POLITECNICO DI TORINO

Master of Science Degree
in ARCHITECTURE FOR THE SUSTAINABILITY DESIGN

Master's Degree Thesis

A residential building project in Turin/Italy, design optimization in the light of low carbon materials: environmental impact assessment using LCA methodology

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*My deepest gratitude to Professor Francesca Thiebat for her invaluable guidance, support, and encouragement throughout the course of this research.
Her expertise and insights have been instrumental in the completion of this thesis.*

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ABBREVIATIONS

BIM: Building Information Modeling

BREEAM: Building Research Establishment Environmental Assessment Method

CASBEE: Comprehensive Assessment System for Built Environment Efficiency

CEN: European Committee for Standardization (Comité Européen de Normalisation)

CLT: Cross-Laminated Timber

CO2: Carbon Dioxide

CO2e: Carbon Dioxide equivalent

DGNB: German Sustainable Building Council (Deutsche Gesellschaft für Nachhaltiges Bauen)

EPD: Environmental Product Declaration

EC: Embodied Carbon

EN: European Norm (Standard)

GGBS: Ground Granulated Blast-furnace Slag

GLULAM: Glued Laminated Timber

GWP: Global Warming Potential

HE: H-section European Beam

IPE: I-section Parallel Flange European Beam

ISO: International Organization for Standardization

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LEED: Leadership in Energy and Environmental Design

OPT: Optimization

OSB: Oriented Strand Board

PCM: Phase Change Material

PCR: Product Category Rules

WELL: WELL Building Standard

WLC: Whole Life Carbon

XPS: Extruded Polystyrene

INTRODUCTION

"The significant problems we face cannot be solved by the same level of thinking we used in creating them" - Albert Einstein

Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs[1]. Considering our planet has finite resources and all the global challenges that we face today such as global warming due to increasing greenhouse gas concentration in the atmosphere which also cause climate changing and irregular weather patterns, water scarcity, loss of biodiversity, loss of nonrenewable energy resources, environmental degradation and so on emphasize the importance of the necessity for sustainable actions.

The most common and long-lasting objects in human society are buildings. Long after they were created, they continue to have a significant impact on both the biosphere's health and human existence. As far as the environmental impact is concerned, the architecture and building construction sector cannot be overlooked. Buildings and construction are responsible for 39% of carbon emissions globally out of which 28% from energy consumption and 11% from construction materials[2]. Building and construction is the most heavily emitting sector in the world, and in Europe alone, buildings are responsible for 36% of CO_2 emissions and 40% of energy consumption – yet, in many countries, there remains little political and public awareness around how tackling embodied carbon in the built environment can, and must be, a critical piece of the climate crisis solution[3]. Reducing atmospheric greenhouse gas emissions in this century will require both significant performance gains in our stock of existing buildings, and the design, construction and operation of super high performance new buildings [4]. In the United States, for example, buildings account for 40% of materials use, 38% of CO_2 emissions, and 30% of waste output [5].

With the guidance of technology and the knowledge of nowadays, there are several methods to take better actions for the planet in the architecture and construction sector. Goals of sustainable buildings should have a large range of aspects to consider. Such as energy efficiency, water consumption control, durability, cost/benefits ratio, building materials, quality of life of its occupants, indoor air quality, re-usage of the materials in the end of the building, the environmental impact and potential longevity of construction materials, material sourcing, embodied energy, recyclability, durability, and environmental certifications, carbon footprints etc. In order to understand how sustainable a building is, some frameworks done and buildings created with this goal can obtain standardized green building certifications such as LEED (Leadership Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method) assess many aspects including the methods and analysis pointed out and they provide standardized frameworks to evaluate the sustainability of a building. To obtain one of these certificates there are several criteria that a building must comply with.
We can understand how architects play a great role and have a very complex job. Thus, they have to be well-informed before creating something on the planet we live in

This may be the most challenging part of the architecture. While creating a sustainable architectural work architects should also create socially, architecture and design can help us feel good about who we are and where we live; it can foster or inhibit social interaction and contribute to or mitigate against social cohesion and so economically, well-designed, well-connected buildings and places clearly attract investment and create jobs. Working in buildings and places that offer a variety of spaces, which provide inspiring, comfortable and controllable environments, enhances the recruitment, retention, satisfaction, motivation, productivity and performance of staff [7].

On the other hand, we cannot deny the reality of today, a number of pressing global challenges ahead, sustainability in architecture has become even more critical. Thus, it should be one the most important criteria that architects consider. It is crucial to take correct acts in the architecture and building sector to minimize negative environmental impacts and maximize more sustainable choices. In order to accomplish this, Life Cycle Assessment (LCA) Analysis is an useful approach to determine which design choices will help reduce buildings' carbon footprint, which materials are causing more greenhouse emissions, and how to design ''greener'' and more efficient buildings based on reliable, quantifiable data.

This thesis will focus on demonstrating how to contribute to a more sustainable future by making more sustainable choices for the building materials/structures. In pursuit of this goal, we should consider different aspects. It would be a mistake to look superficial to a material's carbon footprint without considering if it has been collected from local resources or it has been recycled or it has potential to be recycled or renewed in the future. Every product requires energy to produce it, and many products require a large amount of processing and transport before they reach the consumer. Each process in product manufacturing requires transport, use, maintenance, and finally disposal, all of which use energy that can produce a large variety of emissions with very specific effects on the environment [6].To understand better this point of view, we can say that local resources have a significant importance to make a building more sustainable because using locally sourced materials lowers energy and transportation-related emissions, lowering carbon footprints which is crucial for this thesis. Furthermore, these materials match the local climate and surroundings with harmony and more effectively. Local materials have more probability to be recyclable or renewable, structures made of them tend to have a smaller environmental impact. An architectural design made with using locally obtained materials can integrate smoothly to its surroundings and most probably also will carry architectural characteristic of the place. Overall, this approach is essential for a sustainable design.

The core of this thesis will be to demonstrate this hypothesis concretely. In order to do this, LCA analysis will be applied to the current status of a case study of a residential project in Turin/Italy. Comparison between the current status of the project and a new design proposal with the materials chosen in the light of researches which have less environmental impact will show us how in the design phase building materials/structure decisions play a huge role to reduce the strain on nature.

HYPOTHESIS

Architects play a unique and important role in addressing these serious issues through their design choices and decision-making, especially in light of the enormous environmental degradation, resource depletion, and climate change that our world is currently facing. Since buildings play a significant role in the world's resource consumption and carbon emissions, architects must embrace sustainable solutions that can lessen these effects. The environmental impact of buildings and infrastructure can be greatly decreased by architects by emphasizing sustainable designs and using alternative low carbon materials.

Furthermore, using alternative low carbon /locally obtained materials can significantly lessen the need for non-renewable resources and the carbon footprint left by using conventional building materials like steel and concrete.

Such sustainable practices are essential for protecting natural resources in addition to helping to cut down on energy use and carbon emissions. Architects may contribute to preserving these resources for future generations by creating structures that use or pollute less during their lifespan. Furthermore, by making buildings more resilient to the effects of climate change, including extreme weather events, sustainable designs can help to create a society that is both more resilient and sustainable.

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[1] United Nations General Assembly (1987) Report of the World Comission of Environment and Development: Our Common Future

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RESEARCH QUESTIONS

- How can understanding the environmental impact of building structures and materials decisions during the design phase underscore the importance of sustainable architecture?
- What are the sustainable building structure options used nearby Turin/Italy?
- What local resources and low-carbon material options are available near Turin/Italy, and which of these options are suitable to be used in a residential project?
- How can optimizing a design evaluating alternative building structures and sustainable building materials can affect carbon emissions?

THESIS STRUCTURE

1. CHAPTER ONE : BACKGROUND

Whole Life Carbon (WLC), Green Building Council (GBC) roadmap will be discussed. This initial explanation will create a background for the further steps of the thesis

2. CHAPTER TWO : LIFE CYCLE ASSESSMENT (LCA) APPROACH

Understanding life cycles and building life cycle models, along with what Life Cycle Assessment (LCA) analysis is and its purpose, will be discussed. To achieve this, product category rules (PCR), Environmental Product Declarations (EPD), and International Organization for Standardization (ISO) standards will be examined to better understand the LCA concept.

3. CHAPTER THREE : CASE STUDIES IN NEARBY AREAS AND LOCAL RESOURCES

3.1 Examples of local structures/resources and research about what kind of strategies they carried on to make a project sustainable will be discussed. While doing this, what kind of building structures and materials have been used will be searched. In addition, low carbon and more sustainable materials which can replace the most used building structures and materials will be searched.

3.2 According to these researches there will be a critical analysis. Which of the materials or building structures can be suitable to be applied in Italy for a residential project will be discussed. After that, the materials and building structures searched in the chapter three, they will be filtered in order to reduce a project's environmental impact .To do that, understanding their characteristics and coherence with the new design ideas will be taken into consideration.

4. CHAPTER FOUR : DESIGN PROPOSALS AND ENVIRONMENTAL ANALYSIS

4.1 General information about the project, definition of Life cycle assessment analysis goals and functional unite will be discussed. Which elements of the building will be included to LCA analysis and system boundaries will be defined.

4.2 Business-as-usual (BAU) scenario of a residential building in Italy designed by a firm will be presented. In order to apply all the previous researches concretely to the project, LCA analysis will be applied to see which are the most contributing building structure and materials and their environmental impact and bill of quantity will be presented.

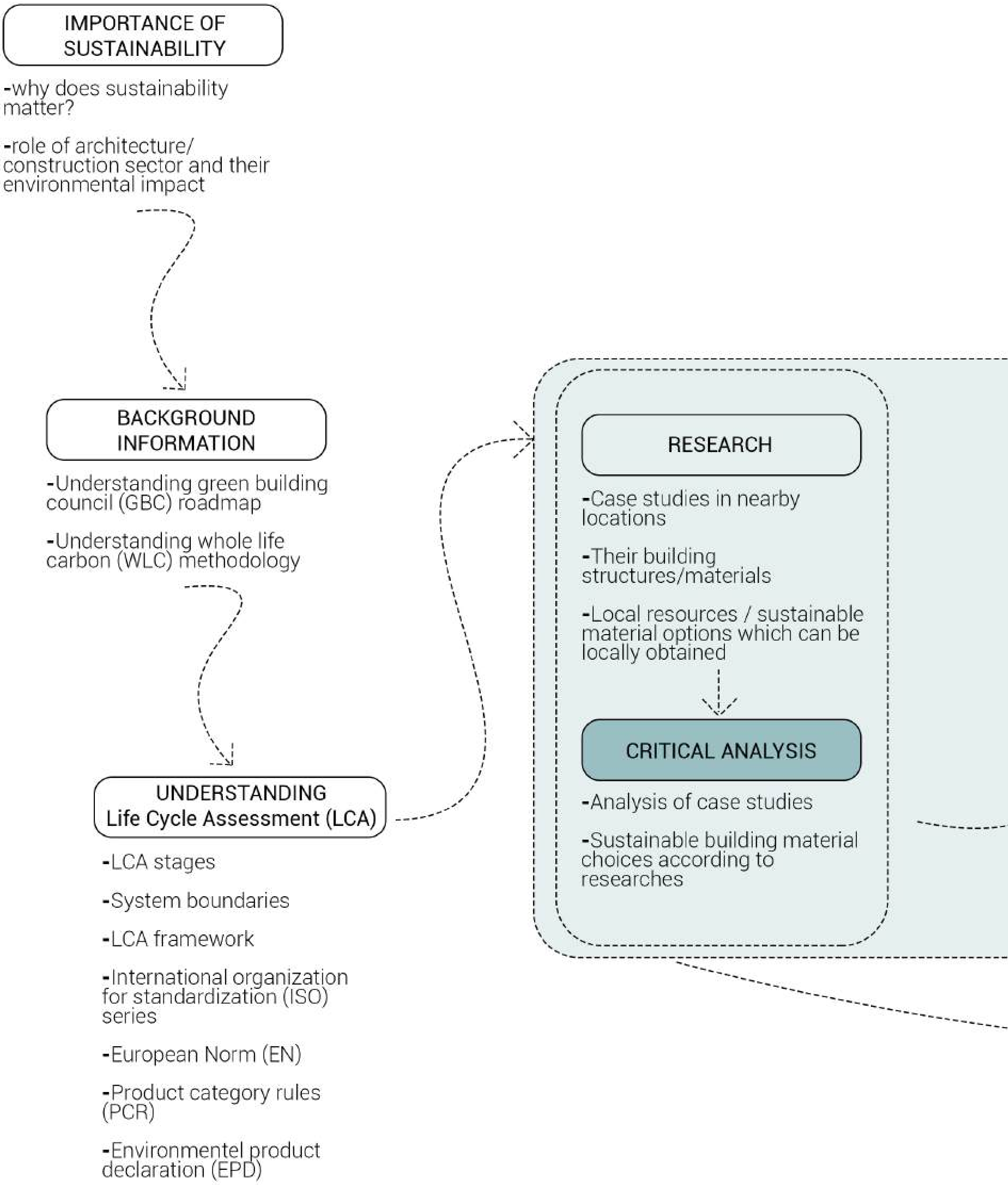
4.3 Business-as-usual scenario will be optimized. Design optimization, applying the filtered building structures/materials according to the chapter 3 will be presented.

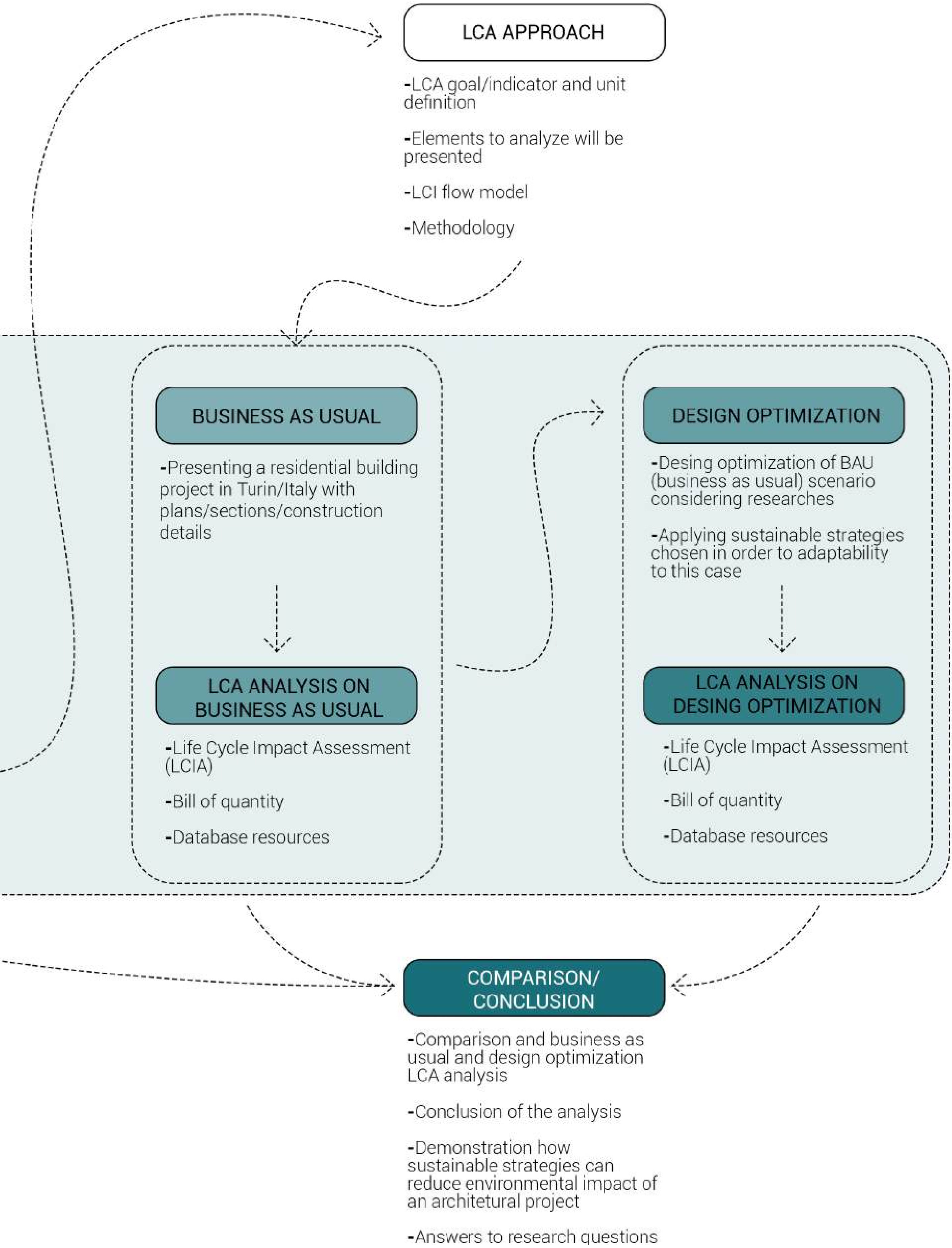
4.4 Results of LCA analysis of the design optimization and bill of quantity will be presented.

5. CHAPTER FIVE : COMPARISONS AND CONCLUSION

Comparison between two different designs' environmental impact will be presented. The conclusion of importance architects' role will be underscored.

THESIS WORK-FLOW




LCA APPROACH
-LCA goal/indicator and unit definition
-Elements to analyze will be presented
-LCI flow model
-Methodology
BUSINESS AS USUAL
-Presenting a residential building project in Turin/Italy with plans/sections/construction details
LCA ANALYSIS ON BUSINESS AS USUAL
-Life Cycle Impact Assessment (LCIA)
-Bill of quantity
-Database resources
DESIGN OPTIMIZATION
-Desing optimization of BAU (business as usual) scenario considering researches
-Applying sustainable strategies chosen in order to adaptability to this case
LCA ANALYSIS ON DESING OPTIMIZATION
-Life Cycle Impact Assessment (LCIA)
-Bill of quantity
-Database resources
COMPARISON/ CONCLUSION
-Comparison and business as usual and design optimization LCA analysis
-Conclusion of the analysis
-Demonstration how sustainable strategies can reduce environmental impact of an architetural project
-Answers to research questions

chapter 1

BACKGROUND

BACKGROUND

We live in the world where sustainability became a major factor that concerns businesses, governments and consumers and that is why comprehending the whole cost of goods and services is paramount.

In today's world, architectural design must necessarily include the three dimensions of sustainability within the ideation process as the tangible expression of the creative and research process. Architects are required to tackle this complex process in a responsible, knowledgeable manner; this process includes the whole life cycle of the building and the effects the built environment has on the environment and those who live in it (Thiebat, F. , 2019) [1].

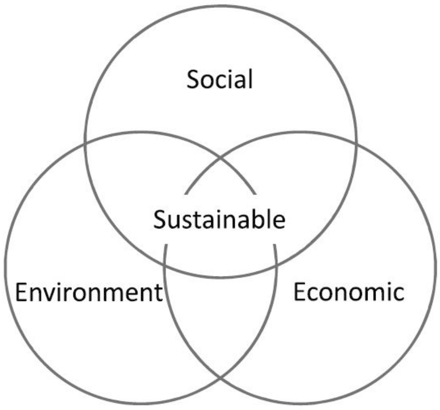


Figure 1. Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins.

The concept of sustainability encompasses three interconnected pillars: In the environmental perspective, the nature is affected; in the social perspective, society is impacted; and in the economic perspective, economy is influenced.

•Environmental sustainability concerns the conservation of the environment and the resources as well as reducing pollution and impacting the environment in the least way possible.
•Social sustainability is about fairness and quality life of every citizen within a society, with attention to accessibility of needs and participation in the decision making.
•Economic sustainability focuses on economic strength with relation to stock, production and wealth apart from conservation of resource and thinking of the consequences.

The principles of sustainability on these three pillars are important to create sustainable development that provides the need for the present to be met without consuming the resources that will be needed by the next generation. In this thesis we will mostly focus on environmental sustainability. To understand what are the actions for environmental sustainability we can look closer to green buildings and world green building council (GBC).

1.1 GREEN BUILDINGS

1.1.1 WHAT IS GREEN BUILDING?

A green building or a sustainable building is a building that is planned, built, used, and maintained in a way that has least detrimental impact on the environment or that minimizes human public health impacts of the building's practices. Essentially, these principles seek to ensure that the environmental impact of constructing and using the building is as low as possible for the duration of the building's performance, use, and deconstruction. Which is not an easy goal to be achieved. To achieve this concept, there are a lot of parameters to consider for architects and engineers.

A green building is any structure whose construction, use by its occupants and facility management, and decommissioning is done in a manner that ensures it consumes natural resources efficiently while minimizing its effect on the environment (USGBC, n. d.) [2].
They intended to minimize the energy use, water utilization and waste production but at the same time improve the indoor environmental quality and occupants' comfort. Furthermore, green buildings also consider practices when constructing it to ensure that there is minimal wastage and encourage the recycling of waste or using recycled material (World Green Building Council, 2020) [3].

Another important consideration in green building construction is materials and its choices, especially emphasis should be laid on the use of organic and recycled, eco-friendly or relatively non-toxic materials that would have least negative impacts on the environment and health of the occupants (U. S. Environmental Protection Agency, 2020) [4].

Shortly, green buildings are development and structures that are responsible to the surrounding environment, conservatively consumed resources, and provide health facilities to those who live, work, and play in the structure. These and other concepts of Green Buildings make a valuable contribution to the preservation of the physical environment by decreasing the negative impact of human activity and stabilizing the use of natural resources in construction.

1.1.2 ABOUT GREEN BUILDING COUNCIL (GBC)

The World Green Building Council (WorldGBC) is a global network leading the transformation of the built environment, to make it healthier and more sustainable. Collectively, with our Green Building Councils (GBCs) in around 70 countries, we accelerate action to deliver on the ambition of the Paris Agreement, by eliminating the buildings and construction sector´s emissions by 2050 [5].

1.1.3 THE PARIS AGREEMENT

A legally binding global climate change agreement, the Paris Agreement, was ratified by 196 nations at United Nations Climate Change Conference also known as COP21, in 2015. It seeks to keep global warming to pre-industrial levels or well below 2ºC, ideally 1.5ºC. According to the guidelines of the Paris Agreement, nations are required to submit nationally determined contributions (NDCs) every five years. In essence, NDCs are action plans that specify how each nation will lower its emissions and adjust to climate change [6].

In 2019, WorldGBC published its Bringing Embodied Carbon Upfront report, which outlines a hierarchy of actions to optimize resources.

1. Prevent: The best way to reduce embodied carbon is to avoid unnecessary new construction and prioritize renovation.

2. Reduce and optimize: Databases and building simulation tools can optimize building designs and renovations to minimize the use of new material and foster circularity.

3. Plan ahead: New buildings and renovations must integrate circular economy principles, whole life carbon (WLC) assessments and natural systems restorations, among other strategies, to mitigate end-of-life emissions.

4. Offset: After maximizing the available techniques, technologies and resources, residual carbon emissions must be appropriately and effectively offset.

1.1.4 EUROPEAN CONTEXT:

A number of initiatives at the EU level aim to speed the move to a fully decarbonized built environment based on the concepts of sustainability, full life cycle assessment (LCA), circularity, and transparency. In December 2019 The EU Green Deal was released which lays out a plan of action for achieving climate neutrality by 2050, reducing pollution, recovering biodiversity, and transitioning to a clean, circular economy. As already seen, the EU has a broad 2050 vision of becoming a net-zero emitter of emissions, a vision that cannot be attained without Data, the voluntary reporting framework developed by the Commission. It provides the common, precise and measurable package which can be used to evaluate the environmental profile of newly constructed and existing residential and commercial buildings from the inception of their life cycles to their decommissioning. These six different sustainability themes are:

- greenhouse gases (GHG)'s
- resource use efficiency
- water use
- indoor environmental quality
- resilience
- accessibility to cost and value

Each indicator should create a link to such goals of sustainability as is provided at the European level within a building and the impact.

1.1.5 GREENHOUSE GASES (GHG)'S

Greenhouse gases GHGs are gases in the atmospheric that retain heat which is useful in greenhouse effect that is beneficial in making the earth habitable. But human activities have caused the enlargements of these gasholder and has enhanced the green house effect and therefore global warming. Some of the major GHGs are **Carbon dioxide** which is emitted through the burning of fossil fuels and afforestation (IPCC, 2014) [7]. **Methane** which is emitted by agriculture and landfilling and **nitrous oxide** which is emitted by agricultural research, and industries. Moreover, **fluorinated gases**, which are employed in diverse industrial processes, have a high global warming potential (GWP).

Due to the increased levels of the greenhouse gases results in climate change in that the global and annual mean temperatures rise, severe weather conditions become frequent, and ecosystems are affected (IPCC, 2018) [8]. Reducing GHG emissions, through the increased deployment of renewable energy, supply chain optimization and increased efficiency, can help to minimize the negative impacts on the climate and global stability.

1.1.6 GLOBAL WARMING POTENTIAL (GWP)

The ability of greenhouse gases to cause global warming is represented as an index in relation to CO2. Methane, for instance, has a global warming potential of 25, which means that it traps heat 25 times more effectively than CO2. With a potential for 298 global warming, nitrous oxide is an even more potent greenhouse gas, and fluorinated gasses are very potent as well. Quantities of greenhouse gases other than CO2 emissions are frequently discussed in terms of their CO2 equivalency (CO2e).

Greenhouse Gas	Global Warming Potential*	Percent of U.S. GHG Emissions
Carbon dioxide (CO_2)	1	81%
Methane (CH_4)	25	10%
Nitrous Oxide (N_2O)	298	6%
Fluorinated gases	7,390-22,800	3%

Figure 2. Greenhouse gas emissions from human activity: global warming potential and percent of total (U.S. EPA, 2019).

1.1.7 GREEN BUILDING COUNCIL ROADMAP

World green building council on the report of 2019 "bringing embodied carbon upfront" emphasize the urgency to take action now and create a roadmap/goal for the next ten years to lessen carbon footprint caused by our actions:

The IPCC (Intergovernmental Panel on Climate Change) report "Global Warming of 1.5°C." highlights the urgent need to achieve radical emissions reductions in the next decade to avoid catastrophic climate breakdown. With operational carbon still the major portion of our sector's impact, we must not accept low operational performance levels now, that will need costly upgrades in the future – indeed, we should scale up decarbonisation efforts for operational carbon (eg via energy efficiency technologies, grid decarbonisation). While embodied carbon currently accounts for 11% of emissions globally, as operational carbon is reduced and development accelerates in parts of the world including China and Africa; it is estimated that more than half of total carbon emissions from all global new construction between 2020 and 2050 will be due to upfront emissions from new building construction and, to a lesser degree, from building renovations in Europe in particular (WorldGBC, 2019) [9].

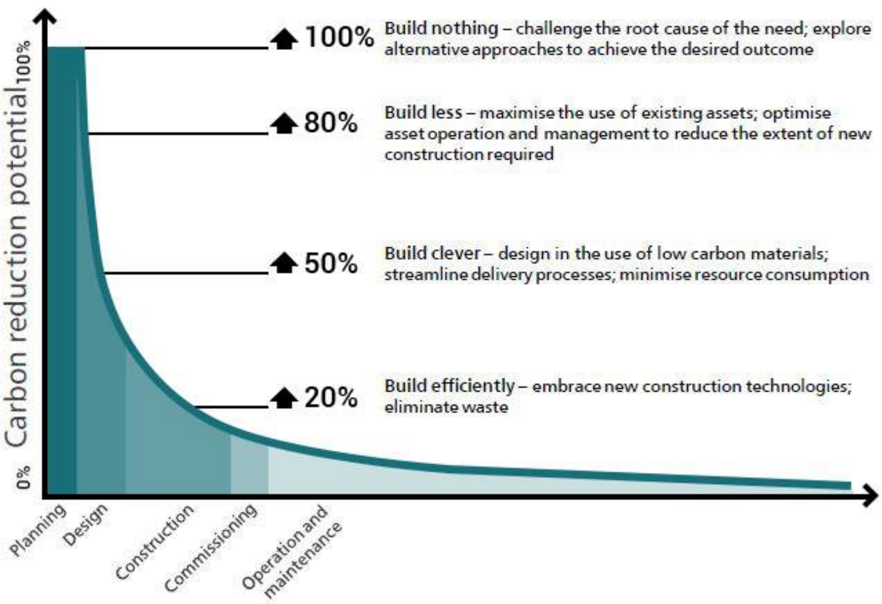


Figure 3. Opportunities to reduce embodied carbon from stage of design process.
Redrawn figure source: HM Treasury. (2013). Infrastructure Carbon Review.

You can reduce carbon at any point in the delivery process, but the opportunities are greater the earlier you start. Adopting the concepts of Figure 3. It may require clients, consultants, contractors and suppliers to rethink some of their business models, many of which are fundamentally based on creating assets. However, helping clients to avoid construction, with its attendant cost and emissions, opens up new business opportunities (HM Treasury, 2013) [10]. In order to reduce carbon emissions in architectural field we should understand the life cycle stages and which stages are related to specific carbon emissions.

1.2 WHOLE LIFE CARBON

Different terminology and definitions exist in the context of greenhouse gas emissions of products, buildings and related infrastructure across the entire building life cycle. The meanings and definitions of each of these concepts may differ among the various segments of the market or between different countries and regions. When stating the following definitions of LCAs, we will refer to the life cycle stages or modules mentioned in the European, widely practicing normative document EN 15978 of Figure 2.

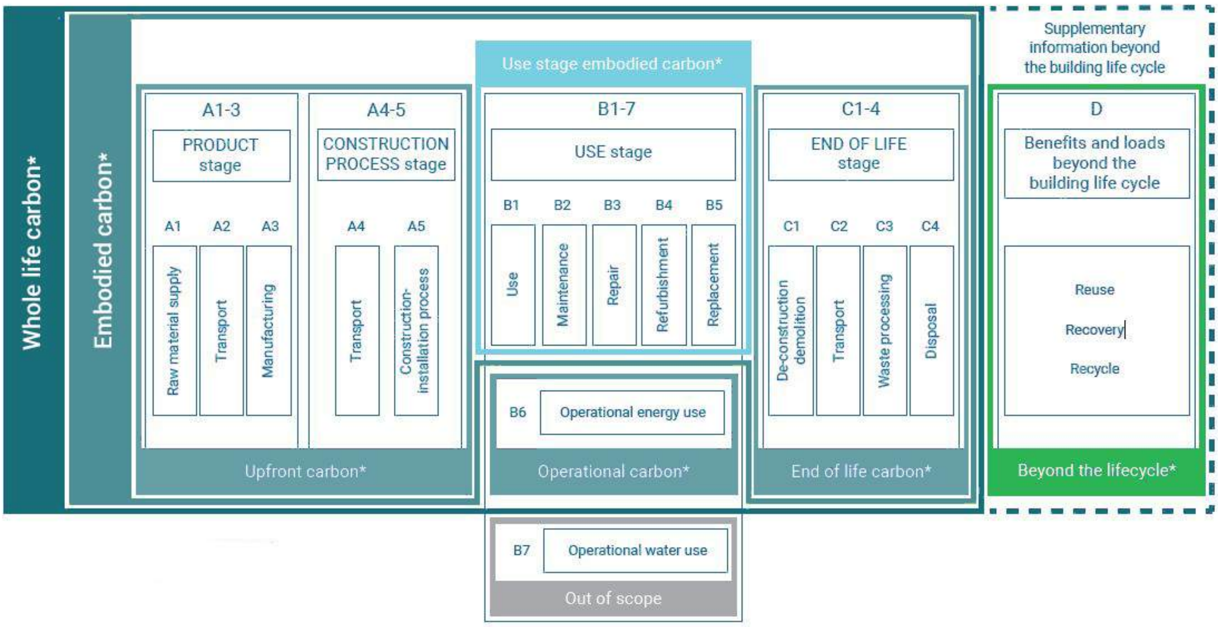


Figure 4. Redrawn figure origin: "terms and lifecycle stages defined in EN 15978" WorldGBC (2019) : Bringing embodied carbon upfront

1.2.1 EMBODIED CARBON

Embodied carbon (EC), or life cycle embodied carbon, is the total amount of CO2e released during the acquisition of building materials, the transport of building material and components, installation of the materials and components, periodic maintenance, and at the end of the materials' useful life, recycling, recovery, or disposal. EN 15978 is an European standard which concerns with measuring and declaration of environmental performance of building, where embodied carbon is classified as one of the most significant contributors to environmental load. As specified in the EN 15978, Life Cycle Assessment (LCA) is a valuable methodology that demonstrates the amount of embodied carbon in a building and construction products throughout construction and beyond.

This standard categorizes the life cycle into distinct stages: Product Stage includes three attributes namely A1 to A3 and Construction Process Stage includes two attribute, that is, A4/A5 Use Stage includes seven attributes, namely B1 to B7, and End-of-Life Stage includes four attributes, namely C1 to C4. All stages make some input to the overall embodied carbon of the building (Construction Environmental Notes, (CEN) 2011) [11].

1.2.1.1 UPFRONT CARBON

Upfront carbon the emissions generated during the lifecycle's first five phases (A1–5) of material production and construction, before the structure or infrastructure begins to use. These emissions have already been released into the atmosphere earlier than the building being occupied or the infrastructure starting to function, in contrast to other emission categories that we will mention.

1.2.1.2 USE STAGE EMBODIED CARBON

Use stage embodied carbon refers to carbon emissions after the construction phase finished when an infrastructure begins to be used and, being maintained, repaired, refurbished or replaced and all these stages refers from B1 to B5.

1.2.1.3 OPERATIONAL CARBON

Operational carbon is a greenhouse has that is emitted from the energy used in occupying the building or structure or the energy for the physical operation of an infrastructure, differently from upfront carbon. This includes the electricity and fuel required for heating, cooling, lighting, ventilation, and running appliances and plant within the building.

1.2.1.4 END OF LIFE CARBON

End of life carbon,the additional carbon emissions that result due to the deconstruction or demolition of building. The operational and post-use development stages of a building or infrastructure can be looked at as follows: (C1) transport from site, (C2) waste processing, and (C3, C4) waste disposal.

1.2.2 BEYOND THE LIFECYCLE

Quantity of carbon emissions or reduction of emissions due to material recycling or reusing them/or emissions avoided through using waste as fuel for another process (module D). To understand how materials are to be utilized towards the last useful period, attention must be given to the module D.

1.2.3 WHOLE LIFE CARBON (WLC)

Whole life carbon is an assessment of the total quantity of carbon dioxide emissions during the course of a whole life cycle of any given construction project, including the embodied and operational emissions. Conducting before, during, and after construction, it covers extraction of raw materials to the disposal of the building at the end of its life cycle. Following to the EN 15978 standard, whole life carbon includes A1 to C4 elements, while D is reported separately to reflect the additional credits that include the loads beyond the system boundary (CEN, 2011) [11].

CHAPTER 1 FIGURES:

[1] Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins.

[2] Greenhouse gas emissions from human activity: global warming potential and percent of total (U.S. EPA, 2019).

[3] Redrawn figure source: HM Treasury. (2013). Infrastructure Carbon Review. Opportunities to reduce embodied carbon from stage of design process.

[4] Redrawn figure origin: "terms and lifecycle stages defined in EN 15978" WorldGBC (2019) : Bringing embodied carbon upfront

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[1] Thiebat, F. (2019). Life Cycle Design: An Experimental Tool for Designers.

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chapter 2

LIFE CYCLE ASSESSMENT (LCA) APPROACH

The thesis "A residential building project in Turin/Italy, design optimization in the light of low carbon materials: environmental impact assessment using LCA methodology", focuses on a rational methodical approach to the evaluation of environmental burdens of building materials and design options based on Life Cycle Assessment (LCA). To begin the analysis, the first step will be to adopt a literature review that will help in developing the theoretical foundation of the study based on sustainability in architecture, green building practices, and whole life carbon. It will also involve a critical evaluation of the green building council strategic plan as well as other structures of reference.

Next, the LCA approach will be explained in order to understand in which way it works and why it is essential in building design and how global warming potential (GWP) is an important factor of emissions in this sense. Then, current state examples of sustainable building projects from near Turin or close areas and local resources will be reviewed to assess the common approach in terms of the materials used and the design solutions. This includes gathering information pertaining to the building structures, building construction materials and the construction/design measures that are being put in place; then sorting out the information to get the best low carbon building materials, measure, strategy that is available.

2. LIFE CYCLE ASSESSMENT APPROACH

Life Cycle Assessment (LCA) is a comprehensive approach dedicated to identify and quantify the ecological footprint linked to each step of the existence of a product right from its extraction of raw materials, through production, transportation, usage and disposal. LCA encompasses product's usage through its entire life-cycle and impacts all aspects of the product, it can give a great insight into its environmental effects and help the stakeholders make informed decisions in an endeavour to lessen the line product's environmental impact or in our case buildings.
Life Cycle Assessment is a method defined by the International Organization for Standardization (ISO) 14040 and 14044. The proper definition of the introduction chapter of ISO 14040 has been made as follows :
LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave) [1].

LCA can assist in :

- identifying opportunities to improve the environmental performance of products at various points in their life cycle,
- informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),
- the selection of relevant indicators of environmental performance, including measurement techniques, and
- marketing (e.g. implementing an eco-labeling scheme,making an environmental claim, or producing an environmental product declaration) [1].

Even though this definition has been made for as called ''product'', LCA analysis is a methodology that can be applied for processes, services in our case for a residential architectural project.

2.1 WHAT IS LCA FOR?

LCA is an useful tool for many fields to better understand potential environmental hotspots and to detect the points which can be improved at the point of sustainability. Not only for the product producers but also for businesses, governments, researchers and in our case for architects, designers and disciplines in the construction sector LCA is a valuable tool to be applied. It can provide essential data considering the phases from the very beginning of the design decision point for creating better strategies for material choices and construction methods, for understanding how extraction of the raw materials and their processing and transportation to the site can have less impact to the environment, for analyzing energy consumption during the use phase and maintenance and to have comparison between various strategies until the end of life of a building to consider separation and recycling the materials used in the building and the waste management. LCA results can also be used for eco-labeling, product development, policy-making, and informing consumer choices towards more environmentally friendly options.

2.2 LIFE CYCLE STAGES

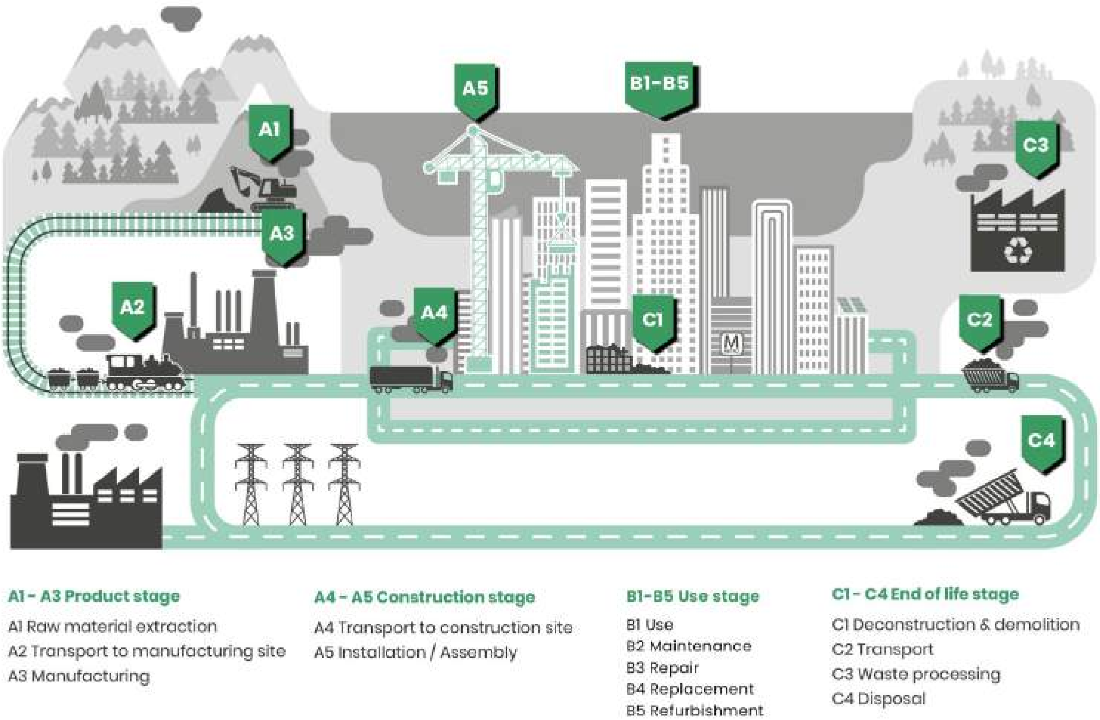


Figure 5. "Life Cycle Stages" article by Shaun Masson.
Retrieved from One Click LCA official website

When implementing LCA, which seeks to assess the environmental effects at different stages, having a grasp of the distinct life cycle phases is highly beneficial. Because this enables them to compare who is benefiting from switching from one life cycle stage to another to reduce impacts and enhance sustainability. It can help the architects in assessing environmental impacts from inputs, product and effects down to impacts.

To apply the LCA approach, it is necessary to understand the stages of life, which can be considered as the strength of this methodology. In further chapters, we will outline which of these phases will be considered for LCA analysis for design optimization and BAU (business as usual) scenario.

These lifecycle modules indicated in the figure 5 above, are defined by an European norm, EN19578:2011 "Sustainability of construction works — Assessment of environmental performance of buildings — Calculation method", developed and published by the European Committee for Standardization (CEN). This standard gives the direction that can be followed in evaluating the capability of a building to perform in the environmental sector. It also provides information on how to approach the assessment of several elements of environmental impact at various stages of construction of a building.

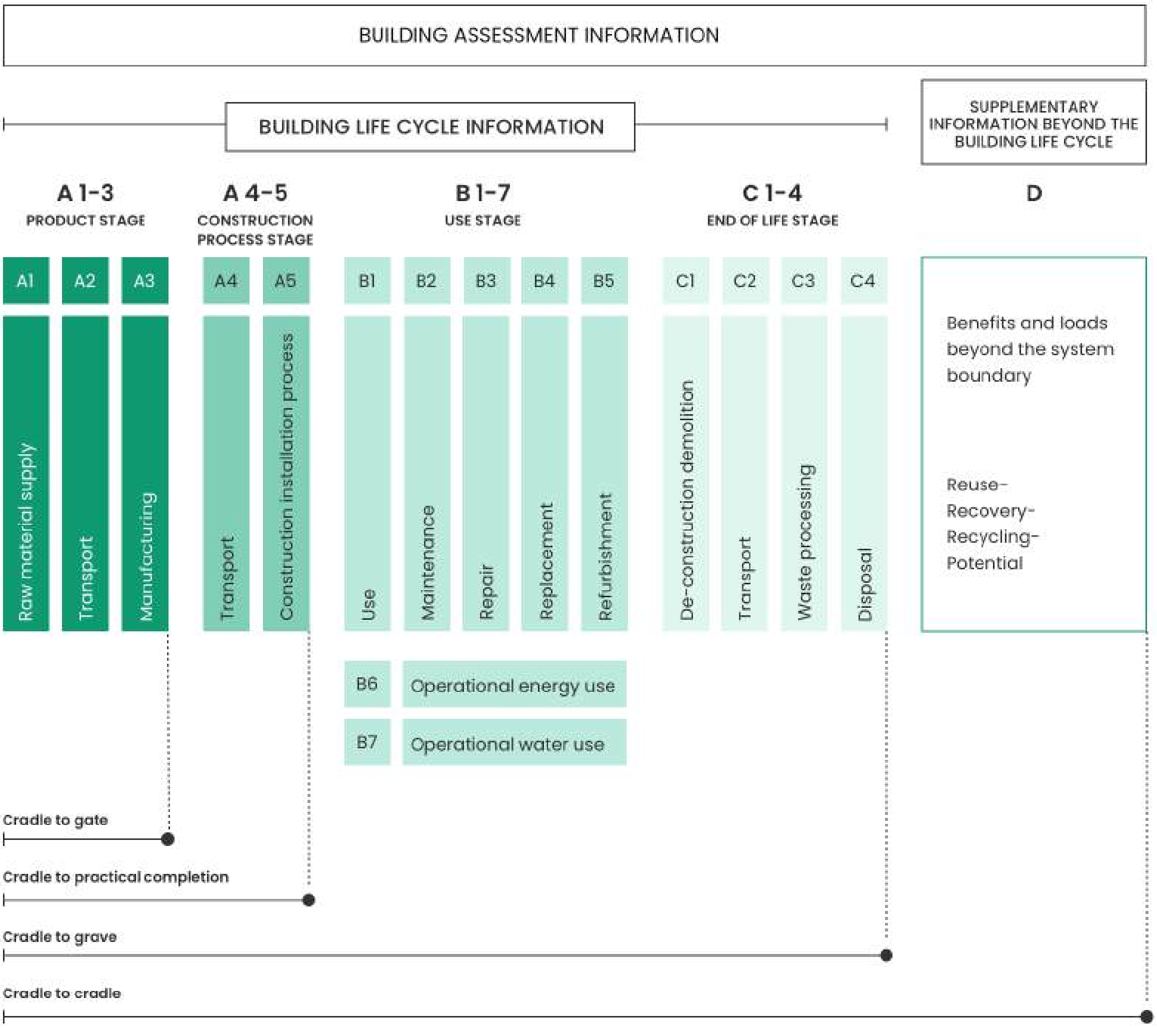


Figure 6. "Building Assessment Information" article by Shaun Masson.
Retrieved from One Click LCA official website

It is possible to define Modules A1, A2, and A3 together as one module A1-A3. All phases involve the supply of all raw materials, finished goods, and energy. They also involve processing waste to the point of end-of-waste or the product stage's final residual disposal. Only the building and its components are considered in the assessment; furnishings and appliances, for instance, are not. All effects and factors connected to any losses that may occur during this phase of the building process are included in stages A4 and A5. (i.e. manufacturing, transport, and waste processing, as well as disposal of the lost products and resources). In addition, stages B6 and B7 cover the transportation and provision of all goods and materials, as well as the provision of water and energy, the processing of waste to the point of end-of-waste, and the ultimate residual disposal during this portion of the usage stage. Provision and transportation, provision of all products and resources, and associated water and energy use are all included in the C phases. Module D permits the consideration of additional data outside of the building lifetime. This implies that for construction materials, consideration can be given to the advantages and disadvantages of disposal following demolition. A cradle-to-cradle methodology is congruent with the use of Module D.

• Cradle-to-Gate:
The "cradle–to–gate" phase deals with the last step of the life cycle that starts from the extraction of raw materials "cradle" up to the time the product is finished to be shipped out the factory gate. This phase deals with the environmental burden that is created before the raw materials are purchased and extend to the point where the products are manufactured right from the factory but not the impacts that occur as a result of transporting the products to the site, construction, use of the building or end of life. For example, cement manufacturing includes the extraction of limestone and its logistics, as well as other transformations necessary for generating cement dust but it does not include cement transportation to construction site or its installation process.
It covers the modules from A1 to A3 shown on the figure 6.

•Cradle-to-Practicle Completion
The "Cradle to practical completion" is the entire process from the manufacturing of raw materials at the factory, up to the practical completion of construction until the building is ready for use. This includes bringing of the materials to site, actually construction processes as well as the effects of construction processes. For instance, the bringing of cement to the construction site through transportation, blending it with other materials to form concrete, then the construction phase involves the construction of the actual structures.
It covers the modules from A1 to A5 shown on the figure 6.

•Cradle-to-Grave:
This is a fuller life cycle approach that looks at every stage of a building right from the time the raw materials needed for construction are obtained all through until the last days before the building is demolished. This includes all phases: Since it is directly related to built environment, it involves extraction of raw material, manufacturing of components, transportation of all materials to construction sites, construction of a building structure, utilizing the building for various purposes, caring for the built environment, and at the end, dismantling or abandoning a building structure. For instance the life cycle of a building would be characterized by the extraction of raw materials for construction, construction of the building, and its use and maintenance for some decades, and the dismantling of the building and handling of waste.
It covers the modules from A1to C4 shown on the figure 6.

•Cradle-to-Cradle:
The idea of the linear model of 'cradle to grave' whereby products are used then disposed of is not encouraged when implementing the 'cradle to cradle' idea where the lifecycle of the product is renewed after use. This approach seeks to improve value by ensuring that when constructing buildings, and choosing the materials to be used, the items can be taken apart and used again. For instance, in 'Cradle to Cradle' materials used in a building after demolition could be reused in construction to form a loop.
It cover all the modules shown on the figure 6 from A1 to D module to be able to use again from the A1.

2.3 LCA FRAMEWORK

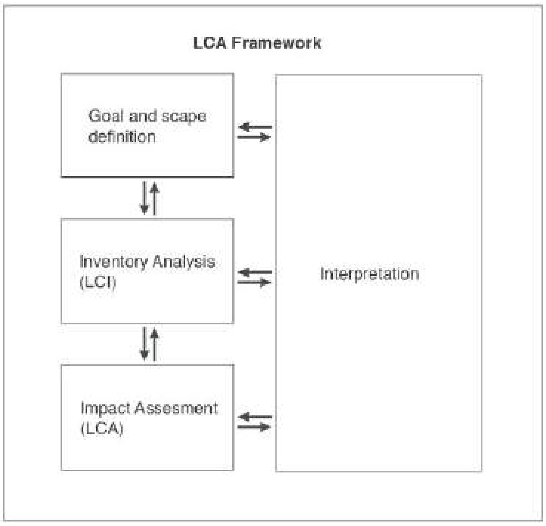


Figure 7. Diagram of the structure of the LCA based on ISO 14040/14044, the figure was redrawn based on the source: Thiebat, F. (2019). Life Cycle Design, An Experimental Tool for Designers. Turin, Italy: PoliTO Springer Series

•GOAL AND SCOPE DEFINITION

Goal Definition: Definition of the main purpose and objectives of the LCA study. We need to look at what we will actually analyze. What are we trying to assess or compare? It could be a product, a material, a building or an entire company. To give an example it may be a comparison of the environmental impact of two different products or carbon emission during the production of two different materials.

Scope Definition: "How much will we need to analyze?" so this phase is about determination of the boundaries of the LCA study, including which stages of the product's life cycle you will include and any specific environmental impact categories and also the definition of what not to assess.

Briefly, the definitions of:
- what to analyze
- the functional unit
- the system
- the life cycle (cradle to gate / cradle to grave / cradle to cradle)
- what not to assess

•INVENTORY ANALYSIS (LCI)

This step is about collecting the data on all environmental inputs and outputs. To create a clearer explanation, the main goal of inventory analysis is to collect comprehensive and correct data about all related inputs such as raw materials or energy and outputs such as emissions and waste. After data collection, the next step is creating a "Life Cycle Inventory Flow Model" that illustrates the flow of materials and energy during each step of the life cycle.

•LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Once the inventory analysis is done, this step helps to understand the environmental impacts of all the inputs and outputs that were participated in the previous step. The main goal of impact assessment is evaluating and quantifying the potential environmental impacts of these inventory items. Impact categories include resource depletion, global warming potential, ozone depletion, acidification, eutrophication, human toxicity, and more.

•INTERPRETATION

After concluding inventory analysis and impact assessment, the main goal of interpretation is to reach meaningful conclusions, to identify the strong and weak points and to meet the goals set during the first stage. Following that a sensitivity analysis may help to understand how variations or assumptions affect the results.

2.4 REGULATION STANDARDS AND CODES

2.4.1 INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

The International Organization for Standardization (ISO) is a worldwide federation of national standards organizations, known as ISO member bodies, that has its headquarters in Geneva, Switzerland. The organization is involved in a wide range of standardization activities embracing virtually every aspect of manufacturing, scientific, and commercial activity [2].
ISO is a voluntary organization which was founded in 1947. It brings together experts, stakeholders, and representatives from different countries around the world to work together on the development of standards. These standards provide several benefits such as quality assurance, safety, market access, regulatory compliance, minimizing environmental impact.

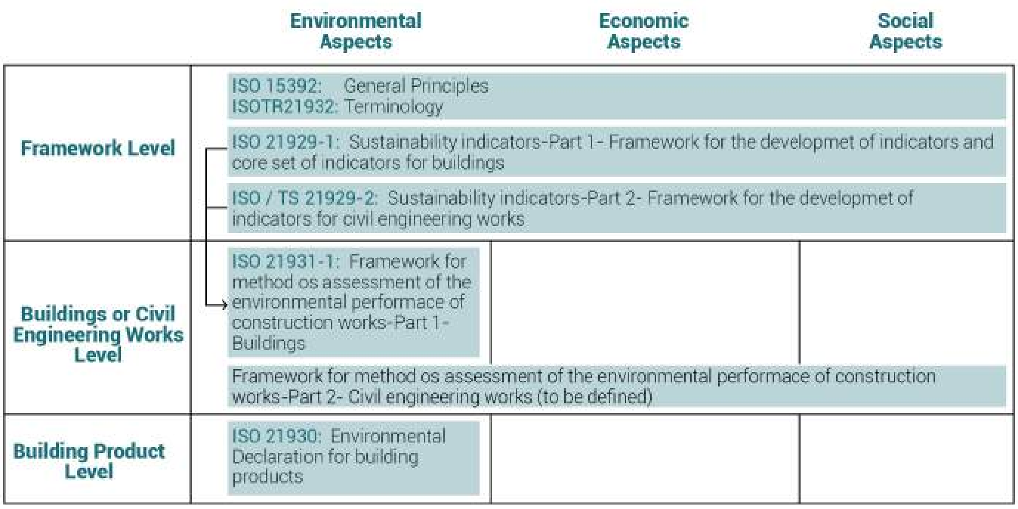


Figure 8. IS0-TC59-SC17 working group on the environmental performance of buildings / Redrawn figure by author
resource: Thiebat, F. (2019). Life Cycle Design, An Experimental Tool for Designers. Turin, Italy: PoliTO Springer Series

There are several series which are separately related to different aspects. Some of the ISO standards for building sector are:

ISO 21930:2017 - Sustainability in buildings and civil engineering works - Core rules for environmental product declarations of construction products and services.
ISO 21930:2017 gives a basis for specifying core criteria and indicators for the production of Environmental Product Declarations of construction products and services. It provides the norms and stipulations on how lifecycle assessment should be done with relevance to construction materials and products (ISO, 2017a) [2].

ISO 15978:2019 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.
ISO 15978:2019 describes the approach that may be used to quantify the environmental impact of buildings during their entire lifecycle. It outlines the method of data collection, the way calculations will be performed, and method of assessment of environmental impacts like Greenhouse gases emission, Resource depletion amongst other environmental impacts (ISO, 2019) [3].

ISO 21931-1:2010 - Sustainability in building construction - Framework for methods of assessment for environmental performance of construction works - Part 1: Buildings.
ISO 21931-1:2010 is a rating tool that is used to evaluate the intensity of impacts on the environment of buildings. It provides methods of assessing environmental effects according to the steps of the product life cycle; acquisition of raw materials, manufacturing, use, and the disposal or recycling phase (ISO, 2010) [4].

On the other hand ISO standards to be consider for LCA approach are:

ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework.
ISO 14040:2006 sets the key doctrines and the basic line of argument to conduct life cycle investigations. The goal is to pursue the following sequences: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation, (ISO, 2006a) [5]
ISO 14044:2006 - Environmental management - Life cycle assessment - Requirements and guidelines.
ISO 14044:2006 sets out the principles and requirements for life-cycle assessment. This standard contains specific instructions, for example, the procedures of LCA like data collection, the impact assessment methods, and the reporting (ISO, 2006b) [6].

2.4.2 THE EUROPEAN COMMITTEE FOR STANDARDIZATION (CEN)

The European Committee for Standardization (CEN) is one of the biggest producers of technical specifications and EU Standards for the European Market.

	Environmental Aspects	Economic Aspects	Social Aspects	Technical Characteristics
Framework Level	EN15643-1 Sustainability Assessment of Buildings-General Frame work			
	EN15643-2 Framework for Environmental Performance of Buildings	EN15643-4 Framework for Economic Performance of Buildings	EN15643-3 Framework for Social Performance of Buildings	Service Life Planning -General Principles (ISO 15686-1)
	EN15643-5 Framework for Sustainability Assessment of Civil Engineering Works			
Buildings or Civil Engineering Works Level	EN15978 Environmental Performance of Buildings	EN16627 Economic Performance of Buildings	EN16303 Social Performance of Buildings	CEN Standards on Energy Performance of Buildings Directive (EPBD)
	CEN/TR 17005 Additional Environmental Impact Categories and Indicators			
	PR Sustainability Assessment of Civil Engineering Works (WG6)			
Building Products Level	EN15804 Environmental Product Declarations	See note below*	See note below*	Service Life Prediction (ISO 15686-2) Feedback from Practice (ISO15686-7) Referance Service Life (ISO 15686-8)
	CEN/TR 16970 Guidance to EN15804			
	EN 15942 Communication Format B2B			
	CEN/TR 15941 Generic Data	Note: At present technical information related to some aspects of social and economic performace are included under the provisions of EN 15804 to form part of EPD		

Figure 9. Standards developed by CEN/TC350 "sustainability of construction works" / Redrawn figure by author
resource : Thiebat, F. (2019). Life Cycle Design, An Experimental Tool for Designers. Turin, Italy: PoliTO Springer Series

EN standards are related for building sector and LCA approach we should consider :

EN 15978:2011 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.

Life Cycle Stages: It, in fact, is a very comprehensive one as it starts with raw material extraction then discusses all other stages such as production processes, use and end-of-life disposal, and comprehensive assessment.
Environmental Indicators: It identifies what kind of indicators should be used to validate the claims and these can be Global Warming Potential(GWP), ozone layer depletion, and acidification potential.
Data Requirements: The standard mandates that data required must be specific to the assessment and the consistency and precision of the results must be assured.
Reporting: They provide guidelines on how to report the features of the assessment and hence the findings are easily and universally compared and can be seen by interested parties(CEN, 2021)[7].

EN 15804:2012+A1:2013 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.

Product Category Rules (PCR): It is designed to be the list of specific rules for deduction of the environmental performances of construction products, hence facilitating EPDs by a standard set of data used for different products and manufacturers.
Life Cycle Stages: It examines the entire lifecycle regarding construction products, such as production, construction process, use, and end-of-life and beyond system boundary (D module) stages.
Environmental Indicators: It itemizes the indicators to be used in the EPDs, such as GWP, energy consumption, and water use.
Additional Modules: A2: 2019 adds new modules that cover typical situations like, where materials are at the end of their life, they can be reused, recovered, or recycled (CEN, 2019) [8].

2.4.3 PRODUCT CATEGORY RULES (PCR)

LCA with a goal of generating an environmental product declaration the golden scope should be built around the methods that are required by the regulatory bodies. This is why LCA does not necessarily need to be comparable with another one. If you compare two assessments with a different goal in mind they might not be compatible with each other. To overcome this problem PCR plays its role. It standardizes the creation of an environmental product declaration (EPD) in a product category, so they can later be comparable. Take for instance a construction material concrete, if product category rule is followed for this category it would be able to compare two different concrete products to another.
PCRs offer some distinct benefits: greater consistency and comparability of assessments based on the same rules; modularity of assessment scope ;transparency of requirements and in the development process; guidance and clarity to users undertaking assessments within product sectors; and flexibility of use by any entity [5].

2.4.4 ENVIRONMENTAL PRODUCT DECLARATION (EPD)

Environmental Product Declaration (EPD) is a standardized document that provides information about a product's environmental footprint considering its entire life cycle. EPDs are based on the principles of Life Cycle Assessment (LCA) and are used to provide transparent information to consumers or in general who might be interested in the environmental impacts of products. EPDs should have gone through independent verification to confirm that the data and methodology were produced as per the standards or/and PCR provided by a company or/and the references like ISO 14025 or EN 15804.

2.4.5 ABOUT ONECLICK LCA TOOL USED FOR THE THESIS

After this theoretical foundation, we should emphasize that Oneclick LCA tool with BIM (Buiding Information Modeling) integration, will consider EN15804+A1/+A3 European norm standardization which is also correct for this case because the BAU scenario (business as usual) is located in Turin/Italy.

As they explain on their official website :
"EPD verification requires numerous checks, some of which can be supported by automation. One Click LCA provides a software-enabled verification capability, which speeds up the process. One Click LCA EPD Generator's pre-verified status also means that numerous parameters are guaranteed by the software itself, and thus do not require an inspection for each EPD. Oneclick LCA EPD Generator is an automated and affordable tool for developing robust environmental product declarations. EPD Generator complies with ISO 21930, 14025, 14040, 14044, 14067, and EN 15804 A1 and A2 standards." [9]

2.5 RATING SYSTEMS

Rates of construction and sustainability of buildings are addressed by such systems as BREEAM, LEED, WELL, DGNB, Green Star, and CASBEE that determine the approach of standard methods that can be employed in the assessment of building sustainability. They are valuable for promoting environmental sustainabilities to designers, builders and managers of buildings, civil engineering structures and infrastructure. The European and American systems for certification have their own set of fields of specialization and tier of certification depending on the aspect of sustainability and requirements of the region.

In this thesis LCA analysis will be done according to an European framework called Level(s).

2.5.1 LEVEL(S)

Level(s) is a framework created by the European Union (EU) that aims at giving the general approach to the assessment and reporting of sustainability performance of buildings at different stages of their life cycle. These macro-objectives encompass six broad goals that are geared towards sustainability of buildings and establishing EU wide comparability of such assessments. In contrast with rating systems that award certificates, Level(s) is a set of indicators and recommendations aimed at the synchronization of national and regional instruments [10].

Macro-objectives of Level(s):

1. Greenhouse Gas Emissions: Several important aspects of emission decrease during a building's life cycle.

2. Resource Efficient and Circular Material Life Cycles: Increasing awareness on resource efficiency and the implementation of circular economy.

3. Efficient Use of Water Resources: The control of water usage to help increase the possibilities of efficiency More regarding Water undertaking to help improve efficiency.

4. Healthy and Comfortable Spaces: Provision of health and general welfare of the people using the facility.

5. Resilience to Climate Change: The augmentation of the building's climate change adaptability.

6. Optimized Life Cycle Cost and Value: Safeguarding the ideas of economic efficiency by managing all the expenses throughout the building's lifecycle [10].

Indicators and Reporting:

•Level(s) gives a list of core indicators that are described above and relate to the mentioned macro-objectives. These indicators help in the measurement and assessment and the reporting system to demonstrate coherence and comparability in the EU area.

•It also promotes the improvement and the compatibility with the EU sustainability objectives through an operational approach that details how these indicators might be employed in the building's life cycle — starting from design up to the demolition [10].

Implementation:

•The Level(s) framework is currently proposed to be scalable and is aimed at building practitioners, building developers, and governmental bodies to enable sustainable agriculture.

•Echoing numerous sustainability initiatives across the nation and region, Level(s) assists in harmonization of the EU's endeavors simplifying their adoption and application by the stakeholders [10].

LCA analysis of business-as-usual scenario and the design optimization will be done following Level(s) EN 15804 + A1.

Together, LCA, EN 15804, and Level(s) form an extensive and comprehensive set of tools for construction products and buildings' sustainability improvement. Thus, by connecting the scientific approach of LCA, assigning environmental impacts throughout the life cycle of a building, with the procedural structure of EN 15804 for EPD and the complex indicator of Level(s), all these tools and frameworks allow the stakeholders to evaluate, benchmark, and enhance the environmental, social, and economic performance of construction products and buildings systematically. This makes it possible to cover all aspects of a life cycle of a building and find the most efficient measures to make transportations, usage and disposing processes of construction materials as environmentally friendly as possible, which in its turn contributes to making the general tendencies in construction industry much more sustainable.

CHAPTER 2 CONCLUSION:

As the contexts that were introduced as the life cycles, the LCA framework, and international or European standardization studies, these sources are valuable for the progress of the thesis to the following stages. These researches help in setting up the scope and limiting parameters of the LCA study which will be carried out for BAU scenario and the optimization of it. The application of the LCA framework is very useful, especially regarding the positioning and definition of certain impacts, including those in connection with the selection of specific building materials and structure. Because the method on how the life cycle modules are understood in the EN 15987 implies that product transport to the site is also to be determining.

These insights indicate the desire for better understanding of local resources since in order to optimize the BAU scenario and to stress all the crucial decisions that an architect has to make within the scope of the strategy, the emissions in transportation have to be added to the life cycle carbon footprint of materials. In this manner, the thesis can affirm that there are, indeed, ways to decrease the carbon imprint and other negative trends.

To that effect, the next chapter will focus on case studies to be conducted in and around the city of Turin in Italy where the nature of formwork used for construction of buildings will be considered. The resources that would be available in the project area and the general environment that will dictate the carrying out of the project will be identified.

By these cases, the thesis will thus show how specifying locally sourced materials can reduce the emission of carbon from the transport of materials and the compatibility of the constructed project to the environment. Furthermore, this study will show that with knowledge of the existence and application of the LCA in practice in various fields, its real implementation in practice will give a proper foundation for sustainable decision-making in cases of architectural & construction projects.

CHAPTER 2 FIGURES:

[5] "Life Cycle Stages" article by Shaun Masson. Retrieved from One Click LCA official website

[6] "Building Assessment Information" article by Shaun Masson. Retrieved from One Click LCA official website

[7] Diagram of the structure of the LCA based on ISO 14040/14044, the figure was redrawn based on the source: Thiebat, F. (2019). Life Cycle Design, An Experimental Tool for Designers. Turin, Italy: PoliTO Springer Series

[8] IS0-TC59-SC17 working group on the environmental performace of buildings Thiebat, F. (2019). Life Cycle Design, An Experimental Tool for Designers. Turin, Italy: PoliTO Springer Series

[9] Figure 9. Standards developed by CEN/TC350 "sustainability of construction works" Thiebat, F. (2019). Life Cycle Design, An Experimental Tool for Designers. Turin, Italy: PoliTO Springer Series

CHAPTER 2 REFERENCES:

[1] [International Organization for Standardization. ISO 14040:2006. Environmental management - Life cycle assessment - Principles and framework. Geneva, Switzerland: International Organization for Standardization.

[2] ISO. (2017a). ISO 21930:2017 - Sustainability in buildings and civil engineering works - Core rules for environmental product declarations of construction products and services. International Organization for Standardization.

[3] ISO. (2019). ISO 15978:2019 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. International Organization for Standardization.

[4] ISO. (2010). ISO 21931-1:2010 - Sustainability in building construction - Framework for methods of assessment for environmental performance of construction works - Part 1: Buildings. International Organization for Standardization.

[5] ISO. (2006a). ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework. International Organization for Standardization.

[6] ISO. (2006b). ISO 14044:2006 - Environmental management - Life cycle assessment - Requirements and guidelines. International Organization for Standardization.

[7] CEN. (2011). EN 15978:2011 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. European Committee for Standardization.

[8] CEN. (2019). EN 15804:2012+A2:2019 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. European Committee for Standardization.

[9] OneClick LCA official website : https://oneclicklca.com/why-us/capabilities/automated-epd-process?_gl=1*113kq5i*_up*MQ..&gclid=Cj0KCQjwsaqzBhDdARIsAK2gqnekNZyxTPlCx8tXtLepTagtjBTGfTAj6xJnegWYcPxL8Nn9-OixkQUaAoTiEALw_wcB

[10] European Commission (2023). Level(s) - European Framework for Sustainable Buildings. European Commission.

chapter 3

CASE STUDIES NEARBY AREAS AND LOCAL RESOURCES

LOCAL RESOURCES

In the era of climate change and environmental consciousness, the construction industry faces an important challenge: exploring measures for embracing an environmentally conscious approach to the provision of infrastructure to provide for the increasing demands. Among others, one huge approach that could help in the achievement of this goal being implemented is the use of locally sourced materials in constructions. This strategy is very significant to reduce environmental impacts in building sector to minimize carbon emission during the life cycle of the building materials. Using locally obtained materials can reduce environmental impact from the raw materials supply to construction installation process. What is more, as it has been pointed out from the case of Turin, Italy favoring local resources makes sense both in environmental impacts. It is also important to point out using natural materials which are available in near areas. Consideration of these material's availability to be recyclable can also provide an occasion to reuse them in the end of life of the building or using reused materials will definitely decrease the environmental impact of a building.

This is especially evident since local materials are comparatively more sustainably sourced for use and consumed in more optimal proportions as opposed to imported materials that are transported across continents and countries. It is important to notice that constructions in the past have follow procedures that does not contribute a lot to waste production. For instance, the use of timber from locally growing natural forests can be increased in a sustainable manner hence the source of the product is renewable while the forest is kept untouched.

The establishment of the construction principles which stipulate that building materials should be sourced locally has been highly regarded in the sustainable construction practices. It gives significant potential for its positive effectiveness as it cuts off the carbon emission and enhances the energy management. From an economic standpoint, it is beneficial for businesses within the community as well as lowers the costs associated with sustainable practices, thereby increasing sustainability. On the cultural level, there is a continuance of history, as well as the development of togetherness in the community. Nevertheless, if all the requisite support and innovation is input, local materials could be utilized to the maximal and create a new scope of construction that is more sustainable and resistant.

With this goal it is useful to search case studies near Turin/Italy to understand what are the sustainable local resources available in this area. This research will also help to understand the sustainable strategies of different projects and to create an idea for the design optimization of business-as-usual scenario.

Figure 10. Turin/Italy and nearby regions and countries map illustration by author, source: google earth

3.1 CASE STUDIES

LOCATION OF THE PROJECT: Turin, Piedmont Region, Italy

BUILDING FUNCTION OF THE PROJECT: Residential single-family house

SYSTEM BOUNDARIES OF THE RESEARCH:

RESEARCH LOCATIONS:

-Lombardy Region, Italy

-Valle d'Aosta Region, Italy

-Normandie Region, France

Analyzing local resources of the closest areas constitutes the proper knowledge to comprehend when managers and planners are working on regional activity. In this regard, more specific focus would be made, to outset, on the regions nearest to Piedmont in Italy, namely Lombardy and Valle d'Aosta. These neighboring regions offer abundant requirement references and background knowledge which may pose effect toward project plans. Therefore, through an analysis of the available local resources of Lombardy and Valle d'Aosta, climatic characteristics of the area and environmental factors, it is possible for the Piedmont region planners to accrue important insights that pinpoint to similar location. However, to gain further insight into the closest influences and resources, the research area may be further extended to encompass the neighboring countries in order to obtain the big picture. In this regard, France is in point of fact a perfect example. Due to geographical proximity to Italy and other European countries, climatic and environmental factors that may affect the Piedmont region and France are similar. Thus, estimating the resources and practices in France can contribute even more layers of understanding and could offer the novel ideas and successful practices that have worked with similar conditions.

RESEARCH BUILDING FUNCTION: Residential

RESEARCH BUILDING MATERIALS: Low-carbon, natural based, locally obtained

RESEARCH BUILDING STRUCTURE: Timber

3.1.1 LA CASA QUATTRO

TYPE: RESIDENTIAL

DESIGNER: LCA Architetti

YEAR: 2016

LOCATION: MAGNANO, LOMBARDY, ITALY

CERTIFICATE: CASACLIMA CLASS A

Figure 11. Turin and Magnano cities on map illustration by author, source: google earth

Figure 12. La Casa Quattro location source: official website of LCA architects

Figure 13. La Casa Quattro source: official website of LCA architects

“La Casa Quattro” is an environmentally friendly approach to the worldwide notion of sustainability in architecture. It is useful to take an example of an Italian architectural house built with sustainable principles. This advanced home defines the standard for environmentally friendly architecture in the modern day by offering the maximum degree of sustainability applied not only in the living process but also in the materials and parts used in construction.

''La Casa Quattro''is referred to as **“the house of wood, cork, and straw”.** It is a sustainable private home that emphasizes serenity and a relationship with the natural world. The house blends in perfectly with the surrounding environment of the small town of Magnano near Milan thanks to its basic wood frame, insulation given by rice straw and cork cladding panels printed in 3D **by Technosugheri**, and interior finishes that include stone and oak wood. Direct communication with nature is given priority in the architecture, which provides expansive views of the countryside, and the sky. Systems utilizing both passive and active solar energy guarantee self-sufficiency and low carbon emissions. Casa Quattro illustrates life-cycle thinking by utilizing simple materials and a bio-ecological approach.

In official website of Technosugeri, La Casa Quattro is descriped as:
''Located in Magnago (MI), Casa Quattro, designed by the architect. Luca Compri, is made with a wooden frame structure, internally insulated with rice straw and covered with exposed CORKPAN expanded cork. The building designed by the studio LCA Architetti stands as a reference for those who aim to create buildings according to the principles of bio-architecture. Casa Quattro demonstrates how the use of natural materials such as expanded cork, wood and rice straw represent construction technologies that are now mature and ready for widespread diffusion[1].''

The home is further insulated through the use of straw, which is traditionally used as an insulator for other rural dwellings like barns and henhouses. The straw insulation consists of repurposed discarded rice plants handed over by nearby farmers in the area. The materials used are almost completely natural and can be easily recycled once the building is decommissioned.

Figure 14. La Casa Quattro Site Plan source official website of LCA architects

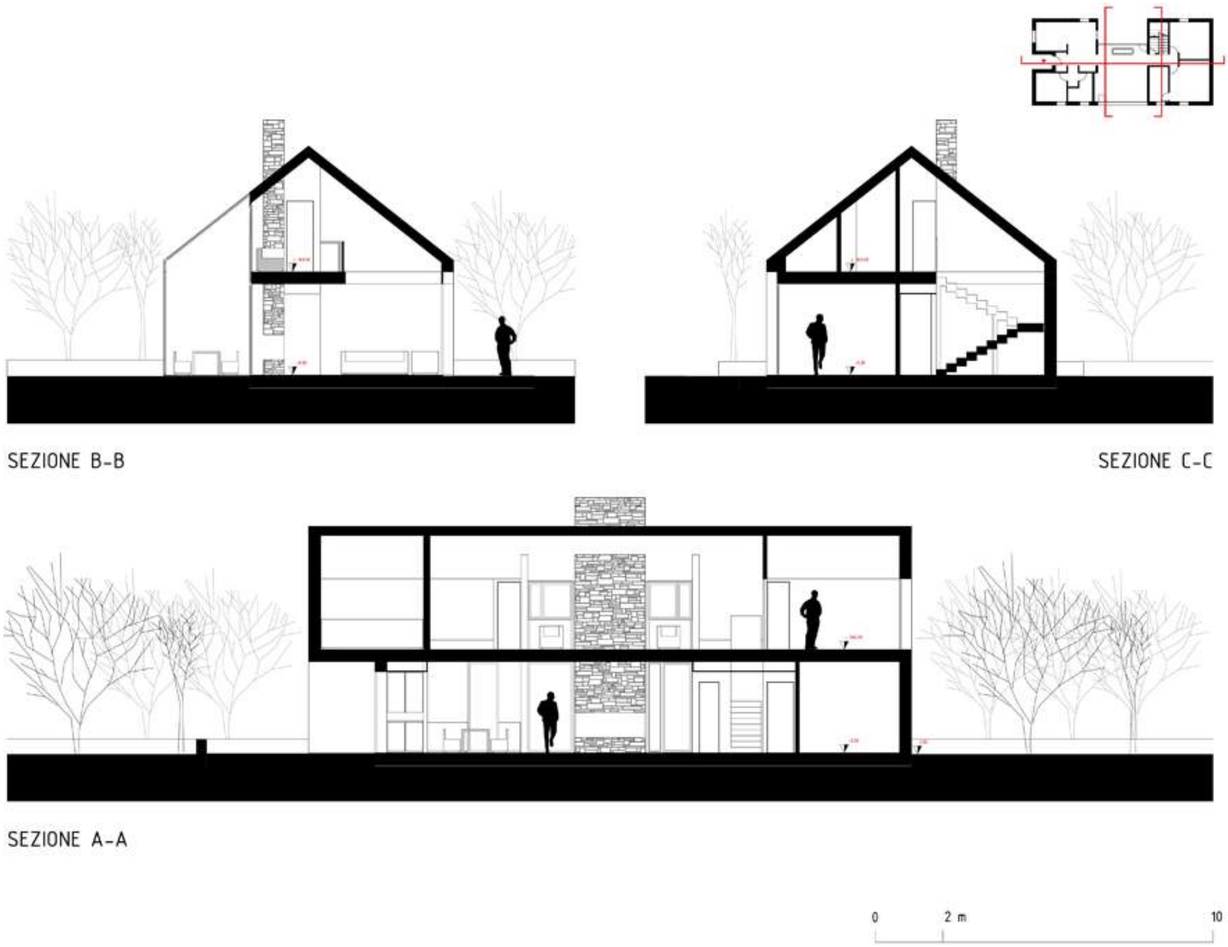


Figure 15. La Casa Quattro sections source official website of LCA architects

ROOF LAYERS

ABOVE
-flat roofing tiles
-battens under tiles 54 mm
-ventilation battens 48mm
-OSB panel 18mm
-C24 grade timber barge board/High density wood fiber 220mm
- OSB3 Panel 12mm
-gypsum board 12,5mm
BOTTOM

INTERMEDIATE SLAB

ABOVE
-OSB3 panel 18mm
-wooden beams 240mm
-wood fiber 100mm
-OSB3 panel 12mm
-battens for service space 40mm
-gypsum board 10mm
BOTTOM

VERTICAL WALL

INTERIOR
-gypsum board 10mm
-battens for service space 48mm/ wood fiber 40mm
-OSB3 panel 15mm
-wooden frame 200mm/ rice straw 200mm
-bracing boarding
-Cork panel 80mm
EXTERIOR

GROUND FLOOR SLAB

ABOVE
-larch flooring
-slab 60mm
-lightweight subfloor 160mm
-mat foundation 240mm
-foamglass 100mm
-lean mix 100mm
-red gravel
BOTTOM

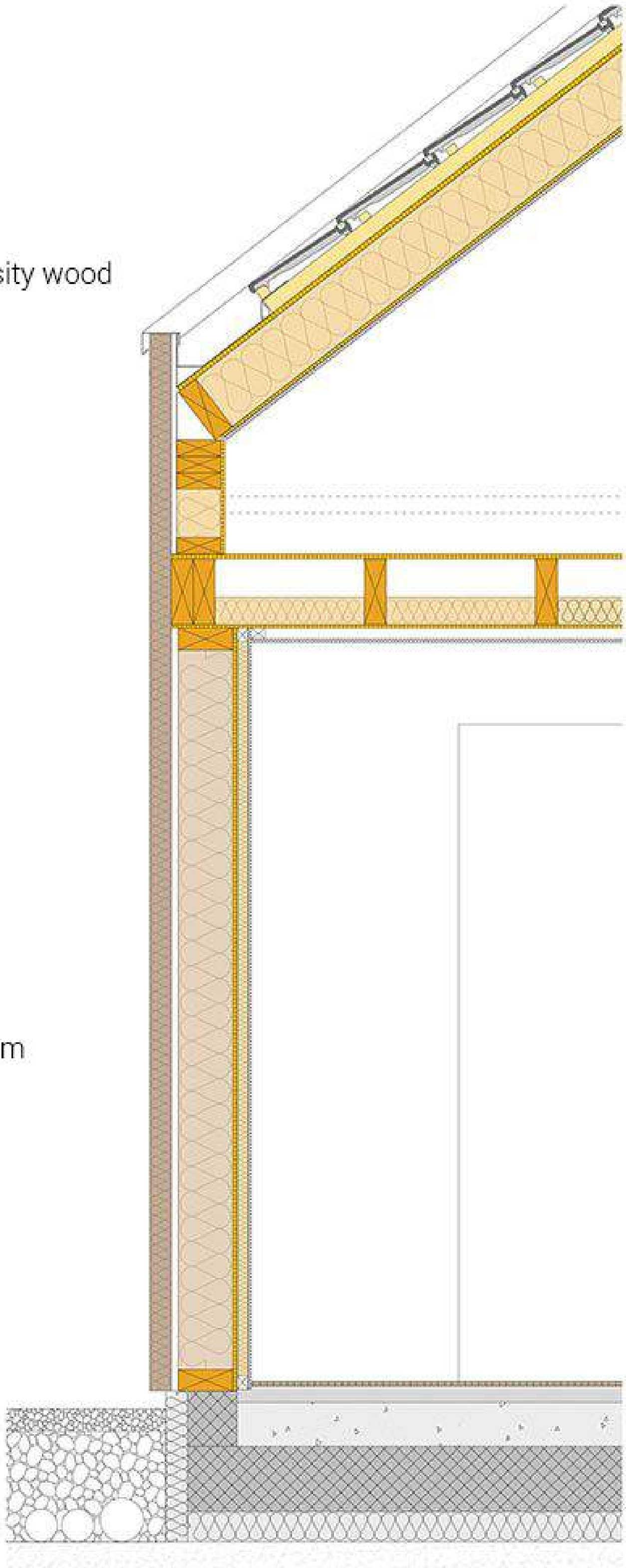


Figure 16. La Casa Quattro Building Section Detail
Source: infobuildingenergia.it

MAIN BUILDING MATERIALS USED:

1. WOOD:

Structure: Wood, a renewable resource with a lower environmental impact than more common building materials such as steel or concrete especially used the most in building structures in Italy, is used to construct the house’s fundamental structure.

2. RICE STRAW:

Insulation: Straw made of rice is used as insulation. It is a highly beneficial thermal insulation byproduct of rice farming. Utilizing rice straw in building contributes to a decrease in agricultural waste even if it is not a common method used in Italian construction sector, la casa quattro is a great example for alternative building materials can be used in this area near Turin. Repurposed discarded rice plants handed over by nearby farmers in the area is a great point of utilizing local resources.

3.CORKPAN PRODUCED BY TECHNOSUGHERI:

Insulation and Exterior Finish: Among natural insulators, cork is perhaps the best known, although even in this area, some clarifications should be made regarding the concept of natural. Among the cork insulating panels, CORKPAN, made of expanded cork (ICB – Insulation Cork Board) is the only one certified for green building (natureplus and ANAB-ICEA), 100% natural, made without chemical glues and raw materials derived from petroleum, recyclable and reusable at the end of its life. After decortica, the oak bark, after being extracted from the cork groves near the factory, is delivered to the “Amorim Cork Insulation factories”. The industrial process that leads to the agglomeration of the CORKPAN panel via a thermal process, commonly called “toasting”, is based here [2].

Figure 17. Cork cladding detail, source: official website of LCA architects

4. STONE:

Interior finishes: The natural and sturdy elements used in the interior finishes of the house, such as oak wood and stone, add to its sustainable theme. We should point out that Italy has rich stone resources and historical expertise in stone craftsmanship.

4. WOOD FIBER:

Insulation: Wood fiber insulation is generally manufactured using both chips or shavings of wood that are broken down into fiber form. These fibers are then made into a paper and to this a binder (such as starch or any other natural adhesive) is added and it is pressed into boards or batts.

3.1.2 CASA SOLARE

TYPE: RESIDENTIAL

DESIGNER: Studio Albori

YEAR: 2010-2011

LOCATION: VENS, VALLE d'AOSTA, ITALY

Figure 18. Turin and Vens cities on map illustration by author, source: google earth

Figure 19. Casa Solare, source: website of Archdaily

The idea for the project came from the site's breathtaking outlook and its especially generous solar exposure. Casa solare is located in the Valle d'Aosta, behind the little settlement of Vens, at an elevation of 1750 meters above sea level. It faces an arc of mountains that stretches from Monte Emilius to the mountain of Gran Paradiso and Grivola.The large windows on the south façade, which faces the sun and the landscape, showcase the wooden frame that supports the structure and is visible from all interior spaces. The frame is complemented with a robustly isolated timber casing on the other sides.
In Studio Albori's official website the wood used in casa solare described as:
"The wood used in the structure and on the façades is **local larch**, which is untreated and unpainted. Most of the house furniture was constructed by us with **scrap materials**" [3].

Figure 20. Casa Solare construction
source: website of archilovers

Figure 21. Casa Solare
source: website of archilovers

As can be seen from the construction image in figure 20, in the wall Oriented Strand Board, also known as OSB, has been used. They have decided to leave the OSB in view without any other finishings such as plaster or painting.
On the other hand, as can be seen in figure 21, on roofing we can see the usage of stone roofing which is very traditional in mountain houses in Villa d'Aosta or Piedmont region.

If we will look deeper the stone usages in closed regions to Piedmont, Italy we can count several of them some of them has **local origins**, on the other hand some of them can be transported from Greece or Norway.

A research paper done by Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Torino, Italy shows that:

Stone roofing has to last for centuries, to be reused several times and to hold to the loading of snow. In addition, the supply of stone slabs coming from nearby areas brings economic and environmental advantages, due to a lower cost, as well as the **decreasing of transportations emissions** and providing work to local companies and people [4]. Roofs, made with stone slabs, are one of the specific characteristics of the Aosta Valley architecture.

Petrographic name	Acronym	Country of origin
Gneiss	PL	Piedmont (Italy)
	BS	Switzerland
Morgex Calcschist	CM	Aosta Valley (Italy)
Serpentine	SE	Lombardy (Italy)
Phyllite "Porfiroide"	PO	Lombardy (Italy)
Quartzite	QC	China
Quartzite	QG	Greece
Quartzite	QN	Norway

Figure 22. Different types of roofing stone employed in the Aosta Valley, Source: Journal of Building Engineering Elsevier

Figure 23. Calcshist CM roofing in Lignod after renovation Source: Journal of Building Engineering

Figure 24. Porfiroide roofing near the new roofs of gneiss on the left and Quartzite on the right in Antagnod. Source: Journal of Building Engineering Elsevier

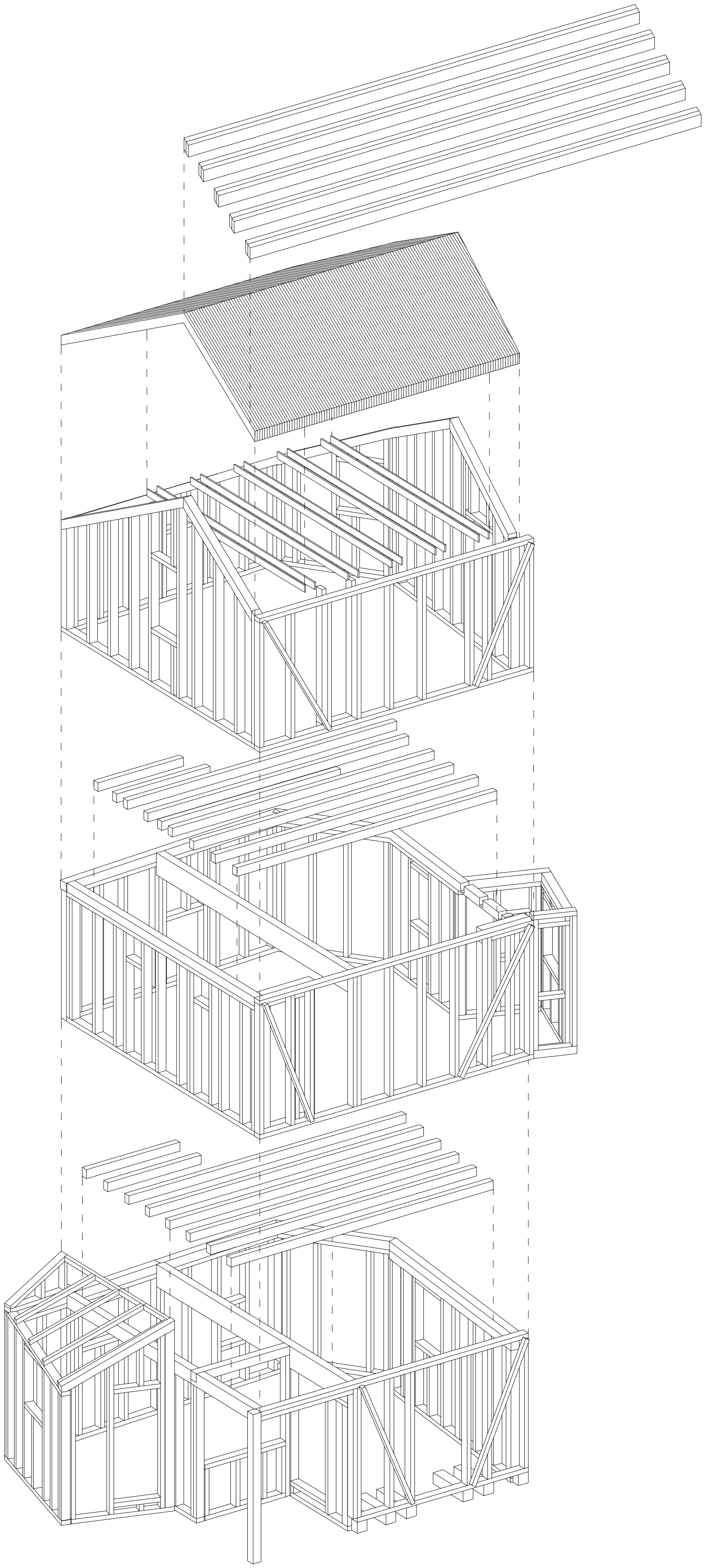


Figure 25. Casa solare wooden structure scheme.
Source: website of Archdaily

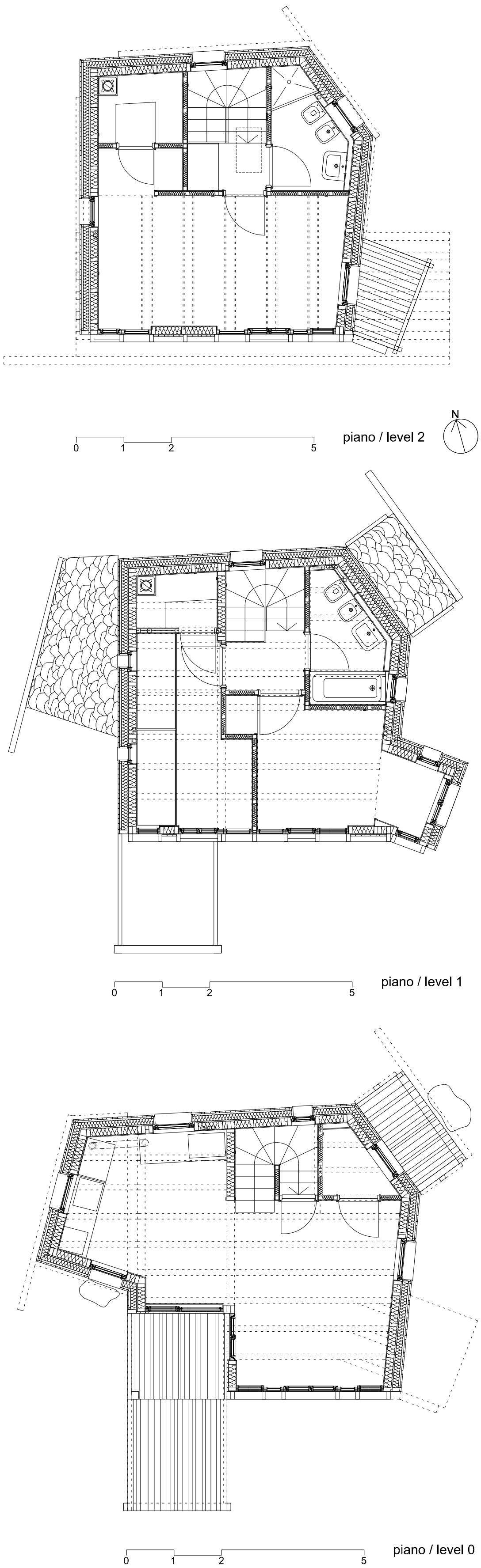


Figure 26. Casa solare floor plans
Source: website of Archdaily

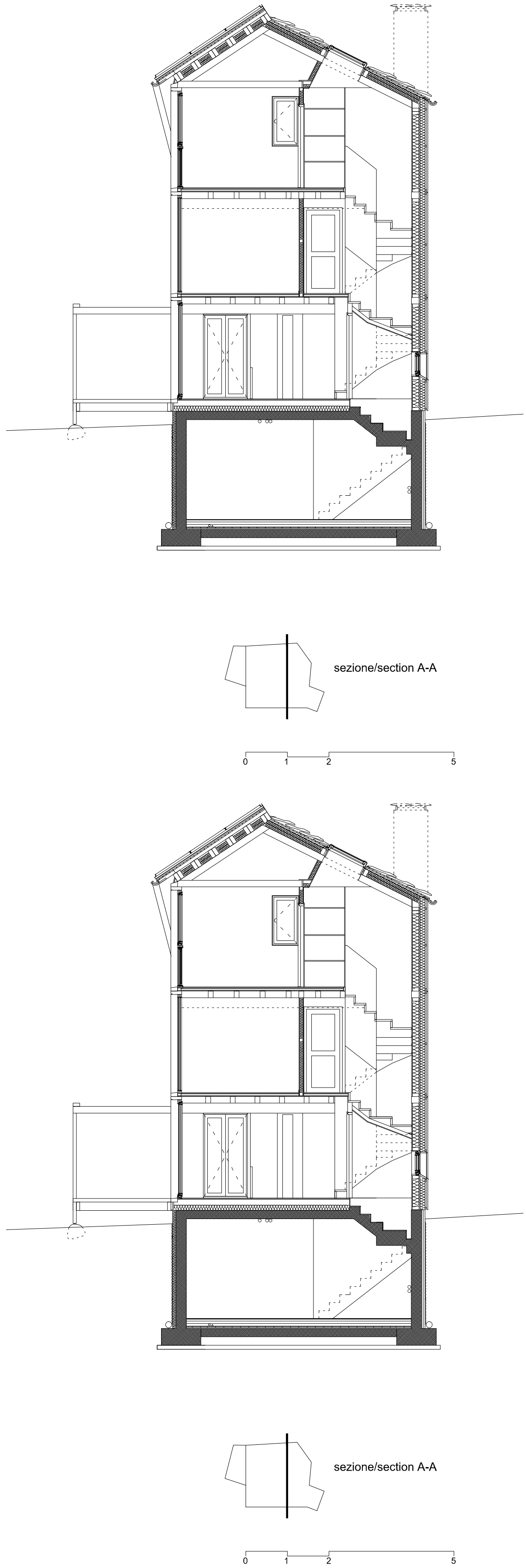


Figure 27. Casa solare sections
Source: website of Archdaily

As we can see from the plans, we see two layers of insulation between the locally obtained wooden structure and from the section we see that concrete was used only in the basement and in the foundation part of the building.
Apart from these materials, another sustainability aspect of the house is profiting solar energy. As they explained on the official website of Studio Albori, Solar energy is used here in three different ways: direct accumulation through the windows on the south façade, stored and released slowly by the mineral salts contained in the PCM (Phase Change Material) panes which complete the façade, transformed into electricity by the photovoltaic panels placed on the roof [3].

Incorporating phase change materials in the enclosure between the double or multiple glass panes is an innovative technique for improving the thermal inertia of glazing units and reducing energy consumption in buildings [5]. The authors calculated the energy consumption and CO2 emitted that CO2 emissions are reduced by about 18% by replacing conventional glazing system with a double glazing unit with a circulating water chamber in the façade [5].

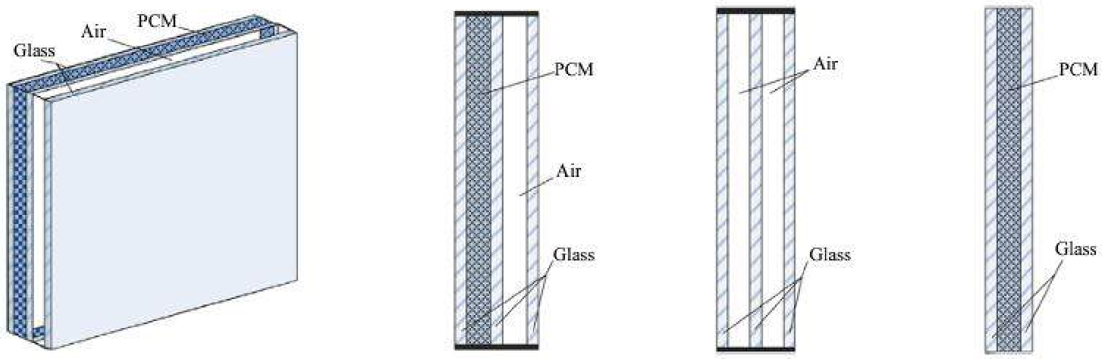


Figure 28. Structure comparison of the three kinds of windows considered
Source: Energy Build. 56 (2013) [6]

MAIN BUILDING MATERIALS USED:

1. WOOD (LOCAL LARCH): Structure and Facade

2. OSB (Oriented Strand Board): Wall finishes in interiors

3. PCM GLAZING: Windows and Doors

4. LOCAL STONE: Roofing

5. CONCRETE: Basement and Foundation

3.1.3 LE COSTIL HOUSE

TYPE: RESIDENTIAL

DESIGNER: Anatomies d'Architecture

YEAR: 2022

LOCATION: SAP-EN-AUGE, NORMANDIE, FRANCE

Figure 29. Turin and Sap-en-auge cities on map illustration by author, source: google earth

Figure 30. Le Costil House
Source: website of Archdaily

In the beginning, there was a question: "How do you recontextualise the act of construction?" The answer, from the cooperative Anatomies d'Architecture, comes across as bravado: 0% concrete, 0% plastic, 100% natural materials, sourced within a radius of less than 100 km. Duly acknowledged – in 2022, the architects who form the Paris and Marseille-based cooperative (Mathis Rager, Raphaël Walther and Alice Mortamet, alongside anthropologist Emmanuel Stern), with the help of local professionals and volunteers, complete the renovation of 'Le Costil', an 83-sq.m house in Normandie, for a private – and enlightened – client [7].

Figure 31. Le Costil House cladding
Source: Anatomies d'Architecture. (2023, March)

Chestnut cladding, cut 120 kilometers away. Horses were used to recover and carry the chestnut rods. This approach is a great example to cradle to practical completion minimizing the emissions from raw material supply to the transportation (A1-A5 modules of life cycle).

Figure 32. Le Costil House additional structure scheme
Source: Anatomies d'Architecture. (2023, March)

Douglas fir frame, thirty kilometers away. In order to prevent the need for industrial plywood, diagonal bracing is utilized to reinforce the frames of the south-facing addition to the house. The wood is unprocessed and devoid of chemicals, adhesive, or processing. Utilizing unprocessed wood reduce significantly also the indoor air quality because additional chemicals and adhesives used in wood has hazards for human health and also increase carbon emissions.

Foundations in black locust, sourced 30 kilometres away. Flooring built of 'quenouilles' made with raw earth, sourced on the site. Implemented over the course of a workshop, 650 'quenouilles' – wood sticks rolled up in a layer of straw and clay – were laid to make up the floor.

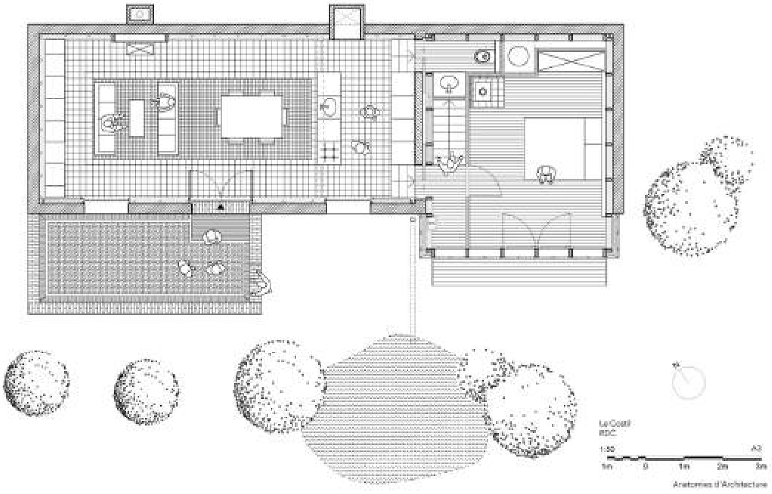
Figure 33."quenouilles" raw earth, wood sticks,straw and clay
Source: Anatomies d'Architecture. (2023, March)

Hemp insulation produced 45 kilometers distant. Batts of hemp wool were installed between the rafters to insulate the roof. Hemp is combined with earth and applied by projection for the walls.

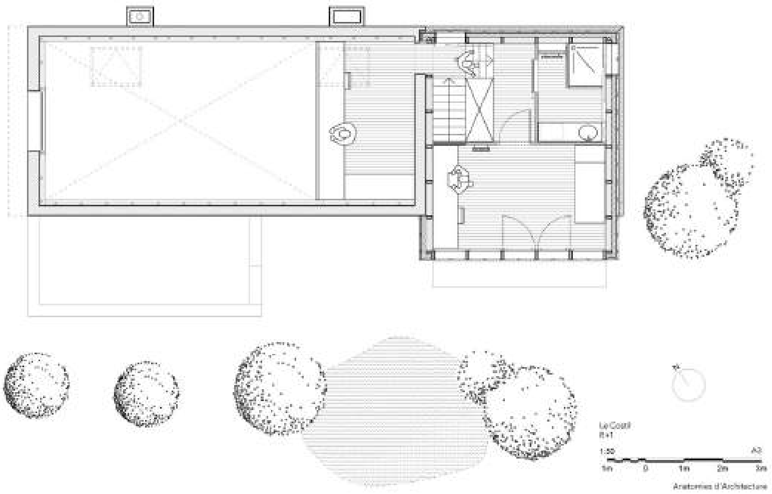
Figure 34. Hemp insulation installation
Source: Anatomies d'Architecture. (2023, March)

Figure 35. Reused bricks in view
Source: Anatomies d'Architecture. (2023, March)

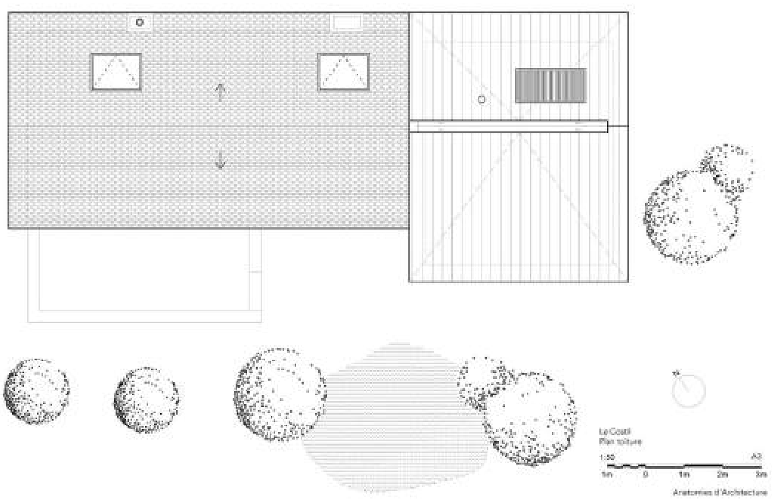
Bricks that were saved during the demolition of the old walls. 3000 bricks were taken out and examined, and then they were utilized to construct the façade facing south. Reusing materials is also a very important point to reduce carbon emissions as well as using bio-materials. Considering bricks are also one of the most used building material in Turin/Italy it is beneficial to consider to re-utilize bricks to prevent not only new productions and transportation emissions but also for the waste management in the end of life of the material.



GROUND FLOOR PLAN



FIRST FLOOR PLAN



ROOF PLAN

Figure 36. Le Costil House floor plans
Source: website of Archdaily

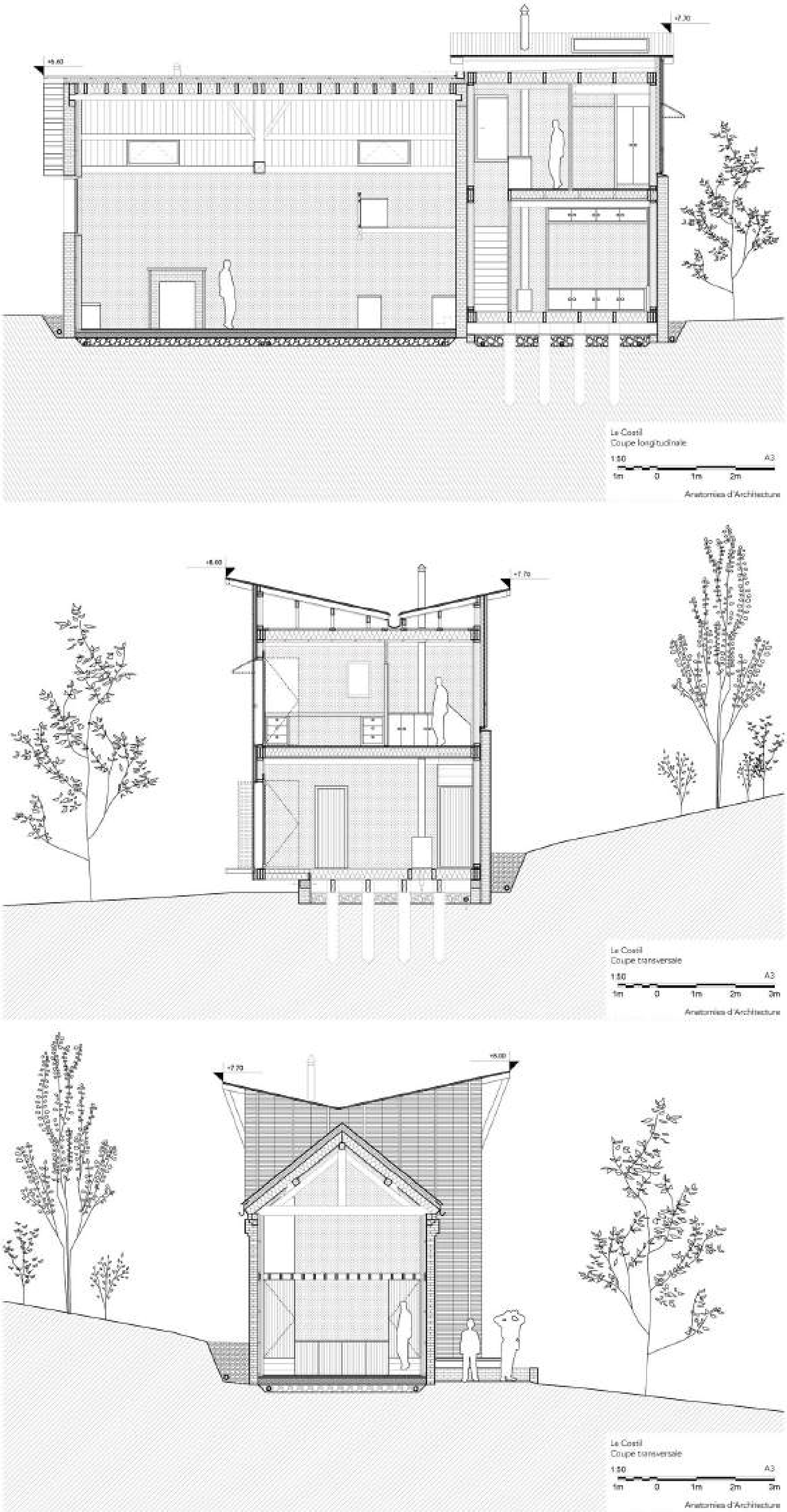


Figure 37. Le Costil House sections
Source: website of Archdaily

Le Costil House is a great example for renovation projects where using local resources and natural materials, re-utilizing demolition materials and reducing environmental impact as much as possible are the visions for the construction of the project.
In this example we can see some methods which are not quite common in conservative construction sector as well as the natural materials such as:

1.'quenouilles" raw earth, wood sricks,straw and clay: Flooring

2. Hemp: Insulation

In Le Costile house we see hemp not in blocks but sprayed but when it comes to using hemp in construction, the most important field is the so-called "hempcrete" – the material, created out of the woody core of the hemp plant stem or 'shiv/hurd' when combined with lime mortar. This combination leads to the production of sustainable building material that is light in weight, has insulating properties and is mostly made up of sand.

Figure 38. Hempcrete block
Source: website of Schönthaler hempcrete producer

As well as these natural materials we should also highlight:

3. Reused bricks: Wall element

On the other hand the main structure material of the additional part is wood as we saw also in the other case studies.

3.2 CRITICAL ANALYSIS

In the light of case studies we can see the examples of natural low-carbon building materials mostly locally obtained. In the figure 39, it is possible to see highlighted building materials have been used according to buildings parts of each case study. This practice will provide information about different low-carbon building materials available in near Turin and lead material filtering for the new design proposal.

	BUILDING STRUCTURE	INSULATION	WALL ELEMENTS	FACADE	ROOF
CASA QUATTRO	wood	Rice straw Cork Wood fiber	Wooden frame Gypsum board insulation	Cork panel	Roofing tile
CASA SOLARE	wood	Robust insulation	Wooden frame OSB insulation	Larch	Natural stone
LE COSTIL HOUSE	wood	Hemp Straw	Wooden frame Insulation Bricks	Chestnut	Roofing tile

Figure 39. Table of highlighted building materials of case studies according to building parts

It is possible to see that wood has been used for all case studies as building structure with the goal of sustainability. If we will look to conservative examples in Turin/Italy we will see concrete and steel are mostly used materials as building structure. Not only in Turin but we can say that quite all around the world. But these case study examples provide us more sustainable and locally available materials which are available to replace common use of concrete and steel.

Another important point about material selection would be considering if they are reused, reusable or recyclable. Some of the potential advantages of reused, reusable or recyclable building material include conservation of resources. In many construction projects, new resources are utilized which are non-renewable resources such as minerals, and fossil fuels. Common use of raw material that could be used again or that could be recycled will create more the need for the new raw materials. Considering this, we can give as an example, the utilization of recycled timber or metals is much less damaging to logging or mining and as a result, leaves less impact on forests and wildlife.

Besides, production and transportation of these building materials account to a greater portion of the emission of greenhouse gases in the atmosphere. For instance, the production of cement, half of which is used in concrete, is responsible for significant emissions of carbon dioxide. When materials are selected that are still in use in structures being demolished or are obtained in scrap yards as for example, recycled steel, the energy required in manufacturing and transportation is significantly reduced. Also, most materials that are processed for recycling need less energy than it takes to create other products using new raw materials. Such energy conservation and efficient utilization slashed emissions thus helping to fight climate change.

As can be seen in Figure 40 which presents a comparative analysis of the types of building materials used in the case studies, specifically which of them were reused, reusable, or recyclable. This will create the basis for a brainstorming session, and more importantly, decisions of the right materials for the design optimization of BAU scenario. By considering the sustainability, scope and capability of each material and trying to balance between aesthetic and functional aspects with environmental sustainability aspects effectively, it is possible to set up a good design.

	REUSED	REUSABLE	RECYCLABLE
WOOD	●	●	●
STRAW	●	●	●
CORK		●	●
HEMP		●	●
WOOD FIBER		●	●
ROBUST INSULATION		in condition	in condition
GYPSUM BOARD		in condition	in condition
OSB		●	●
BRICKS	●	●	●
NATURAL STONE		●	●
ROOFING TILE		●	●

Figure 40. Table of highlighted building materials of case studies into categories "reused/reusable/recyclable'

As can be seen in the table above, the robust insulation and gypsum board has to be in good conditions to be reusable or recyclable. Mineral wool or cellulose is an example of robust insulation that can be reused if it has not been damaged, has no toxicity, and is moisture resistant while recycled insulation can only be recycled if the insulation is clean from contaminants and there are facilities that can recycle the material. Likewise, the gypsum boards can be used again if they are intact, of standard dimension, free from the hazardous material and the gypsum boards can be recycled if the boards are clean, sorted and processed at recycling centers.

In addition to these materials we should also emphasize the most common construction materials have been used in Turin:

1. Concrete
2. Steel
3. Wood
4. Bricks
5. Stone
6. Clay
7. Terracotta

CHAPTER 3 FIGURES:

[10] Turin/Italy and nearby regions and countries map illustration by author, source: google earth

[11] Turin and Magnano cities on map illustration by author, source: google earth

[12] La Casa Quattro location source: official websites of LCA architects: https://www.lcarchitetti.com/proj/residential/casa-quattro-bioarchitettura-architetto-varese-milano-ticino-prefabbricata-in-legno-bioedilizia

[13] La Casa Quattro image from official websites of LCA architects: https://www.lcarchitetti.com/proj/residential/casa-quattro-bioarchitettura-architetto-varese-milano-ticino-prefabbricata-in-legno-bioedilizia

[14] La Casa Quattro site plan source: official website of LCA architects: https://www.lcarchitetti.com/proj/residential/casa-quattro-bioarchitettura-architetto-varese-milano-ticino-prefabbricata-in-legno-bioedilizia

[15] La Casa Quattro sections souce: official website of LCA architects: https://www.lcarchitetti.com/proj/residential/casa-quattro-bioarchitettura-architetto-varese-milano-ticino-prefabbricata-in-legno-bioedilizia

[16] La Casa Quattro Building Section Detail: https://www.infobuildenergia.it/progetti/casa-quattro-legno-paglia-sughero-abitare-naturale/

[17] Cork cladding detail: https://www.lcarchitetti.com/proj/residential/casa-quattro-bioarchitettura-architetto-varese-milano-ticino-prefabbricata-in-legno-bioedilizia

[18] Turin and Vens cities on map illustration by author, source: google eart

[19] Casa Solare, source: website of Archdaily: https://www.archdaily.com.br/br/01-58886/casa-solar-studio-albori/1339826067-dscn1774

[20] Casa Solare construction source: website of archilovers https://www.archilovers.com/projects/67677/casa-solare-gallery?492426

[21] Casa Solare source: website of archilovers https://www.archilovers.com/projects/67677/casa-solare-gallery?492426

[22] Different types of roofing stone employed in the Aosta Valley
Source: Journal of Building Engineering Elsevier

[23] Calcschist CM roofing in Lignod after renovation Source: Journal of Building Engineering

[24] Porfiroide roofing near the new roofs of gneiss on the left and Quartzite on the right in Antagnod. Source: Journal of Building Engineering Elsevier

[25] Casa solare wooden structure scheme. Source: website of Archdaily https://www.archdaily.com/245260/solar-house-studio-albori?ad_source=-search&ad_medium=projects_tab

[26] Casa solare floor plans Source: website of Archdaily: https://www.archdaily.com/245260/solar-house-studio-albori?ad_source=sear-ch&ad_medium=projects_tab

[27] Casa solare sections Source: website of Archdaily https://www.archdaily.com/245260/solar-house-studio-albori?ad_source=sear-ch&ad_medium=projects_tab

[28] Structure comparison of the three kinds of windows considered
Source: Energy Build. 56 (2013) [6]

[29] Turin and Sap-en-auge cities on map illustration by author, source: google earth

[30] Le Costil House Source: website of Archdaily https://www.archdaily.com/991971/le-costil-house-renovation-anatomies-dar-chitecture/636c0a512179836a98b88215-le-costil-house-renovation-anato-mies-darchitecture-photo?next_project=no

[31] Le Costil House cladding Source: Anatomies d'Architecture. (2023, March)

[32] Le Costil House additional structure scheme Source: Anatomies d'Architecture. (2023, March)

[33] ''quenouilles'' raw earth, wood sricks,straw and clay Source: Anatomies d'Archite-cture. (2023, March)

[34] Hemp insulation installation Source: Anatomies d'Architecture. (2023, March)

[35] Reused bricks in view Source: Anatomies d'Architecture. (2023, March)

[36] Le Costil House floor plans Source: website of Archdaily https://www.archdaily.com/991971/le-costil-house-renovation-anatomies-darchitecture/636c11b90036592d72298eb8-le-costil-house-renovation-anatomies-darchitecture-ground-floor-plan

[37] Le Costil House sections Source: website of Archdaily https://www.archdaily.com/991971/le-costil-house-renovation-anatomies-darchitecture/636c11bb0036592d72298eb9-le-costil-house-renovation-anatomies-darchitecture-section?next_project=no

[38] Hempcrete block Source: website of Schönthaler hempcrete producer https://www.hanfstein.eu/

[39] Table of highlighted building materials of case studies according to building parts

[40] Table of highlighted building materials of case studies into categories "reused/reusable/recyclable'

CHAPTER 3 REFERENCES:

[1] Description of La Casa Quattro in offical website of Technosugheri: https://www.tecnosugheri.it/intervento/casa-quattro-paglia-sughero-legno-lca-architetti-compri/

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[4] Bellopede, R., Zichella, L., & Marini, P. (2021). Stone roofing in the Aosta Valley, Italy: Technical properties and durability of traditional Lithotypes. Journal of Building Engineering, 35, 102068.

[5] Li, D., Wu, Y., Wang, B., Liu, C., & Arıcı, M. (2020). Optical and thermal performance of glazing units containing PCM in buildings: A review. Construction and Building Materials, 233, 117327.

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[7] Anatomies d'Architecture. (2023, March). Regional solidarity. Architecture Aujourd'hui, 32, 100-107.

chapter 4

DESIGN PROPOSALS AND ENVIRONMENTAL ANALYSIS

To initially present general information about the project it outlines the broad overview of the top level of the project in preparation for the subsequent analysis and discussion. This can be described as a background that gives a detailed description of the goals of the Life Cycle Assessment (LCA) analysis in detail based on the fact that it is imperative to determine the environmental influences of building materials and structures throughout the lifespan of the building materials. The functional unit which is a core component of the LCA assessment is clearly defined to facilitate consist and accurate comparisons. The chapter then identifies which parts of the building will be in the scope of the LCA study as this helps in designing relevant and effective analysis.

After such general backgrounding, the chapter brings the reader to the business-as-usual (BAU) scenario with respect to a residential building constructed in Turin/Italy by an architectural firm. This case serves as a realistic background for the practical application of the theoretical research described earlier. This is done through the use of the LCA technique which is studied and meticulously applied to this BAU scenario in order to find out which of the building structures and materials precinct most of the impacts. In this analysis, there is also the bill of quantity which provides the detailed description of all the used material and their amounts. From the result section, there are certain areas of strength that coincides with the aspect to be improved.

From the obtained results of the BAU scenario, the chapter then proceeds to the optimization stage. The current project is evaluated and targeted at the identification of its fallibilities, while a new design proposal will be created. Chapter 3 detailed filtered building structures and materials in this proposal to be used in the project optimization in terms of having lower level impacts to the environment. The optimization details are described, and it is evident that concept designs and material selection can lead to great improvement in lowering environmental footprint of the BAU scenario. This section is used to elaborate how results from the LCA studies can be used in actual project work, a part of reality check section.

The chapter is concluded with the results of the LCA conducted for the design optimization of business-as-usual scenario to bring refinement to the point. This involves and adjustment of the bill of quantity which is prepared at this stage as an attempt to make improvement. The following is a list of the changes that outline the fact that the results clearly depict that the new design works towards minimizing the effects on the environment in a negative way. In regard to this, the chapter focuses on the establishment of knowledge based improvement and innovation of constructions to achieve higher levels of sustainability. Therefore, the chapter aims to identify further research opportunities and applied strategies for the application of LCA in building projects and provide insights into the enhancement of construction organizations’ sustainable development objectives.

4.1. GENERAL INFORMATION

Business-as-usual (BAU) scenario is a restoration project design by an architecture studio called "Officina8a Architetti e Associati" located in Turin / Italy. BAU scenario while being a restoration project, it required mostly to be demolished and reconstructed because of the conditions of the structure itself. The project is a residential single-family house designed for private clients with kids.

The project is located in Piedmont region in Italy, in a near town to Turin city called Pecetto Torinese.

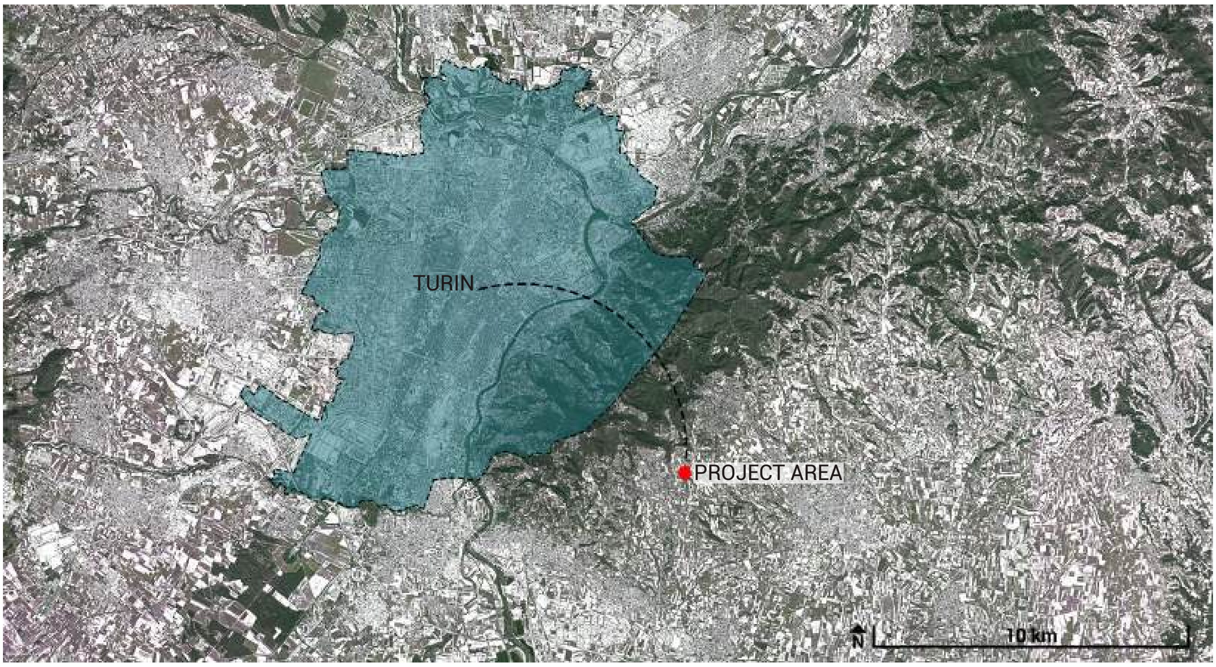


Figure 41. Turin city and project area map
Illustrated by author, map base source: google earth

Figure 42. Pecetto Torinese and project area map
Illustrated by author, map base source: google earth

Apart from the main building's functions projects includes a large outdoor space and an additional structure for the guests which is much more smaller than the main building. In this thesis we will focus only on the main building. As can be seen from the figures below the project is located in countryside surrounded by various fields.

Figure 43. Project area site plan

Figure 44. Project masterplan

DEMOLITION / RECONSTRUCTION

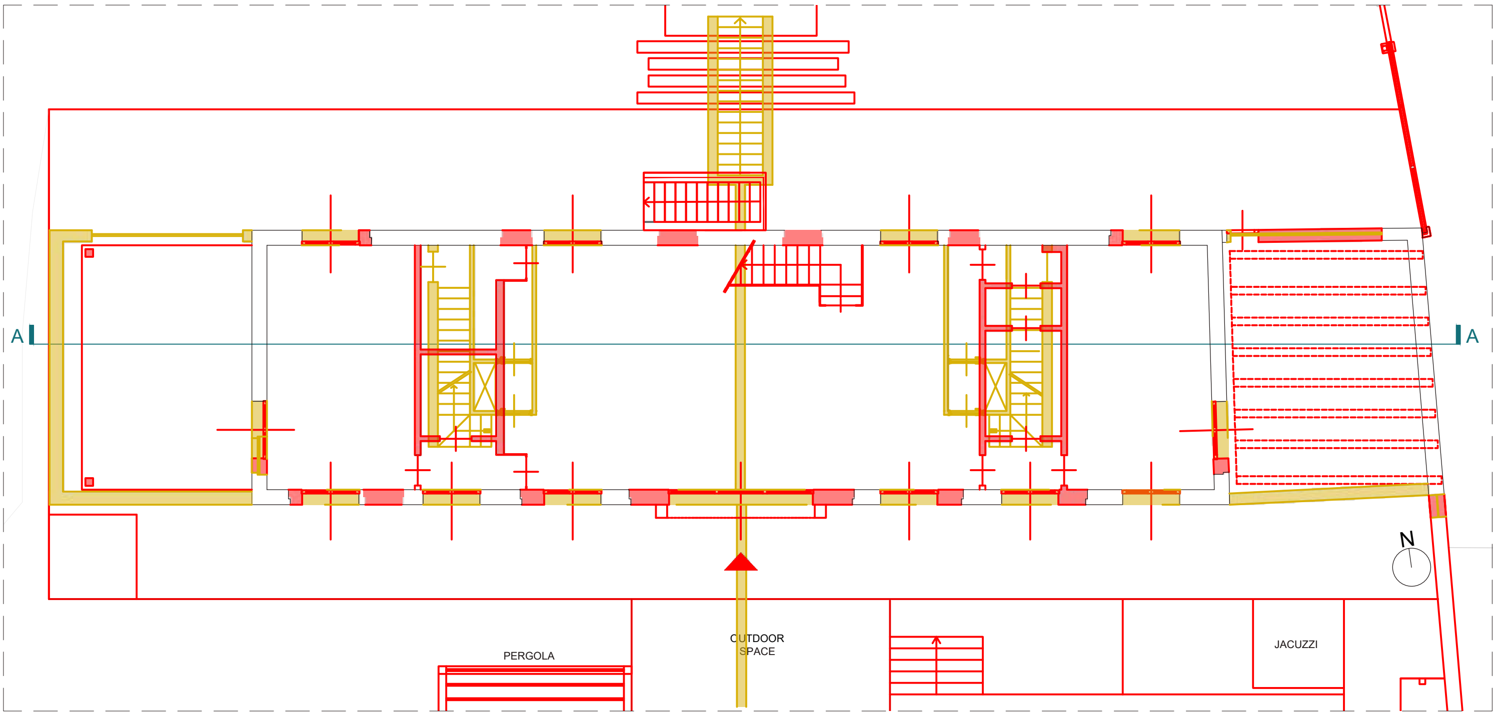


Figure 45. Demolition/reconstruction GROUND FLOOR PLAN

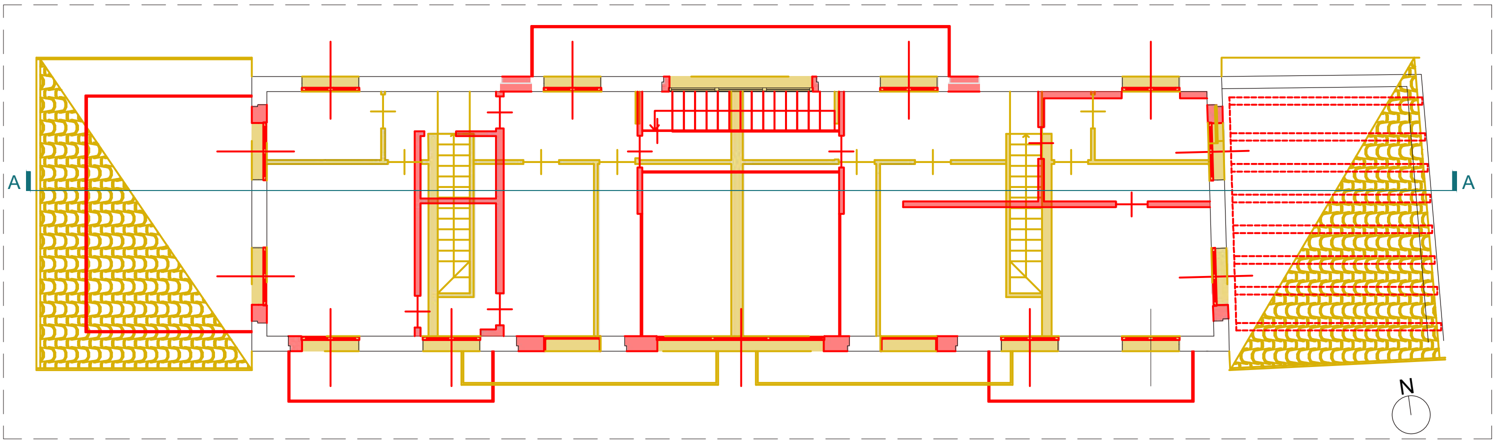


Figure 46. Demolition/reconstruction FIRST FLOOR PLAN

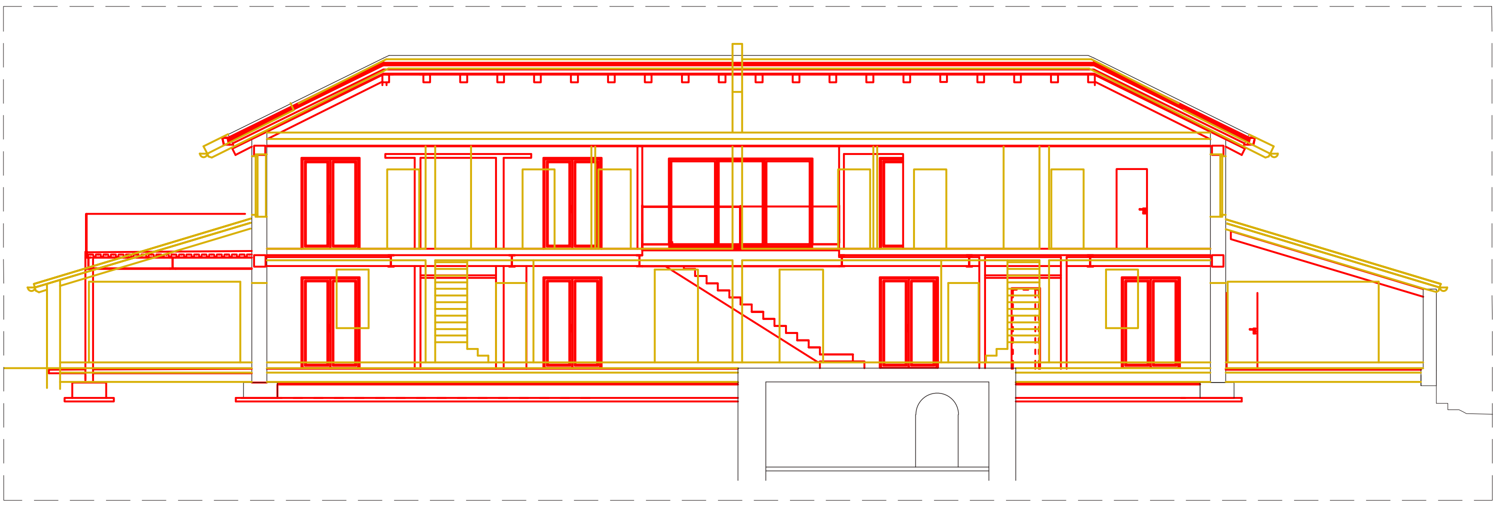
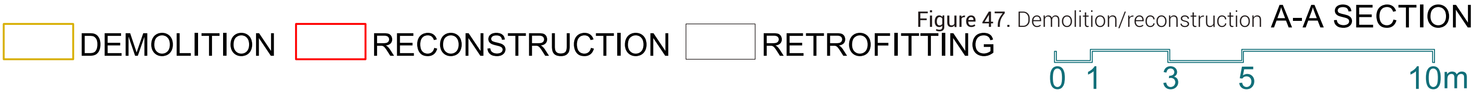


Figure 47. Demolition/reconstruction A-A SECTION



As seen on the plans and A-A section, business-as-usual scenario is a restoration project of an existing house. Despite it is a restoration project, most of the building required reconstruction because of the current situation of existing building and clients' wishes.

All outdoor area is reconstructed. Position of outdoor stairs which lead to the existing basement is changed as horizontal orientation instead of vertical orientation in order to gain more space for outdoor spaces on the backyard.

In the main building, position of the windows and openings are changed according to indoor distribution and facade designing. Roofs on the two sides of the building are demolished in order to have an only pergola area on the east side and create a terrace on the west side of the building. Walls under the roofs that are surrounding two sides of the building are demolished in order to have more open space connected with indoor space.

On the other hand, position of the balconies are distributed according to indoor distribution and the instead of long and narrow form, shorter but larger form is chosen for reconstruction.

For the indoor circulation instead of stairs on the two sides of the building one central stairs right in front of the entrance is chosen. To be able to do this, the wall in the center of the building which divides indoor spaces in half is demolished in order to create a more homogeneous indoor distribution.

Roof and its structure are reconstructed because of the condition of the current situation of the existing building which was almost destroyed.

The basement of the existing building was in good conditions to be retrofitted. In this thesis the basement and it's foundation, pergola on the east site of the building are not included to optimization of the business-as-usual scenario and also in the LCA analysis of both design proposals.

4.1.1 LCA GOALS AND FUNCTIONAL UNIT

GOAL AND SCOPE

The primary objective is to optimize business as usual scenario and demonstrate how building structure and material choices make difference on the environmental impact of a residential building. In order to do this EC (Embodied Carbon) emissions of the residential house during it's entire life cycle (modules A1-A3 (Production), A4, C2 (Transport) and C1-C4 (End-Of Life) as defined by EN 15978.

SYSTEM BOUNDARIES:

LCA analysis are done considering cradle to grave. Life span of the residential building is decided as 50 years. The assessment includes A1-A3, A4, A5, C1-C4, B4-B5 modules. B1-B3 and B6-B7 modules are excluded in the LCA analysis. (Use, maintenance, repair stages' carbon and operational carbon are excluded in the LCA analysis.)

LCI:

Building parts included to LCA analysis:
1.Foundation
2.Building structure
3.External walls
4.Internal walls
5.Floor slabs
6.Roof

Building parts excluded to LCA analysis:
1.Windows
2.Doors
3.Internal glass use
4.Terrace parapets
5. Existing basement and it's foundation

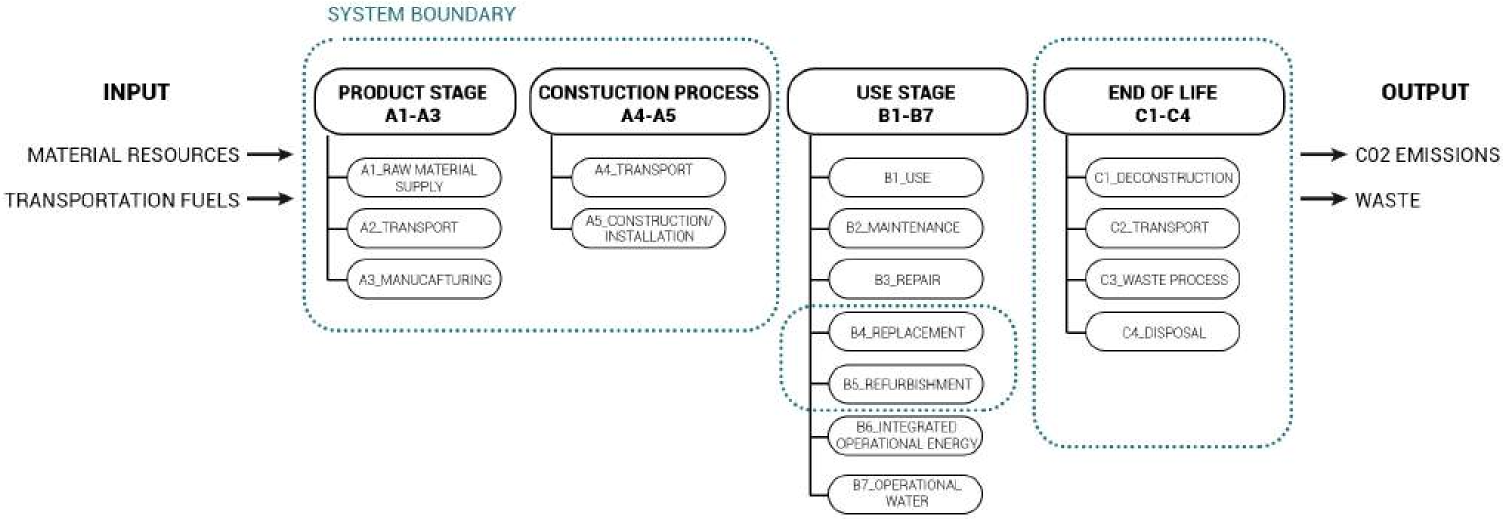


Figure 48. Life Cycle Inventory (LCI) flow model and system boundary

LCIA AND FUNCTIONAL UNIT:

GWP - Green House Gas (GHG) emissions in kg CO2-eq per m2 per year, called as Global Warming Potential (GWP) is defined as impact category. Biogenic carbon is not considered in the total results.

4.1.2 METHODOLOGY

A residential building project in the city of Turin in the BAU (business-as-usual) scenario will be presented and its carbon footprint determined by means of the LCA analysis using Oneclick LCA tool. Subsequently, the appropriate low-carbon materials and strategies will be incorporated in redesigning / optimizing the project, and a LCA analysis will be done for the optimized project design again using Oneclick LCA tool. The impact analysis of the proposed changes will be done by comparing the outcomes of BAU and the designs that are obtained after applying the third-party optimization techniques.

Last, the outcomes of this research will be presented and conclusions made as well as recommendations for future works on sustainable buildings and for future research in this field. Efficiency of this methodology supports a comprehensive assessment of environmental impacts and provides actual recommendations for decreasing carbon intensity in residential construction.

4.1.2.1 Tools of LCA analysis: Oneclick LCA and Building Information Modeling (BIM)

One Click LCA is a licensed web based software from Finland and is customized for buildings. It is compatible with different green building certification systems, such as BREEAM and LEED. The user manually types the amount of construction material for the analyzed building. Data for the specific manufacturer for each construction material can be found in One Click LCA's different databases [1].

Oneclick LCA has very large and current databases available, various EPDs provided by well-known firms in the world which makes it a useful tool to obtain proper LCA results. It also provides building information modeling (BIM) integration which simplify the calculation of the amount of building materials or recognizing building parts such as building structure frame thanks to revit families but the user can modify recognized materials' category manually on Oneclick LCA tool in order to categorize them properly. For example metal framing for gypsum board applications of BAU scenario, weight (kg) of metal studs inserted manually (calculated as 1,1 kg per linear meter).
In this thesis LCA analysis will be done with Revit BIM tool together with Oneclick LCA according to Level(s).

Figure 49. Oneclick LCA integrations
source: Oneclick LCA

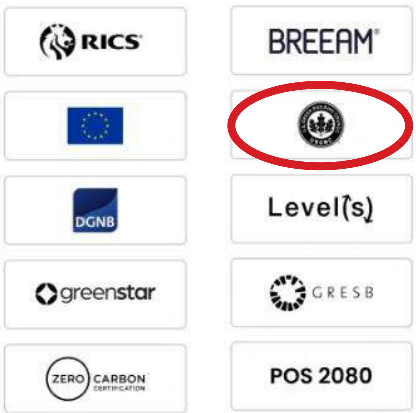


Figure 50. Oneclick LCA building certification systems
source: Oneclick LCA

[1] Ida Östling (2018). *Life cycle analysis as a tool for CO2 mitigation in the building sector* (Master's Thesis UMEA University)

4.1.2.2 Analysis Process

Business-as-usual scenario and optimization projects are separately modelled using Revit BIM program. Creating parts in the model (all the layers of building elements such as a wall family with all structures and substances with correct thickness and correct materials) is crucial to have a correct mapping in Oneclick LCA tool.

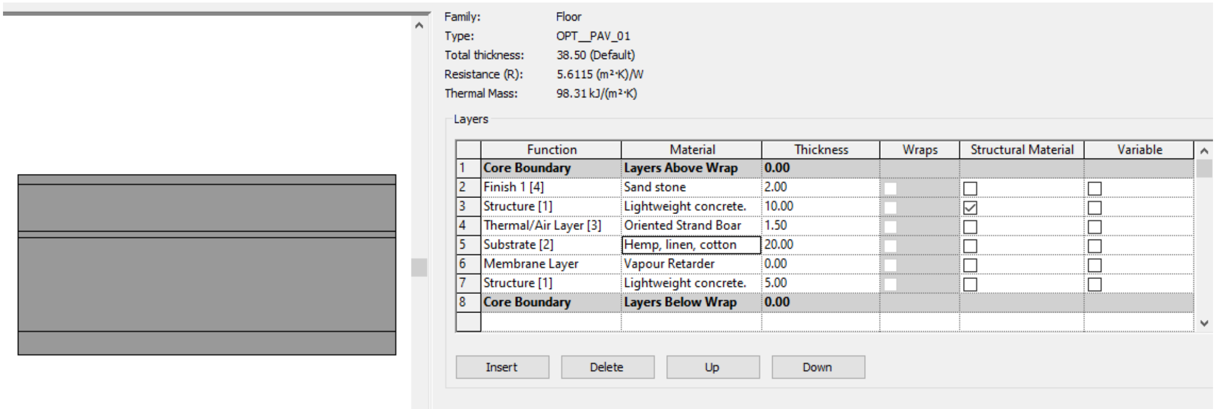


Figure 51. Creating parts of floor slab, source: screenshot from Revit program

Completing all the projects' model is the first step to be able to start LCA analysis on Oneclick LCA tool in Cloud. After completing the model using Oneclick LCA plugin the model is imported to Oneclick LCA in Cloud.

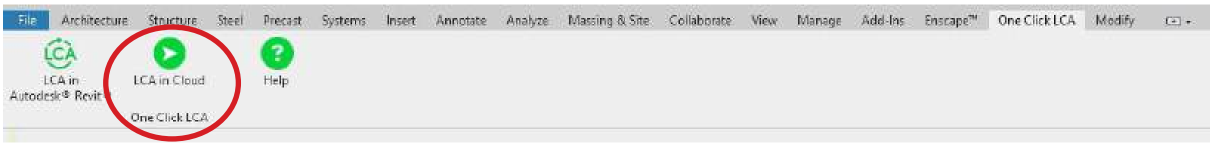


Figure 52. Oneclick LCA plugin, source: screenshot from Revit program

After importing data from Revit program to LCA in Cloud the initial settings are set. The tool is chosen as Level(s) life-cycle assessment (EN 15804 + A1).

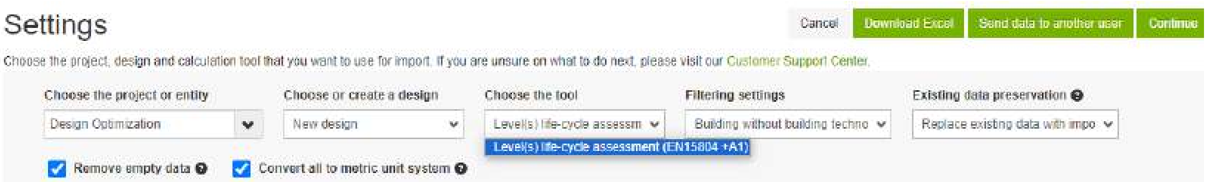


Figure 53. Starting settings for LCA analysis, source: screenshot from Oneclick LCA in cloud

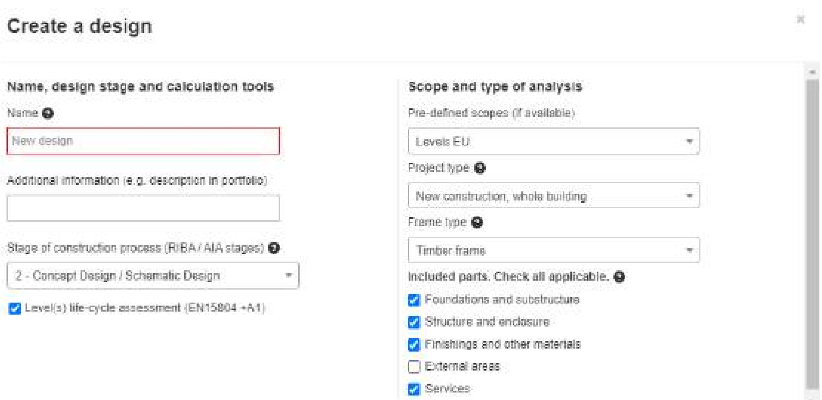


Figure 54. Creating design for LCA analysis
source: screenshot from Oneclick LCA in cloud

While creating the design scope and the type of analysis is set. For example for the optimization of the BAU, pre-defined scopes is set as Level(s) EU, project type is set as new construction whole building, frame type is set as timber frame. External areas are excluded for both projects.

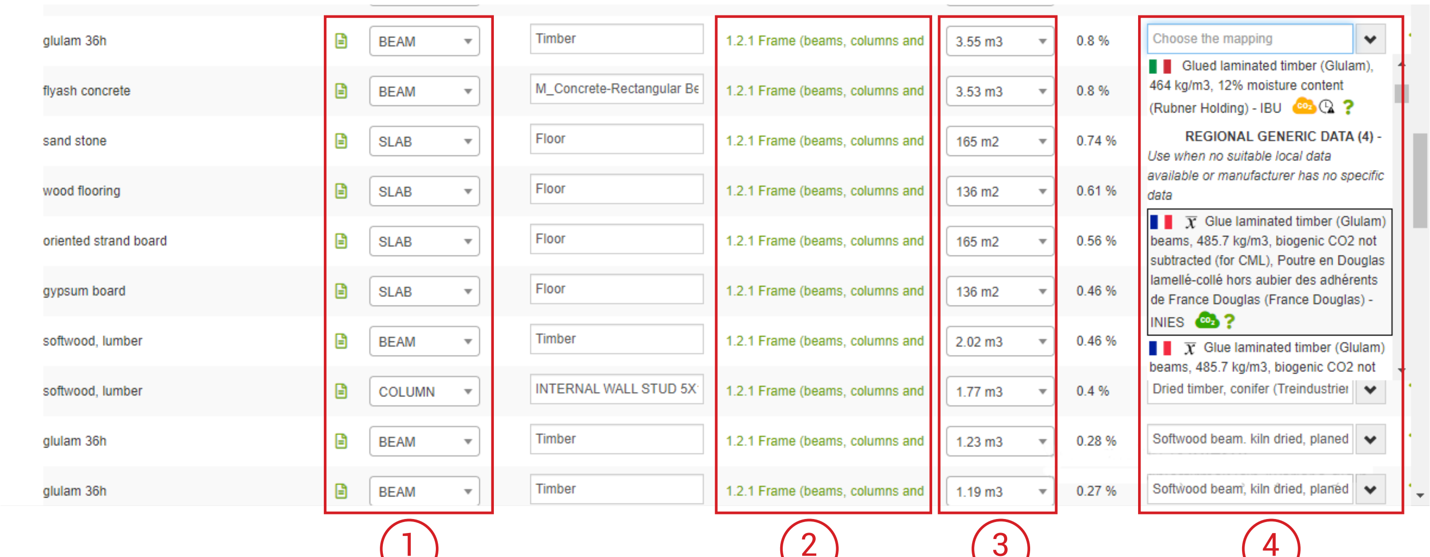


Figure 55. Building material classification for LCA analysis, source: screenshot from Oneclick LCA in cloud

After creating the design and scope pre-definitions all the data imported from the Revit model is recognized by Oneclick LCA tool but it is possibile to modify it.

Step 1.

For each material categories are set.

Step 2.

For each material building part is set. Such as frame (beams, columns and slabs, or internal external/internal wall, ground floor slab, upper floors, balconies, substructre..)

Step 3.

For each material quantity m2 or m3 is recognized as how it was modeled in Revit but it is possible to modify them.

Step 4.

For each material mappings are set. In this steps it is possible to search different EPDs and to see their technical data, environmental impact or other information about the mapping chosen.

Figure 56. Building material mapping and information checking , source: screenshot from Oneclick LCA in cloud

After completing all the mappings in the "input data" section it is possible to set or modify building materials, energy consumption, water consumption, construction site operations, calculation period, emissions and removals and the building area.

Figure 57. Input datas for LCA analysis
source: screenshot from Oneclick LCA in cloud

Figure 58. Building materials section, source: screenshot from Oneclick LCA in cloud

In the building materials section, it is possible to set for each resource transport type and kilometers, wastage percentage or set if the material is reused or locally reused.
For example in the design optimization timber frame glulam structure is set as locally reused.

Figure 59. Wastage value, service life of the materials, reused /locally reused material settings, source: screenshot from Oneclick LCA in cloud

Figure 60. Calculation period of the LCA analysis, source: screenshot from Oneclick LCA in cloud

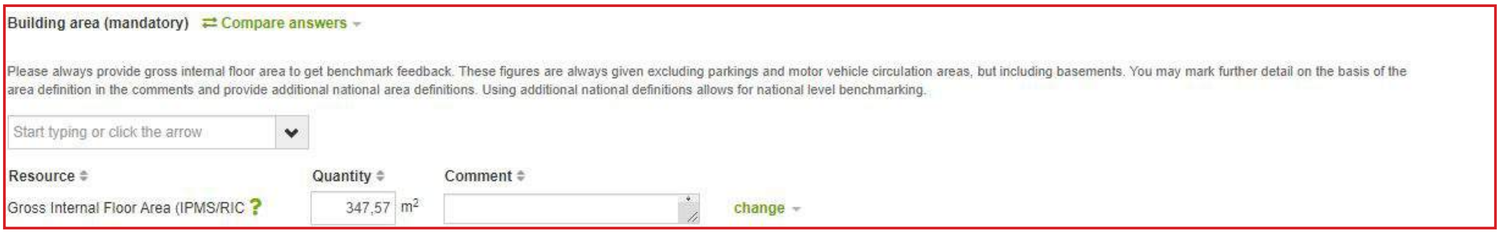


Figure 61. Building area of the LCA analysis, source: screenshot from Oneclick LCA in cloud

Figure 62. Deconstruction/demolition scenarios (C1), source: screenshot from Oneclick LCA in cloud

Setting calculation period, building area and deconstruction demolition scenarios follows the further steps. For both projects calculation period is set as 50 years and gross internal floor area is 401,27 m2. For the deconstruction/ demolition scenario for BAU is chosen demolition of mixed frame building (concrete, timber, steel) on the other hand for the optimization project timber frame building is chosen.

Life-Cycle Assessment for Level(s) in compliancy with EN 15978 Download Results Summary

	Result category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	
A1-A3	Construction Materials	32 988,92	399 008,07	48,32	202,77	62,7	213,94	46,34	425 161,18	Details
A4	Transportation to site	8 077,74		0	1,75	0,36	0,18	0	15 782,52	Details
A5	Construction/installation process	5 611,08		8,07	26,06	7,74	35,2	8,69	55 284,83	Details

Figure 63. General results of LCA analysis, source: screenshot from Oneclick LCA in cloud

Level(s) life-cycle assessment (EN15804 +A1): Construction Materials Show headings Print Close

Construction	Resource	User input	Global warming kg CO_2e	Biogenic carbon storage kg CO_2e bio	Ozone Depletion kg CFC11e	Acidification kg SO_2e	Eutrophication kg PO_4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	Comments
W02 External Wall	Interior clay plaster coating, 3 - 4 mm, 4.17 kg/m2, A4 >500... ?	14,25 m2	9,35 See calculations	0 See calculations	0 See calculations	0,05 See calculations	0,02 See calculations	0,01 See calculations	0 See calculations	47,63 See calculations	W02 Finish

Figure 64. Detail section of results for A1-A3 modules, source: screenshot from Oneclick LCA in cloud

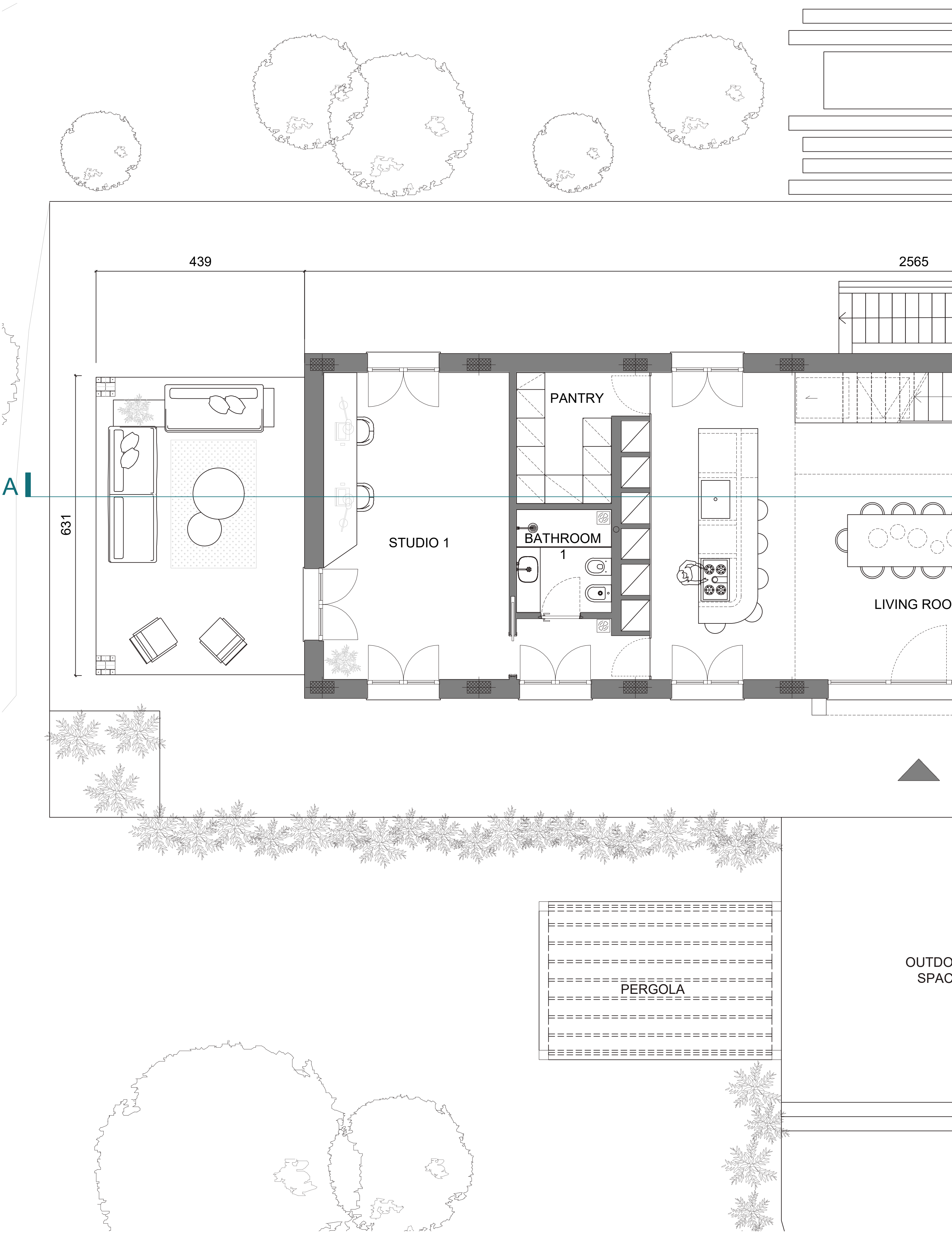
In final results as can be seen in figure 58, it is possible to check "detail" section of each life cycle phase. In this section, it is possible to check the GWP calculations of each building material. **In this thesis, tables of LCIA for modules A1-A3 are manually prepared based on this section as can be seen in figure 59.**

4.2 BUSINESS AS USUAL SCENARIO

Business as usual (BAU) scenario is a restoration project designed by an architecture studio called "Officina8a Architetti e Associati" located in Turin / Italy. BAU scenario while being a restoration project it required mostly to be demolished and reconstructed because of the conditions of the structure itself. The project is a residential single-family house designed for private clients with kids.

In Business-as-usual scenario common practices of a buildings structure will be presented. BAU scenario has a mix structure with reinforced concrete, steel and timber. Main building structure is reinforced concrete, for terrace structure IPE steel beams and HE steel columns has been used. Timber beams are used for the first floor structure. On the other hand, there is one typology for external walls with hollow bricks as the main material. Rockwool as insulation material has been used in external/internal walls as well as in the roof layers. For floor slabs we can see a common lightweight concrete usage.

A part of the main building, outdoor areas and additional structure called guest house, and the retrofitted basement and its foundation/structure will not be included in LCA analysis and will not be presented with details. Following pages will focus on the presentation of the main building as signed on the master plan (figure 44).


439
2565
631
A
PANTRY
STUDIO 1
BATHROOM
1
LIVING ROO
PERGOLA
OUTDO
SPAC

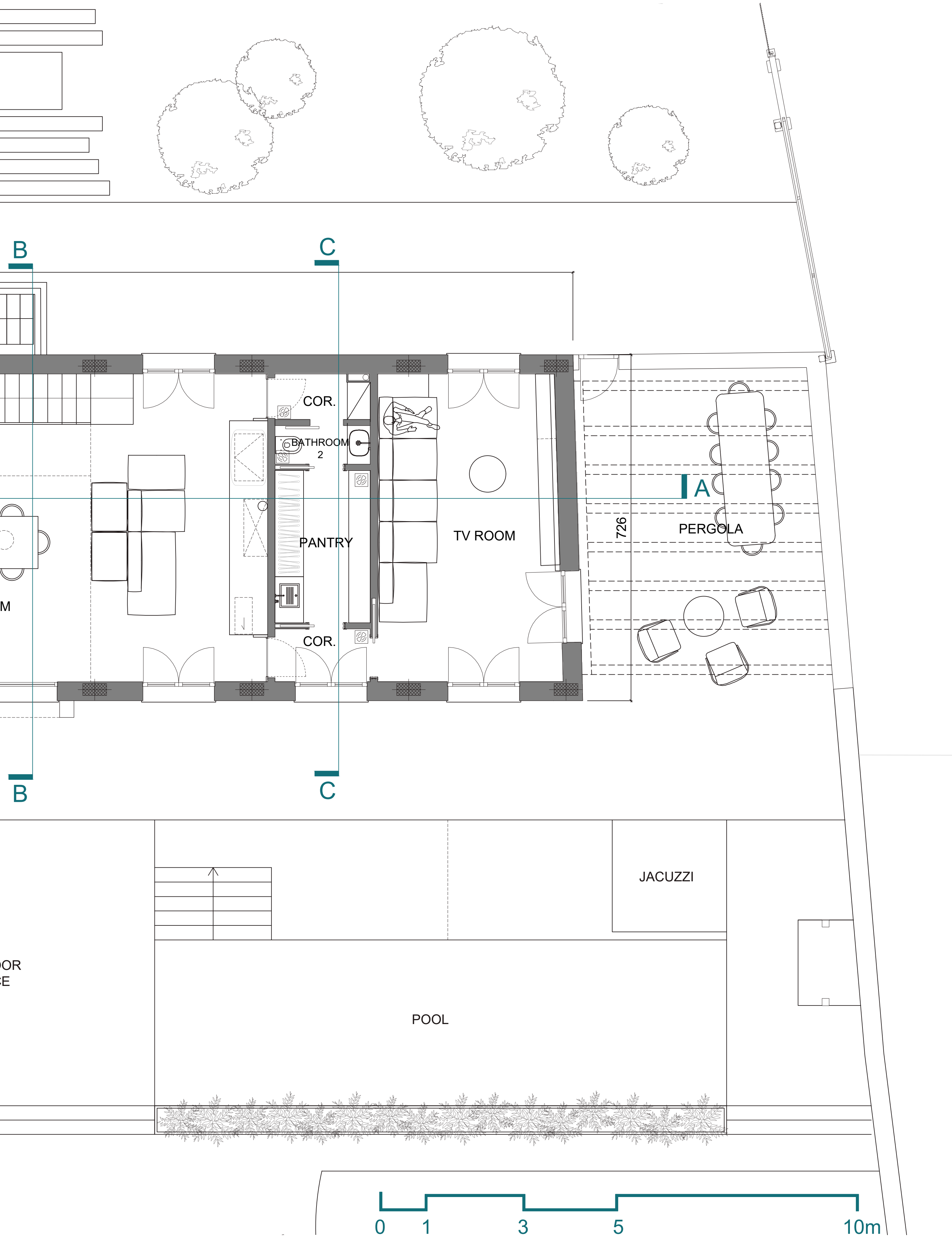
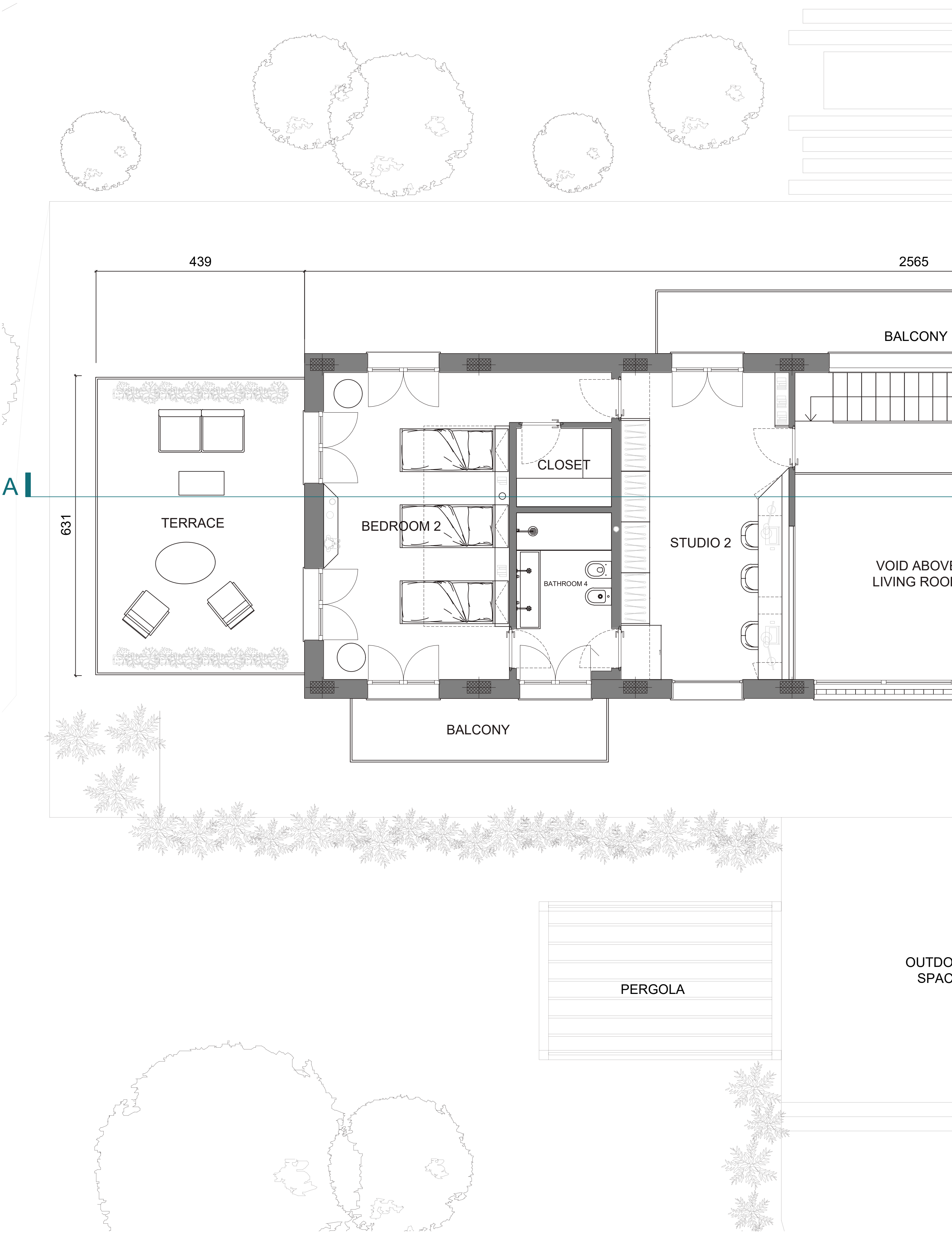


Figure 65. BAU GROUND FLOOR PLAN


439
2565
BALCONY
A
631
TERRACE
BEDROOM 2
CLOSET
BATHROOM 4
STUDIO 2
VOID ABOVE LIVING ROO
BALCONY
PERGOLA
OUTDO SPAC

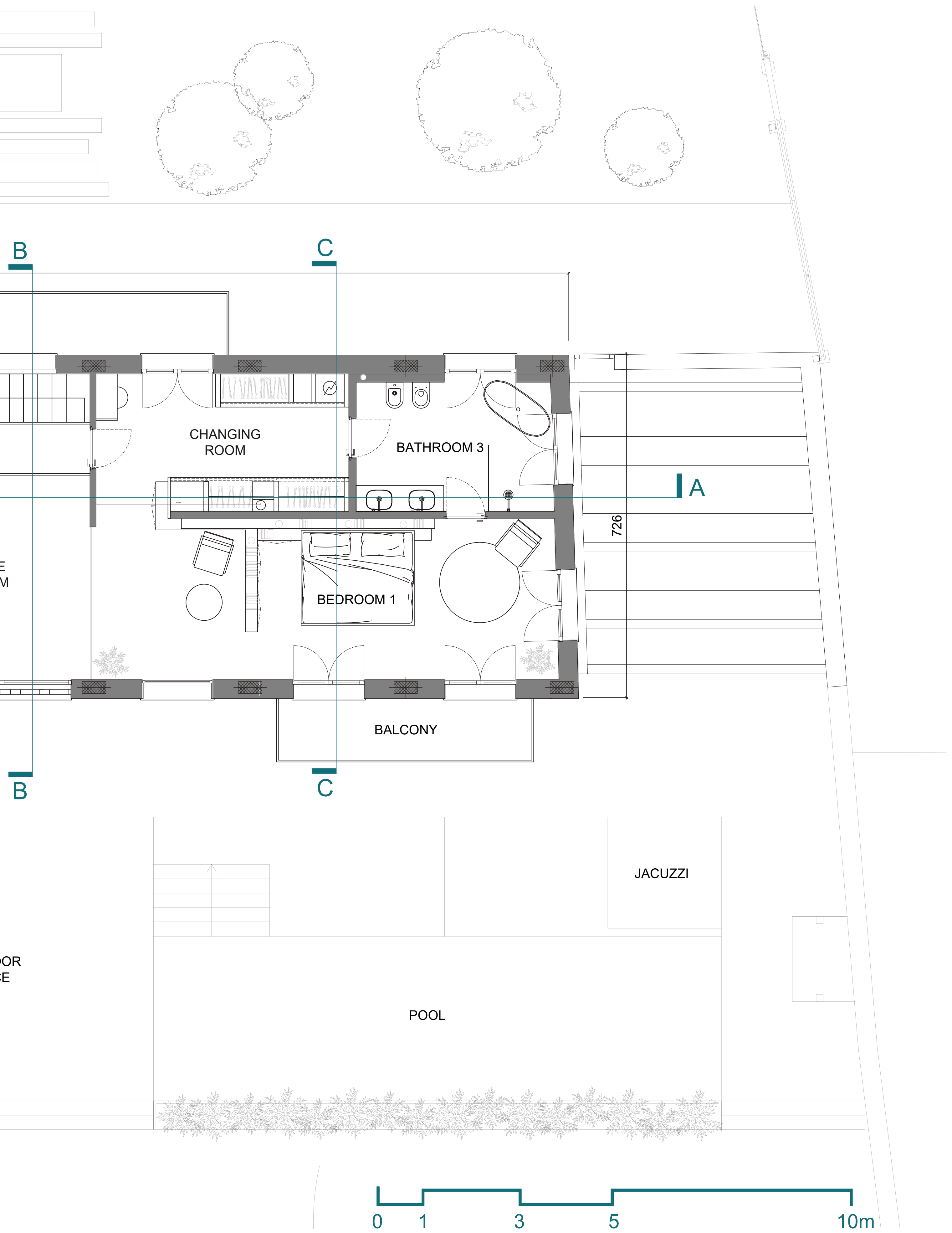


Figure 66. BAU FIRST FLOOR PLAN

Figure 67.

BAU SOUTH ELEVATION SCALE: 1/100

Figure 68.

BAU NORTH ELEVATION SCALE: 1/100

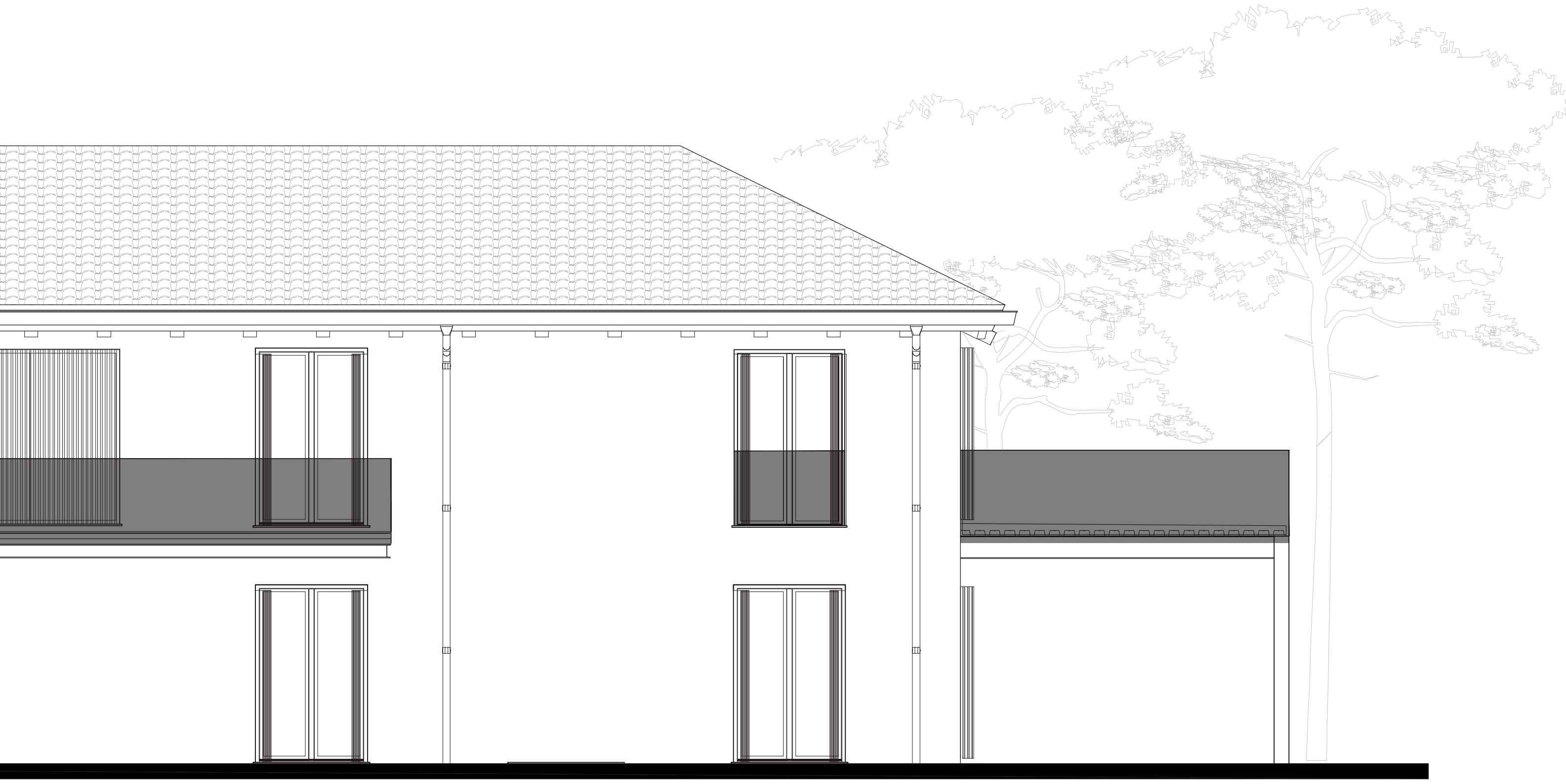


Figure 69.
BAU EAST ELEVATION SCALE: 1/100

Figure 70.
BAU WEST ELEVATION SCALE: 1/100

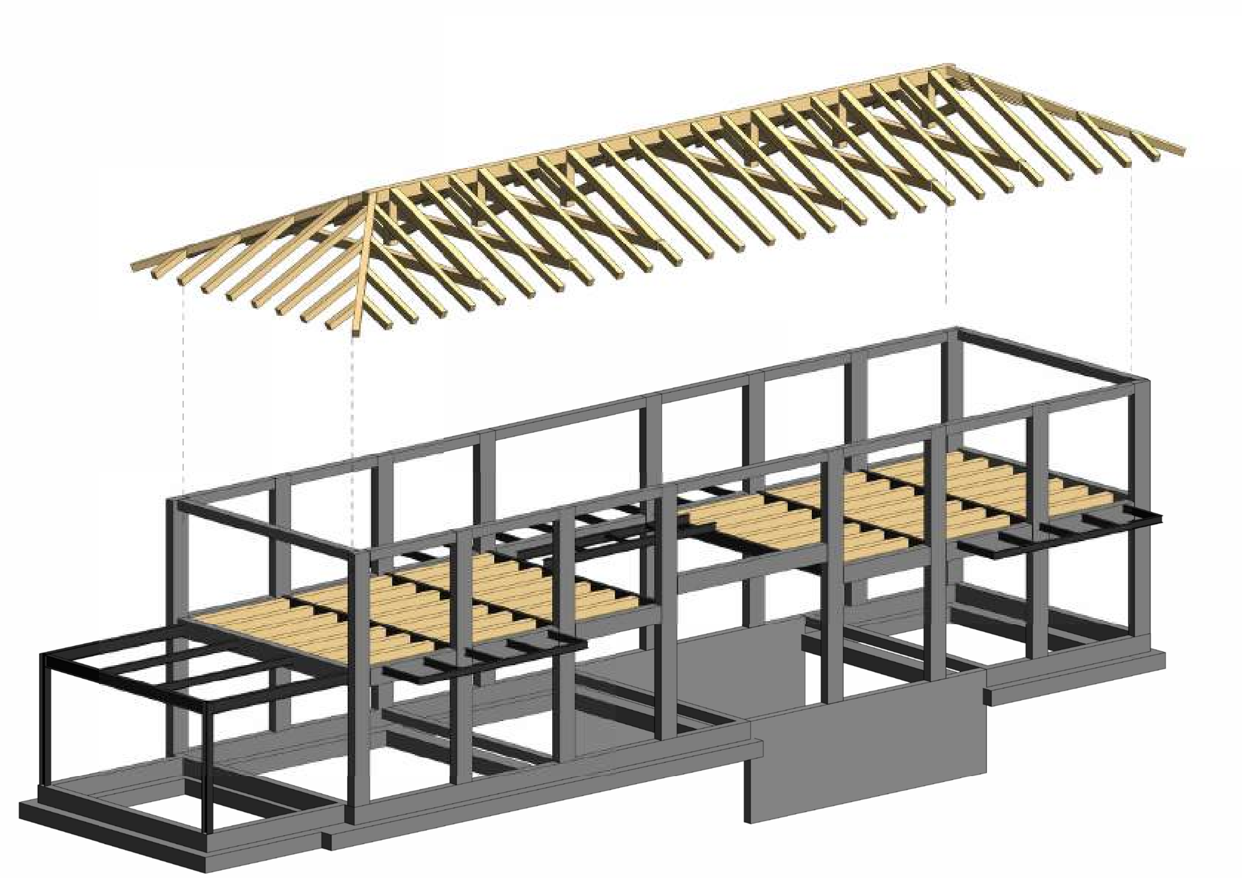


Figure 71. Building structure 3D diagram of business-as-usual

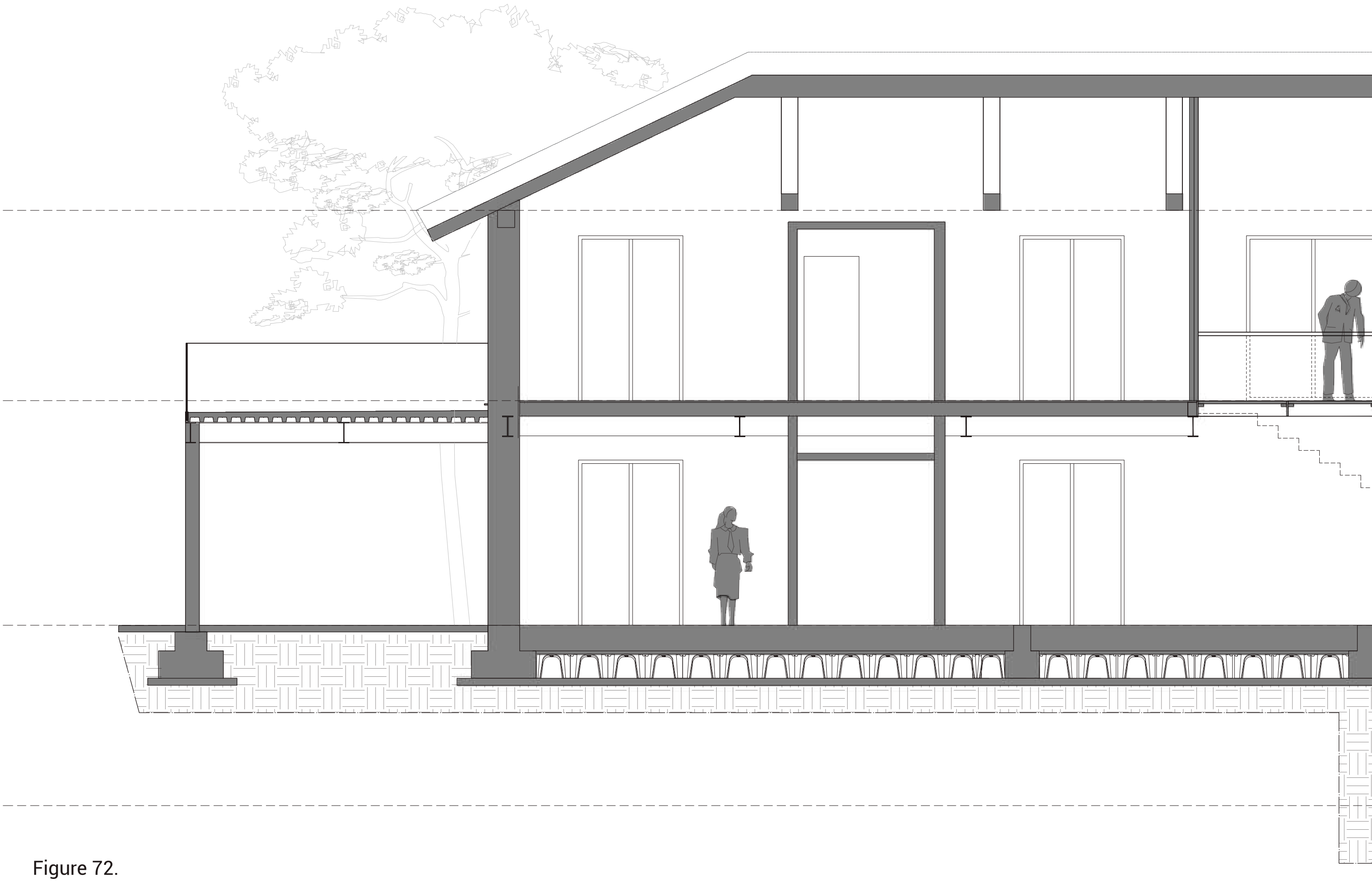
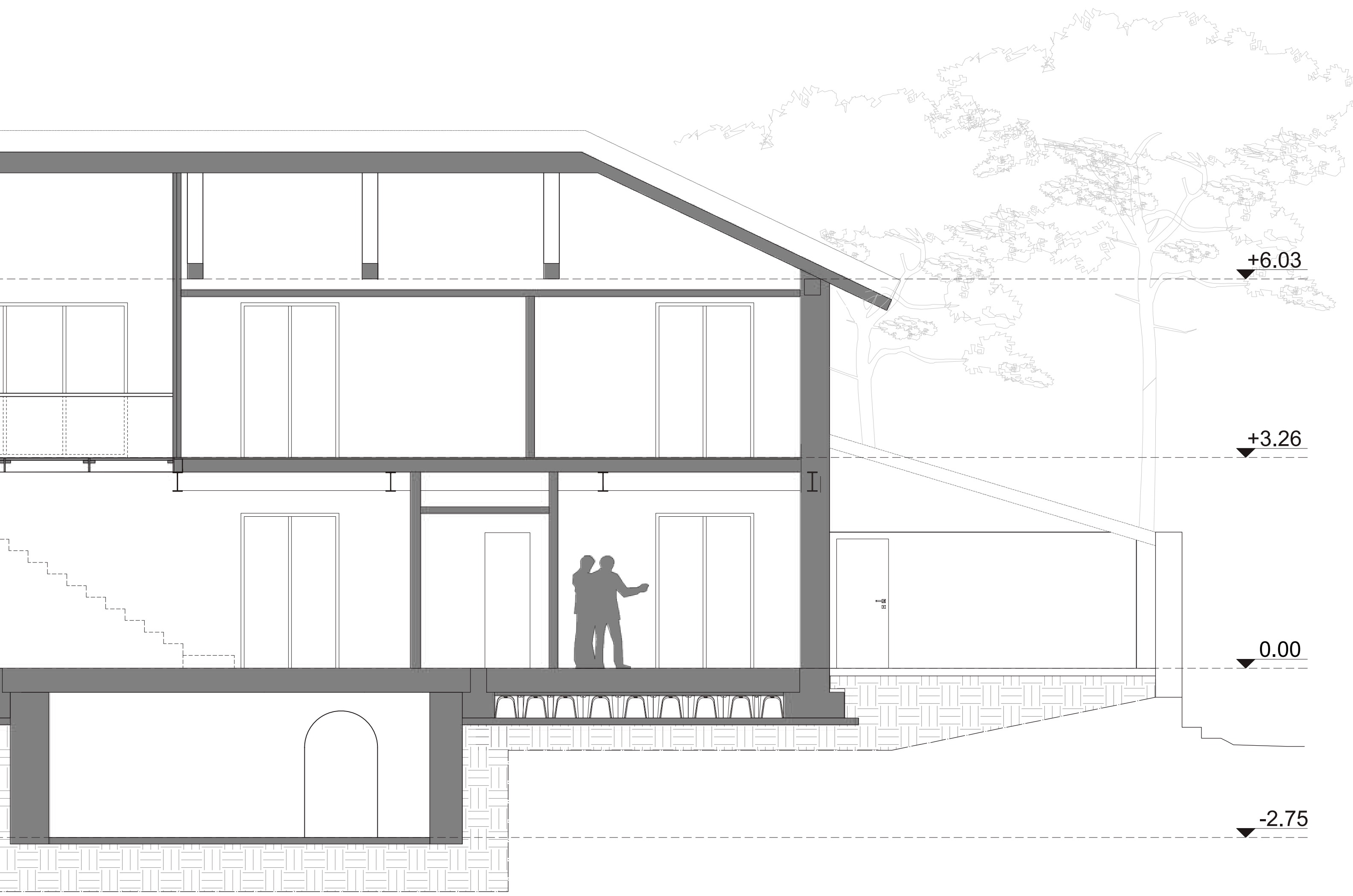


Figure 72.
BAU A-A SECTION SCALE: 1/100


+6.03
+3.26
0.00
-2.75

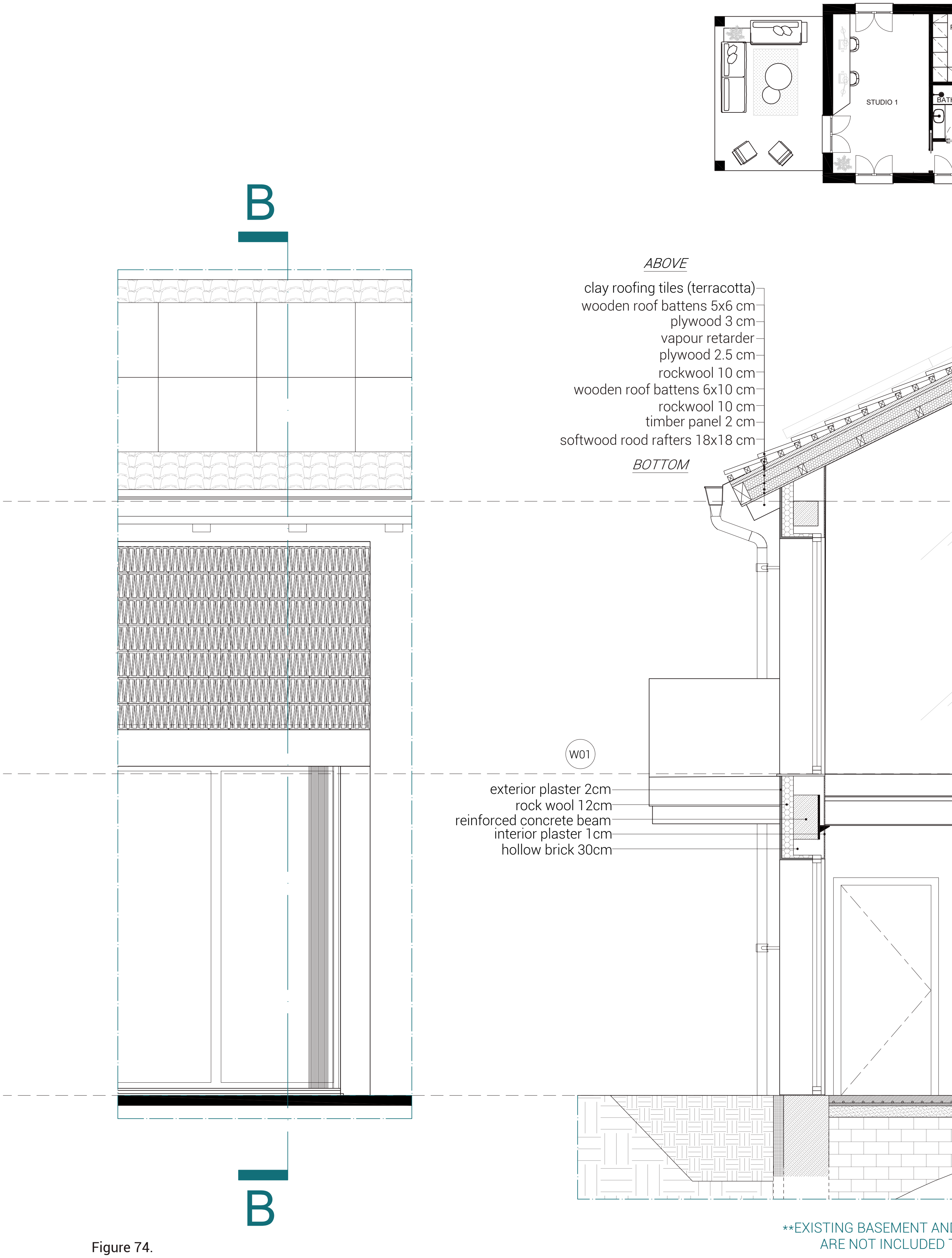


Figure 74.

BAU SOUTH FACADE DETAIL (B-B SECTION)

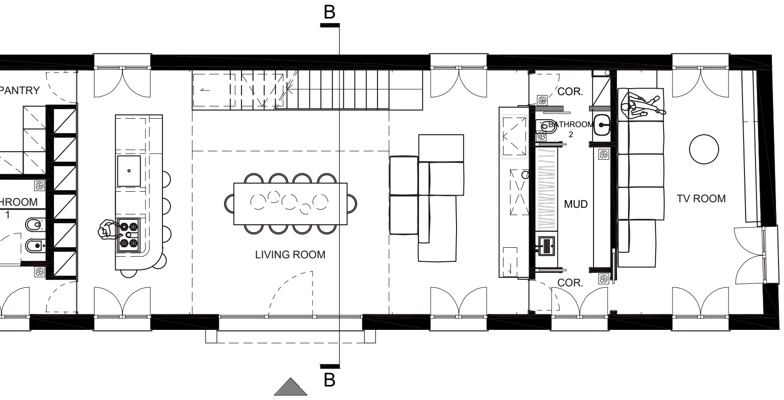


Figure 73. BAU
GROUND FLOOR PLAN
SCALE: 1/200

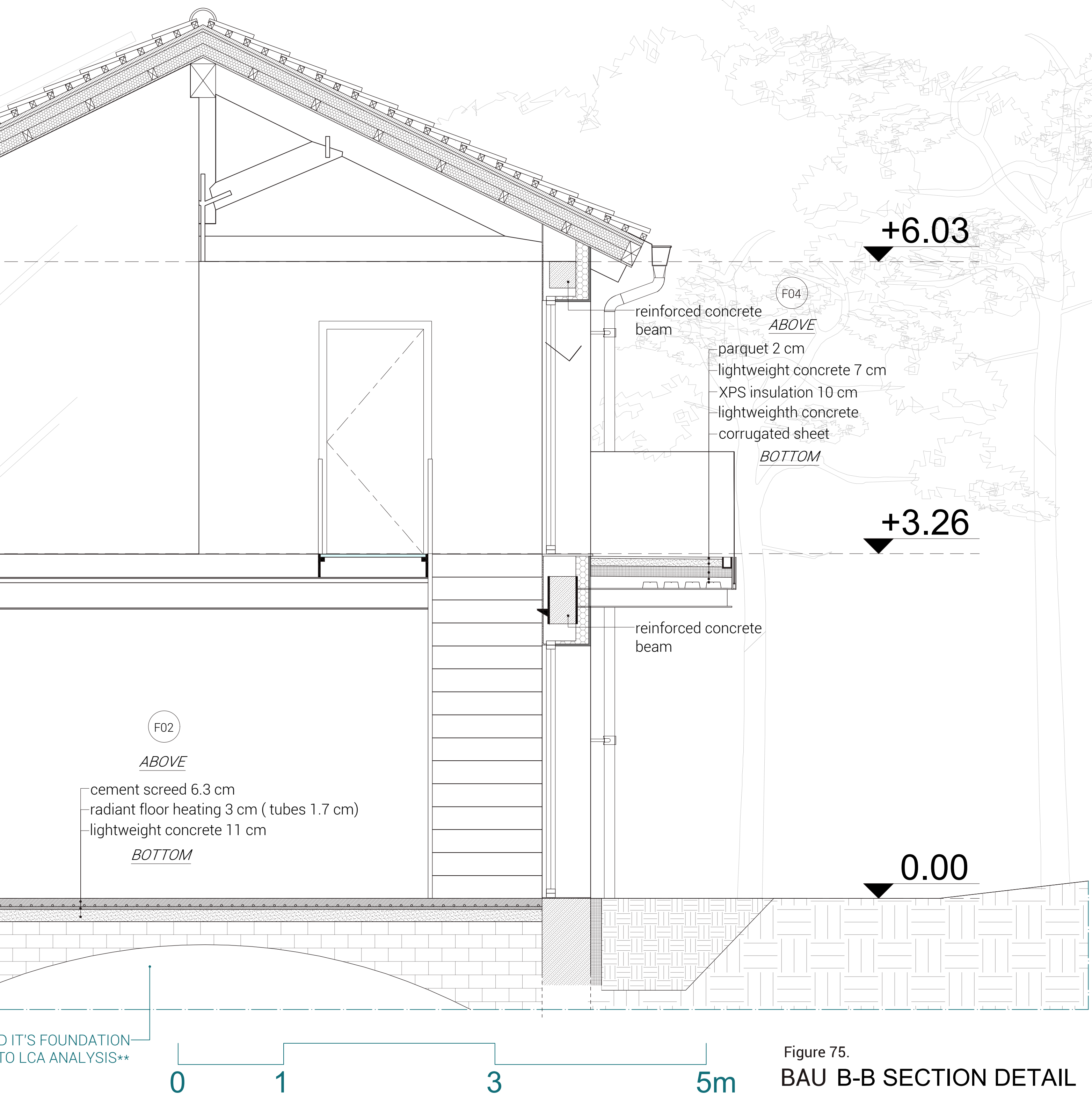
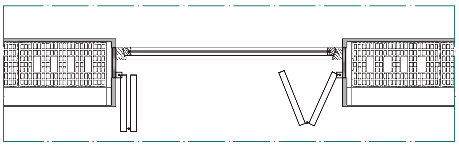
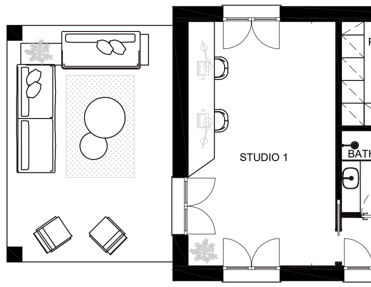


Figure 75.
BAU B-B SECTION DETAIL

Figure 76. BAU WINDOW GROUND FLOOR DETAIL





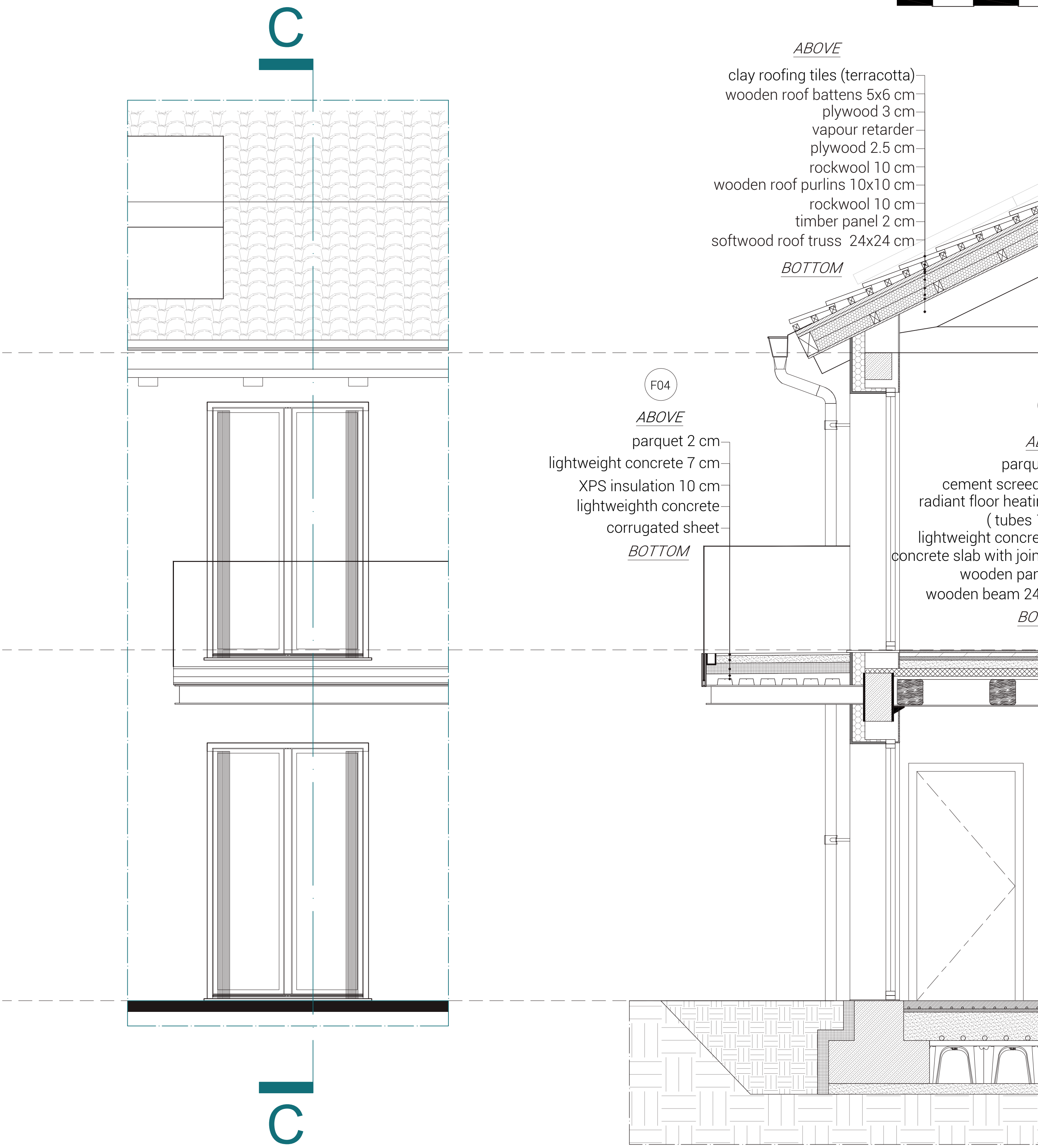
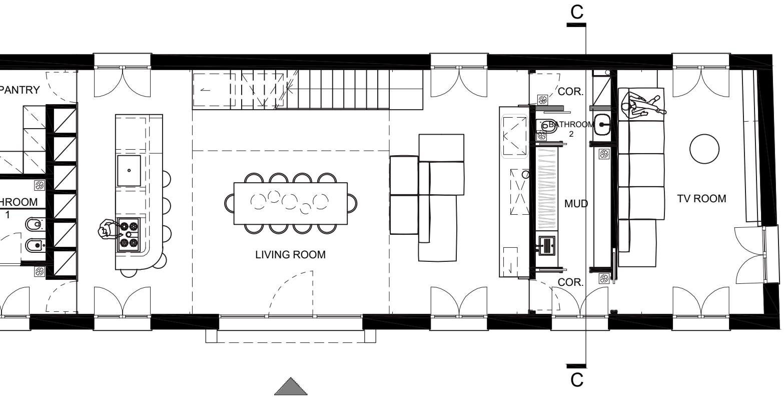


Figure 77.

BAU SOUTH FACADE DETAIL (C-C SECTION)

Figure 73. BAU
GROUND FLOOR PLAN
SCALE: 1/200



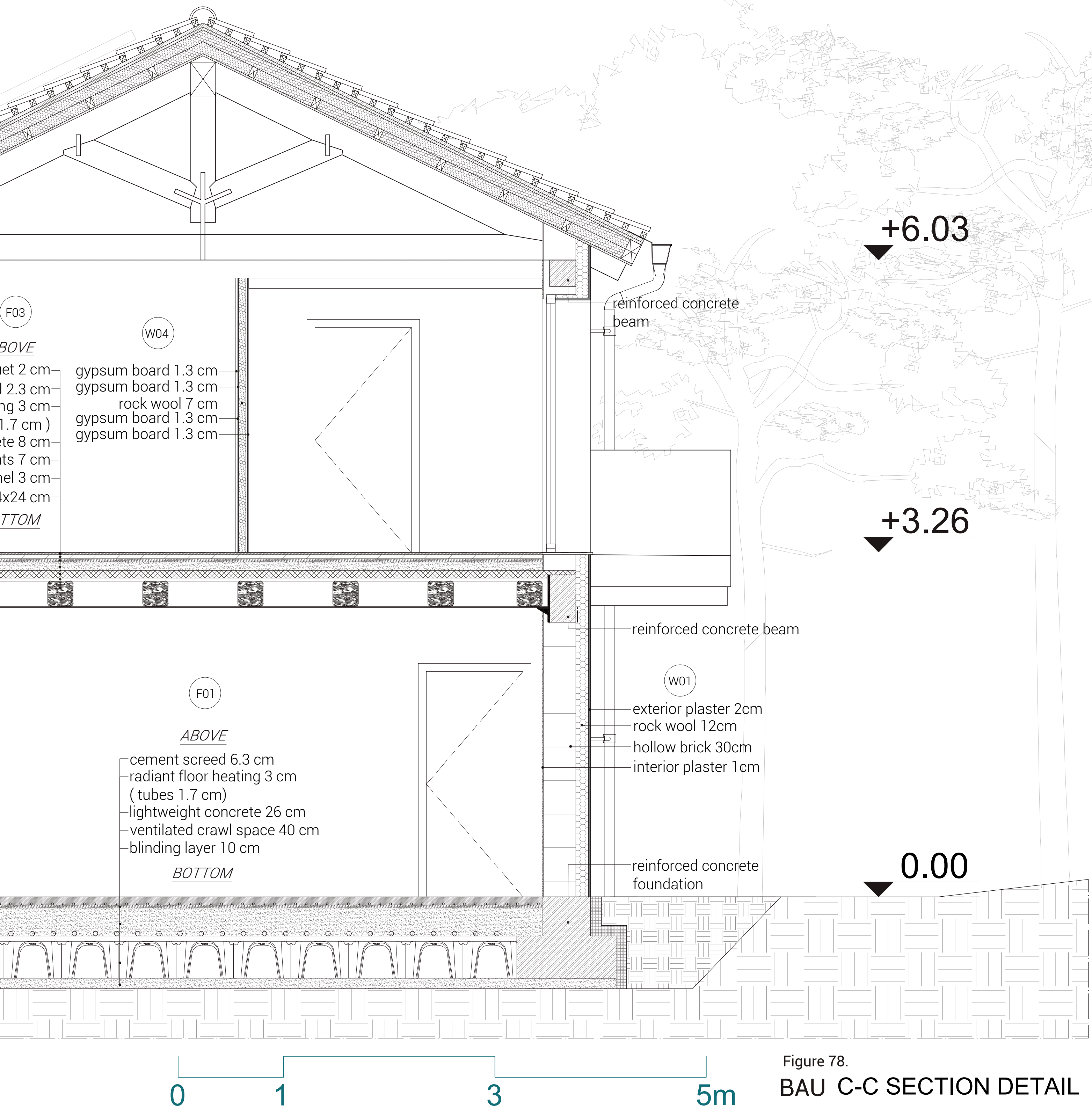


Figure 78.
BAU C-C SECTION DETAIL

4.2.1 LCA ANALYSIS OF BAU SCENARIO

4.2.1.1 LCIA OF CONSTRUCTION MATERIALS FOR MODULES A1-A3

All materials involved in a building construction have association in Oneclick LCA, according to the most appropriate database source possible.

For each resource, the GWP for A1-A3 module described in the 'resource information section', which includes the data background, description of the resource, its technical characteristics and environmental characteristics. Among these profiles they include analogs with default material thickness or mass per square meter density kg/m² density kg/m³ and other parameters.

These characteristics are used in order to get correct quantities of each building material imported so as to come up with the GWP for each imported building material through the Revit model for the A1-A3 modules. It is important to note that in the GWP values given in the resource information of A1-A3 modules, the localization factor is often not included. To obtain the correct GWP value of a material in the "details" section of the general results have been dissected.

The tables below are not directly provided by the Oneclick LCA tool but they are manually prepared based on the results of each building material's GWP calculation details, which can be reviewed in the "details" section of the general results in the Oneclick LCA tool. All the materials' quantity as modeled in Revit program was automatically calculated by Oneclick LCA thanks to BIM integration. Values such as density, mass or weight of each material is available to be reviewed in the "information" section of each mapping material chosen in Oneclick LCA. These values are manually inserted into the tables below.

FOUNDATION

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Blinding layer ready-mix concrete C25/30	177,30	0,10	17,73	2387,04	42322,22	0,0852	3605,43
Reinforced concrete beam 900x400mm			34,13	2406,1	82120,19	0,107	8786,86
Reinforced concrete beam 500x400mm			5,16	2406,1	12415,48	0,107	1328,46
						TOTAL:	**13720,75**

MAIN BUILDING STRUCTURE

	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Reinforced concrete column 250x500mm	12,80	2406,10	30798,08	0,107	3295,39
Reinforced concrete beam 250x400mm	6,27	2406,10	15086,25	0,107	1614,23
Reinforced concrete beam 250x250mm	3,52	2406,10	8469,47	0,107	906,23
				TOTAL:	**5815,86**

GROUND FLOOR LAYERS (F01)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Cement screed	137,60	0,063	8,67	1300,00	11269,44	0,16	1803,11
Lightweight concrete %0 recycled binders	137,60	0,26	35,78	220,00	7870,72	1,0022	7888,04
Outdoor Lightweight concrete (F00) %0 recycled binder	27,48	0,05	1,37	220,00	302,28	1,0022	302,95
						TOTAL:	9691,15

GROUND FLOOR LAYERS (F02)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Cement screed	51,32	0,063	3,23	1300,00	4203,11	0,16	672,50
Lightweight concrete %0 recycled binders	51,32	0,11	5,65	220,00	1241,94	1,0022	1244,68
						TOTAL:	1917,17

FIRST FLOOR STRUCTURE

	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
IPE 300 steel beam	0,20	7850,00	1601,40	3,25	5204,55
IPE 220 steel beam	0,04	7850,00	282,60	3,25	918,45
IPE 100 steel beam	0,03	7850,00	235,5	3,25	765,85
	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Softwood beam 240x240 mm	8,88	440,00	3907,20	62,94	558,91
				TOTAL:	7447,76

FIRST FLOOR LAYERS (F03)

	m²			mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Parquet floor finish	126,23			9,53	1202,97	2,1259	2557,40
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Cement screed	126,23	0,023	2,90	1300,00	3774,28	0,16	603,88
Lightweight concrete %0 recycled binders	126,23	0,08	10,10	220,00	2221,65	1,0022	2226,54
Lightweight concrete with joists	126,23	0,07	8,84	960,00	8482,66	0,4091	3470,25
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Wooden ceiling	126,23	0,03	3,79	189,00	715,72	23,85	90,32
						TOTAL:	8948,39

TERRACE STRUCTURE

	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
IPE 300 steel beam	0,076	7850,00	596,60	3,25	1938,95
IPE 200 steel beam	0,036	7850,00	282,60	3,25	918,45
IPE 180 steel beam	0,110	7850,00	863,50	3,25	2806,38
HE 200 column	0,034	7850,00	266,90	3,25	867,43
				TOTAL:	6531,20

TERRACE LAYERS (F04)

	m²			mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Parquet floor finish	53,70			9,53	511,76	2,1259	1087,95
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Lightweight concrete %0 recycled binders	53,70	0,07	3,76	220,00	826,98	1,0022	828,80
XPS insulation	53,70	0,10	5,37	31,25	167,81	1,9263	323,26
Lightweight concrete %0 recycled binders	53,70	0,03	1,61	220,00	354,42	1,0022	355,20
	m²			mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Aluminium corrugated sheet	53,70			3,40	182,58	12,85	2346,68
						TOTAL:	4941,89

ROOF STRUCTURE

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Softwood ridge 240x320 mm	1,45	440,00	638,00	62,94	91,26
Softwood truss 240x240 mm	10,53	440,00	4633,20	62,94	662,76
Softwood purlins 100x100 mm	3,87	440,00	1702,80	62,94	243,58
Softwood rafter 180x180 mm	7,52	440,00	3308,80	62,94	473,31
Softwood battens 50x60 mm	4,07	440,00	1790,80	62,94	256,17
				TOTAL:	1727,07

ROOF LAYERS

	m²			mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Clay roofing tile (terracotta)	271,63			35,00	9507,05	0,159	1511,62
Vapour barrier membrane	271,63			1,80	488,93	0,033	16,13
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Rockwool insulation	271,63	0,20	54,33	50,00	2716,30	1,23	3341,05
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Softwood ceiling	271,63	0,02	5,43	440,00	2390,34	23,85	129,57
Plywood	271,63	0,025	6,79	900	6111,68	344,00	2336,02
Plywood	271,63	0,03	8,15	900	7334,01	344,00	2803,22
						TOTAL:	10137,61

EXTERNAL WALL LAYERS (W01)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Cement plaster	294,35	0,01	2,94	1400,00	4120,90	0,47	1936,82
Rockwool insulation	294,35	0,12	35,32	50,00	1766,10	1,23	2172,30
Hollow bricks	294,35	0,30	88,31	503,00	44450,00	0,17	7569,84
Cement plaster	294,35	0,02	5,89	1400,00	8241,80	0,47	3873,65
						TOTAL:	15552,61

INTERNAL WALL LAYERS (W04)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Gypsum plaster	192,26	0,02	3,85	400,00	1538,08	0,275	422,97
Rockwool insulation	192,26	0,07	13,46	50,00	672,91	1,23	827,68
Gypsum board	192,26	0,050	9,61	895,00	8598,21	0,218	1874,41
			linear meter	density kg/lm	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
*Metal framing for gypsum board			354,02	1,10	392,72	2,15	844,35
						TOTAL:	3969,41

*only for internal wall applications, windows/doors are excluded

Figure 79. LCIA tables of BAU construction materials for modules A1-A3, source: author

4.2.1.2 LCIA OF TRANSPORT FOR MODULE A4

BUILDING MATERIAL TYPES	TRANSPORTATION VECHILE TYPES	DISTANCE
All concrete types	Concrete mixer truck	60 km (Piedmont region,Italy)
Steel structures (IPE/HE)	Trailer combination 40ton capacity %100 fill rate	370 km (Oneclick LCA data)
Softwood beams/studs	Trailer combination 40ton capacity %100 fill rate	370 km (Oneclick LCA data)
Softwood panel	Diesel lorry, local distribution	220 km (Oneclick LCA data)
Rockwool insulation	Diesel lorry, local distribution	60km (Oneclick LCA data)
Parquet	Diesel lorry, local distribution	220 km (Oneclick LCA data)
Cement plaster	Diesel lorry, local distribution	110 km (Oneclick LCA data)
Roofing tile (terracotta)	Diesel lorry, local distribution	50 km (Piedmont region,Italy)
Hollow bricks	Diesel lorry, local distribution	60 km (Oneclick LCA data)
Gypsum plaster	Diesel lorry, local distribution	110 km (Oneclick LCA data)
Aluminium corrugated sheets	Diesel lorry, local distribution	220 km (Lombardy region,Italy)
Gypsum board	Delivery truck 6ton capacity %100 fill rate	200 km (Lombardy region,Italy)
Metal framing for gypsum board	Delivery truck 6ton capacity %100 fill rate	200 km (Lombardy region,Italy)
Vapour barrier membrane	Delivery truck 6ton capacity %100 fill rate	200 km (Bergamo,Lombardy region,Italy)
XPS insulation	Freight transport via truck	430 km (Oneclick LCA data)
Plywood	Freight transport via truck	265 km (Sabbioneta,Lombardy region,Italy)

TRANSPORTATION VECHILE TYPES	GWP
Concrete mixer truck	0,13 kgCO2e/tonkm
Trailer combination 40ton capacity %100 fill rate	0,0383 kgCO2e/tonkm
Diesel lorry, local distribution	2,8 kgCO2e/l
Diesel delivery truck 6ton capacity %100 fill rate	0,12 kgCO2e/tonkm
Freight transport via truck	0,12 kgCO2e/tonkm
Large delivery truc k 9ton capacity %100 fill rate	0,0928 kgCO2e/tonkm

Transportation vehicle type for each building material is decided considering their sizes and typologies. Resources for each building material chosen during the mapping on Oneclick LCA, it is possible to see information about the resource such as manufacturer or technical data and in the "Default scenarios and assumptions" section default distance of the material is provided. Based on this information, the distances are set by either searching for the manufacturer's location if known or using the default distances provided by Oneclick LCA, depending on the resource data. GWP of transportation vehicle types are provided by Oneclick LCA and the calculation of the GWP of transportations are done automatically following the calculation of the quantity of each material, quantity of vehicle needed for the material quantity inserted, distance of each material type and each vehicle's GWP.

Material quantity / Vehicle capacity: Vehicle quantity
Distance x GWP x Vechile quantity = Whole Life Carbon of Transportation

4.2.1.3 LCIA OF CONTRUCTION / INSTALLATION FOR MODULE A5

On Oneclick LCA, localization is set as "Italy" and "IEA 2022-Electricity Italy" is set for this building phase which influence the analysis of the module A5.
On the other hand also wastage is calculated in A5 life stage of the building. Wastage percentages for each material are set as:

RESOURCES	WASTAGE PERCENTAGE
All concrete types	4%
Rockwool insulation	8%
Cement plaster	13%
Hollow bricks	5%
Steel structures (IPE,HE)	3.3%
Gypsum board	12.5%
Metal framing for gypsum board	10%
XPS insulation	4%
Parquet	17.9%
Softwood panel	17.9%
Softwood beams/studs	17.9%
Plywood	16.7%
Clay roofing tile (terracotta)	5%
Vapour barrier membrane	10%
Gypsum plaster	8%
Aluminium corrugated sheet	7.5%

These values are automatically suggested by Oneclick LCA approximately. GWP of the wastes are calculated depends on the impact potential of each resource chosen for each material in the beginning of the LCA analysis while mapping from the Oneclick LCA database.

4.2.1.4 LCIA OF REPLACEMENT/REFURBISHMENT FOR MODULES B4-B5

In order to calculate GWP of the substitution of building materials, life span of the materials and the external factors such as exposure to outdoor conditions are considered. According to this filtering, two main building materials are selected for calculation.

Considering the life span of the building is set as 50 years, selected materials' life span had to be shorter than the building's life span in order to be a fit to be calculated.

Thus, external cement plaster as coating material and parquet as the floor finish material of the first floor slab (F03) and terrace slab (F04) of BAU scenario is selected and the life span of the material is set as **30 years for each material as suggested by Oneclick LCA tool.**

As seen in the following table their quantities as kg and total GWP for B4-B5 modules

	Quantity (kg)	GWP kgCO2e
External cement plaster	1202,97	3361,79
Parquet floor finish (F03)	511,76	2718,56
Parquet floor finish (F04)	511,76	1467,45
	TOTAL	**7547,80**

Figure 80. LCIA table of replacement/refurbishment for modules B4-B5 of BAU, source: author

Total GWP of the B4-B5 modules is **7547,80 kgCO2e.**

4.2.1.5 LCIA OF END OF LIFE FOR MODULES C1-C4

Deconstruction and demolition type is set as **mixed frame building (concrete, steel, timber).** GWP of mixed frame building demolition is **5,36 kgCO2e / m2** according to Oneclick LCA database.

All building materials' quantities got adapted to the default quantity of related resource mapped, and the final quantity of each material are multiplied by this value in order to calculate end of life emissions of whole building.

4.2.1.6 LCIA TOTAL EMBODIED CARBON OF BUSINESS AS USUAL (BAU)

	RESULT CATEGORY	GWP kgCO2e
A1-A3	CONSTRUCTION MATERIALS	**90 423,17**
A4	TRANSPORTATION TO THE SITE	**20 194,17**
A5	CONSTRUCTION/ INSTALLATION PROCESS	**8 950,1**
B1	USE PHASE	not included
B3	REPAIR	not included
B4-B5	MATERIAL REPLACEMENT AND REFURBISHMENT	**7 547,8**
B6	ENERGY CONSUMPTION	not included
B7	WATER USE	not included
C1-C4	END OF LIFE	**7 998,17**
D	EXTERNAL IMPACTS (not included in totals)	**-47 135,29**
	TOTAL WHOLE LIFE EMBODIED CARBON kgCO2e:	**135 113,4**

HEATED FLOOR AREA: 347,57 m²
UNHEATED FLOOR AREA :53,7 m²
TOTAL FLOOR AREA : 401,27 m²
LIFE SPAN OF THE BUILDING: 50 years

WHOLE LIFE EMBODIED CARBON OF HEATED FLOOR AREA kgCO2e PER m²: **388,73** kgCO2e/m²
WHOLE LIFE EC (kgC02e) / HEATED FLOOR AREA (m²)
(135 113,4 / 347,57)

WHOLE LIFE EMBODIED CARBON OF HEATED FLOOR AREA m² PER YEAR: **7,77** kgCO2e/m²
WHOLE LIFE EC (kgC02e) / HEATED FLOOR AREA (m²) / BUILDING LIFE SPAN (years)
(388,73 / 50)

WHOLE LIFE EMBODIED CARBON OF TOTAL FLOOR AREA kgCO2e PER m²: **336,76** kgCO2e/m²
WHOLE LIFE EC (kgC02e) / TOTAL FLOOR AREA (m²)
(135 113,4 / 401,27)

WHOLE LIFE EMBODIED CARBON OF TOTAL FLOOR AREA m² PER YEAR: **6,73** kgCO2e/m²
WHOLE LIFE EC (kgC02e) / TOTAL FLOOR AREA (m²) / BUILDING LIFE SPAN (years)
(336,76 / 50)

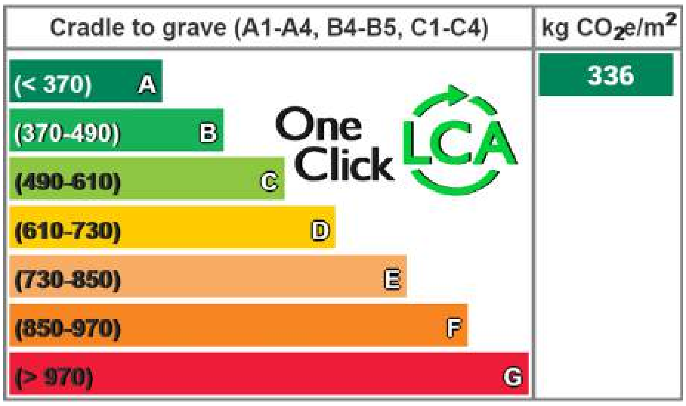


Figure 81. Redrawn carbon heroes benchmark table of BAU, source: Oneclick LCA

Figure 81 is provided by Oneclick LCA but as default it was calculated for 60 years building life span and gross internal floor area which can be inserted in the "building area" section in Oneclick LCA. Thus, to have the correct value, the figure is redrawn calculating EC kgCO2e/m2 applying **50 years of lifespan** and **total gross floor area**. Carbon heroes benchmark is according to " Italy all building types - 2023 Q3-" in Oneclick LCA tool which is possible to modify according to project location or type. Initially "Italy" is set as the project location and "all building types" is automatically set by Oneclick LCA. Other options for Italy were " office excl. MEP- 2023 Q3" and "warehouse excl. MEP-2023 Q3". In this case "all building types" was the most appropriate option as it was set automatically by the tool.

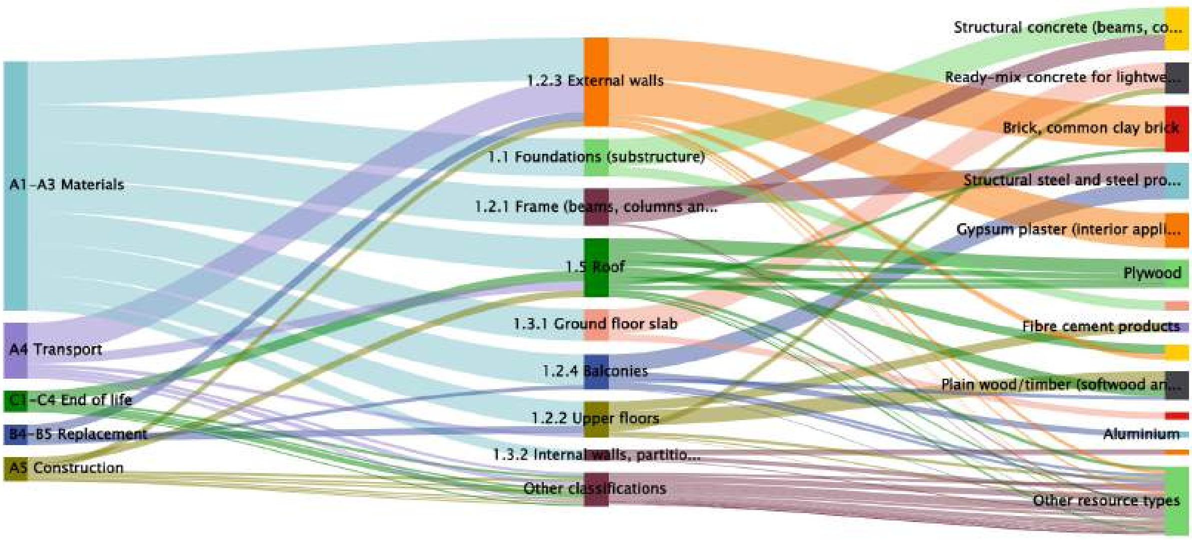


Figure 82. Sankey diagram of GWP of BAU, source: Oneclick LCA

Figure 82 is provided by Oneclick LCA according to the final results of LCA analysis which are presented in the next graphs as "Global Warming kgCO2e-Life Cycle Stages", "Global Warming kgCO2e-Resource Types", Global Warming kgCO2e-Classifications", "Mass kg-Classifications".

GLOBAL WARMING kgCO2 - LIFE CYCLE STAGES

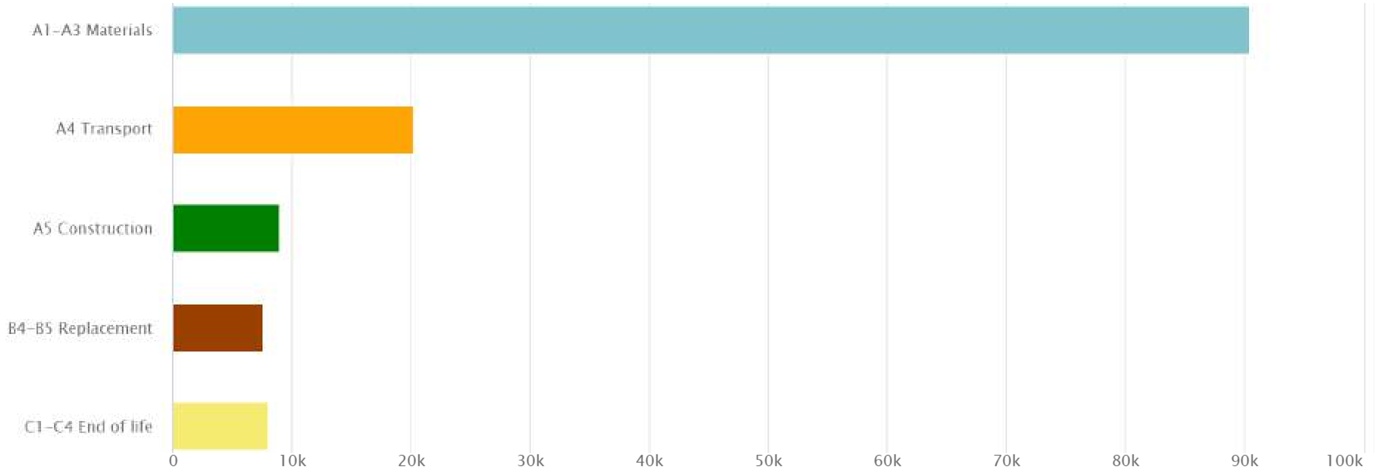


Figure 83. Global Warming kgCO2e Graph of BAU-Life Cycle Stages, source: Oneclick LCA

Item	Value	Unit	Percentage %
A1-A3 Materials	32 988,92	kg CO_2e	55.6 %
A4 Transport	8 077,74	kg CO_2e	13.61 %
A5 Construction	5 611,07	kg CO_2e	9.46 %
B4-B5 Replacement	3 088,71	kg CO_2e	5.21 %
C1-C4 End of life	9 570,60	kg CO_2e	16.13 %

GLOBAL WARMING kgCO2 - RESOURCE TYPES

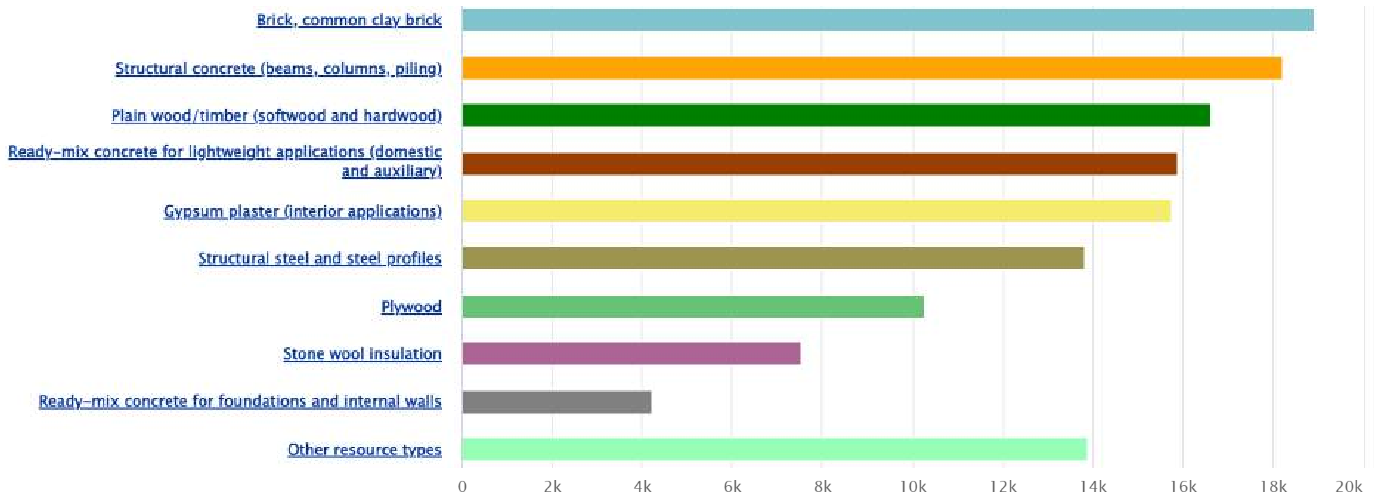


Figure 84. Global Warming kgCO2e Graph of BAU-Resource Types, source: Oneclick LCA

Item	Value	Unit	Percentage %
CLT, glulam and LVL	11 929,23	kg CO_2e	20.1 %
Structural concrete (beams, columns, piling)	11 562,66	kg CO_2e	19.49 %
Plywood	10 266,56	kg CO_2e	17.3 %
Organic insulation	6 486,32	kg CO_2e	10.93 %
Plain wood/timber (softwood and hardwood)	5 785,54	kg CO_2e	9.75 %
Brick, common clay brick	3 015,16	kg CO_2e	5.08 %
Ready-mix concrete for external walls and floors	2 865,46	kg CO_2e	4.83 %
Glass facades and glazing	2 462,85	kg CO_2e	4.15 %
Oriented strand board (OSB)	2 027,48	kg CO_2e	3.42 %
Other resource types	2 985,76	kg CO_2e	4.95 %

GLOBAL WARMING kgCO2 - CLASSIFICATIONS

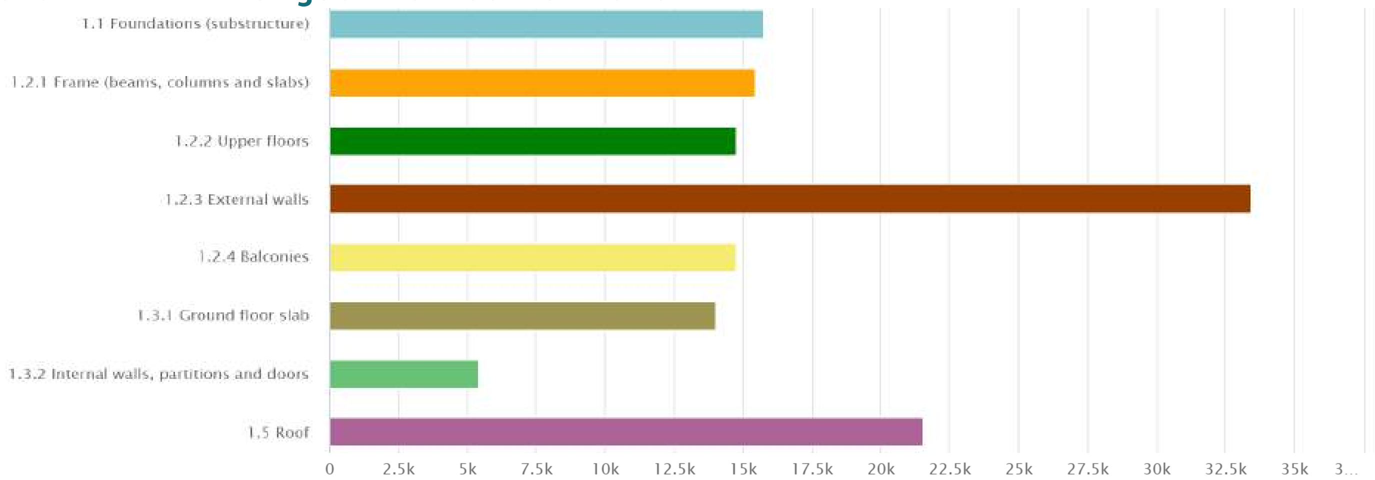


Figure 85. Global Warming kgCO2e Graph of BAU-Resource Types, source: Oneclick LCA

Item	Value	Unit	Percentage %
1. Shell (substructure and superstructure)	4 615,05	kg CO_2e	7.78 %
1.1 Foundations (substructure)	14 428,13	kg CO_2e	24.32 %
1.2 Load bearing structural frame	3 641,77	kg CO_2e	6.14 %
1.2.2 Upper floors	2 915,07	kg CO_2e	4.91 %
1.2.3 External walls	8 225,12	kg CO_2e	13.86 %
1.2.4 Balconies	1 780,07	kg CO_2e	3.0 %
1.3.1 Ground floor slab	2 340,91	kg CO_2e	3.95 %
1.3.2 Internal walls, partitions and doors	624,84	kg CO_2e	1.05 %
1.5 Roof	20 269,52	kg CO_2e	34.16 %
Other classifications	496,54	kg CO_2e	0.84 %

MASS kg - CLASSIFICATIONS

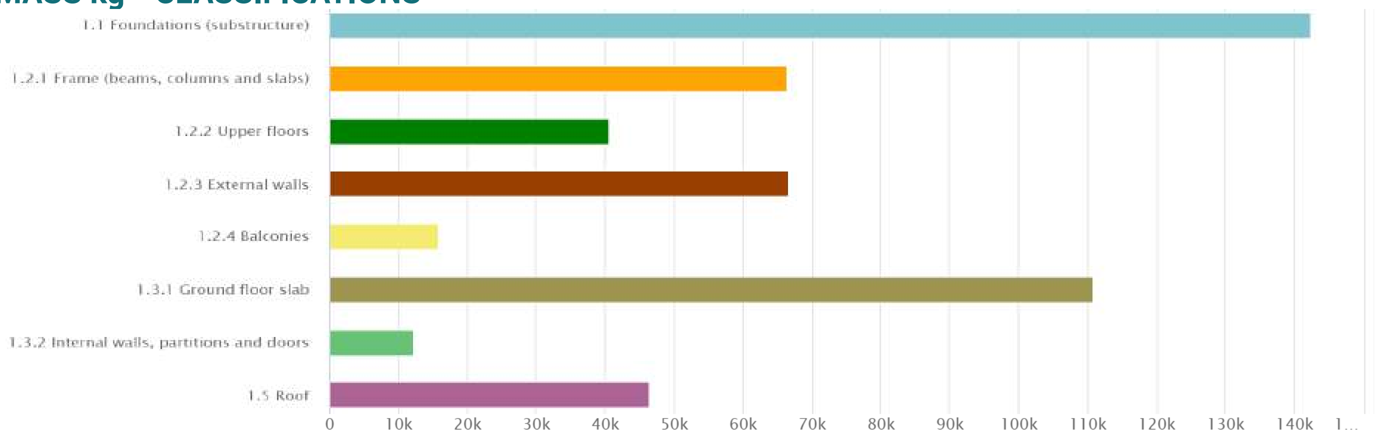


Figure 86. Mass (kg) Graph of BAU-Classifications, source: Oneclick LCA

Item	Value	Unit	Percentage %
1. Shell (substructure and superstructure)	13 239,19	Kg	4.63 %
1.1 Foundations (substructure)	142 571,17	Kg	49.89 %
1.2 Load bearing structural frame	11 200,20	Kg	3.92 %
1.2.2 Upper floors	10 264,93	Kg	3.59 %
1.2.3 External walls	22 537,86	Kg	7.89 %
1.2.4 Balconies	4 589,30	Kg	1.61 %
1.3.1 Ground floor slab	22 147,24	Kg	7.75 %
1.5 Roof	49 276,01	kg	17.24 %
2.1.4 Wall and ceiling finishes	5 700,29	kg	2.0 %
Other classifications	4 218,84	kg	1.48 %

4.2.1.7 BILL OF QUANTITY OF BUSINESS AS USUAL

	MATERIAL	m²	THICKNESS (m)	m³	WEIGHT (kg)
FOUNDATION	*Blinding layer ready-mix concrete C25/30	177,3	0,1	17,73	42322,22
	*Reinforced concrete beam 900x400mm			34,13	82120,19
	*Reinforced concrete beam 500x400mm			5,16	12415,48
MAIN BUILDING STRUCTURE	*Reinforced concrete column 250x500mm			12,80	30798,08
	*Reinforced concrete beam 250x400mm			6,27	15086,25
	*Reinforced concrete beam 250x250mm			3,52	8469,47
ROOF STRUCTURE	*Softwood ridge 240x320 mm			1,45	638
	*Softwood truss 240x240 mm			10,53	4633
	*Softwood purlins 100x100 mm			3,87	1702,8
	*Softwood rafter 180x180 mm			7,52	3308,8
	*Softwood battens 50x60 mm			4,07	1790,8
ROOF LAYERS	*Clay roofing tile (terracotta)	271,63	0,04	10,86	9507,05
	*Vapour barrier membrane	271,63	0,0015	0,40	488,93
	*Plywood	271,63	0,025	6,79	6111,68
	*Plywood	271,63	0,03	8,15	73734,01
	*Rockwool insulation	271,63	0,20	54,33	2716,30
	*Softwood ceiling	271,63	0,02	5,43	2390,34
GROUND FLOOR SLAB (F01)	*Cement screed	137,60	0,063	8,67	11296,44
	*Lightweight concrete %0 recycled binders	137,60	0,26	35,78	7870,72
	*Outdoor Lightweight concrete (F00) %0 recycled binder	27,48	0,05	1,37	302,28
GROUND FLOOR SLAB (F02)	*Cement screed	51,32	0,063	3,23	4203,11
	*Lightweight concrete %0 recycled binders	51,32	0,11	5,65	1241,94

	MATERIAL	m²	THICKNESS (m)	m³	WEIGHT (kg)
FIRST FLOOR STRUCTURE (F04)	*IPE 300 steel beam			0,20	1601,40
	*IPE 220 steel beam			0,04	282,60
	*IPE 100 steel beam			0,03	325,5
	*Softwood beam 240x240 mm			8,88	3907,2
FIRST FLOOR SLAB (F04)	*Parquet floor finish	126,23	0,02	2,52	1202,92
	*Cement screed	126,23	0,023	2,90	3774,28
	*Lightweight concrete %0 recycled binders	126,23	0,08	10,10	2221,65
	*Lightweight concrete with joists	126,23	0,07	8,84	8482,66
	*Wooden ceiling	126,23	0,03	3,79	715,72
TERRACE STRUCTURE	*IPE 300 steel beam			0,076	596,60
	*IPE 200 steel beam			0,036	282,60
	*IPE 180 steel beam			0,110	863,50
	*HE 200 column			0,034	266,90
TERRACE SLAB	*Parquet floor finish	53,70	0,02	1,07	511,76
	*Lightweight concrete %0 recycled binders	53,70	0,07	3,76	826,98
	*XPS insulation	53,70	0,10	5,37	167,91
	*Lightweight concrete %0 recycled binders	53,70	0,03	1,61	354,42
	*Aluminium corrugated sheet	53,70			182,58
EXTERNAL WALL (W01)	*Cement plaster	294,35	0,01	2,94	4120,90
	*Rockwool insulation	294,35	0,12	35,32	1766,10
	*Hollow bricks	294,35	0,30	88,31	44450
	*Cement plaster	294,35	0,02	5,89	8241,80
INTERNAL WALLS	*Gypsum plaster	192,26	0,02	3,85	1538,08
	*Rockwool insulation	192,26	0,07	13,46	672,91
	*Gypsum board	192,26	0,050	9,61	8598,21
	*Metal framing for gypsum board	354,02 linear meter	0,004		844,35

4.3 DESIGN OPTIMIZATION

1. APPROACH

Design optimization aims to reduce environmental footprint of BAU scenario, while choosing low-carbon materials also aims to create a better space solutions to provide more comfortable and joyful areas. With these aims understanding the local climate conditions and making material choices suitable to local climate, understanding which facades are facing the most windy directions in order to decide the opening's quantity, and taking benefit of natural sunlight as much mas possible but in a controlled way without causing over heated spaces in the building.

2. ELEMENTS

A timber frame construction approach is recommended for the design, with building elements like foundation, external and internal walls, floor slabs, terrace and balconies, ground floor passage under the balconies which is created by the continuity of the main building structure which allows to control natural light to prevent overheating. In order to accomplish this and create linearity on the south facade, balconies are enlarged horizontally where the glazed curtain wall provides larger view on the ground floor without causing overheating thanks to the balconies above blocking the direct summer solar radiation.

3. MATERIALS

With the goal of reducing carbon footprint of the building, low-carbon and natural based materials which are researched in the previous chapter have been proposed for the design optimization. Considering also the local resources of the project area, using glulam as the main building structure and timber frames for the walls, hemp,linen,cotton as insulation material, OSB panels as wall and flooring substance, considering the richness of natural stone of Italy sand stone flooring as ground floor finishing, cork panel as general facade cladding, and to stress entrance treated wood cladding on the two sides of the entrance, a curtain glazed wall on the ground floor using insulating argon gas glass which is available to reach from a producer in Bergamo/Italy called saint-gobain, and using concrete only in the foundation for loan transmittance, and for the lightweight concrete applications for the ground floor slabs choosing lightweight concrete with %75 GGBS content are the main materials for the design optimization.

CONCEPT:

Optimizing business-as-usual scenario and ensuring its sustainable development is the main stone of carrying out the LCA approach of this thesis. This approach increases with green building roadmap focusing on sustainability, resource use, and impacts to environment. Implementing these principles helps in conservation of resources and prevention of wastage to make sure that the project is optimized for environmental impact reduction so as for enhancing sustainability.

Preserving the main building area and the functional unit quantities of internal distribution has been the base to have an ''optimized'' project which can be confronted to each other. While doing this, enhancing the potentials of the building to profit the most the natural light, to prevent heat loss from the windows/openings from the most windy facades a strategical decision of the positions and quantity of them, correct system details to support these goals, enlarging the view spectrum of the building but while doing this giving option to control how much view and light wanted, using the main structure itself to create additional passages which contributes to have privacy and a ''in between'' space through outdoor/indoor passage have been the main concept strategies of the optimization of the project.

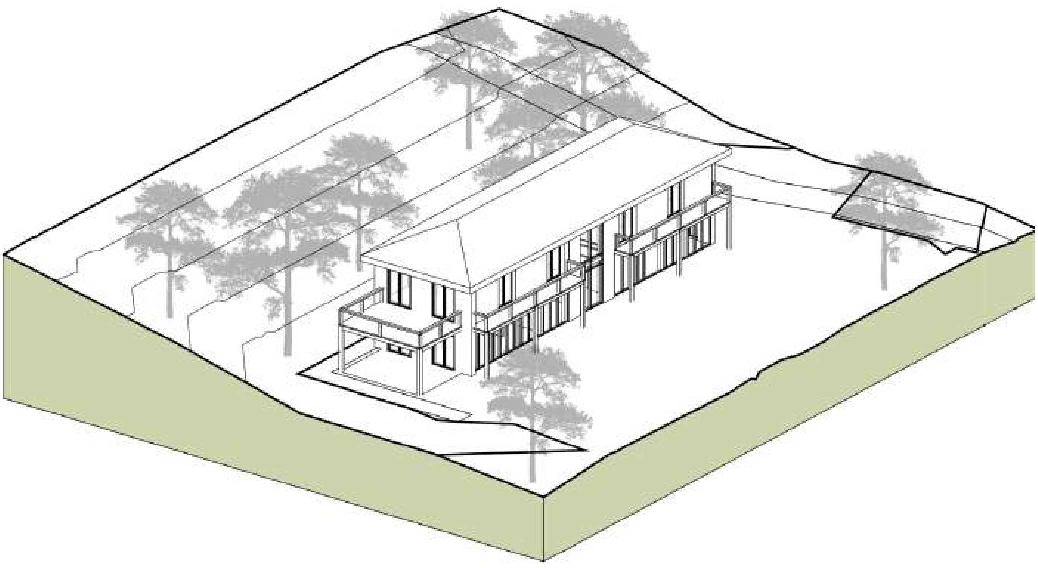


Figure 87. Design optimization general 3D view, source: author

4.3.1 CLIMATE CONDITIONS

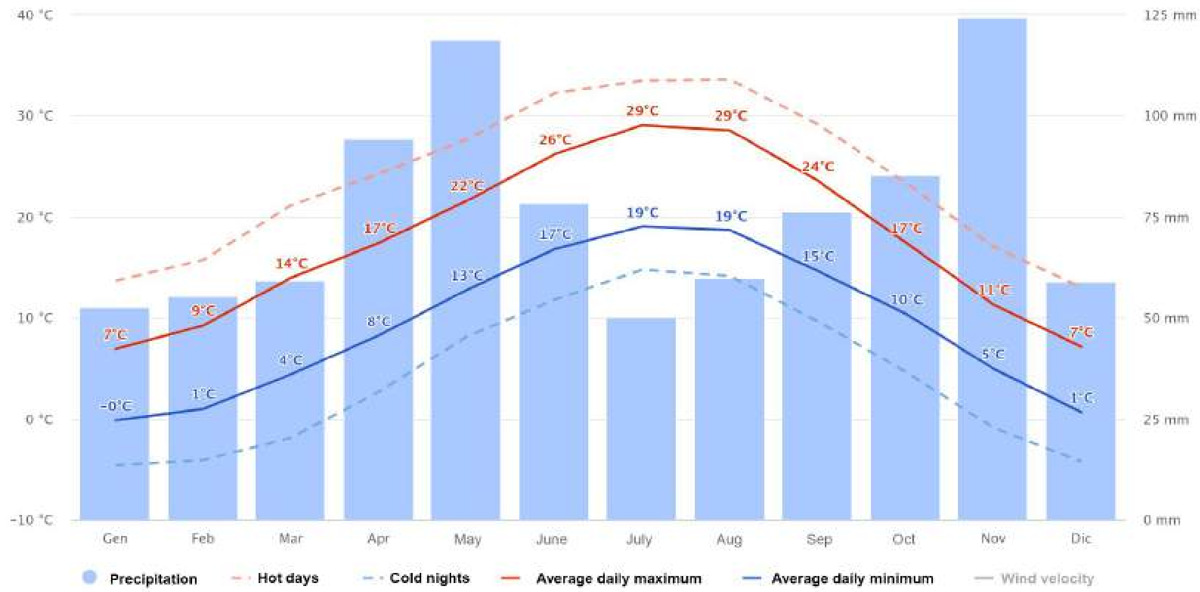


Figure 88. Average temperatures and precipitation, source: meteoblue official website

According to the graph above for designing a residential project in Turin, a good insulation and strategies to avoid heat loss to address the cold winters with temperatures dropping to -0°C, as well as ventilation and shading solutions to mitigate the summer heat with temperatures reaching up to 29°C, while ensuring adequate drainage systems to handle the high precipitation in November are important aspects to consider.

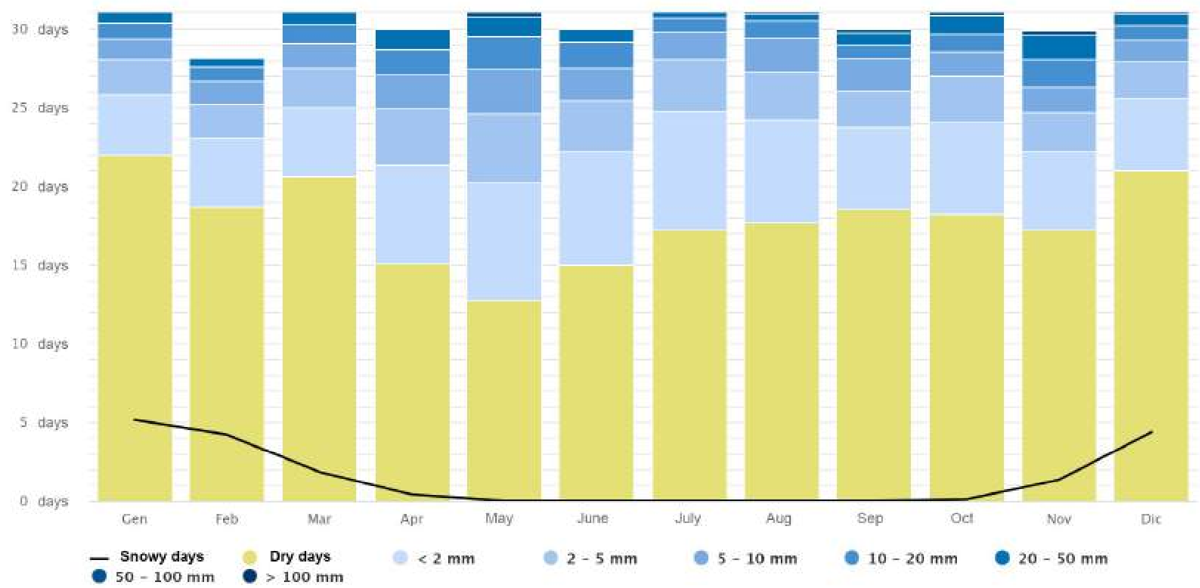


Figure 89. Precipitation, source: meteoblue official website

According to the graph above, approximately 20 to 25 dry days per month, with the remaining days experiencing varying levels of precipitation, peaking in November with more than 10 days of significant rainfall and occasional snowfall, especially in January and December is significant to consider for optimizing BAU scenario. These conditions are useful to ensure well-insulated roof and suitable roof materials.

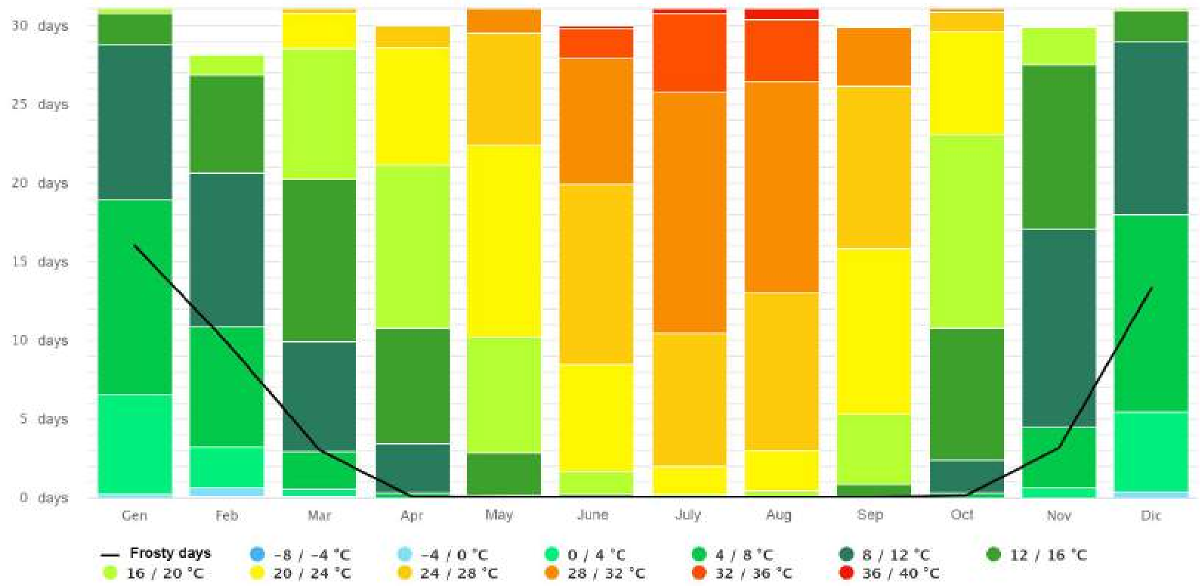


Figure 90. Maximum temperatures, source: meteoblue official website

As seen on the graph above the frosty conditions from December to March, with temperatures dropping to between -8°C and 4°C emphasizes the importance of the coating material. Additionally, coating material also should be resistant for hot summer months from June to August, where temperatures can reach between 28°C and 36°C.

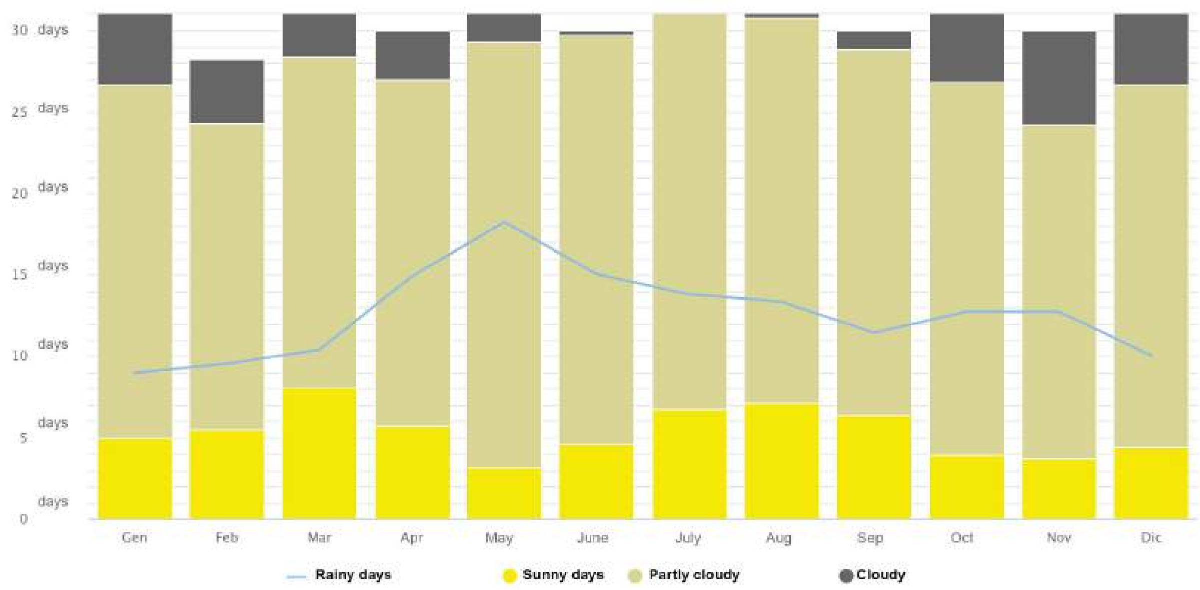


Figure 91. Cloudy, sunny and rainy days, source: meteoblue official website

According to the graph above, predominantly cloudy and partly cloudy days during the winter months (December to February). As sunny days increase from March to May and in the summer months (June to August) abundant sunny days provides indicators to consider to have controlled solar radiation in order to avoid over heating while at the same time allowing for natural light penetration indoors are some of the crucial factors that cannot go unnoticed.

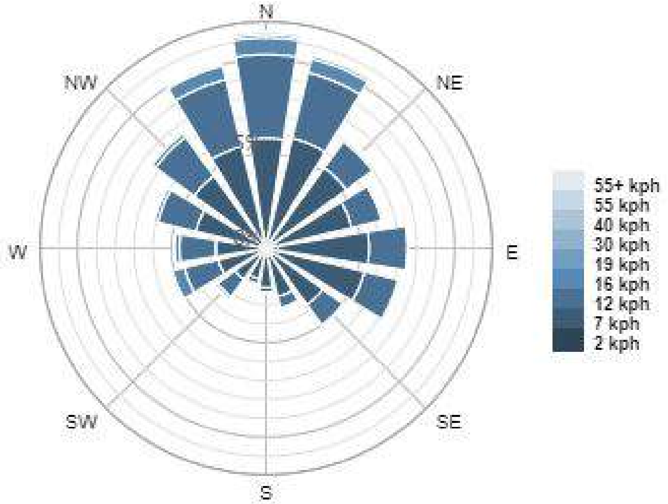


Figure 92. Annual Windrose Diagram generated by author using Autodesk Formit

As can be seen in the annual wind rose the longest bars are towards the North (N), North-Northwest (NNW), and Northwest (NW) directions, indicating these are the prevailing wind directions. Winds from the South (S) and South-Southeast (SSE) directions appear less frequent, as indicated by shorter bars. This gives an idea about which facades should be considered to have less openings and windows.

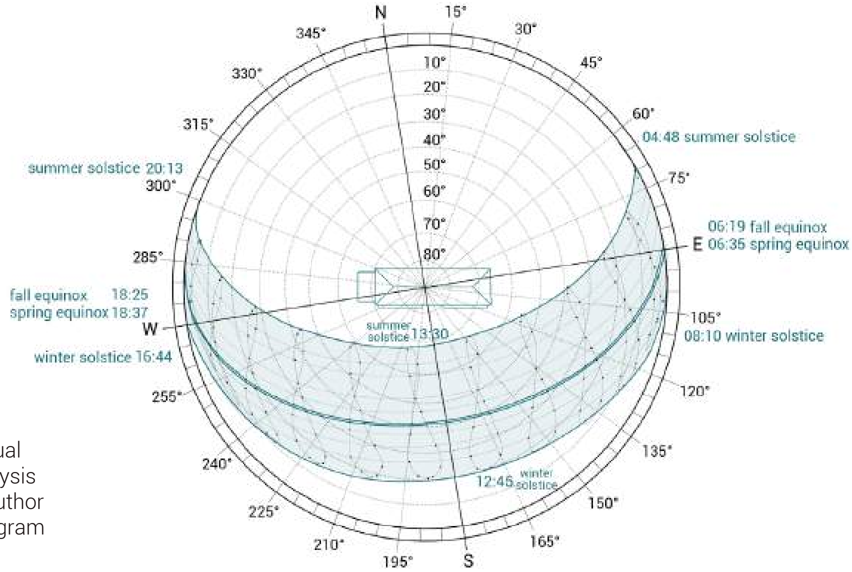


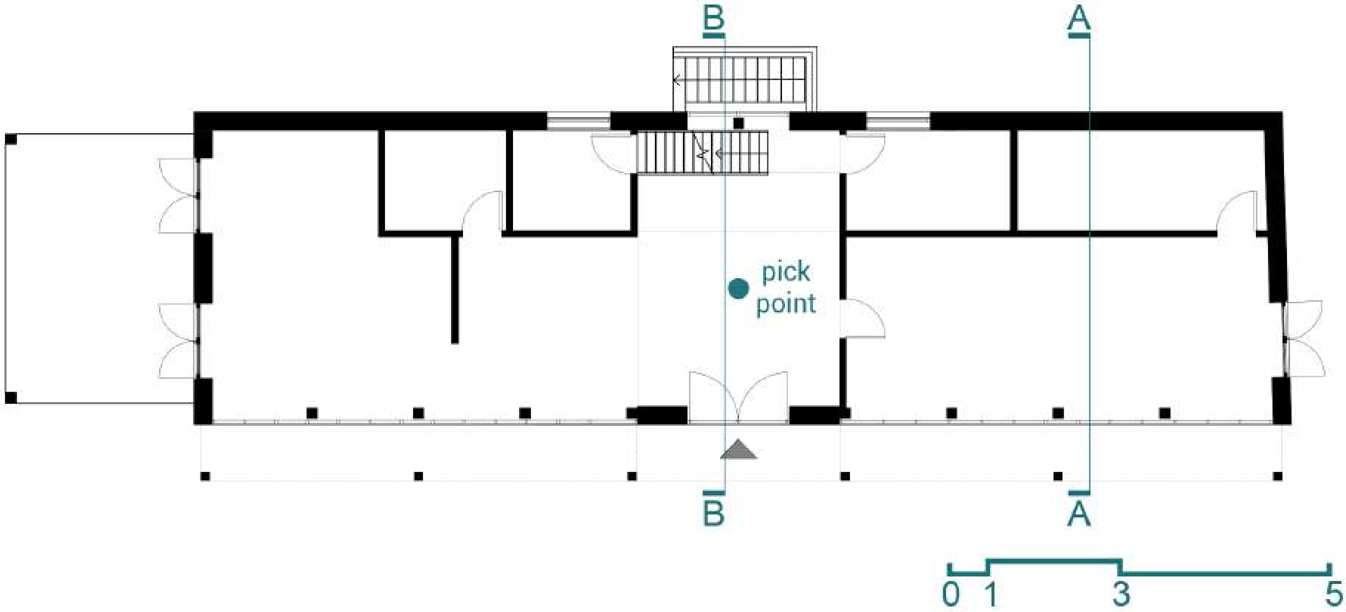
Figure 93. Annual Solar Path Analysis generated by author using Revit program

As can be seen on the annual solar path analysis above, on may 21st, the sun rises at 06:19 am and goes down at 18.37 pm on the direction of the south facade. We can say that the height of the sun path is moderate.

On june 21st, the sun rises at 04.48 am and goes down at 20:13 pm which means the day is quite long. Direction of the sun path is still on the south but we can say that the height of the sun path is quite high so the south facade in june having the daylight but not directly the sunlight inside the building. This allows to increase the view spectrum of the building in the south facade without over heating using the right strategy.

On september 21st the sun rises at 06.19 am and goes down at 18.25 pm. It is very similar to march sun path. So during the autumn and spring the duration of the day and the height gives us idea top profit the natural light during the half of the year

On december 21st the sun rises at 08.10 am and goes down at 16.44 pm which means that the duration of the day is quite short. Considering the height of the sun path is not so high we can say that the south facade is critical to use natural light for the building.



GROUND FLOOR PLAN

Figure 94. Solar analysis pick point on plan, source: author

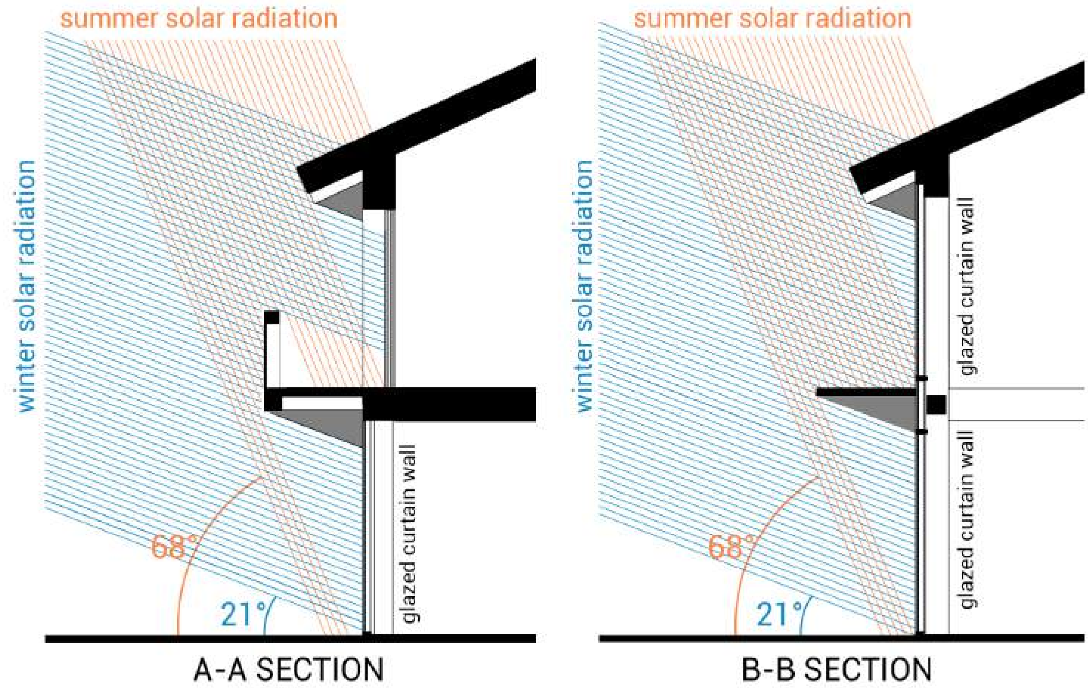


Figure 95. Solar radiation angle scheme generated by author, out of scale.

As can be seen from the altitude lines of the annual solar path analysis (figure 93) the sun is on the highest point in 21st june is at 13:30 with 68 degree angle. On the other hand, when the sun is on the highest point in 21st december is at 12:45 with 21 degree angle which can be seen on the figure 95. The goal is, to make the winter sun enter and to avoid the summer sun penetrate indoors in order to prevent over heating. Thus, the balconies above the glazed curtain wall are supporting this strategy. In the entrance, horizontal sun shade element replaced as can be seen on the B-B section of figure 95 above.

4.3.2 DESIGN STRATEGIES

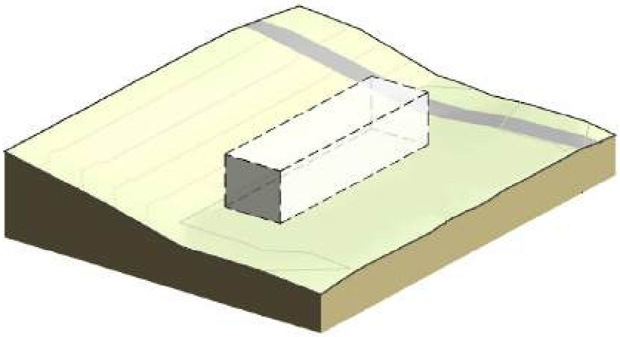


Figure 96. Preserving building settlement diagram
source: author

PRESERVING SETTLEMENT

The settlement of the main building has preserved as BAU scenario. This limit is taken to have a confrontable "optimized" project" and also to have similar bill of quantity of the materials used.

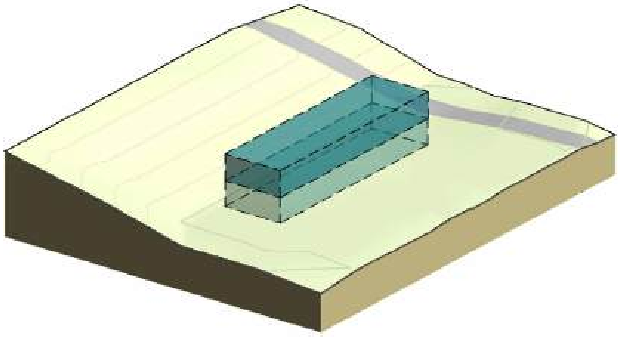


Figure 97. Distribution of private/less private areas diagram,
source: author

PRIVATE / LESS PRIVATE

On the ground floor living room, studio and kitchen placed to provide more privacy on the first floor for the bedrooms. This supports the strategy to create a "in between" space through outdoor and indoor passage.

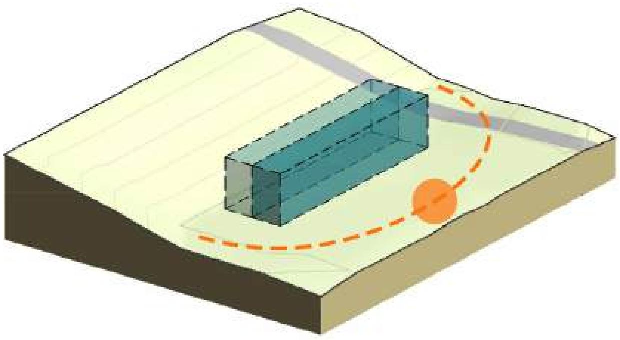


Figure 98. Sun facing facade diagram,
source: author

FACING TO SUN

Indoor areas most used during daily life are located to the south facade to profit the natural sunlight. On the north facade indoor spaces which require less daylight such as service rooms such as bathrooms, pantry,-closest are located. This strategy also support preventing heat loss and having less windows in the north facade which is facing to dominant wind.

ENLARGING THE INDOOR SIGHT

From the central entrance to the main indoor area of the building and probably the most used area during the day is important to provide a large sight. Creating a void on the first floor allows to have this visual connection of the living room with the whole building.

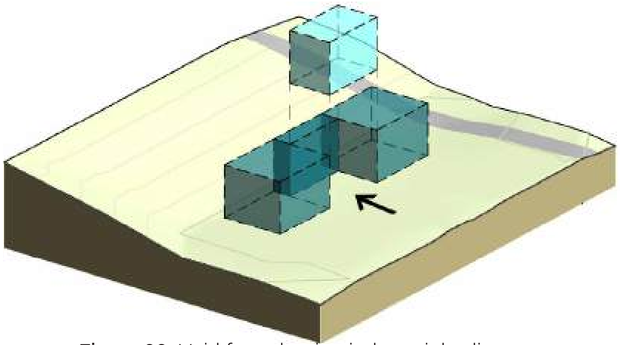


Figure 99. Void for enlarging indoor sight diagram, source: author

FUNCTIONAL UNITS:

- Living room
- Kitchen
- Studio
- Bathroom
- Stairs / circulation
- Bedroom
- Closet/Pantry
- Changing room

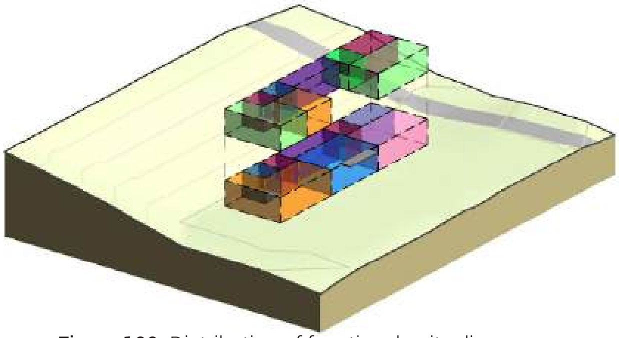


Figure 100. Distribution of functional units diagram, source: author

LINEAR EFFECT OF BALCONIES

Considering the sun path analysis, the south facade is critical to profit the natural sunlight but in a controlled way. Glazed curtain wall supports the connection between the outdoor and indoor spaces but also the privacy and heat controlling must be took into account. Thus, enlarging the balconies which provides linearity on the south facade is also creating a "in between" space under the balconies. This passage helps to control the sunlight according to solar analysis and also supports privacy.

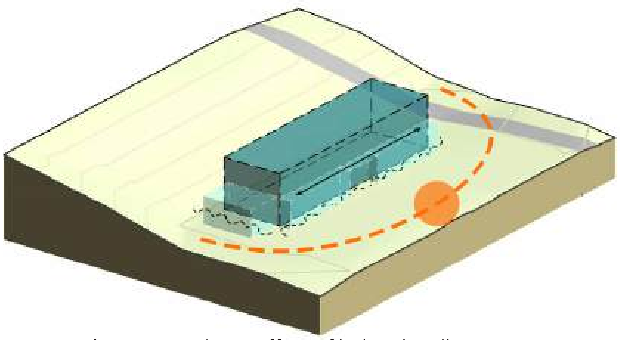


Figure 101. Linear effect of balconies diagram, source: author

4.3.3 OPTIMIZATIONS

MODIFICATIONS IN DESIGN OPTIMIZATION OF BAU SCENARIO:

1.FOUNDATION CONCRETE TYPES
2.MAIN BUILDING STRUCTURE
3.GROUND FLOOR STRUCTURE
4.FIRST FLOOR STRUCTURE
5.TERRACE STRUCTURE
6.ROOF STRUCTURE
7.GROUND FLOOR SLAB ELEMENTS
8.FIRST FLOOR SLAB ELEMENTS
9.TERRACE SLAB ELEMENTS
10.ROOF ELEMENTS
11.TERRACE LENGTH/FORMS
12.INDOOR DISTRIBUTION

Have been change in the design optimization of business-as-usual (BAU) scenario. These modifications are made considering :

•Climate conditions

•Sun path and solar radiation angle and in order to allow solar radiation to enter indoors but in a controlled way to avoid over heating.

•Building structures and building materials are modified according to local resources and materials which have less environmental impact according to CO_2 emissions.

In order to demonstrate better the building parts' modifications part details will be presented by comparison with BAU scenario.

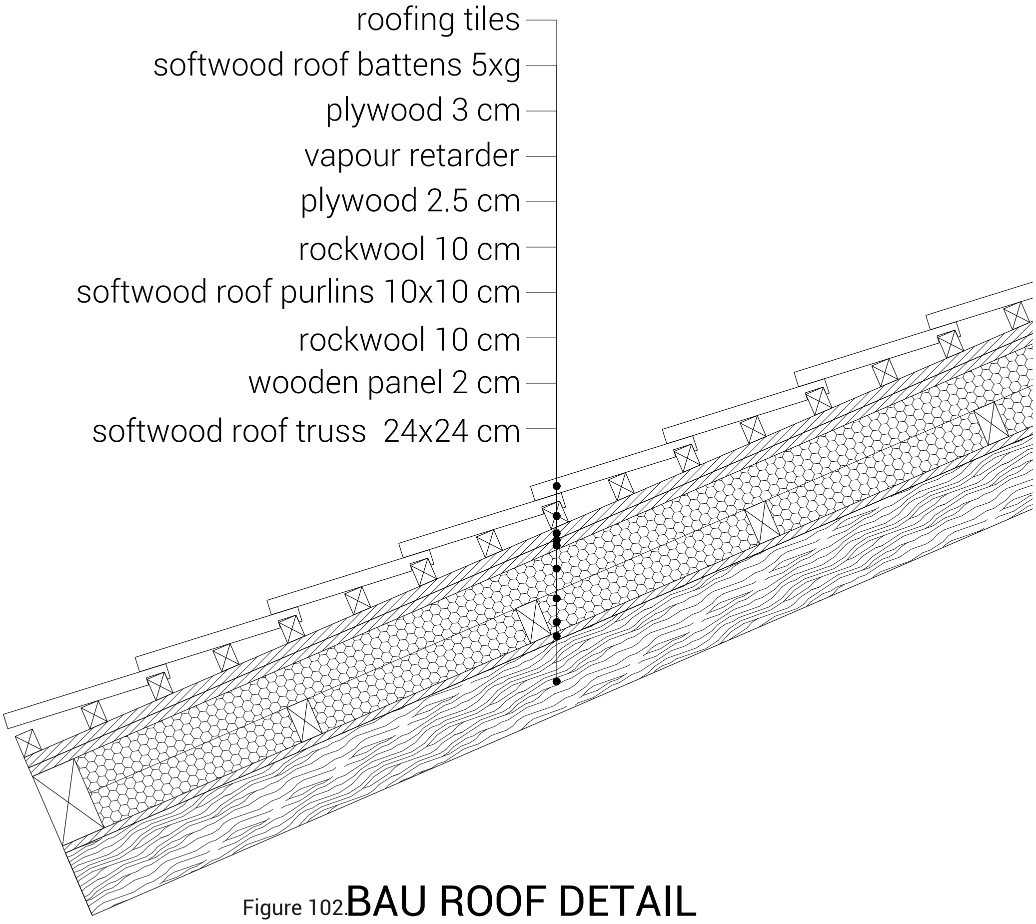


Figure 102.BAU ROOF DETAIL

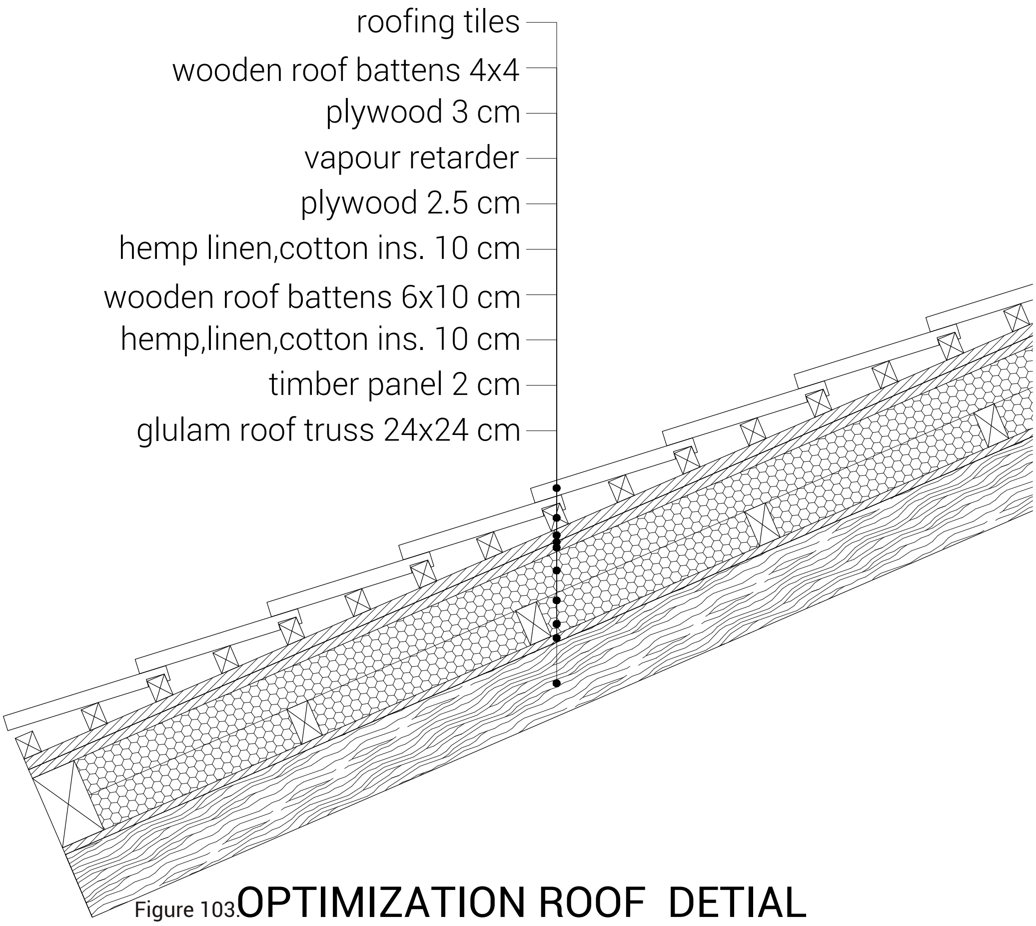


Figure 103.OPTIMIZATION ROOF DETIAL

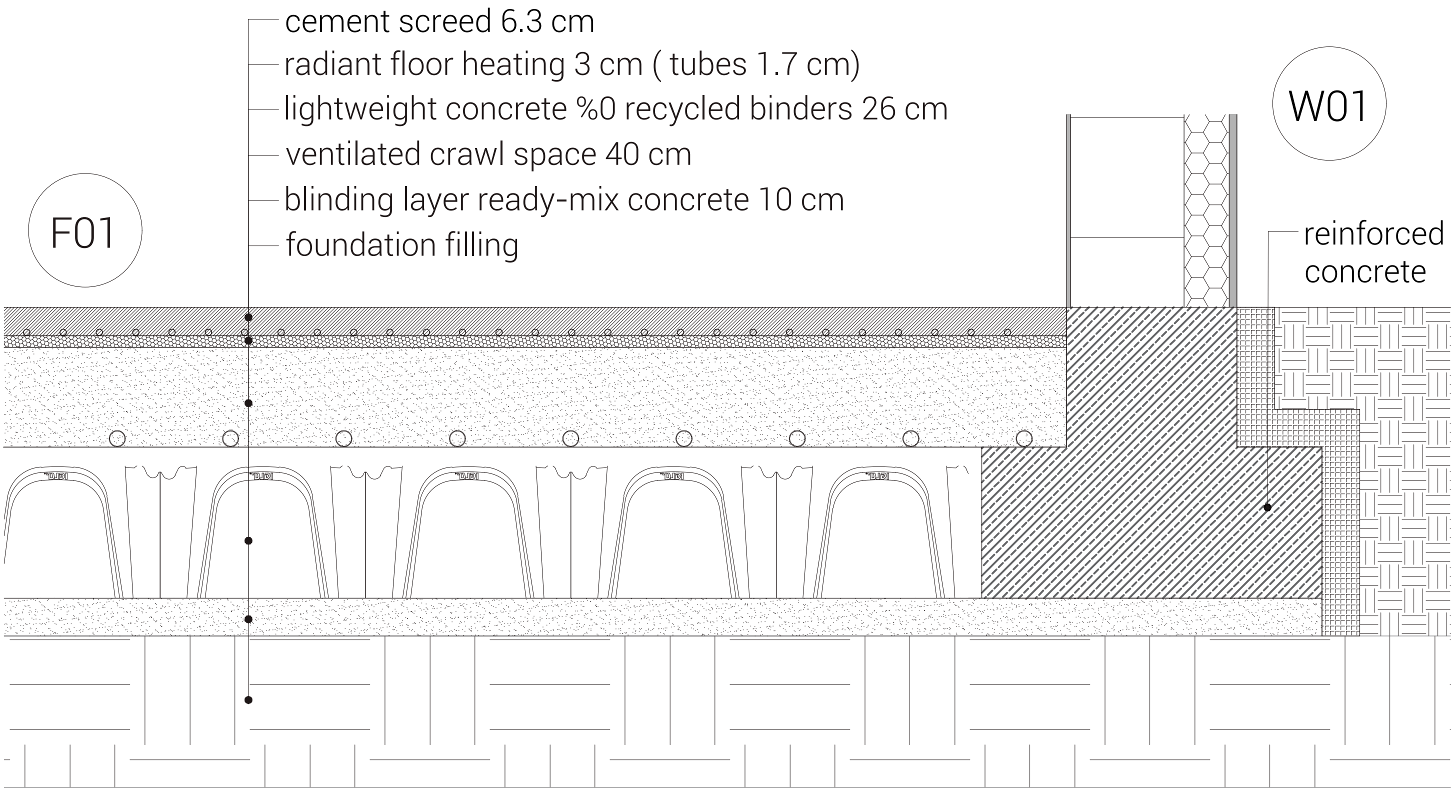


Figure 104. BAU FOUNDATION / GROUND FLOOR SLAB (F01)

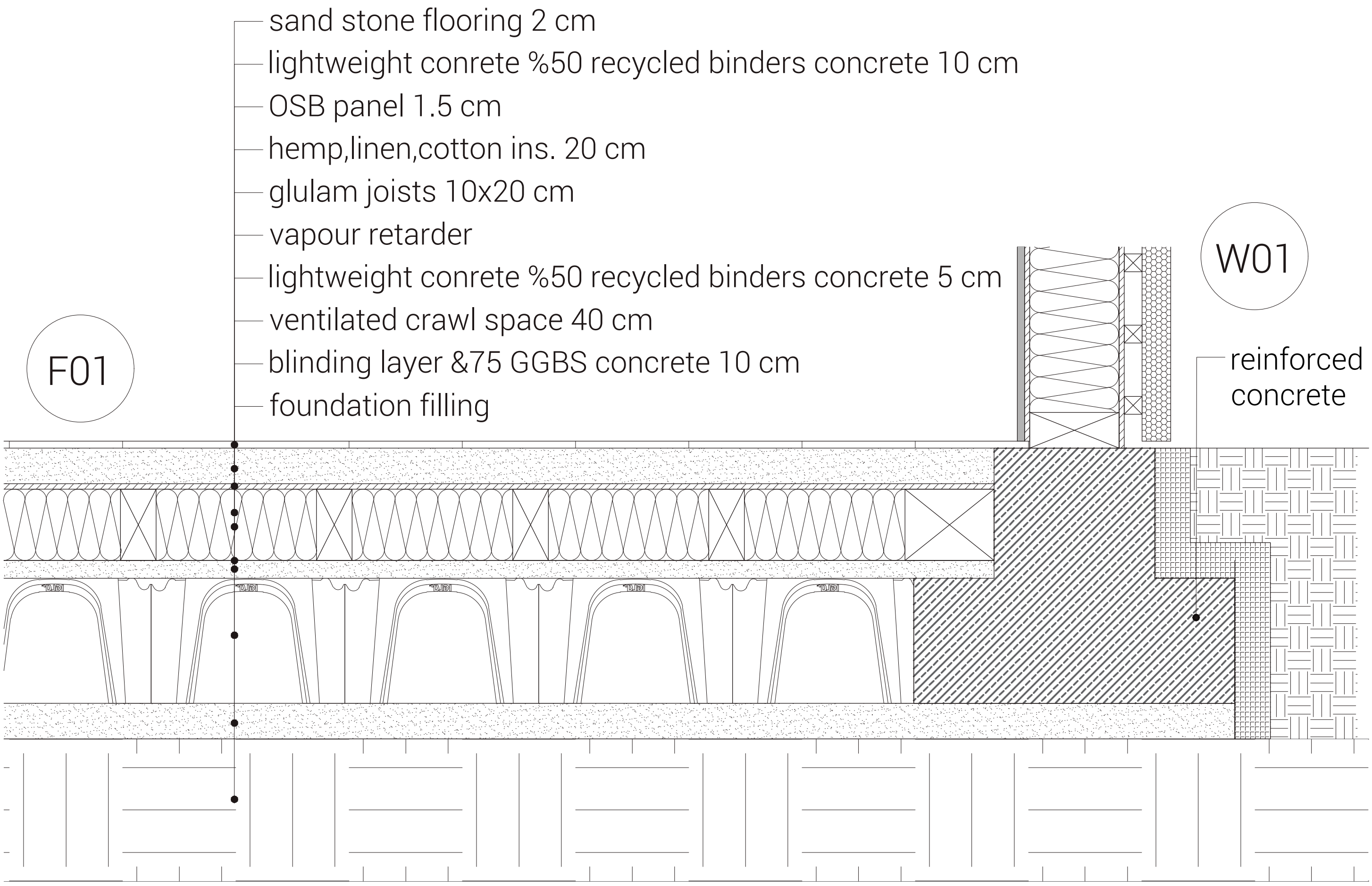


Figure 105.OPTIMIZATION FOUNDATION / GROUND FLOOR SLAB (F01)

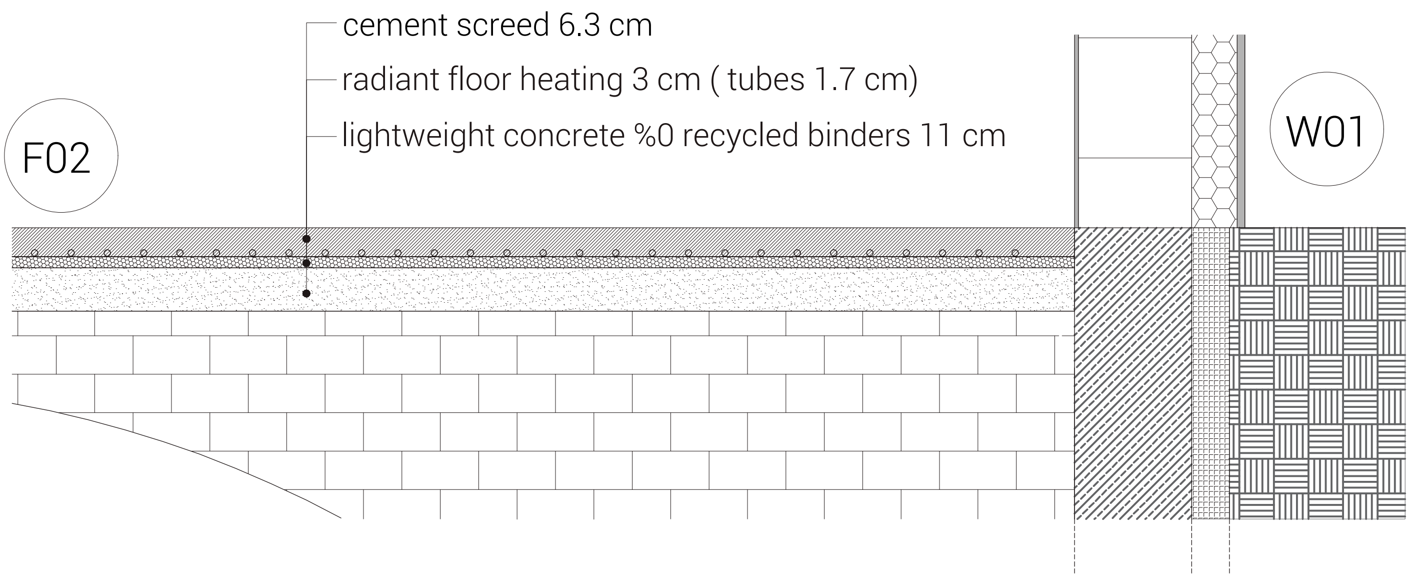


Figure 106. BAU FOUNDATION / GROUND FLOOR SLAB (F02)

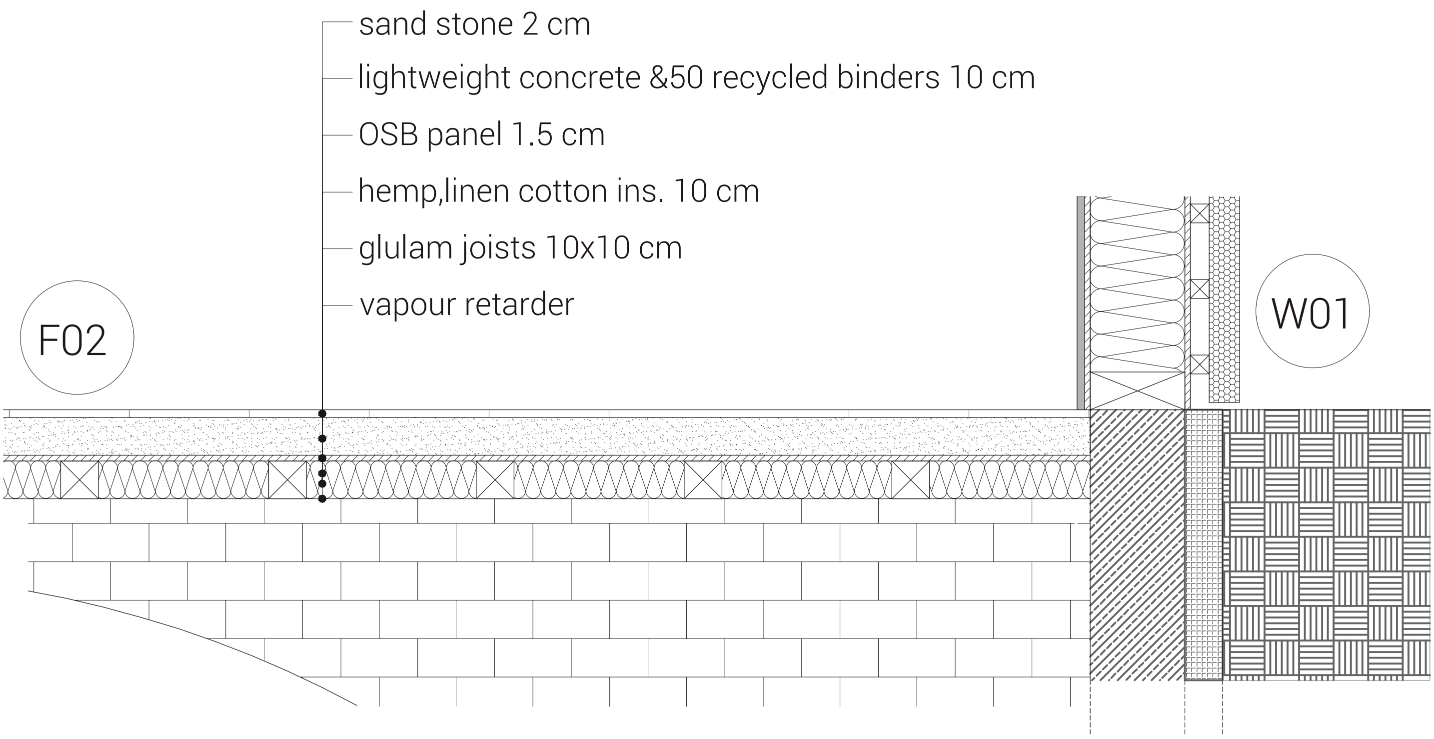


Figure 107. OPTIMIZATION FOUNDATION / GROUND FLOOR SLAB (F02)

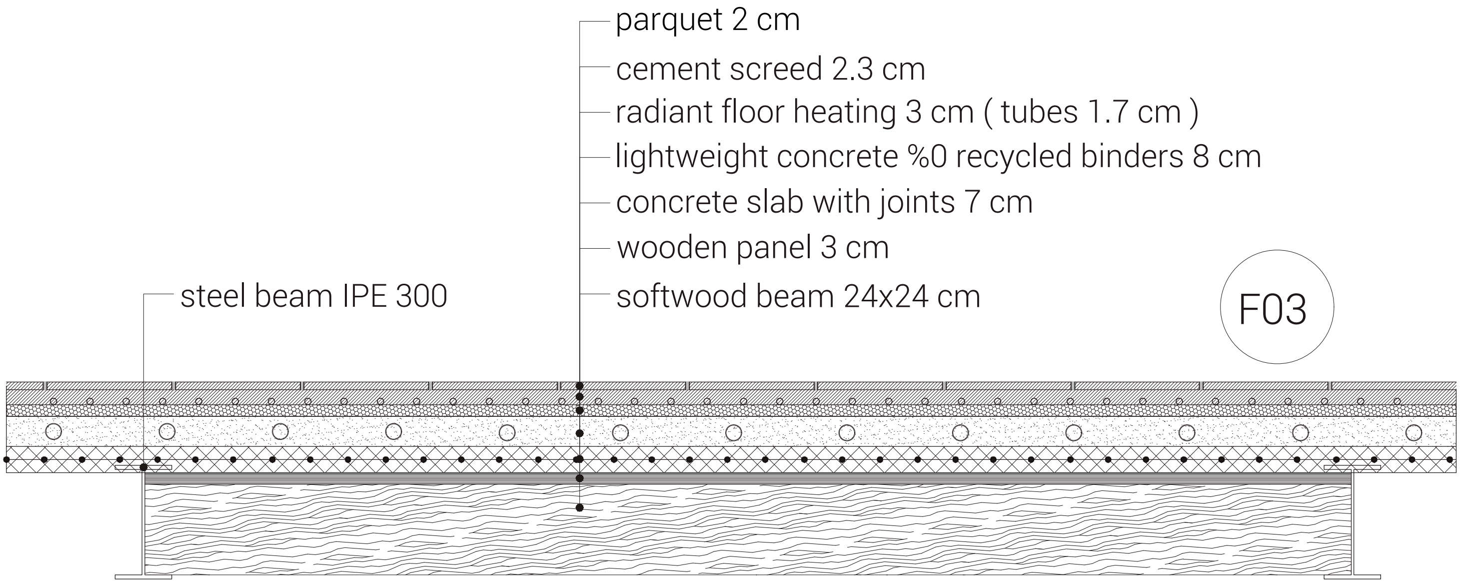


Figure 108. BAU FIRST FLOOR SLAB

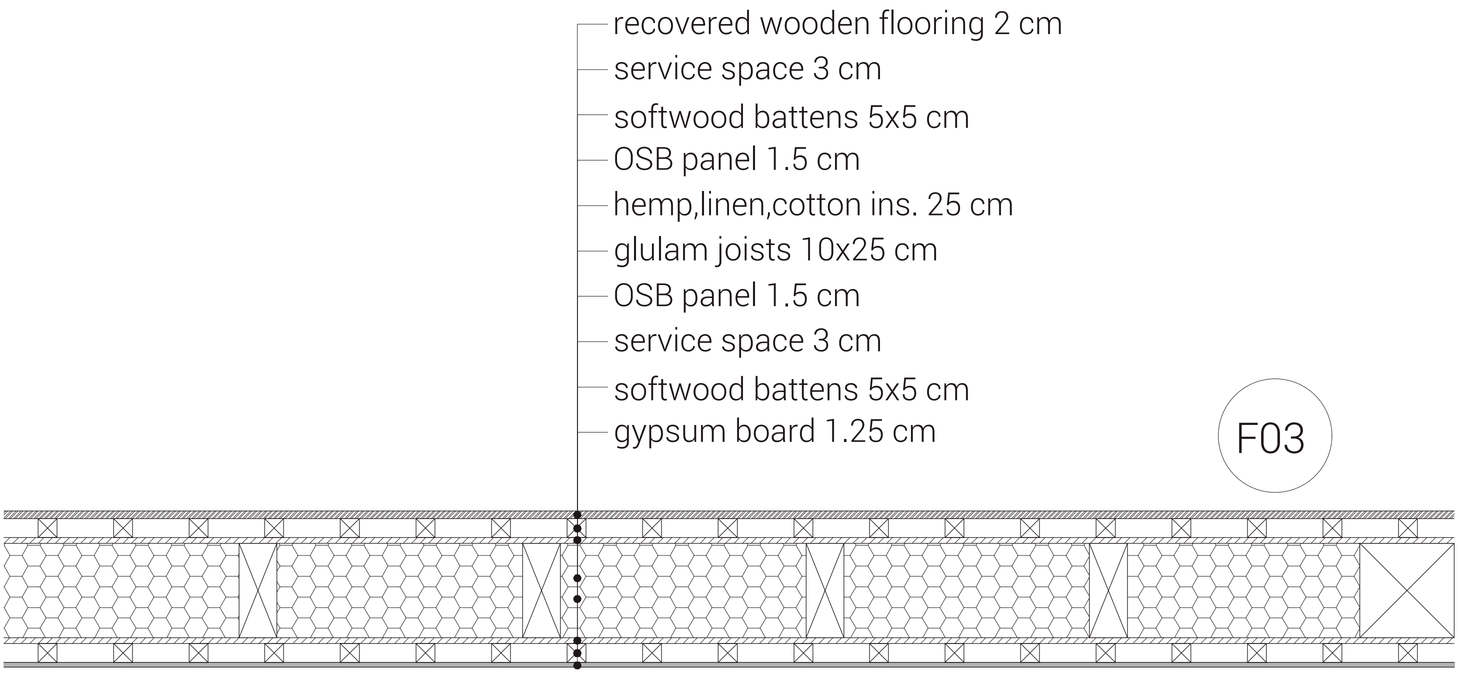


Figure 109. OPTIMIZATION FIRST FLOOR SLAB

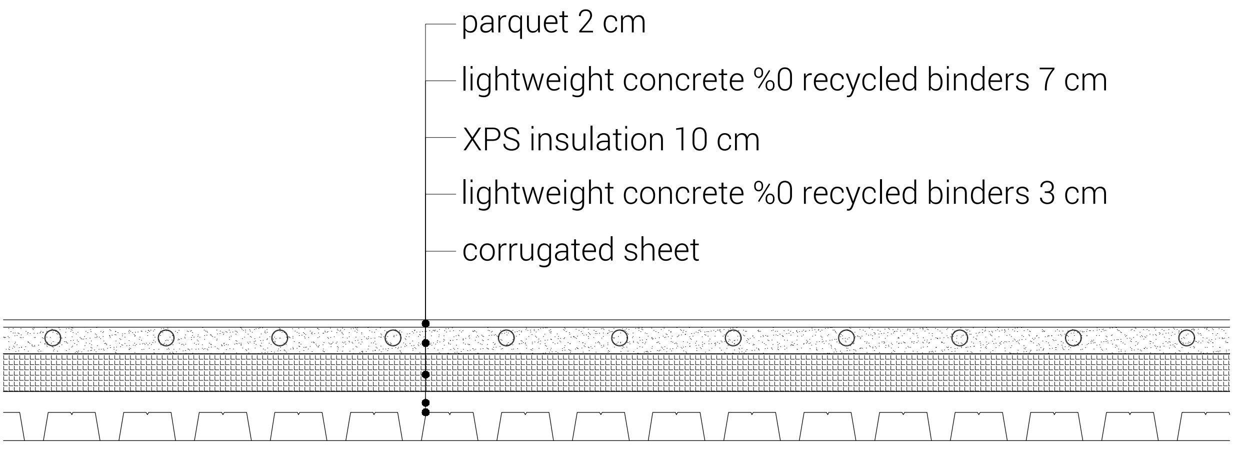


Figure 110. BAU TERRACE SLAB

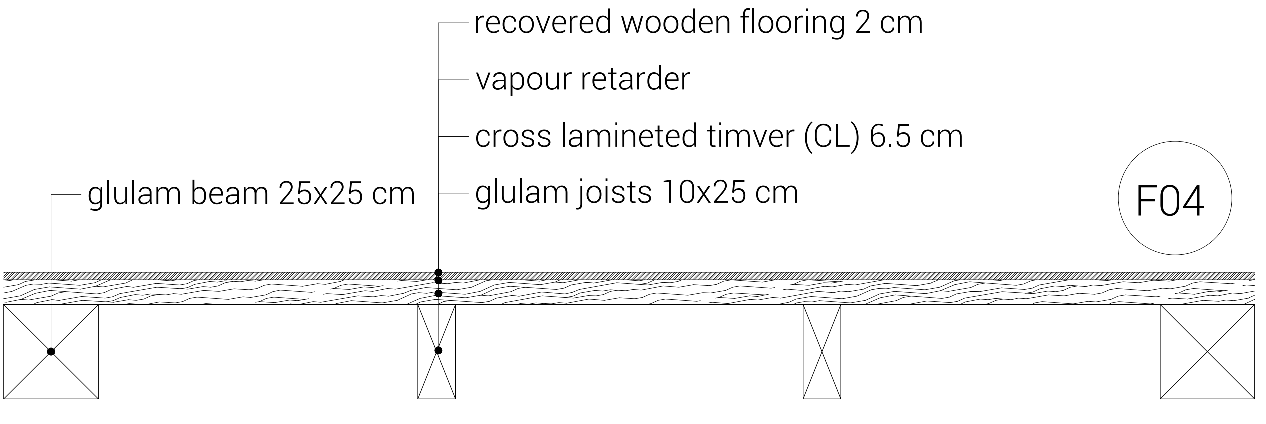


Figure 111. OPTIMIZATION TERRACE SLAB

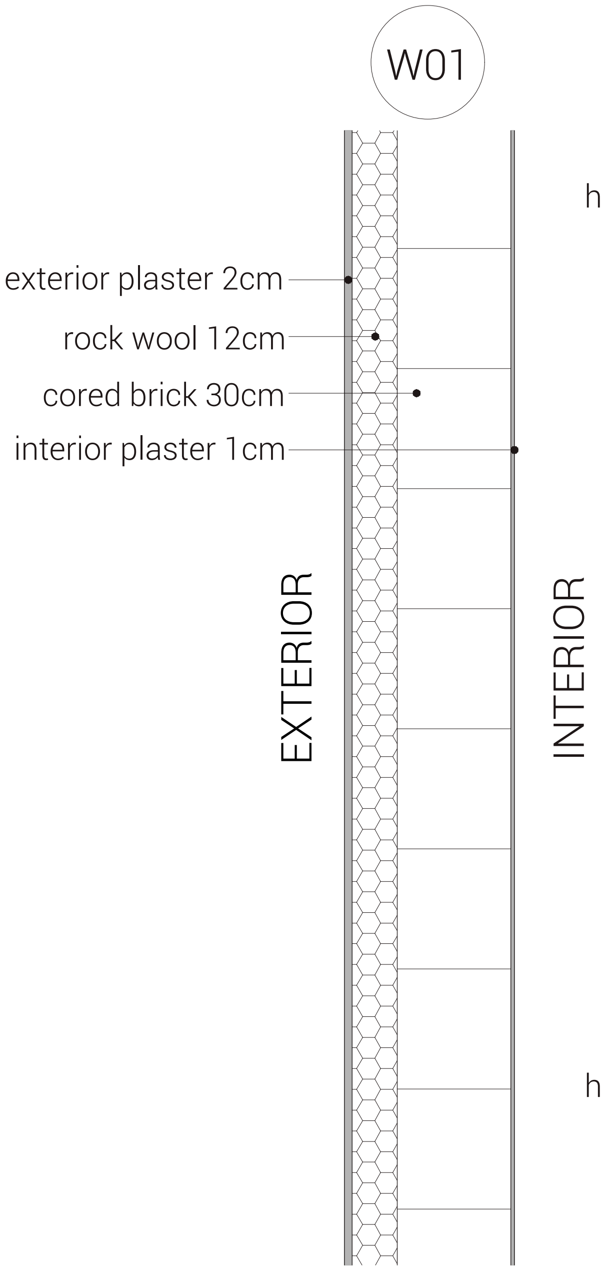


Figure 112. BAU EXTERNALWALL

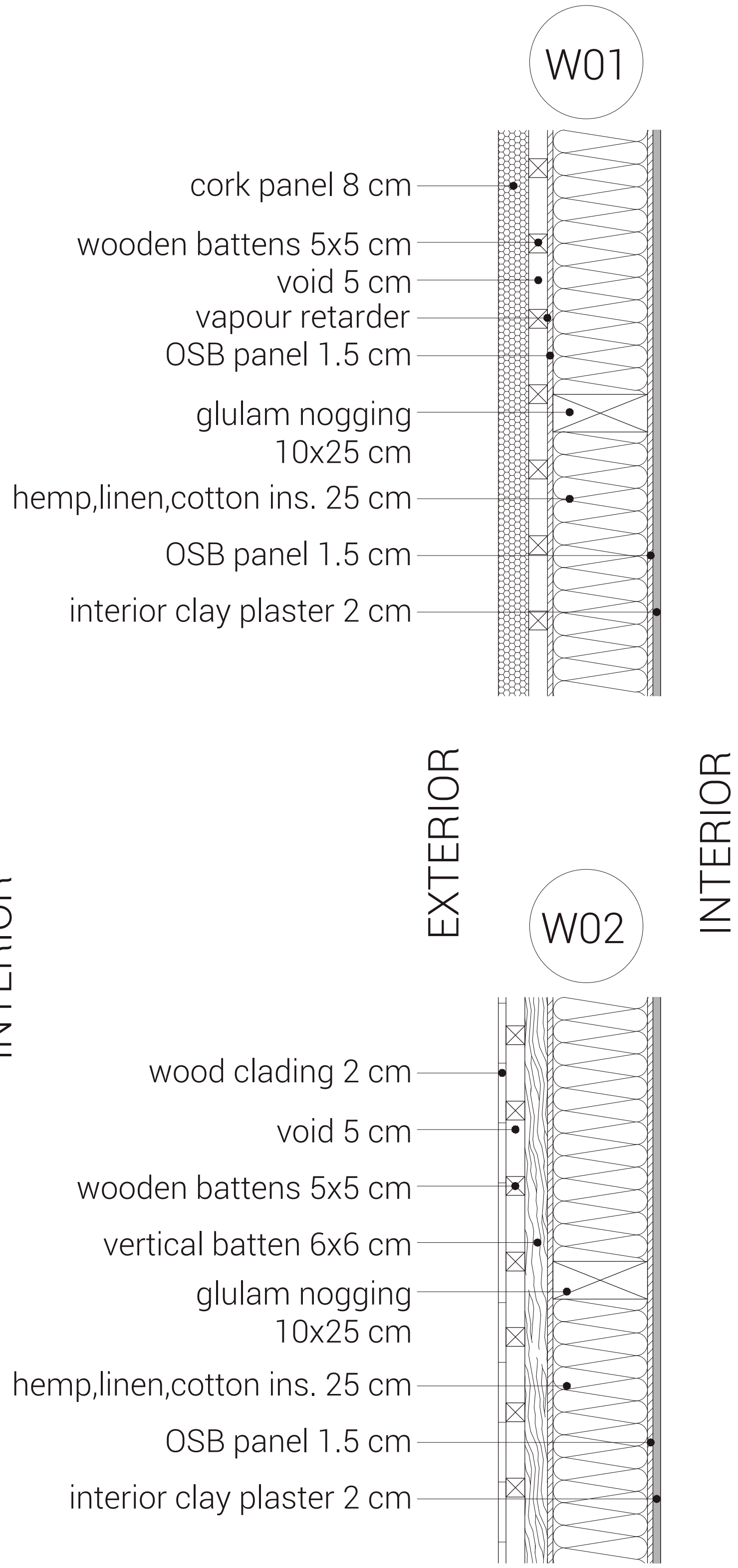


Figure 113. OPTIMIZATION EXTERNAL WALLS

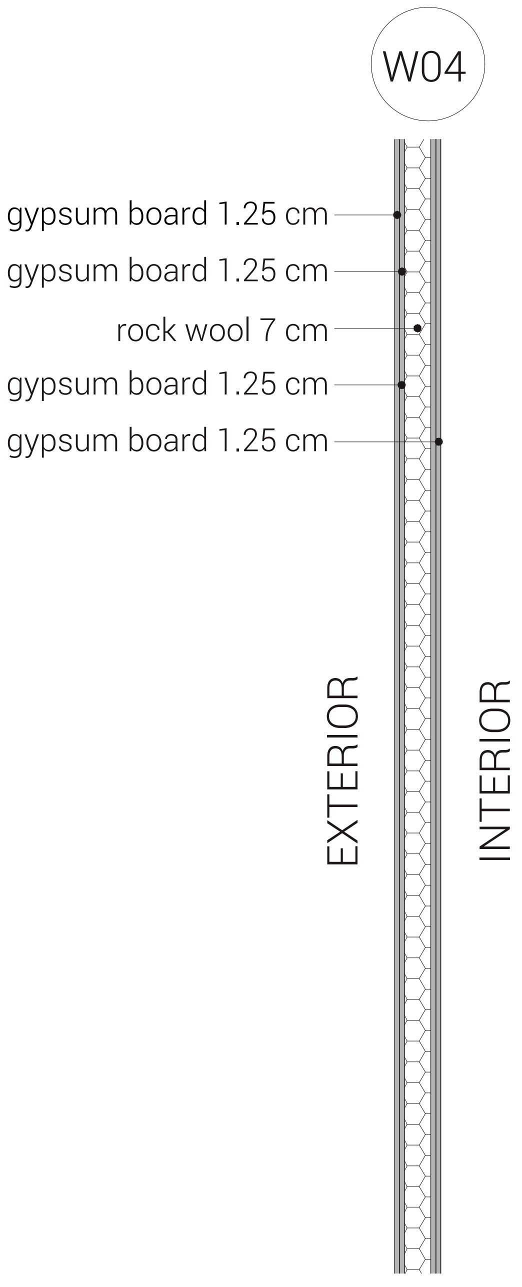


Figure 114. BAU INTERNALWALL

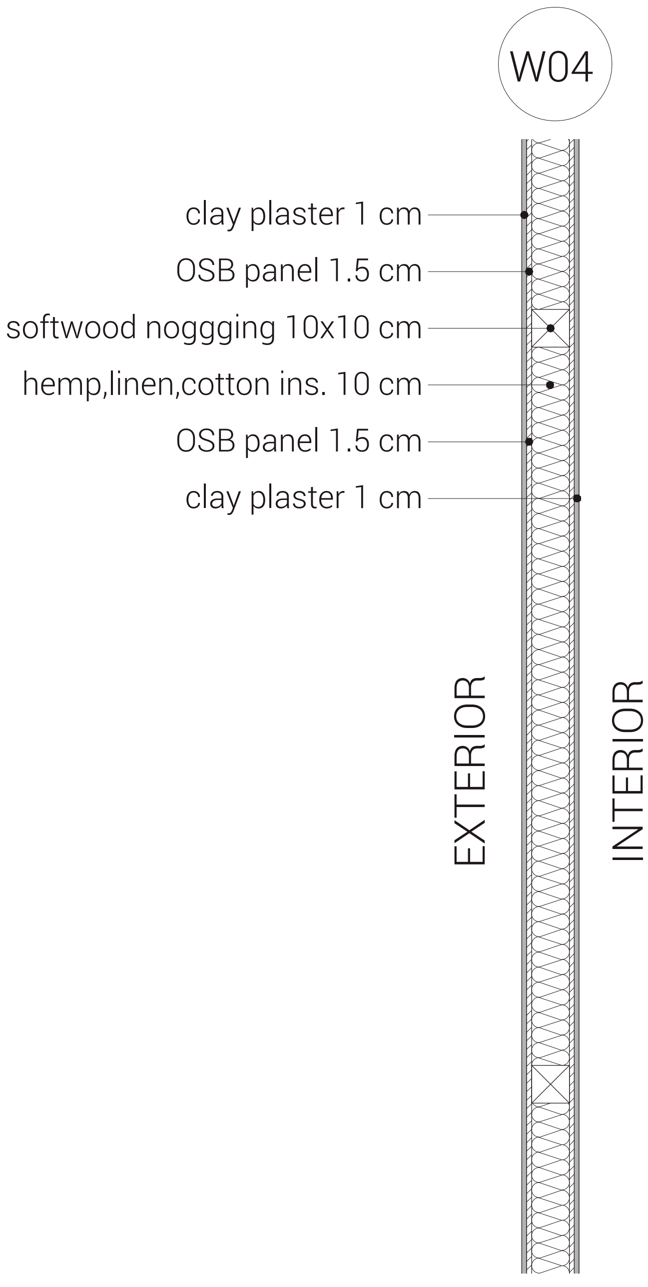
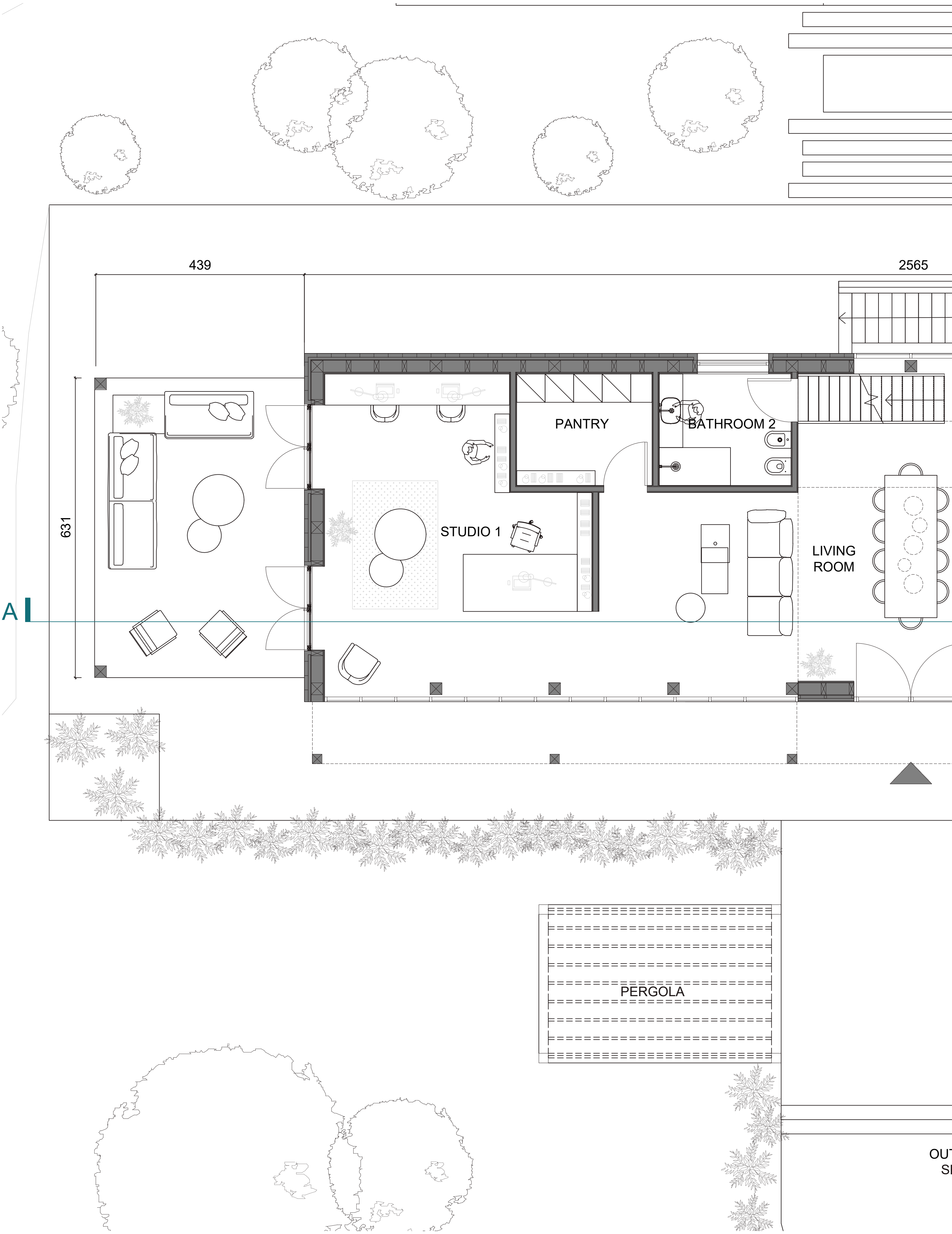


Figure 115. OPTIMIZATION INTERNAL WALL


439
2565
631
A
PANTRY
BATHROOM 2
STUDIO 1
LIVING
ROOM
PERGOLA

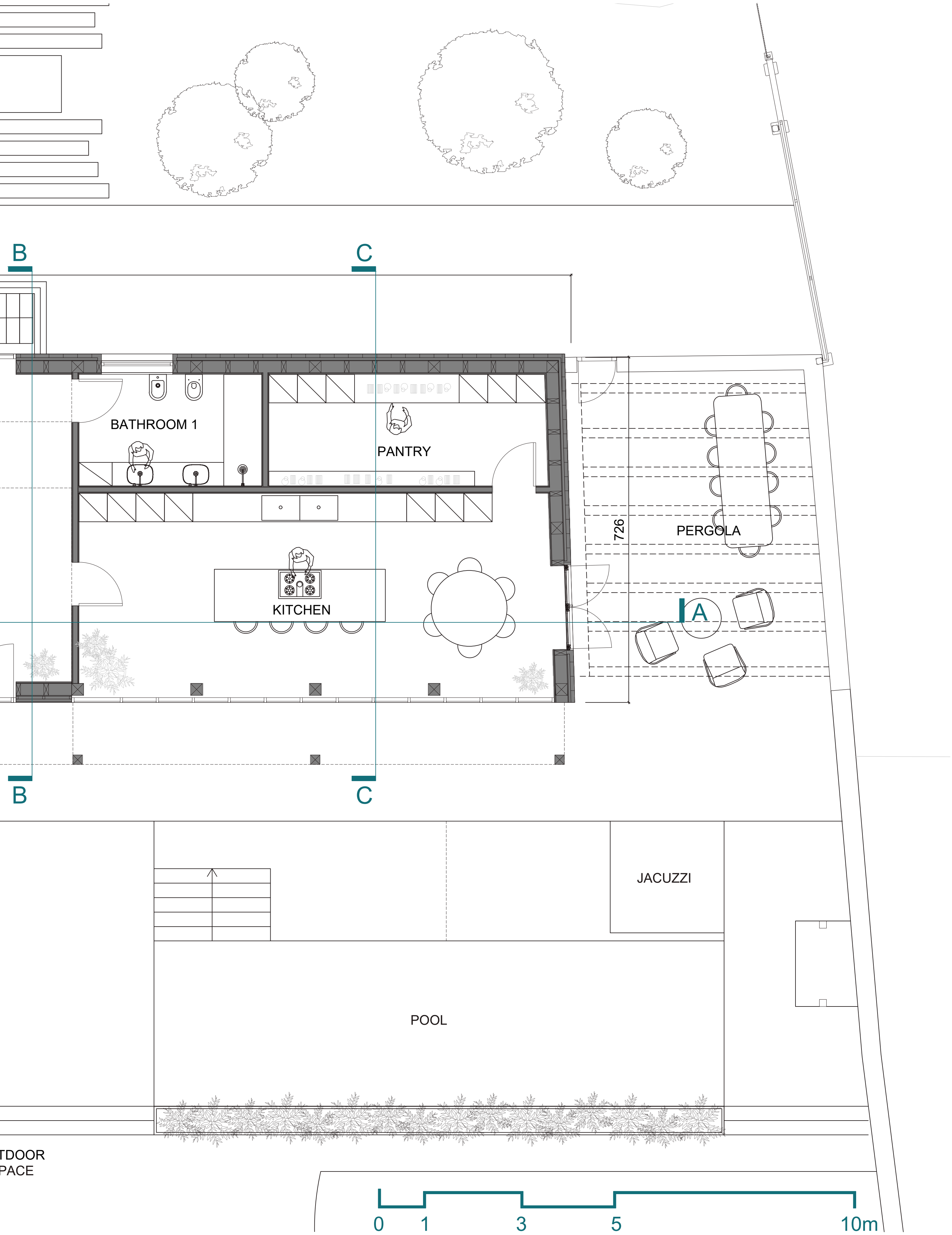
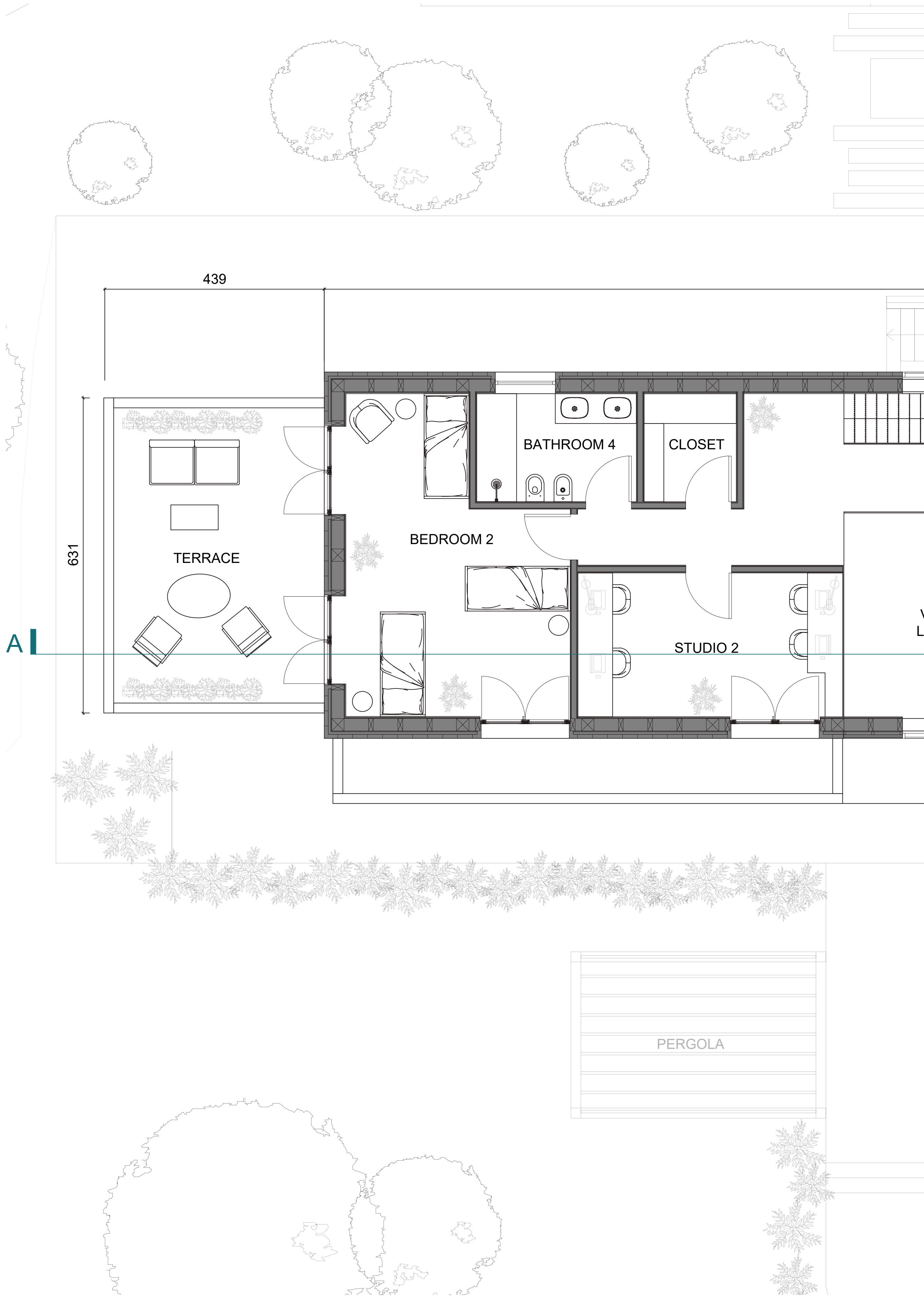


Figure 116. OPTIMIZATION GROUND FLOOR PLAN


439
631
TERRACE
BEDROOM 2
BATHROOM 4
CLOSET
STUDIO 2
PERGOLA
A

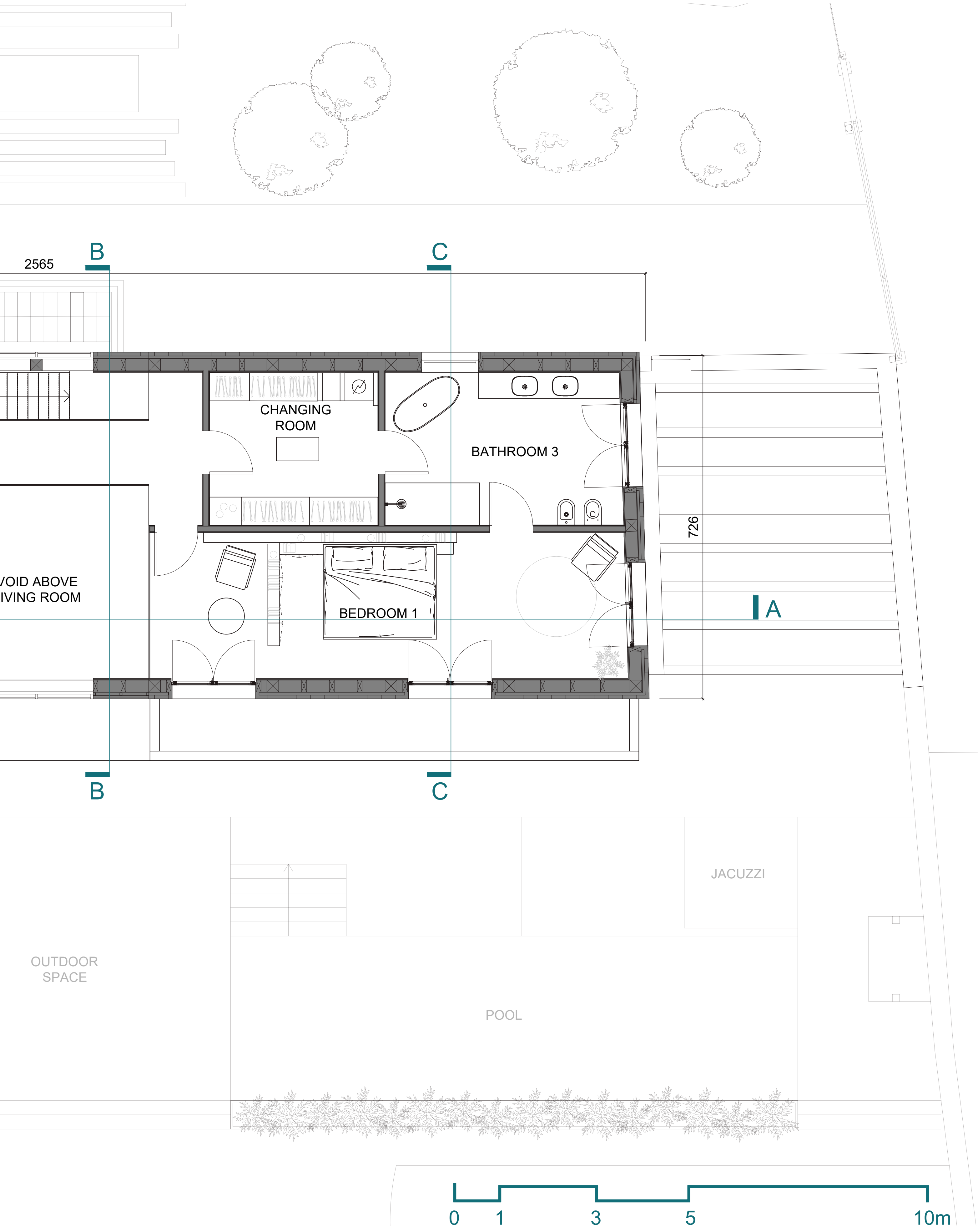


Figure 117. OPTIMIZATION FIRST FLOOR PLAN

Figure 118. OPTIMIZATION
SOUTH ELEVATION SCALE: 1/100

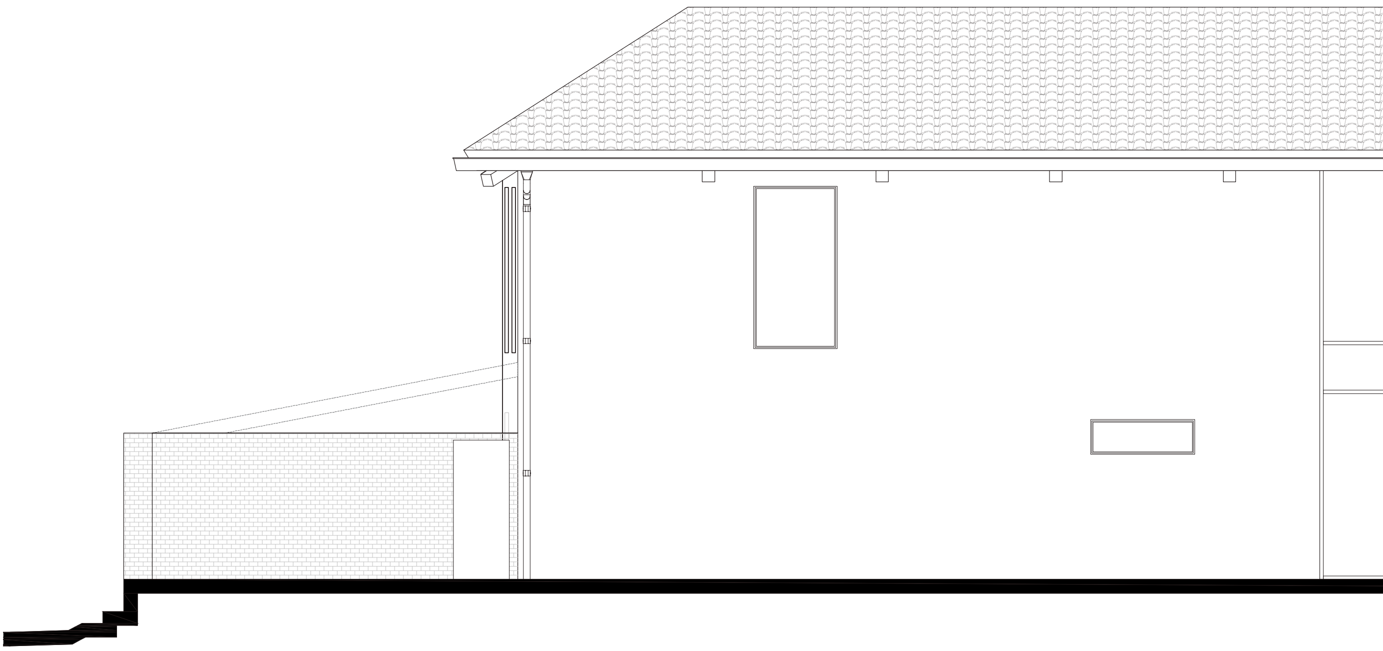


Figure 119. OPTIMIZATION
NORTH ELEVATION SCALE: 1/100

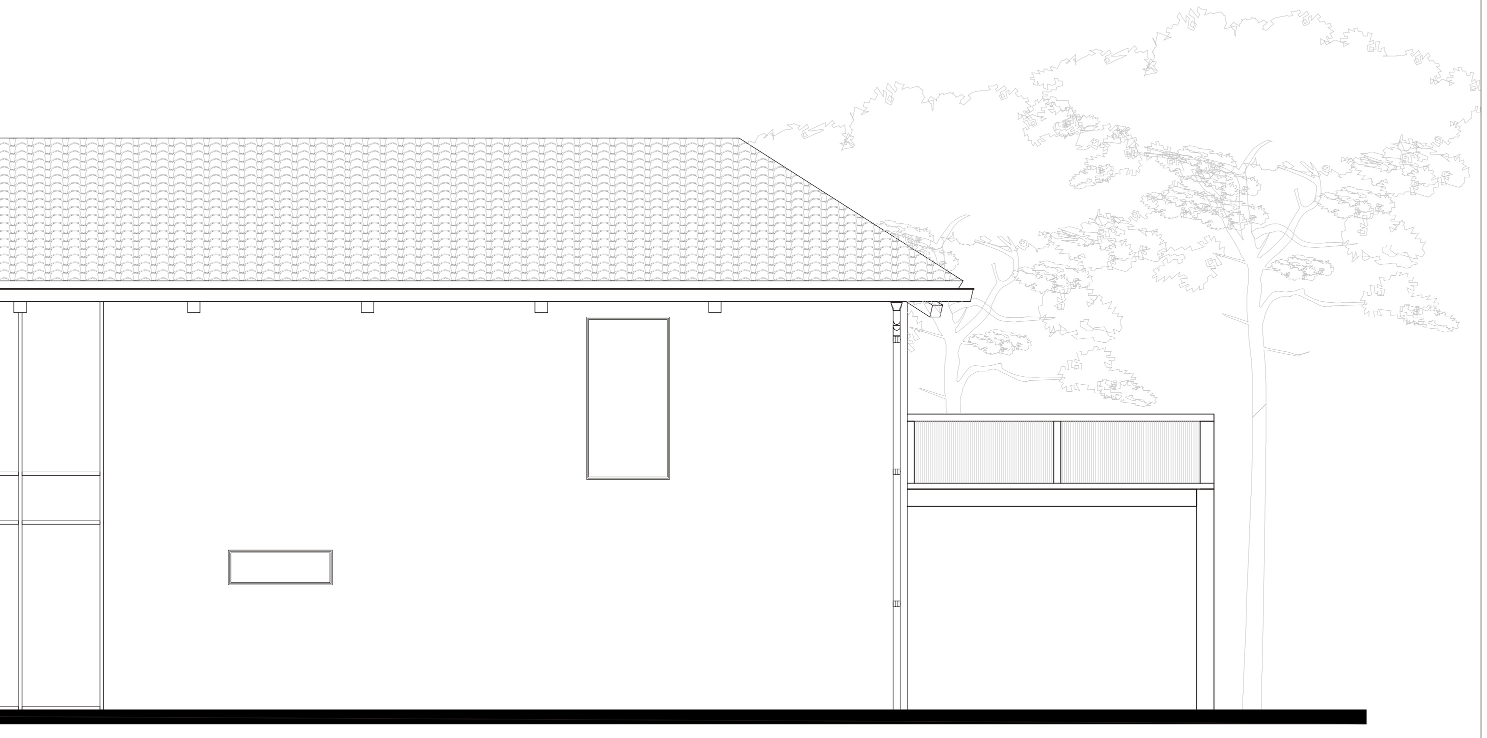


Figure 120. OPTIMIZATION
EAST ELEVATION SCALE: 1/100

Figure 121. OPTIMIZATION
WEST ELEVATION SCALE: 1/100

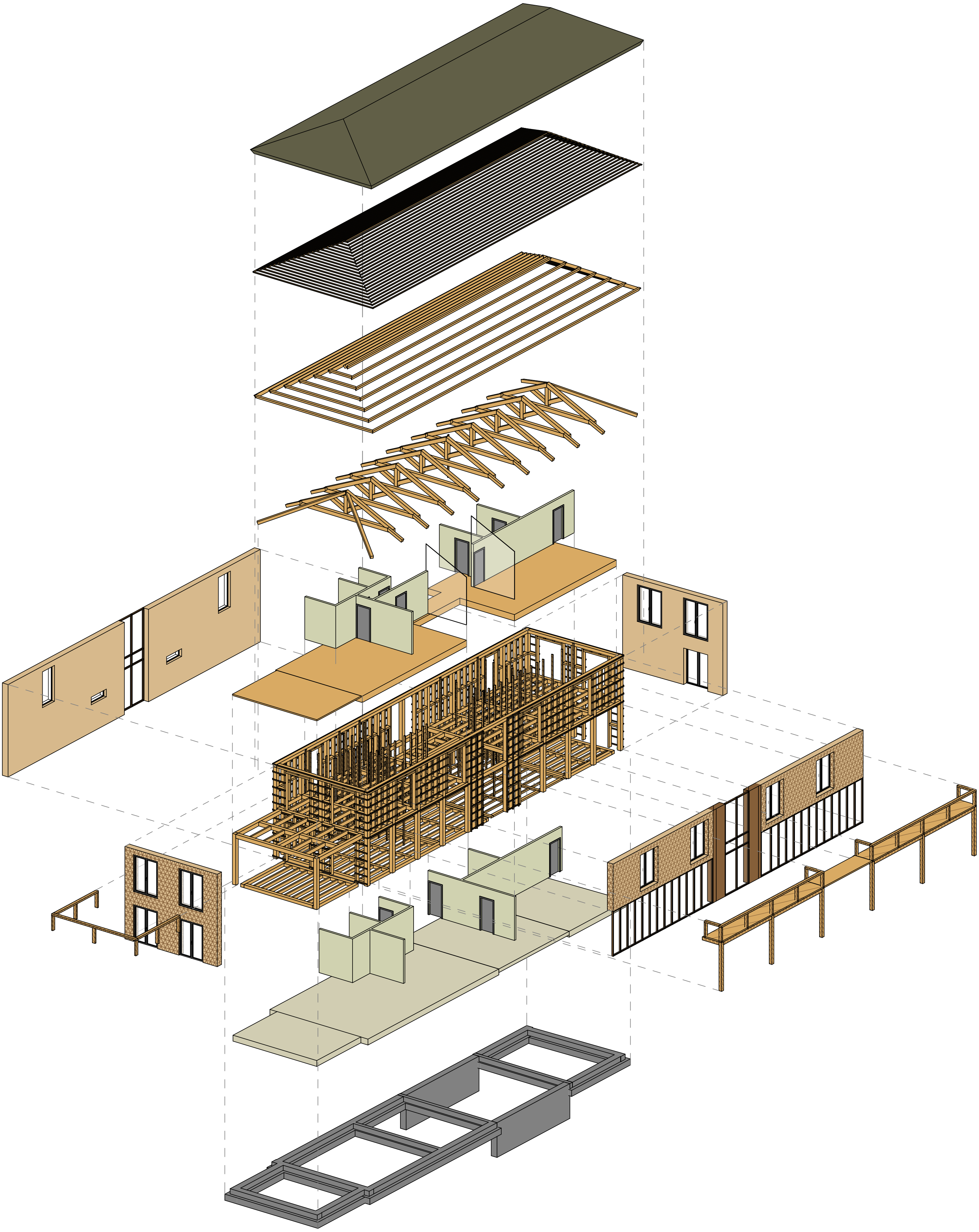


Figure 122. Building parts of design optimization 3D explosion diagram, source: author

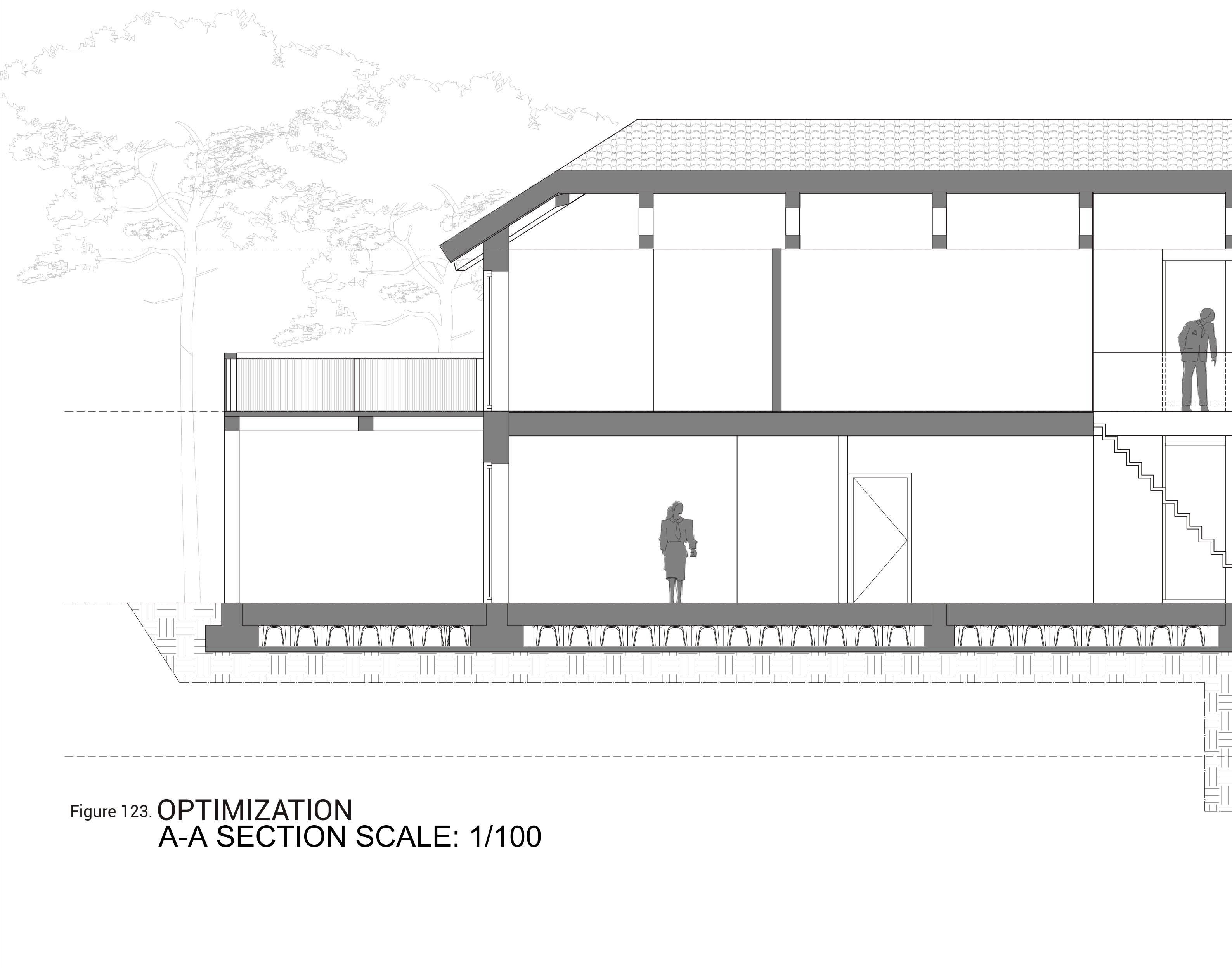
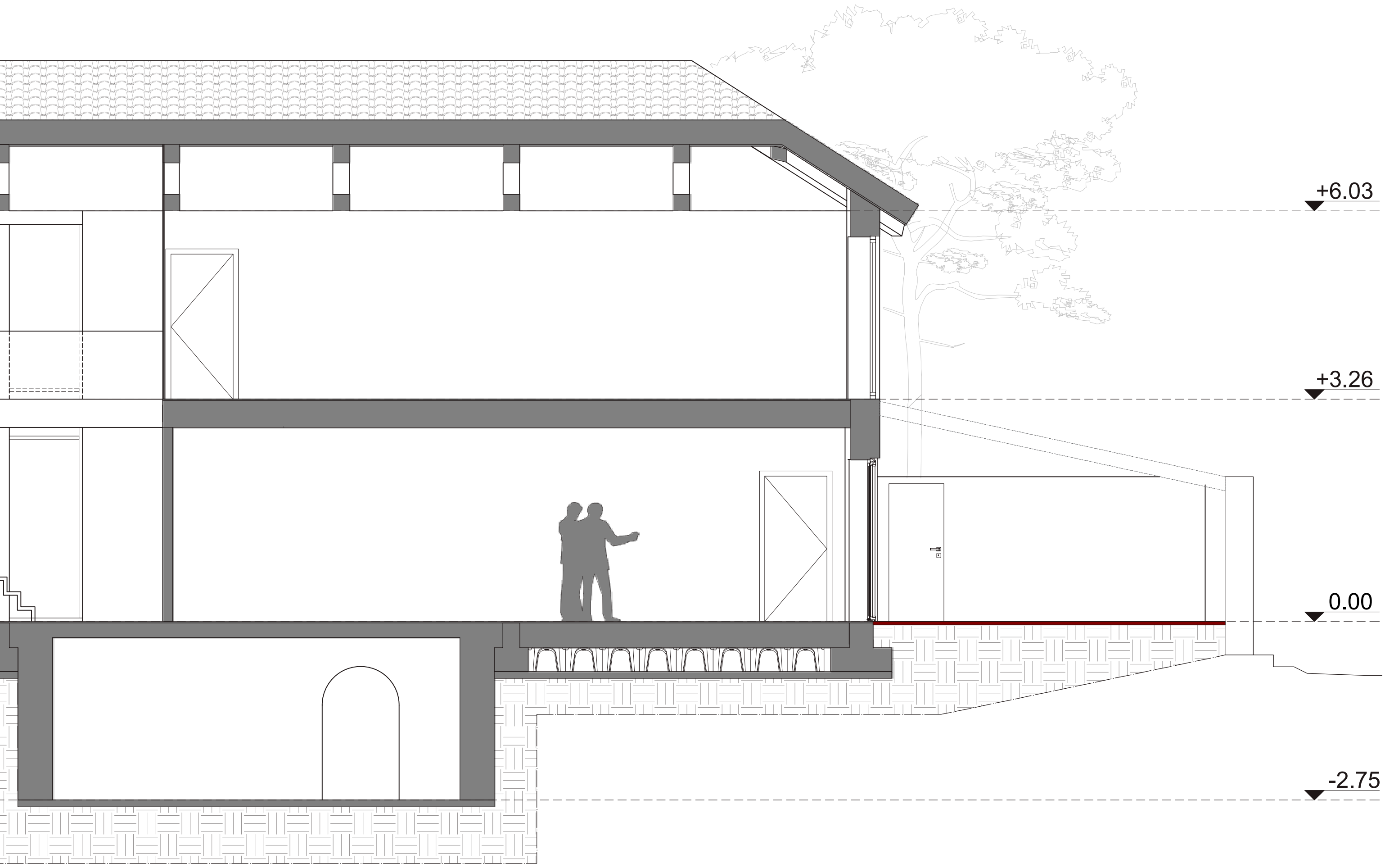


Figure 123. OPTIMIZATION
A-A SECTION SCALE: 1/100


+6.03
+3.26
0.00
-2.75

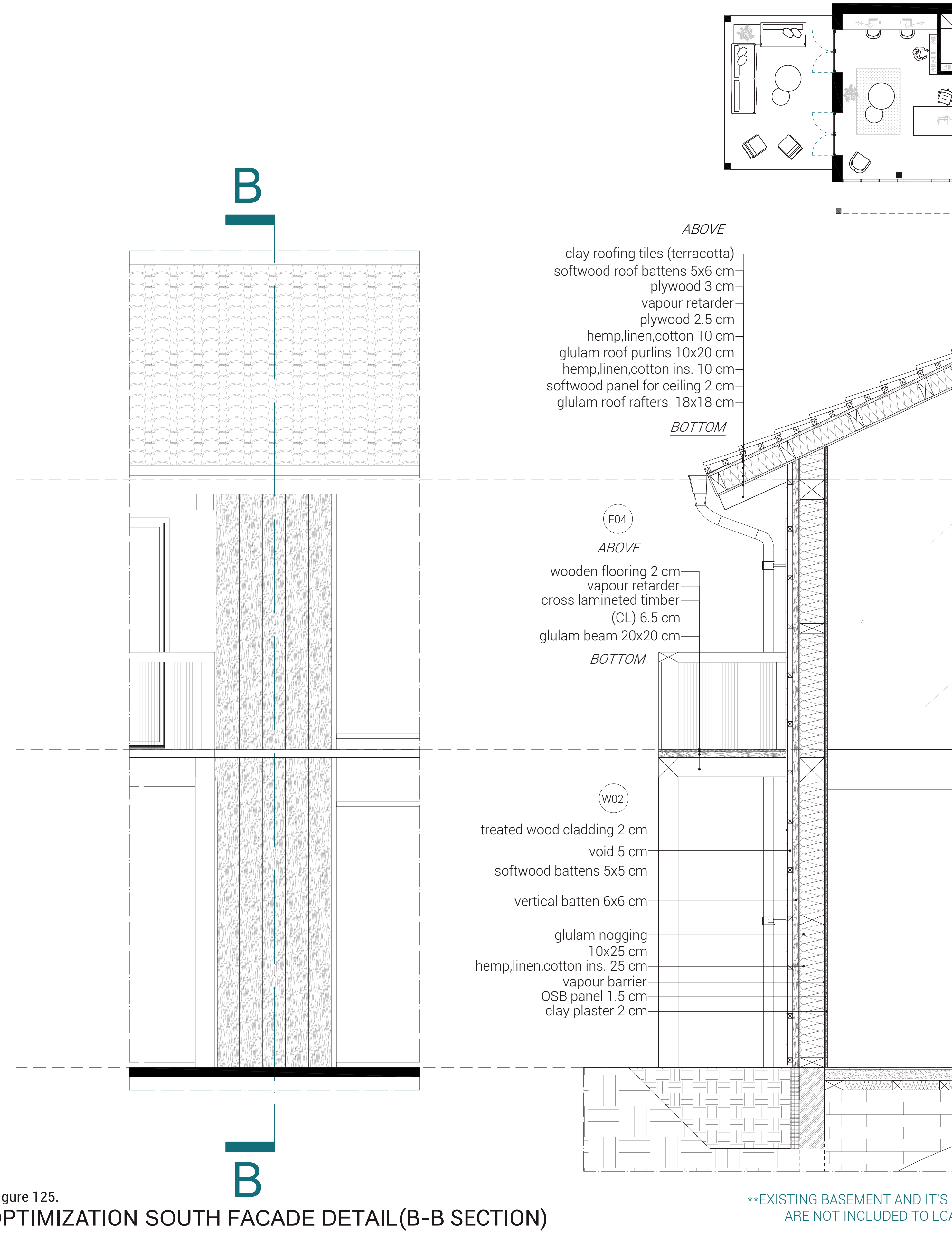
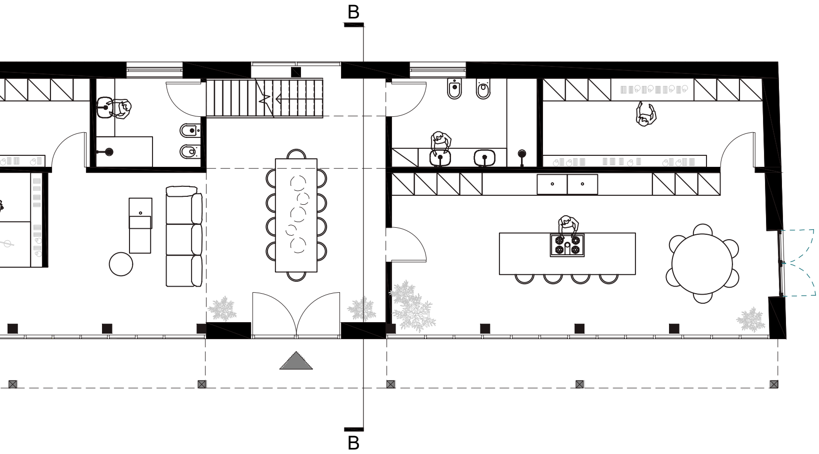


Figure 125.
OPTIMIZATION SOUTH FACADE DETAIL(B-B SECTION)

Figure 124. OPTIMIZATION
GROUND FLOOR PLAN
SCALE: 1/200



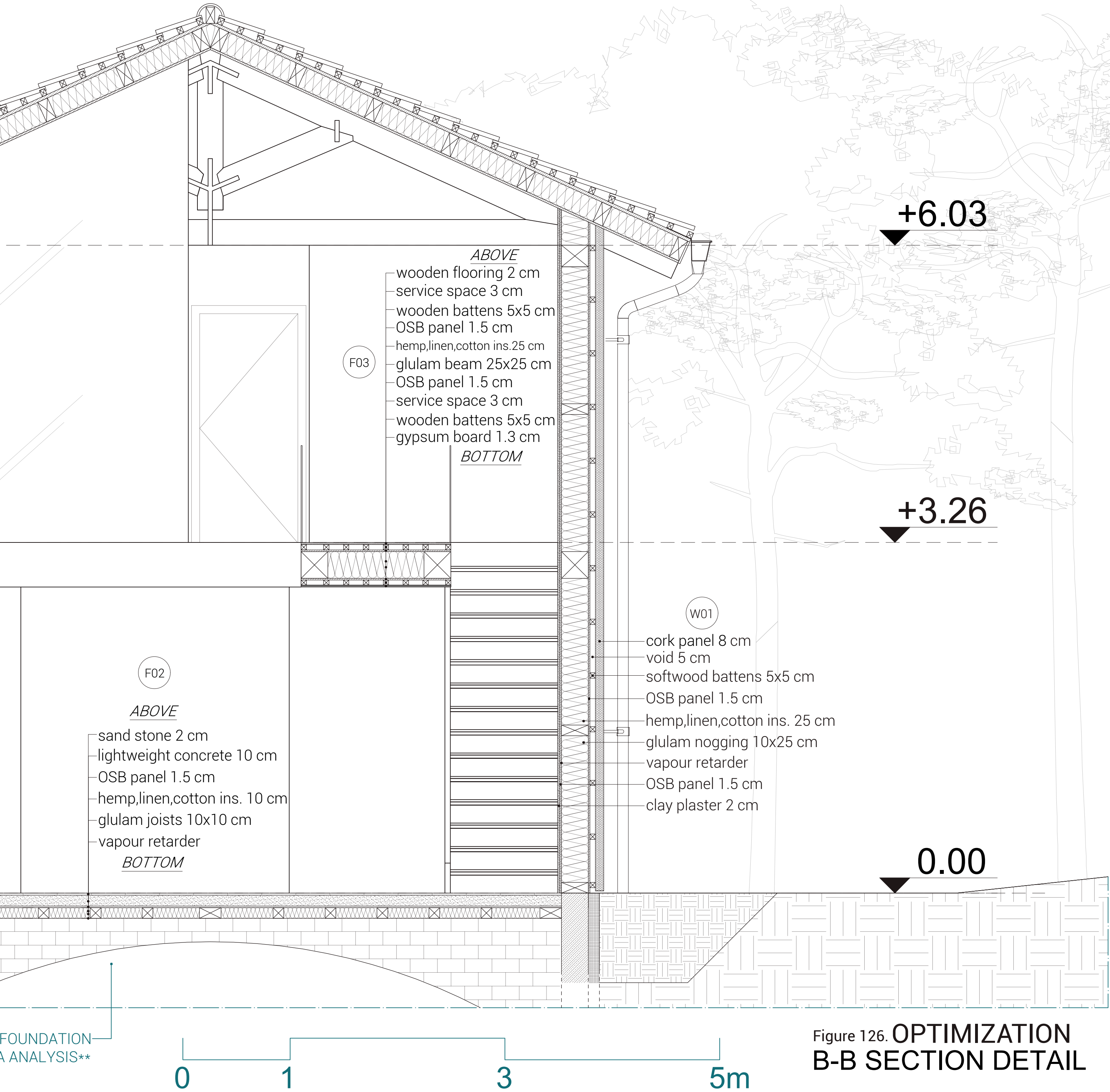


Figure 126. OPTIMIZATION
B-B SECTION DETAIL

Figure 127.

OPTIMIZATION WINDOW FIRST FLOOR DETAIL

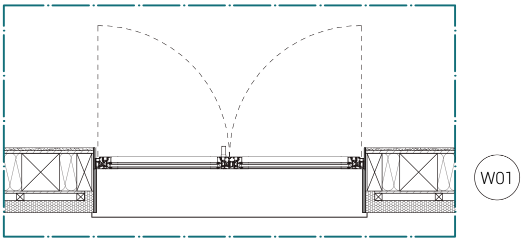
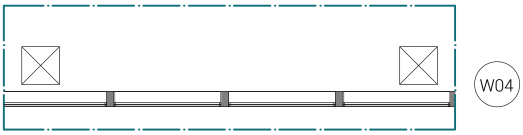
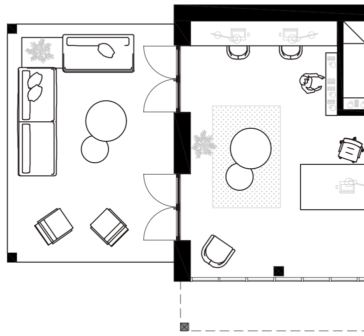


Figure 128.

OPTIMIZATION CURTAION WALL GROUND FLOOR DETAIL





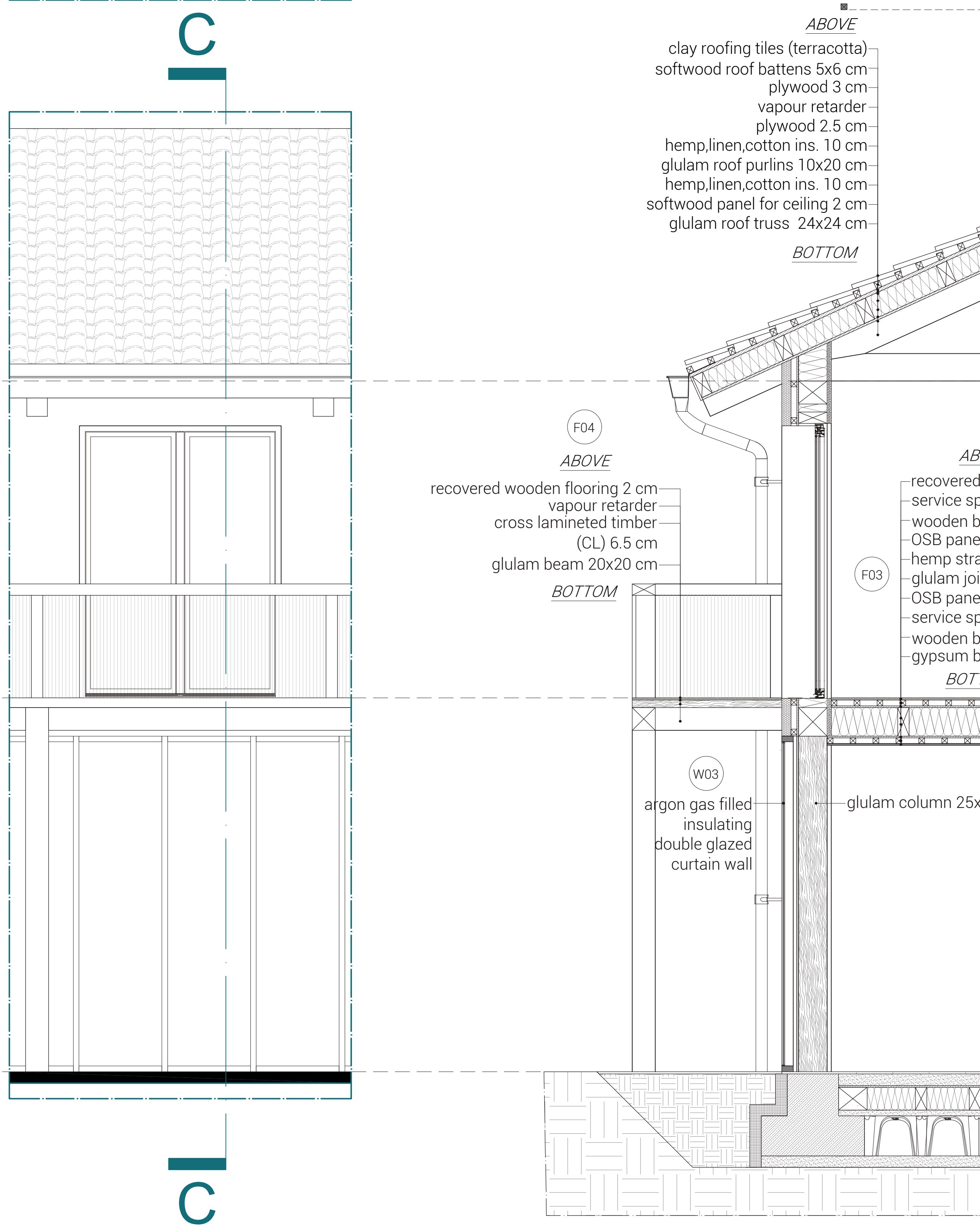


Figure 129.

OPTIMIZATION SOUTH FACADE DETAIL (C-C SECTION)

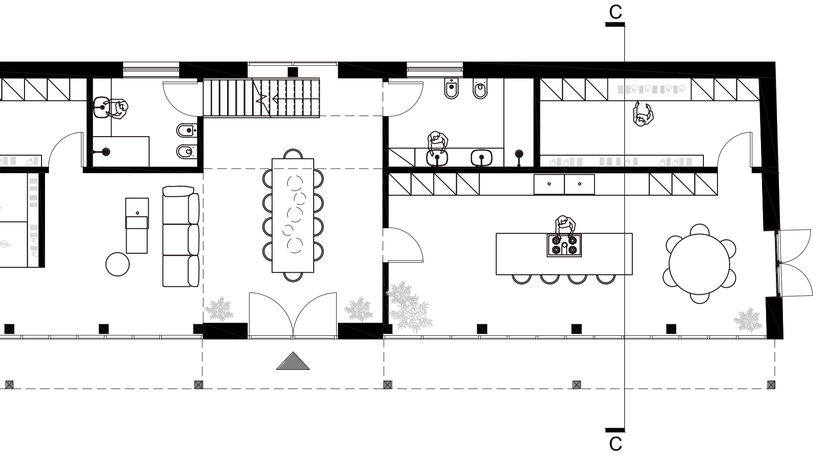


Figure 124. OPTIMIZATION
GROUND FLOOR PLAN
SCALE: 1/200

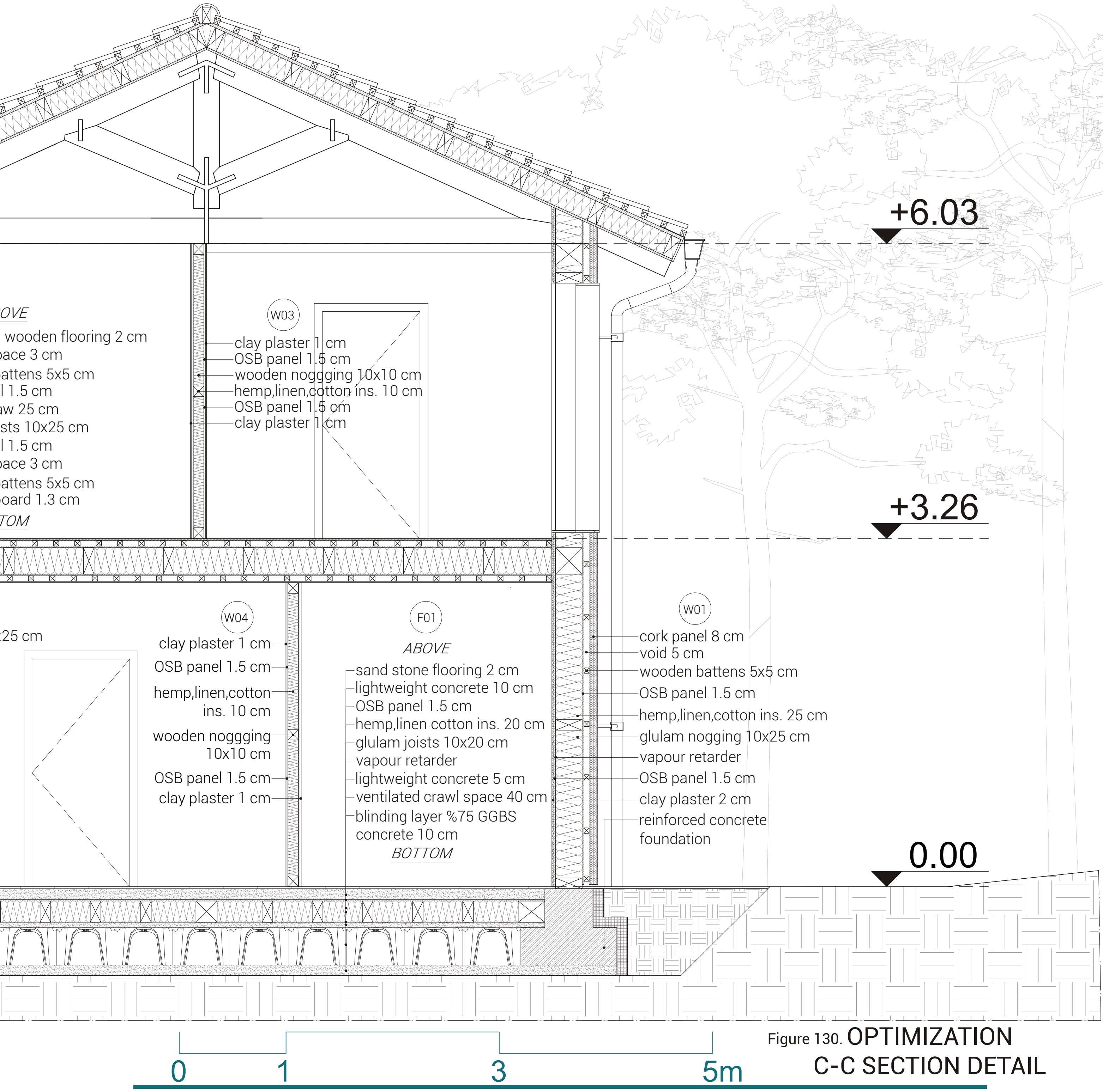
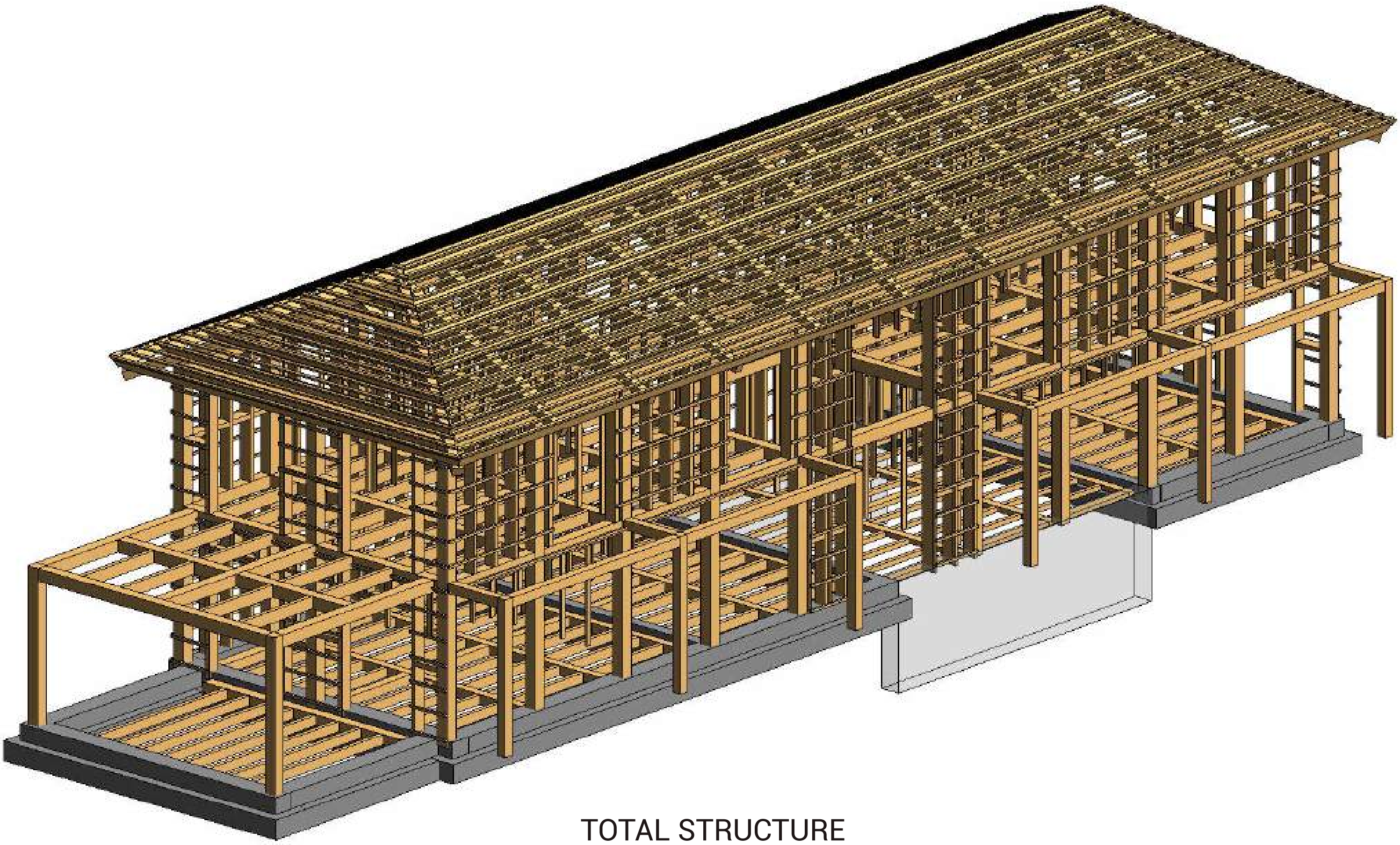


Figure 130. OPTIMIZATION
C-C SECTION DETAIL

4.3.4 STRUCTURAL SCHEME



TOTAL STRUCTURE

Figure 131. 3D view of total building structure of design optimization, source: author

3

FIRST FLOOR STRUCTURE GLULAM BEAMS 25x25 + GLULAM JOISTS 10x25h + GLULAM BALCONY STRUCTURE

2

GLULAM COLUMNS 25x25

1

REINFORCED CONCRETE FOUNDATION WITH GLULAM FRAME

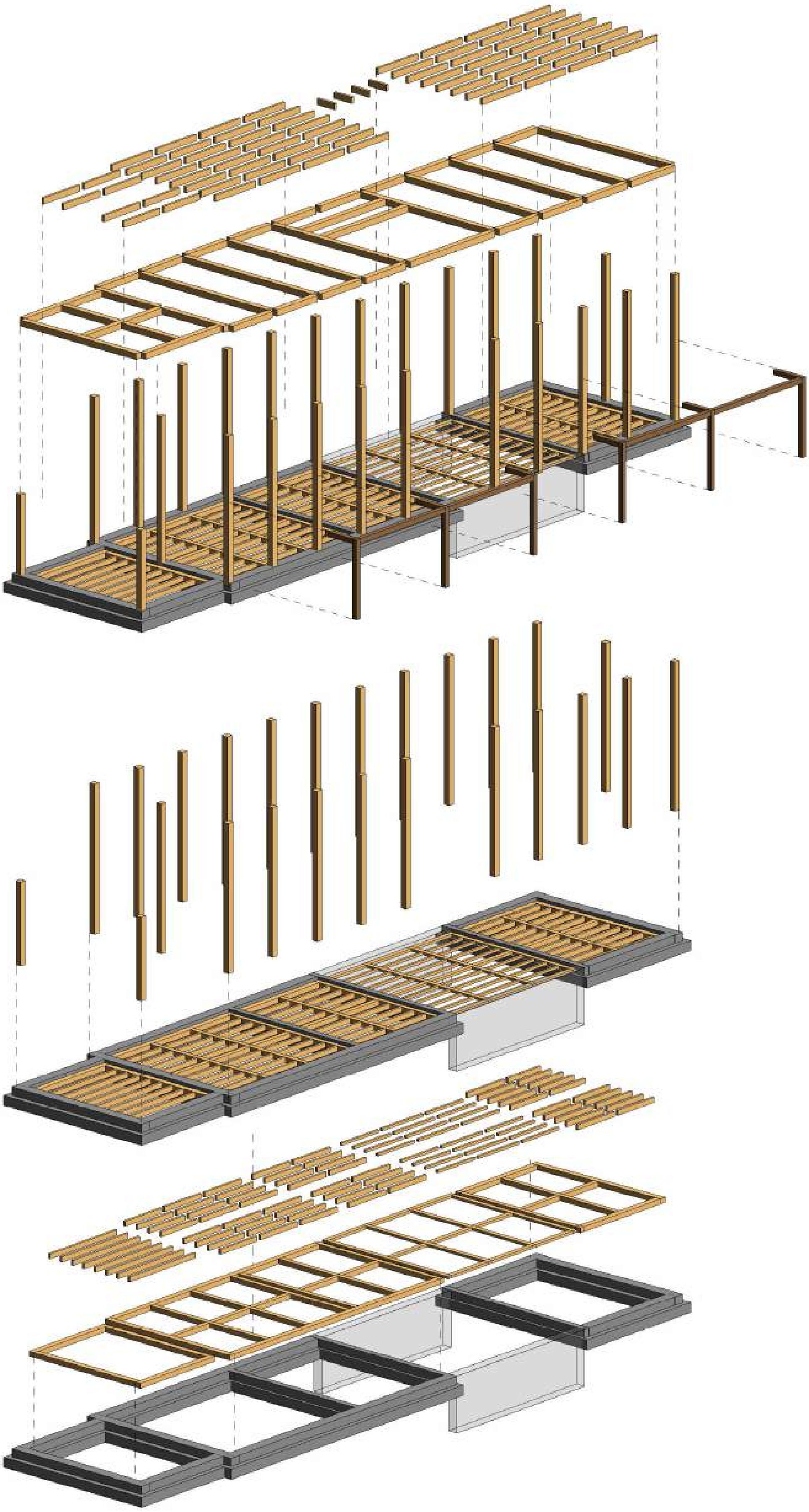
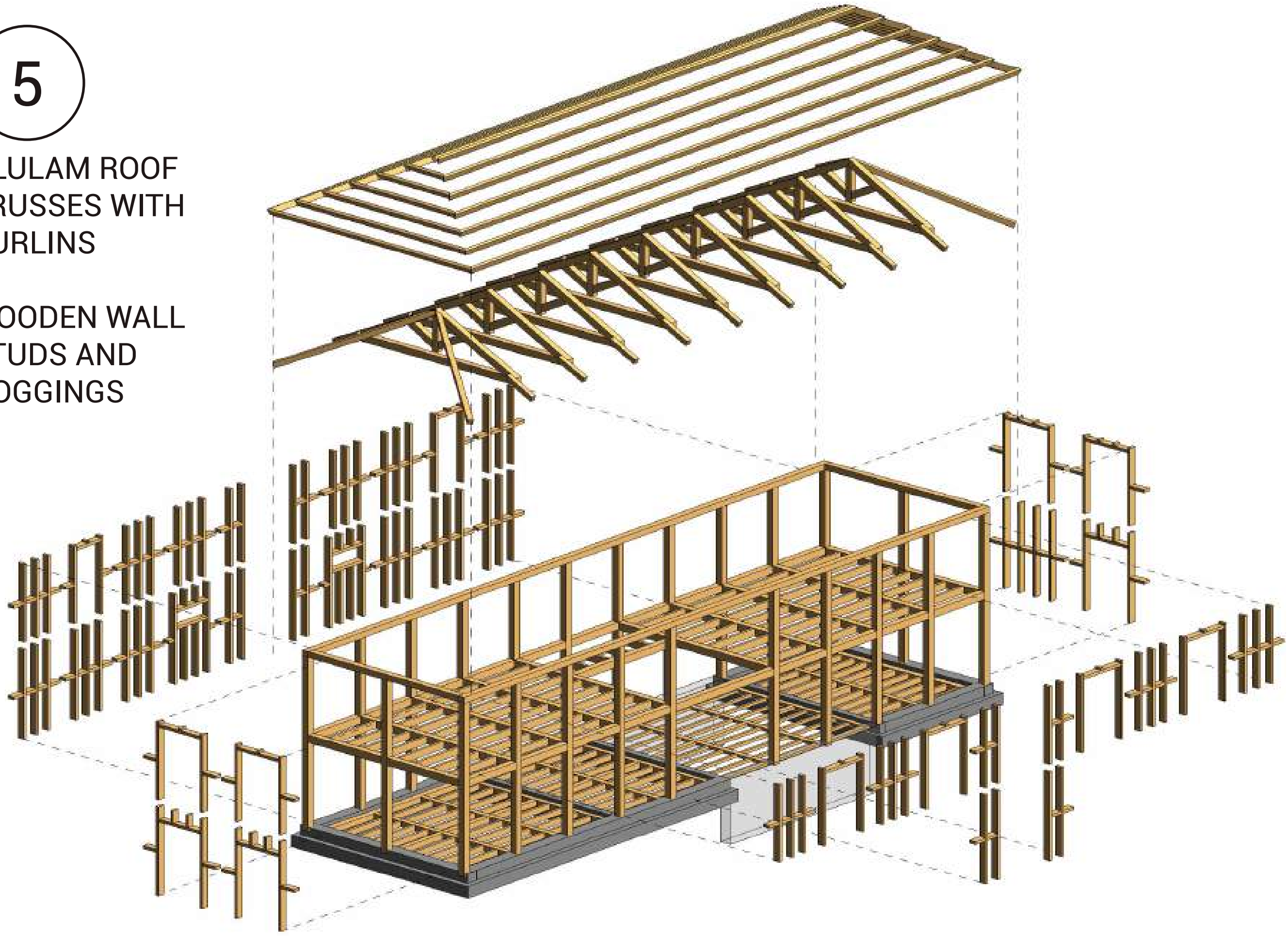


Figure 132. 3D scheme of design optimization construction phases 1-3 , source: author

5

GLULAM ROOF TRUSSES WITH PURLINS
+
WOODEN WALL STUDS AND NOGGINGS



4

GLULAM BEAM UNDER ROOF TRUSSES

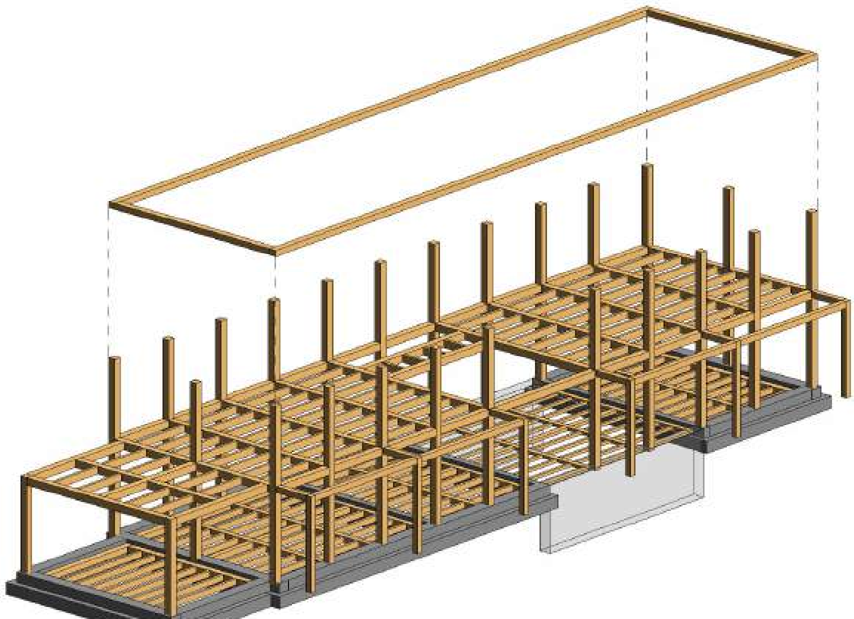


Figure 133. 3D scheme of design optimization construction phases 4-5 , source: author

6

WOODEN WALL AND ROOF BATTENS

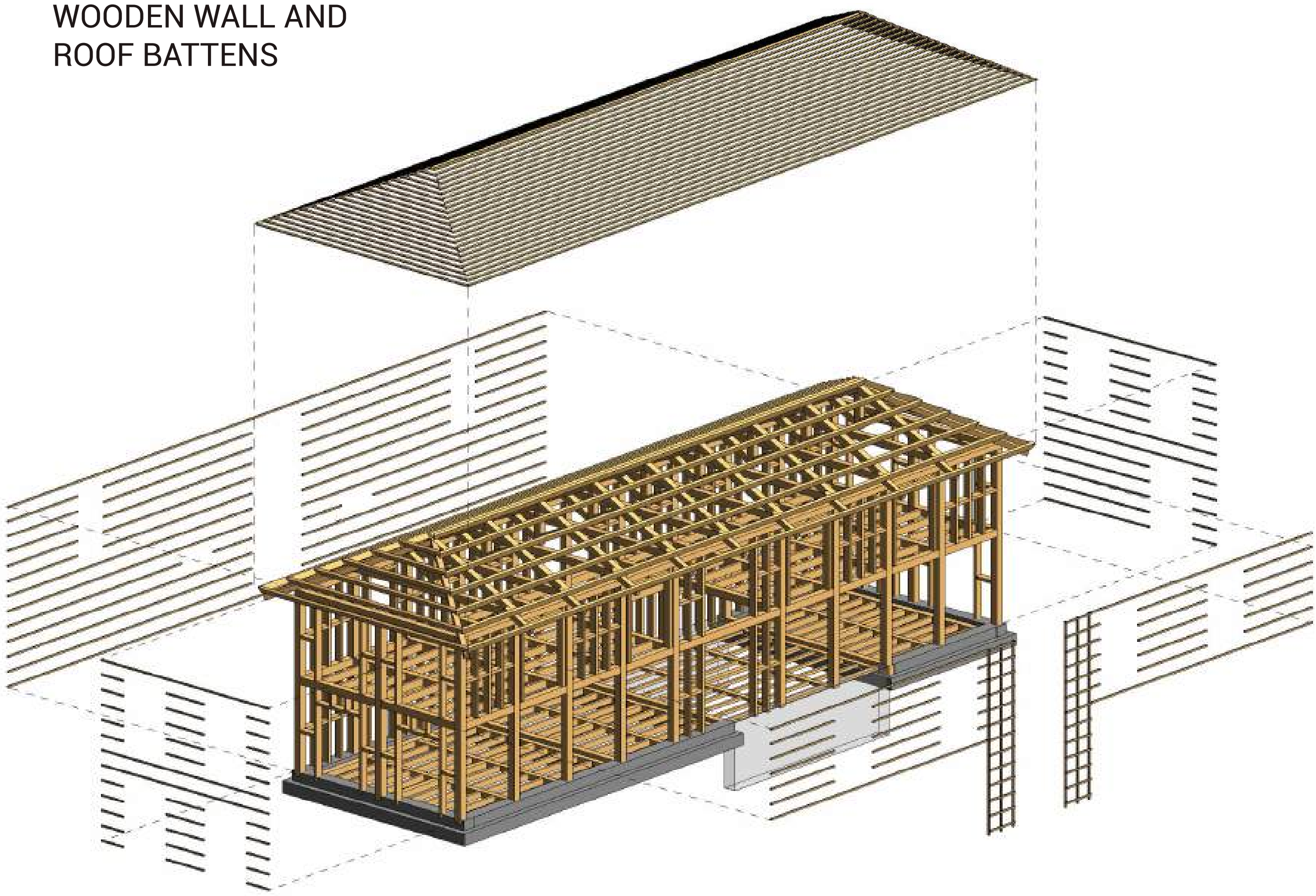


Figure 134. 3D scheme of design optimization construction phases 6 , source: author

4.4 LCA ANALYSIS OF DESING OPTIMIZATION

4.4.1 LCIA OF CONSTRUCTION MATERIALS FOR MODULES A1-A3

All materials involved in a building construction have association in Oneclick LCA, according to the most appropriate database source possible.

For each resource the GWP for A1-A3 module described in the 'resource information section', which includes the data background, description of the resource, its technical characteristics and environmental characteristics. Among these profiles they include analogs with default material thickness or mass per square meter density kg/m^2 density kg/m^3 and other parameters.

These characteristics are used in order to get correct quantities of each building material imported so as to come up with the GWP for each imported building material through the Revit model for the A1-A3 modules. It is important to note that in the GWP values given in the resource information of A1-A3 modules, the localization factor is often not included. To obtain the correct GWP value of a material in the "details" section of the general results have been dissected.

The tables below are not directly provided by the Oneclick LCA tool but they are manually prepared based on the results of each building material's GWP calculation details, which can be reviewed in the "details" section of the general results in the Oneclick LCA tool. All the materials' quantity as modeled in Revit program was automatically calculated by Oneclick LCA thanks to BIM integration. Values such as density, mass or weight of each material is available to be reviewed in the "information" section of each mapping material chosen in Oneclick LCA. These values are manually inserted into the tables below.

FOUNDATION

	m^2	thickness (m)	m^3	density kg/m^3	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Blinding layer ready-mix concrete %75 GGBS content	177,30	0,10	17,73	2400,00	42552,00	0,0542	2306,32
Reinforced concrete beam 900x400mm			34,13	2406,1	82120,19	0,107	8786,86
Reinforced concrete beam 500x400mm			5,16	2406,1	12415,48	0,107	1328,46
						TOTAL:	**12421,63**

MAIN BUILDING STRUCTURE

	m^3	density kg/m^3	weight (kg)	GWP kgCO2e/m^3	GWP kgCO2e
GLULAM beams 250x250 mm	3,65	485,70	1772,81	95,04	346,90
GLULAM beams 250x200 mm	7,12	485,70	3458,18	95,04	676,68
GLULAM columns 250x250 mm	8,99	485,70	4366,44	95,04	854,41
				TOTAL:	**1877,99**

ROOF STRUCTURE

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
GLULAM roof truss 240x240 mm	10,53	485,70	5114,42	95,04	1000,77
GLULAM roof purlins 100x200 mm	11,84	485,70	5750,69	95,04	1125,27
GLULAM roof rafters 180x180 mm	1,23	485,70	597,41	95,04	116,90
Softwood roof battens 50x60 mm	4,07	440,00	1790,80	59,09	240,50
				TOTAL:	**2483,44**

ROOF LAYERS

	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Clay roofing tiles (terracotta)	271,63			35,00	9507,05	0,159	1511,62
Vapour barrier membrane	271,63	0,0015	0,41	1,80	488,93	0,033	16,13
Recovered wooden ceiling	271,63	0,20	54,33	13,15	3571,93	0,0475	169,67
	m²	**thickness (m)**	**m³**	**density kg/m³**	**weight (kg)**	**GWP kgCO2e/kg**	**GWP kgCO2e**
Hemp,linen,cotton insulation	271,63	0,20	54,33	30,00	1629,78	0,000666	1,09
	m²	**thickness (m)**	**m³**	**density kg/m³**	**weight (kg)**	**GWP kgCO2e/m³**	**GWP kgCO2e**
Plywood	271,63	0,03	8,15	900,00	7334,01	344,00	2803,22
Plywood	271,63	0,025	6,79	900,00	6111,68	344,00	2336,02
						TOTAL:	**6837,75**

GROUND FLOOR STRUCTURE (F01)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
GLULAM beams 200x200 mm	2,73	485,70	1325,96	95,04	259,46
GLULAM beams 100x200h mm	1,19	485,70	577,98	95,04	113,10
				TOTAL:	**372,56**

GROUND FLOOR LAYERS (F01)

	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Sandstone floor finish	165,08	0,02	3,30	1,00	165,08	0,0594	9,81
Vapour barrier membrane	165,08	0,0015	0,25	1,80	297,14	0,033	9,81
	m²	**thickness (m)**	**m³**	**density kg/m³**	**weight (kg)**	**GWP kgCO2e/kg**	**GWP kgCO2e**
Lightweight concrete %50 recycled binder	165,08	0,10	16,51	220,00	3631,76	0,06909	250,92
Lightweight concrete %50 recycled binder	165,08	0,05	8,25	220,00	1815,88	0,06909	125,46
Hemp,linen,cotton insulation	165,08	0,20	33,02	30,00	990,48	0,000666	0,66
	m²	**thickness (m)**	**m³**	**density kg/m³**	**weight (kg)**	**GWP kgCO2e/m³**	**GWP kgCO2e**
OSB panel	165,08	0,015	2,48	450,00	1114,29	19,13	47,37
						TOTAL:	**444,02**

TOTAL F01:	247,35+443,69	**816,58**

GROUND FLOOR STRUCTURE (F02)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
GLULAM beams 200x100h mm	0,40	485,70	194,28	95,04	38,02
GLULAM beams 100x100 mm	0,69	485,70	335,13	95,04	65,58
				TOTAL:	103,59

GROUND FLOOR LAYERS (F02)

	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Sandstone floor finish	51,32	0,02	1,03	1,00	51,32	0,0594	3,05
Vapour barrier membrane	51,32	0,0015	0,08	1,80	92,38	0,033	3,05
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Hemp,linen,cotton insulation	51,32	0,10	5,13	30,00	153,96	0,000666	0,10
Lightweight concrete %50 recycled binder	51,32	0,10	5,13	220,00	1129,04	0,06909	78,01
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
OSB panel	51,32	0,015	0,77	450,00	346,41	19,13	14,73
						TOTAL:	98,93
					TOTAL F01:	68,78+98,83	202,52

FIRST FLOOR STRUCTURE (F03)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
GLULAM beams 200x250 mm	3,86	485,70	1874,80	95,04	366,85
GLULAM beams 100x250h mm	4,11	485,70	1996,23	95,04	390,61
Softwood battens 50x50 mm	4,23	440,00	1861,20	59,09	249,95
				TOTAL:	1007,42

FIRST FLOOR LAYERS (F03)

	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Recovered wooden floor finish	136,15	0,02	2,72	13,15	1790,37	0,0475	85,04
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Hemp,linen,cotton insulation	136,15	0,25	34,04	30,00	1021,13	0,000666	0,68
Gypsum board	136,15	0,0125	1,70	895,00	1523,18	0,218	332,05
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
OSB panel	136,15	0,015	2,04	450,00	919,01	19,13	39,07
OSB panel	136,15	0,015	2,04	450,00	919,01	19,13	39,07
						TOTAL:	495,91
					TOTAL F01:	752,86+196,66	1503,33

TERRACE STRUCTURE

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
GLULAM columns 200x200 mm	0,76	485,70	369,13	95,04	72,23
GLULAM beams 250x250 mm	1,51	485,70	733,41	95,04	143,51
GLULAM beams 200x200 mm	0,30	485,70	145,71	95,04	28,51
GLULAM beams 100x250h mm	0,40	485,70	194,28	95,04	38,02
				TOTAL:	282,27

TERRACE LAYERS (F04)

	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Recovered wooden floor finish	54,70	0,02	1,09	13,15	719,31	0,0475	34,17
Vapour barrier membrane	54,70	0,0015	0,08	1,80	98,46	0,033	3,25
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
CL (Cross Laminated Timber)	54,70	0,065	3,56	470,00	1671,09	106,95	380,26
						TOTAL:	417,68

EXTERNAL WALL LAYERS (W01)

	m^2	thickness (m)	m^3	density kg/m^3	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Expanded Cork Panel	231,74	0,08	18,54	115,00	2132,01	0,7654	1631,84
Hemp,linen,cotton insulation	231,74	0,25	57,94	30,00	1738,05	0,000666	1,16
	m^2	thickness (m)	m^3	mass kg/m^2	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Vapour barrier membrane	231,74	0,0015	0,35	1,80	417,13	0,033	13,77
Interior clay plaster	231,74	0,02	4,63	27,80	6442,37	0,02359	151,98
	m^2	thickness (m)	m^3	density kg/m^3	weight (kg)	GWP kgCO2e/m^3	GWP kgCO2e
OSB panel	231,74	0,015	3,48	450,00	1564,25	19,13	66,50
OSB panel	231,74	0,015	3,48	450,00	1564,25	19,13	66,50
						TOTAL:	1931,73

EXTERNAL WALL LAYERS (W02)

	m^2	thickness (m)	m^3	density kg/m^3	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Hemp,linen,cotton insulation	14,25	0,25	3,56	30,00	106,88	0,000666	0,07
	m^2	thickness (m)	m^3	mass kg/m^2	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Vapour barrier membrane	14,25	0,0015	0,02	1,80	25,65	0,033	0,85
Interior clay plaster	14,25	0,02	0,29	27,80	396,15	0,02359	9,35
	m^2	thickness (m)	m^3	density kg/m^3	weight (kg)	GWP kgCO2e/m^3	GWP kgCO2e
Treated wood cladding	14,25	0,02	0,29	525,00	149,63	62,37	17,78
OSB panel	14,25	0,015	0,21	450,00	96,19	19,13	4,09
OSB panel	14,25	0,015	0,21	450,00	96,19	19,13	4,09
						TOTAL:	36,22

EXTERNAL GLAZING CURTAIN WALL LAYERS (W03)

	m^2	thickness (m)	m^3	mass kg/m^2	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Argon gas filled insuating double glazing	79,19	0,025	1,98	20,00	1583,80	1,537	2434,30
			m^3	density kg/m^3	weight (kg)	GWP kgCO2e/m^3	GWP kgCO2e
Treated wood mullions			0,87	525,00	456,75	62,37	54,26
						TOTAL:	2488,56

EXTERNAL WALL SECONDARY STRUCTURES

	m^3	density kg/m^3	weight (kg)	GWP kgCO2e/m^3	GWP kgCO2e
Softwood studs 250x100 mm	9,36	440,00	4118,40	59,09	553,08
Softwood horizontal bettens 50x50 mm	1,38	440,00	607,20	59,09	81,54
Softwood vertical bettens 50x60 mm	0,108	440,00	47,52	59,09	6,38
				TOTAL:	641,01

TOTAL EXTERNAL WALL GWP: 5097,53 kgCO2e

INTERNAL WALL LAYERS (W04)

	m^2	thickness (m)	m^3	density kg/m^3	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Hemp,linen,cotton insulation	181,42	0,10	18,14	30,00	544,26	0,000666	0,36
	m^2	thickness (m)	m^3	mass kg/m^2	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Interior clay plaster	181,42	0,01	1,81	27,80	5043,48	0,02359	118,98
Interior clay plaster	181,42	0,01	1,81	27,80	5043,48	0,02359	118,98
	m^2	thickness (m)	m^3	density kg/m^3	weight (kg)	GWP kgCO2e/m^3	GWP kgCO2e
OSB panel	181,42	0,015	2,72	450,00	1224,59	19,13	52,06
OSB panel	181,42	0,015	2,72	450,00	1224,59	19,13	52,06
Softwood studs 100x50 mm			1,76	440,00	774,40	59,09	104,00
						TOTAL:	446,43

Figure 135. LCIA tables of design optimization construction materials for modules A1-A3, source: author

4.4.2 LCIA OF TRANSPORT FOR MODULE A4

BUILDING MATERIAL TYPES	TRANSPORTATION VECHILE TYPES	DISTANCE
All concrete types	Concrete mixer truck	60 km (Piedmont region,Italy)
GLULAM (Glued Laminated Timber)	Trailer combunation 40ton capacity %100 fill rate	722 km (Verneuil-sur-vienne,France)
Treated wood cladding	Lorry, local distribution	50 km (Piedmont region,Italy)
Softwood	Lorry, local distribution	50 km (Piedmont region,Italy)
Recovered wood floor finish	Lorry, local distribution	50 km (Piedmont region,Italy)
CLT (Cross Laminated Timber)	Lorry, local distribution	50 km (Piedmont region,Italy)
Sandstone floor finish	Lorry, local distribution	50 km (Piedmont region,Italy)
Roofing tile (terracotta)	Lorry, local distribution	50 km (Piedmont region,Italy)
Argon filled insulating glass	Delivery truck 6ton capacity %100 fill rate	150 km (Milan,Lombardy,Italy)
Interior clay plaster	Delivery truck 6ton capacity %100 fill rate	200 km (Lombardy region,Italy)
OSB panel	Delivery truck 6ton capacity %100 fill rate	220 km (Iseo,Lombardy,Italy)
Vapour barrier membrane	Delivery truck 6ton capacity %100 fill rate	187 km (Bergamo,Lombardy,Italy)
Expanded cork cladding	Delivery truck 6ton capacity %100 fill rate	154 km (Milan,Lombardy,Italy)
Gypsum board	Delivery truck 6ton capacity %100 fill rate	200 km (Lombardy region,Italy)
Hemp, linen, cotton insulation	Freight transport via truck	910 km (Saint Gemme La Plaine,France)
Plywood	Freight transport via truck	265 km (Sabbioneta,Lomvardy,Italy)

TRANSPORTATION VECHILE TYPES	GWP
Concrete mixer truck	0,13 kgCO2e/tonkm
Trailer combunation 40ton capacity %100 fill rate	0,0383 kgCO2e/tonkm
Lorry, local distribution	2,8 kgCO2e/l
Delivery truck 6ton capacity %100 fill rate	0,12 kgCO2e/tonkm
Freight transport via truck	0,12 kgCO2e/tonkm

Transportation vehicle type for each building material is decided considering their sizes and typologies. Resources for each building material chosen during the mapping on Oneclick LCA, it is possible to see information about the resource such as manufacturer or technical data and in the "Default scenarios and assumptions" section default distance of the material is provided. Based on this information, the distances are set by either searching for the manufacturer's location if known or using the default distances provided by Oneclick LCA, depending on the resource data. GWP of transportation vehicle types are provided by Oneclick LCA and the calculation of the GWP of transportations are done automatically following the calculation of the quantity of each material, quantity of vehicle needed for the material quantity inserted, distance of each material type and each vehicle's GWP.

Material quantity / Vehicle capacity: Vehicle quantity
Distance x GWP x Vechile quantity = Whole Life Carbon of Transportation

4.4.3 LCIA OF CONTRUCTION / INSTALLATION FOR MODULE A5

On Oneclick LCA, localization is set as "Italy" and "IEA 2022-Electricity Italy" is set for this building phase which influence the analysis of the module A5.
On the other hand also wastage is calculated in A5 life stage of the building. Wastage percentages for each material are set as:

WASTAGE (A5 MODULE)	PERCENTAGE
All concrete types	4%
Treatead wooden cladding	17.9%
Argon gas filled insulating glass	none
Interior clay plaster	13%
Hemp, linen, cotton insulation	8%
OSB panel	16.7%
Vapour barrier membrane	10%
Expanded cork cladding	7.5%
Softwood studs/joists/battens	17.9%
GLULAM (Glued Laminated Timber)	16.7%
Recovered wood flooring	17.9%
GLT (Cross Laminated Timber)	16.7%
Gypsumboard	13%
Sandstone flooring	4.5%
Plywood	16.7%
Clay roofing tile	5%

These values are automatically suggested by Oneclick LCA approximately. GWP of the wastes are calculated depends on the impact potential of each resource chosen for each material in the beginning of the LCA analysis while mapping from the Oneclick LCA database.

4.4.4 LCIA OF REPLACEMENT/REFURBISHMENT FOR MODULES B4-B5

In order to calculate GWP of the substitution of building materials, life span of the materials and the external factors such as exposure to outdoor conditions are considered. According to this filtering, two main building materials are selected for calculation.

Considering the life span of the building is set as 50 years, selected materials' life span had to be shorter than the building's life span in order to be a fit to be calculated.

Thus, external Expanded cork cladding as coating material and hemp,linen,cotton insulation used in external/internal walls, in the first floor slab and in the roof of design optimization is selected and the life span of the material is set as **30 years for each material as suggested by Oneclick LCA tool.**

As seen in the following table their quantities as kg and total GWP for B4-B5 modules are:

	Quantity (kg)	GWP kgCO2e
Expanded cork panel cladding	2132,01	1937,79
Hemp,linen,cotton insulation	4554,76	1150,91
	TOTAL	**3088,71**

Figure 136. LCIA table of replacement/refurbishment for modules B4-B5 of desing optimization, source: author

Total GWP of the B4-B5 modules is **3088,71 kgCO2e.**

Expanded cork panel:

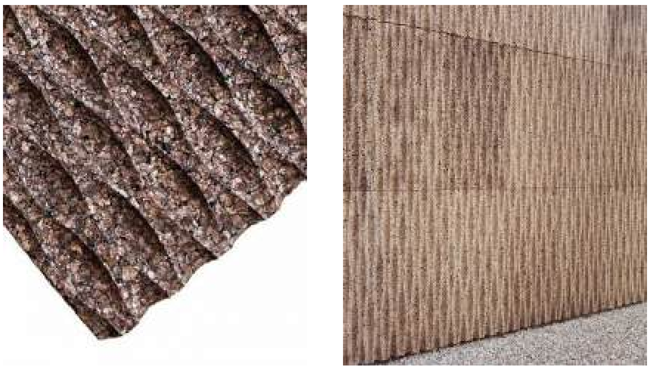


Figure 137. Expanded cork panel images, source: Tecnosugheri

Figure 138. Certification and compliance logos representing environmental standards and quality of expanded cork panel, source: Tecnosugheri

As cladding of the design optimization, according to researches of case studies in the chapter 3, expanded cork panel produced by Tecnosugheri is chosen thanks to its exceptional stability and insensitivity of the material to water and humidity, due to the absence of added glues and the closed-cell structure of the expanded cork as they mention in their official website. As for the CORKPAN panel, the thermal expansion process allows the fusion of the resins naturally contained in the bark, which act as a natural glue to aggregate the granules and form the panel. [2].

For external use of this material as cladding, it is important to mention its installation method to clarify the assembly of each panel. Considering outdoor conditions, it is important to avoid gaps on the facade to prevent water and humidity from passing through.

In the EPD that Tecnosugheri provides, they mention:

The Expanded Insulation Corkboard (ICB) is a natural and fully recyclable solution, consisting only of cork (suberin, lignin and cellulose), with a high thermal, acoustic and anti-vibration performance, especially suitable for use in external and internal walls, slabs and floors, roofs, and ceilings.

Corkboard insulation is installed using shiplap joints to avoid gaps. Shiplap joints are formed by cutting identical rabbets into opposite faces of adjoining boards and then overlapping the rabbets. Installation of panels starts from the base of the wall to its top [2].

Other technical characteristics of the material provided in the EPD:

Density (kg/m³)	Thermal conductivity λ (W/m.ºC)
Up to 115	0.040
140-160	0.043
170-190	0.044
190-210	0.045

Figure 139. Thermal conductivity based on density variation of expanded cork panel, source: material EPD [2]

Satisfies European Standards EN13170 and EN13172. Indoor VOC (Volatile Organic Compounds) emissions according to ISO 16000: Class A+.

PRODUCT RAW MATERIAL MAIN COMPOSITION		
Raw material category	Amount, mass-%	Material origin
Metals	–	–
Minerals	–	–
Fossil materials	–	–
Bio-based materials	100	Portugal

Figure 140. Product raw material main composition expanded cork panel, source: material EPD [2]

4.4.5 LCIA OF END OF LIFE FOR MODULES C1-C4

Deconstruction and demolition type is set as **timber frame building.** GWP of timber frame building demolition is **5,3 kgCO2e / m2** according to Oneclick LCA database.

All building materials' quantities got adapted to the default quantity of related resource mapped, and the final quantity of each material are multiplied by this value in order to calculate end of life emissions of whole building.

[2] Amorim Cork Insulation. Environmental Product Declaration: Expanded Insulation Corkboard (ICB). EPD Hub, HUB-0281, 13 Feb. 2023.

4.4.6 LCIA TOTAL EMBODIED CARBON OF DESIGN OPTIMIZATION

	RESULT CATEGORY	GWP kgCO2e
A1-A3	CONSTRUCTION MATERIALS	**32 988,92**
A4	TRANSPORTATION TO THE SITE	**8 077,74**
A5	CONSTRUCTION/ INSTALLATION PROCESS	**5 611,08**
B1	USE PHASE	not included
B3	REPAIR	not included
B4-B5	MATERIAL REPLACEMENT AND REFURBISHMENT	**3 088,71**
B6	ENERGY CONSUMPTION	not included
B7	WATER USE	not included
C1-C4	END OF LIFE	**9 570,61**
D	EXTERNAL IMPACTS (not included in totals)	**-54 366,66**
	TOTAL WHOLE LIFE EMBODIED CARBON kgCO2e:	**59 337,07**

HEATED FLOOR AREA: 347,57 m²
UNHEATED FLOOR AREA :54,7 m²
TOTAL FLOOR AREA : 402,27 m²
LIFE SPAN OF THE BUILDING: 50 years

WHOLE LIFE EMBODIED CARBON OF HEATED FLOOR AREAkgCO2e PER m²: **170,71** kgCO2e/m²
WHOLE LIFE EC (kgC02e) / HEATED FLOOR AREA (m²)
(59 337,07 / 347,57)

WHOLE LIFE EMBODIED CARBON OF HEATED FLOOR AREA m² PER YEAR: **3,41** kgCO2e/m²
WHOLE LIFE EC (kgC02e) / HEATED FLOOR AREA (m²) / BUILDING LIFE SPAN (years)
(170,71 / 50)

WHOLE LIFE EMBODIED CARBON OF TOTAL FLOOR AREA kgCO2e PER m²: **147,50** kgCO2e/m²
WHOLE LIFE EC (kgC02e) / TOTAL FLOOR AREA (m²)
(59 337,07 / 54,7)

WHOLE LIFE EMBODIED CARBON OF TOTAL FLOOR AREA m² PER YEAR: **2,95** kgCO2e/m²
WHOLE LIFE EC (kgC02e) / TOTAL FLOOR AREA (m²) / BUILDING LIFE SPAN (years)

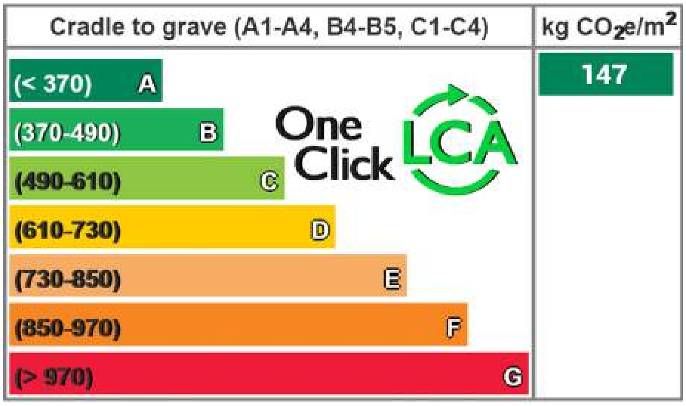


Figure 141. Redrawn carbon heroes benchmark table for design optimization, source: Oneclick LCA

Figure 141 is provided by Oneclick LCA but as default it was calculated for 60 years building life span and gross internal floor area which can be inserted in the "building area" section in Oneclick LCA. Thus, to have the correct value, the figure is redrawn calculating EC kgCO2e/m2 applying **50 years of lifespan** and **total gross floor area**. Carbon heroes benchmark is according to " Italy all building types - 2023 Q3-" in Oneclick LCA tool which is possible to modify according to project location or type. Initially "Italy" is set as the project location and "all building types" is automatically set by Oneclick LCA. Other options for Italy were " office excl. MEP- 2023 Q3" and "warehouse excl. MEP-2023 Q3". In this case "all building types" was the most appropriate option as it was set automatically by the tool.

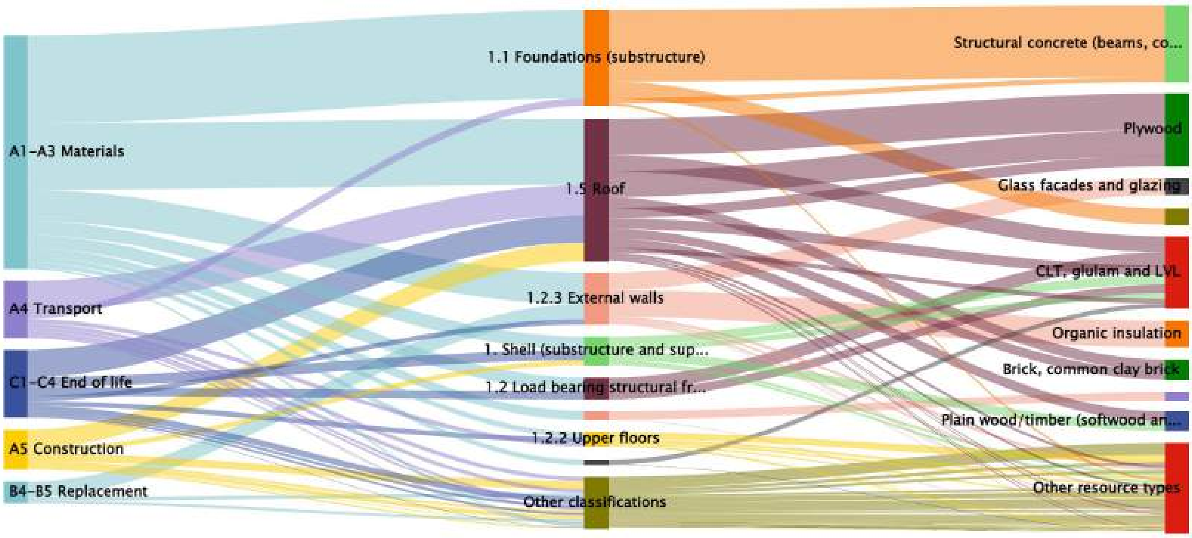


Figure 142. Sankey diagram of GWP of design optimization, source: Oneclick LCA

Figure 142 is provided by Oneclick LCA according to the final results of LCA analysis which are presented in the next graphs as "Global Warming kgCO2e-Life Cycle Stages", "Global Warming kgCO2e-Resource Types", Global Warming kgCO2e-Classifications", "Mass kg-Classifications".

GLOBAL WARMING kgCO2 - LIFE CYCLE STAGES

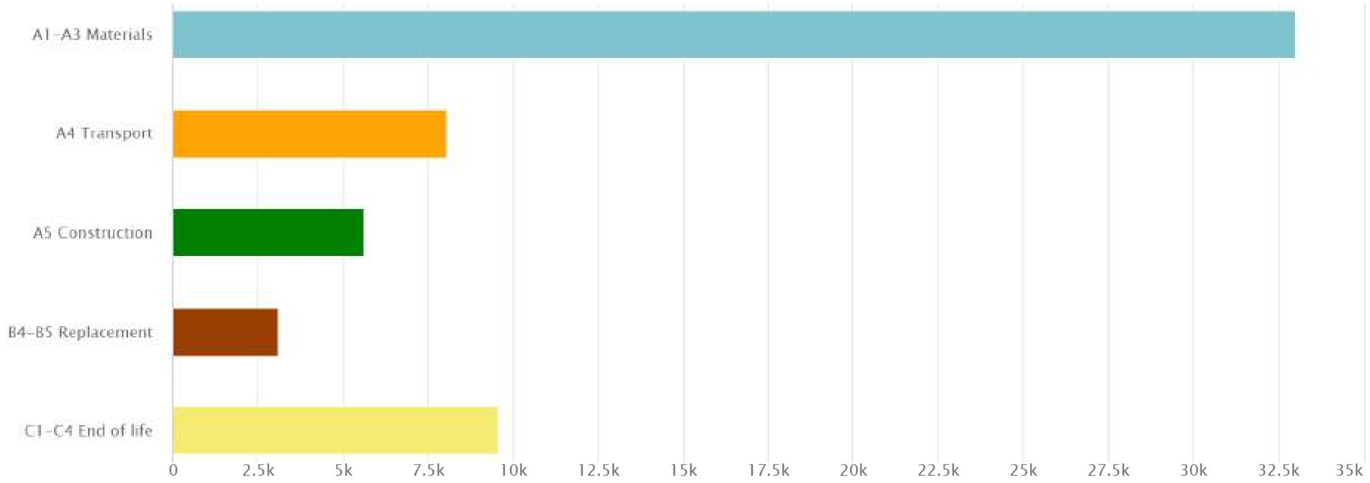


Figure 143. Global Warming kgCO2e Graph-Life Cycle Stages of design optimization, source: Oneclick LCA

Item	Value	Unit	Percentage %
A1-A3 Materials	32 988,92	kg CO_2e	55.6 %
A4 Transport	8 077,74	kg CO_2e	13.61 %
A5 Construction	5 611,07	kg CO_2e	9.46 %
B4-B5 Replacement	3 088,71	kg CO_2e	5.21 %
C1-C4 End of life	9 570,60	kg CO_2e	16.13 %

GLOBAL WARMING kgCO2 - RESOURCE TYPES

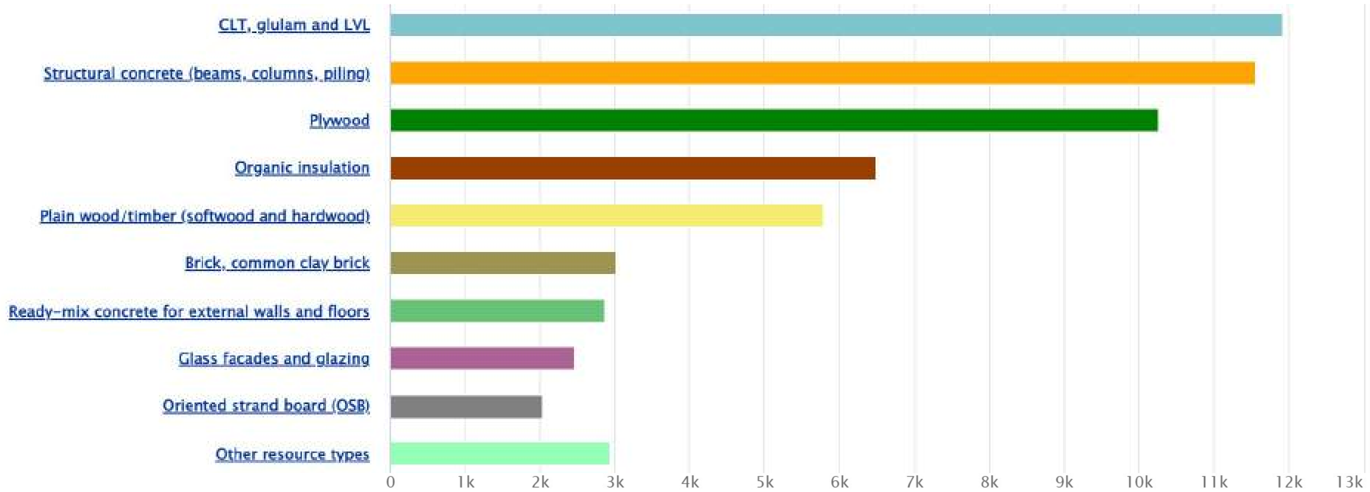


Figure 144. Global Warming kgCO2e Graph of design optimization-Resource Types, source: Oneclick LCA

Item	Value	Unit	Percentage %
CLT, glulam and LVL	11 929,23	kg CO_2e	20.1 %
Structural concrete (beams, columns, piling)	11 562,66	kg CO_2e	19.49 %
Plywood	10 266,56	kg CO_2e	17.3 %
Organic insulation	6 486,32	kg CO_2e	10.93 %
Plain wood/timber (softwood and hardwood)	5 785,54	kg CO_2e	9.75 %
Brick, common clay brick	3 015,16	kg CO_2e	5.08 %
Ready-mix concrete for external walls and floors	2 865,46	kg CO_2e	4.83 %
Glass facades and glazing	2 462,85	kg CO_2e	4.15 %
Oriented strand board (OSB)	2 027,48	kg CO_2e	3.42 %
Other resource types	2 985,76	kg CO_2e	4.95 %

GLOBAL WARMING kgCO2 - CLASSIFICATIONS

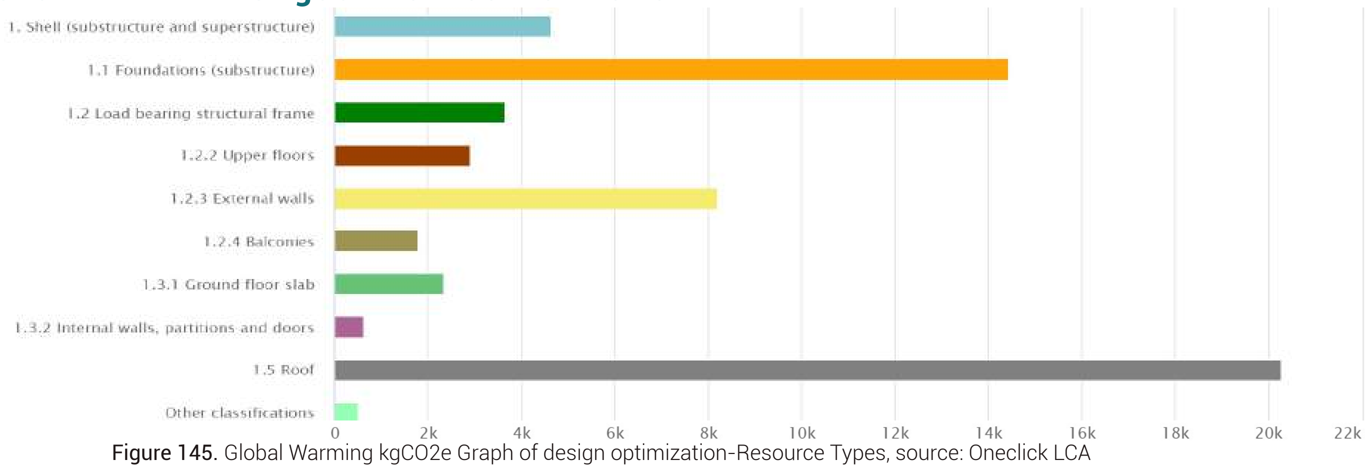


Figure 145. Global Warming kgCO2e Graph of design optimization-Resource Types, source: Oneclick LCA

Item	Value	Unit	Percentage %
1. Shell (substructure and superstructure)	4 615,05	kg CO_2e	7.78 %
1.1 Foundations (substructure)	14 428,13	kg CO_2e	24.32 %
1.2 Load bearing structural frame	3 641,77	kg CO_2e	6.14 %
1.2.2 Upper floors	2 915,07	kg CO_2e	4.91 %
1.2.3 External walls	8 225,12	kg CO_2e	13.86 %
1.2.4 Balconies	1 780,07	kg CO_2e	3.0 %
1.3.1 Ground floor slab	2 340,91	kg CO_2e	3.95 %
1.3.2 Internal walls, partitions and doors	624,84	kg CO_2e	1.05 %
1.5 Roof	20 269,52	kg CO_2e	34.16 %
Other classifications	496,54	kg CO_2e	0.84 %

MASS kg - CLASSIFICATIONS

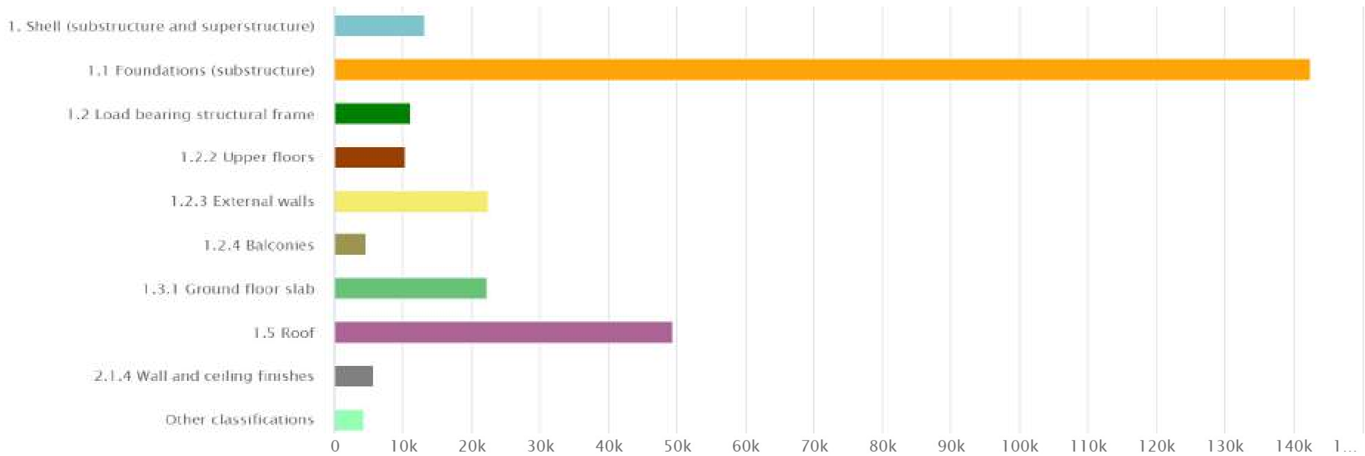


Figure 146. Mass (kg) Graph of design optimization -Classifications, source: Oneclick LCA

Item	Value	Unit	Percentage %
1. Shell (substructure and superstructure)	13 239,19	Kg	4.63 %
1.1 Foundations (substructure)	142 571,17	Kg	49.89 %
1.2 Load bearing structural frame	11 200,20	Kg	3.92 %
1.2.2 Upper floors	10 264,93	Kg	3.59 %
1.2.3 External walls	22 537,86	Kg	7.89 %
1.2.4 Balconies	4 589,30	Kg	1.61 %
1.3.1 Ground floor slab	22 147,24	Kg	7.75 %
1.5 Roof	49 276,01	kg	17.24 %
2.1.4 Wall and ceiling finishes	5 700,29	kg	2.0 %
Other classifications	4 218,84	kg	1.48 %

4.4.7 BILL OF QUANTITY OF DESIGN OPTIMIZATION

	MATERIAL	m²	THICKNESS (m)	m³	WEIGHT (kg)
FOUNDATION	*Blinding layer ready-mix concrete %75 GGBS content	177,30	0,10	17,73	42552,00
	*Reinforced concrete beam 900x400mm			34,13	82120,19
	*Reinforced concrete beam 500x400mm			5,16	12415,48
MAIN BUILDING STRUCTURE	*GLULAM beams 250x250 mm			3,65	1772,81
	*GLULAM beams 250x200 mm			7,12	3458,18
	*GLULAM columns 250x250 mm			8,99	4366,44
ROOF STRUCTURE	*GLULAM roof truss 240x240 mm			10,53	5114,42
	*GLULAM roof purlins 100x200 mm			11,84	5750,69
	*GLULAM roof rafters 180x180 mm			1,23	597,41
	*Softwood roof battens 50x60 mm			4,07	1790,8
ROOF LAYERS	*Clay roofing tiles (terracotta)	271,63	0,04	10,86	9507,05
	*Vapour barrier membrane	271,63	0,0015	0,4	488,93
	*Plywood	271,63	0,03	8,15	7334,01
	*Plywood	271,63	0,025	6,79	6111,68
	*Hemp,linen,cotton insulation	271,63	0,20	54,33	1629,78
	*Recovered wood ceiling	271,63	0,02	5,43	3571,93
GROUND FLOOR STRUCTURE (F01)	*GLULAM beams 200x200 mm			2,73	1325,96
	*GLULAM beams 100x200h mm			1,19	577,98
GROUND FLOOR SLAB (F01)	*Sandstone floor finish	165,08	0,02	3,30	165,08
	*Lightweight concrete %50 recycled binder	165,08	0,1	16,51	3631,76
	*OSB panel	165,08	0,015	2,48	1114,29
	*Hemp,linen,cotton insulation	165,08	0,2	33,02	990,48
	*Vapour barrier membrane	165,08	0,0015	0,24	297,14
	*Lightweight concrete %50 recycled binder	165,08	0,05	8,25	1815,88
GROUND FLOOR STRUCTURE (F02)	*GLULAM beams 200x100h mm			0,40	194,28
	*GLULAM beams 100x100 mm			0,69	335,13
GROUND FLOOR SLAB (F02)	*Sandstone floor finish	51,32	0,02	1,03	51,32
	*Lightweight concrete %50 recycled binder	51,32	0,1	5,13	1129,04
	*OSB panel	51,32	0,015	0,77	346,41
	*Hemp,linen,cotton insulation	51,32	0,1	5,13	153,96
	*Vapour barrier membrane	51,32	0,0015	0,08	92,38
FIRST FLOOR STRUCTURE (F04)	*GLULAM beams 200x250 mm			3,86	1874,8
	*GLULAM beams 100x250h mm			4,11	1996,23
	*Softwood battens 50x50 mm			4,23	1861,2

	MATERIAL	m²	THICKNESS (m)	m³	WEIGHT (kg)
FIRST FLOOR SLAB (F04)	*Recovered floor finish	136,15	0,02	2,72	1790,37
	*OSB panel	136,15	0,015	2,04	919,01
	*Hemp,linen,cotton insulation	136,15	0,25	34,04	1021,13
	*OSB panel	136,15	0,015	2,04	919,01
	*Gypsum board	136,15	0,0125	1,70	1523,18
TERRACE STRUCTURE	*GLULAM columns 200x200 mm			0,76	369,13
	*GLULAM beams 250x250 mm			1,51	733,41
	*GLULAM beams 200x200 mm			0,30	145,71
	*GLULAM beams 100x250h mm			0,40	194,28
TERRACE SLAB	*Recovered floor finish	54,70	0,02	1,09	719,31
	*Vapour barrier membrane	54,70	0,0015	0,08	98,46
	*CL (Cross Laminated Timber)	54,70	0,065	3,56	1671,09
EXTERNAL WALL (W01)	*Expanded Cork Panel	231,74	0,08	18,54	2132,01
	*OSB panel	231,74	0,015	3,48	1564,25
	*Hemp,linen,cotton insulation	231,74	25	57,94	1738,05
	*OSB panel	231,74	0,015	3,48	1564,25
	*Vapour barrier membrane	231,74	0,0015	0,35	417,13
	*Interior clay plaster	231,74	0,02	4,63	6442,37
EXTERNAL WALL (W02)	*Treated wood cladding	14,25	0,02	0,29	149,63
	*OSB panel	14,25	0,015	0,21	96,19
	*Hemp,linen,cotton insulation	14,25	25	3,56	106,88
	*OSB panel	14,25	0,015	0,21	96,19
	*Vapour barrier membrane	14,25	0,0015	0,02	25,65
	*Interior clay plaster	14,25	0,02	0,29	396,15
EXTERNAL WALL (W03)	*Argon gas filled insuating double glazing	79,19	0,025	1,98	1583,80
	*Treated wood mullions			0,87	456,75
EXTERNAL WALL STRUCTURES	*Softwood studs 250x100 mm			9,36	4118,40
	*Softwood horizontal bettens 50x50 mm			1,38	607,20
	*Softwood vertical bettens 50x60 mm			0,108	47,52
INTERNAL WALLS	*Interior clay plaster	181,42	0,01	18,14	5043,48
	*OSB panel	181,42	0,015	2,72	1224,59
	*Hemp,linen,cotton insulation	181,42	0,01	18,14	544,26
	*OSB panel	181,42	0,015	2,72	1224,59
	*Interior clay plaster	181,42	0,01	18,14	5043,48
	*Softwood studs 100x50 mm			1,76	774,40

CHAPTER 4 FIGURES:

CHAPTER 4 REFERENCES:

[1] Ida Östling (2018). *Life cycle analysis as a tool for CO2 mitigation in the building sector* (Master's Thesis UMEA University)

[2] Amorim Cork Insulation. Environmental Product Declaration: Expanded Insulation Corkboard (ICB). EPD Hub, HUB-0281, 13 Feb. 2023.

chapter 5

COMPARISONS AND CONCLUSION

In order to document and illustrate the effectiveness of enhancing a business-as-usual (BAU) scenario to provide a better project where there would be less impacts on the environment, actual results of comparative carbon emissions LCA of two projects will be displayed. In this comparison, all LCIA of A1-A3 Modules of each building part of each project will be taken into account.

By doing this, we will be able to comprehensively evaluate the environmental impact associated with each project. In this way, we will be able to conclude about the environmental effect, connected with the specific project. The total whole-life embodied carbon of the building regarding the project will be expressed as kgCO2e per m² per year of heated and total area and then compared at last.

This comparison is designed to show the currently accepted index of the global warming potential (GWP) of both projects. The findings will reveal the importance of building structure and the materials selected by an architect or managers in the construction and architecture industry. Such decisions can go a long way towards minimizing negative effects their inventions may have on environment. The summarized information of this comparison may be very useful for perspective projects and architects' choices. Indeed, it may be said that it represents a certain level of progress on the way to making the circumstances of practice in the architecture industry noticeably more sustainable. Thus, the findings reveal the specifications of the chosen materials and explain how it would influence the construction process, thus helping other architects and construction companies to emerge with more sustainable appearances and practices.

5. COMPARISONS AND CONCLUSION

5.1. COMPARISON OF GWP OF BUILDING PARTS (A1-A3 MODULES)

FOUNDATION (BAU)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Blinding layer ready-mix concrete C25/30	177,30	0,10	17,73	2387,04	42322,22	0,0852	3605,43
Reinforced concrete beam 900x400mm			34,13	2406,1	82120,19	0,107	8786,86
Reinforced concrete beam 500x400mm			5,16	2406,1	12415,48	0,107	1328,46
						TOTAL:	**13720,75**

LCIA table of foundation of BAU from Figure 79. LCIA tables of BAU construction materials for modules A1-A3

FOUNDATION (OPTIMIZATION)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Blinding layer ready-mix concrete %75 GGBS content	177,30	0,10	17,73	2400,00	42552,00	0,0542	2306,32
Reinforced concrete beam 900x400mm			34,13	2406,1	82120,19	0,107	8786,86
Reinforced concrete beam 500x400mm			5,16	2406,1	12415,48	0,107	1328,46
						TOTAL:	**12421,63**

LCIA table of foundation of optimization Figure 135. LCIA tables of design optimization construction materials for modules A1-A3

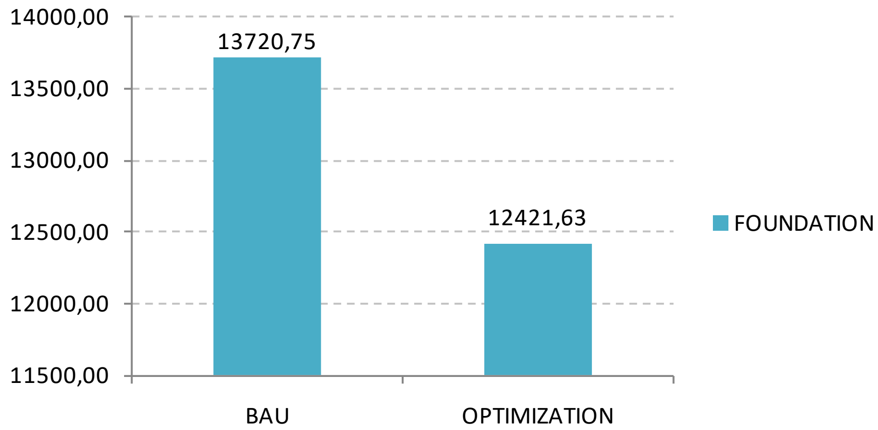


Figure 147. Comparative chart of foundation GWP. BAU vs. Design Optimization

Foundation beams of both projects are reinforced concrete. As seen in the tables above GWP of the foundation beams are the same. On the other hand, blinding layer of the BAU scenario is ready-mix concrete with C25/30 strength. For the design optimization as blinding later ready-mix concrete C25/30 with %75 GGBS content are chosen. As it shown in the figure above GWP difference of two different scenarios is more than 1 ton of GWP which is significant. This comparison demonstrates that the type of the concrete has a great impact for the reduction of CO2 emissions.

MAIN BUILDING STRUCTURE (BAU)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Reinforced concrete column 250x500mm	12,80	2406,10	30798,08	0,107	3295,39
Reinforced concrete beam 250x400mm	6,27	2406,10	15086,25	0,107	1614,23
Reinforced concrete beam 250x250mm	3,52	2406,10	8469,47	0,107	906,23
				TOTAL:	**5815,86**

LCIA table of main building structure of BAU from **Figure 79.** LCIA tables of BAU construction materials for modules A1-A3

MAIN BUILDING STRUCTURE (OPTIMIZATION)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
GLULAM beams 250x250 mm	3,65	485,70	1772,81	95,04	346,90
GLULAM beams 250x200 mm	7,12	485,70	3458,18	95,04	676,68
GLULAM columns 250x250 mm	8,99	485,70	4366,44	95,04	854,41
				TOTAL:	**1877,99**

LCIA table of main building structure of optimization **Figure 135.** LCIA tables of design optimization construction materials for modules A1-A3

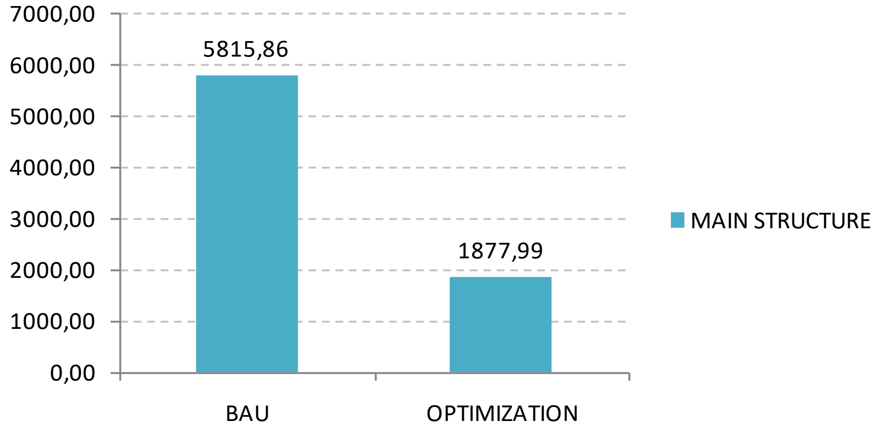


Figure 148. Comparative chart of main building structures GWP. BAU vs. Design Optimization

Main building structure of BAU scenario is reinforced concrete with C25/30 strength with %0 recycled binder content. On the other hand for the design optimization as main building structure GLULAM (Glued Laminated Timber) 250x250mm or 250x200mm beams and 250x250mm colums are chosen. This comparison is a great example to demonstrate the difference of CO2 emissions between concrete and timber as building structures which is around 4 tons. 4 tons of kgCO2e difference is a difference which cannot be overlooked.

GROUND FLOOR SLAB F01 (BAU)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Cement screed	137,60	0,063	8,67	1300,00	11269,44	0,16	1803,11
Lightweight concrete %0 recycled binders	137,60	0,26	35,78	220,00	7870,72	1,0022	7888,04
Outdoor Lightweight concrete (F00) %0 recycled binder	27,48	0,05	1,37	220,00	302,28	1,0022	302,95
						TOTAL:	9691,15

LCIA table of ground floor slab (F01) of BAU from Figure 79. LCIA tables of BAU construction materials for modules A1-A3

GROUND FLOOR SLAB LAYERS F01 (OPTIMIZATION)

GROUND FLOOR STRUCTURE (F01)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
GLULAM beams 200x200 mm	2,73	485,70	1325,96	95,04	259,46
GLULAM beams 100x200h mm	1,19	485,70	577,98	95,04	113,10
				TOTAL:	372,56

GROUND FLOOR LAYERS (F01)

	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Sandstone floor finish	165,08	0,02	3,30	1,00	165,08	0,0594	9,81
Vapour barrier membrane	165,08	0,0015	0,25	1,80	297,14	0,033	9,81
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Lightweight concrete %50 recycled binder	165,08	0,10	16,51	220,00	3631,76	0,06909	250,92
Lightweight concrete %50 recycled binder	165,08	0,05	8,25	220,00	1815,88	0,06909	125,46
Hemp,linen,cotton insulation	165,08	0,20	33,02	30,00	990,48	0,000666	0,66
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
OSB panel	165,08	0,015	2,48	450,00	1114,29	19,13	47,37
						TOTAL:	444,02
					TOTAL F01:	247,35+443,69	816,58

LCIA table of ground floor slab (F01) of optimization Figure 135. LCIA tables of design optimization construction materials for modules A1-A3

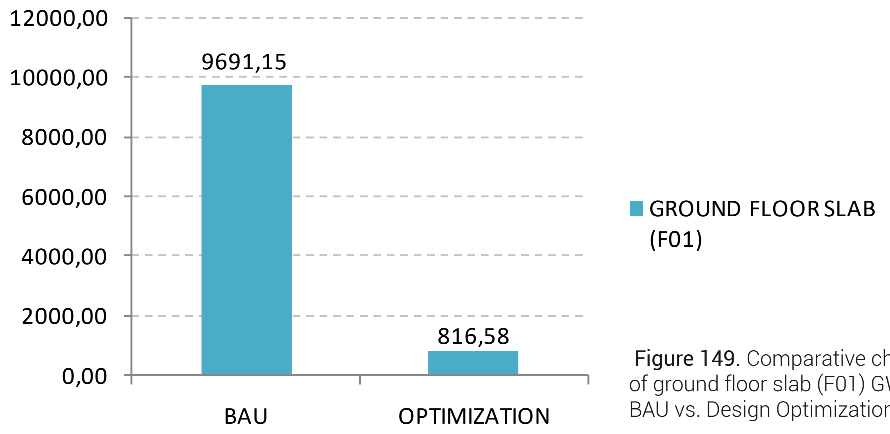


Figure 149. Comparative chart of ground floor slab (F01) GWP. BAU vs. Design Optimization

Reflected in the tables above is the fact that the type of lightweight concrete does affect the GWP of the ground floor slab (F01). Most importantly, the incorporation of the recycled binder content significantly improves GWP reduction of lightweight concrete. Also, it can be seen that the use of hemp, linen, and cotton as the insulation material is fairly a more sustainable choice as evidenced by it's low GWP. Conversely, the GWP of the ground floor slab following the BAU is 9,691.15 kgCO2e whereas the ground floor slab, including its structure which has been optimized has a GWP of 816. 58 kgCO2e; the fact is that the reduction is noticeable here as well.

GROUND FLOOR SLAB LAYERS F02 (BAU)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Cement screed	51,32	0,063	3,23	1300,00	4203,11	0,16	672,50
Lightweight concrete %0 recycled binders	51,32	0,11	5,65	220,00	1241,94	1,0022	1244,68
						TOTAL:	1917,17

LCIA table of ground floor slab layers (F02) of BAU from Figure 79. LCIA tables of BAU construction materials for modules A1-A3

GROUND FLOOR SLAB LAYERS F02 (OPTIMIZATION)

GROUND FLOOR STRUCTURE (F02)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
GLULAM beams 200x100h mm	0,40	485,70	194,28	95,04	38,02
GLULAM beams 100x100 mm	0,69	485,70	335,13	95,04	65,58
				TOTAL:	103,59

LCIA table of ground floor structure of optimization Figure 131. LCIA tables of design optimization construction materials for modules A1-A3

GROUND FLOOR LAYERS (F02)

	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Sandstone floor finish	51,32	0,02	1,03	1,00	51,32	0,0594	3,05
Vapour barrier membrane	51,32	0,0015	0,08	1,80	92,38	0,033	3,05
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Hemp,linen,cotton insulation	51,32	0,10	5,13	30,00	153,96	0,000666	0,10
Lightweight concrete %50 recycled binder	51,32	0,10	5,13	220,00	1129,04	0,06909	78,01
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
OSB panel	51,32	0,015	0,77	450,00	346,41	19,13	14,73
						TOTAL:	98,93
					TOTAL F01:	68,78+98,83	202,52

LCIA table of ground floor slab layers (F02) of optimization Figure 135. LCIA tables of design optimization construction materials for modules

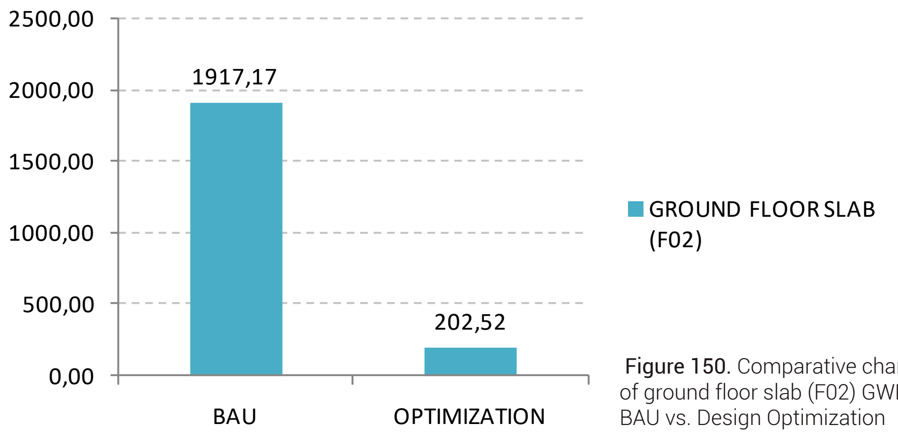


Figure 150. Comparative chart of ground floor slab (F02) GWP. BAU vs. Design Optimization

As seen in the tables above, we can say the changing factors are the same as ground floor slab (F01). The type of the lightweight concrete and it's recycled binder content in it is the game-changer in the total GWP of the ground floor slabs of both design proposals.

FIRST FLOOR STUCTURES F03 (BAU)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
IPE 300 steel beam	0,20	7850,00	1601,40	3,25	5204,55
IPE 220 steel beam	0,04	7850,00	282,60	3,25	918,45
IPE 100 steel beam	0,03	7850,00	235,5	3,25	765,85
	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Softwood beam 240x240 mm	8,88	440,00	3907,20	62,94	558,91
				TOTAL:	7447,76

LCIA table of first floor structures (F03) of BAU from Figure 79. LCIA tables of BAU construction materials for modules A1-A3

FIRST FLOOR STUCTURES F03 (OPTIMIZATION)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
GLULAM beams 200x250 mm	3,86	485,70	1874,80	95,04	366,85
GLULAM beams 100x250h mm	4,11	485,70	1996,23	95,04	390,61
Softwood battens 50x50 mm	4,23	440,00	1861,20	59,09	249,95
				TOTAL:	1007,42

LCIA table of first floor structures (F03) of optimization Figure 135. LCIA tables of design optimization construction materials for modules

FIRST FLOOR SLAB LAYERS F03 (BAU)

	m²			mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Parquet floor finish	126,23			9,53	1202,97	2,1259	2557,40
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Cement screed	126,23	0,023	2,90	1300,00	3774,28	0,16	603,88
Lightweight concrete %0 recycled binders	126,23	0,08	10,10	220,00	2221,65	1,0022	2226,54
Lightweight concrete with joists	126,23	0,07	8,84	960,00	8482,66	0,4091	3470,25
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Wooden ceiling	126,23	0,03	3,79	189,00	715,72	23,85	90,32
						TOTAL:	8948,39

LCIA table of first floor slab layers (F03) of BAU from Figure 79. LCIA tables of BAU construction materials for modules A1-A3

FIRST FLOOR SLAB LAYERS F03 (OPTIMIZATION)

	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Recovered wooden floor finish	136,15	0,02	2,72	13,15	1790,37	0,0475	85,04
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Hemp,linen,cotton insulation	136,15	0,25	34,04	30,00	1021,13	0,000666	0,68
Gypsum board	136,15	0,0125	1,70	895,00	1523,18	0,218	332,05
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
OSB panel	136,15	0,015	2,04	450,00	919,01	19,13	39,07
OSB panel	136,15	0,015	2,04	450,00	919,01	19,13	39,07
						TOTAL:	495,91

LCIA table of first floor slab layers (F03) of optimization Figure 135. LCIA tables of design optimization construction materials for modules A1-A3

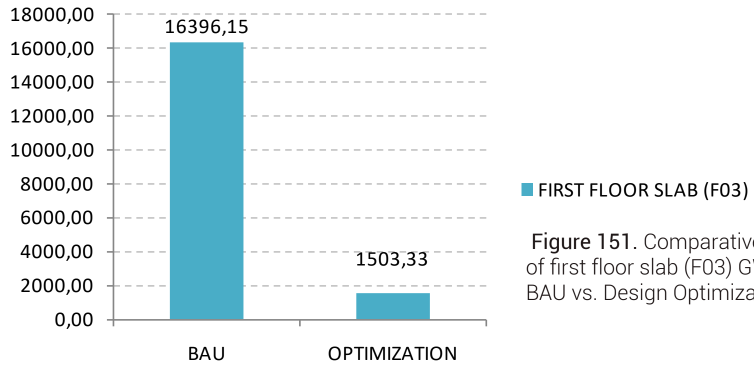


Figure 151. Comparative chart of first floor slab (F03) GWP. BAU vs. Design Optimization

As seen in the tables above, the usage of steel as a structural element has a drastic effect on environmental consideration. Therefore, the value of the first structure on the first floor in the BAU scenario amounts to 7447,76 kgCO2e which considerably contributes to the total CO2e for the first floor slab. At the same time, design optimization of the first-floor structure gives a GWP of 1007,42 kgCO2e. This shows a great decrease, thus timber as a structural material in preference to steel has considerably less GWP.

TERRACE STRUCTURES F04 (BAU)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
IPE 300 steel beam	0,076	7850,00	596,60	3,25	1938,95
IPE 200 steel beam	0,036	7850,00	282,60	3,25	918,45
IPE 180 steel beam	0,110	7850,00	863,50	3,25	2806,38
HE 200 column	0,034	7850,00	266,90	3,25	867,43
				TOTAL:	6531,20

LCIA table of terrace structures (F04) of BAU from Figure 79. LCIA tables of BAU construction materials for modules A1-A3

TERRACE STRUCTURES F04 (OPTIMIZATION)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
GLULAM columns 200x200 mm	0,76	485,70	369,13	95,04	72,23
GLULAM beams 250x250 mm	1,51	485,70	733,41	95,04	143,51
GLULAM beams 200x200 mm	0,30	485,70	145,71	95,04	28,51
GLULAM beams 100x250h mm	0,40	485,70	194,28	95,04	38,02
				TOTAL:	282,27

LCIA table of terrace structures (F04) of optimization Figure 135. LCIA tables of design optimization construction materials for modules

TERRACE FLOOR SLAB LAYERS F04 (BAU)

	m²			mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Parquet floor finish	53,70			9,53	511,76	2,1259	1087,95
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Lightweight concrete %0 recycled binders	53,70	0,07	3,76	220,00	826,98	1,0022	828,80
XPS insulation	53,70	0,10	5,37	31,25	167,81	1,9263	323,26
Lightweight concrete %0 recycled binders	53,70	0,03	1,61	220,00	354,42	1,0022	355,20
	m²			mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Aluminium corrugated sheet	53,70			3,40	182,58	12,85	2346,68
						TOTAL:	4941,89

LCIA table of terrace floor slab layers (F04) of BAU from Figure 79. LCIA tables of BAU construction materials for modules A1-A3

TERRACE FLOOR SLAB LAYERS F04 (OPTIMIZATION)

	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Recovered wooden floor finish	54,70	0,02	1,09	13,15	719,31	0,0475	34,17
Vapour barrier membrane	54,70	0,0015	0,08	1,80	98,46	0,033	3,25
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
CL (Cross Laminated Timber)	54,70	0,065	3,56	470,00	1671,09	106,95	380,26
						TOTAL:	417,68

LCIA table of terrace floor slab layers (F04) of optimization Figure 135. LCIA tables of design optimization construction materials for modules A1-A3

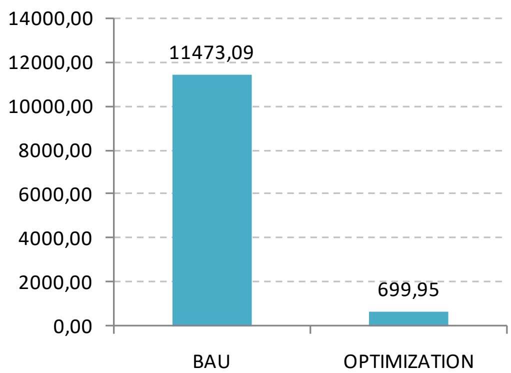


Figure 152. Comparative chart of terrace floor slab (F04) GWP. BAU vs. Design Optimization

As the demonstration of the first floor slab (F03), it is possible to see again the steel usage affects the GWP of the terraces significantly. Additionally in this case, it is also possible to see the difference between concrete and timber usage for the slab layers. Lightweight concrete with %0 recycled binder content and XPS as insulation material has great contribution in increasing the total GWP of the terrace slab in BAU scenario.

ROOF STRUCTURES (BAU)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Softwood ridge 240x320 mm	1,45	440,00	638,00	62,94	91,26
Softwood truss 240x240 mm	10,53	440,00	4633,20	62,94	662,76
Softwood purlins 100x100 mm	3,87	440,00	1702,80	62,94	243,58
Softwood rafter 180x180 mm	7,52	440,00	3308,80	62,94	473,31
Softwood battens 50x60 mm	4,07	440,00	1790,80	62,94	256,17
				TOTAL:	1727,07

LCIA table of roof structures of BAU from Figure 79. LCIA tables of BAU construction materials for modules A1-A3

ROOF STRUCTURES (OPTIMIZATION)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
GLULAM roof truss 240x240 mm	10,53	485,70	5114,42	95,04	1000,77
GLULAM roof purlins 100x200 mm	11,84	485,70	5750,69	95,04	1125,27
GLULAM roof rafters 180x180 mm	1,23	485,70	597,41	95,04	116,90
Softwood roof battens 50x60 mm	4,07	440,00	1790,80	59,09	240,50
				TOTAL:	2483,44

LCIA table of roof structures of optimization Figure 135. LCIA tables of design optimization construction materials for modules A1-A3

ROOF LAYERS (BAU)

	m²			mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Clay roofing tile (terracotta)	271,63			35,00	9507,05	0,159	1511,62
Vapour barrier membrane	271,63			1,80	488,93	0,033	16,13
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Rockwool insulation	271,63	0,20	54,33	50,00	2716,30	1,23	3341,05
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Softwood ceiling	271,63	0,02	5,43	440,00	2390,34	23,85	129,57
Plywood	271,63	0,025	6,79	900	6111,68	344,00	2336,02
Plywood	271,63	0,03	8,15	900	7334,01	344,00	2803,22
						TOTAL:	10137,61

LCIA table of roof layers of BAU from Figure 79. LCIA tables of BAU construction materials for modules A1-A3

ROOF LAYERS (OPTIMIZATION)

	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Clay roofing tiles (terracotta)	271,63			35,00	9507,05	0,159	1511,62
Vapour barrier membrane	271,63	0,0015	0,41	1,80	488,93	0,033	16,13
Recovered wooden ceiling	271,63	0,20	54,33	13,15	3571,93	0,0475	169,67
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Hemp,linen,cotton insulation	271,63	0,20	54,33	30,00	1629,78	0,000666	1,09
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Plywood	271,63	0,03	8,15	900,00	7334,01	344,00	2803,22
Plywood	271,63	0,025	6,79	900,00	6111,68	344,00	2336,02
						TOTAL:	6837,75

LCIA table of roof layers of optimization Figure 135. LCIA tables of design optimization construction materials for modules A1-A3

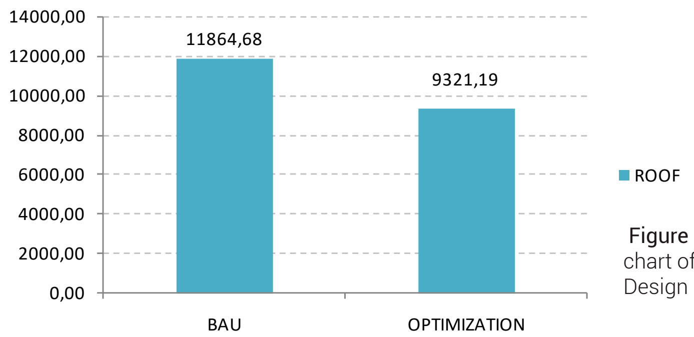


Figure 153. Comparative chart of roof GWP. BAU vs. Design Optimization

EXTERNAL WALL LAYERS W01 (BAU)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Cement plaster	294,35	0,01	2,94	1400,00	4120,90	0,47	1936,82
Rockwool insulation	294,35	0,12	35,32	50,00	1766,10	1,23	2172,30
Hollow bricks	294,35	0,30	88,31	503,00	44450,00	0,17	7569,84
Cement plaster	294,35	0,02	5,89	1400,00	8241,80	0,47	3873,65
						TOTAL:	15552,61

LCIA table of external wall layers of BAU from Figure 79. LCIA tables of BAU construction materials for modules A1-A3

EXTERNAL WALL LAYERS W01 (OPTIMIZATION)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Expanded Cork Panel	231,74	0,08	18,54	115,00	2132,01	0,7654	1631,84
Hemp,linen,cotton insulation	231,74	0,25	57,94	30,00	1738,05	0,000666	1,16
	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Vapour barrier membrane	231,74	0,0015	0,35	1,80	417,13	0,033	13,77
Interior clay plaster	231,74	0,02	4,63	27,80	6442,37	0,02359	151,98
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
OSB panel	231,74	0,015	3,48	450,00	1564,25	19,13	66,50
OSB panel	231,74	0,015	3,48	450,00	1564,25	19,13	66,50
						TOTAL:	1931,73

LCIA table of external wall layers (W01) of optimization Figure 135. LCIA tables of design optimization construction materials for modules A1-A3

EXTERNAL WALL LAYERS W02 (OPTIMIZATION)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Hemp,linen,cotton insulation	14,25	0,25	3,56	30,00	106,88	0,000666	0,07
	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Vapour barrier membrane	14,25	0,0015	0,02	1,80	25,65	0,033	0,85
Interior clay plaster	14,25	0,02	0,29	27,80	396,15	0,02359	9,35
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Treated wood cladding	14,25	0,02	0,29	525,00	149,63	62,37	17,78
OSB panel	14,25	0,015	0,21	450,00	96,19	19,13	4,09
OSB panel	14,25	0,015	0,21	450,00	96,19	19,13	4,09
						TOTAL:	36,22

LCIA table of external wall layers (W02) of optimization Figure 135. LCIA tables of design optimization construction materials for modules A1-A3

EXTERNAL GLAZING CURTAIN WALL LAYERS W03 (OPTIMIZATION)

	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Argon gas filled insuating double glazing	79,19	0,025	1,98	20,00	1583,80	1,537	2434,30
			m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Treated wood mullions			0,87	525,00	456,75	62,37	54,26
						TOTAL:	2488,56

LCIA table of external glazing curtain wall layers (W03) of optimization Figure 135. LCIA tables of design optimization construction materials for modules A1-A3

EXTERNAL WALL SECONDARY STRUCTURES (OPTIMIZATION)

	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
Softwood studs 250x100 mm	9,36	440,00	4118,40	59,09	553,08
Softwood horizontal bettens 50x50 mm	1,38	440,00	607,20	59,09	81,54
Softwood vertical bettens 50x60 mm	0,108	440,00	47,52	59,09	6,38
				TOTAL:	641,01

LCIA table of external wall secondary structure of optimization Figure 135. LCIA tables of design optimization construction materials for modules A1-A3

TOTAL EXTERNAL WALL GWP: 5097,53 kgCO2e

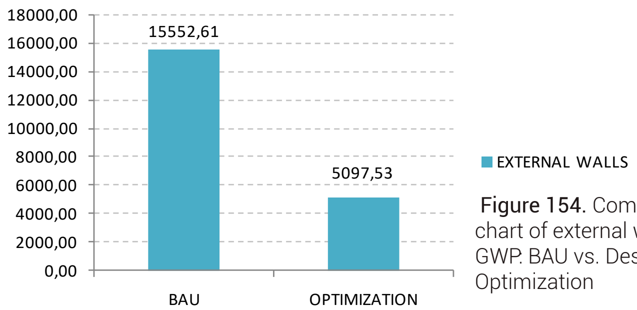


Figure 154. Comparative chart of external walls GWP. BAU vs. Design Optimization

INTERNAL WALL LAYERS W04 (BAU)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Gypsum plaster	192,26	0,02	3,85	400,00	1538,08	0,275	422,97
Rockwool insulation	192,26	0,07	13,46	50,00	672,91	1,23	827,68
Gypsum board	192,26	0,050	9,61	895,00	8598,21	0,218	1874,41
			linear meter	density kg/lm	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
*Metal framing for gypsum board			354,02	1,10	392,72	2,15	844,35
						TOTAL:	3969,41

*only for internal wall applications, windows/doors are excluded

LCIA table of internal walls of BAU from Figure 79. LCIA tables of BAU construction materials for modules A1-A3

INTERNAL WALL LAYERS W04 (OPTIMIZATION)

	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Hemp,linen,cotton insulation	181,42	0,10	18,14	30,00	544,26	0,000666	0,36
	m²	thickness (m)	m³	mass kg/m²	weight (kg)	GWP kgCO2e/kg	GWP kgCO2e
Interior clay plaster	181,42	0,01	1,81	27,80	5043,48	0,02359	118,98
Interior clay plaster	181,42	0,01	1,81	27,80	5043,48	0,02359	118,98
	m²	thickness (m)	m³	density kg/m³	weight (kg)	GWP kgCO2e/m³	GWP kgCO2e
OSB panel	181,42	0,015	2,72	450,00	1224,59	19,13	52,06
OSB panel	181,42	0,015	2,72	450,00	1224,59	19,13	52,06
Softwood studs 100x50 mm			1,76	440,00	774,40	59,09	104,00
						TOTAL:	446,43

LCIA table of external glazing curtain wall layers (W03) of optimization Figure 135. LCIA tables of design optimization construction materials for modules A1-A3

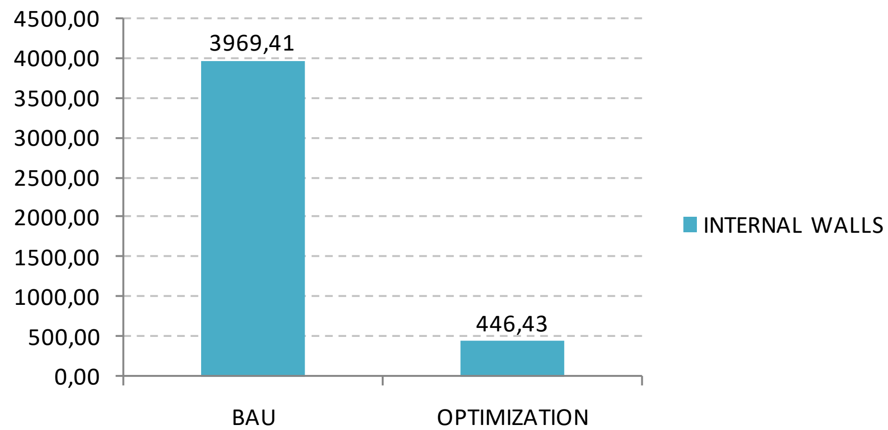


Figure 155. Comparative chart of internal walls GWP. BAU vs. Design Optimization

As seen in the tables above, gypsum board applications have a significant environmental impact. Additionally, the insulation material used in BAU scenario is rockwool has 827,41 kgCO2e GWP. On the other hand hemp,linen,cotton as insulation material for the design optimization has 0,36 kgCO2e GWP. This strong contrast proves that natural based materials have less environmental impact and it is possible to decrease EC of the buildings even only considering insulation material alone.

5.2. COMPARISON OF TOTAL GLOBAL WARMING POTENTIALS

RESULT CATEGORY		GLOBAL WARMING kgCO2e	
A1-A3	Construction Materials	32 988,92 |	-64%
A4	Transportation to site	8 077,74 |	-60%
A5	Construction/installation process	5 611,08 |	-37%
B1	Use phase	not included	
B3	Repair	not included	
B4-B5	Material replacement and refurbishment	3 088,71 |	-59%
B6	Energy consumption	not included	
B7	Water use	not included	
C1-C4	End of life	9 570,61 |	+20%
D	External impacts (not included in totals)	-54 366,66 |	+15%
	Total	**59 337,07**	
	Comparing total results with: BAU SCENARIO		
	BAU SCENARIO Total	**135 113,4**	
	DESING OPTIMIZATION compared with BAU SCENARIO	-56%	

As can be seen above in the comparison of the general results and GWP of each life cycle phase module, it is possible to decrease the EC of a building by more than 50% by choosing more sustainable materials, considering various aspects such as using locally available resources to reduce the environmental impact of transportation to the site, choosing materials that require less work to install, and that are easier to replace and reinstall at the end of the building's life. In this thesis, the use/repair phases (B1-B3 modules), operational carbon (B6-B7 modules), and external impacts (module D) are not included in the LCA analysis. Therefore, the only increase in the life phase of the building in the design optimization compared to the BAU scenario is in the end-of-life phase of the building (C1-C4 modules). This result is due to the greater variety of building materials in the design optimization scenario and their possible waste amount which affects waste management process and their environmental impact. In total end of life scenarios of design optimization require more work and it is an acceptable result considering these increasing works that requires for this phase. Despite a 20% increase in the end-of-life phase, the overall EC comparison shows that a 56% decrease cannot be overlooked.

	TOTAL GWP kgCO2e	TOTAL AREA GWP kgCO2e/m2	HEATED AREA GWP kgCO2e/m2	TOTAL AREA GWP kgCO2e/m2 PER YEAR	HEATED AREA GWP kgCO2e/m2 PER YEAR
BAU	135 113,4	336,76	388,73	6,73	7,77
OPTIMIZATION	59 337,07	147,50	170,71	2,95	3,41

Figure 156. Table of BAU and design optimization GWP

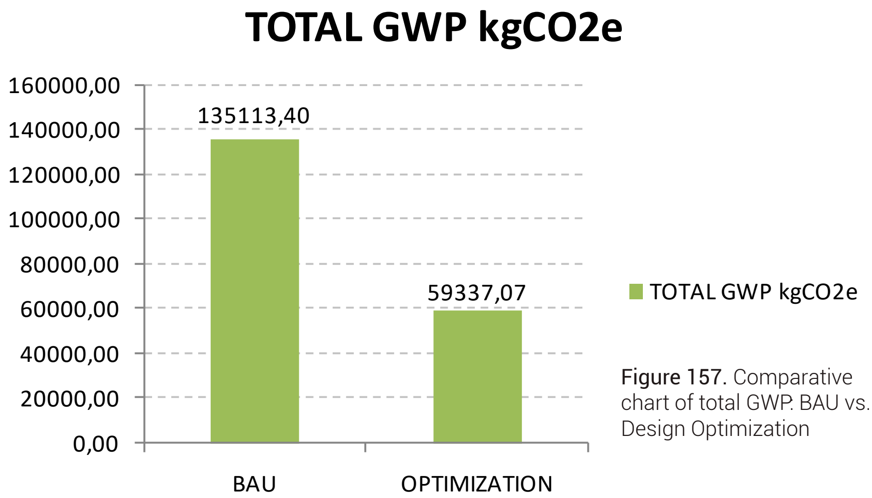


Figure 157. Comparative chart of total GWP. BAU vs. Design Optimization

As seen in the tables above, building structure and building materials choices have a significant role in buildings' environmental impact. Choosing more sustainable and natural-based materials instead of common building materials, considering local resources and choosing the right materials considering each life phase of the building contributes significantly in decreasing the environmental impact of the buildings that we are constructing with common building materials and methods nowadays.

Total global warming potential of two different design proposals. As seen from the graph Business-as-usual project has 135 113,4 GWP kgCO2e which represents a residential project designed with common materials and methods, on the other hand design optimization has 59 337,07 GWP kgCO2e where the building structure and building materials are well-studied in order to lower the carbon footprint of the building. It is significant to stress that using locally reused materials (such as glulam building structure in the design optimization)as much as more sustainable material choices has significant effect to reduce GWP of the building. This reduction is due to avoid/ lessen transport emissions of the material. In order to achieve this result research of the local resources in the chapter 3 has been instrumental to accomplish this material choices with already built examples. If we look closer to some points that cause this difference for environmental impact of the building we can count as building structure, concrete and steel usage in the business-as-usual scenario has a great contribution to total global warming potential of the project. Foundation beams for both design proposals are reinforced concrete but the reinforced concrete is used also for the main structure of BAU scenario which creates a significant difference. Choices of the concrete types used in the blinding layer in the foundation and in the floor types, recycled binder content in the concrete is also playing a great role in the total GWP's of both design proposals. Natural based materials as insulation materials, and timber elements for application of internal walls and minimizing gypsum/cement based applications has an important contribution to lessen the environmental impact in the total value of design optimization.

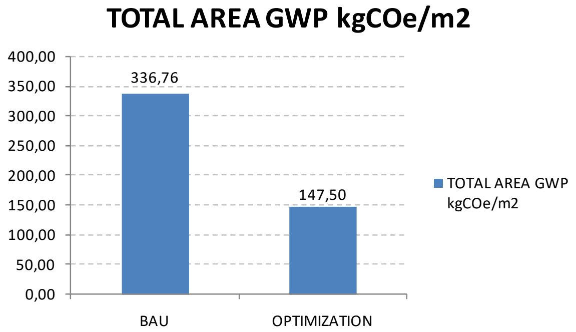


Figure 158. Comparative Chart of Total Area GWP per m2: BAU vs. Design Optimization

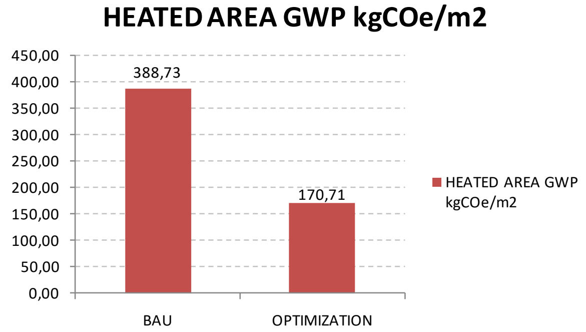


Figure 159. Comparative chart of heated area GWP per m2: BAU vs. Design Optimization

As can be seen in the charts above, EC per square meter both for total area and heated area of the building decreased more than half. Gross floor area of both design proposals are the same. On the other hand, only difference is unheated area square meter which is not a significant amount. BAU scenario with two balconies on the south facade, one on the north facade and one on the west facade has 4 balconies with 53,7 m2 of unheated areas. Design optimization 2 larger balconies on the south facade and one on the west facade has 3 balconies with 54,7 m2 of unheated area. This difference is not a drastic number for the total area square meter. Despite this minor difference, more than %50 decrease of EC per m2 is a significant improvement for the environmental impact of the building.

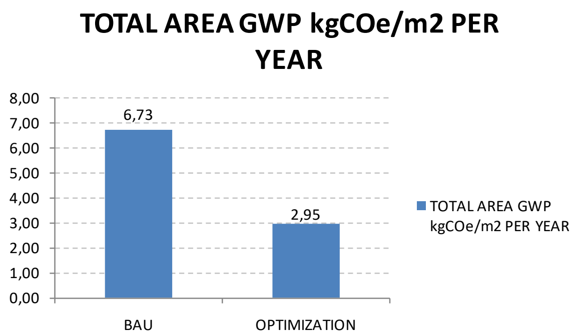


Figure 160. Comparative Chart of Total Area GWP per m2 per year: BAU vs. Design Optimization

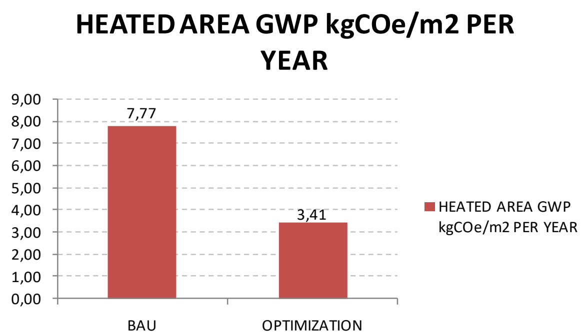


Figure 161. Comparative chart of heated area GWP per m2 per year: BAU vs. Design Optimization

For both design proposals, building life span is set as 50 years. Thus, the results are comparable considering the same amount of life span.

The difference in the results demonstrates that not only the building material decisions but also the methods to construct them, location of these building materials or reusing materials are important to consider if the goal is to lessen carbon emission of the building. All these optimization strategies demonstrates us that the decisions that we take as architects or construction responsibles can decrease the EC of our buildings more than %50 and eventually create great difference in general carbon emissions in the world.

5.3 CONCLUSION

In conclusion, this thesis has meticulously compared the embodied carbon of two distinct design proposals: among which, the study proposed the "Business as Usual (BAU) scenario" and the "Design Optimization" scenario, by using the Life Cycle Assessment (LCA) approach. This makes the comparative analysis show the extent of the environmental difference brought by the difference in building structure and materials selection. This explains how significant the profession of the architects and all construction industry professionals are in determining the carbon footprint of the built environment. Sustainability especially in selection of material and structure of the construction is greatly determined by decisions made in the design phase. Thus, the case points out that Design Optimization, which includes sustainable design and materials with a lower embodied carbon, can help to decrease the environmental impacts in comparison with BAU. This result points out, the answer of the first research question, understanding the environmental impact of building structures and materials during the design phase enhance general sustainability of the buildings and decrease environmental impact of our creations.

In Turin/Italy context, among sustainable building structure options, timber structure is a great locally available alternative which is also used nearby areas to common building structures such as concrete or steel as it can be seen in comparison results where embodied carbon of the building is significantly decreased even only considering the main building structure. Thus, as answer for the second research question, timber structure is a sustainable building structure option used nearby Turin/Italy which is chosen as the main building structure for optimizing business-as-usual scenario where there is no concrete or steel is used as building structure.

Among local resources and low-carbon material options which are available near Turin/Italy we can count timber materials,natural based insulation materials such as hemp,linen,cotton insulation used in design optimization,natural stone which is commonly used in Piedmont region as roofing material, organic insulating panels such as expanded cork panel which is used in la casa quattro project in Lombardy region, roofing tile (terracotta) which is commonly. As seen in the case studies these low-carbon material options are used in residential projects. Thus, as answer of the third research question, these options are great suitable alternatives to be used in a residential project near Turin/Italy.

Implementation of sustainable management strategies in construction, individuals such as architects and stakeholders in the construction can play a huge role in eradicating climatic change. It thereby makes architects and builders some of the most influential people to facilitate sustainable construction practices. It not only impacts the carbon footprint of the particular project, but also entails upon the future regular upkeep of a project, as well as the proper disposal of the project. Thus, the integration of environmentally friendly materials and constructions, along with the application of LCA in construction projects, leads to significant reductions in the overall carbon footprint of a project.

Sustainability should therefore be adopted at every phase in the construction process as suggested in this thesis. On this view, it changes the thinking that sustainability aspects rule, and supports the notion that collaboration between architects, builders and policymakers are required to deliver better built environment. This paper shows that the sustainability is not only an issue of ethical responsibility but it also unveils the efficient best practice that, if embraced, can drastically lower the carbon footprint of the construction industry and support the world's battle against climate change.

Thus, as answer of the last research question,optimizing a design evaluating sustainability aspects and choosing building structures or materials with the goal of contribution to a more sustainable future in mind affects enormously carbon footprint of a building project where we are responsible of our decision as seen this thesis.

PERSONAL THANKS

With deep gratitude,

I would like to thank all people who have been there for me during the whole process of this thesis.

First, I want to express my deepest gratitude to professor Francesca Thiebat for dedicating her time to my thesis and for being available and spending even hours to guide me. I am incredibly thankful for her invaluable guidance, wisdom and the depth of knowledge that she shared with me throughout this process. Not only she assisted me addressing the issues of this thesis but she also helped me to develop. Her precious support as a supervisor has meant a great deal to me. I am truly fortunate to have had the opportunity to learn from her.

Most importantly, I would like to thank my family. Words would not be enough to describe how thankful I am to them. In particular I would like to thank my dearest mother. She has always stood firmly beside me like a mountain which remained constant and unwavering through all the difficult times and has been a part of every success that I have gained in my life. Her love, patience and the belief in me has seen me through the worst of times. This accomplishment would not have been possible without her.

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ANNEX 01: This annexure contains data resources of building materials provided by Oneclick LCA tool for business-as-usual scenario LCA analysis.

ANNEX 02: This annexure contains data resources of building materials provided by Oneclick LCA tool for design optimization scenario LCA analysis.

ANNEX 01: DATA RESOURCES OF BUILDING MATERIALS (BUSINESS AS USUAL)

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source
Aluminium-coated corrugated sheets, for roofing and cladding	0.70 mm	AlumiGard	ColorCote	Australasian EPD System	S-P-01539	EPD for AlumiGard, MagnaFlow and ZinaCore pre-painted roofing and cladding
Cement plaster, grey	bulk density 1.1 kg/dm3, fresh mortar 1.4 kg/dm3, 2-100 mm	Ardex A 950	Ardex	IBU	EPD-ADX-20160076-IBG1-DE	Umwelt Produktdeklaration ARDEX – ARDEX A 950 - Flexspachtel, grau
Extruded polystyrene insulation panel (XPS)	R=1.2 m2K/W, L= 0.033 W/mK, 40 mm, 1.25 kg/m2, 31.25 kg/m3, Lambda=0.033 W/(m.K)	SOPREMA XPS SL 40 mm	SOPREMA SAS	INIES	INIES_IPAN20201224_093327, 25649	FDES
Gypsum plaster, for mechanical application and fire protection	10 mm, 4 kg/m2, bulk density: 450 kg/m3	Igniver	Saint-Gobain PPC Italia Spa,	International EPD System	S-P-01688	EPD Gyproc Igniver
Gypsum plasterboard, fire resistant	12.5 mm, 11 kg/m2	SINIAT pregyflam BA13	Etex Building Performance S.p.A.	EPD Hub	HUB-1419	EPD SINIAT pregyflam BA13
Hollow bricks, for walls	127 kg/m2		CENTRE TECHNIQUE DE MATÉRIAUX NATURELS DE CONSTRUCTION	INIES	INIES_CBRI20180208_104037, 29406	FDES
Lightweight fibre cement slabs, fiber-reinforced, for indoor and outdoor use	12.5 mm, 12 kg/m2, 960 kg/m3, fire resistance class = A1	Aquafire	Bifire srl	International EPD System	S-P-01593	EPD Aquafire and Supersil (6, 9 and 12 mm)
Metal framing components for gypsum plasterboard, carrier (C) and non-carrier (U) types	thickness: 0.4-0.6 to 0.5 - 2.0 mm, 7850 kg/m3		UMS	International EPD System	S-P-00869	EPD Steel Profiles and Accessories

Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)
EN15804+A1	Third-party verified (as per ISO 14025)	2019	New Zealand	GaBi		PCR 2012:01 Construction products and construction services, Version 2.2 (2017-05-03), PCR 2011:16 Corrosion Protection of Fabricated Steel Products, UN CPC 88731, version 2.2 (2017-06-08).
EN15804+A1	Third-party verified (as per ISO 14025)	2013	germany	GaBi	1400.0	PCR geprüft und zugelassen durch den unabhängigen Sachverständigenrat
EN15804+A1	Third-party verified (as per ISO 14025)	2021	france	ecoinvent	31.25	EN15804+A1
EN15804+A1	Third-party verified (as per ISO 14025)	2020	italy	ecoinvent		PCR 2012:01 Construction products and Construction services, ver 2.3
EN15804+A1 , EN15804+A2	Third-party verified (as per ISO 14025)	2024	italy, OCLEPD	ecoinvent		PCR EPD Hub Core PCR version 1.0, 1 Feb 2022
EN15804+A1	Third-party verified (as per ISO 14025)	2018	france	ecoinvent		EN15804+A1
EN15804+A1	Third-party verified (as per ISO 14025)	2019	italy	ecoinvent		PCR 2012:01 Construction products and Construction services, ver. 2.2, 03/05/2017, PCR ACOUSTICAL SYSTEM SOLUTIONS (Construction PRODUCT) (v2.2) PCR 2012:01-SUB-PCR-C
EN15804+A1	Third-party verified (as per ISO 14025)	2017	turkey	ecoinvent	7850.0	PCR 2012:01 Construction products and Construction service, ver. 2.01, 09/03/2016

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source
PVC waterproofing membrane	1.5 mm, 1.80 kg/m2, fire resistance class = E	FLAGON PVC SV/SA-300	Soprema (2021)	International EPD System	S-P-01604, ver. 5	EPD FLAGON PVC, ver. 5
Parquet flooring with birch under-layer	9.53 kg/m2, thickness=14 mm	SP14	Parchettificio Garbelotto S.r.l.	EPD Italy	EPDITALY 0147	EPD Pavimenti in legno Collezione Garbelotto SP14
Plywood board	Thickness: 15 mm, 7 ply layers, Lambda=0.13 W/(m.K)		Panguaneta	International EPD System	S-P-01117	EPD MULTILAYER PANELS OF POPLAR PLYWOOD
Ready-mix concrete for ground slabs	C25/30 XC1/XC2 CEM II/A, 2387.04kg/m3		SNBPE	INIES	INIES_CB ÉT2019072 4_131702, 22908	FDES
Ready-mix concrete, low-strength, generic	C12/15 (1700/2200 PSI), 0% recycled binders in cement (220 kg/m3 / 13.73 lbs/ft3)			One Click LCA	-	One Click LCA
Reinforced concrete beam for seismic zone	2406.1 kg/m3, C25/30 XC3/XC4 CEMII/A		SNBPE	INIES	INIES_CB ÉT2019072 9_151252, 11065	FDES
Roofing tile from clay (terracotta), flat (shingles)	285 x 475 mm (11.2 x 18.7 in), 10 pcs/m2, 3.5 kg/pcs, 35 kg/m2		One Click LCA	One Click LCA	-	One Click LCA
Sawn timber, planed	biogenic CO2 not substracted, 489 kg/m3	Sägewerk Brilon	Fritz EGGER	IBU	EPD-EGG-20140248-IBA2-DE	Oekobau.dat 2017-I, EPD EGGER Schnittholz gehobelt EGGER Sägewerk Brilon GmbH
Screed, self-levelling	3-40 mm, 1300 kg/m3 (bulk)	Novoplan Maxi	Mapei	International EPD System	S-P-00908	EPD for Ultraplan, Ultraplan Eco, Ultraplan Maxi, Novoplan Maxi

Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)
EN15804+A1	Third-party verified (as per ISO 14025)	2019	italy	ecoinvent		PCR 2012:01 Construction products and Construction services, ver. 2.1, 03/05/2017
EN15804+A1	Third-party verified (as per ISO 14025)	2019	italy	ecoinvent		PCR ICMQ-001/15 rev2.1
EN15804+A1	Third-party verified (as per ISO 14025)	2017	italy	ecoinvent	900.0	PCR 2012:01 Construction products and Construction services, ver. 2.2, 30/05/2017
EN15804+A1	Third-party verified (as per ISO 14025)	2019	france	ecoinvent	2387.04	EN15804+A1
EN15804+A1 , EN15804+A2	Internally verified	2018	LOCAL	One Click LCA	2200.0	EN15804+A1
EN15804+A1	Third-party verified (as per ISO 14025)	2019	france	ecoinvent	2406.1	EN15804+A1
EN15804+A1 , EN15804+A2	Internally verified	2023	LOCAL	One Click LCA		EN15804+A1, EN15804+A2
EN15804+A1	Third-party verified (as per ISO 14025)	2016	germany	GaBi	489.0	PCR Vollholzprodukte, 07/2014
EN15804+A1	Third-party verified (as per ISO 14025)	2016	italy	GaBi	1300.0	PCR 2012:01 Construction products and Construction service, ver. 2.01, 09/03/2016

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source
Softwood beam, kiln dried, sawn	440 kg/m3, 10% moisture content, coniferous wood		One Click LCA	One Click LCA	-	One Click LCA
Steel, structural steel construction products, cold formed			Ruukki	-	-	EPD Ympäristöseloste teräsrakenteet, Kylmämuokatuista rakenneputkista ja profiileista valmistettujen, hitsattujen ja pintakäsiteltyjen ristikkorakenteiden ja palkkien ympäristöprofiili, Ruukki 2014
Stone wool insulation panels, unfaced, generic	L = 0.035 W/mK, R = 2.89 m2K/W (16 ft2°Fh/BTU), 50 kg/m3 (3.12 lbs/ft3) (applicable for densities: 25-50 kg/m3			One Click LCA	-	One Click LCA
Structural steel profiles, generic	0% recycled content (only virgin materials), I, H, U, L, and T sections, S235, S275 and S355			One Click LCA	-	One Click LCA

Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)
EN15804+A1 , EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	440.0	EN15804+A1, EN15804+A2
EN15804+A1	Third-party verified (as per ISO 14025)	2014	finland, poland, lithuania	GaBi	7850.0	EN15804+A1
EN15804+A1	Internally verified	2018	LOCAL	One Click LCA	50.0	EN15804+A1
EN15804+A1 , EN15804+A2	Internally verified	2018	LOCAL	One Click LCA	7850.0	EN15804+A1

ANNEX 02: DATA RESOURCES OF BUILDING MATERIALS (DESIGN OPTIMIZATION)

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number
Roofing tile from clay (terracotta), flat (shingles)	285 x 475 mm (11.2 x 18.7 in), 10 pcs/m2, 3.5 kg/pcs, 35 kg/m2		One Click LCA	One Click LCA	-
Sandstone cladding, natural	20 mm, 2550 kg/m3		Casone Group	EPD Italy	EPDITALY0065
Softwood lath (stud), kiln dried, sawn	440 kg/m3, 10% moisture content, coniferous wood		One Click LCA	One Click LCA	-
Treated wooden cladding, generic	15-40 mm (0.59-1.57 in), 9.75 kg/m2 (1.99 lbs/ft2)(for 15 mm/0.59 in), 525 kg/m3 (32.8 lbs/ft3), min. G4-1			One Click LCA	-
Argon gas filled insulating glass unit (IGU) with one tempered and one clear float glass panes, double glazed	4-16-4, 20 kg/m2		One Click LCA	One Click LCA	-
Cross-laminated timber (CLT), biogenic CO2 not subtracted (for CML)	120 mm, 470 kg/m3		LIGNATEC	INIES	INIES_IPAN20171109_122401, 34867
Electricity, Italy				One Click LCA	

Environment Data Source	Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)
One Click LCA	EN15804+A1 EN15804+A2	Internally verified	2023	LOCAL	One Click LCA		EN15804+A1, EN15804+A2
Dichiarazione ambientale di prodotto: rivestimento in pietra serena di firenzuola con superficie naturale e sabbiata con bordi rifilati	EN15804+A1	Third-party verified (as per ISO 14025)	2019	italy	ecoinvent	2550.0	PCR ICMQ-001/15 Construction product and Construction service (rev.2) (v. 1.6, 30.11.2017)
One Click LCA	EN15804+A1 EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	440.0	EN15804+A1, EN15804+A2
One Click LCA	EN15804+A1	Internally verified	2018	LOCAL	One Click LCA	525.0	EN15804+A1
One Click LCA	EN15804+A1 EN15804+A2	Internally verified	2024	LOCAL	One Click LCA, LCA Commons, IDEMAT		EN15804+A1, EN15804+A2
FDES	EN15804+A1	Third-party verified (as per ISO 14025)	2022	france	ecoinvent	470.0	EN15804+A1
LCA study for country specific electricity mixes based on IEA, OneClickLCA 2024		Internally verified	2022	italy	One Click LCA		

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number
Expanded Insulation Corkboard (ICB)	L= 0.040 W/m.K, 1-300 mm, 115 kg/m3		Amorim Cork Insulation	EPD Hub	HUB-0281
Glue laminated timber (Glulam) beams	485.7 kg/m3, biogenic CO2 not subtracted (for CML)	Poutre en Douglas lamellé-collé hors aubier des adhérent s de France Douglas	France Douglas	INIES	INIES_CPOU2 0190219_1111 21, 26811
Gypsum plasterboard, fire resistant	12.5 mm, 11 kg/m2	SINIAT pregyflam BA13	Etex Building Performance S.p.A.	EPD Hub	HUB-1419
Hemp, linen and cotton insulation with PE binder, biogenic CO2 not subtracted (for CML)	L=0.039 W/mK, R=2.55 m2K/W, 100 mm, 3 kg/m2, 30 kg/m3, Lambda=0.039 W/(m.K)	Biofib`Tri o	CAVAC BIOMATERIA UX	INIES	INIES_IBIO20 151110_14344 2, 28292
Interior clay plaster coating	3 - 4 mm, 4.17 kg/m2, A4 >500km		DONNEE ENVIRONNEM ENTALE GENERIQUE PAR DEFAUT	INIES	INIES_DEND2 0190219_1155 49, 9168
OSB ceiling/roofing board	Thickness: 6 - 45 mm, 450 kg/m3, Lambda=0.13 W/(m.K)	Solaio	Posatori Franciatorta	International EPD System	S-P-01101
PVC waterproofing membrane	1.5 mm, 1.80 kg/m2, fire resistance class = E	FLAGON PVC SV/SA-300	Soprema (2021)	International EPD System	S-P-01604, ver. 5

Environment Data Source	Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)
EPD Expanded Insulation Corkboard (ICB) Amorim Cork Insulation	EN15804+A1 EN15804+A2	Third-party verified (as per ISO 14025)	2023	portugal, OCLEPD	ecoinvent	115.0	EPD Hub Core PCR version 1.0, 1 Feb 2022
FDES	EN15804+A1	Third-party verified (as per ISO 14025)	2019	france	ecoinvent	485.7	EN15804+A1
EPD SINIAT pregyflam BA13	EN15804+A1 EN15804+A2	Third-party verified (as per ISO 14025)	2024	italy, OCLEPD	ecoinvent		PCR EPD Hub Core PCR version 1.0, 1 Feb 2022
FDES	EN15804+A1	Third-party verified (as per ISO 14025)	2018	france	ecoinvent	30.0	EN15804+A1
MDEGD_FDES	EN15804+A1	Third-party verified (as per ISO 14025)	2019	france	ecoinvent		EN15804+A1
EPD Dichiarazione Ambientale di Prodotto (EPD) degli elementi costruttivi in legno realizzati da Produttori Franciacorta – copertura, solaio, parete	EN15804+A1	Third-party verified (as per ISO 14025)	2017	italy	ecoinvent	450.0	PCR 2012:01 Construction products and Construction services, ver. 2.2, 30/05/2017
EPD FLAGON PVC, ver. 5	EN15804+A1	Third-party verified (as per ISO 14025)	2019	italy	ecoinvent		PCR 2012:01 Construction products and Construction services, ver. 2.1, 03/05/2017

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number
Plywood board	Thickness: 15 mm, 7 ply layers, Lambda=0.13 W/(m.K)		Panguaneta	International EPD System	S-P-01117
Ready-mix concrete, low-strength, generic	C12/15 (1700/2200 PSI), 40% recycled binders in cement (220 kg/m3 / 13.73 lbs/ft3)			One Click LCA	-
Ready-mix concrete, normal strength, generic	C32/40 (4600/5800 PSI) with CEM III/B, 75% GGBS content in cement (300 kg/m3; 18.7 lbs/ft3 total cement)		One Click LCA	One Click LCA	-
Recovered solid-strip hardwood flooring	thickness range: 8 - 22mm, 5.26kg/m2, 657 kg/m3 oven-dry, moisture content < 13%		One Click LCA	One Click LCA	-
Reinforced concrete beam for seismic zone	2406.1 kg/m3, C25/30 XC3/XC4 CEMII/A		SNBPE	INIES	INIES_CBÉT20190729_151252, 11065

Environment Data Source	Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)
EPD MULTILAYER PANELS OF POPLAR PLYWOOD	EN15804+A1	Third-party verified (as per ISO 14025)	2017	italy	ecoinvent	900.0	PCR 2012:01 Construction products and Construction services, ver. 2.2, 30/05/2017
One Click LCA	EN15804+A1 EN15804+A2	Internally verified	2018	LOCAL	One Click LCA	2200.0	EN15804+A1
One Click LCA	EN15804+A1 EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	2400.0	EN15804+A1, EN15804+A2
One Click LCA	EN15804+A1 EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	657.0	EN15804+A1, EN15804+A2
FDES	EN15804+A1	Third-party verified (as per ISO 14025)	2019	france	ecoinvent	2406.1	EN15804+A1