover cellulose material is usually either thrown away in landfills or burned. It's estimated that around 7 million tons of this type of waste are generated worldwide every year (Material district, 2021). For more than 60 years, cellulose fibre has been used in Scandinavia and North America as a material for thermal and acoustic insulation; in the last twenty years it has also become very popular in central Europe. It could be considered an environmentally friendly material, as the raw material comes from recycled newspapers and the energy expenditure to produce it is low (Fassi and Maina, 2006). In fact, the use of cellulose in loose form, as a foam and pressed into panels is one of the most know uses of this resource as a building material. In recent years research as proven that its potential goes beyond and can comprise many other innovative utilizations. Cellulose is demonstrating its versatility as a renewable natural compound and being processed in creative building materials.

Tiles

An example of cellulose-based tiles were developed by product designer Berta Julià Sala in partnership with the Spanish brand Alted Materials. Alted H01 consists of colorful surface tiles, crafted from recycled paper waste. Designed for indoor use on walls and ceilings, the Alted H01 panels are easy to install and maintain long-lasting performance.

Figure Cp03-04: Alted H01 Cellulose based tiles - by Berta Julià Sala and Alted Materials
Source: https://www.dezeen.com/2023/04/11/alted-materials-h01-tiles-berta-julia-sala-dezeen-showroom/

Cellulose fibreboards

Cellulose fibres possess the ability to be compacted and united to form fibre-board panels, which find application in interior walling, ceilings, and cladding. Honext, an innovative company based in Barcelona, has ingeniously harnessed the potential of cellulose by extracting it from the discarded remnants of paper and cardboard production. Through a clever combination of enzymes and cellulose, they have transformed these waste streams into robust construction boards.

Figure Cp05-06: Cellulose fibre board for interior wall and cladding- by Honext
Source: https://www.dezeen.com/2020/11/26/honext-recyclable-construction-material-cellulose-paper/

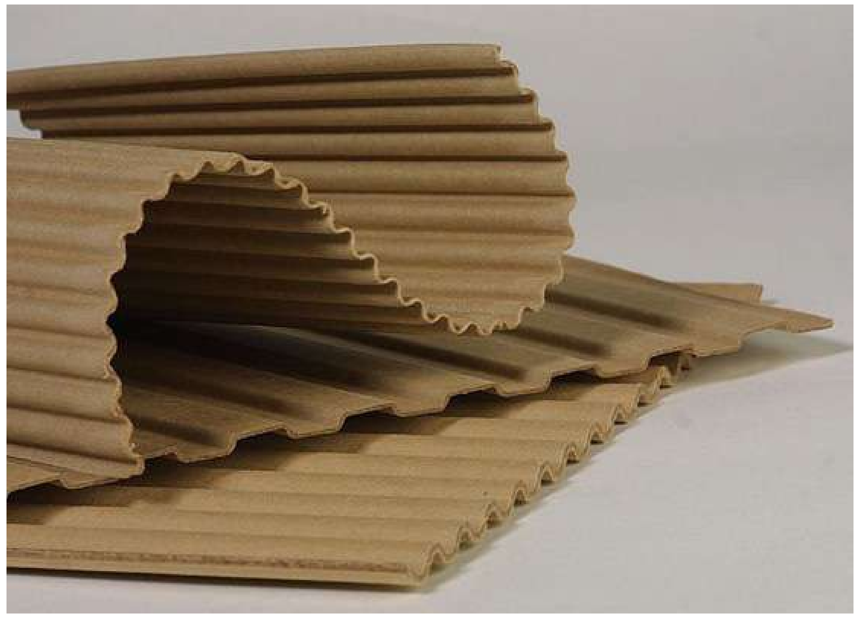


Figure Cp07-08: Wellboard - cellulose fibre board - by Kraftplex
Source: https://materialdistrict.com/material/wellboard/

The Wellboard, developed by the German company Kraftplex, stands out as a corrugated board composed entirely of 100% compressed cellulose (wood pulp), and its formation involves a hot pressing process that eliminates the necessity for additional adhesives. This innovative solution comes in a range of types and sizes to cater to diverse applications.

Nanocellulose Fibreboard

YunTing Lin, a graduate of the Royal College of Art, has innovated a novel material using plant fibers and naturally fermented cellulose to make fibreboards. These Nanocellulose Fibreboard, composed of a composite of plant fibres like flax, bouded together using nanocellulose, a fibrous substance produced through bacterial fermentation. The Fibreboard is fully recyclable and biodegradable, and consisting of 100% non-toxic components. It could be an eco-friendly alternative to MDF or moulded plastic.

Figure Cp09-10: Nanocellulose Fibreboards - by YungTing Lin
Source:
https://www.dezeen.com/2015/07/02/nanocellulose-fibreboard-all-natural-replacement-mdf-moulded-plastic-rca-yunting-lin/

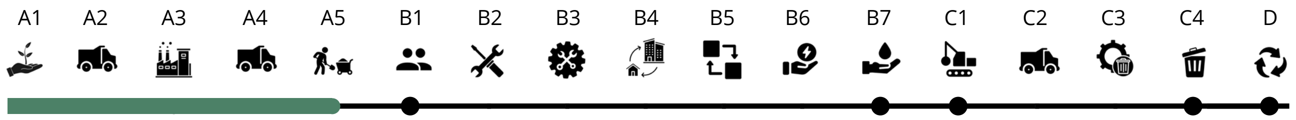
Life cycle assessment

The environmental concerns linked to the production process of paper are numerous and can vary according to different countries and practices. Throughout its life cycle and at various stages it results in environmental concerns including deforestation, energy and water consumption, chemical usage, air pollution, waste generation, transportation impacts, recycling challenges, landfill disposal issues, and potential water pollution, resulting in a significant carbon footprint.
When considering different end products, it is important to preferer ones that come from sustainable forestry and practices.

Therefore, recycling and reusing waste paper is overall a good practice in terms of environmental cost, it promotes less use of the virgin resource, thus lowering the demand, and also reduces waste that goes to landfill. Considering the reuse and processing into other materials low energy methods should be preferred and when creating composite materials, other non-toxic and biodegradable materials should be preferred as to ensure a sustainable end-of-life disposal.

LCA data was obtained from the SimaPro software ad reference cellulose fibre {RoW}| cellulose fibre production | Cut-off, U 1 kg - 100- Compost - Construction\Insulation\Transformation from the Ecoinvent 3 database.

The process describes the production of 1 kg of cellulose fibre from waste paper (post-consumer) used as an insulation material in buildings. Cellulose fibre used for insulation applications has a thermal conductivity of 0.038 W/mK at a density of 30-60kg/m^3. The activity starts with the delivery of sorted waste paper and includes the production process. During production, aluminium hydroxide and boric acid are added as flame retardant. The inventory ends, when insulation material can be provided to customer (not including installation (blowing in) or transport to building site).



GWP

Impact category	Unit	Total
Total	kg CO_2 eq.	**0.253**
Climate change - fossil	kg CO_2 eq.	0.219
Climate change - biogenic	kg CO_2 eq.	0.036
Climate change - CO_2 uptake	kg CO_2 eq.	-0.002
Climate change - land use and transformation	kg CO_2 eq.	0.000

GWP - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 - Characterisation

Embodied energy

Impact category	Unit	Total
Total	MJ	**3.107**
Non renewable, fossil	MJ	2.648
Non renewable, nuclear	MJ	0.270
Non renewable, biomass	MJ	0.000
Renewable, biomass	MJ	0.024
Renewable, wind, solar, geothermic	MJ	0.037
Renewable, water	MJ	0.128

EE - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation

Impact category	Unit	Total
Climate change	kg CO2 eq	0.2488
Ozone depletion	kg CFC11 eq	0.0000
Ionising radiation	kBq U-235 eq	0.0204
Photochemical ozone formation	kg NMVOC eq	0.0011
Particulate matter	disease inc.	0.0000
Human toxicity, non-cancer	CTUh	0.0000
Human toxicity, cancer	CTUh	0.0000
Acidification	mol H+ eq	0.0018
Eutrophication, freshwater	kg P eq	0.0001
Eutrophication, marine	kg N eq	0.0004
Eutrophication, terrestrial	mol N eq	0.0036
Ecotoxicity, freshwater	CTUe	11.0558
Land use	Pt	0.3041
Water use	m3 depriv.	0.0579
Resource use, fossils	MJ	2.7366
Resource use, minerals and metals	kg Sb eq	0.0000
Climate change - Fossil	kg CO2 eq	0.2230
Climate change - Biogenic	kg CO2 eq	0.0255
Climate change - Land use and LU change	kg CO2 eq	0.0002
Human toxicity, non-cancer - organics	CTUh	0.0000
Human toxicity, non-cancer - inorganics	CTUh	0.0000
Human toxicity, non-cancer - metals	CTUh	0.0000
Human toxicity, cancer - organics	CTUh	0.0000
Human toxicity, cancer - inorganics	CTUh	0.0000
Human toxicity, cancer - metals	CTUh	0.0000
Ecotoxicity, freshwater - organics	CTUe	0.0736
Ecotoxicity, freshwater - inorganics	CTUe	0.4997
Ecotoxicity, freshwater - metals	CTUe	10.4825

Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation

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Bio-plastics

Polymers, colloquially referred to as plastics, have become an integral part of modern society, finding applications in various domains, ranging from everyday uses such as packaging to advanced uses for example in the medical industry (Stubbs and Worch, 2022).

In the early 20th century, synthetic plastics emerged, and by the mid-century, the modern plastics industry was established. However, a significant majority of the world's plastics, over 99% of the estimated ≈ 8,300 million metric tons produced until 2017 (Geyer et al., 2017), are derived from non-renewable sources, primarily by-products of fossil fuel refining. The heavy reliance on fossil fuels for plastics presents several challenges. Firstly, fossil fuels are finite resources with limited availability. Secondly, the extraction and consumption of fossil fuels have substantial environmental impacts as for the plastic products derived from these non-renewable sources are typically non-degradable and follow a linear usage pattern, leading to long-lasting ecological issues because of their high durability. As a response, the future materials economy aims to transition from a linear to a circular model, shifting towards renewable biomass resources instead of finite ones for the production of plastic products (Stubbs and Worch, 2022).

Bio-polymers, which are naturally occurring polymers, such as polysaccharides (also referred to as carbohydrates) and polypeptides, serve as the chemical foundation for numerous bio-derived materials. These bio-polymers encompass a range of substances such as starch, cellulose, algin, chitin, and collagen. Therefore, renewable resources can be utilized to produce molecule chains that possess properties similar to petroleum-based polymers. This is achieved through the chemical processes of cracking and re-polymerization. For example, sugars obtained from sugarcane and beets can be fermented, or starch derived from corn can be hydrolyzed[1]. These processes result in the production of ethanol, which serves as a building block for various bio-polymers. Additionally, fermentation can yield other materials such as lactic acid, n-butanol, acetone,

and polyhydroxyalkanoates (Bio Plastic Europe, 2023). Referring to **Bio Plastics Europe**[2], some of the frequently used "bio-based plastics" and their properties are as follows:

PA, PE, PET

Polyamide (PA), Polyethylene (PE), and Polyethylene terephthalate (PET). Partially or completely bio-based (at least 20%), non-biodegradable and non-compostable;

Feedstocks: sugar cane, molasses, vegetable oils;

Properties: comparable to conventional polymers, recyclable, non-biodegradable, easy processing;

Use: all types of packaging, technical parts.

PLA

Polylactic acid (PLA). Completely bio-based, biodegradable and compostable;

Feedstocks: starch (corn), sugar cane, sugar beet, tapioca;

Properties: transparent, rigid, low heat resistance, low barrier effect;

Use: food packaging (trays, foils, cups), cosmetics, moulded parts, bio-composites.

PHA

Polyhydroxyalkanoate (PHA). Partially or completely bio-based, completely biodegradable and compostable;

Feedstocks: starch (corn), sugar (sugar cane, beet), biomass;

Properties: opaque to translucent, rigid to elastomeric, good heat resistance and barrier properties;
Use: bio-composites, moulded parts, packaging film.

PBS

Polybutylene succinate (PBS). Partially or completely bio-based and completely biodegradable;

Feedstocks: starch (corn), sugar (sugar cane, beet), biomass

Properties: heat resistant, flexible, mixable with other bio-based polymers;

Use: food packaging, mulching films, fishing nets, plant pots, hygiene products.

PHBV

Poly (3-hydroxybutyrate-co-3-hydroxyvalerate). Partially or completely bio-based and completely biodegradable;

Feedstocks: starch (corn), sugar (sugar cane, beet), biomass;

Properties: thermoplastic, brittle, low elongation at break, low impact resistance;

Use: controlled release of drugs, medical implants and repairs, specialty packaging, orthopaedic devices, manufacturing bottles for costumers' goods.

Bio-plastics based on Starches

Derived from renewable crops such as corn, potato, wheat, or tapioca, starch-based bioplastics are obtained by extracting starch from these sources and transforming it into a polymer, often known as thermoplastic starch (TPS). TPS serves as an eco-friendly option, offering biodegradability and compostability, making it a viable substitute for conventional plastics, especially in packaging and disposable items.TPS is characterized by the property of absorbing water (hygroscopy), therefore it is usually one of the components that constitute the plastic product, and often combined with other biodegradable polymers such as polyvinyl alcohol, with makes up the insoluble part of the plastic blend. Glycerin can also be added to increase flexibility during processing (Peters, 2011).

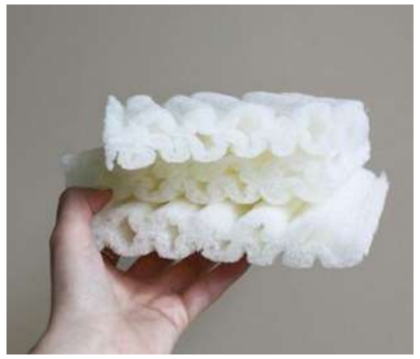


Figure Bp01: Corn starch based bioplastic
Source: https://www.matrec.com/en/materials-news/bio-plastic-in-corn-starch

Bio-plastics based on Vegetable Oils

Produced through chemical modifications of oils sourced from plants like soybean, corn, canola, or palm, bioplastics based on vegetable oils offer a viable alternative. Bio-based polyamides, competing with their petroleum-based counterparts, exhibit similar properties to traditional plastics. In terms of their life cycle, bio-based polyamides demonstrate a reduced carbon footprint compared to petroleum-based ones (Peters, 2011). These materials can be harnessed to create bio-based foams (typically composed of polyols, isocyanates, water, and additives) as well as bio-based resins (also recognized as bio-based epoxy resins).

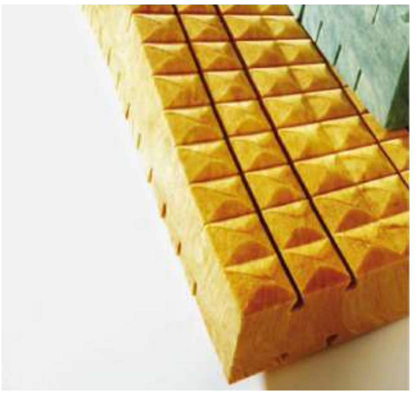


Figure Bp02: Foam made from castor oil
Source: BASF / Elastogram

Bio-plastics based on Cellulose

Derived from plant fibres, wood pulp, or waste paper, cellulose-based bio-plastics originate from renewable sources. Through chemical processing, cellulose can be transformed into materials like cellulose acetate or cellulose nitrate, finding applications in films, coatings, and textiles. Remarkably, cellulose-based plastics can attain light permeability levels of up to 90% (Peters, 2011). Since the cellulose molecules are stiff, the extent to which they can be processed depends on the amount of softener added, for the material to be injected into moulds and subsequently extract the product (Peters, 2011). From cellulose bio-plastic Tencel™ has developed a textile fibre with strong moisture absorbtion for ideal climatic conditions (50% more then cotton products).

Figure Bp03: Tencel™ Textile fabric made from cellulose
Source: https://www.tencel.com/

Figure Bp04: Lignin based bio-plastic pellets by the Swedish company RenCom
Source: https://www.plasticfree-world.com/

Lignin-based bio-plastics

Following cellulose, lignin stands as the second most prevalent bio-polymer in nature. In industrial contexts, lignin is acquired from wood shavings and fibres through a boiling procedure. This extracted lignin is subsequently blended with agents like methanol and hydrochloric acid, resulting in a substance resembling resin. This resin can be integrated into a polymer mix or utilized directly to produce duroplastics. Formulations featuring lignin demonstrate commendable mechanical attributes and substantial rigidity (Peters, 2011), rendering them fitting for uses in automotive components, construction materials, coatings, and packaging.

Figure Bp05: Seaweed bio-plastic by Jessie French and Lichen Kelp
Source: https://www.designhotels.com/

Algae based bio-plastics

Algal-based bio-plastics, also referred to as algae bio-plastics or algal polymers, are biodegradable plastics derived from algae or microalgae. These sustainable bioplastics are created by extracting and processing biomass or specific components from algae, such as lipids, polysaccharides, or proteins, which serve as the building blocks for polymer production. One important aspect of algal bio-plastic is that it does not involve crops cultivated on land. Alginate bio-plastic can be processed into foam materials that could potentially replace expanded polystyrene (EPS) (Peters, 2011), being that is has good insulating and flame-resistant properties and is biodegradable.

Figure Bp06: Bio-plastic made from animal bones and skin - by Valdís Steinarsdóttir
Source: https://www.dezeen.com/2021/01/27/valdis-steinarsdottir-food-packaging-vessels-animal-skin-bones/

Bio-plastics from Animal Sources

Like cellulose, chitin is a polysaccharide, it can be found in exoskeletons of crustaceans, insects, and also exists in the cell walls of fungi. It is formed, for example, by grinding dried crab shells then washing these with caustic soda to form chitosan in a saponification process (Peters, 2011). Chitosan can be processed into a bio-polymer used in bioplastics that offer biodegradability, antimicrobial properties, and potential applications in medicine, biotechnology, and packaging.

The production of plastics worldwide witnessed a significant rise, reaching approximately 359 million metric tons in 2018 compared to 245 million metric tons in 2008. Projections indicate a potential tripling of production by 2050, which could contribute to one-fifth of global oil consumption (Garside,2020). In order to comply with this request without further contributing to environmental pollution, the utilization of these alternatives could lead to a more sustainable option.

Despite the promising progress in utilizing plant-derived bio-plastics, a critical concern is to ensure that agricultural land is not compromised at the expense of global food production and environmental concerns. The question becomes:

Do bio-plastics contribute to adding agricultural strain to the food production?

Can bio-based plastics substitute conventional plastics?

Global production capacities of bioplastic in 2022

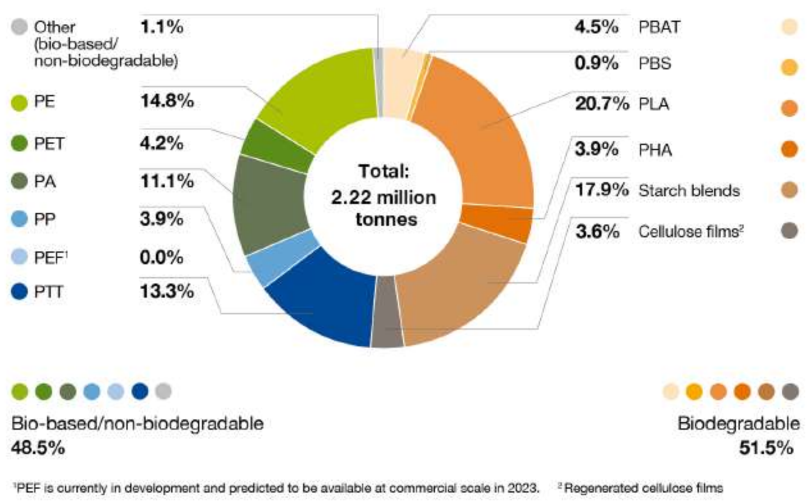
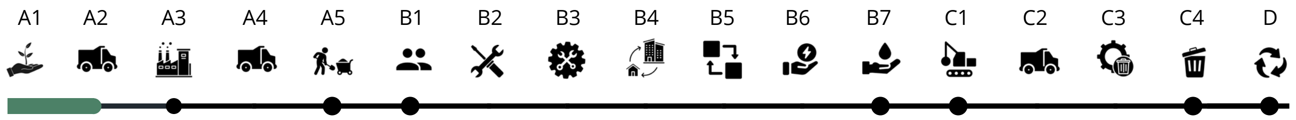


Figure Bp07: Global production capacities of bioplastics in 2022
Source: European Bioplastics, nova - Institute (2022). More information at: www.european-bioplastics.org/market and www.bio-based.eu/market

Life cycle assessment

LCA data was obtained by the SimaPro software. The reference follows Polyester-complexed corn starch bio-polymer {RER}| production | Cut-off, U 1kg 100 Bio-polymers Plastics\Bio-polymers\Transformation EcoSpold01Location=RER (Ecoinvent 3). Comment Inventory refers to the production of 1 kg granulate modified starch. The inventories is based on calculations and extrapolations using highly aggregated background data from the environmental product declaration of Materbi (Novamont, 2004, Italy). Included processes in the inventory of modified starch granulate are the production of input materials corn starch and fossil components (plasticizers and complexing agents), transports of input materials, energy consumption in the processing and packaging at plant as well as waste treatment.

Only high aggregated data were available. So the emissions from energy consumption, waste water treatment and raw material inputs have been subtracted.



GWP

GWP - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 - Characterisation

Impact category	Unit	Total
Total	kg CO_2 eq.	**0.691**
Climate change - fossil	kg CO_2 eq.	1.236
Climate change - biogenic	kg CO_2 eq.	0.188
Climate change - CO_2 uptake	kg CO_2 eq.	-0.734
Climate change - land use and transformation	kg CO_2 eq.	0.001

Embodied energy

EE - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation

Impact category	Unit	Total
Total	MJ	**52.911**
Non renewable, fossil	MJ	41.605
Non renewable, nuclear	MJ	2.486
Non renewable, biomass	MJ	0.000
Renewable, biomass	MJ	7.917
Renewable, wind, solar, geothermic	MJ	0.413
Renewable, water	MJ	0.488

Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation

Impact category	Unit	Total
Climate change	kg CO2 eq	1.271
Ozone depletion	kg CFC11 eq	0.000
Ionising radiation	kBq U-235 eq	0.225
Photochemical ozone formation	kg NMVOC eq	0.005
Particulate matter	disease inc.	0.000
Human toxicity, non-cancer	CTUh	0.000
Human toxicity, cancer	CTUh	0.000
Acidification	mol H+ eq	0.013
Eutrophication, freshwater	kg P eq	0.000
Eutrophication, marine	kg N eq	0.003
Eutrophication, terrestrial	mol N eq	0.031
Ecotoxicity, freshwater	CTUe	37.191
Land use	Pt	17.578
Water use	m3 depriv.	0.175
Resource use, fossils	MJ	40.959
Resource use, minerals and metals	kg Sb eq	0.000
Climate change - Fossil	kg CO2 eq	1.268
Climate change - Biogenic	kg CO2 eq	0.003
Climate change - Land use and LU change	kg CO2 eq	0.001
Human toxicity, non-cancer - organics	CTUh	0.000
Human toxicity, non-cancer - inorganics	CTUh	0.000
Human toxicity, non-cancer - metals	CTUh	0.000
Human toxicity, cancer - organics	CTUh	0.000
Human toxicity, cancer - inorganics	CTUh	0.000
Human toxicity, cancer - metals	CTUh	0.000
Ecotoxicity, freshwater - organics	CTUe	6.196
Ecotoxicity, freshwater - inorganics	CTUe	5.876
Ecotoxicity, freshwater - metals	CTUe	25.119

Bio-plastics

Uses in the building sector

In the building sector, like in many other industries, the utilization of bio-plastics has gained attention as a sustainable alternative to conventional plastics. Their use varies and can constitute:

Building Components: Bio-plastics can be employed in the production of various building components, such as interior finishes, wall panels, partitions and cladding. These components can be manufactured using bio-plastic sheets, films, or moulded bio-plastic materials, offering design flexibility.

Figure Bp08: SIMOWOOD consists of an innovative building material made from Resysta® sheet, an hybrid substance derived from rice husks and a specific thermoplastic variant - by Resysta
Source: https://www.simona-es.com/fileadmin/user_upload/Medien/Mediacenter/Technische_Informationen/tech.info_SIMOWOOD_made_of_Resysta_EN.pdf

Interior Design Elements: Bio-plastics can be integrated into interior design elements, such as furniture, lighting fixtures, and decorative objects.

Packaging: Architecture projects often involve the transportation and packaging of materials and components. Bio-plastics can be utilized for sustainable packaging solutions, providing protection and minimizing waste generation. Bio-plastic films, wraps, or moulded packaging made from renewable sources can help reduce the use of fossil fuel-based plastics.

Glazing: Bio-plastics, in particular transparent bio-plastics such as polylactic acid (PLA) and acrylic sheeting or polycarbonate sheeting, have the potential to be used as an alternative to conventional glass in architectural glazing applications. Bio-plastic glazing can provide thermal insulation, reduce glare, and contribute to energy efficiency in buildings while offering a lightweight solution.

Figure Bp09: Bio-plastic chair by Jean Louis Iratzoki designs "first bioplastic chair" - biopolymer using plant-based resources such as beet, corn starch and sugarcane.
Source: https://www.dezeen.com/2015/01/19/jean-louis-iratzoki-first-bioplastic-chair-alki-polymer/

Case studies / Good Practices

ArboSkin Bioplastic Façade - UrbanNext Lexicon

Figure Bp10: ArboSkin Bioplastic Façade
Source: https://urbannext.net/

Figure Bp11: ArboSkin Bioplastic Façade
Source: https://urbannext.net/

Professors and students from Stuttgart University's ITKE (Institute of Building Structures and Structural Design) conceived the free form façade with the intention of highlighting the structural attributes of a newly developed bio-plastic tailored for the construction field. This project rapresents a new and innovative utilization of bio-plastic in the construction sector.

The company TECNARO GmbH created bio-plastic sheets using bio-polymers, which were later formed into pyramid-shaped pieces through heating by the company BAUER THERMOFORMING GmbH. These parts were then intricately shaped through precise cutting, allowing them to cover irregular surfaces. The waste generated during cutting was recycled to make more sheets. When these parts are no longer needed, they can be composted or disposed of with minimal environmental impact.

urbannext.net

tecnaro.de

bauer-thermoforming.de

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Bio - textile

The utilization of natural fibres for textiles production traces back to ancient times, with flax and wool fabrics discovered at Swiss lake dwellers' excavation sites in the 7th and 6th centuries BCE (Britannica, 2023). Prehistoric societies also employed plant fibres, including hemp, which originated in Southeast Asia and later spread to China around 4500 BCE. Egypt utilized practices of weaving and spinning linen by 3400 BCE, suggesting earlier cultivation of flax. Cotton spinning was reported in India as far back as 3000 BCE. The Chinese developed silk production around 2640 BCE, which led to the creation of sericulture and silk spinning techniques. Over time, textile skills spread internationally, adapting to local needs and resources (Britannica, 2023). The Industrial Revolution in the 18th and 19th centuries spurred machine inventions for processing natural fibres, boosting their production. However, the introduction of regenerated cellulosic fibres like rayon, followed by entirely synthetic fibres like nylon, challenged the utilization of natural fibres (Britannica, 2023).

As a solution an upscaled adoption and substitution with natural fibres and other bio-based alternatives could enhance environmental benefits across all industries.
Among possible solutions of bio-based textile fabrics there are ones deriving from plant-based fibres such as cotton, flax, jute, hemp and kenaf, from animal sources such as wool or silk and then more innovative sources like mycelium and other such as fabrics made from bio-polymers. Examples of bio-polymer fabrics include those made from materials like PLA (polylactic acid), PHA polyhydroxyalkanoates), and other biodegradable polymers, such as those deriving from algae and other organic matter.

Bio-polymers have seen increased utilization in specific sectors such as food packaging, fashion, and design items. Nevertheless, the prevailing approach in architectural technical textiles continues to rely on polymeric composites derived from non-renewable resources. In the realms of lightweight construction and textile architecture, the integration of novel bio-based and bio-polymer materials needs a more comprehensive performance assessment to ensure compliance with the safety demands in building regulations (Zanelli et al., 2020).

Figure Bt01: Fabrics made from algae - by Algaeing
Source: https://specialtyfabricsreview.com/2021/12/01/growing-textiles-from-algae/

Figure Bt02: Mylo "mushroom leather" - by Bolt threads
Source: https://boltthreads.com/

In recent years, the European textile industry has displayed patterns of growth in both the textile and leather goods sector, as well as within the specialized segment of technical textiles (ExportPlanning 2018).

The field of technical textiles includes non-woven textiles (43%), a variety of impregnated, coated, or resin-based fabrics (23.3%) used in textile architecture, and other types of technical textiles (15.6%). Yarns, tapes, and labels for industrial applications make up the remaining 18.1% (ExportPlanning 2018). Impregnated, coated, or resin-based fabrics, along with polymeric foils like TPU, PVC, and PTFE used in textile architecture and membrane structures, form a niche within the textile market. Despite their niche status, they have a significant impact on the well-being of end users and meet requirements for performance, longevity, and safety (Zanelli et al., 2020).

Figure Bt03: Insulation panels made from blue juans - by Soprema (UK)
Source: https://www.soprema.co.uk/en/article/sopravoice/soprema-blue-jeans-sustainable-insulation

Considering the textile manufacturing industry as a whole, addressing environmental sustainability remains a challenge to be faced (Zanelli et al., 2020). According to the European Commission estimations, the EU textile industry generates around 16 million tonnes of waste per year, most of which is disposed in landfills or incinerators. Of this waste only a small portion is recycled into new clothes, and into lower-value applications, such as insulation. Even though recycling is already a more sustainable practice that usual disposal, the integration of bio-based textiles across all industries could further enhance environmental benefits. In the context of Europe, over 60% of the raw materials used in woven and non-woven textiles are synthetic substances derived from fossil fuels and are not biodegradable. The remaining 40% comprises natural fibres but not necessarily or automatically considered "bio".

The textile material deriving from bio-based sources such as cellulose filaments and other bio-polymers are still very limited. The dominant share of raw materials in the textile industry still originates from petroleum-based polymers. (Zanelli et al., 2020). Due to rapid progress in synthesizing renewable raw materials (such as agricultural or forestry surplus or waste) through sustainable fermentation processes involving specific combinations of microorganisms and bacteria, a broader range of bio-polymers can now be generated. However, most of these biopolymers are not biodegradable or compostable, which means only a limited few are effectively “close the loop” (Zanelli et al., 2020). The problem with technical textiles used in the building industry is that they have to, among other things, be durable and resistant to degradation, they have to be able to withstand different environmental conditions and they have to be fire resistance. Researchers are carrying out various studies on bio-based technical textile in order to evolve and comply with needed requirements.

Even though bio-based technical textile for lightweight architecture is limited, there are some examples that are adopting innovative solutions.

Ten Cate outdoor fabrics

TenCate Outdoor Fabrics[1] is a division of the dutch company Royal Ten Cate, known for producing advanced materials for various industries. TenCate Outdoor Fabrics specializes in creating high-quality outdoor textiles for applications like camping, glamping, outdoor furniture, sunshades, and other outdoor leisure products.

[1] More information at: https://www.tencateoutdoorfabrics.com/

TenCate offers many varieties of fabrics that can be utilized in different applications. Moreover, they offer different bio-based solution in their different lines, and they also have a dedicated Eco-Line. in this line every product has been designed and manufactured to minimize its impact on the natural environment. Alongside incorporating biological components, they also utilize materials crafted from 100% recycled sources. Each material has been developed to serve as fully functional tent fabric.

TenCate presents a Cotton Line, that is 100% cotton. This fabric can be used as a tent cloth and it is breathable, moisture-regulating, water-repellent and rot-resistant and mould-resistant.

Alongside the Cotton Line, TenCate presents an Eco-Line fabrics are made from 20% hemp, 50% recycled polyester and 30% organic cotton. Thanks to its composition, TenCate Eco-Line proves to be fitting for robust and more demanding uses, including scout tents, glamping tents, and other scenarios where the need for breathability is coupled with enhanced durability.

Figure Bt04: Eco-Line - by TenCate
Source: https://www.tencateout-oorfabrics.com/blog/het-nieuwe-duurzame-tentdoek-ecohemp/

Figure Bt05-6: Eco-Line - by TenCate as the roof of the Living Pavillion by Company New Heroes
Source: https://www.tencateoutdoorfabrics.com/en/blog-en-2/the-growing-pavilion-tencate-tentdoek/

The research to better environmental cost linked to the textile industry is at the centre of research and studies world wide, a lot of studies are focused on the fashion industry, however their discovering, with needed modifications to meet requirenments, could be trasfered also to other sectors such as for technical textile used in the building industry. An example of this could be:

Lezing™

Lezing™ is a Austrian company[2] that uses plant-based fabrics obtained from wood-based cellulosic fibres. The resulting fabrics are biodegradable and there fore can be disposed as compost. The company complies with sustainable practices that aim at "cloosing the loop". The wood resource relies on responsible forestry that is FSC® and PEFC certificatified.

[2] More information at: https://www.lenzing.com/products/lenzingtm

lenzing.com

Figure Bt07-08: from wood to fibre
Source: https://materialdistrict.com/material/wood-fiber-textiles/

A similar practice is carried out by Spinnova

Spinnova

Spinnova is a Finnish company[3] that produces bio-based textile fabrics that derive from wood. Spinnova has introduced a patented technology that enables the transformation of wood pulp into textile fibre without the requirement for chemical processing, thereby further decreasing its impact on the environment. This fibre creation approach utilizes minimal water, reducing consumption by up to 99% compared to cotton.

[3] More information at: https://spinnova.com/

spinnova.com

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Is it possible to build only with bio-based materials?

The question should not only be is it possible, but also is it right to build only with bio-based solutions.
Although bio-based alternatives are numerous and vary for different types of applications, they still present some limitations. While bio-based materials offer numerous benefits, they might not always meet the specific functional requirements of certain building components, especially structural elements like foundations. In many cases the use of bio-based is not possible as most of these materials are not indicate for this application. In some other cases the longevity and durability of bio-based materials does not meet needed requirements, at other times fire or moisture resistance is not sufficient. Furthermore, other considerations go towards cost of use of bio-based alternatives is too high and therefore not a feasible solution. And even though there are many bio-based alternatives, it might not always be the best solution. Innovations that work towards sustainability in the building sector are gaining a lot of momentum, as of today bio-based is not the only solution, and sometimes rather than forcing one solution, exploring and integrating other alternatives might be best.

Nonetheless, more than ever before bio-based materials are starting to make their way as a valuable option and alternative in the building sector. Many practices, researches, builders, architects, designers, manufactures worldwide are increasing recognition and actively participating towards a "slow" but promising transition.

One of leading subjects is the company New Heroes (also see The Growing Pavilion under /Mycelium). This company, in collaborations with many other entities, is opening new possibilities and providing information through pavilions and online platforms to showcase the potential of bio-based materials in this industry. New Heroes is the founder of the company *Bio-based Creations,* which is a creative hub specializing in installations, projects, and narratives that highlight the shift towards a regenerative and circular practices. Their focus covers a wide spectrum, including renewable energy, bio-based construction, new economic and social models and solutions. *Bio-based Creations* is a network of designers, researchers, artists, and storytellers driven by the shared vision of cultivating a sustainable ecosystem for both people and the environment.

In particular a project that could answer to the initial question of "Is it possible to build only with bio-based materials?" is the *The Exploded View Beyond Building*[1], which is an installation of a "house made out of nature".

Figure 04.4.01: The Exploded View Beyond Building
Source: https://biobasedcreations.com/project/the-exploded-view-beyond-building/

The installation premiered during the Dutch Design Week of 2021 in Eindhoven - (NL). *The Exploded View Beyond Building* stands as an iconic exhibition, taking the form of a house crafted entirely from bio-based materials and employing circular construction methods. It not only embodies the physical structure but also weaves narratives about the evolving value chain as an integral part of design, in rappresentation of a circular future. The creation of the *Exploded View Beyond Building* is the outcome of collaborative efforts and research involving builders, producers, farmers, scientists, designers, government entities, knowledge institutions, storytellers, and artists. They are brought together under the umbrella of The Embassy of Circular & Biobased Building, collectively working to showcase an innovative perspectives for sustainable living in a circular environment.

The design concept of this installation is organized in prefabricated modular systems with a wooden structure, therefore can be adaptable and evolve in time to meet future requirements.

[1] More information at: https://theexplodedview.com/the-exploded-view-beyond-building/

https://theexplodedview.com/wp-content/uploads/2022/01/Image-report-DDW21-1.pdf

https://www.dezeen.com/2021/10/20/biomaterials-house-dutch-design-week-biobased-creations/

The Exploded View Beyond Building features nearly 100 natural and bio-based building materials. In this exhibition, attention is brought to the potential of material resources that are not conventionally used in the construction industry. These materials originate from different sources like food, seaweed, wastewater, existing buildings and agriculture, at the same time it showcases established materials but also highlights those categorized as relevant for today, tomorrow, and the future. Some of these materials are already in use, while others require further development and support to reach their potential.
The exhibit is organized into 7 themed rooms, each exploring a different aspects and materials from divers origins, as follows in the pictures below.

All these themes showcase a variety of materials deriving from the different sources that give the name and theme to each room. Some exaples are in the foolowing page.

Earth

Figure 04.4.02: Material made from earth and clay
Source: https://biobasedcreations.com/project/the-exploded-view-beyond-building/

Water

Figure 04.4.03: Materials fro the world of "water"
Source: https://biobasedcreations.com/project/the-exploded-view-beyond-building/

Fungi / Bacteria

Figure 04.4.04: Materials made from fungi and bacteria
Source: https://biobasedcreations.com/project/the-exploded-view-beyond-building/

Plants

Figure 04.4.05: Materials made from plants
Source: https://biobasedcreations.com/project/the-exploded-view-beyond-building/

Living Materials

Figure 04.4.06: Materials made from living organisms
Source: https://biobasedcreations.com/project/the-exploded-view-beyond-building/

Food

Figure 04.4.07: Materials deriving from food waste
Source: https://biobasedcreations.com/project/the-exploded-view-beyond-building/

Sewage

Figure 04.4.08: Materials made from purified sewage waste
Source: https://biobasedcreations.com/project/the-exploded-view-beyond-building/

Earth

Figure 04.4.09: 1 - WONDERSTONE CLAYLIME - 2 - Permeable blocks made from dredged material from Dutch waterways WATERWEG / BAGGERBE-STRATING - 3 - Rammed earth wall HET LEEMNISCAAT
Source: https://biobasedcreations.com

Water

Figure 04.4.10: 1- Algal textile CAROLYN RAFF STUDIO / ALGAE BASED BIOPOLY-MER - 2 - Pressed seaweed tiles BLUE-BLOCKS, BLUE CITY - 3 - Seaweed tiles STUDIO KLARENBEEK & DROS
Source: https://biobasedcreations.com/project/the-exploded-view-beyond-building/

Fungi / Bacteria

Figure 04.4.11: 1 - Mogu Acoustic mycelium tiles - 2 - Mogu mycelim floor tiles - 3 - Biomason Biolith precast concrete tiles made from bacteria
Source: https://biobasedcreations.com/project/the-exploded-view-beyond-building/

Plants

Figure 04.4.012: 1 - Cork blocks GEN-CORK - 2 - Thermally modifies reclaimed roof decking GEBRUIKTEBOUWMATE-RIALEN - 3 - Insulation THERMO HANF COMBI JUTE
HEMPFLAX
Source: https://biobasedcreations.com

Living Materials

Figure 04.4.13: 1 - Water-buffering green-sloped roof SMARTTY- 2 - Vegetated concrete prefab wall HOLCIM BOUW & INFRA - 3 - Bioreceptive concrete modules ECOLVE SCAPE AGENCY
Source: https://biobasedcreations.com/project/the-exploded-view-beyond-building/

Food

Figure 04.4.14: 1 - Corn husk TOTOMOX-TLE
FERNANDO LAPOSSE - 2 - OESTERPLAT D' WERKPLAATS MARJOLEIN STAPPERS - 3 - Cups made from waste coffee KAFFEEFORM
Source: https://biobasedcreations.com

Sewage

Figure 04.4.15: 1 - Tiles from sewage sludge waste MUDERNISM STUDIO BILLIE VAN KATWIJK - 2 - Panels cellulose fibres recycled toilet paper NABASCO® 8010 NPSP BV- 3 - Printed building elements from water treatment plant OMLAB
Source: https://biobasedcreations.com

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Flowchart

A flowchart for decision-making is a visual representation that outlines the steps or processes involved in making a choice or reaching a conclusion. It helps individuals or teams systematically evaluate options, consider factors, and arrive at a well-informed decision.

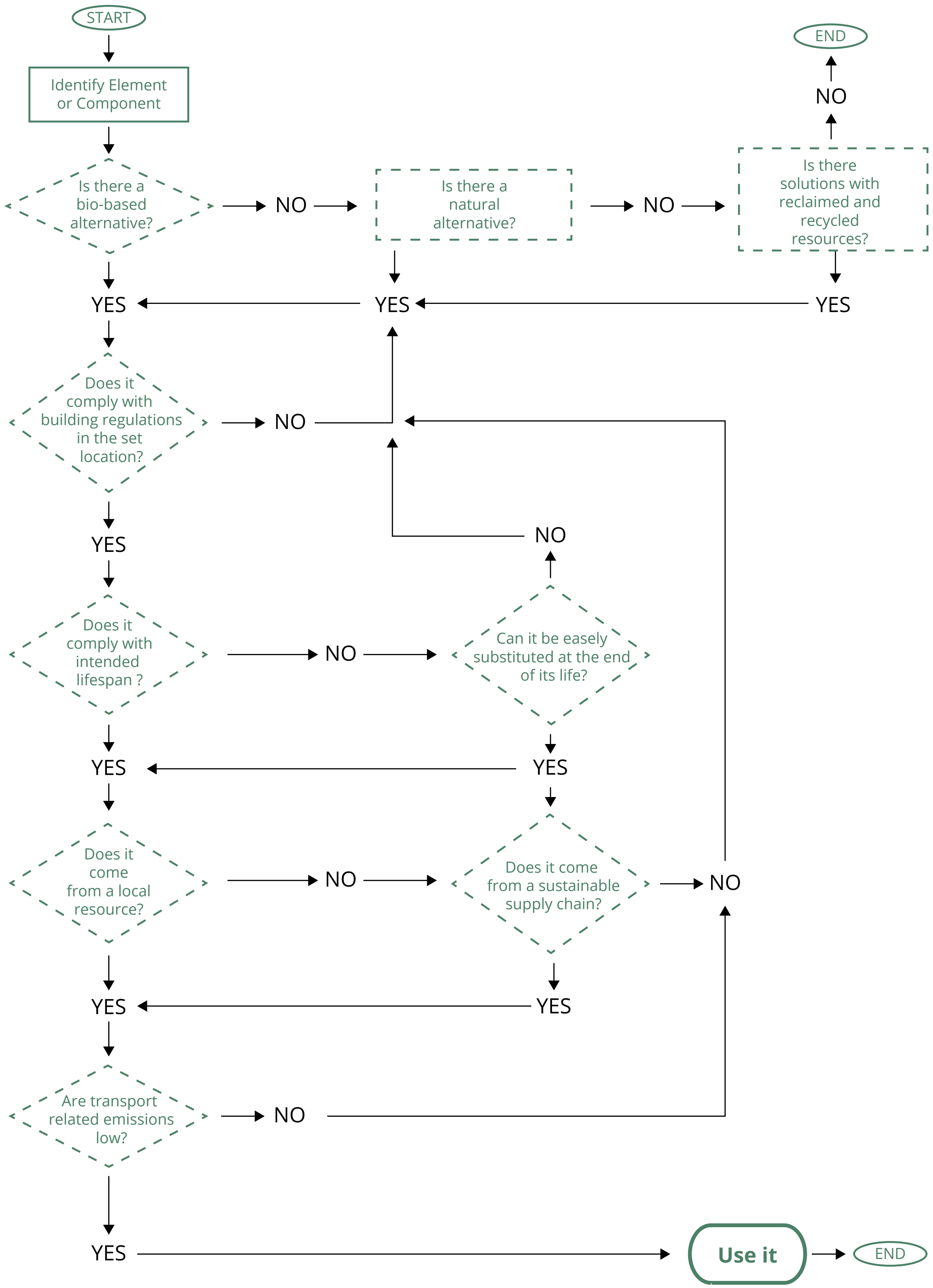
The decision in question: Is there a bio-based alternative that meets the needed requirements?

The decision centres on adopting bio-based solutions instead of conventional building materials, however, it is important to recognize that while a flowchart simplifies the process, reality is much more complex. It involves considering numerous aspects, from technical details and performance, environmental impact and costs and standards and regulations. While a flowchart helps illustrate this process, it is crucial to acknowledge that real-world considerations go beyond its boundaries. Decision-making involves thoroughness, collaboration, and finding the right balance between sustainability, performance, and practicality.

That being said, the following flowchart provides an example of some of the considerations that could be made during decision-making processes. It offers a glimpse into the factors involved in determining the feasibility of adopting bio-based alternatives instead of more conventional building materials that are more impactful to the environment. It can be used at the design phase or when assessing the choices made. It can be used for both new constructions, and in existing constructions in retrofit designs.

Figure 04.5.01: On the right - Decision making - Flowchart
Source: Drawing made by the author of the thesis

Flowchart
Decision-making process to adopt a bio-based solutions



While the questions in this flowchart are simplified for the sake of clarity and ease of visualization, it is crucial to recognize the value of these seemingly straightforward inquiries. In the realm of architectural decision-making, even simple questions can serve as powerful catalysts for thoughtful consideration.
These questions encourage stakeholders to engage in a thought process, where they examine the different aspects of a project. By simplifying complex decisions into smaller parts, these basic questions make it easier to assess different materials and potential alternatives for their environmental impact. This flowchart underscores the idea that simplicity in questions can be a starting point for a more in-depth analysis and encourages thorough exploration of alternatives.

Is there a bio-based alternative?

This question serves as the initial step in exploring sustainable options for construction. It prompts stakeholders to consider whether there are alternative building materials or products available that are derived from renewable, bio-based sources such as plants or recycled materials. It encourages the exploration of eco-friendly alternatives from the outset.

When there is no bio-based alternative available, **Is there a natural alternative?** This question explores the possibility of using natural materials that are also derived from the environment. Natural alternatives can include materials like stone, wood, or clay, which have been used in construction for centuries. Choosing natural materials can reduce the environmental footprint and promote a possible alternative (to conventional materials) with a lower impact depending on the context and project.

If neither bio-based nor natural alternatives are viable, **Is there a solution with reclaimed and recycled resources?** This question encourages the consideration of materials made from reclaimed or recycled resources. Such materials are often derived from salvaged or post-consumer sources, reducing waste and conserving resources. Using reclaimed and recycled materials aligns with sustainability goals by extending the life cycle of materials and reducing the need for virgin resources.

In all three cases the thought process has to delve into other consideration, for example:

Does it comply with building regulations in the set location?

Building regulations and codes can vary significantly from one location to another. This question emphasizes the importance of ensuring that any chosen bio-based - natural or other - alternative complies with the specific building codes, zoning ordinances, and safety regulations applicable to the project's location. It underscores the need for legal and structural compliance. Following another consideration referrers to:

Does it comply with intended lifespan?

The intended lifespan of a building or construction project is a crucial consideration. This question prompts stakeholders to assess whether the selected bio-based alternative is durable enough to meet the project's longevity requirements. It ensures that the chosen material can withstand environmental factors and usage demands over time. When the alternative does not comply, it should be considered if it is easily substitutable and if, at the end-of-life stage, it can "return to the soil" and therefore biodegradable or has to be discarted at a landfill. " Cascading bio-based materials implies subsequent uses for the material followed by final energy recovery or other forms of recovery (e.g., organic recycling if materials are compostable or biodegradable)" - ISO/DIS 59004 - ISO/TC 323 - *Circular Economy – Terminology, Principles and Guidance for Implementation*.

Does it come from a local resource?

This question addresses the sustainability aspect of material selection. It encourages the use of materials sourced locally, which can reduce the environmental impact associated with transportation, support local economies, and contribute to a smaller carbon footprint. It also fosters a sense of community engagement and resilience. The concept of what constitutes a "local" resource can vary significantly depending on the context, industry, and individual perspectives. What is considered local can depend on factors such as transportation infrastructure, cultural norms, and different industries. In manufacturing, the concept of "local sourcing" can vary based on supply chain considerations, transportation costs, and availability of raw materials. Some sustainability certifications, such as LEED (Leadership in Energy and Environmental Design), may have specific criteria for what qualifies as a local material based on environmental impact. When the resource is not local, another consideration can be made for the supply chain: **Does it come from a sustainable supply chain?** This question should not only refer to environmental sustainability but also social - ethical sustainability. When resources, materials, products come from a foreign country (but even in general) at times it is difficult to assess their impact because of lack of transparency, different and local standards that regulate supply chains differently. Some good practices could comprise consulting platforms and EPD and other certifications and declarations for the product and materials to have a better understanding of their origin and journey as well as aiding conscious decisions (Also see - 02.4 Prefabrication and material choice - Wood).

Lastly, another consideration can be directed towards:

Are transport related emissions low?

This question encourages stakeholders to evaluate the transportation-related carbon emissions associated with acquiring and delivering the bio-based alternative to the construction site. Choosing solutions with low transport emissions, as well as using local resources, can minimize overall impact.

/
Summary

Qualitative and quantitative data of materials

Key points

Material	Raw material resource	Availability of raw material	Degree of skills required for resourcing raw material	Degree of pre-fabrication	Awareness
Cork	● ● ● ◒	● ● ○ ○ ○	● ● ● ● ○	● ● ○ ○	● ● ● ● ●
Reed	● ○ ○ ○	● ● ● ● ●	● ○ ○ ○ ○	● ○ ○ ○	● ● ● ● ○
Seaweed	● ● ○ ●	● ● ● ○ ○	● ● ● ● ●	● ● ○ ○	● ● ○ ○ ○
Moss	● ● ○ ○	● ● ● ● ○	● ● ● ○ ○	● ● ○ ○	● ● ○ ○ ○
Mycelium	● ● ○ ●	● ● ○ ○ ○	● ● ● ● ●	● ○ ○ ○	● ○ ○ ○ ○
Plant fibres	● ● ● ○	● ● ● ● ●	● ● ○ ○ ○	● ● ○ ○	● ● ● ○ ○
Straw	● ● ● ○	● ● ● ● ●	● ○ ○ ○ ○	● ● ● ○	● ● ● ● ○
Husk	○ ● ● ●	● ● ● ● ●	● ● ● ○ ○	● ○ ○ ○	● ● ○ ○ ○
Wool	○ ● ● ●	● ● ● ● ○	● ● ● ○ ○	● ○ ○ ○	● ● ● ● ○
Seashells	○ ● ● ●	● ● ● ● ○	● ● ● ● ○	● ○ ○ ○	● ● ○ ○ ○
Cellulose - paper	○ ● ● ●	● ● ● ● ●	● ○ ○ ○ ○	● ○ ○ ○	● ● ○ ○ ○
Bio-plastics	● ● ● ●	● ● ● ● ○	● ○ ○ ○ ○	● ○ ○ ○	● ● ● ● ○
Bio-textile	● ● ● ○	● ● ○ ○ ○	● ○ ○ ○ ○	● ○ ○ ○	● ○ ○ ○ ○

Icon caption

Raw material origin

Virgin/primary resource
Recoverable resource
Recovered/secondary resource
Waste resource

● Yes
○ No
◒ At times

Degree of prefabrication

● Elements
● Components
● Moduls
● Units

Availability of raw material

Degree of skill required for resourcing the raw material

Awareness

● Very low
● Low
● Moderate
● High
● Very high

Applications

Technological units	Technical elements	Products category	Ck	Rd	Sw	Ms	My	Pf
vertical closures	external walls	masonry elements	●	○	●	○	●	●
		panels/boards	●	●	●	○	●	●
		thermo-acoustic insulation	●	●	●	●	●	●
		cladding/shingles/tiles	●	●	●	●	●	●
top closures	roof	cladding/tiles/shingles	●	●	●	○	○	●
		panels /False ceiling	●	○	○	○	○	●
		thermo-acoustic insulation	●	●	●	●	○	●
horizontal closures	slabs	flooring Tiles/Panels/boards	●	○	●	○	○	○
		thermo-acoustic insulation	●	○	○	○	○	●
partitions	vertical partitions	masonry elements	●	○	●	○	●	●
		panels/boards	●	●	●	●	●	●
		thermo-acoustic insulation	●	●	●	●	●	●
	horizontal partitions	flooring Tiles/Panels/boards	●	○	●	●	○	●
		thermo-acoustic insulation	●	○	○	●	○	●

Technological units	Technical elements	Products category	St	Hk	Wo	Ss	Cp	Bp	Bt
vertical closures	external walls	masonry elements	●	●	○	●	○	○	○
		panels/boards	●	●	○	○	●	●	●
		thermo-acoustic insulation	●	●	●	○	●	●	●
		cladding/shingles/tiles	●	●	○	●	○	●	●
top closures	roof	cladding/tiles/shingles	●	●	○	●	○	●	●
		panels/False ceiling	●	●	○	○	●	●	○
		thermo-acoustic insulation	●	●	●	○	●	●	●
horizontal closures	slabs	flooring Tiles/Panels/boards	○	○	○	●	○	●	○
		thermo-acoustic insulation	●	●	●	○	●	●	●
partitions	vertical partitions	masonry elements	●	●	○	○	○	○	○
		Panels/boards	●	●	○	●	●	●	○
		thermo-acoustic insulation	●	●	●	○	●	●	●
	horizontal partitions	flooring Tiles/Panels/boards	○	○	○	●	○	●	○
		thermo-acoustic insulation	●	●	●	○	●	○	●

Environmental impact indicators

When considering different environmental impact indicators, in order to be comparable data about materials must present common characteristics, therefore a limitation lies in the system boundaries as well as the functional unit object of the LCA analysis. In regards to material presented in the guidelines, not all data was obtained from the same software, and not all system boundaries and functional units are the same across material. Therefore, the comparison can be done only for some of the materials. The data reported above refers to LCA obtained from the SimaPro software.

GWP

Impact category	Unit		Ms	Pf2	Pf3	Pf4	Pf5	St	Hk*	Wo
Total	kg CO_2 eq.	Total	**1.417**	**-0.359**	**-2.720**	**-9.655**	**-2.414**	**-1.577**	**0.201**	**22.760**
Climate change - fossil	kg CO_2 eq.		1.291	0.025	1.561	0.913	0.559	0.073	0.055	7.279
Climate change - biogenic	kg CO_2 eq.		0.126	0.053	0.169	0.473	0.000	0.000	0.000	18.841
Climate change - CO_2 uptake	kg CO_2 eq.		-0.001	-0.438	-4.790	-11.043	-2.974	-1.650	0.000	-6.656
Climate change - land use and transformation	kg CO_2 eq.		0.000	0.000	0.340	0.002	0.000	0.000	0.146	3.295

GWP - data obtained from the SimaPro software - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 - Characterisation - Refers to 1 Kg of material / raw material resourcing
* Husk refers to rice husk and LCA does not comprise the cultivation and harvesting of rice

Embodied energy

Impact category	Unit		Ms	Pf2	Pf3	Pf4	Pf5	St	Hk*	Wo
Total	MJ	Total	**14.314**	**5.318**	**68.251**	**134.478**	**34.816**	**18.040**	**1.832**	**126.181**
Non renewable, fossil	MJ		14.151	0.209	12.046	7.642	0.432	0.437	1.809	19.636
Non renewable, nuclear	MJ		0.097	0.014	0.309	0.844	0.005	0.001	0.012	0.687
Non renewable, biomass	MJ		0.000	0.000	0.001	0.001	0.000	0.000	0.000	23.776
Renewable, biomass	MJ		0.007	5.088	55.639	125.516	34.377	17.600	0.000	81.384
Renewable, wind, solar, geothermic	MJ		0.018	0.002	0.059	0.139	0.001	0.000	0.000	0.121
Renewable, water	MJ		0.042	0.006	0.196	0.336	0.3002	0.001	0.012	0.578

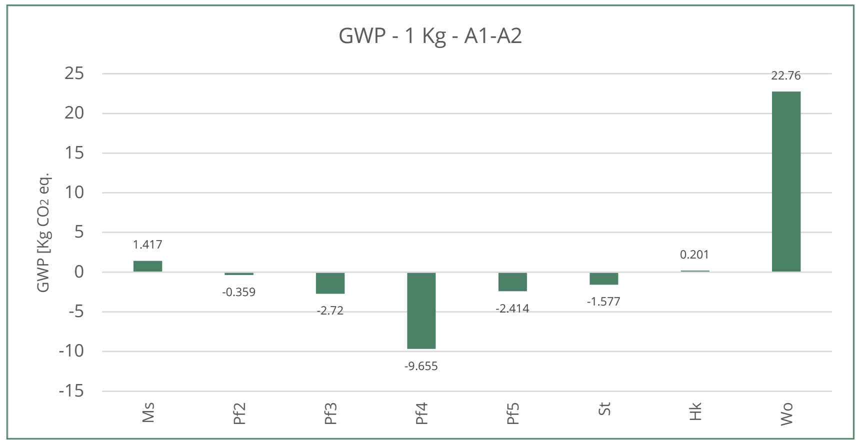
EE - data obtained from the SimaPro software - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation Refers to 1 Kg of material / raw material resourcing
* Husk refers to rice husk and LCA does not comprise the cultivation and harvesting of rice

Impact category	Unit		Ms	Pf2	Pf3	Pf4	Pf5	St	Hk*	Wo
Acidification	mol H+eq.	Total	0.0003	0.0009	0.076	0.031	0.030	0.000	0.003	0.776
Eutrophication, freshwater	Kg P eq.		0.0000	0.0000	0.021	0.000	0.012	0.000	0.000	0.008
Eutrophication, marine	Kg N eq.		0.0001	0.0006	0.037	0.019	0.081	0.000	0.001	0.132
Eutrophication, terrestrial	mol N eq.		0.0010	0.0041	0.335	0.135	0.138	0.002	0.012	3.450
Water use	m³ depriv.		0.0066	0.5852	5.084	18.134	0.014	0.059	0.729	5.819

Data obtained from the SimaPro software - Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation / 1 Kg
* Husk refers to rice husk and LCA does not comprise the cultivation and harvesting of rice

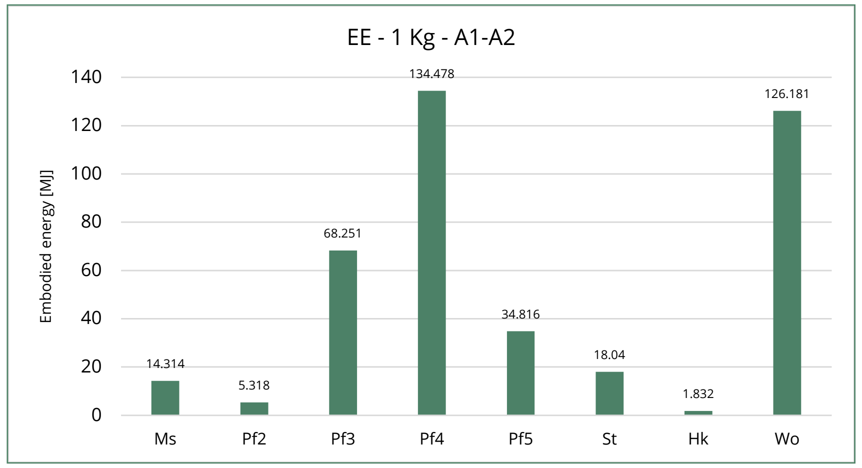
GWP

GWP - data obtained from the SimaPro software - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 - Characterisation
Refers to 1 Kg of material



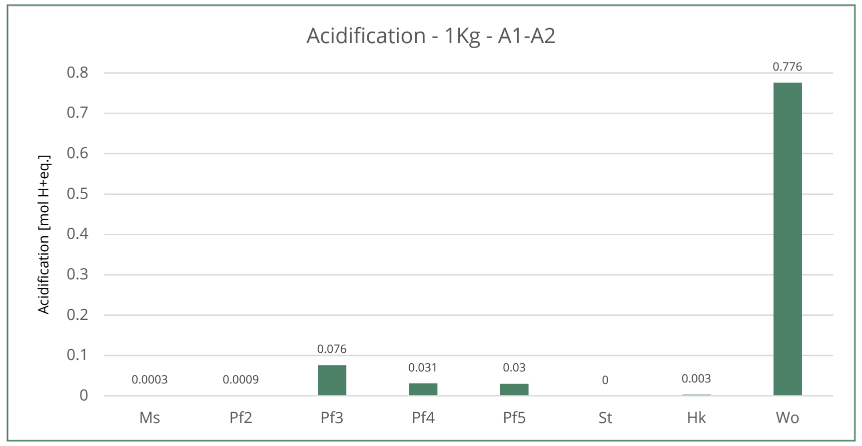
EE

EE - data obtained from the SimaPro software - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation
Refers to 1 Kg of material



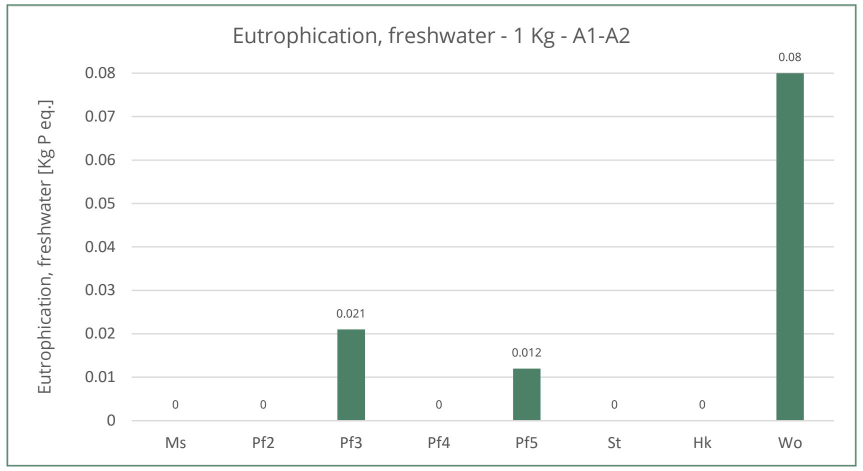
Acidification

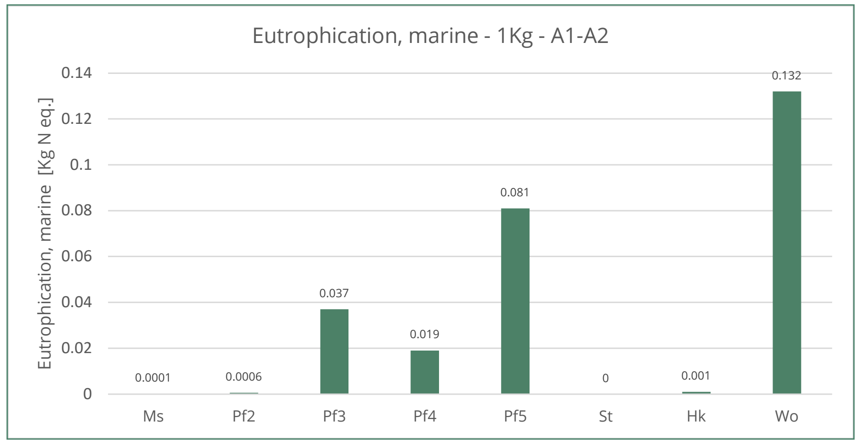
Data obtained from the SimaPro software - Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation / 1 Kg



Eutrophication, freshwater

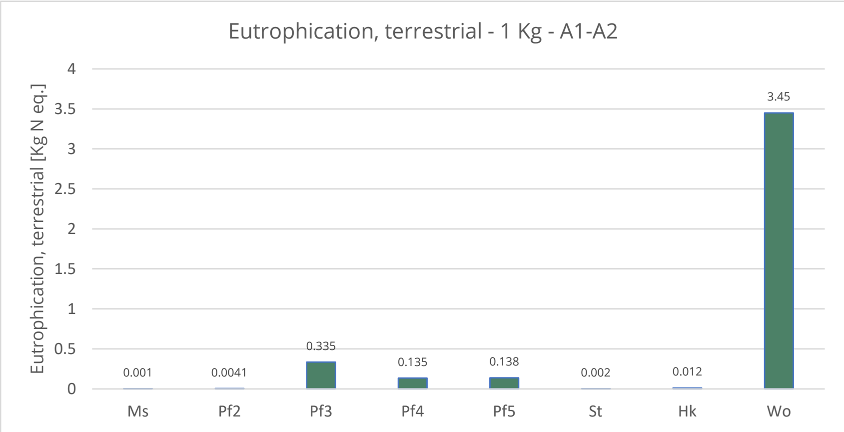
Data obtained from the SimaPro software - Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation / 1 Kg





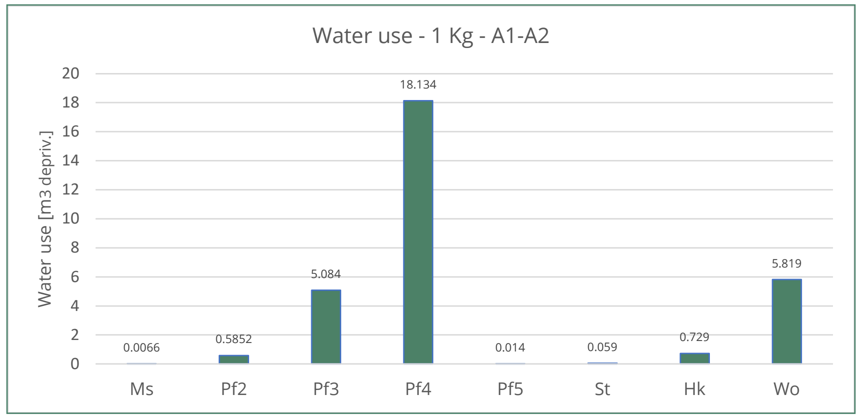
Eutrophication, marine

Data obtained from the SimaPro software - Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation / 1 Kg



Eutrophication, terrestrial

Data obtained from the SimaPro software - Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation / 1 Kg

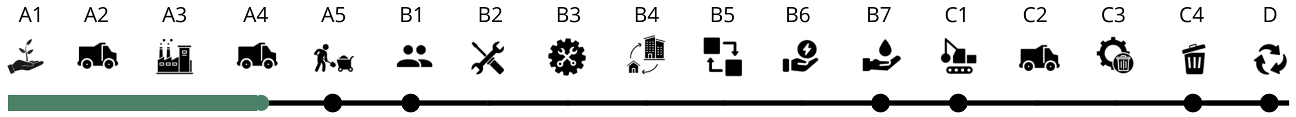


Water use

Data obtained from the SimaPro software - Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation / 1 Kg

The materials that comprised the same system boundaries are Ms - Moss (peat moss for horticulture), Pf2 - Kenaf, Pf3 - Jute, Pf4 - Flax, Pf5 - Cotton, St - Straw, Hk - Husk and Wo - Wool.

The LCA analysis referred to the A1-A2 life cycle stages and 1 Kg of raw material. Notably when considering GWP the highest number is that of wool, as the analysis considered sheep husbandry in terms of wool and sheep live weight. Second to wool is moss, and all other plant fibres and straw present a negative value (biogenic carbon - CO_2 uptake).
Across other impact indicators, wool seams to present the highest impact, with an exception for water use were flax holds the highest values.



GWP

Impact category	Unit	Total	Ck
Total	kg CO_2 eq.		**-10.778**
Climate change - fossil	kg CO_2 eq.		0.013
Climate change - biogenic	kg CO_2 eq.		0.004
Climate change - CO_2 uptake	kg CO_2 eq.		-10.80
Climate change - land use and transformation	kg CO_2 eq.		0.002

GWP - data obtained from the SimaPro software - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 - Characterisation Refers to 1 Kg of material / raw material resourcing

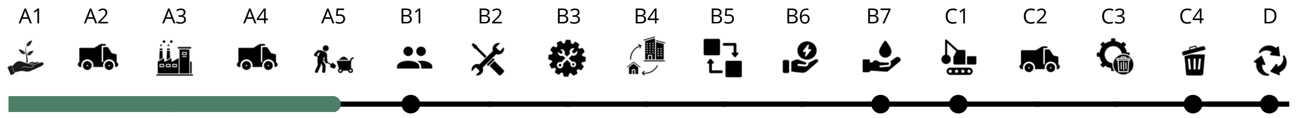
Embodied energy

Impact category	Unit	Total	Ck
Total	kg CO_2 eq.		**117.0212**
Non renewable, fossil	kg CO_2 eq.		0.2018
Non renewable, biomass	kg CO_2 eq.		0.0011
Non renewable, nuclear	kg CO_2 eq.		0.0024
Renewable, biomass	kg CO_2 eq.		116.8153
Renewable, wind, solar, geoth.	kg CO_2 eq.		0.002
Renewable, water	kg CO_2 eq.		0.005

EE - data obtained from the SimaPro software - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation Refers to 1 Kg of material / raw material resourcing

Impact category	Unit	Total	Ck
Acidification	mol H+eq.		0.0001
Eutrophication, freshwater	Kg P eq.		0.0000
Eutrophication, marine	Kg N eq.		0.0001
Eutrophication, terrestrial	mol N eq.		0.0005
Water use	m³ depriv.		0.0053

Data obtained from the SimaPro software - Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation / 1 Kg



GWP

Impact category	Unit	Total	Cp
Total	kg CO_2 eq.		**0.253**
Climate change - fossil	kg CO_2 eq.		0.219
Climate change - biogenic	kg CO_2 eq.		0.036
Climate change - CO_2 uptake	kg CO_2 eq.		-0.002
Climate change - land use and transformation	kg CO_2 eq.		0.000

GWP - data obtained from the SimaPro software - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 - Characterisation Refers to 1 Kg of material / raw material resourcing

Embodied energy

Impact category	Unit	Total	Cp
Total	kg CO_2 eq.		**3.107**
Non renewable, fossil	kg CO_2 eq.		2.648
Non renewable, biomass	kg CO_2 eq.		0.270
Non renewable, nuclear	kg CO_2 eq.		0.000
Renewable, biomass	kg CO_2 eq.		0.024
Renewable, wind, solar, geoth.	kg CO_2 eq.		0.037
Renewable, water	kg CO_2 eq.		0.128

EE - data obtained from the SimaPro software - Cumulative Energy Demand V1.11 / Cumulative energy demand - Characterisation Refers to 1 Kg of material / raw material resourcing

Impact category	Unit	Total	Ck
Acidification	mol H+eq.		0.0018
Eutrophication, freshwater	Kg P eq.		0.0001
Eutrophication, marine	Kg N eq.		0.0004
Eutrophication, terrestrial	mol N eq.		0.0036
Water use	m³ depriv.		0.0579

Data obtained from the SimaPro software - Impact analysis - EF 3.0 Method (adapted) V1.01 / EF 3.0 normalization and weighting set - Characterisation / 1 Kg

Data referrers to the process describes the production of 1 kg of cellulose fibre from waste paper (post-consumer) used as an insulation material in buildings

Material	Elements / Components	Producers / Research	Case studies / Good practices
Cork	Cork insulation panels	Lis - (IT) - EPD - Slim and Lisoflex insulation panels	◦Cork House - Matthew Barnett Howland with Dido Milne and Oliver Wilton - (UK) ◦Poplar Grove - BLDUS - (U.S.A.)
		Tecnosugheri - (IT)	
		Granorte - (PT)	
	Cork rolls / insulation	Portugal Cork Co. - (PT)	
		Biosughero - (IT)	
	Cork flooring tiles	Granorte - (PT)	
		Biosughero - (IT)	
	Cork wall cladding	Portugal Cork Co. - (PT)	
		Tecnosugheri - (IT)	
		Granorte - (PT)	
	Cork blocks	Biosughero - (IT)	
Reed	Reed panels / Insulation	Lacep - (IT)	◦ecoSuites, A Reed-Clad Hotel / Alex A. Tsolakis Architecture ◦Mudhif - Reed vernacular houses - Iraq
		Terragena - (IT)	
		Leobodner - (IT)	
		UKU - (EE)	
		ReedTech - (EE)	
		Hiss Reet - (DE)	
	Reed rolls	Lacep - (IT)	
		Terragena - (IT)	
		Leobodner - (IT)	
		UKU - (EE)	
		Canaplex - (GR)	
	Reed composite panels	Circular matters - (FR)	
	Reed thatching tiles	The Lapa company - (UK)	
Seaweed	Seaweed fibrebords	BlueBlock - (NL)	◦ecoLogic studio - (UK) - Biobolla - Biennale Venezia ◦Sargablock - Mexico
	Seaweed Thatched panels	Kathryn Larsen - (DK)	
	Algae tiles	Ecolurian - (NL)	
	Algae purifying tiles	Indus - (UK)	
Moss	Moss insulation panels	Morandini et al., 2022	◦Moss voltaics Elena Mitrofanova IaaC ◦Green cities solutions - Peter Sänger and Liang Wu - (DE)
	Concrete moss panels	Respyre - (NL)	
	Moss wall panel	MOSSwall® - (IT)	
		Freund GmbH - (DE)	
	Moss mats	MOSSwall® - (IT)	
	Bio-concrete - ECOLVE	Scape Agency - (NL)	
Mycelium	Mycelium brick	Grown.bio (NL)	◦Mycotecture (2009) - U.S.A. ◦HI-FY (2014) - Museum of Modern Art and ◦MycoTree (2017) - Seul Biennale of architecture ◦Growing Pavilion (2019) - Dutch Design week and Floriade Expo (2022) and urbanism MoMA PS1, New York
	Mycelim-flooring - tiles	Mogu Srl – (IT)	
	Mycelim-panels	Grown.bio (NL)	
		Biohm – (UK)	
	Mycelium Acoustic sound absorbing panels	Mogu Srl – (IT)	
		Grown.bio (NL)	

Material	Elements / Components	Producers / Research	Case studies / Good practices
Plant fibres	Hemp-crete blocks	Isohemp - (BE)	◦ Flax bridge - Almere (NL) ◦ FITNESs Hemp and sheep-wool panels - (IT) - Politecnico di Torino ◦ Just BioFiber - (CA)
		Hanfstein - (IT) - Gervasi - (IT)	
		Tecno Canapa Senini - (IT) - Banca della calce - (IT)	
		Batinfo - (FR)	
	Insulation panels	**Hemp**	
		Ton-Gruppe - (IT)	
		Tecno Canapa Senini - (IT)	
		Ekolution - (SE) - EPD	
		Kobe - cz s.r.o - (CZ) - EPD	
		Hgmatthews - (UK)	
		Hemp - Kenaf	
		Artemestieri - (IT)	
		Euchora - (IT) - ANAB cert.	
		Kenaf	
		K.E.F.I. s.p.a. - (IT)	
		Masacustic - (IT)	
		Hemp - Jute	
		Ton-Gruppe - (IT)	
		Jute	
		Ton-Gruppe - (IT)	
		QBat - (CH)	
		Flax	
		Isolina - (IT)	
	Fibreboards / Particleboards	Jory Swart - (NL)	
		Hemp Traders - Canna Grove - (U.S.A.)	
	Mats / Felts	HempFlax - (NL)	
		KOBE -cz s.r.o. - (CZ) EPD	
		Thermo Hanf - (DE)	
		La Masiera - (IT) - Flax and sheep wool	
		Masacustic - (IT)	
	Acoustic panels	Hanfstein - (IT)	
		Silent Fibre - (DE)	
		EcoVerb™ Cotton Fiber Acoustic Panels - (U.S.A.)	
Straw	Straw bales	List of EU producer at: https://strawbuilding.eu/map-of-straw-bale-producers/	◦ Eco46 - Losanne - (CH) ◦ ViVihouse - New EU Bauhaus ◦ Casa Quattro - (IT) - LCA Architects
	Straw Panles	Lehm-laden - (DE)	
		NovoFibre - (DE)	
		Kodukuubis - (EE)	

Material	Elements / Components	Producers / Research	Case studies / Good practices
Straw	Straw Mats	TeMa Technologies & Materials S.r.l. - (IT)	
		SOILTEC - Greenfix - (DE)	
	Straw-Clay blocks	Claytec GmbH - (DE)	
		BCB - Beton Clay Blocks - (NL)	
		De Kleipot - (NL)	
	Lego Straw blocks	Oryzatech - (U.S.A.)	
	Straw Wall component	EcoCocoon - (SK)	
		Paille-tech - (FR)	
		ModCell - (UK)	
		Okambuva.coop - (ES)	
		Strawtec Group - (DE)	
		Strawbuild Ltd - (UK)	
Husk	Husk Acoustic panels	Aotta studio - (RU) - hemp husk	◦Rice House - (IT) ◦Rice House - (IT) - GAIA
		HexBix - (UK) - Wood and cocoa husk	
	Husk panels	Rice House - (IT) - Rice husk	
		Resysta -(DE) - Rice Husk -	
		Apilada Vorachart - (TH) - Corn husk (Cornspan)	
		NaturLoop AG - (CH) - Coconut husk - Cocoboard ©	
		Kedroplast - (RU) - Pine husk	
		Woodpecker - (CO) - Coffee husk panels	
		BIO-SIPs - (AU)	
	Husk bricks	Rice House - (IT) - Rice husk	
	Husk composite	RIWOOD - (NL)	
Wool	Wool Bats / Mats	Thermafleece - (UK) - EPD	◦Architecture workshop with AIT and IWTO - (NZ) ◦ The wool House Pavilion - AUW architectural festival Hello wood (2018)
		Round Tower Lime - (IE)	
		Bausep - (DE)	
	Wool Acoustic panels	Slalom ECOwool - (IT)	
		Tante Lotte - (UK)	
		Wollyshepherd - (UK)	
		Feltstudio - (U.S.A.)	
Seashells	Shellcrete	localworksstudio.com	◦Coquina (shell block) quarry - WE (AU) ◦Oyster-tecture Brooklin, NY - Kate Orff / SCAPE
		construction21.org	
	Seastone	Newtab-22	
	Seashell Thamed glass cladding tiles	luluharrisonstudio.com	
		b-de-c.com	

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Part three

"Designers face an unprecedented urgency to alter their methods and reprioritize their goals to address the accelerating degradation of the environment. This new pressure - intellectual, ethical, and regulatory- demands recognition of the fragility of nature and our responsibility to preserve it for future generations."

William Myers
Bio Design: nature, science, creativity

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Chapter five:

Guidelines application, RE-TREE-T project

05.1 Introduction

The RE-TREE-T project is part of an ongoing research between The Ne[s]t Studio, the Club del Sole and the Politecnico di Torino.

the ne[s]t

The Ne[s]t

The ne[s]t studio is a team of professionals with a strong grasp of architectural design that works in harmony with nature. Their expertise lies in creating prefabricated housing modules. Each of their projects features a unique stylistic approach of 'minimal green,' often drawing inspiration from advanced parametric and bio-mimetic design. Heading the studio is Paolo Scoglio, the Architect Design Manager, who describes his architectural projects as 'natural devices.' These structures blend seamlessly with their environment, designed to be reversible to minimize their impact on the landscape. These designs also prioritize practicality for short-term, intelligent living spaces, seamlessly integrating high-tech elements with natural materials.

The ne[s]t studio is responsible for the design of the RE-TREE-T, a focal point of a research endeavour.

Club del Sole

The Club del Sole organisation is specialized in outdoor holidays. It has 20 holiday villages throughout Italy. The project specifically takes place at the Spina Family Camping Village, in the Lidi Ferraresi, near Comacchio (FE). The Spina Family Village is one of the largest facilities in Emilia Romagna of the Club del Sole, it comprises many accommodation solutions ranging from pitches to bungalows, from mobile homes to glamping. The location is immersed in the nature of the Po Delta Park, between the Comacchio Saline and the Adriatic Sea.

Politecnico di Torino

The Politecnico di Torino, with scientific manager Thiébat Francesca, and myself Fiamma Morselli as part of a research project, are collaborating with the two partners in regards to the assessment of the project and prototype to explore solutions in regard to integration of strategies for a more bioclimatic design as well as for the development of a meta-project, according to the demand-performance approach aimed at the technological design of environmentally friendly modular structures.

The ongoing research project started on the 20th of June 2023. The onsite construction of the RE-TREE-T project took place in Lido di Spina, Comacchio at the Spina Family Camping Village from the 26th and 31st of July 2023.

Figure 05.1.1 Construction site - Lido di Spina - Comacchio - (FE) - collaboration - research project
Source: Picture taken by the author of the thesis

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RE-TREE-T

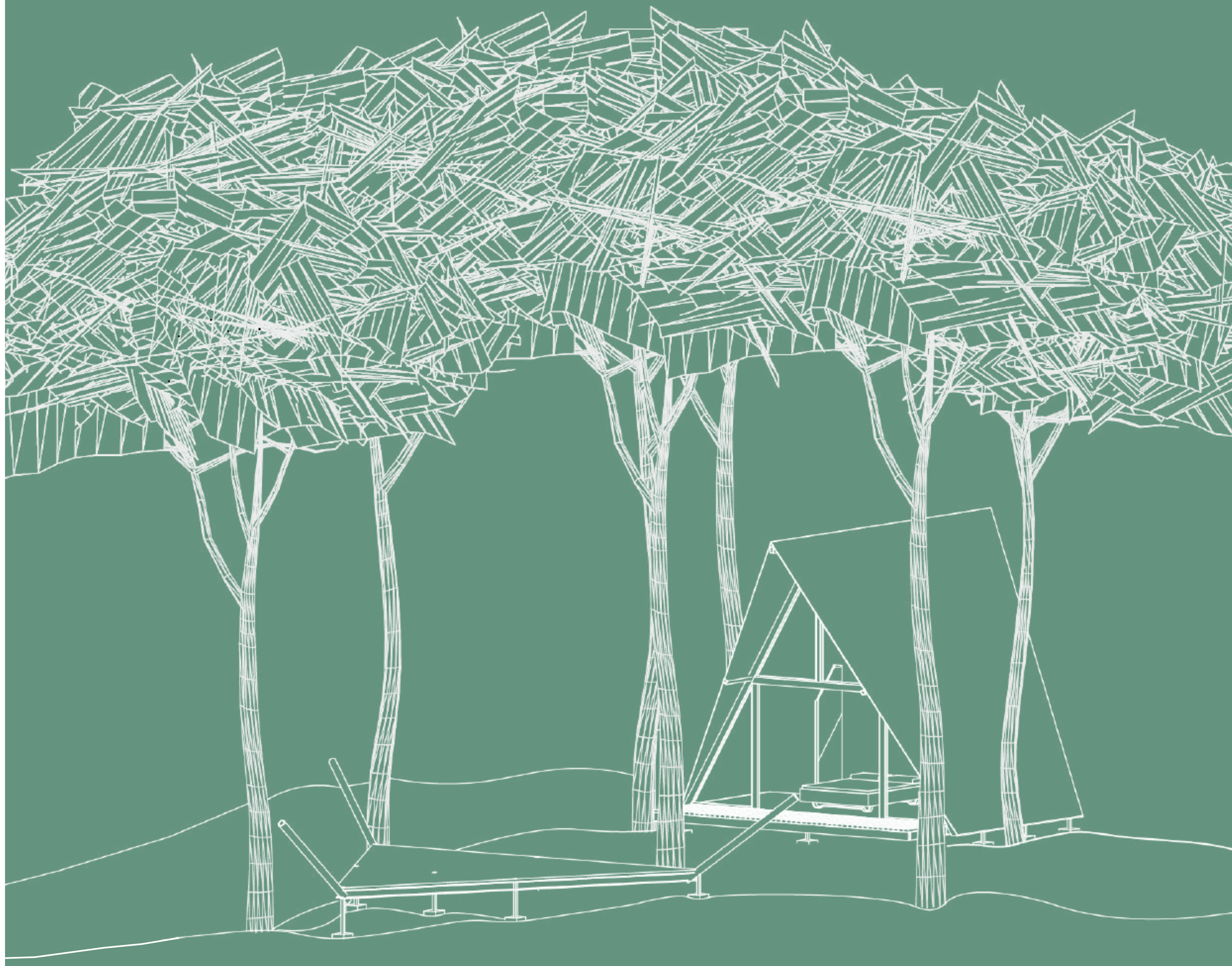
Client
Club del Sole

Architects
The Ne[s]t

Company
Scaffsystem

Surface
29 mq + 23 mq

Time
1 month Project design
1.5 month Off-site construction
6 days On-site assemblage



05.2 The research project

The RE-TREE-T project stems from the desire to create spaces intended for open-air hospitality dwellings in symbiosis with nature, with low environmental impact, rapidly transformable, modular and modifiable over time to meet evolving requirements. The challenge is to propose a different way of living in the natural space. The prototype of the RE-TREE-T project will be contextualized in the Spina Family Camping Village.

The collaboration between the three entities strives to create an innovative solution that is founded on sustainability and circularity principles, as wetll as integrates bio-climatic strategies and design.
The project is divided into different stages to assess and integrate the technological design of the prototype that has been constructed from 26/07 to 31/08 2023. Parallel to the construction of the prototype, a climatic survey station and sensor have been set up at the site to monitor both the external and internal conditions to evaluate how the prototype design responds to said conditions. Following this first analysis there will be an assessment of collected data and exploration of possible passive strategies.

The project takes on a multifaceted approach, encompassing its innovative design philosophy, real-world implementation, and data-driven analysis. This approach underscores its evolving nature, drawing inspiration from and harmonizing with the natural environment it inhabits.

Figure 05.3.1 Lido di Spina location - Comacchio - (FE)
Source: Drawing made by the author of the thesis

Figure 05.3.2 Lido di Spina - in the Delta del Po Natural Park
Source: Drawing made by the author of the thesis

05.3 The context

Location: Lido di Spina, Comacchio - (FE) - Italy
Coordinates: 44°37'40.1"N 12°15'25.8"E
Elevation: 2 m.s.l.

The context in which the project is located is The Spina Family Camping Village near Comacchio (FE) and set in between the Saline and Spina Lake and subsequently the beach on the Adriatic Sea, the major body of water adjacent to the location.

The site is completely immersed in the natural context of the Parco Delta del Po (Delta del Po Regional Park) that is part of the UNESCO World Heritage. It's a regional park in northern Italy, located in the Po Delta, where the Po River flows into the Adriatic Sea. The park is known for its unique wetland ecosystem, rich biodiversity, and important role as a sanctuary for various bird species and aquatic life. The area is characterized by lagoons, marshes, dunes, and coastal environments, making it a significant natural and cultural heritage site. The landscape is characterized by a rich tapestry of trees and plants. The vast area of the village site is for the most part covered by a pine forest that creates a suitable shaded ground for open-air holidays. The Pine forest hosts different types of dwelling and facilities but mainly provide a isolating and protecting environment to fully immerse in nature.

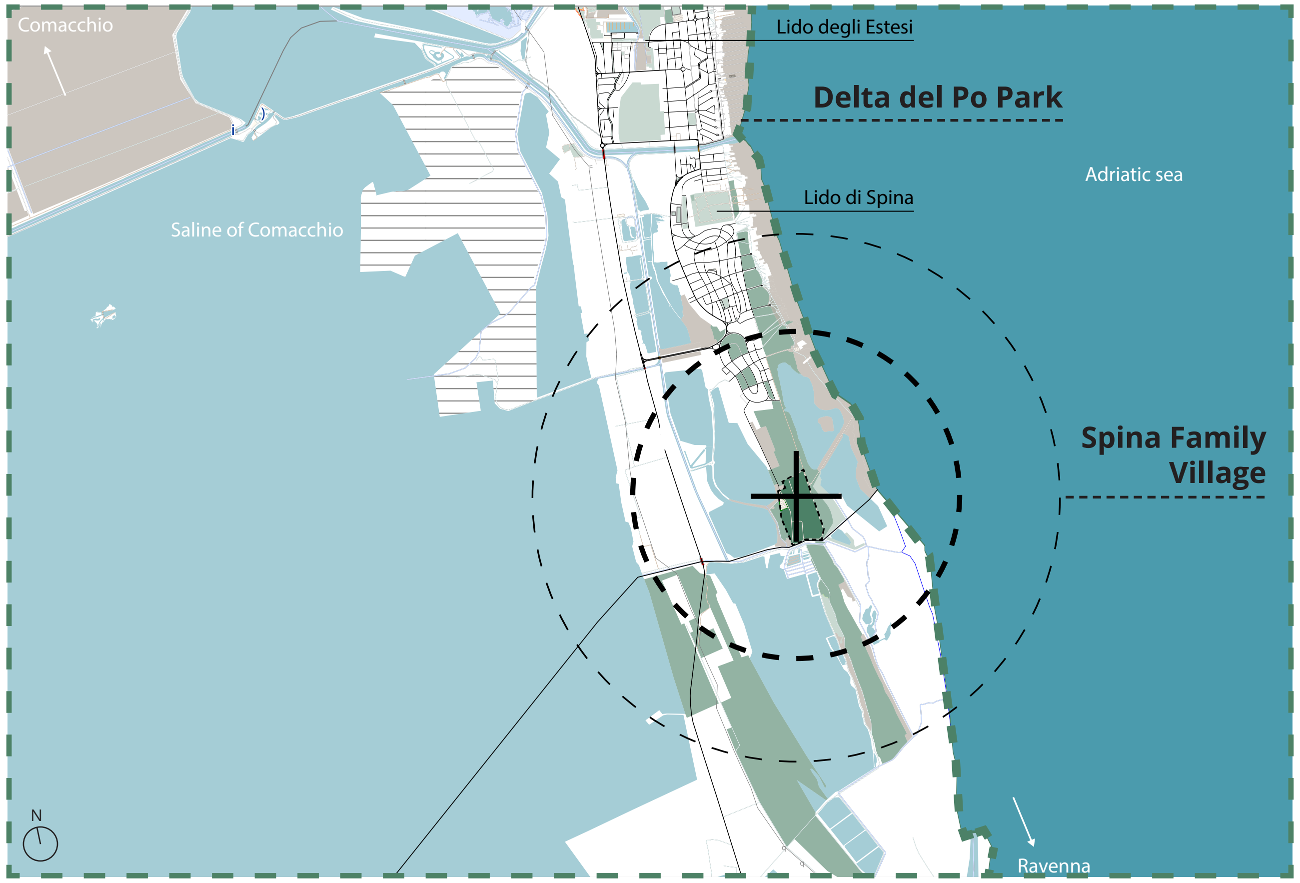


Figure 05.3.3 Lido di Spina - context
Source: Drawing made by the author of the thesis

Out of scale

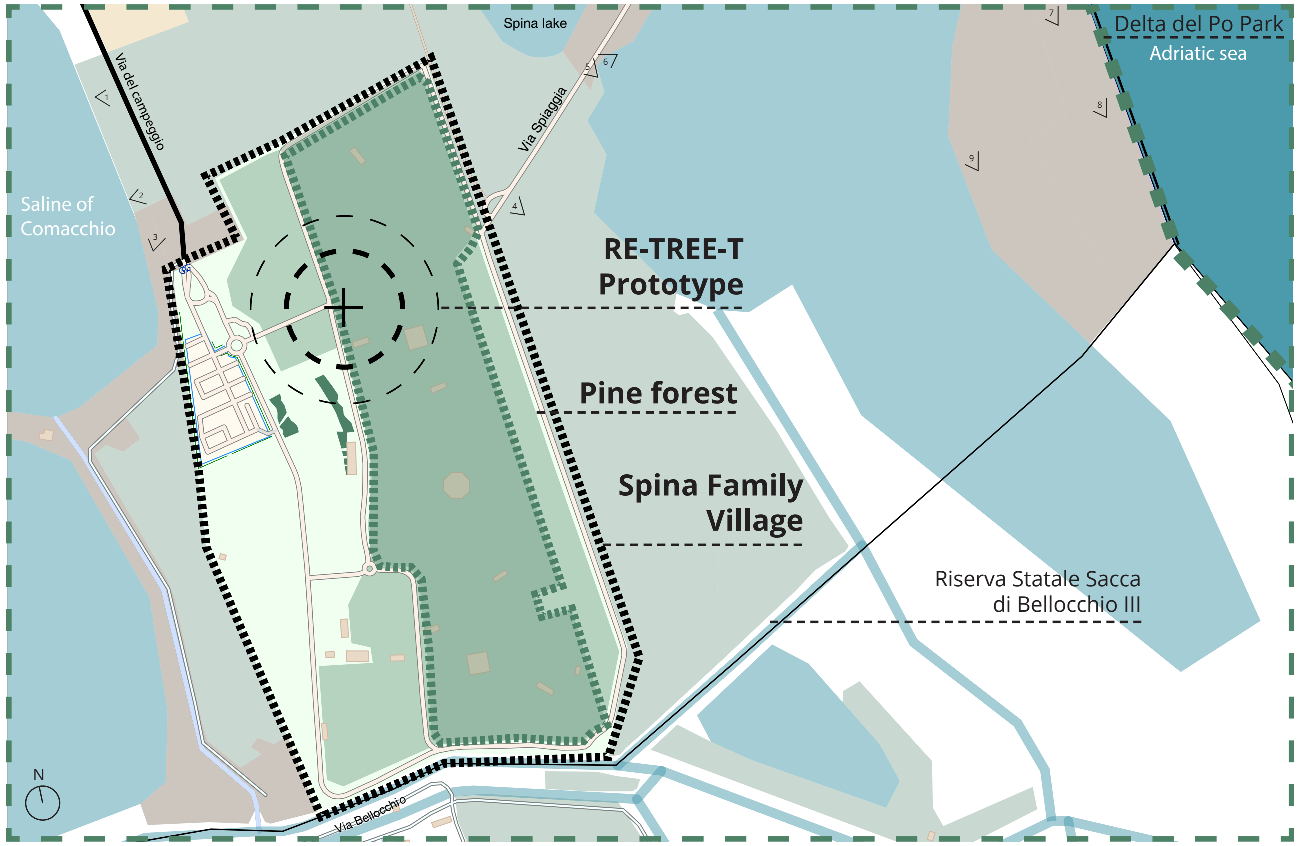


Figure 05.3.4 Lido di Spina - Spina Family Village - RE-TREE-T prototype
Source: Drawing made by the author of the thesis

Out of scale

The Saline

Figure 05.3.5: Saline of Comacchio (1)
Source: Picture taken by the author of the thesis

Figure 05.3.6: Saline of Comacchio (2)
Source: Picture taken by the author of the thesis

Figure 05.3.7: Saline of Comacchio (3)
Source: Picture taken by the author of the thesis

Spina Lake

Figure 05.3.8: Bird watching tower in front of Riserva Statale Sacca di Bellocchio III (4)
Source: Picture taken by the author of the thesis

Figure 05.3.9: Riserva Statale Sacca di Bellocchio III (5)
Source: Picture taken by the author of the thesis

Figure 05.3.10: Riserva Statale Sacca di Bellocchio III (6)
Source: Picture taken by the author of the thesis

Adriatic Sea - Spina beach

Figure 05.3.11: Adriatic Sea (7)
Source: Picture taken by the author of the thesis

Figure 05.3.12: Adriatic Sea (8)
Source: Picture taken by the author of the thesis

Figure 05.3.13: Adriatic Sea (9)
Source: Picture taken by the author of the thesis

Pine Forest

Figure 05.3.14: Pine Forest in front of the restaurant facilities of the Spina Family Camping Village (1)
Source: Picture taken by the author of the thesis

Figure 05.3.15: Pine Forest inside Spina Family Camping Village (2)
Source: Picture taken by the author of the thesis

Figure 05.3.16: Pine Forest outside Spina Family Camping Village (3)
Source: Picture taken by the author of the thesis

05.4 The architectural project

The RE-TREE-T architectural project originates from the natural context it is immersed in. The restrictions and limitations of the site have given the boundaries of the design: temporality and reversibility, adaptation to the specific of the landscape both in regards to the trees of the pine forest and the sand dune and finally a design that allows for direct engagement with the surroundings. The starting point of the project was a detailed analysis of the site with a digital mapping of the area to document the flora of the Spina Family Camping Village's centuries-old pine forest and thus be able to integrate the housing facilities among the existing trees, without altering their current ecosystem. For this reason, the project envisaged a reversible anchoring of the foundation system that comprises of steel plates. The RE-TREE-T dwelling consists of two modular elements, a main tent and a platform, which, are located at different heights and connected via a staircase system. The two modules incorporate a combination of different technologies and materials. The main tent is a prefabricated module in a triangular shape that consists of a steel frame, spruce plywood external walls, partitions and flooring panels, and a tensile fabric that covers the whole construction. This prefabricated system is set on a steel frame that is connected to the soil through steel plates. The main tent is conceived more as a comfortable dwelling provided with a bathroom, dressing room and a bedroom. Similarly, the platform in a triangular shape consists of a steel frame on top of steel plates and covered with massaranduba wood as a decking floor. The edge of the triangular platform presents three angled posts on which a secondary suspended tent is anchored. Need it be that the evolving and dynamic nature of the design must accommodate and satisfy different requirements over time the spaces can be changed. For example, the suspended tent can be removed and give space to a functional terrace for relaxing and conviviality.

The Prototype

The first prototype of the project, characterized with the configuration described above, is located on a plot at the intersection of the two main roads of the village, one central spine and the other projected towards the see.

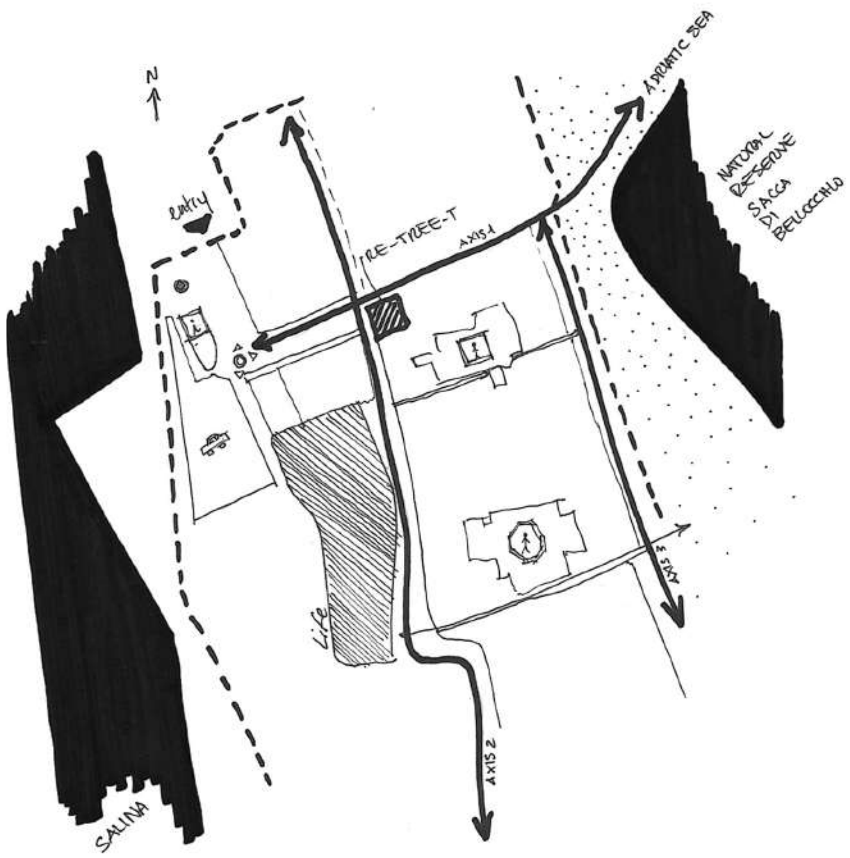
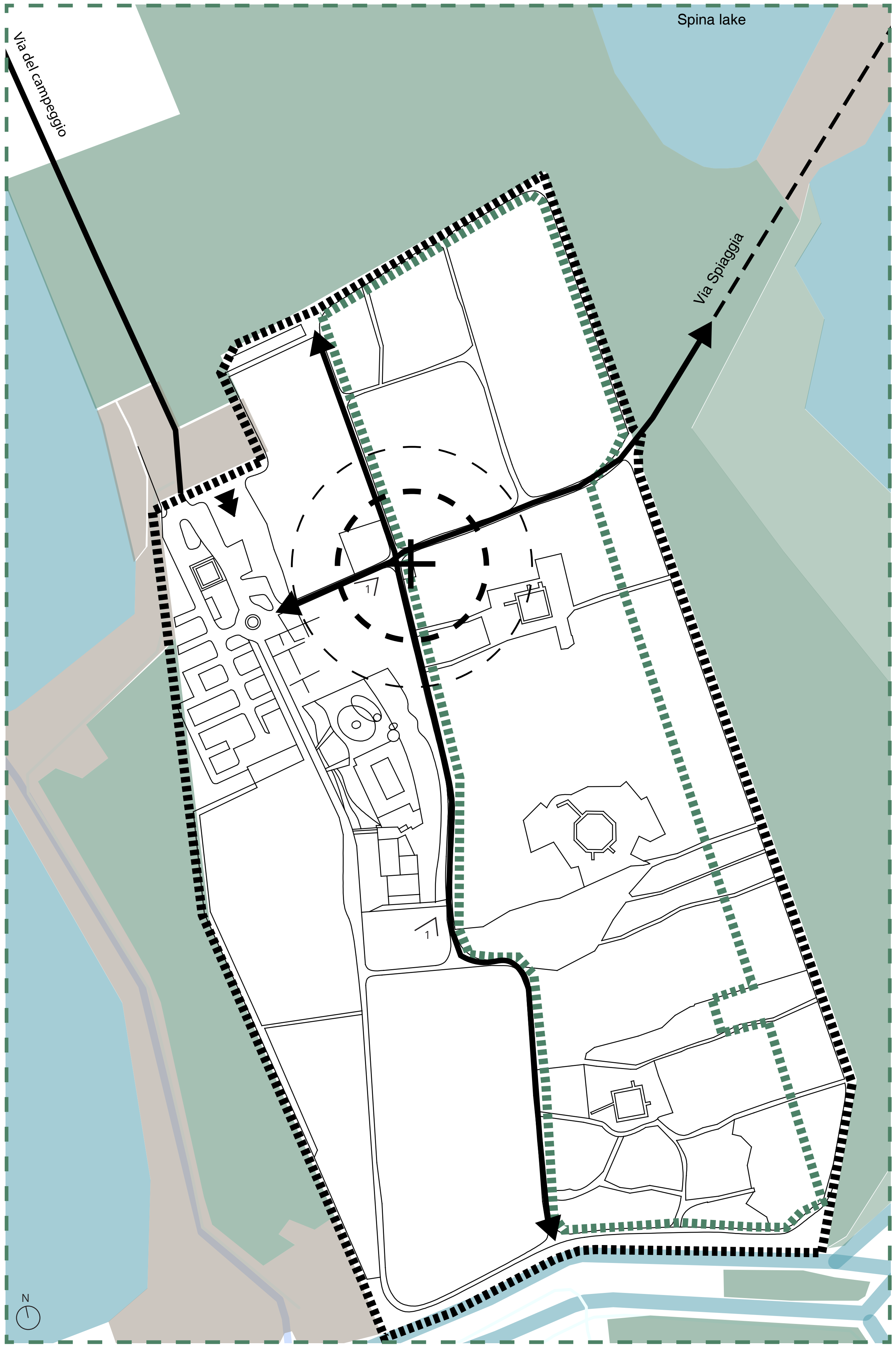


Figure 05.4.1: Sketch of the site - context - the RE-TREE-T location on the main 2 axis - the services - the viability
Source: Drawing made by the author of the thesis

Figure 05.4.2: Sketch of the site - context under the pine forest
Source: Drawing made by the author of the thesis

Figure 05.4.3: Map - The site -of the Spina Family Camping Village - out of scale
Source: Drawing made by the author of the thesis



Floor Plan

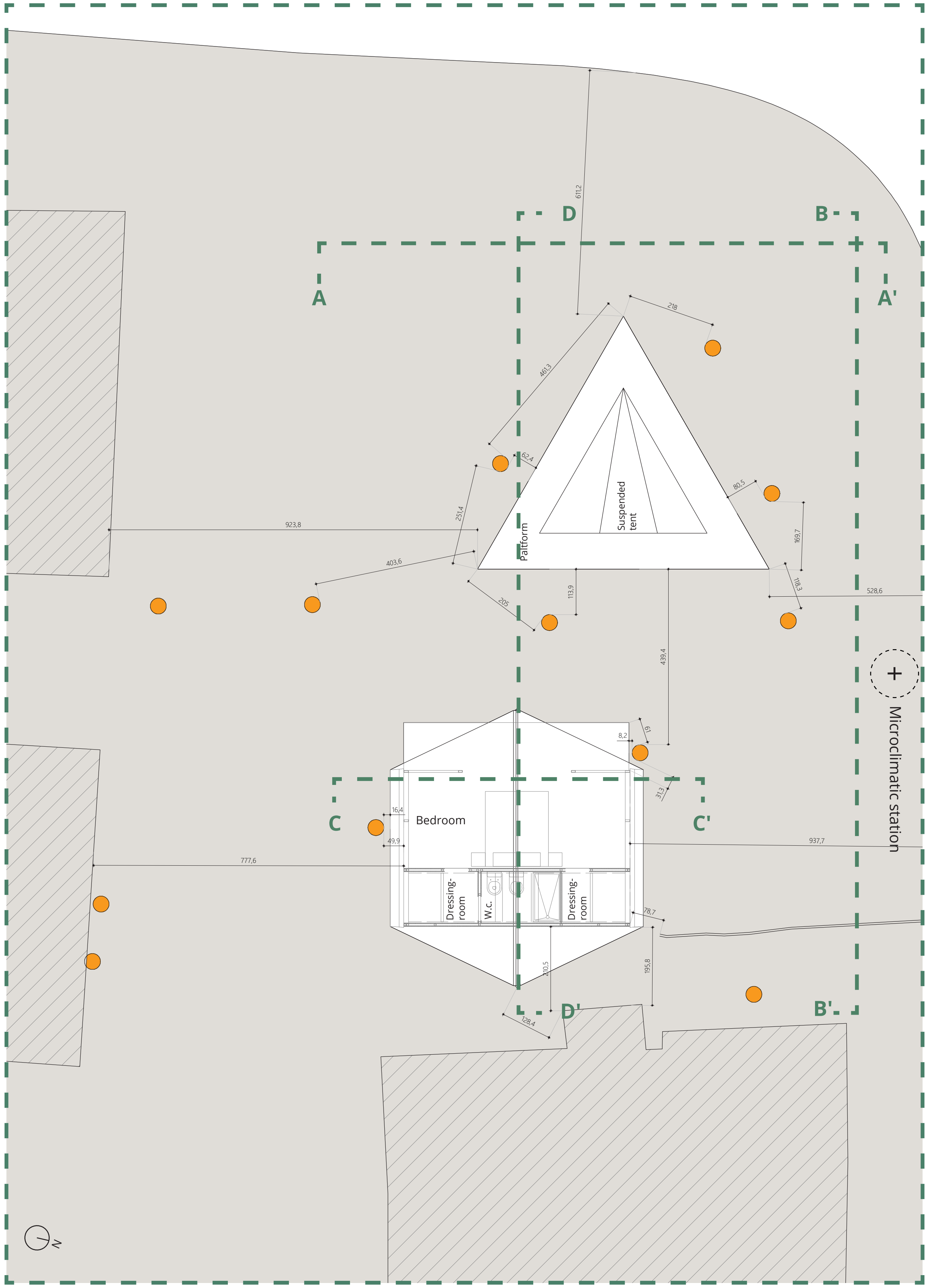


Figure 05.4.4 RE-TREE-T Floor plan
Source: Drawing by the ne[s]t studio and re- elaborated by the author of the thesis

Elevation AA'

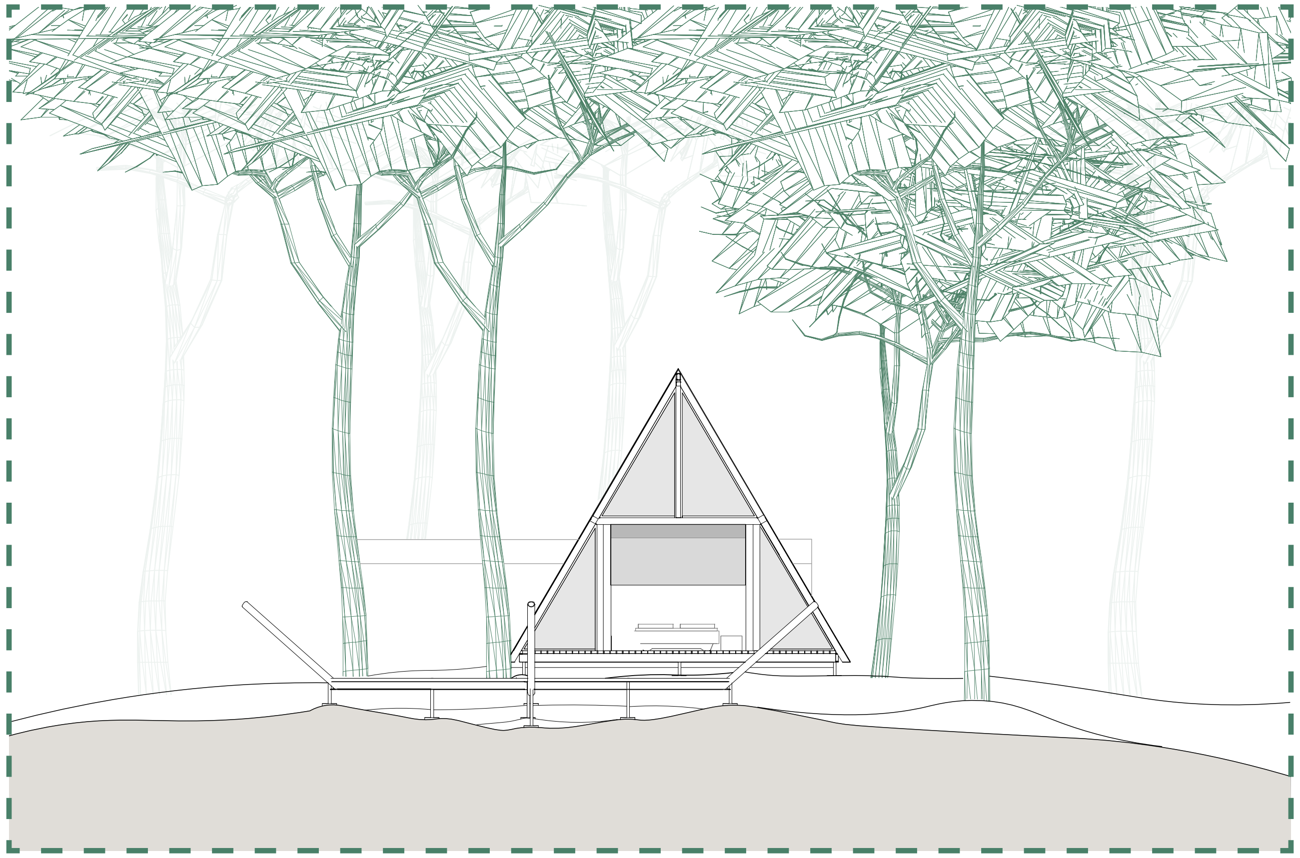


Figure 05.4.5 Elevation AA'
Source: Drawing made by the author of the thesis

Elevation BB'

Figure 05.4.6 RE-TREE-T Elevation BB'
Source: Drawing made bythe author of the thesis

Section CC'

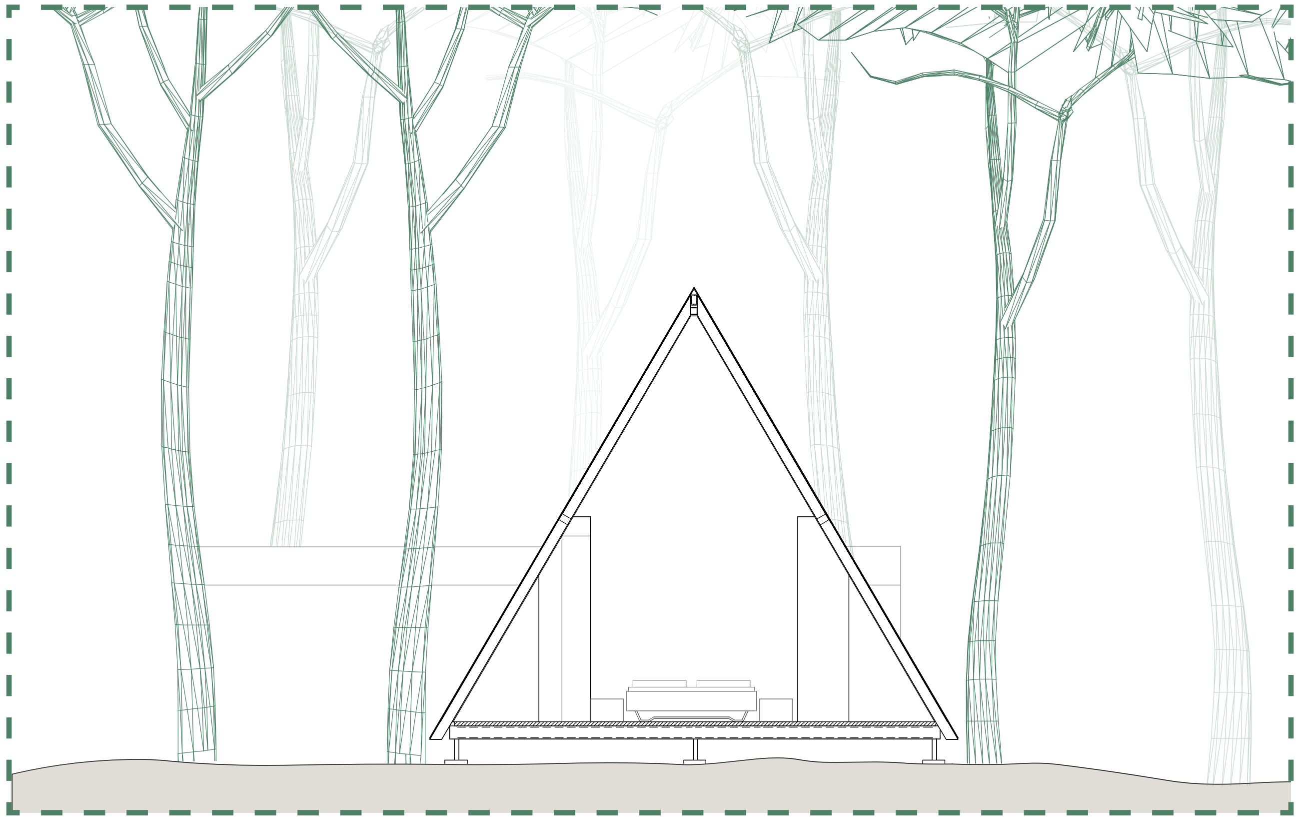


Figure 05.4.7: RE-TREE-T Section CC'
Source: Drawing made by the author of the thesis

Section DD'

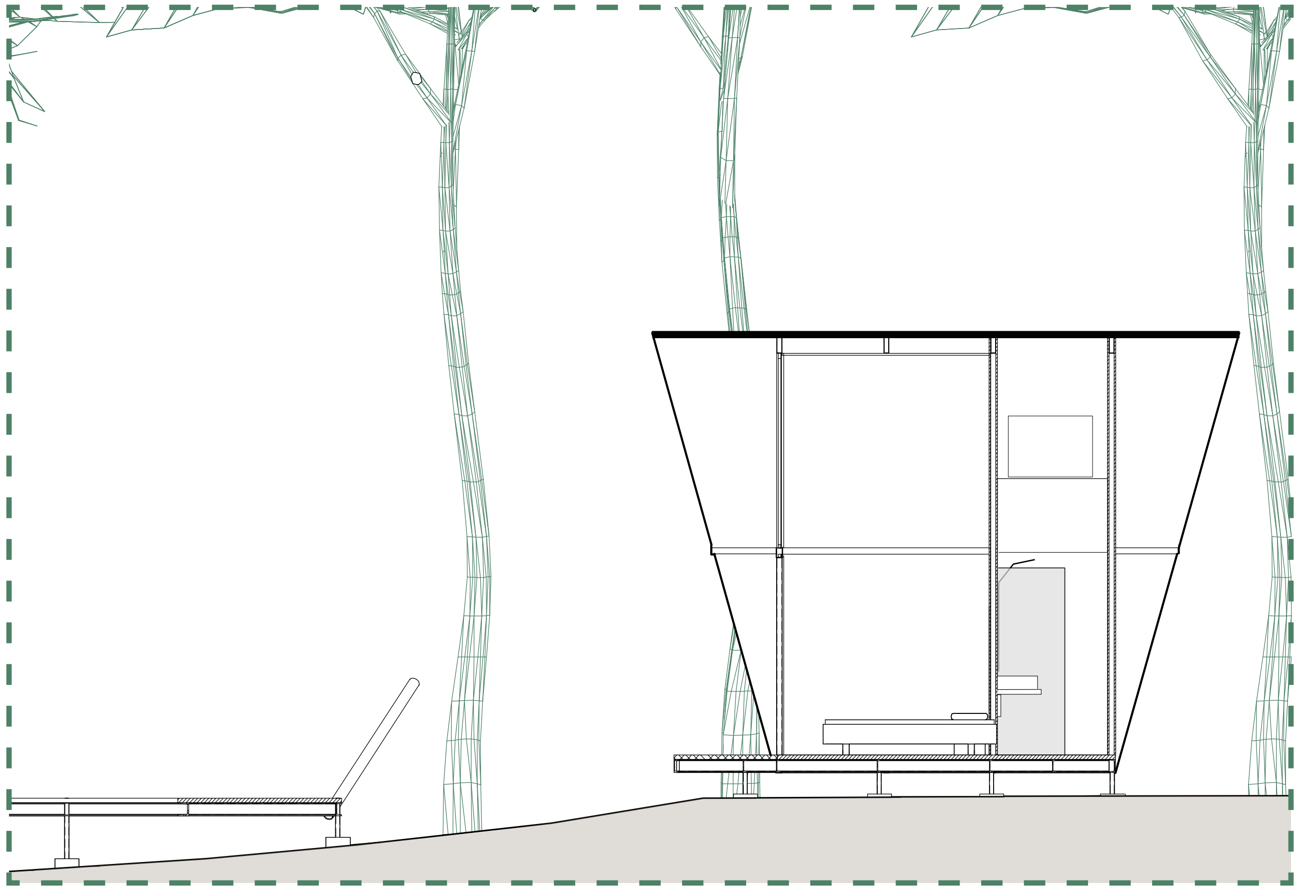


Figure 05.4.8: RE-TREE-T Section DD'
Source: Drawing made by the author of the thesis

05.5 *Report di Cantiere*

Construction process

- Phase one prefabrication of the bathroom and dressing room module

27/07/23

- Construction of the foundation system - steel plates and steel *Mechano* frames of both the main tent and the platform (until the 28th)
- Installation of the prefabricated module on top of the steel frame

28/07/23

- Assembly of the prefabricated steel structure of the bedroom + installation flooring spruce plywood panels
- Installation of the envelope - first inner fabric layer and then outer fabric layer

29/07/23

- Installation of the windows and automated door-screens
- Installation of the AC unit in the main tent

30/07/23

- Installation of the micro-climatic survey station
- Installation of the platform deck - *massaranduba* wood

31/07/23

- Installation of the deck of the main tent
- Assembly of the suspended tent

Offsite

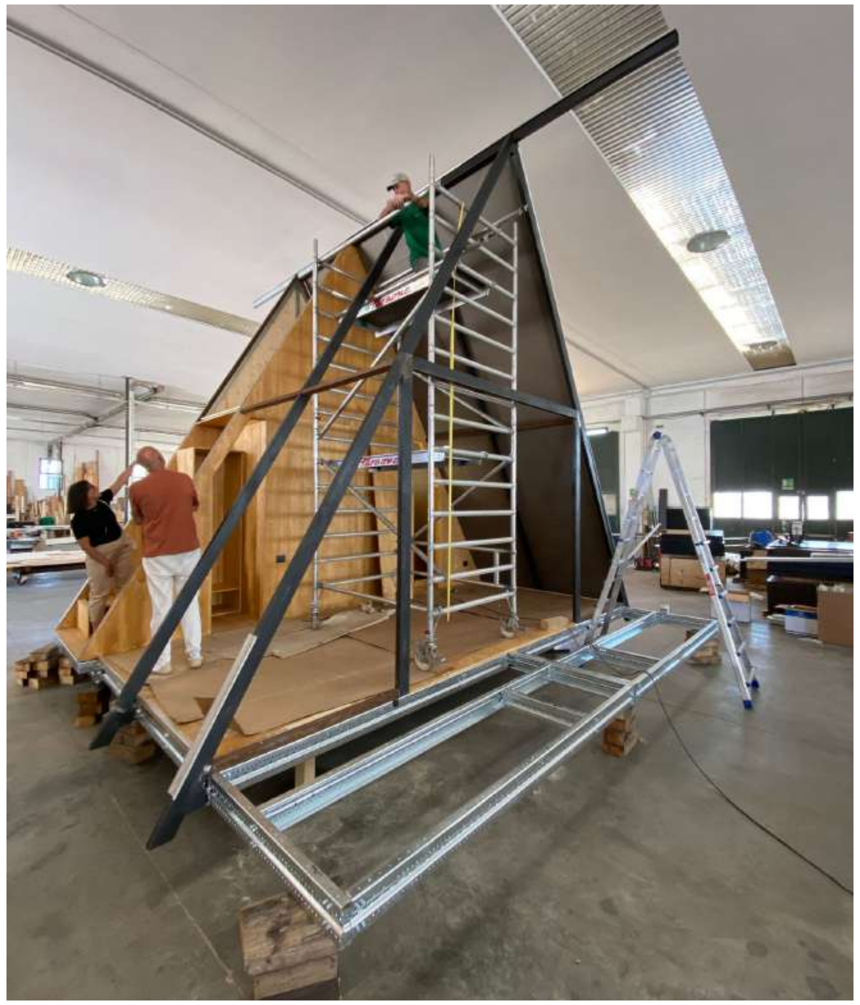


Figure 05.5.1-5: Images of the prefabrication process - bathroom and dressing room module - Images provided by Paolo Scoglio
Source: Pictures taken by the author of the thesis

Onsite

27/07/23

Figure 05.5.6-10: Images of the installation of the prefabricated bathroom and dressing room module
Source: Pictures taken by the author of the thesis

28/07/23

Figure 05.5.11-15: Images of the assembly of the prefabricated steel frame and installation of the envelope inner and outer fabric layers
Source: Pictures taken by the author of the thesis

29/07/23

Figure 05.5.16-20: Images of the installation of the automatic door screen and AC unit
Source: Pictures taken by the author of the thesis

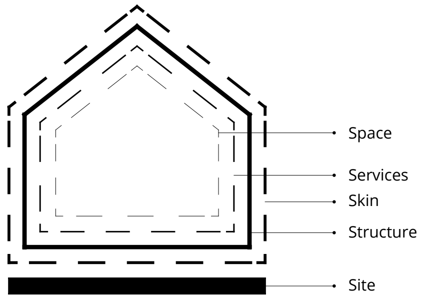
30/07/23

Figure 05.5.21-24: Images of the installation of the platform deck - installation of the micro-climatic survey station
Source: Pictures taken by the author of the thesis

31/07/23

Figure 05.5.25-26: Images of the suspended tent
Source: Pictures provided by Paolo Scoglio

05.6 RE-TREE-T Building systems



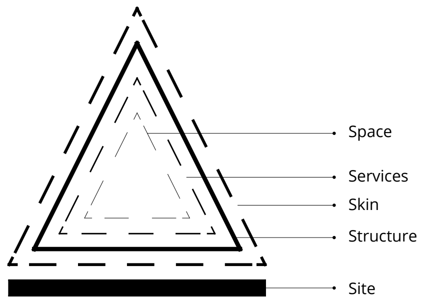


Figure 05.6.1 Parallel between the Brandt and Duff (1994) building layer diagram and the RE-TREE-T project layers
Source: Drawing made by the author of the thesis

The parallel between the Brandt and Duff diagram (1994) of the main building systems is applied to breakdown the RE-TREE-T project, to analyse and contextualize it.

Starting from the site of the project and its relation to the natural and climatic context it is immersed in. Subsequently, the project will be analysed, with a focus on the structure and the skin, exploring the design choices as well as material choices to implement with strategies that include both practices more in line will circularity and also material substitution towards bio-based alternatives. For this reason, only the first three layer will be analysed.

The dwelling is provided with an electrical system that is attached to the electricity grid of the village. The indoor spaces are provided with lighting as well as a an active cooling system.

The spaces are divided between the main dwelling, that has a bedroom, a bathroom and a dressing room, and the external platform with the suspended tent to sleep and relax.

Site

Spina Family Camping Village	
Lido di Spina, Comacchio (FE)	
Site specific coordinates: 44°37'39" N, 12°15'25" E - 2 m.s.l.	
Microclimate survay - waether station	
Sand dune	
Pine forest	

Structure

Foundations	
Foundation steel plinths	1
Scaffsystem Mechano steel frame - Cold bent profiles - Dry assemblage	2
Elevation structure	
Prefabricated steel frames	3

Skin

Flooring	
Internal: Spruce Plywood panels - part of the prefabricated modul External: Massaranduba wood deck	4 5
Roof	
Textile tent - PVC	6
External Walls	
Spruce Plywood panels - part of a prefabricated modul	7
Partitions	
Spruce Plywood panels - part of a prefabricated modul	8
Windows	
Steel frame - glass	9

Services

Electrical system
Lighting
Air conditioning
Automated opening for door-screen

Spaces

Living space - bedroom
Bathroom
Wardrobe - dressing room
Elevation structure
Detached platform (exyernal) - suspended tent

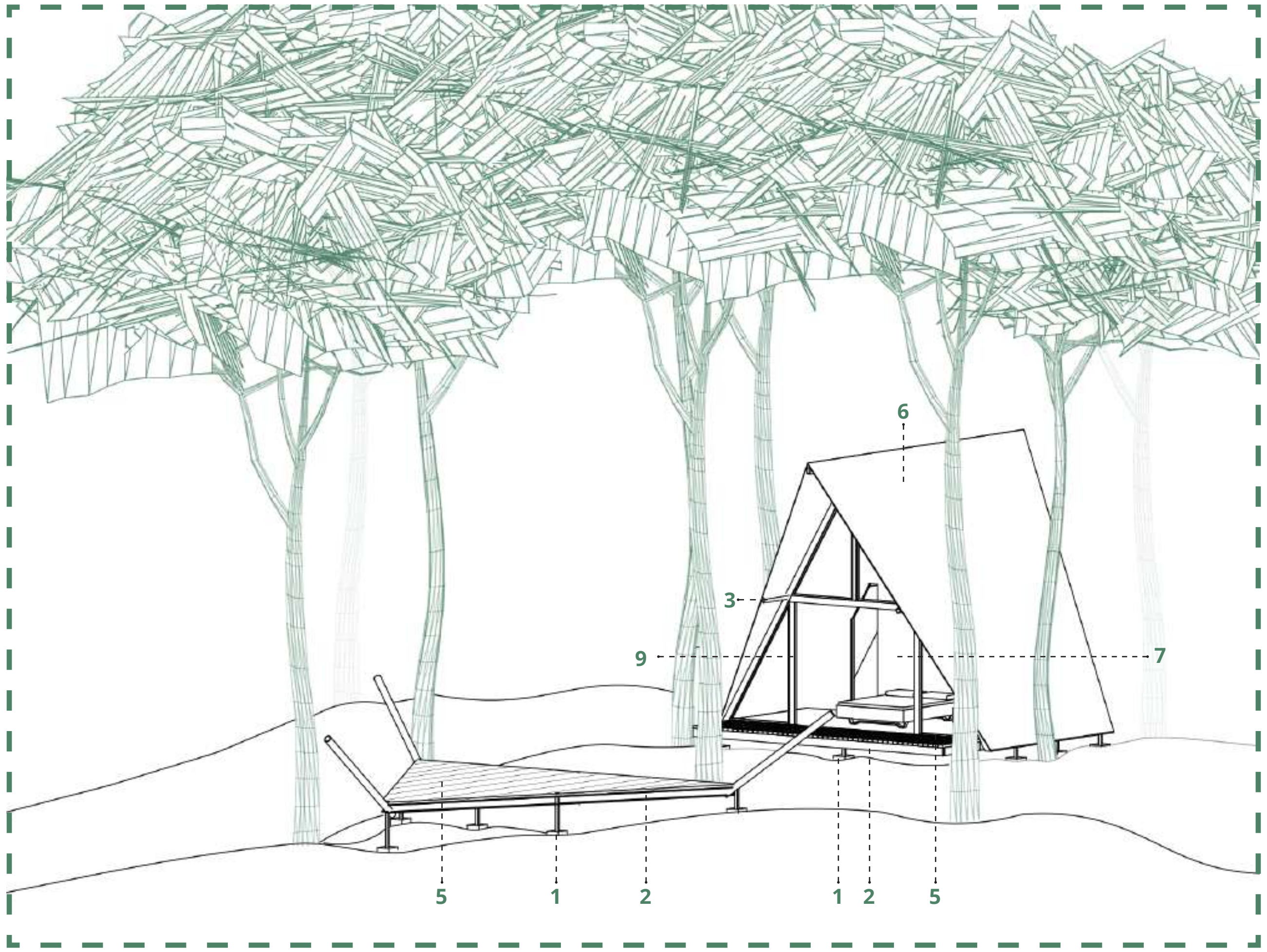


Figure 05.6.2: RE-TREE-T systems
Source: Drawing made by the author of the thesis

4 main materials

- Spruce wood
- Steel
- Massaranduba wood
- PVC fabric

Figure 05.6.3-9: RE-TREE-T systems
Source: Drawing made by the author of the thesis

The Site

Figure 05.6.10: Site location - Intersection of the two main roads (1)
Source: Picture taken by the author of the thesis

Figure 05.6.11: Digital mapping of the site
Source: Image by Paolo Scoglio.

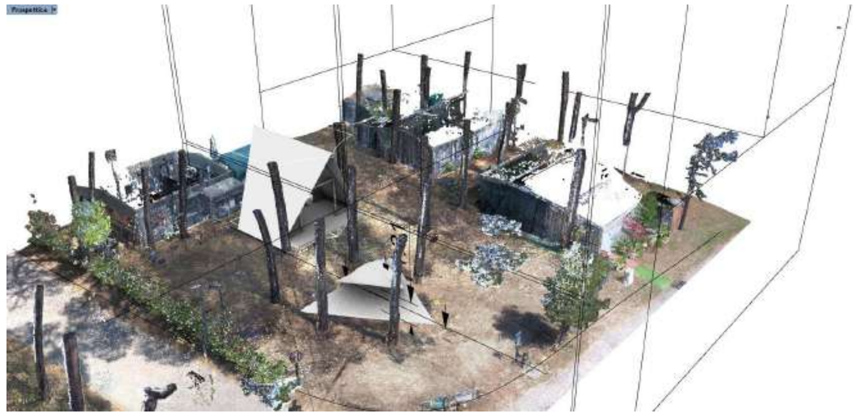


Figure 05.6.12: Digital mapping of the site
Source: Image by Paolo Scoglio.

Figure 05.6.13: Digital mapping of the site
Source: Image by Paolo Scoglio.

The Micro-climate

Climatic Zone: E

To optimise the material choices and the orientation/shape of volumes, design and outdoor space, the micro-climatic context of the prototype site will be analysed. Parallel to the site survey, the aim was to install a weather station to collect data regarding temperature levels, humidity levels, wind speed and direction, precipitation rate and solar irradiation. The micro-climatic station was positioned specifically at Elevation 4 m, 44.63 °N, 12.26 °E. The station was set up and connected to a global network of weather stations on the Wunderground[1] platform. This device is an amatorial weather station.
ID: ICOMAC27

Parallel to the analysis conducted by this micro-climatic station, two Testo professional sensors were installed. One external and one internal to the main tent to understand the performance of the design and the envelope and possibly make proposals based on the data collected.

The real-time data collected from the micro-climatic station and Testo sensors offer a dynamic understanding of how the prototype performs and interacts with its surroundings. This foundation enables the project team to evaluate and integrate in an effective way different passive strategies and make informed decisions on the optimization of design elements and the possibility of material substitution from the perspective of biogenic materials. By combining the insights gained from the microclimatic station, the Testo sensors, and a thorough review of bio-climatic principles, the project pursues the achievement of a harmonious synergy between form, function, and environmental responsiveness. This multidimensional approach not only enhances the prototype's immediate liveability but also contributes valuable insights to the broader discourse on sustainable and adaptive architectural practices.

[1] https://www.wunderground.com/dashboard/pws/ICOMAC27

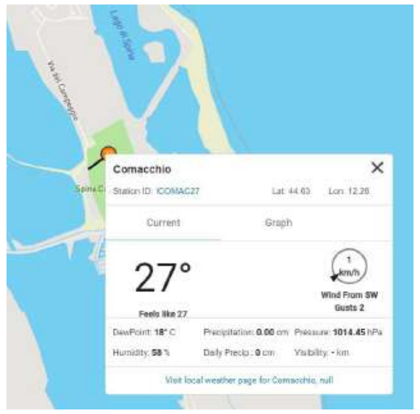


Figure 05.6.14: Icomac27 - survey station
Source: www.wunderground.com/dashboard/pws/ICOMAC27

Figure 05.6.15: Testo professional sensors - installed during site survey - one on the outside of the main tent and one on the inside.
Source: Picture taken by the author of the thesis

Figure 05.6.16: ICOMAC27 - Micro-climatic station installed on site during the site survey.
Source: Picture taken by the author of the thesis

Figure 05.6.17: ICOMAC27 - Micro-climatic station control panel installed on site during the site survey.
Source: Picture taken by the author of the thesis

Specific requirements

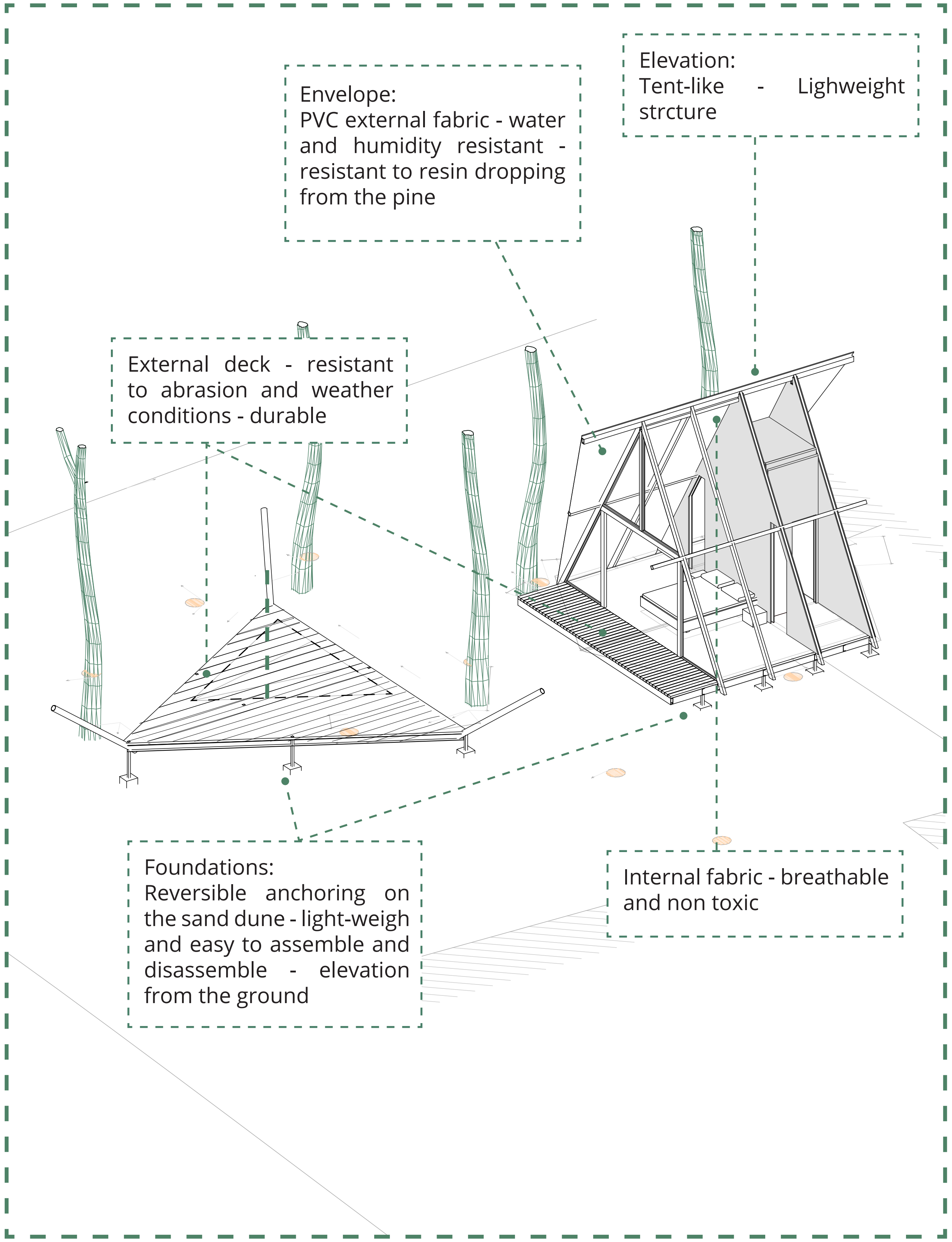
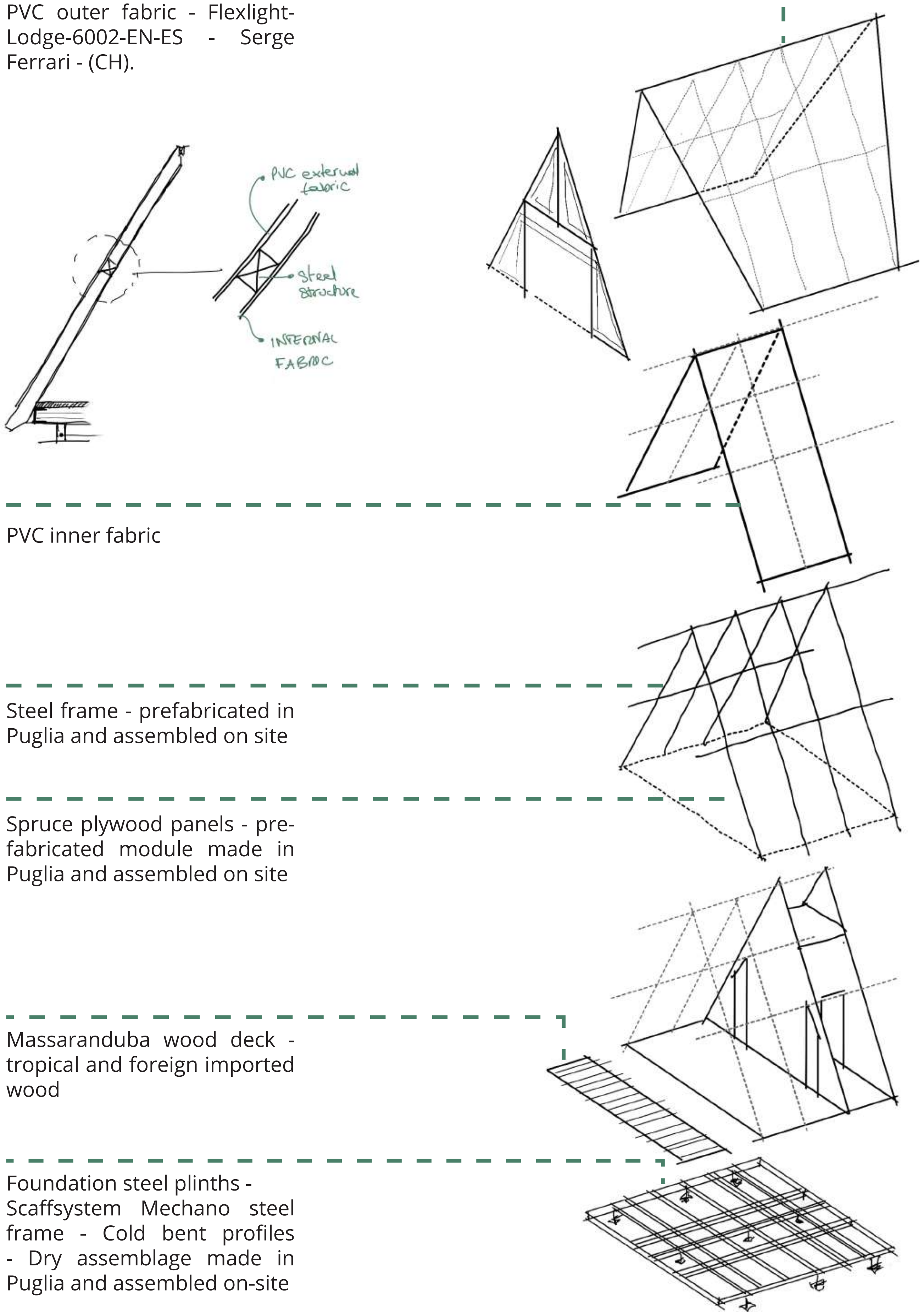


Figure 05.6.18: RE-TREE-T specific requirements
Source: Drawing made by the author of the thesis

Figure 05.6.19: RE-TREE-T The Skin - the structure - page on the right
Source: Drawing made by the author of the thesis

The Skin and the structure



05.7 Interview - Arch. Paolo Scoglio The Ne[s]t

1. What were the main inspirations for the design concept and compositional choices of the project?

"First of all, as a studio, we have been specializing in micro-hospitality in nature for decades, with a focus on designing small experiential architectural projects for primarily tourism-oriented contexts. We love to fully integrate functional aspects into our architectural creations, encompassing a range of activities, from tourism to work, and more broadly, to living in harmony with nature. The challenge with Club del Sole arose in the past year, in 2022, when I was engaged by the management and the owners to begin the design process for an entire village. This project spanned from the scale of individual structures to that of an architectural functional masterplan for a settlement that covers an enormous expanse – 25 hectares of landscape.

Figure 05.67.1: Arch. Paolo Scoglio - the ne[s]t
Source: Image provided by Paolo Scoglio

The characteristics of this landscape are absolutely unique. Lido di Spina, our primary focus, is situated within a UNESCO biosphere area, a UNESCO World Heritage site, and simultaneously, a haven of immense biodiversity. It exists within a larger system, the Po Delta Park, resulting in a variety of operational restrictions. On one hand, there is the necessity to work on innovative hospitality, which entails anthropizing certain areas of the village – gradually reclaiming them from the "wild" nature of the location. On the other hand, there is the critical need to protect this biodiversity extensively. Every action on the landscape had to be, and still must be, measured. Hence, the decision to work on the principle of complete reversibility – designing anthropic settlements with a zero-footprint approach. This has implications both structurally, as supports or anchorages must be reversible, and in terms of action and gesture, which must be calculable with the necessary safety margins for accommodating people. At the same time, it is crucial to ensure that no trace is left behind by these design actions. We follow this philosophy in all our creations – the idea that everything is transitional is fundamental to our project. The notion that what is here now could be different in ten years or simply restored to its original condition is a fundamental premise.

The RE-TREE-T project, therefore, is based on these premises, drawing inspiration from the world of camping – an environment characterized by textile architectures, simply placed, and the hybridization of materials including wood and steel. This occurs even in somewhat unconventional capacities, where couples, families, or groups of friends could aggregate into larger grouping. Hence, the challenge was to conceive innovative hospitality architectures that could be extremely versatile. I like to think that this prototype of RE-TREE-T, as the initial creation, is the first evolutionary step in a series of progressively evolved objects. These developments are influenced by user behaviour and environmental conditions. Currently, we have chosen the pine forest as the location – beneath these wonderful, almost monumental trees, that grow from the sandy dune, which is also untouched. Working on digitally mapping the site's topography became paramount. If this prototype is followed by other instances, an adaptive settlement has to be created, integrating into an ecosystem that changes gradually as it penetrates the pine forest. The challenge is formidable because adaptive systems evolve by definition. However, we are confident that, thanks to our collaboration with the Politecnico and meticulous data mapping, interesting choices can be derived from these efforts".

2. In regards to the RE-TREE-T project, what are the technologies and construction systems used?

"We attempted to hybridize different materials and technologies. Textiles were somewhat the elective material because from the very beginning, the client spoke to us about tents. Tents can have various interpretations and can be approached in various ways. In our case, the forms certainly draw from a known repertoire, but they also tend to evolve in a very futuristic key. So, there's the idea of creating a settlement with textile architectures, but in my mind, this concept takes shape with contemporary and futuristic lines, blended with construction systems that I love to explore—discovering first and experimenting later. These systems often hold positive surprises, particularly related to the theme of complete reversibility. Dry construction systems, characterized by a very high level of prefabrication with reversible joints that can be disassembled in each connection, are essentially the technological translation of the initial assumptions.

Our choice then fell upon a steel prefabrication system, but one using cold-formed profiles. This approach involves low energy consumption for the transformation of the semi-finished product. This way, we can essentially pre-bend coils of metal sheets and construct elements that are perforated, bent, and consequently connectable with bolted joints. This allows us to envision a future lightweight dismantling of these architectures. The third material is wood, which is somewhat my preferred material, the one I've always started with. I try to use it in most cases because I believe that this ultimately makes a difference to the end user's experience. You can create a beautiful architecture that functions well *from a technological and construction perspective, but if it feels alien to the end user, like an unfamiliar object, then it doesn't quite hit the mark. In reality, providing that softness and warmth that's found in this prototype helps a lot in reconciling humans with these evolved systems, both in their construction, design, and monitoring. So, textiles, metal, and wood—by combining and melding these materials together, I find the results to be extremely compelling."*

3. Could you provide an overview and timeline of the various phases of the RE-TREE-T project?

"The development timeline encompassed a lengthy phase of project conception. This was essential to understanding how to engage with the ground within the dune, as part of the UNESCO biosphere. The initial notion of detachment from the ground was momentarily suspended, in fact we remained quite connected to the soil. From this standpoint, we were able to work primarily based on weight and gravity. Our structures are essentially anchored, and therefore are capable of countering contextual forces, all this converted in the current configuration, and we transitioned to the engineering phase.

One of the intriguing aspects is that this prototype inherently features an extensive technical array that extends down to the details of the bolting. It encompasses a truly intricate assembly kit. While not a "easy" object, complexity here doesn't imply difficulty. It is simply composed of numerous elements that must function correctly. The engineering of all this required a period of time that paradoxically was shorter because we meticulously defined the characteristics that our prototype should possess.

Regarding the construction phase, as is often the case when you excel in designing the initial detail and delve into the engineering of each component, the construction phase should be as swift as possible. This is especially true in this instance, where unfortunately, timing compelled us to operate during the peak operational period of the village. This introduces an additional layer of difficulty, necessitating both speed and discretion in accomplishing tasks so as not to extend beyond the planned duration.

The assembly of this prototype is projected to take around five days, after which the project will come to life. When viewed in relation to the weeks required for engineering and even more so, the months of the preceding project, this time is absolutely negligible."

4. Are there specific design elements that enhance the system's flexibility for different layouts or future modifications? What are the innovative features incorporated into the project?

"Firstly, it's a system that employs components, and as such, I like to describe it as a technological device that can be upgraded. At present, we have frozen a version –as a demo – which can be studied in terms of its environmental and bio-climatic behaviour. We are also focusing on refining the user interface. Once this device provides responses, we'll have the capability to fine-tune and enhance it.

In terms of composition, purely speaking of architecture, the spaces within the tent, for instance, are surprisingly spacious despite being micro-architectures. They can be further divided to accommodate more people than currently envisioned. For example, we can work with levels. In this initial release, we have deliberately opened up and expanded spaces for maximum comfort. However, it is generally possible to further partition the space by adding horizontal divisions or mezzanines. The sleeping area can be placed above, while leaving the living area below, creating a more functionally comprehensive space.

The suspended tent – a truly wonderful object for sleeping and relaxing among the tree branches – can be quickly assembled and disassembled. Within 5 minutes, it can be removed, making way for other uses of the deck below. This area can accommodate seating, such as lounge chairs where one can relax, converse, or read. Notably, it's also feasible to integrate off-grid pools adjacent to the platform – the deck – which can be either at ground level or elevated.

Consequently, the system is configured with numerous variables, as if there were a configuration capable of creating unique specimens tailored to specific needs and functions."

5. Have strategies been implemented to reduce the ecological footprint throughout the project's life-cycle?

"The considerations I mentioned earlier somewhat align with this direction: firstly, the theme of complete reversibility, driven by the characteristics of the hosting site, which is a protected UNESCO biosphere. Secondly, the use of materials that come with a sustainability DNA. This includes the cold-formed pre-bent metal structure, requiring lower energy consumption, bolted systems allowing for disassembly, high-efficiency textile membranes, partially derived from recycled PVC, and sustainably sourced wood from certified origins, attesting to its initial sustainability.

All of this is certainly improvable, but for now, these are the measures we have immediately employed to ensure that this creation offers an extra layer compared to what is typically seen in modular architectures for open air tourism. One only needs to look around to find perhaps slightly dated solutions that incorporate materials that have been improved upon, subsequently enhancing the sustainability standards from the past."

6. Natural and biogenic construction materials are generally associated with benefits such as low environmental impact, non-toxicity, and returning to nature at the end of their life cycle. At the same time, they are living materials, and for this reason, they change over time. They might have lower durability compared to more conventional materials and often require a higher economic investment. Would you be willing to consider their use and further integration in this project and any future projects?

"Absolutely, yes. Because this is a prototype that It needs to evolve, and like all living organisms, it will lead us to improvement and envision its use in different locations. This is an innovative hospitality laboratory. We are testing an object from both the bio-climatic perspective and the user standpoint – the occupant's

well-being and the technological design. Decades ago, the modules had internal finishes, floors, and coverings, nearly all derived from plastic. Even in terms of touch, the sensation of interacting with them is very different from what we will experience when entering this prototype."

7. How do you perceive the interest of end users in projects like RE-TREE-T?

"There is a tremendous curiosity. I am quite accustomed to not immediately receiving easily digestible responses from end users. Our studio has always had forward-looking visions, attempting to glimpse at what will happen in the next ten years and beyond. This enables us to provide significant strategic advantages to our clients. It's not about chasing the trend of the moment by creating something that is absolutely successful in that particular season. Instead, it is about envisioning where this type of hospitality can go in this specific location and how people might respond.

The proof of this lies in the fact that what we have always done is deeply ingrained in our DNA long before the pandemic era. After the pandemic, we all discovered a love for nature, proximity-based tourism, and social distancing. However, we were already on this path before. In a way, we arrived at these ideas due to dramatic reasons, but the vision was already taking shape, and the pandemic accelerated it. The interest is immense, and we like to think that our visitors, the curious individuals who are already visiting the construction site, already have in mind to experience this creation and understand the impressions it can evoke."

8. The project presents an innovative solution, both in terms of the construction system and compositional choices. At the same time, it bears resemblances to Indonesian vernacular architecture, particularly the Batak Toba houses, known for integrating passive strategies to ensure indoor comfort. In the context of potential improvements to the RE-TREE-T project, could the fusion of innovation and tradition be a winning strategy?

"Absolutely, I have always believed that nothing is truly invented; we simply make connections. I trust that true genius lies in connecting things. Some may do it roughly, and over time, this process can be refined. Undoubtedly, there is a global repertoire that offers inspiration, solutions, material usage, shading techniques, and approaches to environmental stimuli – it is all there, waiting to be taken and developed further by adding innovation as a contribution.

Even the approach of using laser scanning for surveying allowed us to design this structure nestled among the trees of the pine forest, reinforcing the theme of integration – something that architectures from years ago did not always achieve. This positions the project as evolved and contemporary to our times.

Similarly, integrating passive strategies, such as natural ventilation, is significant. In the existing structures in the village, it is quite easy to address challenges through artificial climate control systems, providing comfort in extreme conditions. The real challenge lies in reducing and minimize this aspect."

9. Do you think that climate change might lead to an evolution of the traditional model of open-air vacations?

"Certainly, yes. Just in these recent days, we have witnessed sudden and significant shifts in climate scenarios – from wind patterns changing from normal to highly anomalous, to heavy rainfall resulting in substantial water masses. Assuming all this is a consequence of climate change attributed to human activities on the planet, if we want to spend time outdoors and connect with nature, we cannot disregard these aspects. This matrix underlies everything that has been discussed so far. An adaptive approach is crucial, particularly in response to these shifting conditions.

I was discussing this very topic the other day with Professor Thièbat. Approaches can be categorized into two types: either a maximalist approach, akin to the Egyptian Pyramids that defy time through the most massive construction possible, limiting possibilities of projects, especially in locations like these, and certainly making them less reversible; or alternatively become aware that these architectures must increasingly align with reversibility – including designed end-of-life strategies. If strong winds damage a part of the structure of the RE-TREE-T project, there is no need to remove the entire structure. Instead, it is designed with replaceable components. The end-of-life part is swapped with a new element that reinstates the original techne.

For example, the Trabocchi along the Adriatic coast provide a clear illustration of this principle. These structures have persisted through decades if not centuries, never exactly the same as when first built, but with an unchanging structural concept. Only the components that storms destroy are replaced, thereby perpetuating the presence of these objects in our landscapes and lives. My aspiration is to follow that logic, infusing it with the current innovation at our disposal. I would be happy with the work done if that could be achieved."

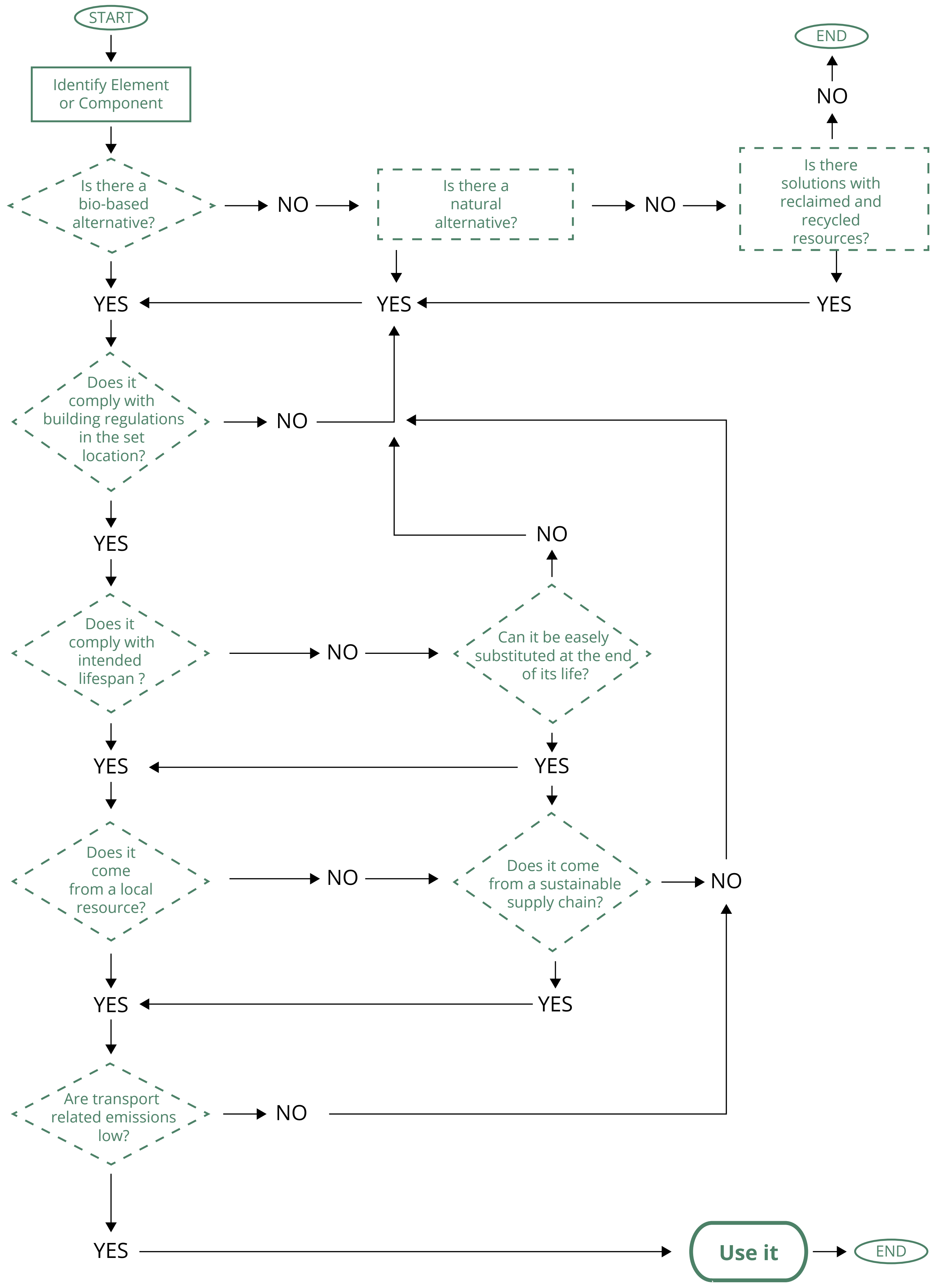
05.8 Strategies for future optimization

The methodology to assess possibilities of optimization and integration with bio-based solutions will follow the flowchart (image on the right) and information presented in the guidelines of CH03-04. However, being that the ongoing research and micro-climatic survey has not yet been obtained, the solutions will be presented more like suggestion, that once data is obtained and further analysed will be re-evaluated and also change accordingly to satisfy both specific requirements already presented but also requirements that may arise after the survey is completed.

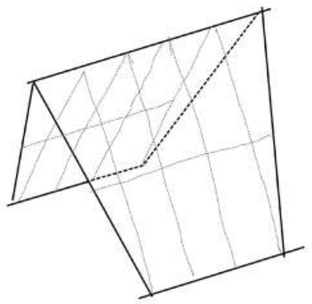
The suggestions will comprise the main elements and components of the RE-TREE-T project based on information obtained through the research, analysis, site survey, interview, and datasheet provided by the architect Paolo Scoglio. It will follow a simple decision making and it will be followed by a possible suggestion of material substitution or integration of circularity principles.

Figure 05.8.1 on the right: Flowchart - decision making process
Source: Drawing made by the author of the thesis

Flowchart
Decision-making process to adopt a bio-based solutions



PVC technical fabric - outer layer



RE-TREE-T prototype - Outer fabric layer - Sergio Ferrari - Flexlight

START

Identify Element or Component

Is there a bio-based alternative?

YES →

TenCate EcoHemp - EcoLine: 20% Hemp / 50% recycled polyester / 30% organic cotton

Does it comply with building regulations in the set location?

YES →

Excellent breathing and moisture regulating properties of cotton, with the strength of polyester fibres
- water- and dirtrepellent
- Dark colour for - resin resistant

Technical Datasheet at: https://www.tencateoutdoorfabrics.com/wp-content/uploads/2022/11/Pages-from-20220569-Bladerbaar-collectie-boek-Tenten-losse-paginas.pdf

Does it comply with intended lifespan ?

YES

! Durable / Resistant For intensive use (includignt scouting tents) - combined with PVC - not compostable

Does it come from a local resource?

NO → It comes from Nijverdal - (NL) !

Does it come from a sustainable supply chain?

YES

Are transport related emissions low?

NO → Needs to be evaluated depending on transportation method chosen - compare to original product from Switzerland

YES → **Use it** → END

Figure 05.8.2 Flowchart - decision making process - outer layer
Source: Drawing made by the author of the thesis

Flexlight
Lodge 6002

Figure 05.8.3: Current outer layer
Source: Picture taken by the author of the thesis

Current product chosen for the prototype

	Flexlight Lodge 6002	Flexlight Lodge 6002 Blackout - Opaco	Standards - Normas
Technical properties - Características técnicas			
Yarn - Hilo	550 / 1100 dtex PES HT	550 / 1100 dtex PES HT	TERSUISSE
Weight - Peso	630 g/m² - 18.6 oz/sqyd	730 g/m² - 21.5 oz/sqyd	EN ISO 2286-2
Width - Ancho: - Plain and dual-coloured Lisos y bicolores	260 cm - 102.4 inches	260 cm - 102.4 inches	
Physical properties - Propiedades físicas			
Tensile strength (warp/weft) Resistencia a la tracción (urdimbre/trama)	250 / 250 daN / 5 cm		EN ISO 1421
Tear strength (warp/weft) Resistencia al desgarro (urdimbre/trama)	20 / 20 daN		DIN 53.363
Adhesion - Adherencia	8 / 8 daN / 5 cm		EN ISO 2411
Surface treatment - Tratamiento de superficie			
Finish - Acabado	Matt PVDF varnish - Baniz mate PVDF		
Flame retardancy - Reacción al fuego			
Rating - Clasificación	**M2**/NFP 92-507 — **B1**/DIN 4102-1 **Classe 2**/UNI 9177 **VKF 5.3**/SN 198898 BS 7837 — **1530.3**/AS/NZS **Method 2**/NFPA 701 **Class A**/ASTM E 84 — CSFM T19 CAN ULCS 109 - **M2**/UNE 23727 — CPAI 84	**M2**/NFP 92-507 **B1**/DIN 4102-1	
Euroclass	**B-s2,d0**		EN 13501-1
Management systems - Sistemas de gestión			
Quality - Calidad			ISO 9001
Certifications, labels, guarantees, recycling - Certificados, etiquetas, garantías, reciclabilidad			

Figure 05.8.4: Flexlight Serge Ferrari - (CH) - Technical Datasheet
Source: https://www.sergeferrari.com/products/flexlight-range

Figure 05.8.5: Growing pavilion - (NL) - EcoHemp roof
Source: https://thegrowingpavilion.com

Possible substitution - TenCate - EcoHemp

EcoHemp was also used in the The Growing Pavilion in NL - (also see Mycelium and Bio-textile in chapter 04) RE-TREE-T projects requires an outer protective durable and resistant layer that is in a dark colour as it is subject to resin falling from the pine trees above.

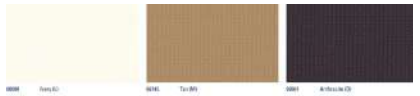
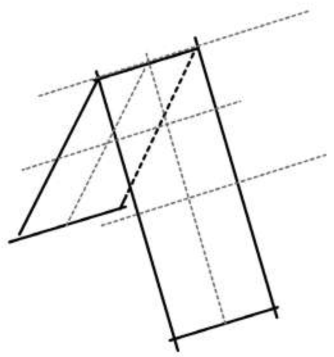


Figure 05.8.6: TenCate EcoHemp Datasheet
Source: https://www.tencateoutdoorfabrics.com

TECHNICAL DATA TENCATE ECOHEMP EN / NL / DE / FR

Reference	Test method	CA-10
Material / Materiaal / Material / Matérial		20% hemp / 50% recycled polyester / 30% organic cotton
Finish / Finish / Ausrüstung / Finissage		water- and dirtrepellent
Width / Breedte / Breite / Largeur	ISO 22198	175 cm
Weight / Gewicht / Gewicht / Poids (+/- 5%)	ISO 3801	280 g/m²
Tensile strength / Treksterkte / Höchstzugkraft / Rés. Dynamométrique	ISO 13934-1	
Warp / Ketting / Kette / Chaîne (5 cm)		1200 N
Weft / Inslag / Schuss / Trâme (5 cm)		900 N
Tearing strength / Scheurweerstand / Weiterreissfestigkeit / Rés. à déchirure	ISO 13937-1	
Warp / Ketting / Kette / Chaîne (4,3 cm)		36 N
Weft / Inslag / Schuss / Trâme (4,3 cm)		26 N
Dimensional change in wet condition / Krimp / Schrumpfverhalten im nassen Zustand / Changement dimensionnel de l'état humide	NFG 07-052	
Warp / Ketting / Kette / Chaîne		- 3%
Weft / Inslag / Schuss / Trâme		- 1%
Watercolumn / Waterkolom / Wassersäule / Schmerber*	ISO 811	30 cm
Colour-weather-fastness / Kleur-weerechtheid / Farb-wetterechtheit / Solidité aux intempéries	ISO 105 B04	≥4

PVC technical fabric - inner layer



START

Identify Element or Component

Is there a bio-based alternative?

YES → TenCate Cotton - EcoLine: 100% organic cotton

Other suitable products could also come from linen, hemp, jute and kenaf

Does it comply with building regulations in the set location?

YES → It is strong and has great breathing and moisture regulating properties. With its water repellence, mildew resistance and dirt repellence treatment the canvas is resistant to all weather conditions. Non / toxic fabric.

Technical Datasheet at: https://www.tencateoutdoorfabrics.com/wp-content/uploads/2022/11/20220408-Kwaliteit-Cotton.pdf

Does it comply with intended lifespan ?

YES → Durable / Resistant

Does it come from a local resource?

NO → It comes from Nijverdal - (NL) !

NO → Does it come from a sustainable supply chain?

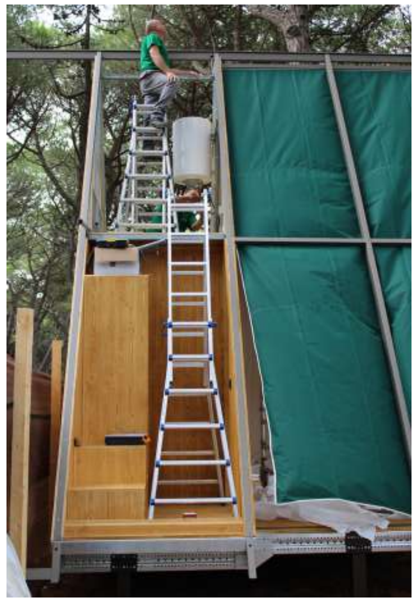
YES

YES

Are transport related emissions low?

NO → Needs to be evaluated depending on transportation method chosen

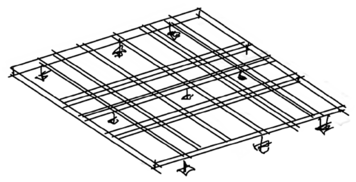
YES → Use it → END



RE-TREE-T prototype - Inner fabric layer

Figure 05.8.7 Flowchart - decision making process - inner layer
Source: Drawing made by the author of the thesis

Mechano steel frame



RE-TREE-T prototype - External platform steel frame - dry assembly - bolts

START

Identify Element or Component

Is there a bio-based alternative?

YES → Wood structure

Does it comply with building regulations in the set location?

NO

Given the nature and purpose of the structure, namely reversability, durability and strenght, easily assembled and disassembled / (Dry) - wood might not be the best option - particularly for disassmbly and recovery in end-of-life scenario.

Is there a natural alternative?

NO

Is there solutions with reclaimed and recycled resources?

YES → The best option could be to maintain a steel structure that presents cold bent profiles and dry assemblage but that comes from a recycled (secondary) or recovered resource.

! A consideration can be made about the chosen construction system: the environmental cost of the cold pressed and dry assembled option can already be considered a good practice, however the raw material comprises a high environmental cost for the extraction.

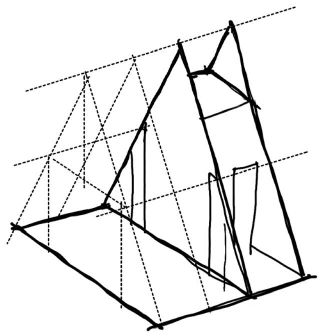
RE-TREE-T prototype - External platform steel frame

Figure 05.8.8 Foundation - *Mechano* steel frame - *Scaffsystem*
Source: Drawing made by the author of the thesis

Spruce plywood panels

Wood is a **bio-based** material

However, in order to preserve its low environmental impact and low embodied carbon, some important considerations have to be made when choosing wood-based elements and components.



RE-TREE-T prototype - prefabricated module - spruce plywood panels

Also refer to :Leti (2023) , LETI Low Embodied Carbon Specifi cation and Procurement Guide: For Low and Net Zero Carbon Buildings

Watch points

- Ensure FSC certified forests for raw materials
- Use renewable species
- Low carbon energy in processing methods
- Local forests (local economies & minimise transport
- Low carbon transportation
- Optimise buildability and design to disassemble
- End-of-life - biodegradable - repurpose - reuse - recycle - (no chemicals and glues)

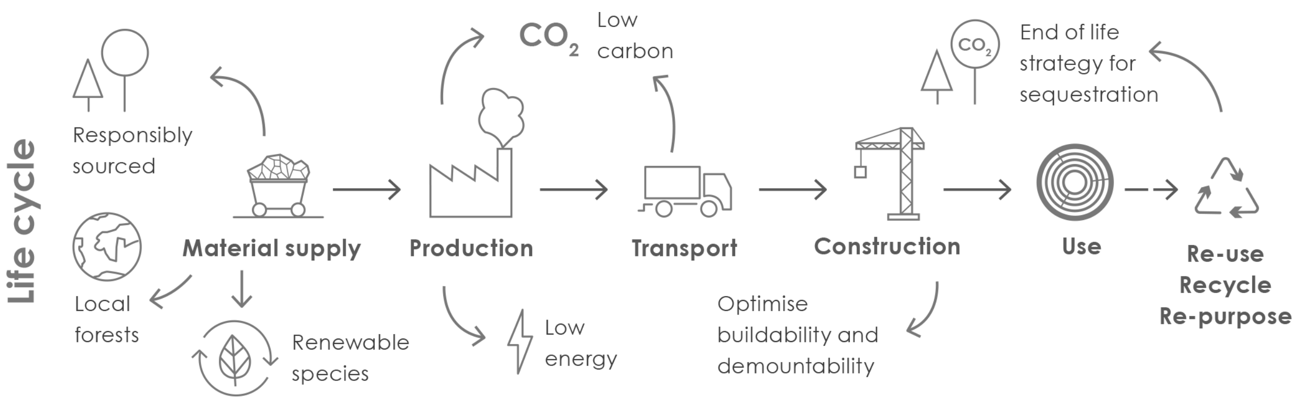


Figure 05.8.9: Wood life cycle - low embodied carbon considerations
Source: Leti (2023) , LETI Low Embodied Carbon Specifi cation and Procurement Guide: For Low and Net Zero Carbon Buildings

Figure 05.8.10 on the right: Massaranduba wood considerations
Source: Drawing made by the author of the thesis

Massaranduba wood

Wood is a **bio-based** material

However, in order to preserve its low environmental impact and low embodied carbon, some important considerations have to be made when choosing wood-based elements and components.

Source: http://panatrees.com/massaranduba/

In this case specifically, Massaranduba wood, also known as Brazilian redwood, comes from the *Manilkara bidentata* tree. This tree is native to Central and South America, including countries like Brazil, Peru, Colombia, and Venezuela. Massaranduba wood is highly regarded for its durability, density, and resistance to decay, which makes it a popular choice for outdoor applications such as decking, which characterizes the use in this project.

Being that is well suited for the chosen utilization as it is very durable and resistant, the questions that follow become:
Is there a valuable and **comparable solution from local and certified resources**?

If not, considering an imported product, does it come from a certified and sustainable and ethical supply chain? In order to assess the origin and sustainability one can consult platforms such as **ATIBT, Amazon Initiative** and **Help desk**

Massaranduba deck - platform - RE-TREE-T prototype

More infromation at:
www.atibt.org
https://www.amazoninitiative.org/
https://www.vvnh.nl/Milieu-Helpdesk

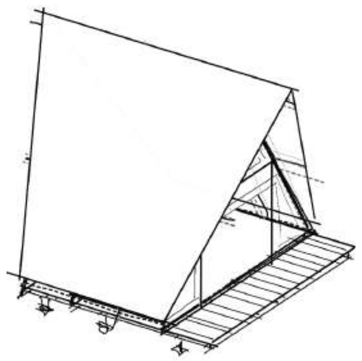
In this case some information about sustainable forestry practices in the amazon - **Amazon Initiative** - can provide useful information for making a conscious decision.

Additionally it is important to consider emissions related to transport as they could increase environmental impact of the imported product.

If low impact transport is available the choice can be evaluated and assess in terms of feasibility but also - in terms of - IS IT WORTH IT?

Some examples of **Passive strategies**

The design and configuration of the RE-TREE-T project bare some parallels with the architectural heritage of Tongkonan houses—a hallmark of the Toraja ethnic group of South Sulawesi, Indonesia.



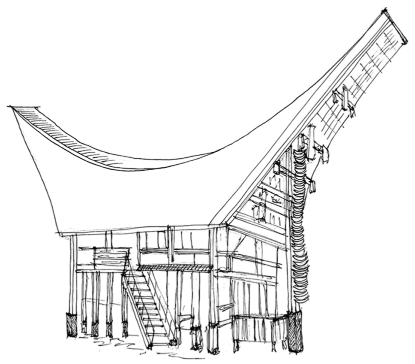


Figure 05.8.11: RE-TREE-T structure
Source: Drawing made from the author of the thesis

Figure 05.8.12: Tongkonan houses - vernacular architecture from the South Sulawesi ethnic group in Indonesia.
Source: Drawing made from the author of the thesis

Tongkonan houses stand as a testament to the fusion of architectural and cultural attributes. Foremost among these features is the iconic boat-shaped roof crafted from bamboo and thatch, which not only serves as an architectural feature but also functions as an effective insulator,allowing hot air out through tactically positioned roof vents. The exterior of Tongkonan houses is adorned with intricate wood carvings, depicting Torajan motifs, ancestral figures, and cultural symbols, thereby showcasing the artistic finesse of the Toraja community. Raised on wooden pillars, these structures offer both structural stability and improved natural ventilation, coupled with resilience against potential floods. The architectural orientation, often north-facing, combined with buffalo horn embellishments, emblematic of affluence and eminence in Torajan culture, underscores the cultural significance of this architectural style. The utilization of bamboo or woven bamboo mats for wall construction is a further testament to the thoughtful consideration of natural airflow and allowing for indoor air quality as well as comfort. Understanding the passive strategies integrated in this vernacular design could allow for possible optimization of the RE-TREE-T project. Like the Tongkonan house, the RE-TREE-T main tent also is elevated from the ground, this allows for ventilation under the living spaces - thus provides a cooling passive strategy. Another similar feature can be found in the shape of the roof that provides a shadowing system for the main façade.

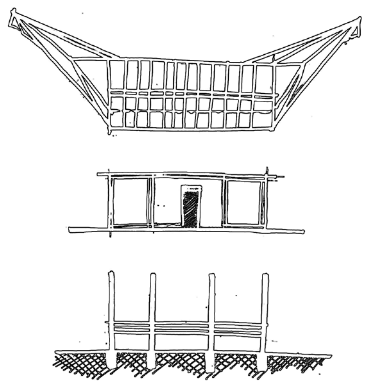


Figure 05.8.13: a. The bamboo roof structure **b.** Structure of the living spaces -bamboo **c.** Elevated foundation structure
Source: Drawing made from the author of the thesis

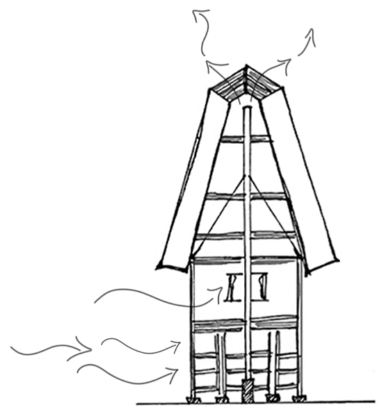


Figure 05.8.14: Natural ventilation passive strategies - elevated foundations and roof vents to allow for hot air to exit the living spaces
Source: Drawing made from the author of the thesis

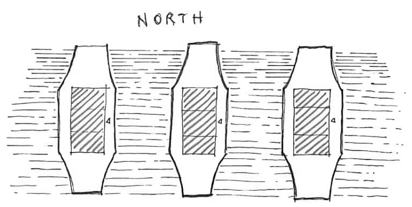


Figure 05.8.15: The orientation - symbolic but also allows for ventilation in between the parallel dwellings
Source: Drawing made from the author of the thesis

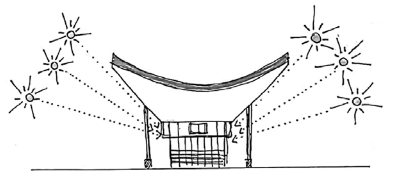


Figure 05.8.16: Shading roof - overhang
Source: Drawing made from the author of the thesis

The micro-climatic survey started during the construction in July 2023, can provide useful information to allow for integrations of passive strategies. For example through data about wind direction and gust, the RE-TREE-T project could also see strategies of natural ventilation for cooling that could possibly reduce dependence to active systems. As data still has to be obtained and analysed - part of following stage of the research project that has yet started - these proposals are suggestions and will be further studied when more information will be available.

Natural ventilation

The original project for the RE-TREE-T main tent presented a much higher elevation of the foundation system, however due to the site of the prototype the high was reduced. However, a further increase would be beneficial to allow for further insulation from the ground and allow for ventilation to pass under the living spaces.

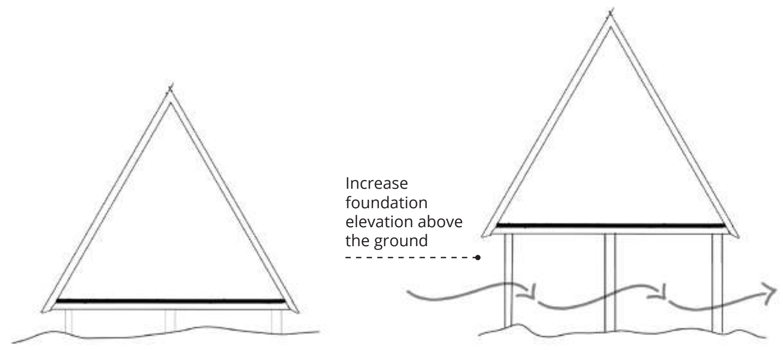


Figure 05.8.17: Elevation increase of the foundation system like proposal of the original project.
Source: Drawing made from the author of the thesis

Another passive strategy that encompasses natural ventilation - also learning from the Tongkonan houses - is to allow for hot heat exit the living spaces through the top. Given the fact that it would not be ideal to create openings in the fabric - also due to the intense presence of mosquitoes on site - air flow could be channelled providing different layers of the roof with gaps in between, similar to a ventilated façade and roof system.

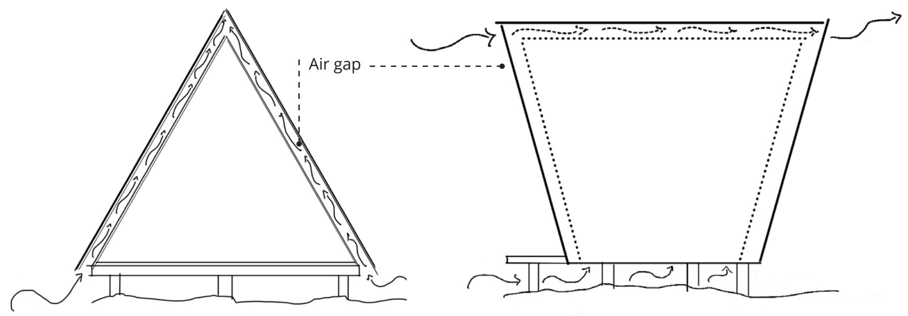


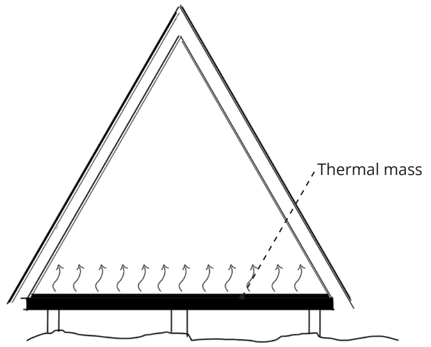
Figure 05.8.18: Creating gaps between outer and inner layer to allow for natural ventilation letting air flow.
Source: Drawing made from the author of the thesis

The air flows in between outer layer - protective layer - and inner layer and finds an exit in the sides of the structure.
Natural ventilation provides improved indoor air quality, and enhanced occupant comfort while reducing environmental impact and operational costs as it decreases demand for AC and provides as a passive cooling strategy.

Incorporating thermal mass floor into the RE-TREE-T main tent could provide a practical and effective way to contribute to regulate indoor temperatures. During the day, the floor absorbs heat, preventing drastic temperature fluctuations within the tent, which is especially important temperatures rise in the living spaces. Then, as the temperature drops at night, the stored heat is slowly released. This passive cooling strategy also could reduces the need for energy-consuming cooling systems, making for a more eco-friendly and cost-effective solution.

A possible way of integrating thermal mass could see the substitution of the spruce plywood panels for a solutions that incorporates a high density insulation, for example sandwich panels, with a layer of insulation, for example Celenit panels, that are rigid insulating panels composed of wood fibre stabilized with a small percentage of Portland cement or magnesium.

Thermal mass - insulation of the envelope



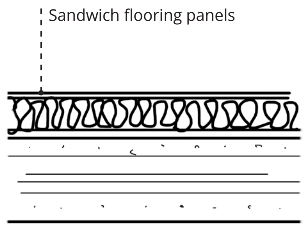


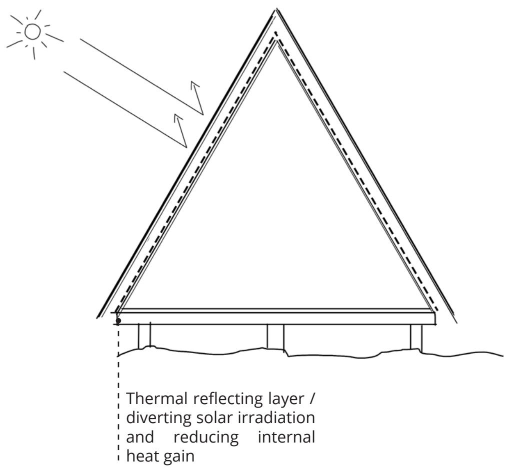
Figure 05.8.19: Adding thermal mass in the flooring system to capture heat during the day and help regulate indoor temperatures.
Source: Drawing made from the author of the thesis

Another passive strategy could integrate a thermal reflective layer into the tent envelope. This addition could help keep the interior cooler by deflecting incoming solar heat and contribute to lowering internal heat gain withing the living spaces, enhancing comfort, and also reducing the need for energy-intensive cooling systems.

A possible solution could be the TRISOLAIN - max - Actis - thermal reflective layer. This system combines a reflecting sheet with sheep wool insulation, this solutions ensures air, water, and vapour impermeability.

Thermal reflective layer in the tent envelope to divert solar irradiation and internal heat gain

Figure 05.8.20: Trisolane - max- Actis
Source: and datasheet at: https://www.actis-isolamento.com/files/actis/pdfs/it/scheda-tecnica/PZ282%20FT%20TRISOLAINE-MAX%200123%20BD.pdf



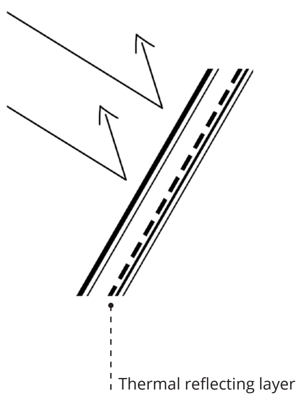


Figure 05.8.21: Adding a thermal reflective layer in the tent envelope to divert solar irradiation and reducing heat gain.
Source: Drawing made from the author of the thesis

05.9 Final considerations

The next steps of the ongoing project involve analysing the micro-climatic data collected from the sensors and survey station. This analysis will enable a performance-based evaluation of design and material choices, as well as an exploration of passive strategies and other potential enhancements for the initial prototype.

The RE-TREE-T research project exemplifies the integration of eco-conscious solutions within the context of open-air hospitality. Its primary goal is to establish living spaces that coexist harmoniously with nature while minimizing their environmental footprint. This collaborative initiative among the three entities underscores the significance of interdisciplinary approaches in achieving sustainability and innovative design.

The project's multifaceted nature, encompassing elements of design philosophy, construction, data-driven analysis, and a performance-oriented approach, highlights its comprehensive vision. It goes beyond creating a sustainable structure; it represents a sustainable process. With its adaptability and holistic perspective, the project illustrates an ever-evolving and dynamic design. It aspires and aims not only to produce an innovative structure but also to a symbiosis with the natural context it is immersed in, fostering a deeper connection to our environment. In doing so, it paves the way for a more harmonious and eco-conscious future of hospitality and design.

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Conclusions

Why choose to explore bio-based building materials?

As stated in the introduction of this thesis, in a world where consumption and production patterns have undoubtedly improved quality of life, a critical inquiry arises: What is the environmental cost of this progress? This question gains prominence in light of the urgent need to achieve net-zero emissions by 2050. The construction sector, responsible for a significant portion of global energy consumption and energy-related CO_2 emissions, emerges as a focal point for transformative change. While efforts to enhance building efficiency have gained momentum, it is imperative to examine the complete life-cycle emissions of buildings and address the complexities surrounding embodied energy and material efficiency.

This research has explored the environmental challenges within the construction sector, particularly its significant role in climate change. As of today, the focus to enhance sustainability within this sector seems to target mainly operational energy, however despite efforts to improve building efficiency, fully assessing the environmental impact of construction processes, which includes both operational and embodied energy, remains an unresolved challenge. Limitations lie in the need for comprehensive data collection, but also in the absence of universally accepted assessment methods, resource constraints and availability, as well as regulations and standards that make assessing and lowering the embodied energy of projects and materials mandatory.

In the face of current and future adversities world-wide, not only in the constructions sector, the main aim and objective has to be focusing on possible solutions and not only problems.

Why choose to explore bio-based building materials?

Among possible mitigation strategies for reducing embodied energy and carbon in the built environment, there is a transition towards circularity and material efficiency. When considering material efficiency, a valuable solution is the integration of prefabrication both in terms of design strategy as well as a manufacturing process. However, prefabrication, even though it could be done in various materials, still relies mainly on steel and concrete. As mentioned above, as buildings are becoming increasingly more efficient, material efficiency is crucial. The gap in material choice in prefabrication practices towards sustainable options often relies on wood as an elective material, however, there are many other natural and biogenic materials that can be adopted.

The primary objective of this thesis was to highlight the **potential** of bio-based materials as sustainable alternatives to conventional construction materials, emphasizing their role in enhancing material efficiency and circularity.

Bio-based building materials offer a multitude of significant **benefits**. Firstly, they come from renewable resources like plants, reducing the dependence on finite fossil fuels. This renewable nature also contributes to a lower carbon footprint, as well as acting as carbon sinks and contributing to biogenic CO_2 uptake. Biogenic materials are also biodegradable, and can reduce the burden on landfills and offer an end-of-life solution that aligns with ecological and circular principles. They are non-toxic, and they are characterized by properties that enhance indoor air quality and comfort. Additionally, many bio-based materials can be locally sourced, reducing transportation emissions and supporting local economies. These materials promote circularity in the construction sector, as they can often be recycled or re-purposed, thus contributing to a more sustainable and resource-efficient built environment. Cascading bio-based materials involves utilizing the material for multiple successive purposes, with the final step typically involving energy recovery or other forms of recovery, such as organic recycling in the case of compostable or biodegradable materials. Overall, bio-based building materials hold promise in addressing various sustainability challenges within the construction industry and very importantly could reduce dependence on fossil-derived resources and products.

The use of biogenic and natural materials is not a novel solution; in fact, before the advent and discovery of petroleum-based materials, these have been the only used building materials for centuries all over the world. Ancient civilizations used readily available natural materials like clay, mud, stone, and wood that came from local resources for constructions. As of today, we have a vast and rich repertoire of traditional building techniques and possible uses of these materials. However, designers, architects, and manufacturers often disregard ancient strategies and knowledge opting for more modern and high-tech options.

Realistically speaking in our modern society, it is highly unlikely if not impossible to use traditional building techniques linked to natural and biogenic materials in most projects. Therefore, finding a middle ground between “high tech” and “low tech” is crucial (Thiebat and Veglia, 2023)[1].

[1] Thiebat and Veglia (2023) High-Tech Meets Low-Tech. Springer Nature Switzerland AG

Other **challenges** that limit the adoption of biogenic materials are mainly elevated costs, lack of availability and awareness of industry stakeholders.

Considering this premise, integrating prefabricated production processes of biogenic building materials could be a possible solution. The potential for mass production of biogenic products raises both opportunities and environmental concerns. While any mass production process has associated environmental implications, the reduction in the use of other conventional materials could potentially lower the overall environmental impact of the building sector. Moreover, the idea should never be to propose a substitution for traditional building techniques with raw bio-based materials, but to integrate and more importantly substitute the conventional ones to favor a massive transition towards circularity and material efficiency – in terms of material substitution. The integration of prefabrication processes should always follow good practices in terms of materials efficiency and circularity, also considering local resource availability and low and clean energy manufacturing as well as transportation.

The realm of bio-based materials is characterized by a rapid **evolution** and constant innovation. Across the globe, researchers and innovators are dedicated to creating, exploring, and experimenting with these materials. Through an examination of material constraints and possibilities, innovative solutions emerge. However, it is important to recognize that despite increasing demand, the construction industry remains **hesitant** to embrace bio-based materials due to concerns about their material properties, especially long-term durability and also most of these solutions are not yet available on the market or are very costly. Consequently, the importance of disseminating information and data as well as raising awareness about bio-based materials, research and integration of a efficient production process could facilitate the industry towards their upscaling.

The body of this research, comprising of the bio-based material and prefabrication guidelines, aims at creating collective and comprehensive information that can be used by different stakeholders to aid conscious material choices and work towards a predictive control in the design for construction and retrofitting processes.

The incorporation of biogenic materials into the construction industry often involves their transformation into basic elements, representing the initial stage of prefabrication. However, there is a compelling opportunity to explore further transitions, advancing from these elements to more intricate components, units, and modular systems. This progression could favour a multitude of advantages, including cost reduction, heightened time efficiency, and enhanced quality control throughout the production and construction process.

Future Outlooks

Future Outlooks for Bio-Based Materials and Overcoming Challenges include:

• **Advanced Material Development**: Ongoing research and innovation in bio-based materials must prioritize overcoming existing limitations. Achieving this necessitates refining production processes - exploring prefabrication production processes - and engineering materials with enhanced properties. Collaboration among material scientists, engineers, architects, and manufacturers will be pivotal in driving these advancements.

• **Standardization and Certification**: Collaboration between the construction industry and regulatory bodies is essential for establishing standardized testing methods and certification processes tailored to bio-based materials. These standardized measures will enhance clarity and instill confidence among builders and consumers, facilitating the wider adoption of these alternatives. Furthermore, significant investments in research and development are imperative to unlock the potential of bio-composites, addressing challenges such as durability, strength and fire resistance.

• **Market Expansion**: To surmount challenges related to limited availability and higher costs, governments and industry stakeholders should incentive the production and adoption of bio-based materials through a multifaceted approach. This includes standardization, incorporation into building regulations, information dissemination, and enhancing transparency within the supply chain. Such comprehensive support could not only scale up production and adoption but also contribute to cost reduction over time.

• **Regulatory Support**: Governments and regulatory bodies should actively introduce policies that endorse the use of bio-based materials. These policies may encompass green building codes and sustainability certifications, providing both incentives and a regulatory framework for the widespread adoption of these materials.

• **Diversification of Sources**: Encouraging the exploration of a wide array of resources, including agricultural residues and non-food crops, is crucial to ensure a stable supply chain for bio-based materials. Research institutions and agricultural initiatives could play a pivotal role in promoting alternative crop cultivation and use of by-products and waste as well as supply diversification.

• **Local Sourcing Networks**: Collaborative efforts among local communities, farmers, and construction professionals could establish networks for sourcing bio-based materials locally. This approach not only reduces transportation missions but also bolsters regional sustainability.

• **Composting, Recycling and Ruse**: The construction industry should allocate resources towards research and technology development aimed at creating efficient recycling and repurposing methods for bio-based materials. This could ensure that these materials remain within a circular economy, encompassing solutions and products that are entirely bio-based and biodegradable at the end of their life cycle.

• **Architectural Integration**: Raising awareness among building material manufacturers, architects, and designers is crucial for the integration of bio-based alternatives within the construction sector. Keeping stakeholders informed about the latest developments in bio-based materials and actively incorporating them into designs, while considering functionality, as well as environmental impacts and benefits will be paramount.

• **Consumer Preference**: Elevating consumer awareness regarding the benefits of bio-based materials and their availability as construction products is vital. Public education campaigns and labeling initiatives could hold the potential to stimulate grater demand and broader adoption, fostering a market that appreciates the advantages of these sustainable alternatives.

In conclusion, it is vital to recognize that achieving sustainability in the construction industry has to rely on a **multitude** of different **approaches** that extend beyond any singular solution, such as exclusive reliance on bio-based materials. Sustainable practices should require a comprehensive strategy that encompasses various elements such as material selection, energy efficiency, waste reduction, and community engagement. To truly reduce the environmental impact of the built environment, the vast spectrum of alternatives has to be combined and integrated synergistically. This approach may involve the use of renewable energy sources, advanced construction techniques, traditional construction techniques, efficient water management, green infrastructure, and the incorporation of low-carbon design principles. Moreover, it demands collaboration among all different stakeholders, including architects, engineers, builders, manufactures and local communities, to develop and implement solutions that address the unique challenges of each project in different contexts. Adopting a more holistic perspective and considering a multitude of solutions could hold the potential to enhance sustainability within the built environment and contribute to a change in direction.

Transitioning towards a bio-economy and circularity - therefore adopting bio-based materials - is one of the many solutions toward an ecological transition, and one crucial aspect within the building sector and the building material industry is that **architects and manufacturers have to design processes, not just projects and products**.

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Tools

1 https://www.elsevier.com/solutions/scopus

The research on which the thesis is based on is primarily from the Scopus database.

Scopus[1] is Elsevier's abstract and citation database launched in 2004. This database covers a wide range of academic disciplines, such as and provides access to a vast collection of research articles, conference proceedings, and other scholarly materials. It offers tools for searching, tracking citations, and analyzing research trends. Scopus compiles information from over 25,000 currently active publications and 7,000 publishers, all of which undergo thorough evaluation and selection by an independent review committee.

Other research and information were also obtained from other research databases and platforms such as: ReasearchGate, Google Scholar, Academia.edu, Science Directs. The research tool Pico Polito from Politecnico di Torino was used, as well as an extensive collection of book and magazines from the BCA "Roberto Gabetti" of Politecnico di Torino.

Data and general information were obtained by an extensive number of online resources such as different websites of the European Union and Commission, research from different Universities from EU and non-EU countries.

For materials and products information was also obtained from companies, product datasheets and article from online platforms such as Dezeen, Material District and Archdaily.

Life cycle assessment data was obtained from different articles and research papers from Scopus database as well as from Research gate and Science Direct databases.

2 https://simapro.com/

For specific materials (when declared) data was obtained from the SimaPro[2] 9 software. SimaPro includes various impact assessment methods that help calculate impact assessment results such as carbon and water footprint and life cycle assessment for projects and products, it also allows to conduct EPD product declaration. The SimaPro software can consider the entire product life cycle or only certain phases. This is made possible by the high customisation of input data and the numerous databases that can be selected. The functional unit is defined by the user according the requirements of the analysis. The output of analysis can be numeric data but also graphics and tree schemes in regard to different impact categories.

The chosen database to obtain data are as follows.

Selected	Name
☑	Agri-footprint 5 - economic allocation
☑	Agri-footprint 5 - gross energy allocation
☑	Agri-footprint 5 - mass allocation
☐	Ecoinvent 3 - allocation at point of substitution - system
☐	Ecoinvent 3 - allocation at point of substitution - unit
☑	Ecoinvent 3 - allocation, cut-off by classification - system
☑	Ecoinvent 3 - allocation, cut-off by classification - unit
☐	Ecoinvent 3 - consequential - system
☐	Ecoinvent 3 - consequential - unit
☑	EU & DK Input Output Database
☑	Industry data 2.0
☑	Methods
☑	USLCI

Given the nature of bio-based materials, often coming from agricultural and food supply chains, by-products and waste products, as well as manufacturing and other industries, different databases[1] were selected in order to have a wide range of datasets to obtain information about environmental impact (LCA) of different bio-based materials.

[1] More information on the databases available on the SimaPro software at: https://simapro.com/

Agri-footprint is an extensive life cycle inventory (LCI) database that specifically deals with agricultural items, encompassing feed, food, and biomass. In its most recent iteration, Agri-footprint 6.3, it addresses various impact categories, including those associated with water, land utilization, land use changes, fertilizers, and pesticides.

Ecoinvent, located in Zurich, Switzerland, is a non-profit organization focused on making high-quality sustainability assessment data available worldwide. The Ecoinvent Database provides information for users looking to assess the environmental impacts of what they offer. This extensive repository spans various sectors on both global and regional scales and holds over 18,000 reliable life cycle inventory datasets, each representing different human activities or processes. These datasets delve into the details of industrial or agricultural processes they model, including resource usage, emissions to water, soil, and air, demand for products like electricity from other processes, and the production of goods, by-products, and waste.

Industry Data 2.0 comprises data gathered from a variety of industry associations. Industry Data 2.0 encompasses more than 300 datasets originating from sectors like plastics, surfactants, detergents, and steel. These datasets are sourced from various industry associations, including Plastics Europe, ERASM, World Steel, International Molybdenum Association, and the Alliance for Beverage Cartons and the Environment.

The U.S. Life Cycle Inventory Database (USLCI) offers detailed assessments, including gate-to-gate, cradle-to-gate, and cradle-to-grave analyses, which account for the energy and material flows linked to the production of a material, component, or assembly within the United States.

As bio-based materials have been more explored in recent years, therefore are relatively new to the market, most databases do not present information in their regards to perform a LCA analysis.

The calculation methods chosen are the Cumulative Energy Demand (CED) - IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00 and the Ecological Footprint (EF) 3.0[2].

[2] https://simapro.com/wp-content/uploads/2021/12/DatabaseManualMethods930.pdf

The **Cumulative Energy Demand (CED)** calculation method relies on the approach initially introduced in Ecoinvent version 1.01. It has been further developed by PRé to encompass energy resources present in the SimaPro 7 database. Additionally, it includes additional substances in line with the Ecoinvent database version 2.0.

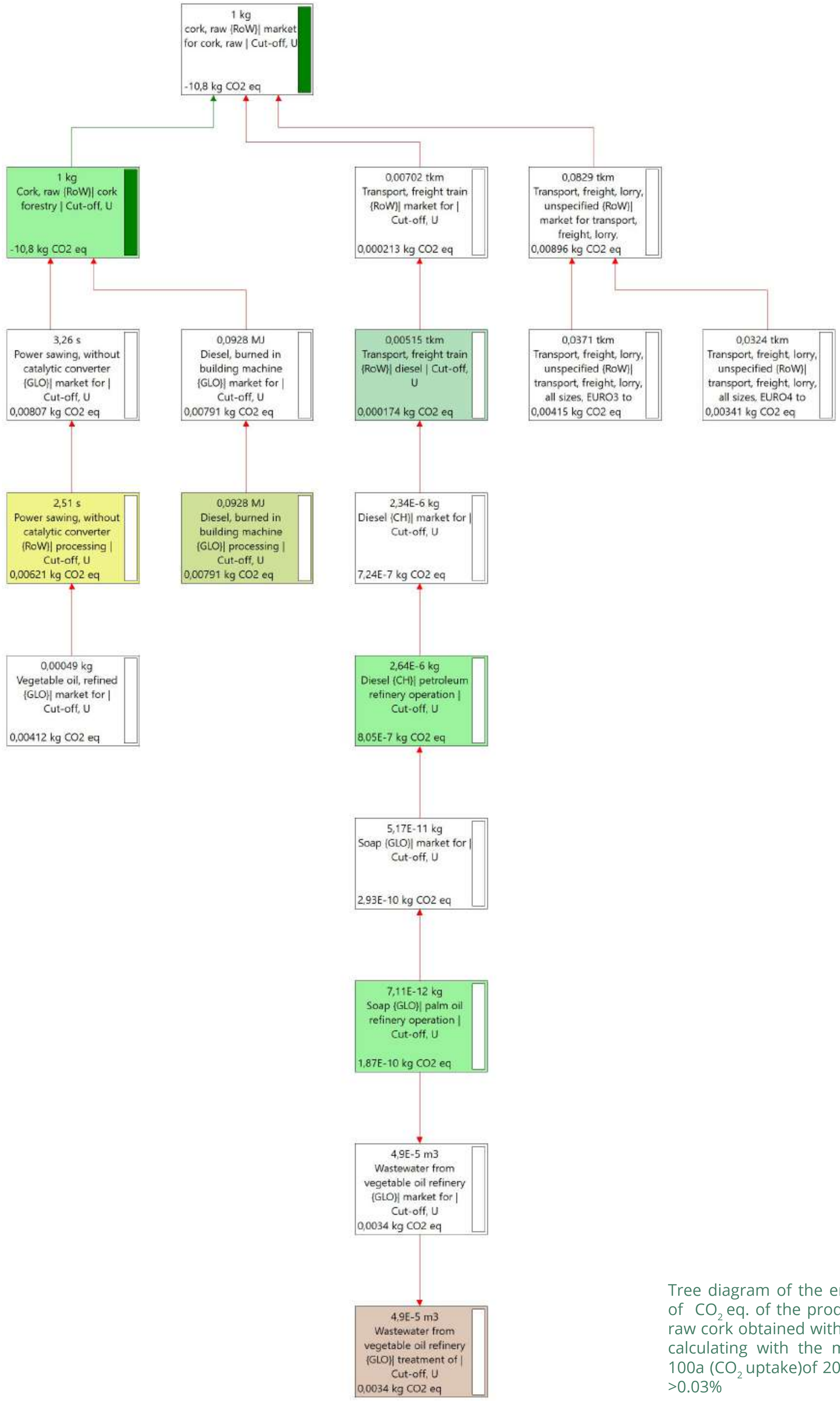
The **IPCC 2013 GWP 100a (incl. CO_2 uptake) V1.00** is a revised version of the IPCC 2007 methodology, which was developed by the International Panel on Climate Change. This updated method provides a compilation of the climate change factors outlined by the IPCC, considering a 100-year time frame.

The **Ecological Footprint 3.0 (EF)** method serves as the impact assessment technique within the Environmental Footprint (EF) initiative, initiated by the European Commission. The version of this method integrated into the SimaPro Professional database has undergone several adjustments to ensure compatibility with the data libraries offered within SimaPro. The EF 3.0 method based on EF method version 3.0, the latest version of the method and has numerous changes, especially for human toxicity, eco-toxicity and land use.

/
Annex

Cork, raw material -

Tree diagram of the emissions in terms of CO_2 eq. of the production process



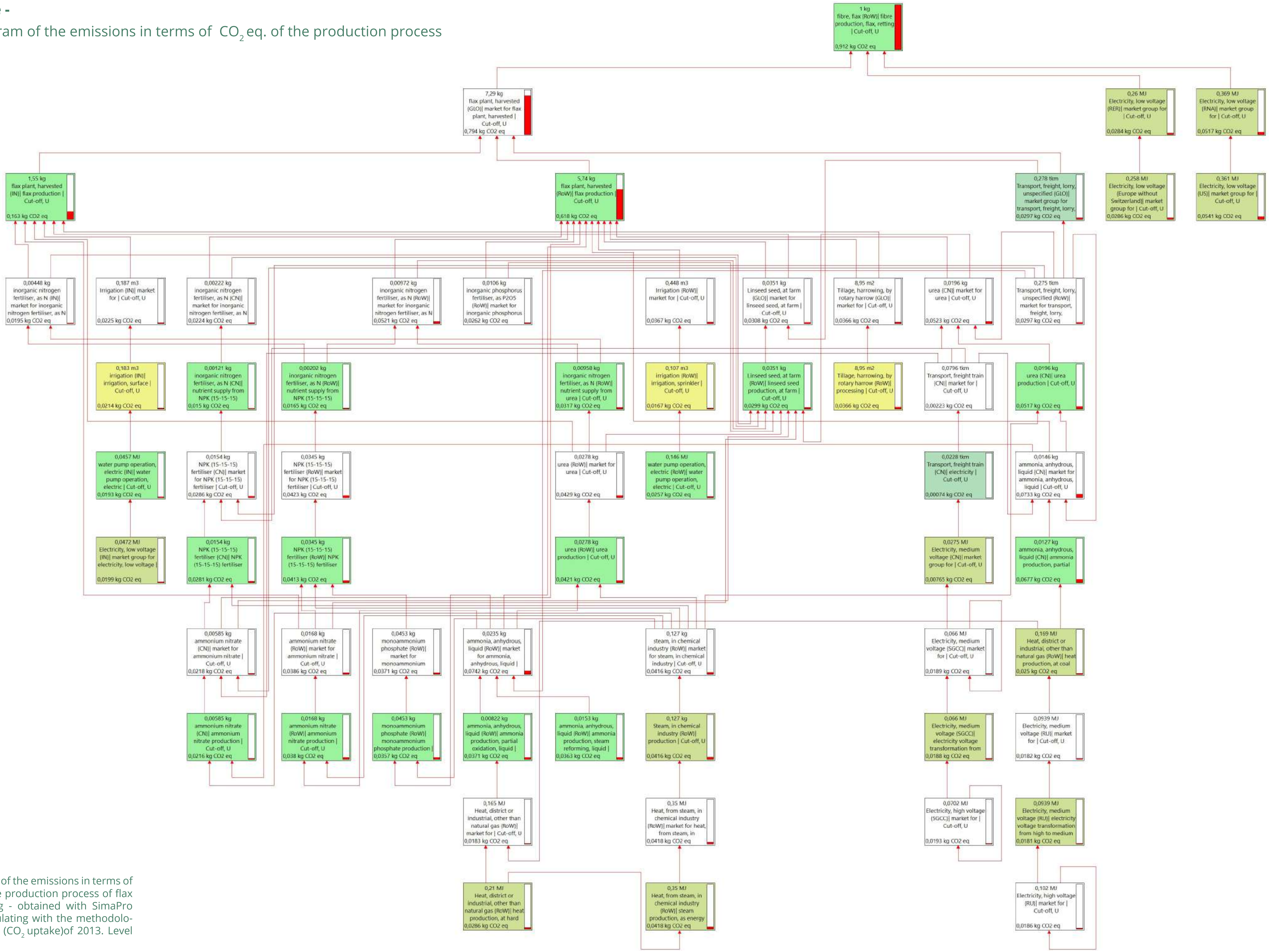
Tree diagram of the emissions in terms of CO_2 eq. of the production process of raw cork obtained with SimaPro sofware calculating with the methodology IPCC 100a (CO_2 uptake)of 2013. Level of detail >0.03%

Peat moss for horticulture -
Tree diagram of the emissions in terms of CO_2 eq. of the production process

Tree diagram of the emissions in terms of CO_2 eq. of the production process of peat moss for horticulture obtained with SimaPro sofware calculating with the methodology IPCC 100a (CO_2 uptake)of 2013. Level of detail >0.03%

Flax fibre -

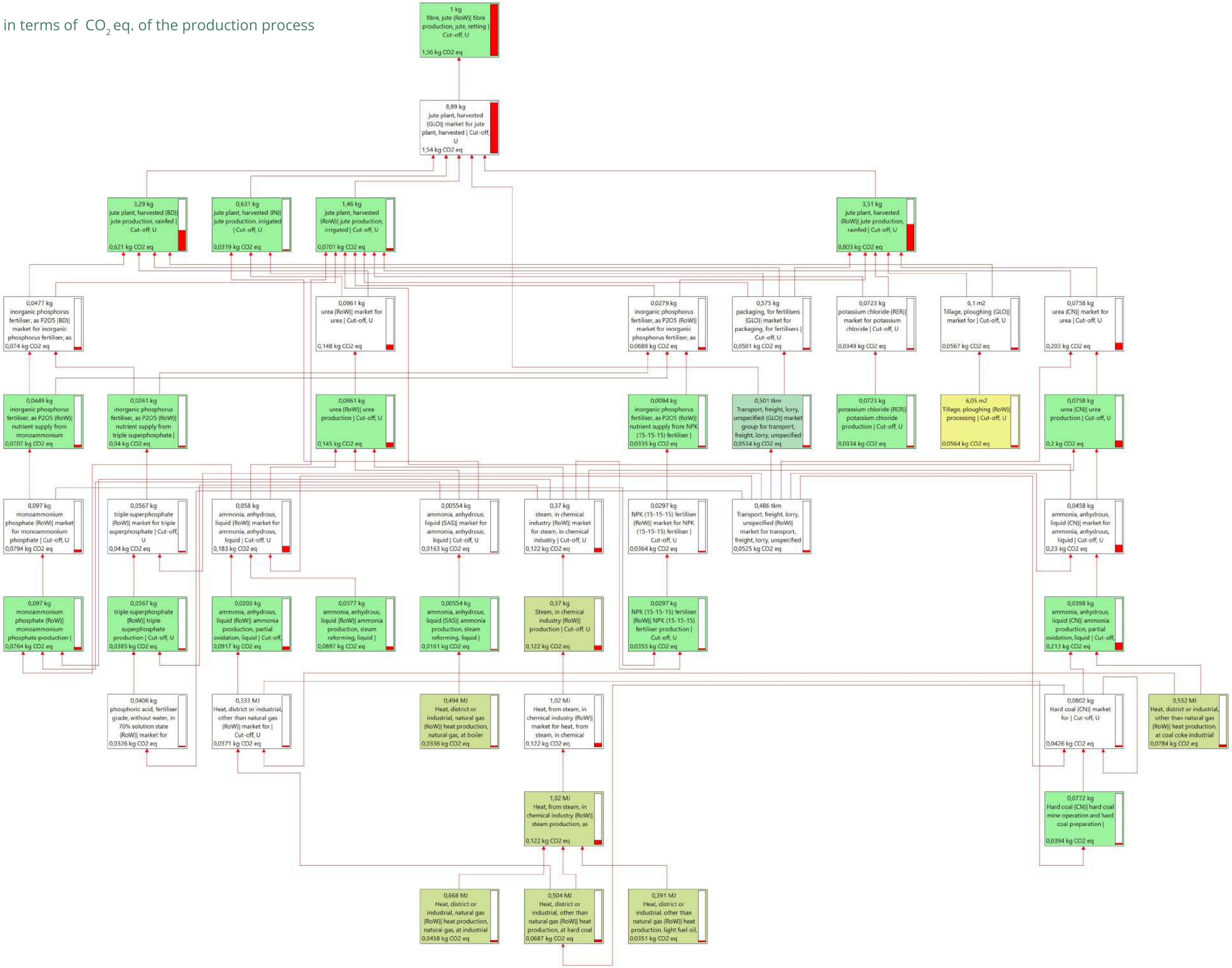
Tree diagram of the emissions in terms of CO_2 eq. of the production process



Tree diagram of the emissions in terms of CO_2 eq. of the production process of flax fibre - retting - obtained with SimaPro sofware calculating with the methodology IPCC 100a (CO_2 uptake)of 2013. Level of detail >2%

Jute fibre -

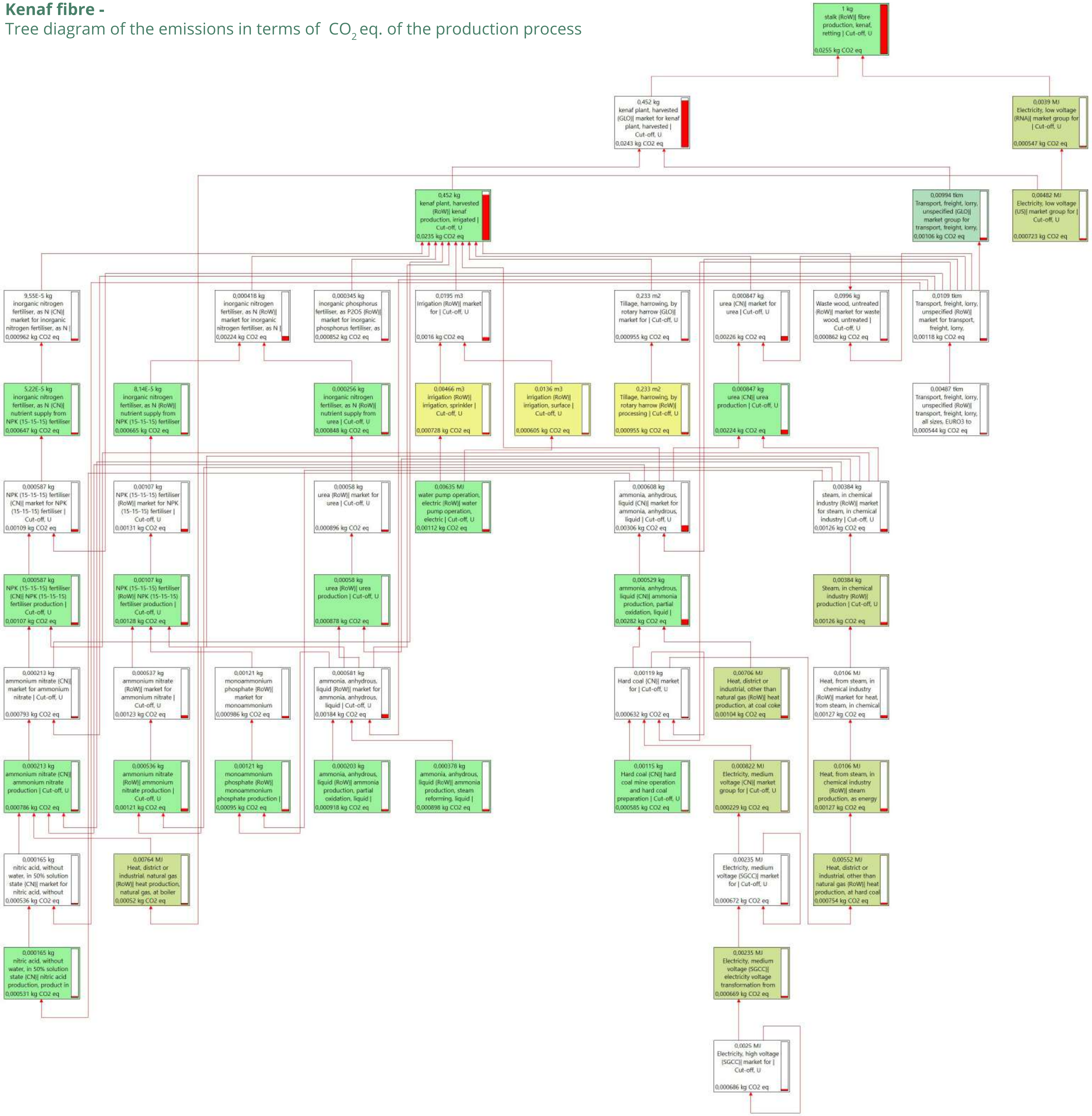
Tree diagram of the emissions in terms of CO_2 eq. of the production process



Tree diagram of the emissions in terms of CO_2 eq. of the production process of Jute fibre - retting - obtained with SimaPro sofware calculating with the methodology IPCC 100a (CO_2 uptake)of 2013. Level of detail >2%

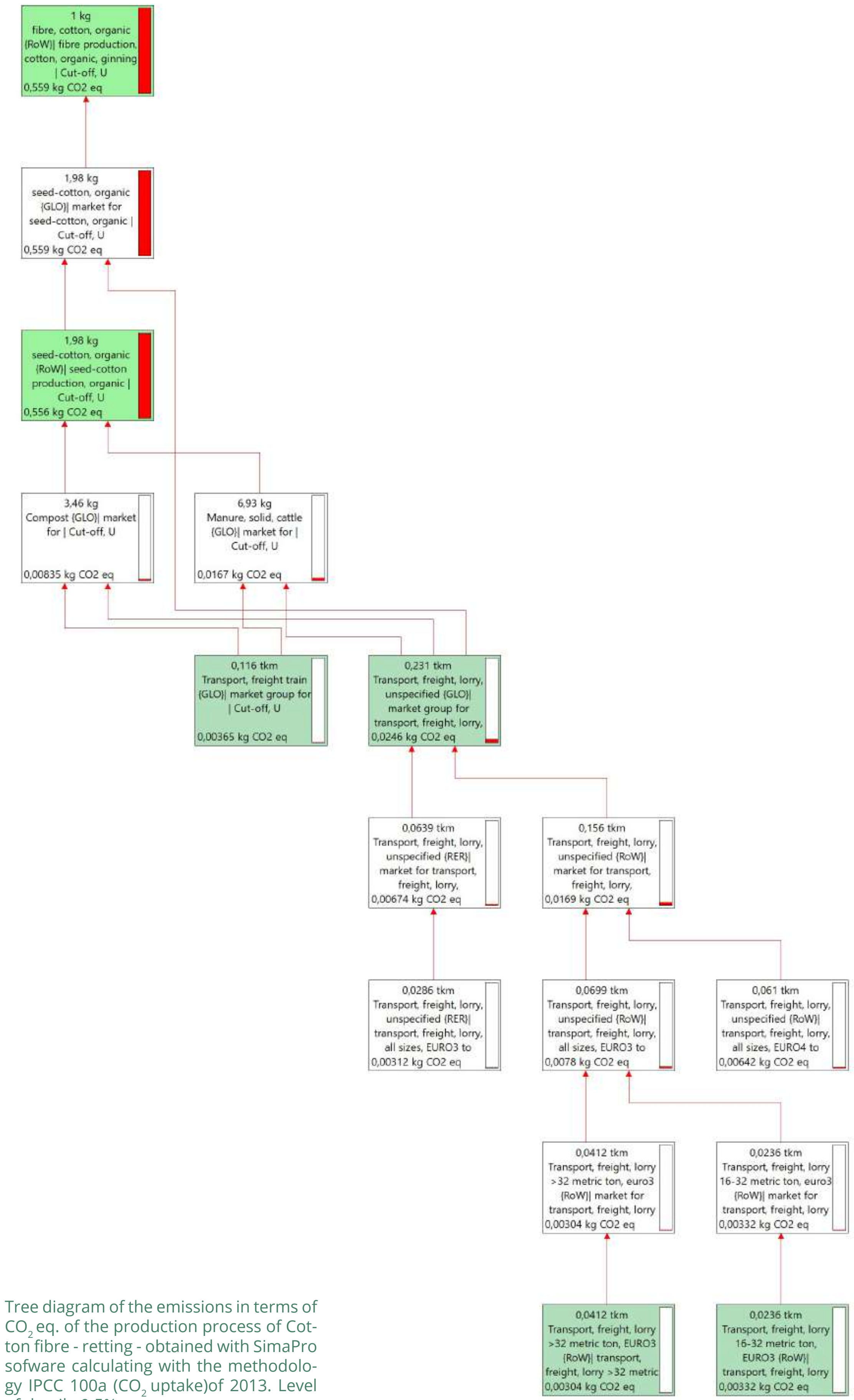
Kenaf fibre -

Tree diagram of the emissions in terms of CO_2 eq. of the production process



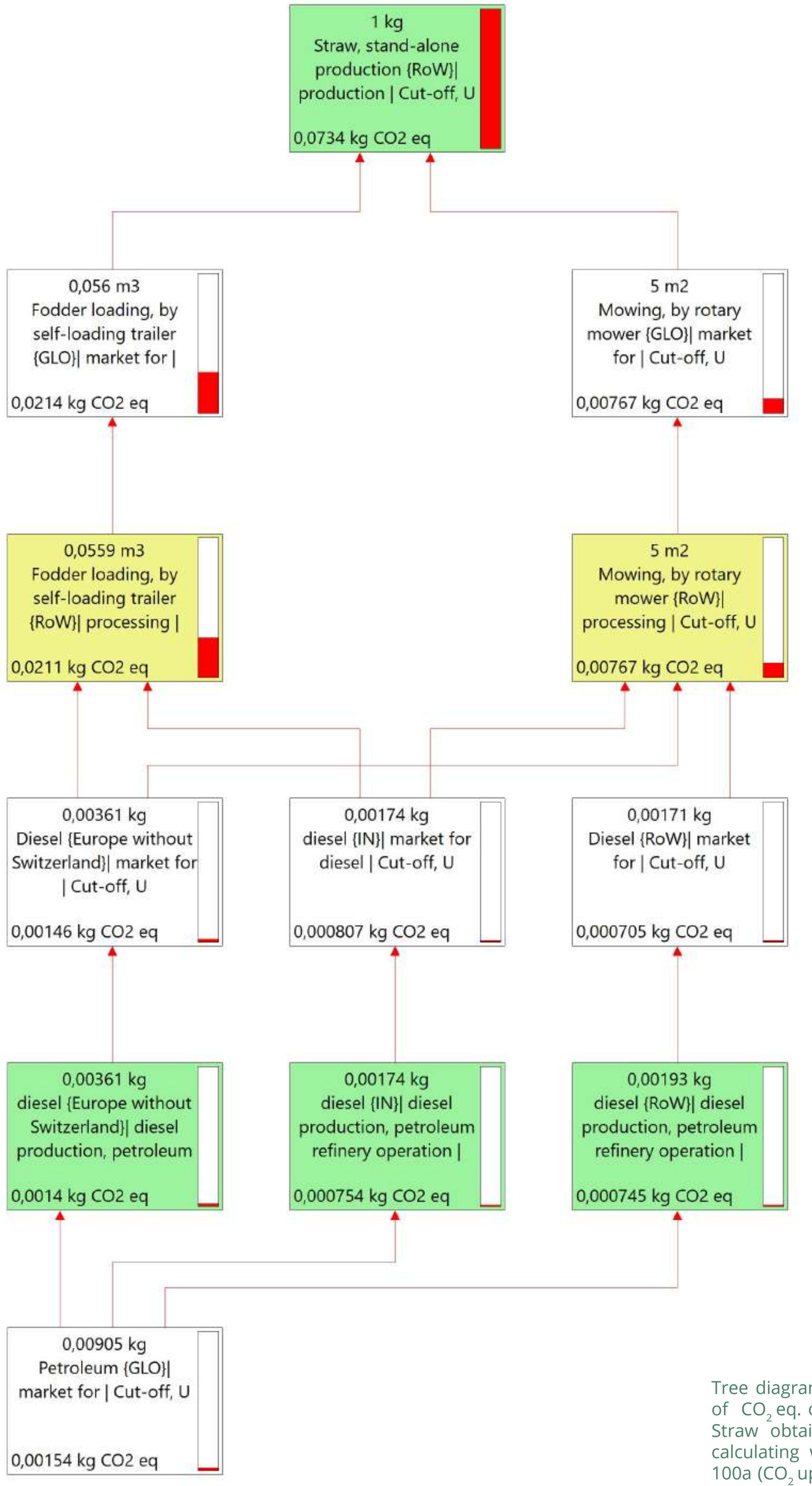
Tree diagram of the emissions in terms of CO_2 eq. of the production process of Kenaf fibre - retting - obtained with SimaPro sofware calculating with the methodology IPCC 100a (CO_2 uptake)of 2013. Level of detail >2%

Cotton fibre -
Tree diagram of the emissions in terms of CO_2 eq. of the production process



Tree diagram of the emissions in terms of CO_2 eq. of the production process of Cotton fibre - retting - obtained with SimaPro sofware calculating with the methodology IPCC 100a (CO_2 uptake)of 2013. Level of detail >0.5%

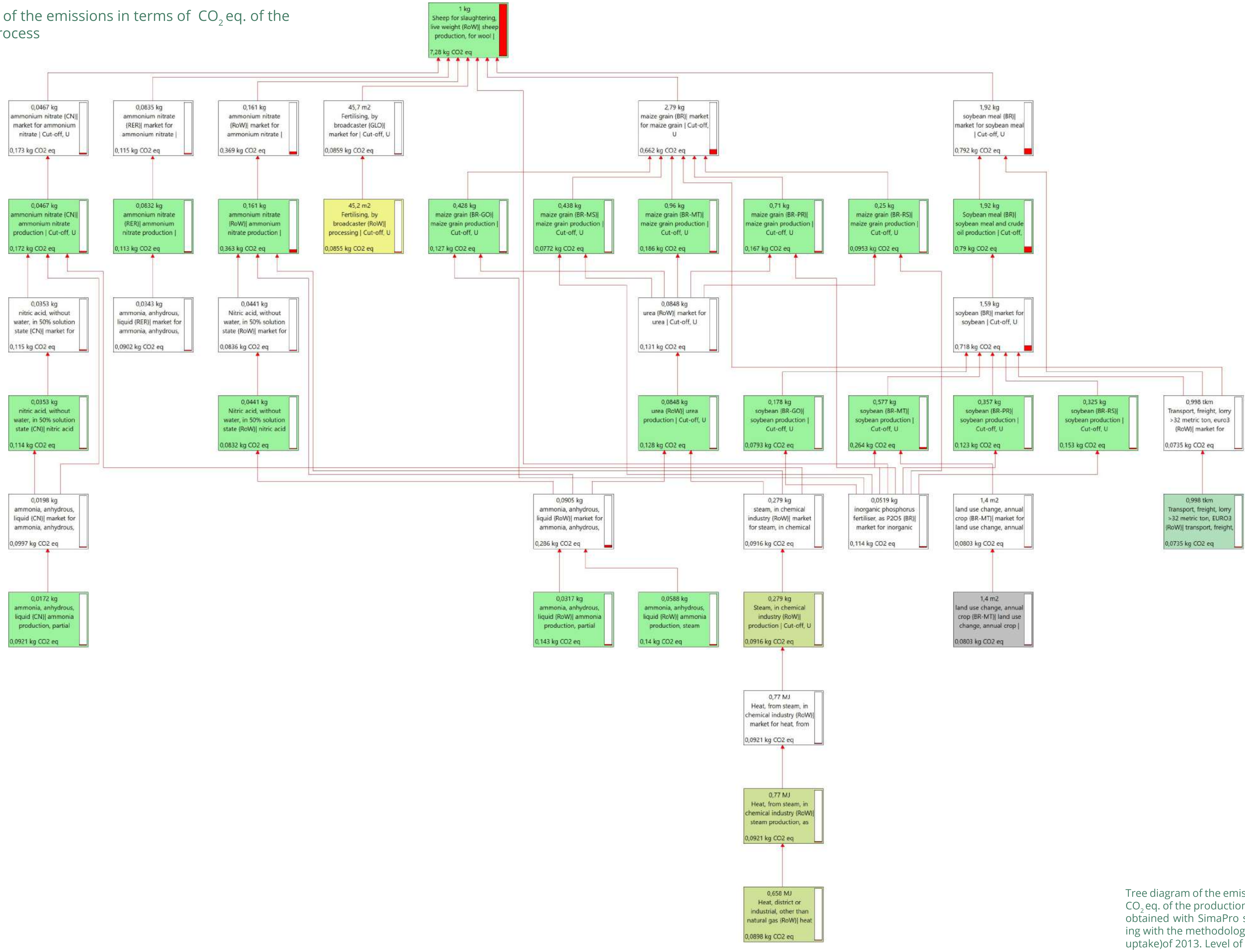
Straw -
Tree diagram of the emissions in terms of CO_2 eq. of the production process



Tree diagram of the emissions in terms of CO_2 eq. of the production process of Straw obtained with SimaPro sofware calculating with the methodology IPCC 100a (CO_2 uptake)of 2013. Level of detail >1%

Wool -

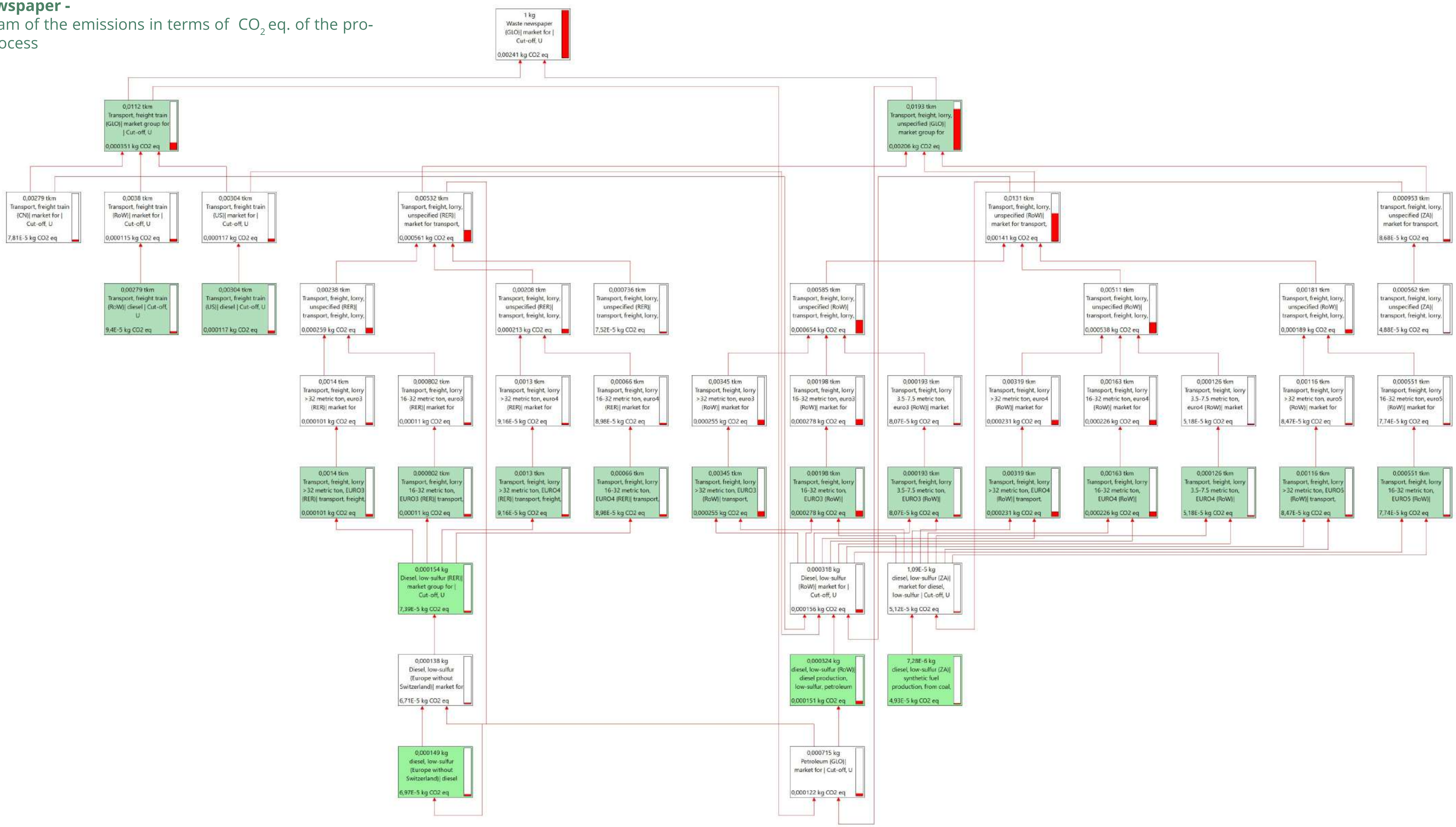
Tree diagram of the emissions in terms of CO_2 eq. of the production process



Tree diagram of the emissions in terms of CO_2 eq. of the production process of wool obtained with SimaPro sofware calculating with the methodology IPCC 100a (CO_2 uptake)of 2013. Level of detail >2%

Waste newspaper -

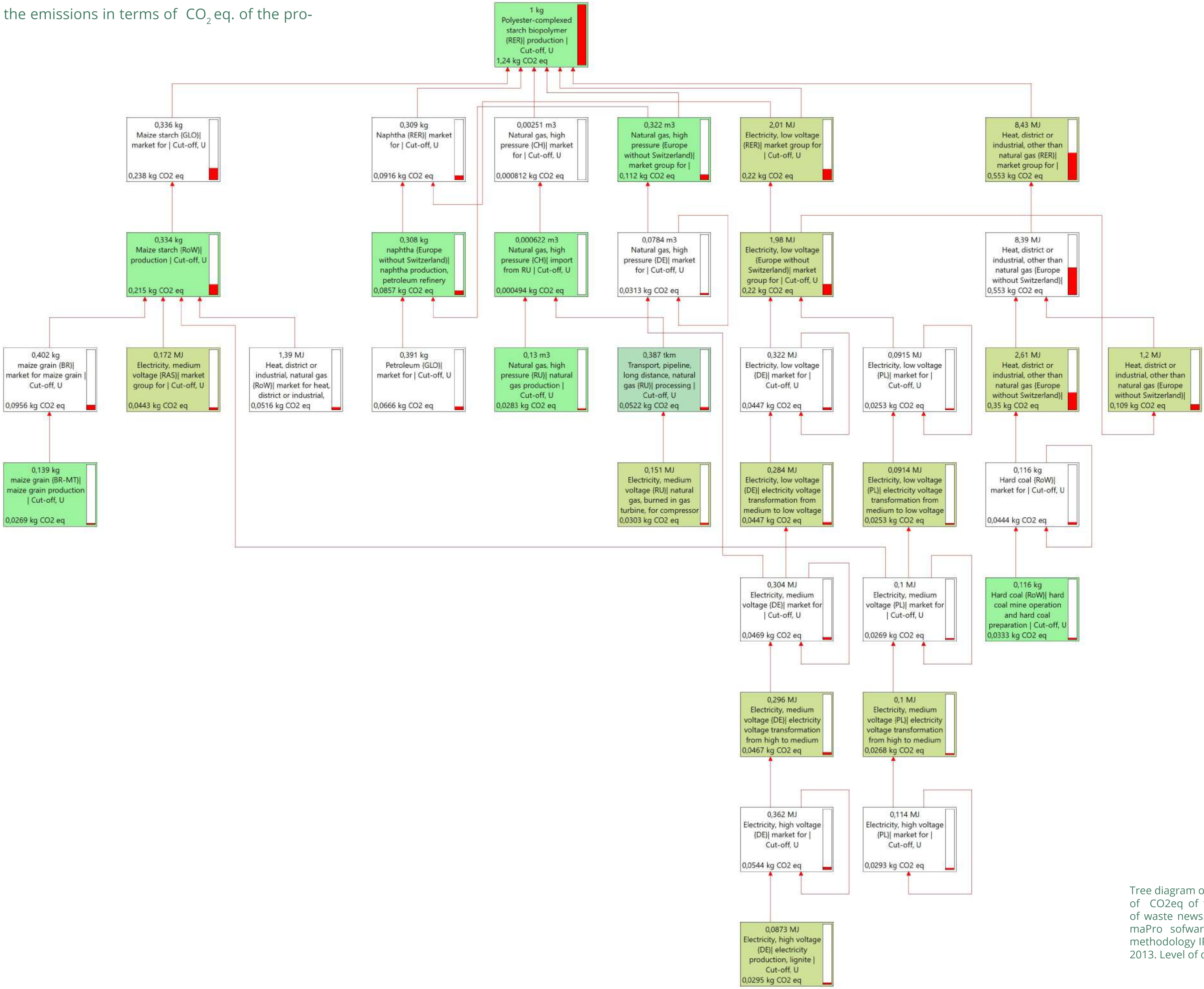
Tree diagram of the emissions in terms of CO_2 eq. of the production process



Tree diagram of the emissions in terms of CO_2 eq. of the production process of waste newspaper obtained with SimaPro sofware calculating with the methodology IPCC 100a (CO_2 uptake)of 2013. Level of detail >2%

Bio-plastic -

Tree diagram of the emissions in terms of CO_2 eq. of the production process



Tree diagram of the emissions in terms of CO2eq of the production process of waste newspaper obtained with SimaPro sofware calculating with the methodology IPCC 100a (CO_2 uptake)of 2013. Level of detail >2%