BUILDING WITH EARTH

An exploration on contemporary earth architecture

Carolina Miguez
Master Thesis 2025

Examiner: Walter Unterrainer
Supervisors: Tina Wik and Marli Swanepoel

Chalmers School of Architecture
Department of Architecture and Civil Engineering

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ABSTRACT

In response to the climate crisis, the building industry must fundamentally rethink how materials are sourced and used. As the environmental impact of conventional construction becomes increasingly evident, this thesis investigates the potential of earth as a sustainable, low impact building material. Urban areas generate significant amounts of excavated soil from construction activities, which are often discarded as waste. However, this material holds immense potential for reuse in building construction.

The focus of this thesis is to examine how earth can be used in highly urbanized and industrialized contexts to support sustainable densification, particularly in urban gaps. Drawing on the rich history of earthen construction, this research explores the viability of clay and soil as future circular building materials. Earth is abundant, infinitely recyclable, and has a low carbon footprint, offering an alternative for large-scale modern construction.

The design component of this thesis proposes a residential building in the Masthugget district of Gothenburg, Sweden, employing earth-based construction techniques in a material-driven approach to design, demonstrating how earth can meet both contemporary standards and environmental goals. Ultimately, this project seeks to showcase the transformative potential of earth as a building material, both for its minimal environmental impact and for the powerful narrative it brings to the future of architecture.

Key-words: Earth architecture, Low-impact materials, Life Cycle Assessment, Sustainable housing, Urban densification.

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BACKGROUND

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"Build your architecture from what is beneath your feet."

Hassan Fathy

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CHAPTER 01

INTRODUCTION

Background and discourse

The Building Construction Industry and Carbon Dioxide Emissions

The building construction industry is a significant contributor to global carbon dioxide (CO_2) emissions. According to the United Nations Environment Programme, the sector is responsible for approximately 37% of the CO_2 emissions worldwide. This substantial impact is due to energy-intensive processes involved in the extraction, production, and transportation of raw materials, as well as the energy consumed during the construction and operation of buildings (UNEP, 2023).

The operation of buildings, which includes energy demand for heating, cooling, lighting, and appliance use, is a major contributor to emissions. In 2022, the International Energy Agency reported that building operations accounted for 26% of global energy-related CO_2 emissions. (International Energy Agency, 2022)

Apart from operational emissions, another significant source of emissions in the sector comes from the production of materials such as cement, steel, and glass. The production of cement alone accounts for approximately 8% of global CO_2 emissions, primarily due to the chemical process of calcination and the high temperatures required for kiln operation. The energy required for these processes often comes from fossil fuels, further contributing to the industry's carbon footprint (Lehne & Preston, 2018).

Throughout a building's entire lifecycle, carbon emissions are released not only during its operational life and manufacture of construction materials, but also during transportation, construction and end-of-life phases. According to the World Green Building Council, embodied carbon accounts for around 11% of all global carbon emissions.

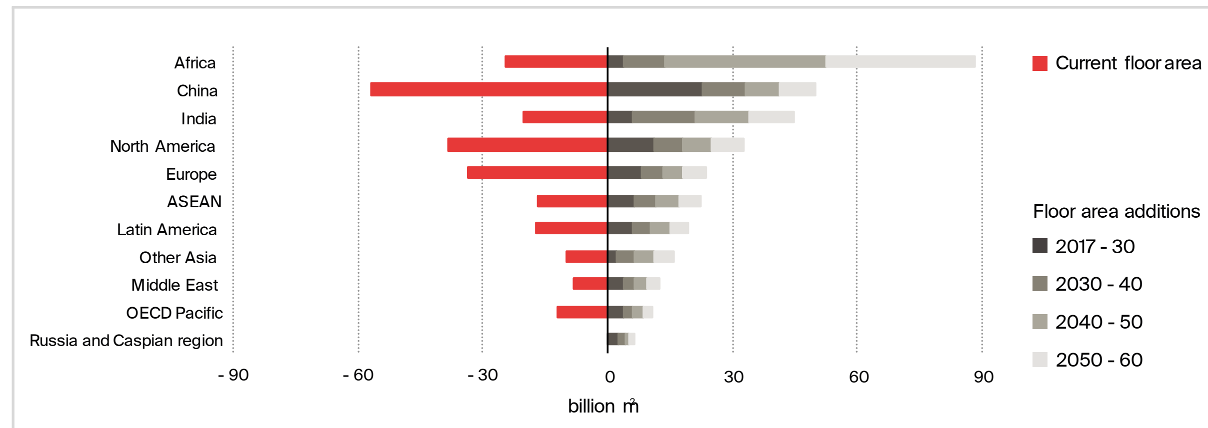
Materials that are particularly carbon-intensive, such as concrete and aluminum, significantly contribute to the upfront emissions of new construction projects. When these buildings are demolished, the carbon that is locked into the structure from the moment they are built is released back into the atmosphere. (World Green Building Council, 2019).

Urbanization and Population Growth

A significant portion of the world's population resides in urban areas, and this number is projected to increase. The United Nations estimates that by 2050, nearly 68% of the global population will live in urban areas (UN, 2019). This rapid urbanization presents both opportunities and challenges for sustainable development.

As cities expand, the demand for new buildings and infrastructure increases, leading to higher resource consumption and greater environmental impact. According to the Global Status Report 2017, the global building stock is estimated to double by 2060, resulting in an addition of 230 billion square meters in floor area (UN Environment and International Energy Agency, 2017).

Perpetuating current construction practices and the use of conventional materials will only increase the negative impact of human activity on the planet. Without significant changes, the global extraction of raw materials as well as the use of construction materials is predicted to almost double by 2060 (OECD, 2019).



Notes: OECD Pacific includes Australia, New Zealand, Japan and Korea; ASEAN = Association of Southeast Asian Nations.

Figure 1. Floor area additions to 2060 by key regions (adapted from UN Environment and International Energy Agency 2017).

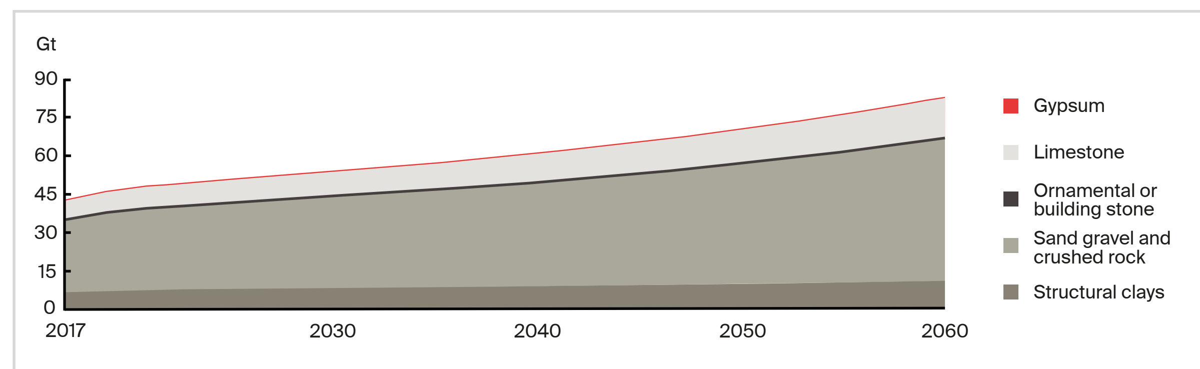


Figure 2. Materials' use for materials directly entering construction in Gt (adapted from OECD, 2019).

The Need for Decarbonization in the Building Sector

The building sector is responsible for a substantial portion of global energy consumption and greenhouse gas emissions. These emissions contribute heavily to climate change and are projected to increase as the global building stock expands, and if not addressed, they could derail climate targets. The building sector plays a crucial role in the global effort to fight climate change, and its decarbonization is essential to meet the goals set by the Paris Agreement, which aims to limit global warming to well below 2°C above pre-industrial levels, with efforts to keep it to 1.5°C (UN, 2015).

According to the Global Status Report for Buildings and Construction 2024, despite some progress, the sector remains off track to achieve the goal of net zero emissions by 2050. The Global Buildings Climate Tracker, which monitors progress towards decarbonization of the building stock, indicates that the gap between the current state and the desired decarbonization path is widening (UNEP, 2024b).

The Emissions Gap Report 2024 highlights the urgency of strong actions and emphasizes the scale of the challenge: a 42% reduction in global emissions is needed by 2030 to stay on track for the 1.5°C target, and emissions must fall by 57% by 2035 (UNEP, 2024a).

Decarbonizing the building sector is urgent to tackle the climate crisis. Data and statistics from the reports highlight the substantial efforts required to reduce its emissions. The enormity of the challenge is undeniable. Simultaneously, there is space and opportunity for systematic change, sustainable practices, and innovation for accelerating the green transition.

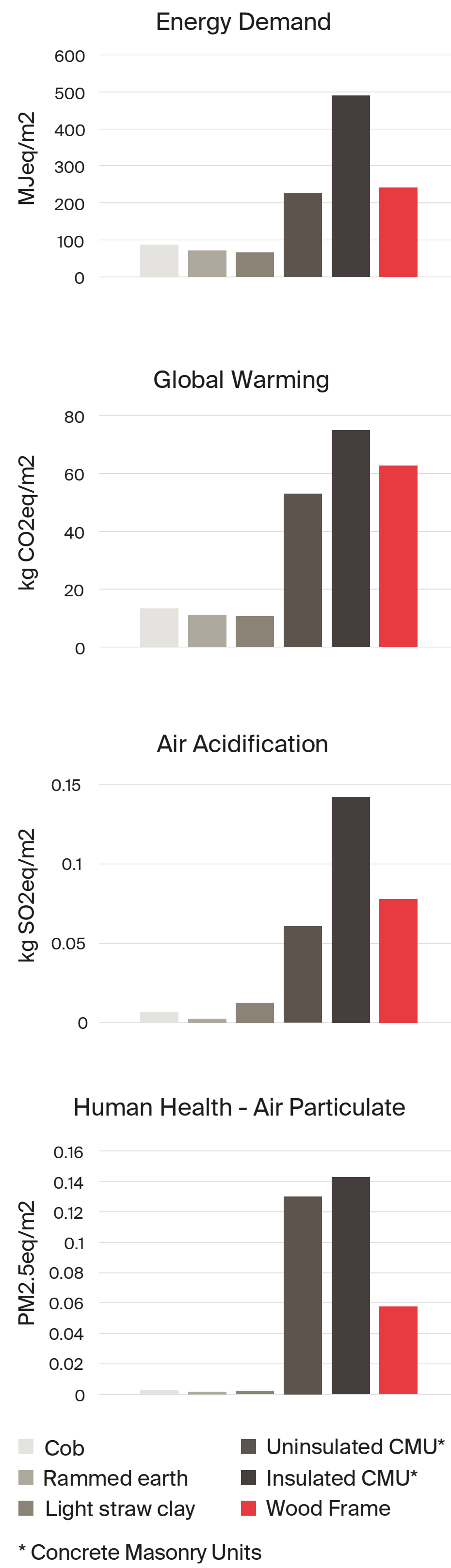


Figure 3. Environmental embodied impacts comparison among different wall systems (adapted from Ben-Alon et al., 2019).

A Case for Earth

The urgency to decarbonize the building sector underscores the pressing need for sustainable alternatives that can help mitigate climate change. In recent years, there has been an increasing interest in raw earth as an alternative construction material that could answer to those needs. Ancient practices are being revisited and updated to meet contemporary demands and standards, modernizing earth construction techniques.

Earth buildings offer several environmental benefits, including lower embodied energy and CO_2 emissions compared to conventional materials such as concrete and wood, as shown in Figure 3 (Ben-Alon, 2020). It is found all around the world, can be locally sourced and infinitely recycled without the use of chemical-based additives and stabilizers, responding to the cradle-to-cradle concept.

Furthermore, around 75% of the waste generated by the construction industry in the European Union consists of soil and stones that could be repurposed for earth-based construction. Since these materials are commonly produced during earthworks, often near construction sites, transportation needs are minimized. Reusing this waste for buildings could help preserve natural resources typically used in the extraction and production of conventional materials and reduce the demand for landfill space. (Fabbri et.al. 2021)

Case studies demonstrate the adaptability of earth construction to diverse climates and socio-economic contexts (Minke, 2012). Nevertheless, despite the advantages, earthen materials are not widespread in mainstream construction. They often face regulatory hurdles, lack of standardization, and skepticism regarding their performance in extreme weather conditions. Addressing these barriers requires further research, education, and advocacy to build confidence among architects, builders, and policymakers (Ben-Alon, 2020).

This master thesis advocates for a broader implementation of earthen materials in the building industry. It focuses on earth as a modern construction material and how it could be used to design a residential building in an urbanized and industrialized context, contributing to the discourse on sustainable architecture and material innovation.

Purpose and exploration

In the past few years there has been a renewed interest in earth as a building material due to growing environmental concerns and demands for climate action, prompting a discussion on how earthen architecture can contribute to a more sustainable future. This shift in the architectural discourse and revival of earthen construction methods has led to an evolution of building techniques, showcasing the potential of prefabrication for streamlining earth construction in industrialized contexts.

However, there are still obstacles to upscaling earth building. It is important to build trust in earth as a viable construction material, and this can be addressed through education and well-documented flagship projects that demonstrate the durability and resilience of earth buildings.

Currently, most examples of contemporary earth architecture are “extraordinary” structures: private residences in the countryside, healthcare facilities in developing countries, or educational institutions, also largely in warmer climates. The purpose of this thesis is to examine how it could also be a viable material for “ordinary” buildings in industrialized urban contexts in colder climates, where it could have a bigger positive impact and larger contribution for future sustainable development.

Therefore, the aim of this thesis is to explore the advantages, and potential of earthen materials and showcase them in a centrally located project in Gothenburg, Sweden, discussing urban densification through infill strategies and low-impact materials. The challenges faced when building with earth in a Nordic context, such as thermal insulation and weather protection of exposed surfaces, are important to the learning and knowledge creation processes during the thesis development. The design is intended as a flagship project to raise awareness, spark curiosity and increase discussions about the impact of unsustainable construction industry.

Thesis questions

The main research question that this master thesis will address is as follows:

> **How can technology and innovative construction methods in earth architecture be used to design a residential building on an urban infill site in Gothenburg, supporting urban densification with low-environmental impact?**

In order to answer this main research question, the following sub-questions are raised:

> **What are the challenges and opportunities of using earthen materials in Swedish contemporary architecture?**
>
> **What other materials can be combined with earth to support a resource efficient and low-impact construction?**
>
> **How can environmental impact analysis support the implementation of earth buildings?**

Methods

This master thesis follows a research-for-design and research-by-design methodology, structured in two distinct phases. The knowledge development phase (research-for-design) aimed to build a foundation of knowledge around the main topics of the thesis. The design phase (research-by-design) applied and further developed this knowledge through an iterative design process. Both approaches are common in architectural research where the combination of theoretical investigation and practice-led experimentation is needed to address complex, real-world challenges.

The methods employed in this thesis are described below, including a definition of each method, its relevance to the research questions, and its application in the project.

Literature Studies: In this thesis, literature reviews were conducted on three main themes: urban densification, earthen building materials, and the integration of BIM and Life Cycle Assessment (LCA) for environmental impact analysis. The aim was to establish a theoretical background, identify current knowledge gaps, and inform the subsequent design phase. Literature was selected from articles, books, and industry reports for collecting, evaluating, and synthesizing previous research on the specific topics.

Case Study Analysis: Case study research is an empirical method that investigates a phenomenon within its real-life context (Yin, 2018). In this thesis, selected architectural projects using earth-based construction techniques were analyzed. These case studies were chosen based on their relevance to prefabrication, urban contexts, and sustainability ambitions. The analysis focused on construction methods, material applications, and spatial qualities, providing references and precedents to inform design decisions.

Site Analysis: Site analysis involves the investigation of a location's physical, social, and historical characteristics to understand the context for architectural interventions (Rowe, 1987). In this thesis, the site in Gothenburg was analyzed in terms of urban morphology, accessibility, existing infrastructure, and environmental factors. Broader research was also conducted into the historical use of earth as a construction material in Sweden, to contextualize the cultural appropriateness and potential acceptance of earth-based architecture.

Climate Analysis: Climate analysis examines local environmental conditions to inform climate-responsive design strategies (Olgyay, 1963). For this thesis, Gothenburg's climatic data—including temperature ranges, precipitation, humidity, and solar patterns—were studied. The goal was to select materials and design strategies that enhance thermal comfort and energy performance.

Life Cycle Assessment (LCA): Life Cycle Assessment (LCA) is a standardized method used to quantify the environmental impacts associated with all stages of a product's life (International Organization for Standardization, 2006). In this thesis, a LCA was conducted using the tool One Click LCA to evaluate the environmental performance of the final design proposal.

Delimitations

This master thesis will focus on earth as a modern construction material and how it can be combined with other low-impact materials to design a residential building in an urbanized and industrialized context, counteracting housing shortage and supporting urban densification. By assessing its environmental performance and comparing it to conventional construction methods through the calculation tool One Click LCA, this research aims to contribute to sustainable architectural practices that reduce the environmental footprint of the construction industry in cities.

This thesis will:

- investigate the potential earthen materials have for contemporary architecture in terms of their environmental impact
- explore earthen building materials in housing design for a specific urban infill site in Gothenburg, Sweden
- focus on reducing the environmental impact of buildings and measure it through Life Cycle Assessment analysis

This thesis will not:

- create guidelines on how to build with earth
- present detailed information about earth's technical properties
- compile the history of earthen architecture
- focus on economic aspects of building with earth
- focus on building regulations and laws that prevent the use of earthen materials
- investigate the characteristics of the soil in Gothenburg

CHAPTER 02

EARTH AS A BUILDING MATERIAL

Earth is one of the most sustainable building materials available. Unlike concrete, which has a significant carbon footprint, earth has minimal environmental impact. It is abundant, readily available in most parts of the world, and can often be sourced directly from the building site, reducing transportation needs and associated emissions. Additionally, earth is fully recyclable and biodegradable, meaning it can return to its natural state at the end of a building's lifecycle without causing harm to the environment.

However, a common misconception about earth is that it is a fragile material, particularly in harsh weather conditions, making it unsuitable for modern construction. While earth is water-soluble and susceptible to erosion, these concerns can be addressed through appropriate construction techniques. Numerous historical and contemporary examples from around the world demonstrate the durability of earth buildings across various climates.

Earth building techniques are also highly adaptable to different labor and technological contexts. In recent decades, modern prefabrication methods have allowed for the production of standardized earth elements that comply with building codes. These prefabricated components can be manufactured off-site and assembled on-site, reducing labor costs and making earth construction feasible even in industrialized regions with high labor cost, significantly broadening its potential for sustainable, large-scale use in modern building practices.

This chapter is organized in five different sections. First, it dives into the background of earthen architecture, presenting a historical overview of earth construction - in general and then with a focus on Scandinavia - and a brief description of different methods of building with earth.

The second section of the chapter introduces the basics of earth as a building material, presenting its properties and the advantages of its use. The third dicusses challenges and modern developments for upscaling earth as a building material. The fourth part reviews Life Cycle Assesment for earthen architecture, inclundig topics such as current research and challenges. Finally, the last section presents four different case studies considered relevant for this master thesis.

Background on earthen architecture

Historical Overview

The use of earth as a building material dates back to the Neolithic period, known for more than 9000 years and associated with human sedentarization. Earth was combined with other natural and locally available materials to construct not only dwellings, but also sacred buildings, monuments, and fortifications (Minke, 2012). Earth building practices are evident in various Neolithic centers of origin, such as the Fertile Crescent, Mesoamerica, and China. Initially, earth was used in mortars, plasters, and as infills for timber frame structures, known as wattle and daub (Fabbri et al, 2021). In Central Europe, there are settlements uncovered by archeologists dating back to the 5th or 6th century BC using skeleton frame constructions with wattle walls coated with clay (Volhard, 2016).

Over the course of history, various earth construction techniques have emerged across different regions. Cob and Adobe appeared early in the Neolithic period in the Near East, while Rammed Earth was developed around six thousand years later in the Western Mediterranean. In the 19th century, Compressed Earth Blocks (CEB) gained prominence and their use expanded with the advent of industrial presses in the 1950s (Fabbri et al., 2021). In parallel, mixtures with higher fiber content were introduced in different cultures to improve insulation and reduce density. Light Earth, developed in Germany after 1920, optimized thermal performance by incorporating lightweight aggregates such as straw into the earth mixture (Volhard, 2016).

These earth construction techniques spread from their places of origin and were adopted by various cultures worldwide, depending on favorable natural conditions, such as suitable soil and climate, and sociocultural acceptability. Techniques evolved and adapted to local environments and needs throughout the years, leading to diverse local construction practices (Fabbri et al, 2021).

Earth buildings can be found all over the world and reflect the evolution of this construction material (Figure 4). It is estimated that nowadays one third of the world's population lives in earthen houses (Minke, 2012). Furthermore, 15% of UNESCO World Heritage sites are fully or partially made of earth, such as the Alhambra in Spain and the Great Wall of China (Alex, 2018).

Despite its global and historical significance, the 19th and 20th centuries witnessed a decline in earth construction due to industrialization. New building materials were gradually replacing traditional local materials, offering the advantages of reduced labor demands and enabling faster and larger-scale construction (Heringer et al, 2020.) For a long time, earthen materials were left excluded from modernization processes.

Figure 4. World map showing tradional earth construction areas with the locations of the UNESCO world heritage sites (adapted from Gandreau, D., & Delboy, L., 2012).

Construction practices adapt over time in response to social changes and availability of resources, emerging, evolving, expanding, and occasionally disappearing. Over its 10,000-year history, earth construction has undergone numerous golden ages, periods of decline, and revivals driven by these dynamics (Fabbri et al, 2021). Material shortages during and after both World Wars, for instance, led to a resurgence in earth building, yet this revival lasted only a few years until the construction materials industry recovered (Volhard, 2016).

The production of industrialized materials, however, often requires processes that harm the environment, contributing to the consumption of non-renewable resources and greenhouse gases emissions (Ben-Alon, 2019). The growing awareness of the environmental impact of human activities after the mid-20th century has led to a renewed interest in sustainable building materials. As a result, earth construction is once again experiencing a renaissance as part of a broader movement towards low impact solutions, including the emergence of new technologies that allow standardization and compliance with building codes. These new developments are of great value for a broader implementation of earthen materials in mainstream construction and will be described in a following section of this chapter.

History of Earth Construction in Scandinavia

While wood has historically dominated construction in Scandinavia, particularly in the forest-rich regions of Sweden, Norway, and Finland, earth-based materials have also been used, especially in areas where wood was scarce. In Denmark, where forest cover was below 1% by the 18th century, earth was more extensively implemented compared to other Nordic countries.

In Sweden, earth was often combined with timber. During the late Middle Ages, rural populations commonly built log houses that were sometimes plastered with clay on the interior. In the wood-scarce southern region of Skåne, half-timbered farms with clay-plastered or earth-brick infill walls were common. Additionally, in Lapland, the Sami constructed winter huts covered with soil and turf.

During the 18th century, Sweden sought to reduce the use of timber in construction due to its importance for iron production. As a result, load-bearing earth structures gained attention, with several publications on these techniques emerging around the late 18th and early 19th centuries. By the end of the 1700s and early 1800s, several estates and farms used clay for building purposes. Today, a number of these buildings remain preserved, showcasing the use of this material in various ways, such as Perstorps Chapel (Figure 5) and Svalbo (Figure 6 and Figure 7).

In the 20th century, material shortages during and after World War II reignited interest in earth construction across Scandinavia. Books on the subject were published in Sweden, Norway, and Denmark, inspiring the construction of several rammed earth buildings in the 1920s.

After a period of decline, earth construction experienced a renewed revival in the mid-1980s and 1990s, driven by various projects and publications. Today, interest in earth construction continues to grow, as it is increasingly seen as an environmentally friendly and sustainable alternative to conventional building materials (Lindberg, 2002).

Figure 5. Perstorps kapell from 1860 is one of Sweden's oldest surviving Baptist chapels. It is a rammed earth building designated as a historic monument in 1996. Image retrieved from Länsstyrelsen Skåne (2025).

Figure 6. Svalbo is a building constructed with sun dried clay bricks in the second half of the 18th century in Järle, 30 km north of Örebro. Image retrieved from Svalbo (n.d.).

Figure 7. Exposed mudbricks during Svalbo's renovation. Image retrieved from Svalbo (n.d.).

Traditional Earth Construction Techniques

Earth construction techniques are usually classified based on three different criteria which allow for a clearer understanding of their characteristics and applications: the water content of the mixture, the method of implementation, and the structural role of the earth element.

The first classification criterion is the water content of the mixture, which distinguishes between dry/compression densification and wet/shrinkage densification techniques. Wet processes involve placing the earth mixture in a plastic state, with mechanical strength developed as the material dries and shrinks. In contrast, dry processes utilize earth mixtures at optimum water contents, where strength is primarily achieved through compaction rather than shrinkage.

The second criterion concerns the method of implementation, which categorizes earth construction based on how the material is used in the building process. Masonry units involve dry, pre-formed units assembled with mortar. Direct implementation refers to earth placed directly to form monolithic walls. Infill techniques use earth as a filling material within a structural framework. Lastly, overlying techniques apply earth as a surface coating, as is the case with earthen plasters.

The final classification is based on the structural role of the earth element, which can either be load-bearing or non-load-bearing (Hamard et al., 2016).

Over the years, various earthen construction techniques have been developed. As each requires different constructions methods, soil mixtures, and occasionally additional components such as organic fibers, their appearance, mechanical, thermal, and physical properties will vary considerably. Below, some of the most common earth construction techniques will be described.

1. Rammed Earth

Rammed earth is a monolithic construction technique in which a stiff to semi-solid mixture of soil—typically composed of clay, sand, silt, and gravel—is poured in layers into formwork and compacted to form structural or non-structural elements (Schroeder, 2015). Each layer, usually 10 to 15 cm thick, is compacted manually or mechanically using pneumatic rammers, resulting in a dense, solid wall. The process is repeated until the desired wall height is reached, after which the formwork is removed.

This compaction process significantly increases the material's compressive strength, making rammed earth one of the most structurally robust earth construction methods (Ben-Alon, 2020).

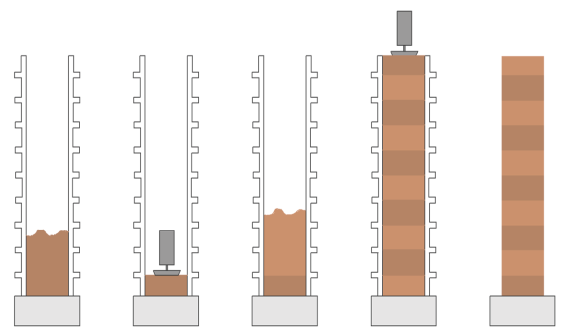


Figure 8. Construction sequence of a rammed earth wall, from layer preparation to formwork removal (adapted from Anysz & Narloch, 2019).

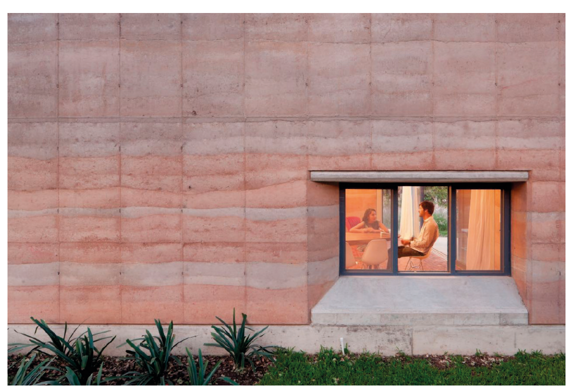
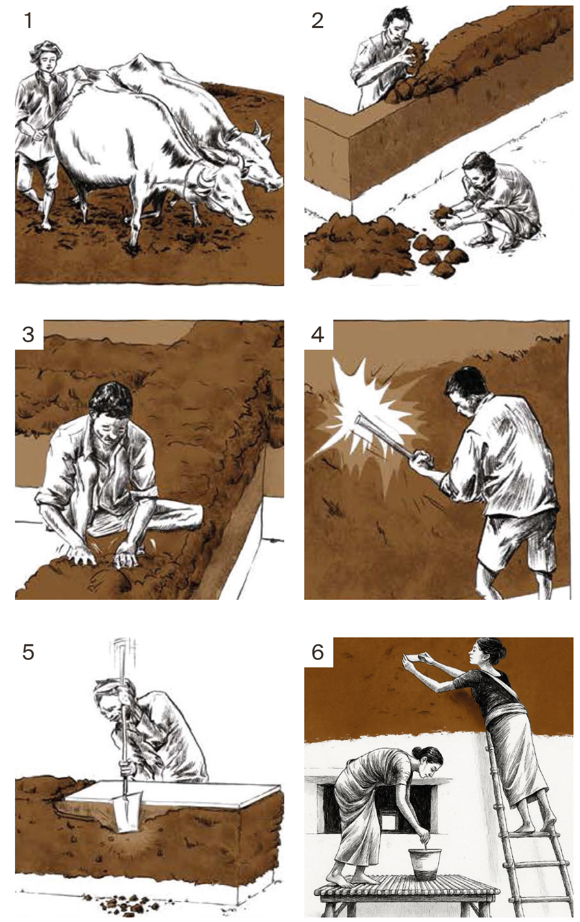


Figure 9. Rammed earth wall at Ajijic House. Photo © Iwan Baan

2. Cob

Cob is a traditional construction technique that uses a plastic mixture of clay-rich soil, straw or other fibers, and water. The mixture is manually shaped into coarse balls, which are successively stacked in layers to form monolithic walls without the need for formwork. Once dry, this technique creates a dense and cohesive mass with good compressive strength, making it suitable for load-bearing walls and other structural elements (Schroeder, 2015)



(1) The earth mixture is kneaded into a plastic state (2) It is shaped into small balls by hand (3) The balls are stacked in 50–60 cm layers and pressed together (4) Each layer is tamped to close cracks formed during drying (5) Excess material is trimmed with a shovel and guide board (6) The wall is ready for plastering.

Figure 10. Step-by-step process of traditional cob wall construction (adapted from Franke, 2017) .

Figure 11. Cob wall under construction at METI School in Bangladesh (top) and finished cob wall at METI School (bottom). Photos ©Kurt Hoerbst

3. Earth Blocks (Adobe and CEB)

These are modular building materials made from pressed or hand-shaped earth. Earth blocks are typically rectangular and can be made solid or perforated, using various methods such as compression, hand-throwing, or ramming (Schroeder, 2015).

Adobe is a traditional method that utilizes molded, air-dried earth blocks, often stabilized with chopped straw and laid with earth or lime mortar to build load-bearing or freestanding walls (Volhard, 2016).

Compressed Earth Blocks (CEB) are made by compressing a mix of inorganic soil, water, and sometimes chopped fiber into blocks. These unfired bricks can be industrially produced using powerful presses and be used to build load-bearing or freestanding walls. When a chemical binder is included in the earth mixture, usually cement, they are called Compressed Stabilized Earth Blocks (CSEB) (Ben-Alon, 2020).

4. Infill Methods (Wattle-and-Daub and Light Straw Clay)

Infill methods use earth as a non-loadbearing infill material within a structural frame, typically made of timber.

Wattle-and-Daub is a traditional technique that involves applying earth mixed with fibers in a plastic state, implemented wet, on an interwoven wooden structure.

Light Straw Clay is a method that involves mixing earth with straw or other lightweight materials to create an insulating infill for structural frames. The mixture is typically fluid and can be poured into formwork and compressed, carried out on-site or prefabricated (Volhard, 2016).

5. Earth Mortars

Earth Mortars are mixtures of fine-grained soil, aggregates, and water, used for masonry work or plastering. Earth mortars can be designated as mineral or fiber reinforced and be used to coat indoor or outdoor surfaces (Schroeder, 2015).

Figure 12. Adobe production in Madagascar. Photo © Pierre-Yves Babelon (top) and Compressed Earth Blocks installation at Venice Architecture Biennale 2016. Photo © Samuel Dématraz (bottom)

Figure 13. Traditional wattle and daub infill in timber framing in Heiligenstadt, Germany. Photo by Immanuel Giel.

Properties of Earth

As usual practice in architecture, the term earth is used when referring to the building material. However, for characterization purposes, the words soil and loam are frequently used as scientific terms. Therefore, in the subsequent sections both terms were adopted to adhere to common terminology.

1. Soil Composition

Loam consists of a mixture of clay, silt, sand, and sometimes larger aggregates like gravel and stones. The classification of its components is based on particle size, specifically its diameter, with clay being the smallest (less than 0.002mm), followed by silt (0.002–0.06mm), and sand (0.06–2mm). Larger particles are categorized as gravel or stones. Clay acts as a binder in the mixture, while silt, sand, and aggregates serve as fillers (Minke, 2012). The proportion of these components determines the soil's characteristics, as many of its technical and hydrological properties are related to the particle size distribution. (Fabbri et al., 2021)

2. Mechanical Properties

The mechanical properties of earth-based building materials are crucial for determining their suitability and performance in construction. These properties - compressive strength, tensile strength, shear strength, and modulus of elasticity - are influenced by factors such as the raw materials used, i.e. the type and amount of clay and grain size distribution, as well as the manufacturing methods. It is therefore recommended to conduct tests for every soil mix to determine its mechanical properties.

3. Thermal Properties

Thermal properties, such as thermal conductivity, heat storage capacity, and thermal effusivity, significantly influence earth buildings' performance. Thermal conductivity measures a material's ability to transfer heat, heat storage describes how much heat it can absorb, and thermal effusivity indicates how quickly heat is absorbed or emitted.

The conductivity of earth materials varies depending on its components and moisture content, ranging from 2.4 W/m·K in a wet state to 0.6 W/m·K when dry. Since the insulation properties depend on the amount and volume of voids within the material as well as its moisture content, lighter materials with more voids and lower moisture content provide better insulation.

Earth materials are generally good thermal regulators due to their high thermal mass and storage capacity, and their ability to absorb, store, and slowly release heat. Compressed earth blocks (CEB), for instance, exhibit a thermal mass of 1740 kJ/(m^3·K), while adobe has a thermal mass of 1300 kJ/(m^3·K), values comparable to fired bricks at 1360 kJ/(m^3·K).

Another characteristic of earth-based materials is their thermal inertia, which slows down heat transfer and contributes to stabilizing interior temperatures. This delay, or time lag, ensures that heat takes longer to penetrate or leave buildings. Studies indicate that CEB walls can have a thermal delay up to 5.5 hours longer than concrete blocks and fired bricks.

These properties help in stabilizing interior temperatures, reducing the need for artificial heating and cooling and are important for creating comfortable, energy-efficient buildings.

4. Hygroscopic Properties

Earthen materials are hygroscopic, meaning they have the ability to adsorb and desorb moisture from the surrounding air due to their porosity, which facilitates the movement of water and water vapor within the material. The hygroscopic nature of earthen materials contributes to their ability to passively regulate indoor relative humidity, potentially reducing energy consumption required for maintaining thermal comfort. However, water significantly impacts earth-based materials, affecting their strength, durability, and longevity.

Increased moisture content weakens intergranular bonds, reducing stiffness and compressive strength. If moisture accumulates, especially at the foundation, it can lead to structural damage, including wall collapse. Repeated wetting and drying cause shrinkage and swelling, gradually degrading mechanical properties, while prolonged exposure to rainfall and capillary rise can erode unstabilized earth buildings, compromising structural integrity over time. While stabilization techniques can improve water resistance, they may also reduce the material's ability to buffer moisture and prevent recyclability.

While hygroscopic properties can contribute to the energy efficiency of earth buildings, careful water management is crucial to prevent deterioration. Proper design and maintenance strategies are essential for ensuring the long-term durability of earthen structures.

5. Fire resistance

Earth-based building materials vary in fire resistance depending on their density and composition. According to the German norm DIN 4102, materials with densities above 1700 kg/m³ are non-combustible. Lower-density variants, often reinforced with organic fibers, have reduced fire resistance dependent on the quantity of combustible components.

Interestingly, fire exposure may enhance the mechanical properties of unstabilized earth by inducing mineralogical changes that transform the clay fraction into a denser, rock-like structure. This process, similar to the firing of clay in brick production, increases strength and stiffness but reduces moisture buffering capacity and hygrothermal inertia.

Despite these findings, research on the fire behavior of earth structures remains limited. The lack of experimental data makes it difficult to establish precise conclusions on how different types of earth-based materials respond to fire.

6. Acoustic properties

Although relatively under-researched, earth-based building materials are believed to have high acoustic absorption due to their open porous structure. Specific characteristics of these materials, such as material's density, moisture content, and pore size significantly influence sound propagation.

The hygroscopic nature of earth materials, which allows them to absorb and release moisture, can alter their acoustic behavior. As moisture levels fluctuate, the pore size within the material changes with swelling and shrinkage, which in turn affects sound propagation.

Despite the potential of earth materials for acoustic absorption, further research is needed to fully understand and optimize the use of earth materials for acoustic control in buildings.

The Advantages of Earth-Based Building Materials

Earth-based building materials offer numerous advantages over common industrial materials, making them a sustainable alternative for construction. Among these benefits are their ability to balance indoor climate, reduced environmental impacts, and cradle-to-cradle life cycle.

1. Natural Indoor Climate Regulation

Loam is excellent at balancing indoor humidity and temperature, contributing to comfortable and healthier living environments. Its ability to absorb and release moisture outperforms that of conventional materials, allowing it to stabilize indoor air humidity effectively (Figure 14). Experiments from the University of Kassel in Germany show that unbaked bricks can absorb up to 30 times more humidity than fired bricks when indoor relative humidity suddenly rises from 50% to 80%. Additionally, with high density and high thermal mass, earthen building components store heat efficiently, making them an excellent thermal regulator. This capacity is particularly valuable in areas with significant day-night temperature fluctuations or where solar heat gain can be retained and used for passive heating systems (Minke, 2012).

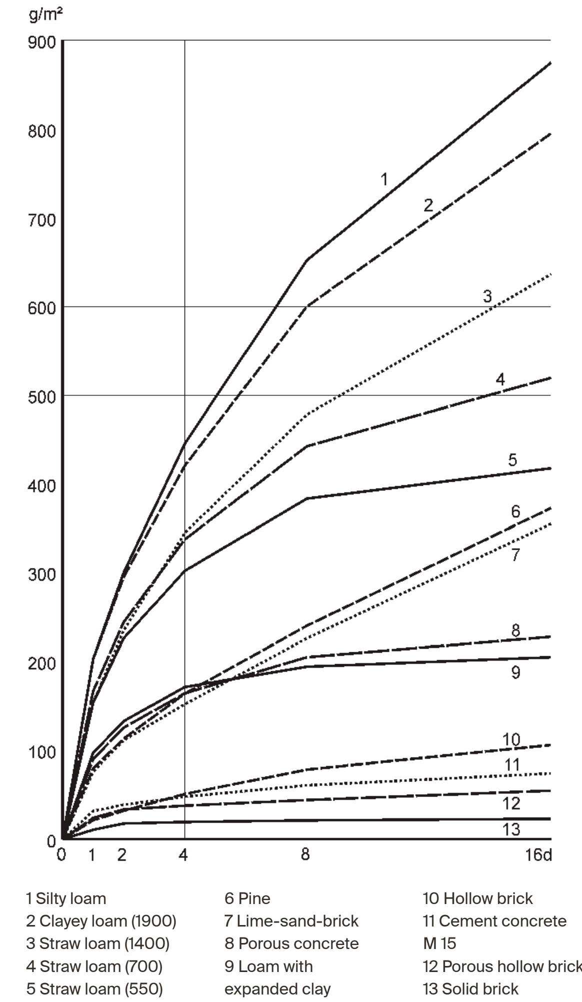


Figure 14. Absorption curves of 11.5 cm-thick interior walls with both sides exposed at 21°C after an abrupt rise in humidity from 50 to 80% (Minke, 2012)

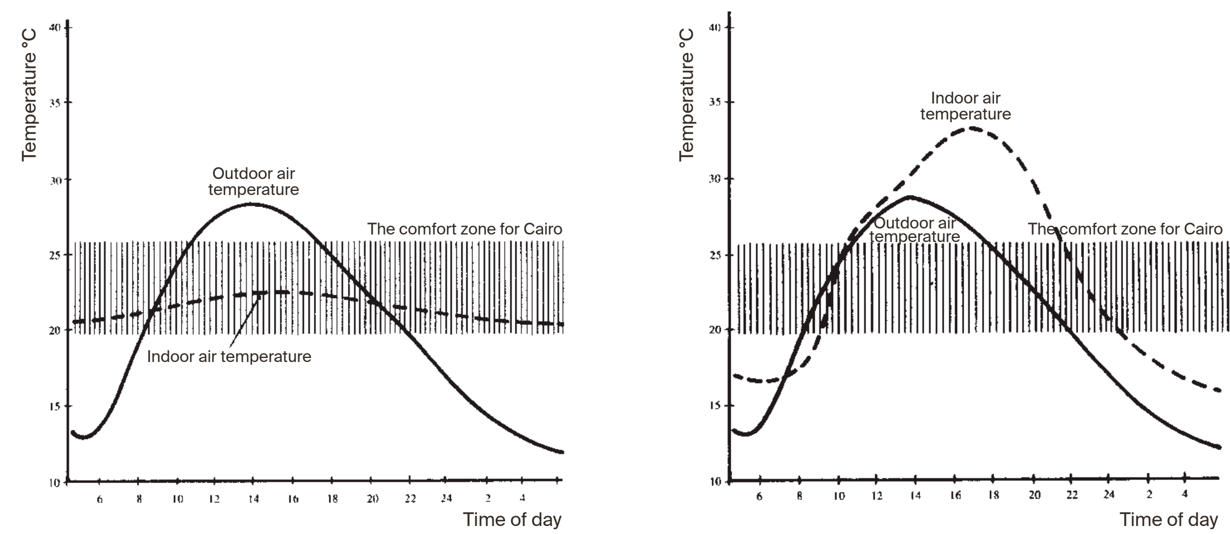


Figure 15. Diurnal variation of indoor and outdoor temperatures in two buildings of equal volume in Egypt: one with 50 cm-thick earth walls and mud brick vaults (left), the other with 10 cm-thick pre-cast concrete elements and a flat roof (right) (originally from Fathy (1986), as reproduced in Minke (2012, p. 30).

2. Environmental Benefits

Throughout their lifecycle, earthen building materials have significantly lower environmental impacts compared to conventional industrial materials. Environmental Life Cycle Assessment (LCA) studies demonstrate that earthen materials consume less energy and generate fewer greenhouse gases (GHG) emissions. (Ben-Alon, 2019). Furthermore, since the material is abundant and easily found in or around construction sites, the need for material transportation and associated emissions are reduced. The use of excavated soil from foundation and earthworks is also advantageous from a waste management and circular economy perspective, as a material that is usually treated as waste and demands proper destination can be repurposed in construction, avoiding unnecessary landfilling.

3. Reusability

Loam is a building material that can be reused indefinitely. Unlike industrial materials, which often require energy demanding recycling processes, loam can be rehydrated and reshaped as needed, ensuring that no material is wasted at the end of a building's lifecycle. After soaked in water, clay's binding forces are reversed, allowing earth-based materials to return to their original state. The material can be plasticized and then reused or, since it is biodegradable, it can either return to earth, answering to the cradle-to-cradle concept (Figure 16).

4. Preservation of Organic Materials

Loam enhances the durability of timber and other organic materials used in construction due to its high capillarity and low equilibrium moisture content. When in contact with wood, it prevents damage caused by fungi or insects by keeping it dry. Additionally, loam also preserves small amounts of organic fibers mixed into its structure, ensuring the longevity and resilience of natural building components.

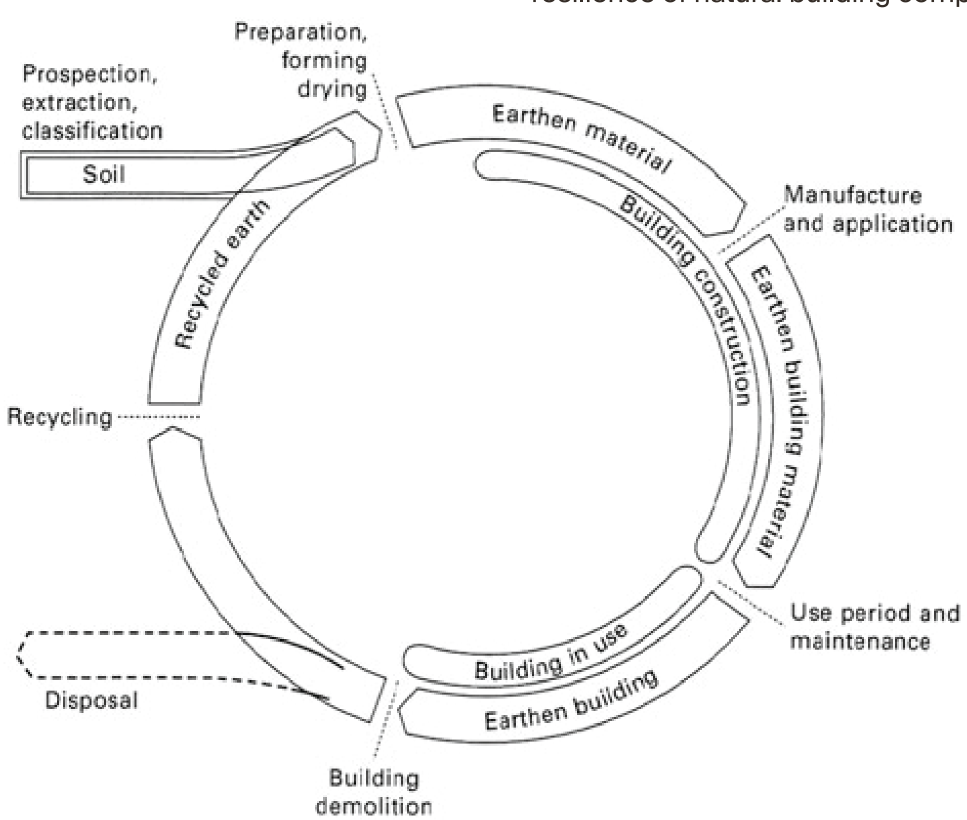


Figure 16. Cradle to cradle life cycle of earth as a building material (Schroeder, 2016)

Upscaling earth

Despite its advantages, earth construction faces several challenges regarding its broader implementation. A lack of universally accepted international standards for earth materials makes it difficult to apply construction methods consistently across different regions. This is compounded by gaps in research, particularly concerning the physical properties of earthen materials and the lack of standardized testing methods. Additionally, there is limited awareness and knowledge about earth building within the construction industry and among regulators. Finally, potential issues with erosion and material variability further complicate its adoption.

Stabilization of earthen materials is a commonly used technique to enhance their structural performance. By modifying the composition of these materials, their durability, strength, and resistance to environmental factors can be improved. However, the choice of stabilization method significantly influences the ecological impact and recyclability of the material. Stabilization methods can be broadly categorized into organic and inorganic approaches. Organic stabilization utilizes natural additives such as straw, husk, linseed oil, or cow dung to improve cohesion and reduce water absorption, while inorganic stabilization relies on chemical binders like cement or lime to increase strength and durability.

While cement is commonly used to stabilize earthen materials in many modern applications, its adoption is highly problematic from an environmental standpoint. Even when used in small quantities within earthen mixtures, cement significantly increases the material's embodied carbon, undermining one of the core environmental advantages of building with earth. Additionally, stabilized earth with cement loses its recyclability and ability to return to the soil at the end of life, losing connection to circular construction principles. Importantly, stabilization with cement is not only harmful but also unnecessary: careful planning and appropriate architectural detailing are sufficient to ensure the durability and performance of earthen buildings, even in challenging climates. In the context of this thesis—where sustainability, low-carbon design, and material circularity are guiding values—the use of cement as a stabilizer is therefore considered incompatible and not acceptable.

Current research aims to develop eco-friendly additives and alternative stabilization techniques that enhance performance without compromising sustainability. Geopolymers are being explored as substitutes for cement, while hygroscopic silicone-based admixtures can reduce water penetration without affecting moisture buffering capacity (Vyncke et al., 2018). Additionally, the use of natural or artificial pozzolans, as well as recycled fibers from industrial or household waste, can improve durability while reducing embodied energy and environmental impact (Fabbri et al., 2021).

Prefabrication is another alternative for upscaling earth as a building material, particularly in industrialized contexts, as it addresses limitations related to labor costs, material consistency, and construction timelines. It enables the production of earth components in a controlled environment, independent of weather and site conditions, and allows for the creation of modular elements that can be easily integrated into various designs. Some manufacturers provide a variety of prefabricated products for construction, including earth and light-earth blocks in various sizes, as well as large-format panels and building boards. Additionally, ready-mixed dry masonry and plaster mortars are available, simplifying the use of earth building materials for greater quality,

Figure 17. Drone spraying earth material on a textile formwork by MuDD architects. Photo © NAARO

Figure 18. Robotic fabrication of rammed earth elements - Digital Building Fabrication Laboratory (DBFL) at TU Braunschweig. Photo ITE/TU Braunschweig

Figure 19. 3D printed earth house prototype - TECLA project. Photo © Iago Corazza

efficiency and speed.

Digital production techniques are also being explored and may offer solutions to some of the challenges associated with earth construction. Robotic fabrication and additive manufacturing can increase the precision and efficiency of construction, reducing variability in material properties and improving structural performance. These technologies can also enable the creation of complex geometries that are difficult to achieve through traditional methods, allowing innovative designs. Digital methods facilitate automation, reducing the need for manual labor and costs, and can also reduce waste by optimizing material usage and implementing on-site production, lowering transport emissions and costs.

Additive Manufacturing, especially 3D printing using earth mixtures, is demonstrating significant potential, where clay or earth mixtures are extruded layer-by-layer to form structures. Robotic rammed earth involves using robots to guide slipforms and compact earth, creating precise rammed earth elements with minimal formwork. Another approach involves CNC-controlled spraying of earth onto textile formwork or directly onto walls. These techniques range from creating smaller, modular components, to on-site monolithic structures, demonstrating the diverse potential of combining earth and digital fabrication.

Finally, Life Cycle Assessment (LCA) can be an important tool to highlight the benefits of using earth as a building material and encourage its wider adoption. Comparative studies on building LCA emphasize its low embodied energy, recyclability, and ability to contribute to a circular economy, contrasting with the negative impacts associated with conventional materials such as concrete. To explore this topic, the following section will discuss the environmental performance assessment of earthen buildings.

Life Cycle Assesment of earthen buildings

Life Cycle Assessment (LCA) is a standardized method for quantifying the environmental impact of a product, material, or system across all stages of its life cycle, from raw material extraction to end-of-life. Commonly used in architectural projects as a comparison and evaluation tool, LCA helps assess environmental sustainability by measuring impacts such as Global Warming Potential (GWP) and Cumulative Energy Demand (CED), supporting the analysis of different design alternatives and validating design choices.

Applying LCA to earthen architecture and comparing it with other construction methods enables informed decision-making, as this standardized approach ensures data reliability and avoids comparative biases (Estève et al., 2022). However, the environmental LCA of earthen materials remains underexplored, and existing studies, though significant, are often not directly comparable to conventional construction methods. When comparisons are made, they typically focus on specific architectural elements, such as a square meter of wall, rather than adopting a holistic approach to building design. Additionally, many existing LCAs define system boundaries that cover only the extraction and manufacturing phases, overlooking the use and end-of-life stages (Ben-Alon, 2020).

Technology, particularly Building Information Modeling (BIM), has the potential to facilitate the implementation of LCA in architectural practice. An integrated BIM-LCA framework can lead to more efficient workflows in the design process, being especially beneficial during the early design phases, when fundamental decisions about constructions systems are made. It is at this stage that architects have the greatest opportunity to reduce a building's environmental impact. By integrating BIM with LCA tools, the calculation of embodied carbon and other environmental impacts is automated, providing real-time feedback on the sustainability implications of design choices and allowing architects to optimize the design for environmental performance (Estève et al., 2022).

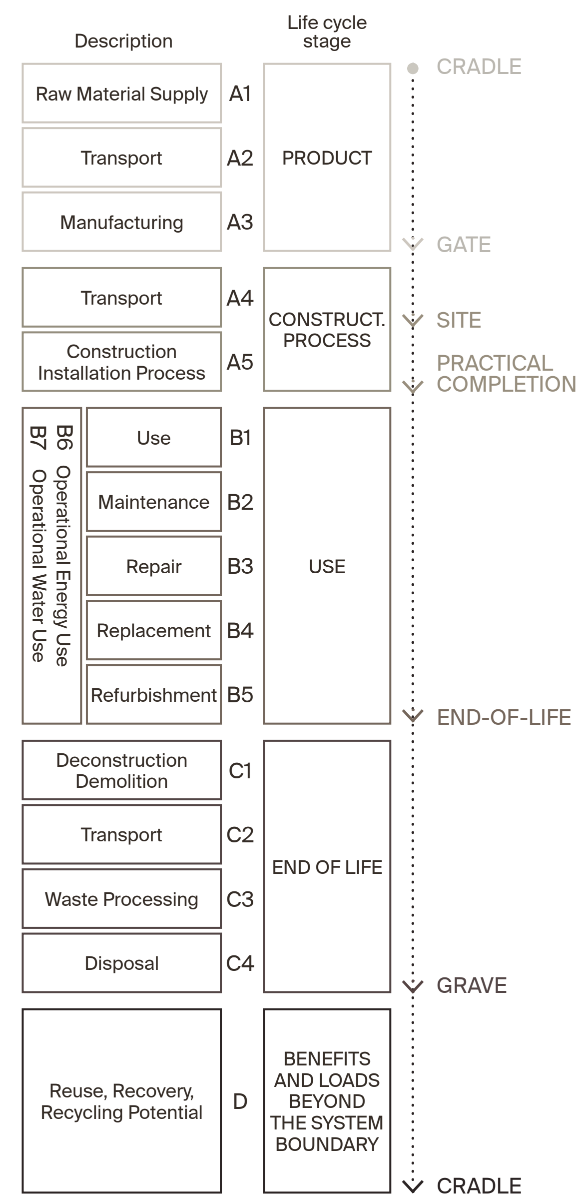


Figure 20. Building's LCA stages according to EN 15978, elaborated by the author.

The effectiveness of BIM-LCA depends on access to reliable and standardized environmental data for various building materials. However, there is a lack of comprehensive and consistent data on the technical performance of earthen materials. One of the biggest challenges in implementing this integrated approach is the variability of LCA data for earthen architecture, primarily due to the strong contextual dependence of earth construction properties. The characteristics of earthen materials can vary significantly based on the source of the soil and specific methods used for construction, which makes it difficult to establish standardized data.

> **"Such synthesis requires using consistent test procedures in materialstest studies, as well as proper documentation and analysis of results. To date, researchers studying earthen materials have adopted different established test methods (...). These result in a considerable range of reported data that cannot be directly compared."**
>
> (Ben-Alon et al., 2019, p. 8)

Nevertheless, while a direct comparison across studies is challenging due to varying methodologies, functional units, and system boundaries, studies generally show that earth-based materials, particularly when unstabilized or minimally stabilized, perform better than conventional materials in terms of embodied energy and global warming potential (GWP) (Fabbri et.al., 2021).

Case studies - reference projects

The following reference projects have been selected as examples of materiality, construction techniques, and urban integration. While all four projects share a common emphasis on earthen materials, each was chosen for its relevance to specific challenges and opportunities in this master's thesis.

Mauritzberg Summerhouse provides insights into adapting earthen materials to the Swedish climate and building culture, combining prefabrication with a low-tech approach in a hybrid construction. Haus Rauch demonstrates the full potential of earth while also proving its feasibility and resilience in a climate similar to Gothenburg. Dirty Harry was chosen not only for its use of earthen materials but also for its approach to urban living. This project explores new ways of dwelling in the city, discussing how architecture can encourage interaction and community building. Lastly, Quatre Cheminées showcases a strong focus on sustainablity with the use of prefabricated rammed earth panels within a dense urban context, demonstrating the scalability of such construction method.

Mauritzberg Summerhouse

Location: Mauritzberg, Sweden
Architect: Sverre Fehn
Year: 1992

The Mauritzberg Summerhouse was conceived as a prototype project which aimed to merge modern architectural design with sustainable construction techniques, demonstrating the potential of light earth building as an ecological alternative to conventional materials.

The walls were built using prefabricated light earth blocks made from locally sourced clay and straw. Their prefabrication followed a systematic approach, aligning with the 2-meter module of the timber frame that served as the primary load-bearing structure of the house while the straw-clay blocks filled the spaces between the columns.

The blocks were assembled using a clay-based mortar. The exterior walls were finished with a clay-sand plaster, sometimes mixed with fibers, and treated with a silicate solution or cow manure. Interior walls were rendered with a lime-sand plaster. For some external walls that did not require good thermal insulation, rammed earth was used.

Figure 21. Photo by unkown photographer. Source: Nasjonalmuseet for kunst, arkitektur og design, Norway.

Figure 22. Interior photo by Lars Hallén. Source: Nordiska museet, Sweden.

Haus Rauch

Location: Schlins, Austria
Architects: Boltshauser Architekten and Martin Rauch
Year: 2008

Haus Rauch demonstrates the application of untreated, unstabilized earth as a primary building material, transforming excavated soil from the construction site into an innovative project. Its experimental approach highlights the material's environmental and structural suitability for Central European climates.

The project was facilitated by the unique circumstance in which the client, landowner, master builder, and co-designer were the same person, allowing for the exploration of unconventional construction techniques without usual liability and risk concerns. The thick load-bearing rammed earth walls are entirely recyclable and provide significant thermal mass for passive heating and cooling. Following the principle of calculated erosion, protruding tiles were incorporated to protect the walls from weathering, which also define the building's external appearance. Internally, the walls are finished with a white earthen plaster that helps regulate indoor humidity.

The project aimed to prove the viability of earth-based construction techniques in a contemporary architectural context, testing the material as a design principle and demonstrating its sustainability and resilience.

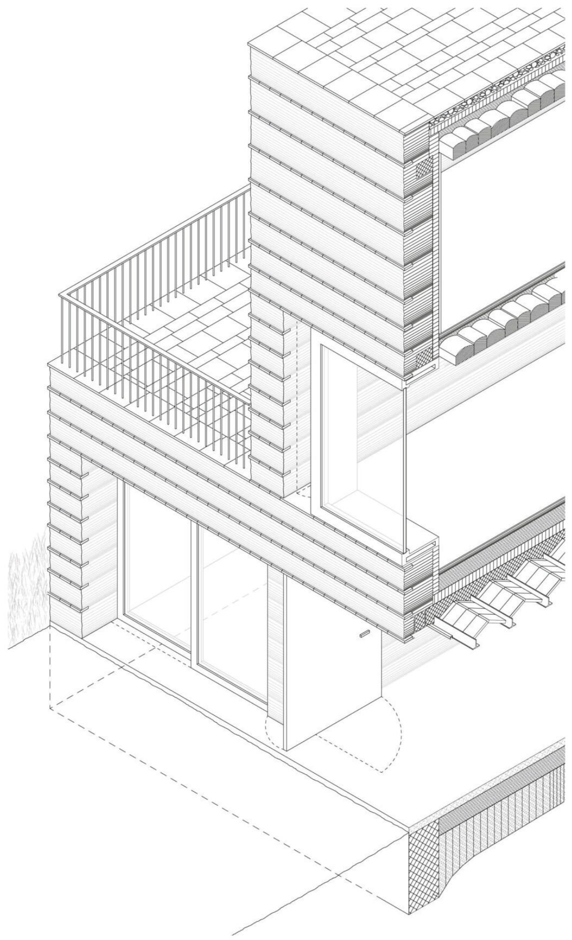


Figure 24. Axonometry section. Image courtesy of Boltshauser Architekten.

Figure 23. Detail image of the facade with protuding tiles as erosion checks. Photo © Beat Bühler

Figure 25. Interior featuring clay plastered walls and rammed earth flooring. Photo © Beat Bühler

Dirty Harry

Location: Basel, Switzerland
Architects: Atelier Neume
Year: 2022

Dirty Harry is a minimalist residential building located in a former warehouse area of Basel. A non-profit housing developer purchased the site and leased it for construction to a cooperative, in which the architects were also involved as initiators and residents. This compact building houses eleven apartments designed with flexible layouts to meet contemporary ways of dwelling. Interchangeable spaces adapt the residential units to contain between 2.5 to 4.5 rooms and suit the changing needs of the residents throughout their lives. Furthermore, the building offers a variety of communal areas, including a commercial kitchen for shared or rental use on the top floor and a rooftop terrace facing both the street and the inner courtyard of the block.

The clay bricks used on the façade for the double-shell walls were industrially produced with excavated material and stabilized with 4% of cement. Despite being suited for structural purposes, the walls are non-load bearing. Their high thermal mass, however, reduces the need for artificial heating and cooling. Wooden roller shutters complement the façade and act as a sun protection system, minimizing heat gain and increasing the building's energy efficiency.

Figure 27. Interior image. Photo © Daisuke Hirabayashi

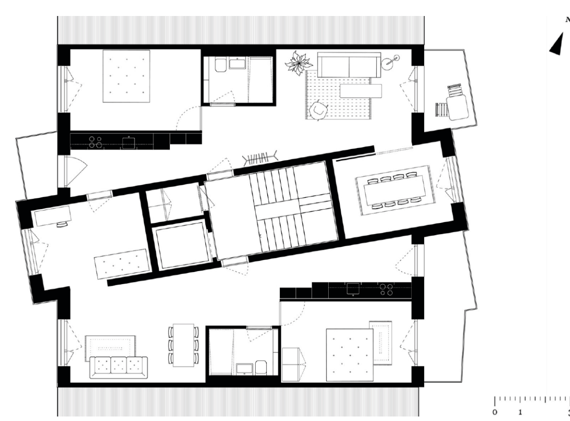


Figure 26. Typical floor plan. Image courtesy of NEUME.

Figure 28. Exterior view from the street. Photo © Daisuke Hirabayashi

Quatre Cheminées

Location: Boulogne-Billancourt, France
Architects: Déchelette Architecture
Year: 2023

Located in a Parisian suburb, the Quatre Cheminées project is an example of local and biomaterials used in a high-density urban context. Comprising eight social housing units and a commercial space on the ground floor, the five-stories building features a distinctive earthen façade on the street side, a solid stone base, and a wooden façade facing the garden.

The main façade was constructed using prefabricated rammed-earth blocks produced by a specialist company, Terrio, and installed by a general contractor that had never worked with the material. These blocks, dried off-site for three months, allowed for rapid on-site assembly within a month, guaranteeing a clean and efficient construction process. Prefabrication also significantly reduced costs, cutting them by almost half in comparison to rammed in-place earth.

The prefabricated blocks are not cement-stabilized, which enables the material to return to its original state at the end of the building's lifecycle. The design also sought to minimize the use of concrete and most structural elements are made from cross-laminated timber (CLT) panels.

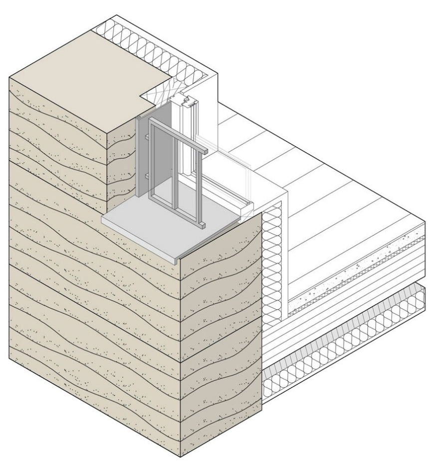


Figure 29. Detail axonometry of prefabricated rammed earth wall. Image courtesy of Déchelette Architecture.

Figure 30. Photo of the facade towards the street. Photo © Salem Mostefaoui

Figure 31. Prefabricated rammed earth elements during construction. Photo © François Baudry

Reflections and relevance to the design project

The background research and case studies presented in this chapter demonstrate that earth is a viable construction material with strong potential to reduce the environmental impact of the building sector. However, realizing this potential in industrialized, urban contexts—particularly in colder and wetter climates such as Gothenburg—requires careful adaptation.

A central insight from the research is the role of prefabrication in enabling earth construction within these settings. Prefabricated earth elements can help overcome climate-related limitations, reduce on-site labor demands, and ensure higher quality control. Case studies illustrate how prefabrication can allow for cleaner and faster construction processes, and may also improve acceptance among contractors and regulatory bodies.

Another important theme is the integration of earth within hybrid construction systems, combining it with other materials to address structural, thermal, and regulatory requirements. In several examples, earthen materials are used in combination with timber or other low-impact materials to create systems that are both sustainable and technically feasible in a strategy that offers flexibility in adapting to local construction practices.

The case studies further show that context-sensitive detailing—such as protections for exposed surfaces, passive design strategies, and moisture control—is essential when working with earth in challenging climates. Lessons from these projects emphasize the need for weather protection, appropriate insulation, and climate-responsive design to ensure long-term durability and comfort.

Lastly, while Life Cycle Assessment (LCA) is still limited in the field of earthen architecture, it holds promise as a tool to quantify the environmental benefits of using earth and to support arguments for broader adoption. LCA can highlight the strengths and limitations of specific design strategies and products and offer insights into how to improve the applicability of the material in future projects.

Together, these insights inform the development of the design project in this thesis by outlining strategies that can make earthen construction both feasible and impactful in urban environments like Gothenburg. They serve as guiding principles for exploring how this traditional material can be reinterpreted in contemporary architecture to meet today's societal challenges.

CHAPTER 03

URBAN CONTEXT

Population growth and housing shortage in Gothenburg

Gothenburg has experienced steady population growth over the last decades, and like some other growing metropolises, it is facing a persistent housing shortage. The city's population is expected to reach 707,200 by 2040, an increase of 120,000 people from 2022. To meet future needs, the municipality estimates that between 4,000 and 5,000 new homes must be built annually until 2030 (Fastighetskontoret, Göteborgs stad, 2022).

Although housing construction was high in recent years, there's been a sharp decline in the number of started homes (påbörjade bostäder). Sweden is currently in an economic downturn, impacting the housing market with rising interest rates, increased living costs, and a slowdown in construction. High production costs are considered a major limiting factor for housing construction in the Gothenburg region (Länsstyrelsen, Västra Götaland, 2024).

At the same time, the affordability of housing remains a pressing issue. The shortage is particularly evident among young adults and newly arrived immigrants (Fastighetskontoret, Göteborgs stad, 2022). The municipality acknowledges the need for more affordable housing, reflecting an unequal housing market where certain groups struggle to secure a home due to financial constraints and lack of suitable options (Länsstyrelsen, Västra Götaland, 2024).

Gothenburg's housing challenges are further complicated by the need for more diverse housing options. As the population grows and demographics shift, a broader range of housing types and sizes is necessary to meet the varied needs of residents. These demographic changes, combined with shifts in household structure, significantly influence housing demand (Fastighetskontoret, Göteborgs stad, 2022). In the Gothenburg region, even though the number of people per household is decreasing, it is estimated that the demand is relatively evenly distributed across different housing sizes (Länsstyrelsen, Västra Götaland, 2024).

Urban Densification

In the context of population growth, the city faces urgent challenges not only in housing and affordability but also in urban planning. The pressure to address the housing shortage drives project development and land allocation plans, often resulting in urban sprawl and, consequently, the depletion of natural resources, destruction of ecosystems, reduction of green areas, and strain on agricultural lands. Urban expansion can also lead to habitat fragmentation, causing biodiversity losses (Elmqvist, Zipperer, & Güneralp, 2016).

As an alternative, rather than expanding outwards into undeveloped land, urban densification refers to increasing the population and building density within existing urban areas. By densifying, it is possible to make better use of existing infrastructure, reduce land consumption, and potentially revitalize existing urban areas. Densification not only supports resource conservation but also helps reduce transportation emissions. Higher population density enables shorter commutes, making walking, cycling, and public transport more viable options.

There are different methods of urban densification, each presenting different strategies to optimize space within the city. One approach is transforming the functions of existing buildings by changing the use or adapting underutilized spaces for new purposes. Another method involves utilizing free spaces within the city by constructing new buildings on vacant plots, adding extensions to existing structures or filling gaps in between buildings. Densification can also occur by vertical expansion, such as adding new stories or creating underground spaces. Lastly, there is the replacement of existing buildings, where existing structures are demolished to make way for new ones, often with a higher density (Pelczynski & Tomkowicz, 2019). These methods, individually or in combination, can contribute to making urban areas more efficient and accommodating to growing populations and could be particularly relevant in Gothenburg, given the economic barriers to large-scale new developments.

Despite its benefits, densification presents challenges that can significantly impact urban life. Over-densification may reduce access to natural light and green spaces, increase noise and pollution, and intensify urban heat islands. The transformation of neighborhoods can also pose a risk to local identity and urban heritage, potentially losing the unique character of an area. Large-scale densification projects can also drive-up living costs, potentially leading to gentrification and displacement of existing communities. Additionally, the environmental impact of construction and demolition associated with densification can contribute to emissions, traffic congestion, and waste production, increasing the burden on the environment (Pelczynski & Tomkowicz, 2019).

Densification alone cannot fully address the city's housing challenges. Careful planning is necessary to ensure that densification efforts also prioritize sustainability and livability, addressing both the immediate housing crisis and long-term urban resilience. Sustainable construction practices which implement low-carbon materials can support continued development while reducing environmental impact and alleviating pressure on the planetary boundaries.

In the next chapter, this integrated approach will be explored through the design of a residential infill project on a selected urban gap in Gothenburg. The selection of the building site was guided by the following criteria:

1. The underdeveloped plot should be in a central area of the city, where density is higher with abundant infrastructure.

2. The site should have good visibility within the city to serve as a showcase for earthen architecture.

3. The proposed use should align with the surrounding urban context and address both the city's and its inhabitants' needs.

According these criteria, the chosen plot for the project is located at Andra Långgatan 16, in the vibrant Långgatorna area (Figure 32).

Figure 32. Site location. Based on aerial photograph from the City of Gothenburg Open Data Portal (2025), edited by the author.

Site analysis

Långgatorna in Masthugget district

Långgatorna is a unique and historically significant area in Gothenburg, characterized by its blend of residential, commercial, and industrial buildings, a diverse mix of architectural styles, and a vibrant street life. The area is known for its lively and creative atmosphere, where the mix of people, businesses, and buildings helps create its sense of authenticity and local identity.

The area's development is rooted in Gothenburg's history as a port city. Initially, the area grew outside of the city gates to avoid regulations and to support harbor activities. The establishment of the "Long Streets" (Långgatorna) in the 19th century led to a mix of buildings, reflecting the diverse needs of the population including merchants, workers, and sailors. Over time, the area became a confluence of social classes and cultures, which contributed to its identity. The presence of workshops, small-scale industries, and a strong working-class culture laid the foundation for the area's creative and entrepreneurial spirit. Today, it retains its historic feel and remains a center for a grassroots culture (Hultgren et al., 2012).

The Långgatorna area is characterized by a dense, compact urban structure with eight long enclosed blocks of buildings. Along the streets, most buildings are three or four stories high, with taller structures found on the periphery. The architecture reflects a blend of styles primarily from 1860 to 1930, including neo-Renaissance, Art Nouveau, and National Romantic. Narrow facades with marked vertical divisions characterize the streetscape, often featuring street-level businesses. Balconies are occasionally present, typically on buildings' corners or along the main streets. Another common architectural feature includes sloping roofs towards the streets that are accentuated by distinct eaves, while behind the buildings, often enclosed and small courtyards create

Figure 33. Map over Långgatorna area showing the buildings' age (Adapted from Itgren, Å., Lissvall, M., Holmström, S., & Häggdahl, M., 2012).

Figure 34. Map over Långgatorna area showing the buildings' use and street level activities (Adapted from Itgren, Å., Lissvall, M., Holmström, S., & Häggdahl, M., 2012).

more private spaces (Hultgren et al., 2012).

The street-level businesses in Långgatorna contribute to the area's overall character, reflecting its rougher, more alternative culture. Historically lower rents attracted entrepreneurs, artists, and small business owners with limited resources, creating a dynamic environment with a high turnover of businesses as people test new ideas. This ever-evolving landscape has made the area a hub for innovation and creative expression that is largely supported by the local community (Hultgren et al., 2012).

The existing environment, including the historic buildings and street-level activities, contributes to Långgatorna's attractiveness. Overdevelopment and homogenization could lead to the destruction of its unique character, damaging its authenticity and community. The area's mix of old and new, of residential and commercial, gives it a dynamism that cannot be easily replicated if lost. Preserving its structure, diverse architectural styles, and street culture is important to support its sense of community and heritage.

The "Long Streets"

Each of the four main streets in the area has a distinct character. Första Långgatan serves as a major thoroughfare, with larger-scale buildings and office blocks. It is wider than the other Långgatorna and supports mobility and connectivity to the harbor, making it less pedestrian-friendly.

Andra Långgatan is known for its lively street life with a dense concentration of small businesses, pubs, and restaurants. It has a more vibrant pedestrian feel and is the most active of the four.

Tredje Långgatan features a mix of contrasts with quieter areas, a variety of building styles, and unique structures like the former police station. It includes cultural institutions, making it a blend of calmer residential areas and lively hubs.

Fjärde Långgatan is generally perceived as a more quiet, residential street with more modern architectural elements compared to the other Långgatorna. It still retains historical buildings and workshops but primarily functions as a residential area.

Figure 35. Annotated aerial image of the area with transportation routes and nodes. Based on aerial photograph from the City of Gothenburg Open Data Portal (2025), edited by the author.

Detail plan from 1948

In 1948, a new detail plan was introduced for the Långgatorna area. Most of the current buildings had already been built, but their diverse, mixed-use functions were opposed to the ideals of that time. While the street layout remained unchanged, the blocks were reorganized based on function. Residential areas were concentrated in the southern blocks, where courtyards would be made more suitable for housing by removing existing courtyard buildings. The northern blocks were primarily allocated for commercial use, with courtyards allowed to be built over up to five meters to accommodate commercial activities.

The plan was implemented in parts of the northernmost blocks, where properties were merged and more large-scale, continuous buildings were constructed. In the Smacken block, some of the courtyard buildings were demolished but not replaced with new structures, as it was intended in the plan, leaving the area with relatively open and green courtyard spaces, unlike most blocks in Långgatorna.

The selected project site, located within the Smacken block at Andra Långgatan 16, is highlighted in the image below, cropped from the 1948 detail plan map.

Figure 36. Cropped section of detail plan 1480K-II-2545 from Göteborgs Stad, edited by the author.

According to the detail plan, the property is designated only for commercial use, as indicated by the letter H, although spaces for other uses may be incorporated if deemed appropriate by the building authority. The maximum number of stories is four, represented by the Roman numeral IV, and the maximum building height, marked by rectangles on the plan, is 13.5 meters. The maximum roof slope, shown inside the triangles, is 30°. In the courtyard area, the maximum height must not exceed 5 meters, and the roof slope should be limited to 3°. Finally, buildings on the property must be constructed to allow for coordinated development, meaning they should be designed to connect or be built together, as specified by the S symbol in the detail plan.

The building site

At Andra Långgatan 16, there is a one-storey building owned by Wilhelmsnääs 7:5 Kommanditbolag, currently operating as a strip club. Research on the property indicates that its development is still regulated by the 1948 detail plan.

The existing low-rise structure creates a noticeable gap in both the streetscape and the block, standing out against the taller adjacent buildings, which are four stories high (excluding attics) with residential units on the upper floors and businesses at street level. Other buildings within the Smacken block range from three to four stories in height, occasionally reaching five when including converted attics. The one-story structure at Andra Långgatan 16 weakens the sense of enclosure in the inner courtyard.

The first building in the block was constructed in 1866, with most of the other plots developed into residential buildings between 1880 and 1905. All the original structures still stand today, with many facades designed in the Neo-Renaissance style. The building at Andra Långgatan 16 was, in fact, the last to be constructed in the block.

Its neighbour to the east features a mansard roof and a light-brown brick facade facing the street, while the building to the west has a gable roof with a light-yellow brick facade on the upper floors and white painted bricks at street level. In contrast, the existing building at Andra Långgatan 16 stands out with its black plastered façade, which does not align with the materiality of the adjacent buildings. Its unconventional use as a strip club gives it an anonymous and closed-off appearance, with only three doors and no windows.

The building occupies the entire plot, and a visit to its interior revealed that it actually houses two floors with very low ceiling heights - around 220cm on the first floor and 230cm on the second. Combined with a lack of openings, this severely compromises natural ventilation and daylight, creating an overall poor indoor environment. Additionally, the building's low construction quality, structural limitations, and absence of architectural or historical significance make a case for its demolition and redevelopment.

Figure 37. View of the existing building at Andra Långgatan 16 (Photo by author, 2025).


Figure 38. View from the top of the roof towards east (left) and west (right) (All photos by the author, 2025).


Figure 39. Images from inside of the building on the first (top) and second floors (bottom) (All photos by the author).

CHAPTER 04

DESIGN PROJECT

As discussed in the previous chapter, Gothenburg's persistent housing shortage highlights the need for alternative housing solutions that address affordability, diversity, and social sustainability. Cooperative housing presents an opportunity to respond to these challenges by offering a model that seeks to strengthen community ties while addressing the need for accessible, adaptable, and environmentally conscious urban living. Although more common in other European countries, as seen in projects like Dirty Harry, there are also a few examples within Sweden.

This project explores the potential of cooperative housing as an alternative to conventional residential models, aiming to create a community-oriented living environment. Unlike traditional ownership or rental structures, cooperative housing supports collective decision-making, shared responsibilities, and a sense of belonging among residents. This approach helps to promote social cohesion and can offer a more sustainable and affordable way of living.

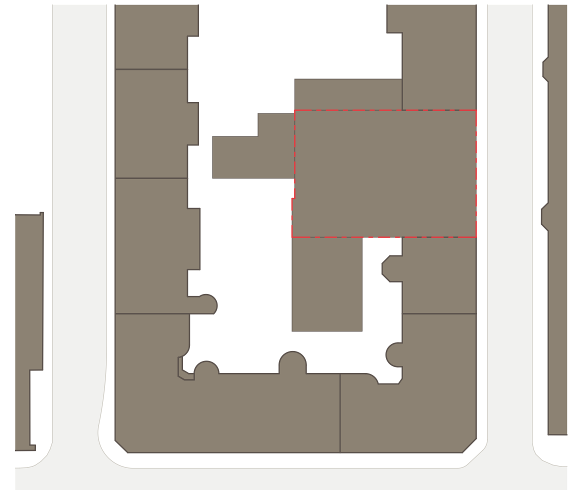
The project to be presented later in this chapter is designed to accommodate a diverse group, including young adults, young families, and senior adults living alone. By bringing together different generations and household compositions, this housing model encourages social interaction, exchange, and mutual support.

To support this new use, the project is guided by a few spatial transformation strategies. Following the demolition of the existing building, the site will be partially depaved and re-naturalized, restoring permeability and introducing new green areas.

A new built volume connects the two adjacent buildings, reaching a total of five storeys with a footprint of approximately 250 square meters. As an infill project, it aligns in height with its immediate context, filling the existing urban gap. Reflecting a characteristic feature of the surrounding area, the proposal builds upon pre-existing facade rhythms: the elevation is vertically segmented, with clearly defined roof eaves and a distinct ground floor that contrasts in materiality with the upper levels.

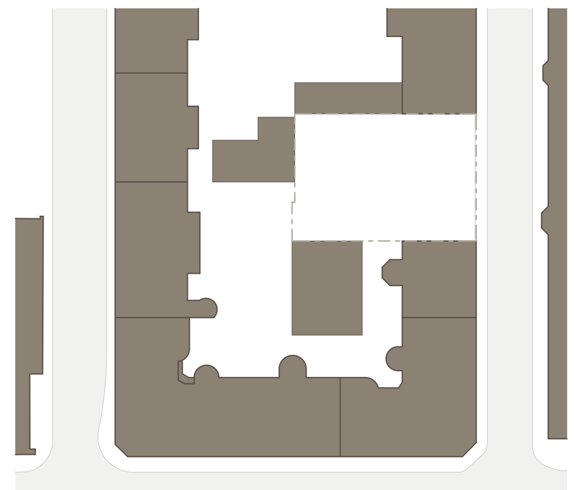
Following the same principle, the design draws from existing patterns to position building elements such as the stair and elevator core and a single-storey annex, in a way that dialogues with the spatial logic of the interior courtyard. The diagrams on the next page (Figure 40) illustrate these transformation strategies adopted in response to the site's conditions and its urban context.

Contextual strategies and site transformation



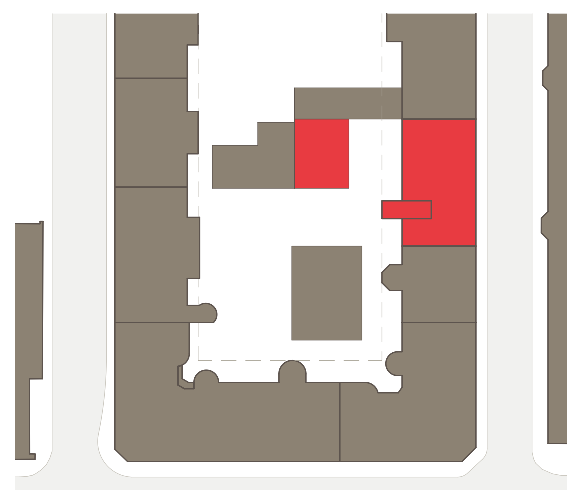
1. Existing situation – site plan

A. Existing situation – street elevation



2. Reducing impervious surfaces

B. Filling the urban gap



3. Building on pre-existing patterns

C. Respecting facade rhythms

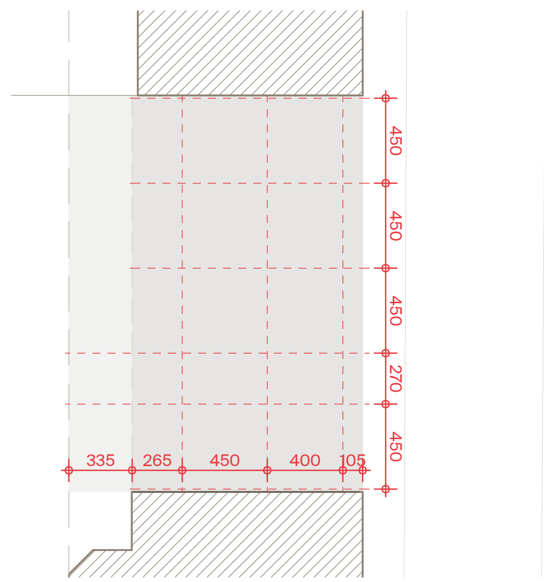
Figure 40. Existing conditions and strategies guiding the project's integration into the urban fabric.

Design principles

The project is shaped by core design principles aimed at reinforcing its spatial, social, and environmental intentions.

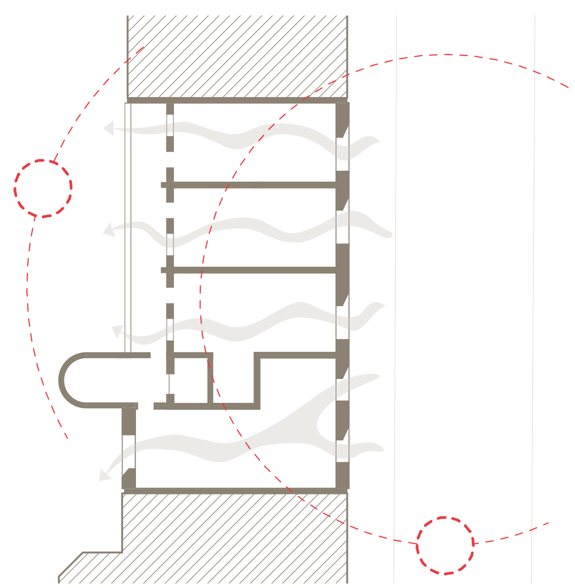
Modularity

The project adopts a modular structural system with spans that do not exceed 4.5 meters. This decision reflects a commitment to construction rationality and simplicity, avoiding unnecessarily complex structural solutions. More importantly, the modular and independent structure enhances flexibility, allowing the building to adapt to future programmatic changes.



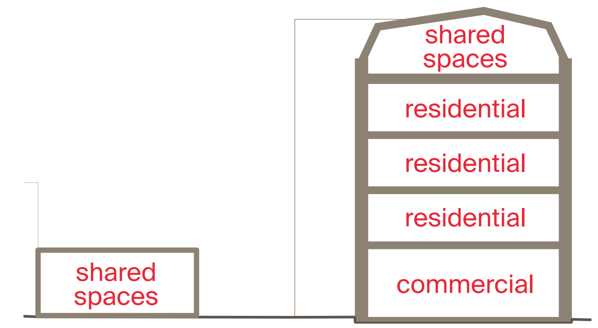
External Circulation

The project adopts external circulation through open-air access balconies, which serve as shared entrance corridors. This strategy ensures dual orientation for all apartments. By opening toward both the northwest and southeast façades, each unit benefits from daylight on two sides and the possibility of cross ventilation.



Functional Distribution

The project is structured through a clear vertical distribution of functions. A rentable commercial space is placed on the ground floor to activate the street level and serve as a source of income for the cooperative. This level also houses support functions, including a single-storey annex at the back of the plot. The intermediate floors are dedicated to residential units, while the top floor accommodates the main common living area, connected to a rooftop terrace.



Program Overview

The architectural program is organized across five levels, with a clear distinction between public, private, and shared functions. On the ground floor, the project combines common areas—including a co-working/study space, laundry room, technical spaces, workshop, and garden—with a commercial unit facing the street, envisioned as a café. Additional shared facilities include storage spaces and a bicycle storage area.

The intermediate floors accommodate twelve residential units, with a stronger emphasis on smaller apartments. Each unit has access to shared external balconies, promoting social interaction and providing outdoor space for residents.

The top floor hosts the main communal area: a shared kitchen and dining room directly connected to a rooftop terrace, designed as the central gathering point for the community. It also includes a playroom and a guest room for collective use.

Program Summary

Number of apartments: 12

6 one-room units
3 two-room units
3 three-room units

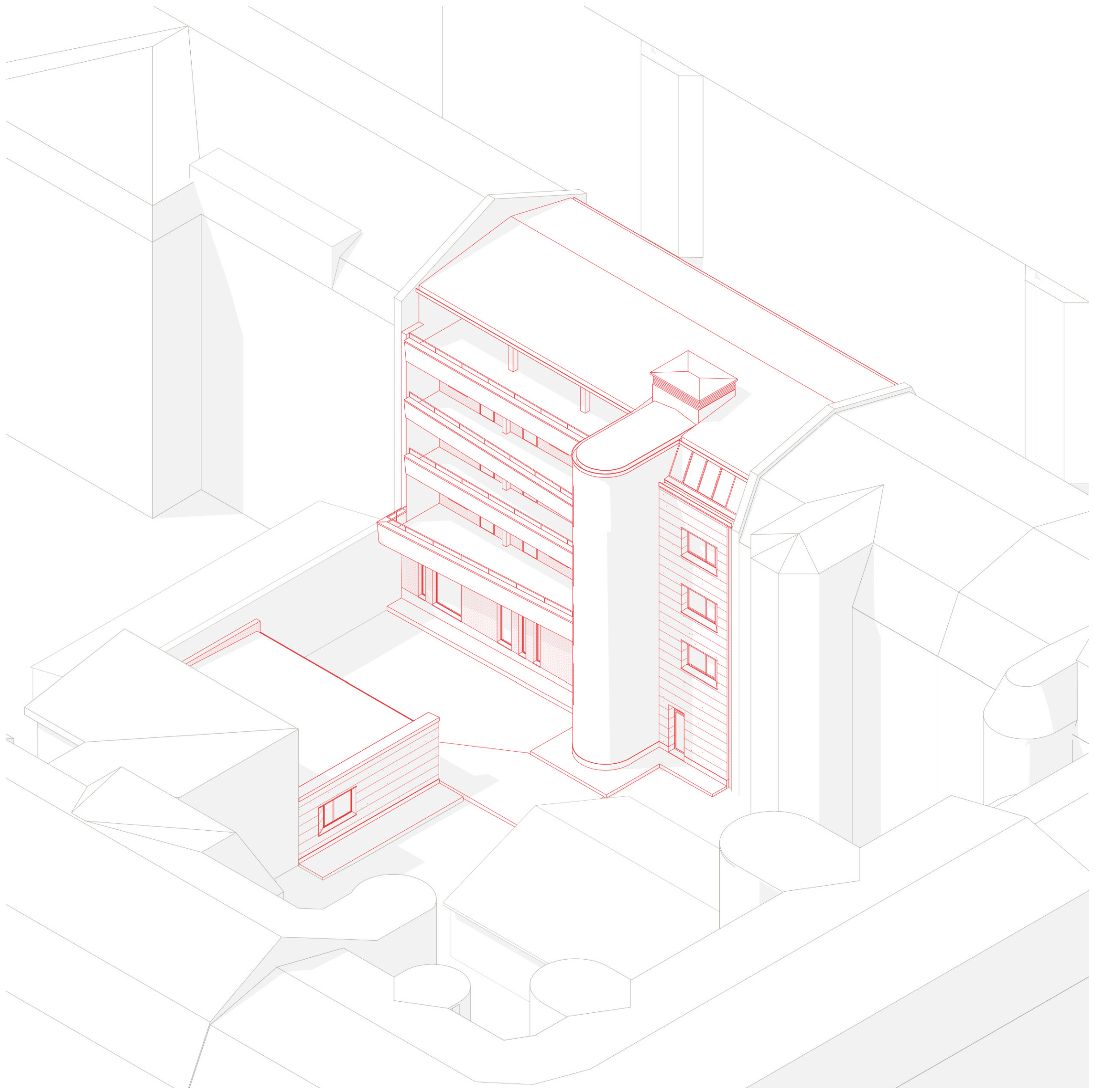
- Total apartment area: 509 m²

Shared facilities: Co-working/study area, laundry room, workshop, common kitchen, playroom, and guest room

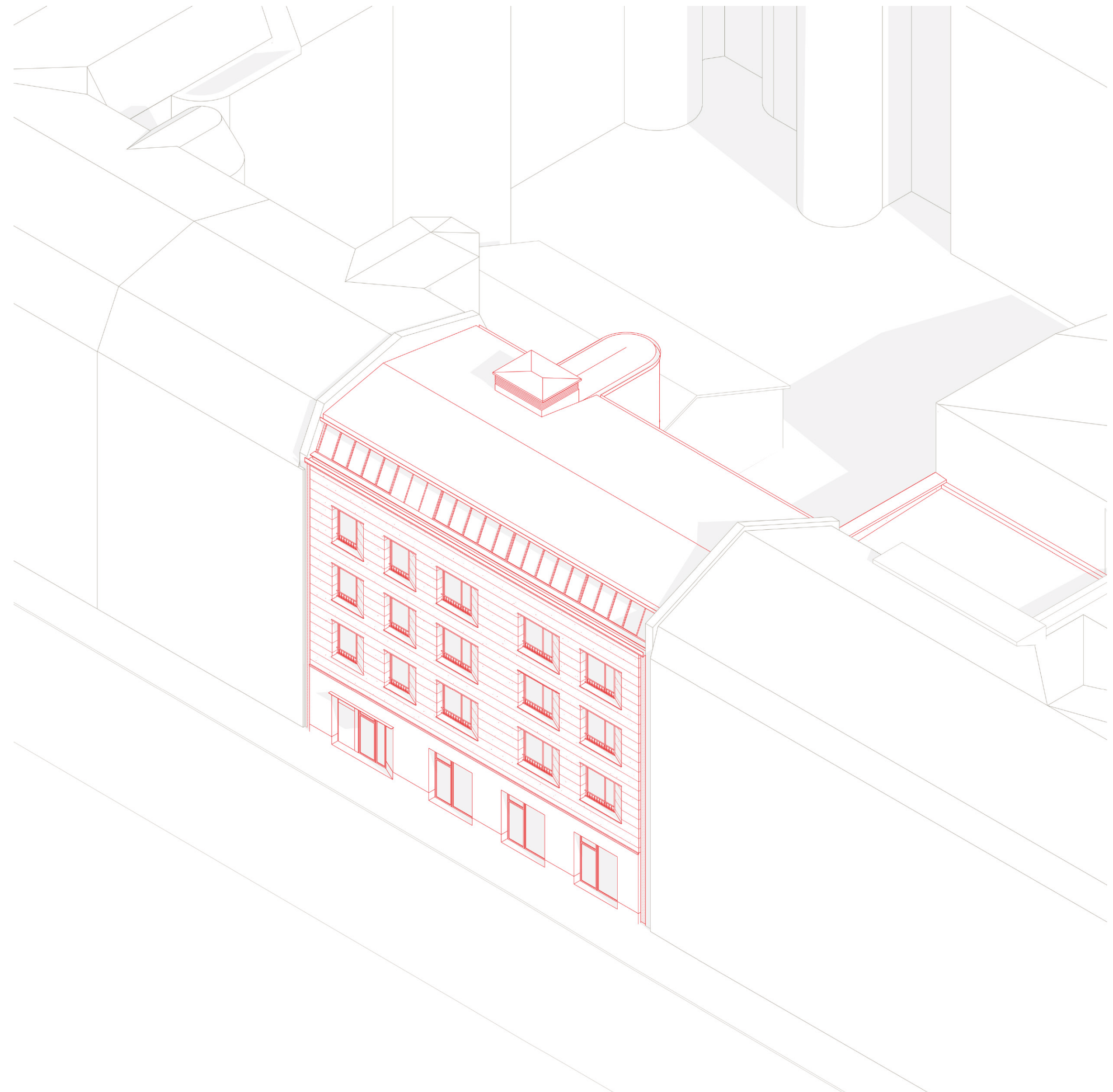
Other support spaces: Storage room, garbage room, bicycle parking, stroller/wheelchair storage, and technical rooms

- Total area – shared facilities: 351,5 m²
- Total area – shared balconies: 92.5 m²
- Total area – rooftop terrace: 53 m²
- Total commercial area: 92 m²

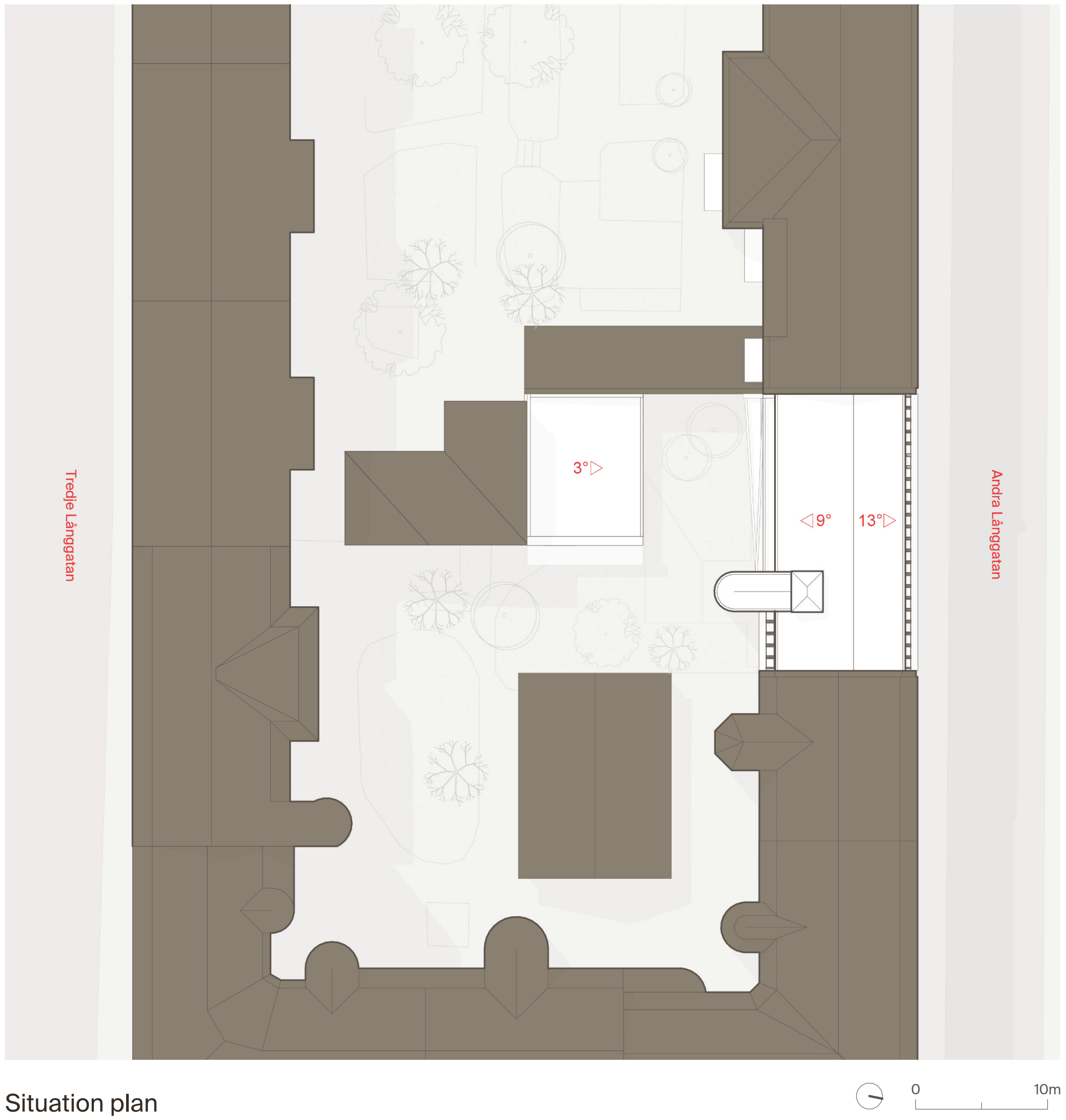
Final design



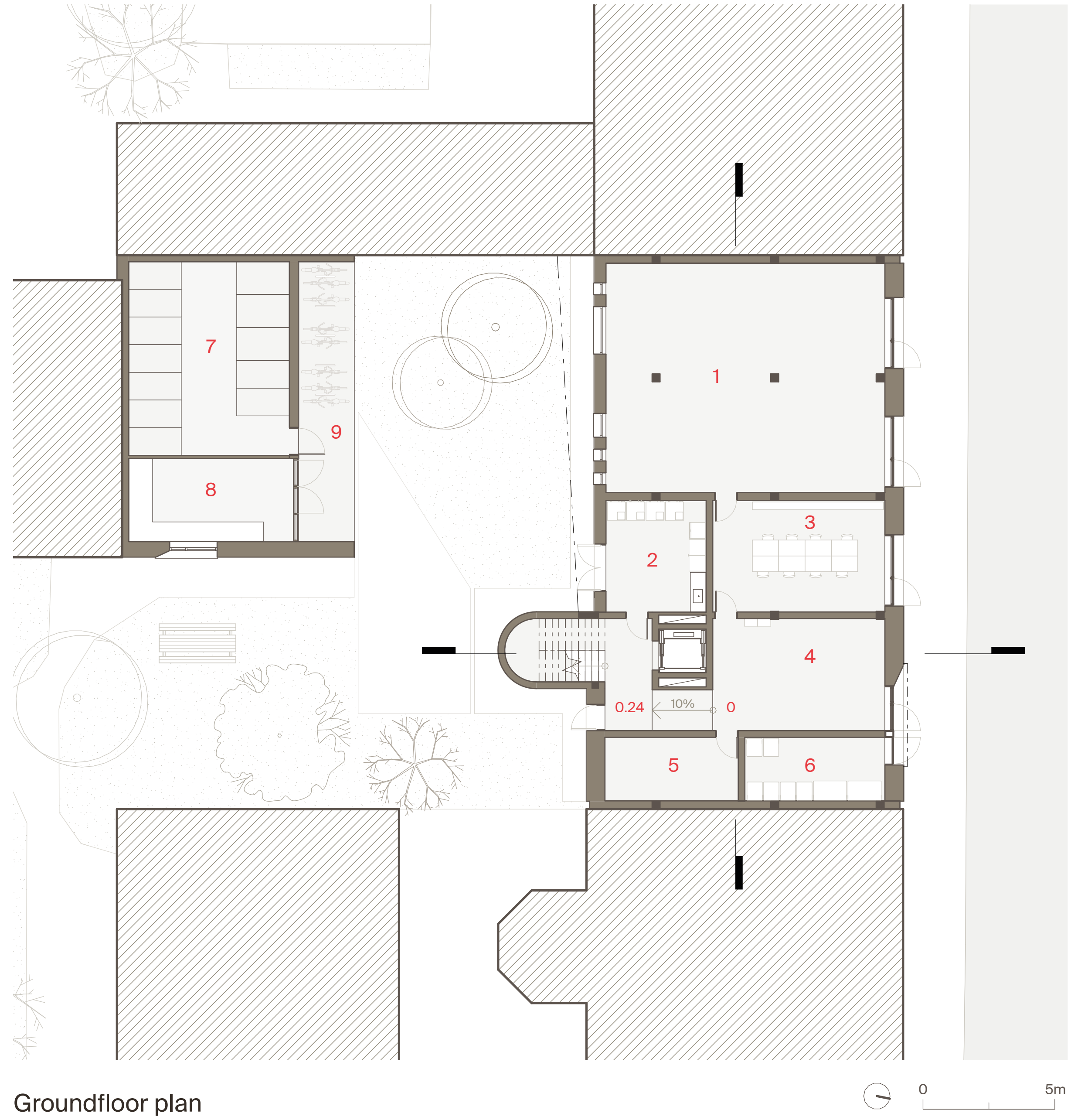
Axonometric view from the courtyard side of the new building



Axonometric view from the street side of the new building



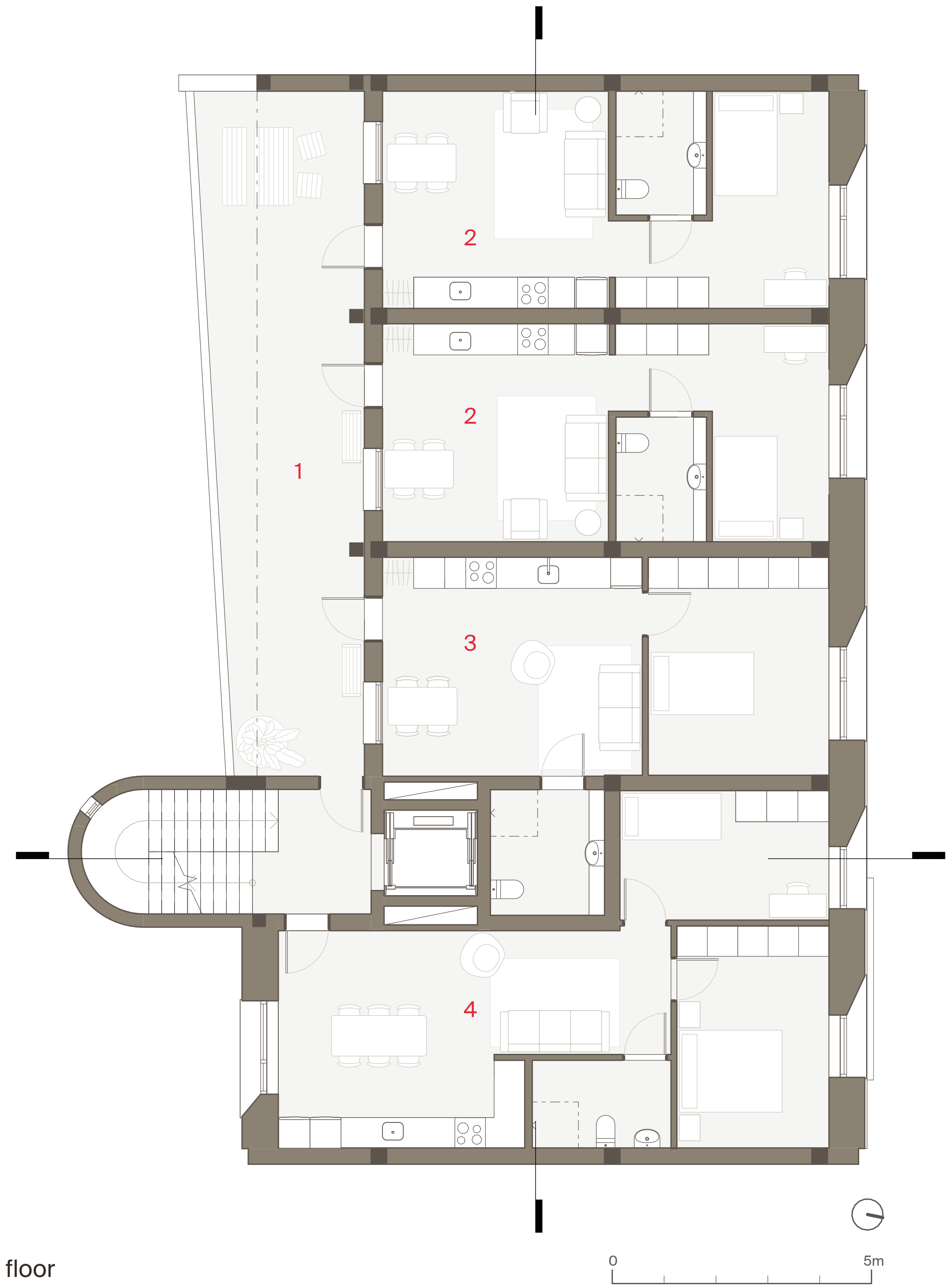
Situation plan
1:500



Groundfloor plan
1:250

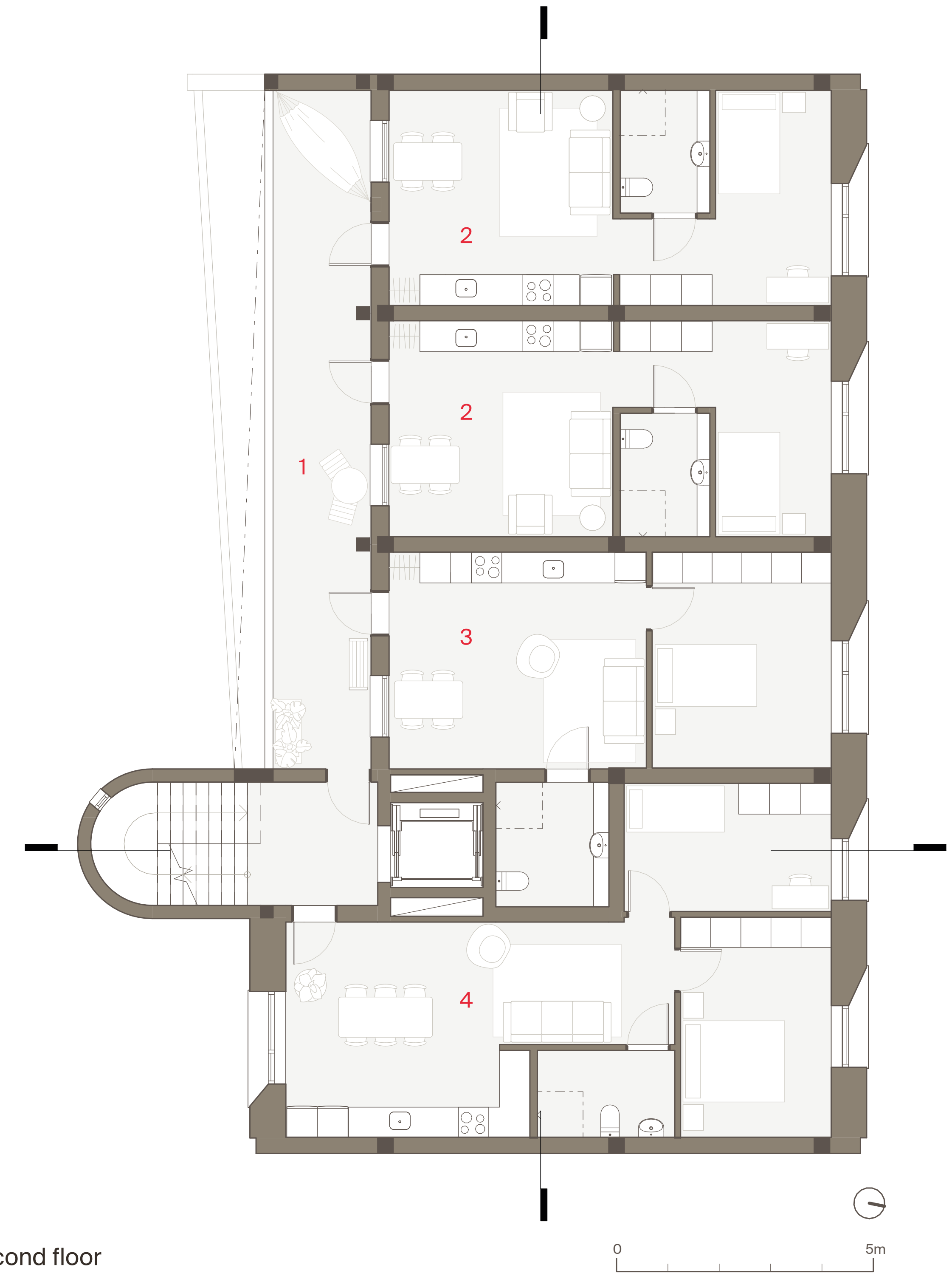
1. Rentable space - 92m²
2. Laundry room - 17m²
3. Co-working - 28m²
4. Strollers/wheelchair area
5. Techinical room - 12m²
6. Garbage room - 13m²
7. Storage room - 45m²
8. Workshop - 20m²
9. Bicycle parking

The ground floor is organized into two distinct zones: to the west, a commercial unit activates the street frontage, while to the east, the residential entrance provides access to the vertical circulation core and a series of supportive spaces, including a laundry room, garbage room, technical room, and dedicated areas for stroller and wheelchair storage. At the back of the plot, a smaller, separate building offers practical amenities for the residents, containing a workshop, a storage room, and a sheltered bicycle parking area.



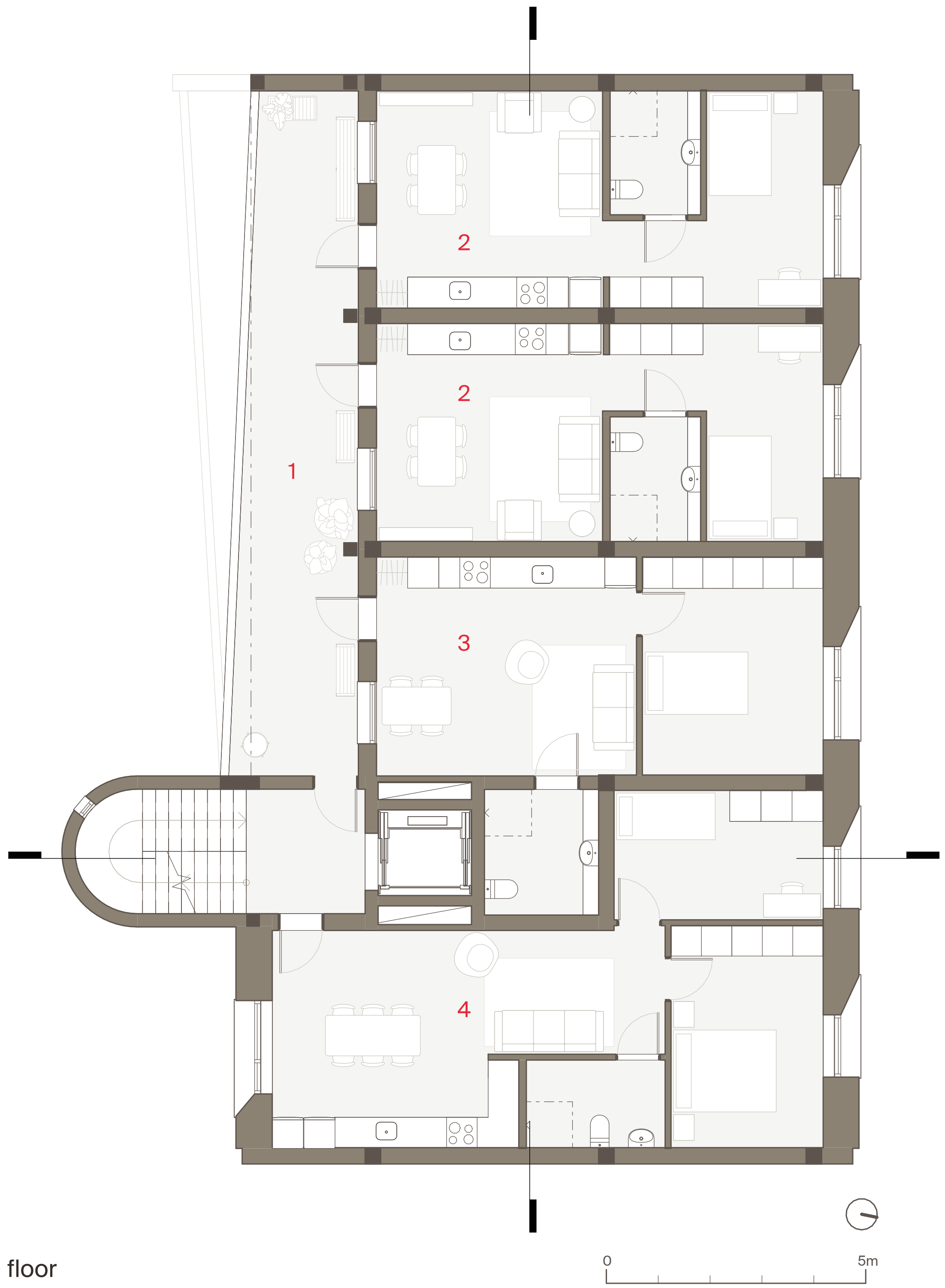
First floor
1:125

1. Entrance balcony - 38m²
2. 01 room apartment - 36m²
3. 02 room apartment - 42m²
4. 03 room apartment - 55m²



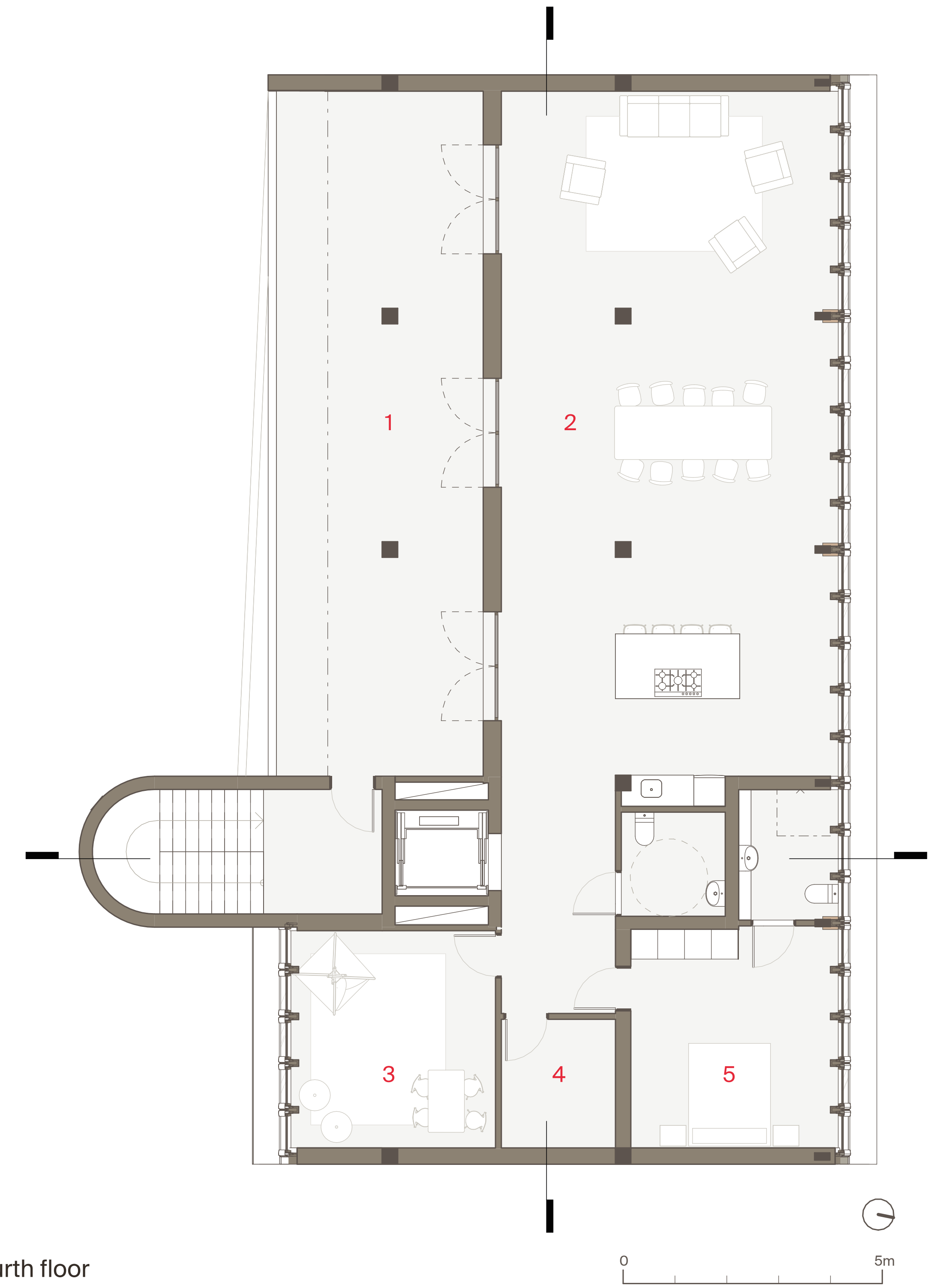
Second floor
1:125

1. Entrance balcony - 25m²
2. 01 room apartment - 36m²
3. 02 room apartment - 42m²
4. 03 room apartment - 55m²



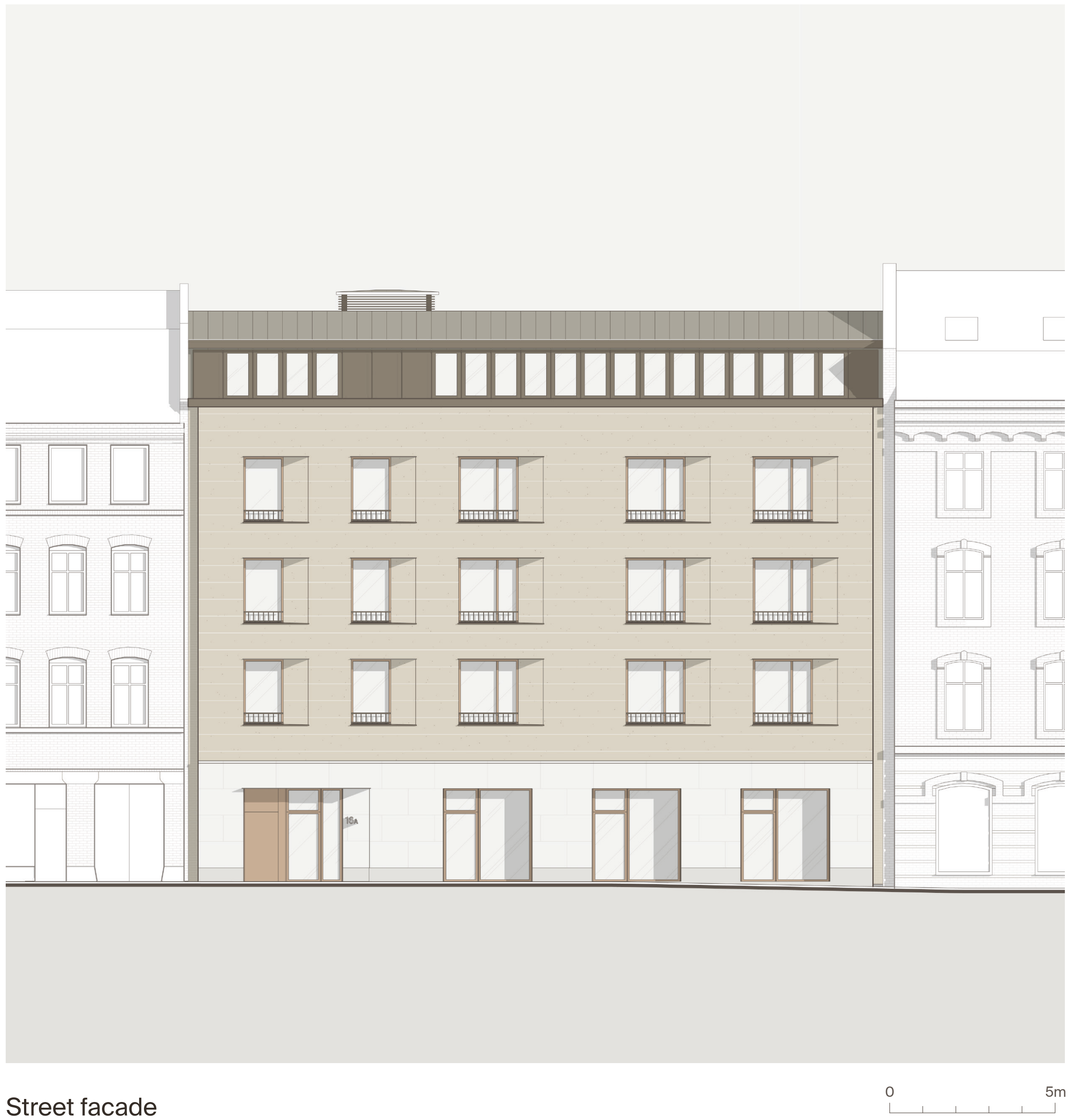
Third floor
1:125

1. Entrance balcony - 29m²
2. 01 room apartment - 36m²
3. 02 room apartment - 42m²
4. 03 room apartment - 55m²



Fourth floor
1:125

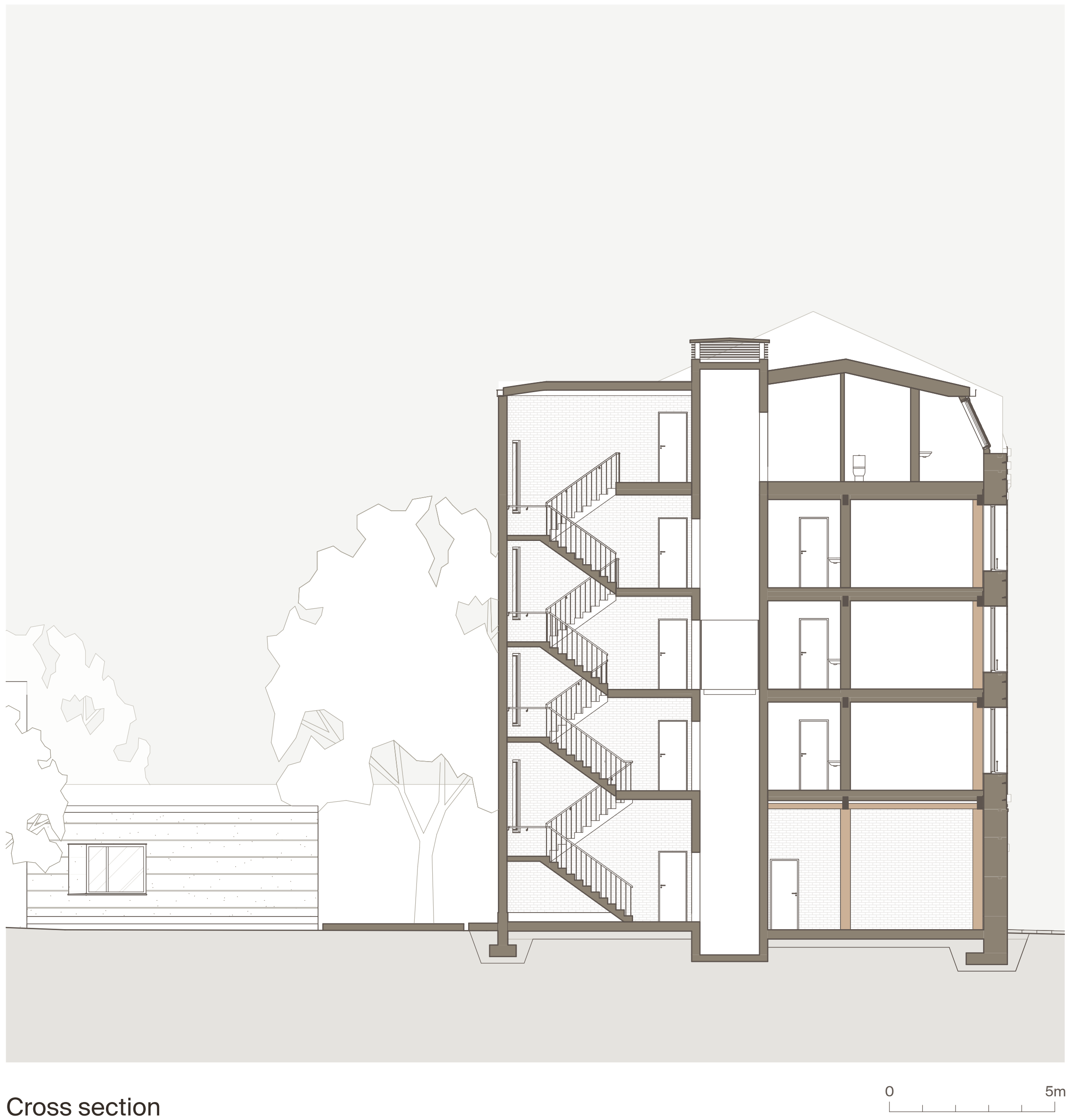
1. Roof terrace - 53m²
2. Common kitchen - 102m²
3. Playroom - 17m²
4. Technical room - 5m²
5. Guest room - 22m²



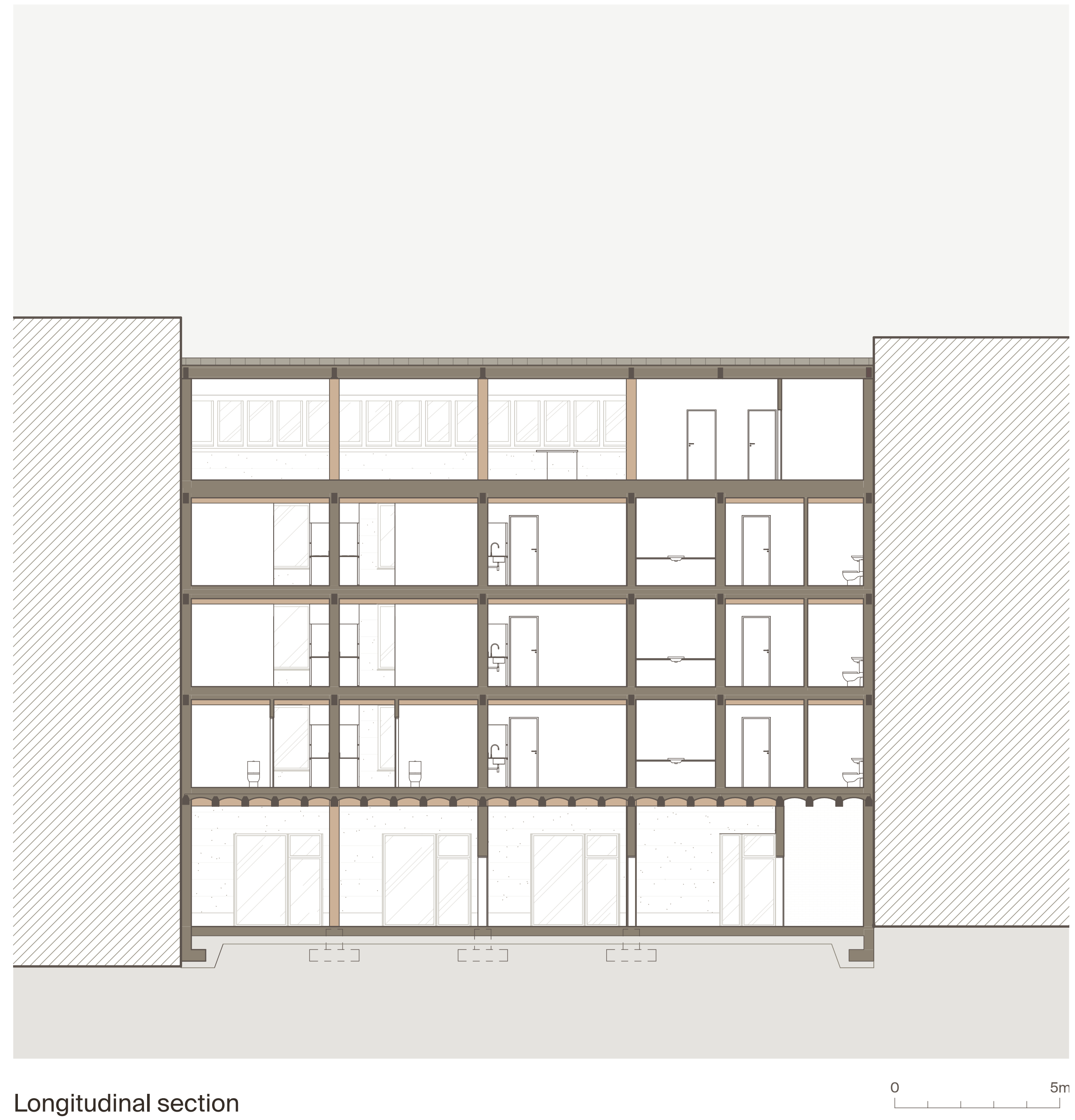
Street facade
1:200

Courtyard facade
1:200

Movement through the residential floors is structured around an exterior circulation system. Apartments are accessed through entrance balconies that overlook the courtyard, conceived as communal spaces to encourage interaction among neighbors.



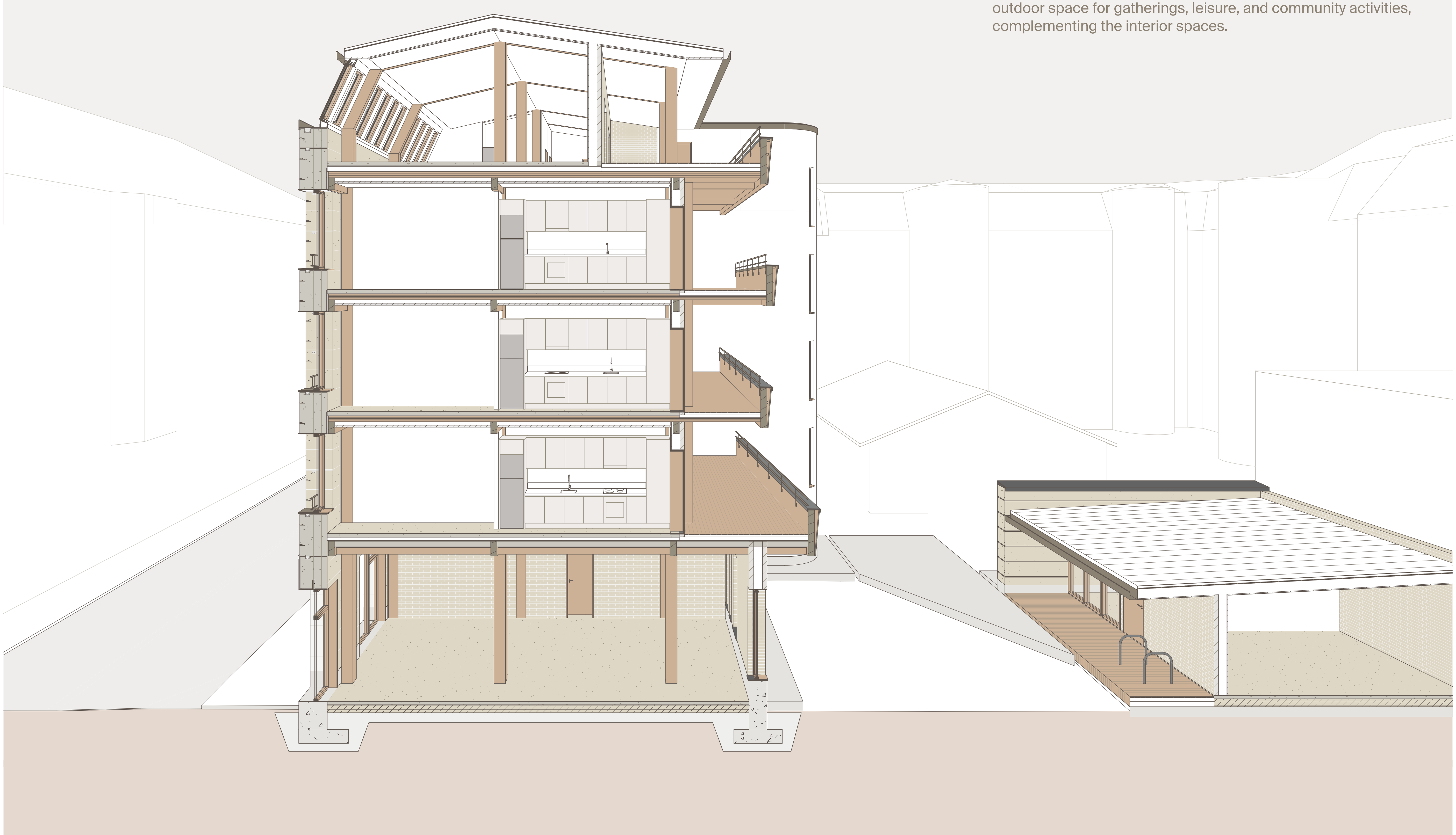
Cross section
1:200



Longitudinal section
1:200

The ground floor is designed with an increased floor-to-ceiling height to accommodate flexible commercial uses. Above, the ceiling structure introduces a tactile and expressive architectural detail: compressed earth blocks form an arch between timber beams spaced 90 centimeters apart, creating a hybrid system that defines the character of the interior space through its texture, rhythm, and natural tones.

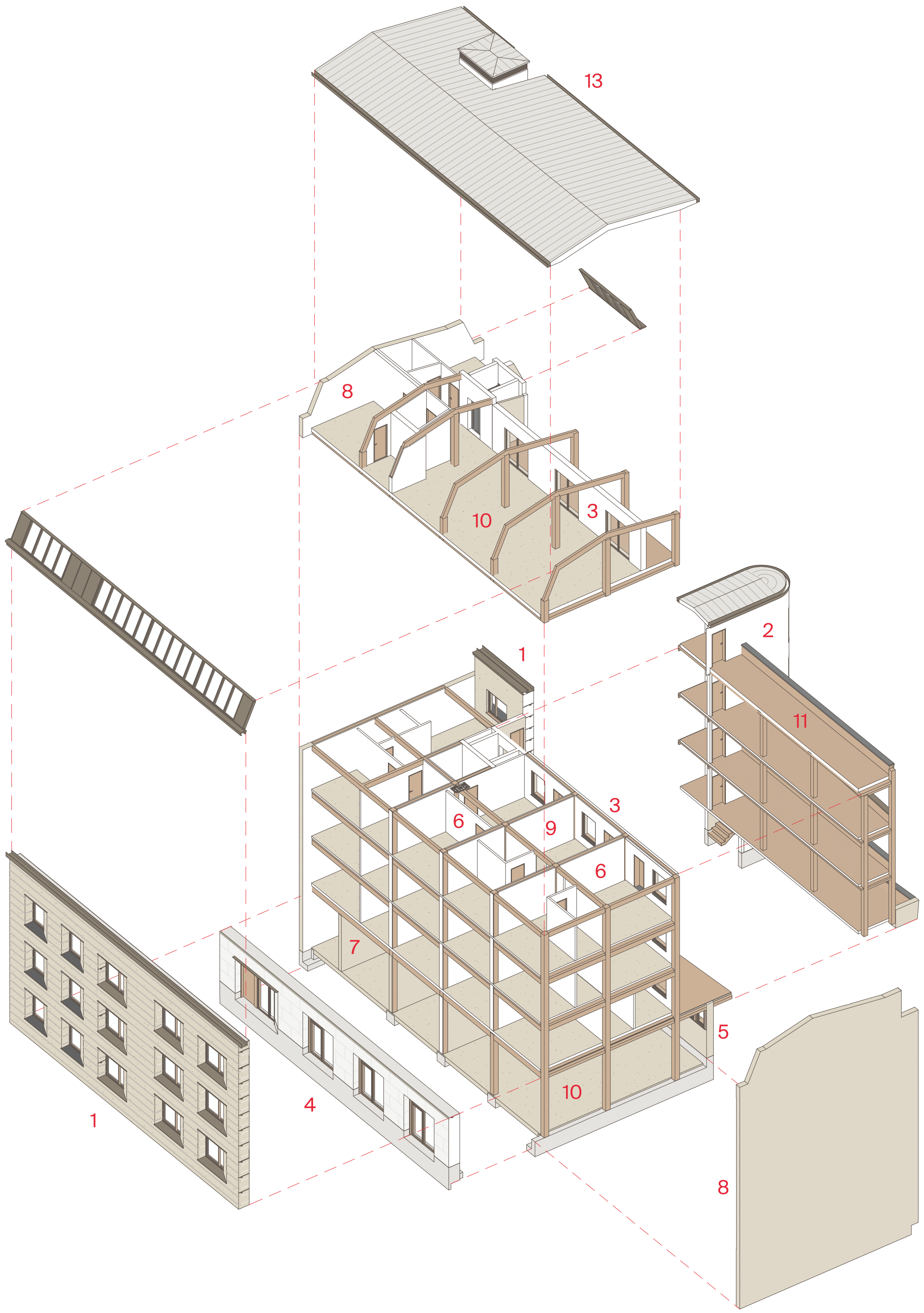
The top floor forms the heart of the collective life within the building, where a shared kitchen and playroom are located. The spatial character of this floor is shaped by the roof form, which features three distinct slopes. A large glazed section opens up toward the northwest, capturing the prolonged daylight of the Swedish summer evenings. Adjacent to the indoor common rooms, a south-facing roof terrace provides a sunny outdoor space for gatherings, leisure, and community activities, complementing the interior spaces.



Exterior perspective from the street (top) and interior perspective of the rentable space (bottom).

Interior perspective from one of the smalller apartments (top) and interior perspective of the common space on the top floor (bottom).

Material discussion



Exterior walls

1. Prefabricated rammed earth panels
2. Lime plastered CEB walls
3. CEB + clay panels on wooden studs
4. Prefabricated rammed earth panels with stone cladding
5. CEB walls

Interior walls

6. Clay panels on wooden studs
7. CEB walls
8. Light clay blocks
9. Light clay blocks + clay panels on wooden studs

Floors

10. Rammed earth floor
11. Wood decking

Roofs and ceilings

12. Clay panels
13. Natural zinc roof

In this project, the material strategy was central to the design process, exploring the use of different industrialized earthen construction techniques in combination with other bio-based materials, prioritizing low embodied energy, circularity, and adaptability over time.

The primary structure consists of cross-laminated timber (CLT) floor slabs and glued laminated timber (GLT) beams and columns. Even though some earthen wall construction methods can function as load bearing, the choice for a post and beam system was based on increasing flexibility for potential future demands and uses.
In line with circular building principles, engineered timber components also allow for disassembly and reuse.

Earth, the focus material in this thesis, is applied in multiple forms—across exterior and interior walls, ceilings, and floors.
The following section provides a detailed overview of the material applications by building components.

Exposed facades

The exposed facades are constructed using prefabricated rammed earth panels with integrated insulation. Each panel consists of two outer layers of rammed earth with a 20 cm core of foam glass granulate, compacted directly during the ramming process. This results in a total wall thickness of 69 cm, with the earth surface exposed on both the interior and exterior.

Based on the techniques developed by Martin Rauch, the outer layer includes trass-lime erosion checks placed every 50 cm to protect the wall surface from running water, improving weather resistance without requiring additional cladding or coatings. In addition, protective metal copings are installed on top of the walls, which are mounted on a plinth rising at least 40 cm above ground to prevent water infiltration from both above and below.

To facilitate transport and installation, each prefabricated panel weighs less than 4 tonnes and does not exceed 120 cm in height, 350 cm in length, or 70 cm in thickness. On site, the panels are assembled using a crane in a running bond pattern to increase structural integrity and lateral stability, as illustrated in Figure 41.

Sheltered exterior walls

The compressed earth blocks (CEB) used in the project are entirely free of cement stabilization. For this reason, they are applied only in exterior walls that are protected from direct rainfall—such as beneath balconies or roof overhangs—ensuring durability through architectural design strategies rather than chemical additives.

The CEBs are left visible on the exterior, revealing the natural textures and color variations of the earth. On the interior side, the wall system consists of clay building boards fixed to a wooden stud frame, with wood fiber insulation between the posts. These boards are finished with clay plaster and clay paint.

On the ground floor, where the commercial space gives the area a more public character, the inner drywall system with rendered clay boards is replaced by an exposed inner layer of CEBs, increasing the wall thickness from 35 cm to 45 cm.

The layered composition of these walls highlights the tactile qualities of earth while creating a breathable building envelope that contributes to a healthy and comfortable indoor climate.

Interior Walls

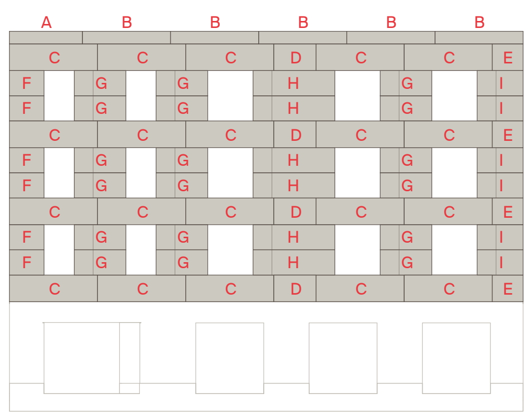
Partitions within apartments:

Interior partitions within each apartment unit are constructed using clay wall boards mounted on wooden studs, finished with clay plaster and clay paint. This dry construction system is lightweight, modular, and reversible, allowing for future adaptability. In shower areas, where moisture exposure is high, clay wall boards are not recommended. Instead, light clay blocks are used and finished with tadelakt—a traditional lime-based plaster with a polished, water-resistant surface that maintains a natural aesthetic and tactile quality.

Apartment separation walls:

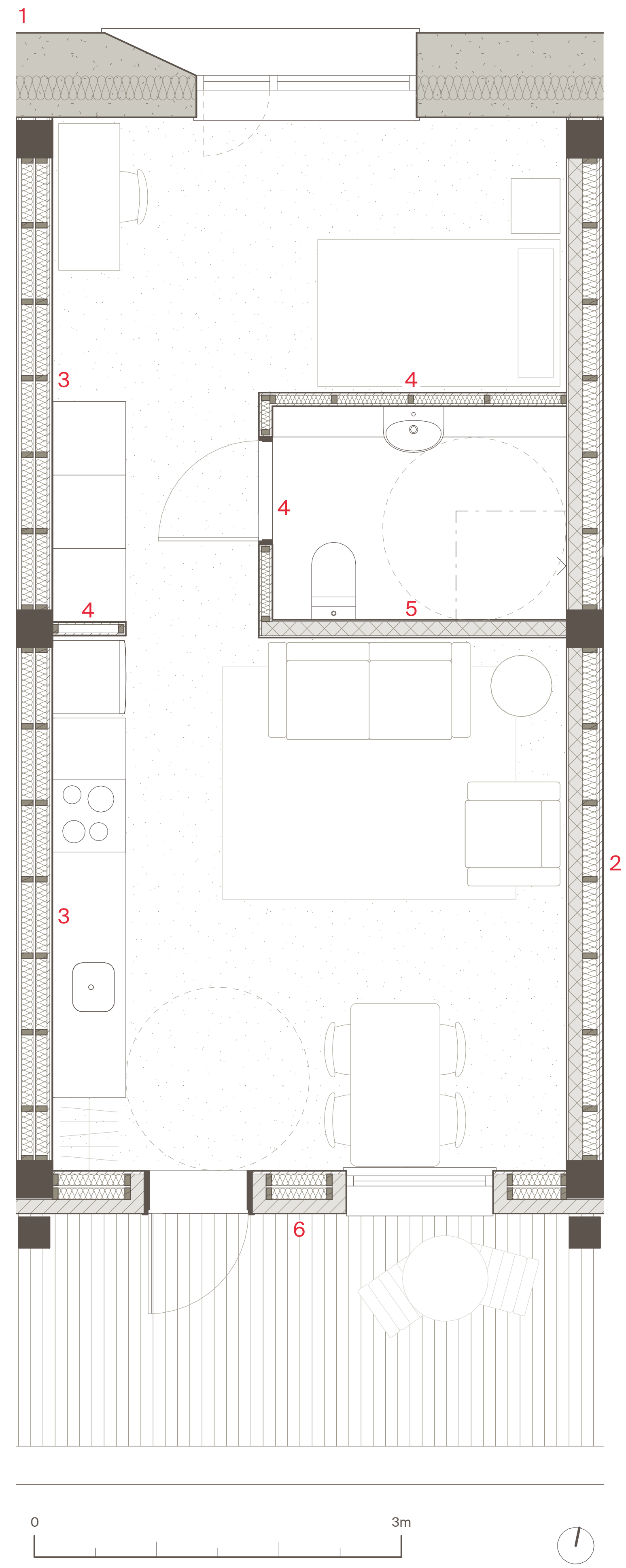
For separation between apartment units, a double-stud wall system is used, clad with clay boards and insulated with wood fiber, then finished with clay plaster and clay paint. In cases where these walls are adjacent to wet areas, a layer of light clay blocks replaces one side of the studs and boards, with tadelakt finish for moisture resistance.

For walls adjacent to neighboring buildings, a double layer of light clay blocks with reed insulation is used. These walls are also finished with clay plaster, creating a unified interior material palette throughout the building.



A. 290 x 50 x 69 cm
B. 350 x 50 x 69 cm
C. 350 x 106 x 69 cm
D. 167,5 x 106 x 69 cm
E. 122,5 x 106 x 69 cm
F. 137,5 x 100x 69 cm
G. 205 x 100x 69 cm
H. 325 x 100x 69 cm
I. 182,5 x 100x 69 cm

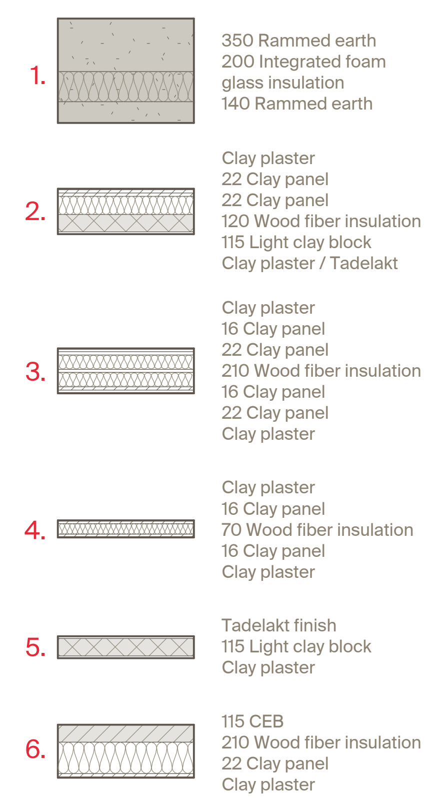
Figure 41. Diagram for the different types of prefabricated rammed earth panels with respective dimensions - street facade elevation



Flooring

On the ground level, a polished rammed earth floor finished with natural wax extends the material expression of the facade and interior walls into the public areas of the building. On the upper levels, the interior floors are constructed with polished and waxed rammed earth with in-floor heating system, installed over footfall sound insulation and laid on top of the CLT slabs.

In the the entrance balconies and roof terrace, a raised timber decking system is used. This consists of weather-resistant wooden planks mounted on a ventilated substructure, allowing for drainage of rain and snow.



Smaller apartment plan 1:50

Roof

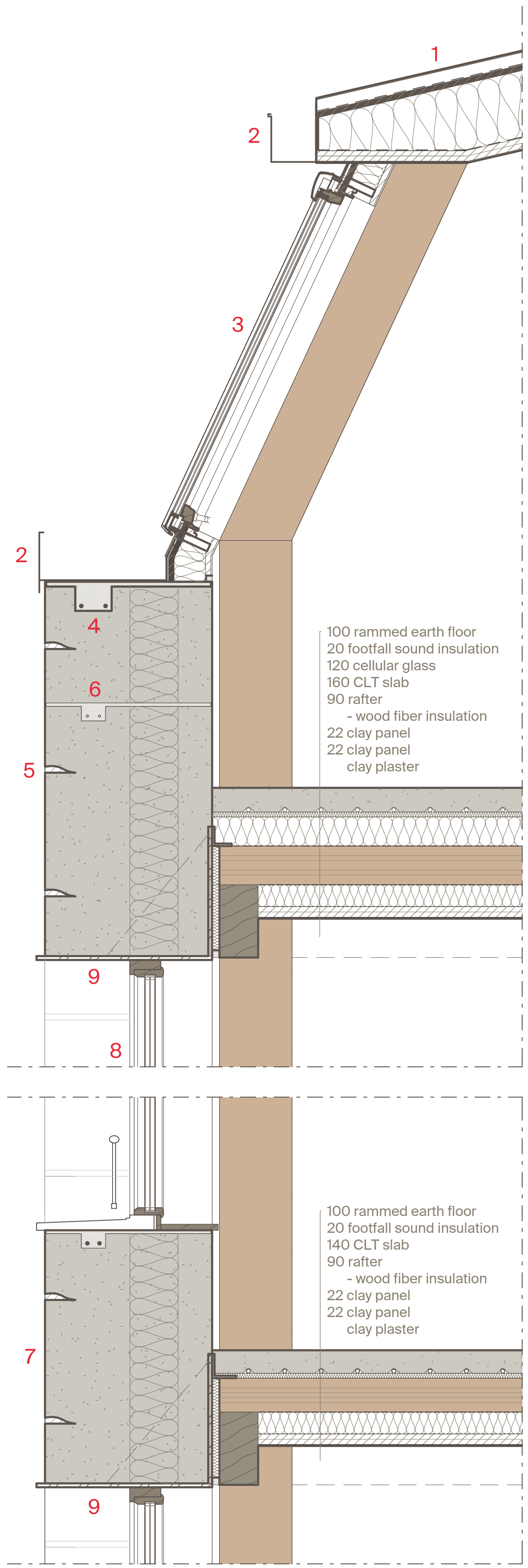
The sloped roof is clad with natural standing seam zinc sheets, chosen for their durability, recyclability, and low maintenance over time. Installed over ventilated battens and a wood substrate, the zinc develops a protective patina that improves longevity without the need for coatings. Below, the insulation layer is composed of wood fiber placed between the GLT beams, and the interior finish consists of clay panels rendered with clay plaster, forming a breathable roof assembly.

Ceilings

In the apartment units, the ceiling construction below the CLT slabs serves both acoustic and fire protection functions. A suspended ceiling system is installed, consisting of wood fiber insulation placed between wooden battens and two layers of clay panels, finished with clay plaster and clay paint.

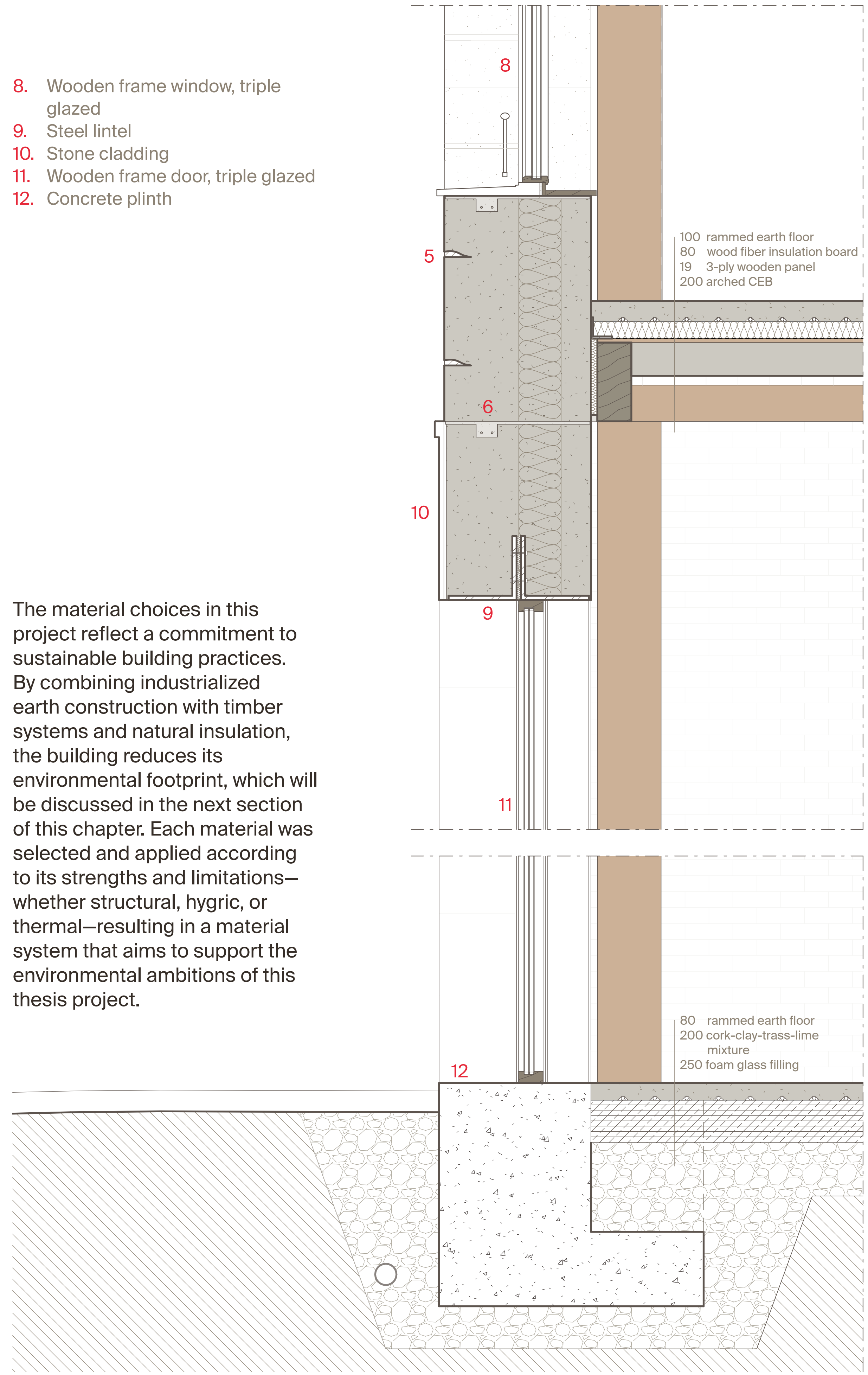
1. Standing seam zinc roof
2. Corten steel gutter
3. Wood-metal frame window, triple glazed
4. Reinforced trass-lime ring beam 15x10cm
5. Trass-lime check
6. Reinforced trass-lime conector
7. Prefabricated panel 350 rammed earth + 200 foam glass gravel insulation + 140 rammed earth

Wall section - front facade
1:25



8. Wooden frame window, triple glazed
9. Steel lintel
10. Stone cladding
11. Wooden frame door, triple glazed
12. Concrete plinth

The material choices in this project reflect a commitment to sustainable building practices. By combining industrialized earth construction with timber systems and natural insulation, the building reduces its environmental footprint, which will be discussed in the next section of this chapter. Each material was selected and applied according to its strengths and limitations—whether structural, hygric, or thermal—resulting in a material system that aims to support the environmental ambitions of this thesis project.



Environmental impact of the final design

To evaluate the environmental performance of the proposed design, a Life Cycle Assessment (LCA) was carried out using One Click LCA, a tool widely used in the construction industry for quantifying embodied and operational carbon impacts. The analysis follows the EN 15804 +A2 standard and covers the full life cycle of the building—cradle to grave—including production, transport, construction, use, and end-of-life stages (modules A1–A4, B4–B5, and C1–C4). It considered a 50 years calculation period and Gross Internal Floor Area equal to 1012.55m². This approach offers an integrated perspective on the carbon footprint of the building and supports critical reflection on the design strategies and material choices.

The LCA was based on a BIM model exported from Revit as an IFC file. While the export included key elements such as walls, floors, roofs, windows, doors, structure, and finishings, some components were not exported for this assessment. These include the foundations and substructure, and interior structural elements such as wooden studs in drywall partitions, which were not represented separately in the material mapping.

LCA Results Overview

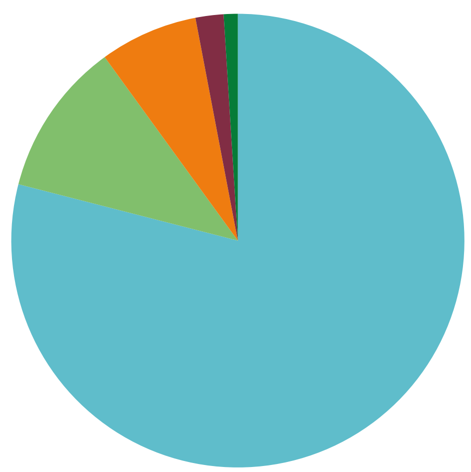
The building achieves a Global Warming Potential (GWP) of 90 kg CO_2e/m^2, placing it in Class A according to the Swedish benchmark classification by One Click LCA. This is well below the lowest regulatory threshold of 190 kg CO_2e/m^2 for apartment buildings without mechanical, electrical and plumbing (MEP) systems, highlighting the significant potential of bio-based, low-carbon, and prefabricated earthen materials in reducing embodied emissions.

Life Cycle Contribution Breakdown

- The vast majority of embodied emissions (about 79%) come from the product stage (A1–A3), related to material production and processing.
- Transport to site (A4) accounts for approximately 7%, while component replacement during the use phase (B4–B5) contributes 11%.
- End-of-life stages—waste transport (C2) and waste processing and disposal (C3, C4)—add another 3% to the overall footprint.

These figures reinforce the importance of early-stage material choices in reducing a building's total carbon impact.

Embodied carbon by life-cycle stage



- A1 - A3 Materials - 79%
- A4 Transport - 7%
- B4 - B5 Replacement - 11%
- C2 Waste transport - 2%
- C3 Waste processing - 1%

Contribution by Building System

When broken down by building system, excluding electricity use, the primary contributors to GWP are:

1. Electricity use (operational energy) – 74.9%
2. External walls – 10.0%
3. Structural frame (beams, columns, slabs) – 8.3%
4. Façade openings - 3.1%

This dominance of electricity use in the total GWP emphasizes the role of operational energy in life cycle performance—even in a low-carbon design. Although the project prioritizes natural ventilation, this aspect was not modeled in detail, and further refinement of the energy model could shift this balance.

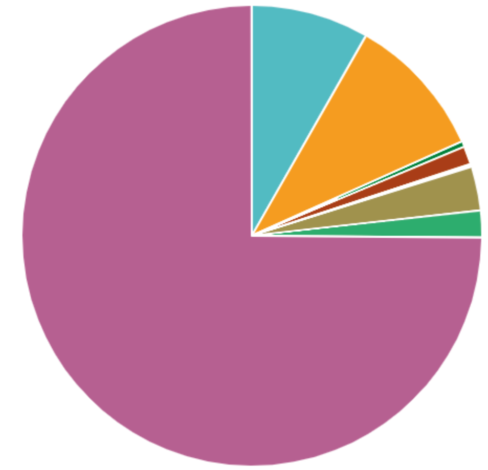
Material Contribution and Mass Distribution

In terms of material classification, the main construction materials contributing to GWP are:

1. CLT, glulam, and LVL elements – 24.7%
2. Ready-mix concrete – 24.0%
3. Common clay bricks – 14.1%
4. Wooden frame windows – 10.3%
5. Zinc - 9.4%

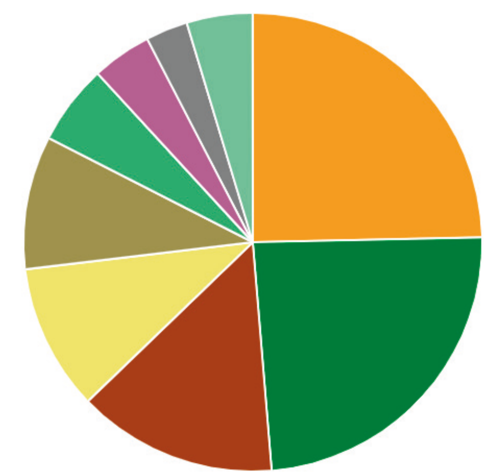
When assessing the material mass distribution, external walls dominate, making up 58.8% of the building's total mass, while the structural frame accounts for 29.5%, highlighting the environmental relevance of the wall systems.

Global Warming Potential total kg CO_2e - Classifications



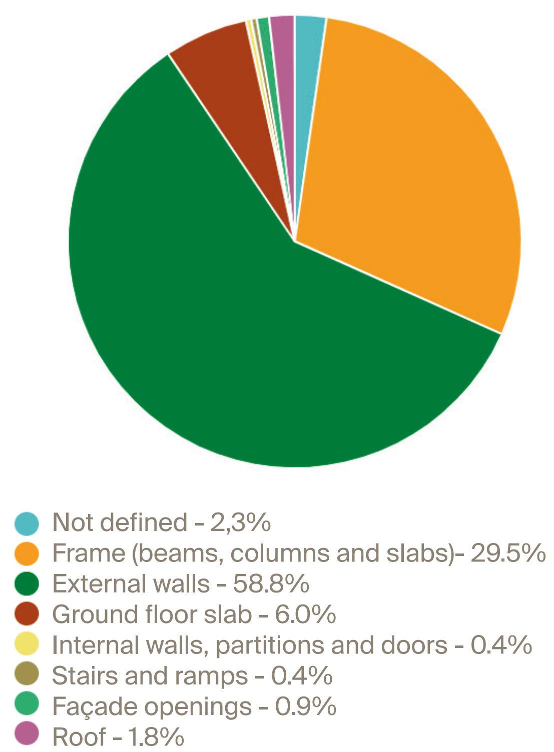
- Frame (beams, columns and slabs) - 8.3%
- External walls - 10.0%
- Ground floor slab - 0.4%
- Internal walls, partitions and doors - 1.3%
- Stairs and ramps - 0.2%
- Façade openings - 3.1%
- Roof - 1.9%
- Electricity use - 74.9%

Global Warming Potential total kg CO_2e - Resource types

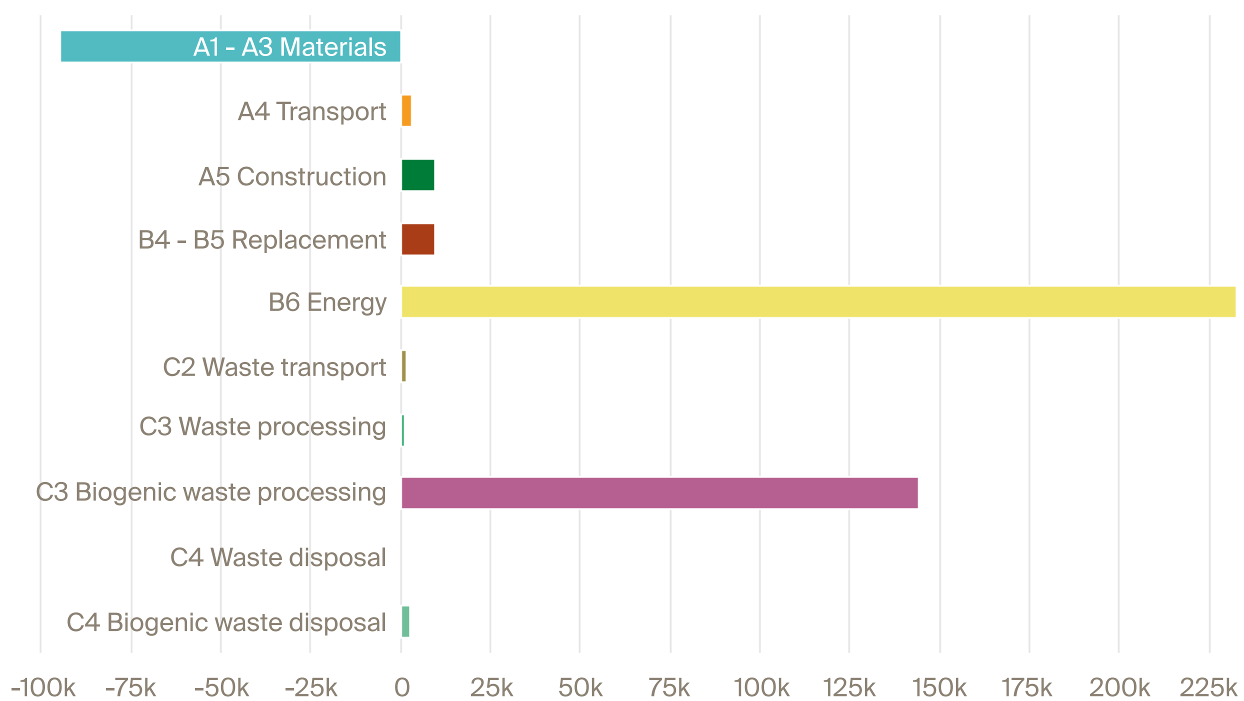


- CLT, glulam and LVL - 24.7%
- Ready-mix concrete - 24.0%
- Brick, common clay brick - 14.1%
- Wooden frame windows - 10.3%
- Zinc - 9.4%
- Cellular glass insulation - 5.7%
- Gypsum plaster (interior applications) - 4.2%
- Wood and wood board doors - 3.0%
- Other resource types - 4.6%

Mass kg - Classifications



Global Warming Potential total kg CO_2e - Life-cycle stages



Interpretation and Reflections

Some of the materials included in the model—such as cross-laminated timber (CLT) and wooden cladding—were selected from product-specific Environmental Product Declarations (EPDs), including those issued by Stora Enso, a manufacturer based outside Sweden. Although these EPDs reflect production in other countries, One Click LCA automatically recalculates transport emissions (Module A4) and end-of-life impacts (Modules C1–C4) based on the selected project location. In this case, the "Nordics" setting was used, ensuring that the life cycle results reflect regional conditions and remain consistent with local benchmarks and regulations. This feature allows the assessment to maintain both product-level specificity and geographic relevance.

The life cycle assessment also includes biogenic carbon accounting, in accordance with the EN 15804 +A2 standard. For bio-based materials such as CLT and wooden cladding, carbon dioxide absorbed during the growth of the biomass is recorded as a negative emission during the production stage (Modules A1–A3), reflecting temporary carbon storage within the building materials. However, this stored carbon is released back to the atmosphere at the end of life (Modules C3–C4), resulting in a balancing positive emission. Therefore, while some materials in the assessment show negative values for Global Warming Potential (GWP) in early stages, these are typically offset over the full life cycle, unless the material is reused, stored long-term, or displaces fossil-based alternatives.

End-of-Life Credits and the Case of Earthen Materials

This assessment includes Module D, which captures potential environmental benefits beyond the building's lifespan, such as material recovery or substitution. In the current model, timber-based materials—such as CLT, GLT, and wooden cladding—receive end-of-life credits, reflecting assumptions of reuse, recycling, or incineration with energy recovery. However, no credits are applied to the earthen materials used in the design. This constitutes a notable gap, considering that unfired earth can be disassembled, rehydrated, and reused with minimal processing, or returned directly to the soil without generating emissions or hazardous waste. These processes avoid both the extraction of new resources and the need for waste treatment, and thus should, in principle, be recognized as having equivalent—or even superior—environmental benefits compared to conventional recycling or combustion.

The omission of such credits reflects a broader limitation in current LCA tools and databases, which are often not configured to account for cradle-to-cradle lifecycles of regenerative or non-standard materials. As a result, the true environmental potential of earthen construction systems may be systematically undervalued in quantitative assessments. Future research should aim to develop more accurate modeling frameworks and datasets that can reflect the recyclability, non-toxicity, and ecological reintegration of natural building materials within the LCA framework.

A full material inventory and environmental breakdown per building part is available in the Appendix.

DISCUSSION

A Speculative Project within the Swedish Context

This thesis proposes a residential building designed with industrialized earthen-based materials - an approach that remains largely speculative within the Swedish construction industry. While the presented project is technically viable, it relies on products, techniques, and standards that have not yet been industrialized or widely adopted in Sweden. Instead, many of the construction systems referenced throughout the design are developed and manufactured in neighboring European countries, including Germany, Austria, France, and Switzerland. Companies such as ERDEN, Claytec, Terrabloc, and Terrio have served as critical sources of knowledge and precedent, offering insights into the possibilities of modern earthen construction at an industrial scale.

The lack of similar industries in Sweden reflects a broader challenge: despite the country's strong environmental ambitions, the building sector remains dependent on high-emission materials such as concrete and steel. Locally, there is limited availability of industrialized earthen building products, a shortage of skilled labor trained in earthen techniques, and a regulatory environment that has only recently begun to acknowledge the potential of clay-based construction materials. Consequently, this project situates itself within a speculative framework—not because it is unrealistic or technically unfeasible, but because the infrastructural, industrial, and cultural conditions for its realization are not yet fully established.

At the same time, this speculative character is what lends the project its critical value. By envisioning an architecture built with natural and low-carbon materials, the thesis raises a pressing question: what if Sweden were to support and develop an industry for earthen construction? What if earthen materials—currently sidelined as niche or alternative—were instead normalized as industrial products suitable for high-performance buildings in urban contexts? These questions resonate with ongoing shifts in European building culture and could play a key role in shaping future directions for sustainable architecture in Sweden.

Regulatory Developments and the Emergence of Earthen Construction

The speculative nature of this thesis project must be understood not only in terms of current industrial limitations, but also in relation to an evolving regulatory scenario. Since January 1, 2022, Sweden has implemented a mandatory Climate Declaration (Klimatdeklaration) for new buildings, which requires reports on the carbon footprint of construction materials and processes. Although the regulation has yet to establish maximum emission limits, it signals a significant shift in how building materials are evaluated—no longer just for their structural or aesthetic properties, but for their environmental impact throughout the building's life cycle.

In this context, earthen materials, which are inherently low-carbon, locally sourced, and minimally processed, present an alternative to conventional construction systems. While current declarations might not affect material choices thus far, the introduction of emission limit values would increase pressure on the industry to transition toward lower-impact solutions. This anticipated policy evolution positions natural materials as increasingly attractive—both environmentally and economically—especially in the early design stages where material selection can significantly influence total emissions.

Recent developments further reinforce this trajectory. On February 10, 2025, the Swedish Standards Institute (SIS) adopted new national standards for unfired clay, marking a step in formalizing earthen construction within the Swedish building codes. Standardization is an important precursor to wider adoption, as it provides criteria for quality, safety, and performance—essentials for insurability, public procurement, and integration into architectural practice.

Simultaneously, a growing number of reference projects are helping to legitimize and demystify the use of earth as a building material. The office Kaminsky Arkitektur recently designed a large-scale project using clay, straw, and wood (Figure 42), a significant case for the visibility of natural materials in the country. Such projects contribute not only to practical knowledge but also to shifting public and professional perceptions, showing that earthen materials are viable for modern, sustainable construction.

Together, these regulatory and professional developments indicate a momentum that aligns with the ambitions of this thesis. While the project remains speculative in terms of its immediate feasibility, it is situated within a broader transition—a turning point where speculation can serve as both critique and proposal, pushing the boundaries of what is considered possible and permitted in Swedish architecture.

Figure 42. Residential buildings in Uppsala to be built using clay boards and clay plaster. Image courtesy of Kaminsky Arkitektur.

Scalability: From Niche to Mainstream

While earthen architecture is gaining recognition for its environmental benefits, scaling it beyond isolated projects into a widely adopted construction method remains a challenge. The transition from artisanal or small-scale applications to industrialized systems is essential if earthen materials are to significantly contribute to climate goals and be competitive in a high-technological construction market like the one in Sweden.

In countries such as France, Germany, Switzerland, and Austria, the presence of specialized manufacturers, trained labor, and certification systems, has enabled earth to re-enter the construction industry with credibility and technical refinement. On the other hand, Sweden currently lacks these foundations. For earthen materials to scale, there is a need to establish local production facilities—potentially using excavated urban soils or industrial byproducts—and to train a new generation of builders, architects, and engineers in earthen techniques.

Equally important is the evolution of standards. Earthen construction is often perceived as incompatible with the technical demands of contemporary buildings, especially in terms of precision, moisture resistance, and regulatory compliance. However, emerging systems—such as the prefabricated rammed earth panels proposed in this thesis—demonstrate how traditional materials can be adapted for modern performance requirements, meeting standards for thermal comfort, airtightness, and fire safety while maintaining a low environmental impact.

To support scalability, standardization efforts must evolve to accommodate these earthen-based products. This includes updating technical standards and introducing performance-based criteria that allow for simplification in material choice. Integrating earthen construction into digital planning tools, such as BIM libraries and LCA databases, will be decisive in streamlining design and procurement processes for earthen buildings.

Lastly, the success of scaling earth architecture also depends on policy incentives and market demand. Public procurement frameworks that prioritize low-carbon materials, subsidies for climate-positive building systems, and carbon accounting in building permits can all play a role in accelerating adoption. At the same time, raising awareness among clients and developers about the long-term value and benefits of earthen buildings is necessary to shift market preferences. Scalability, then, is not solely a technical issue—it is also cultural, regulatory, and economic. It requires a coordinated effort to redefine what is mainstream in architecture and construction.

Economic Viability

Another barrier to the wider adoption of earthen building systems in Sweden is cost. In the current construction market, where speed and economy often outweigh long-term sustainability, earthen materials remain more expensive than conventional alternatives, especially if sourced internationally and applied using labor-intensive methods.

The lack of local production facilities means that many of the materials and prefabricated components must be imported from countries with more mature earth-building industries. Transporting heavy earthen products across borders adds substantial costs and carbon emissions, weakening the environmental rationale for their use. Moreover, specialized labor is scarce in Sweden, which increases the cost of both design and execution. Traditional techniques require experience and time, and newer prefabricated systems require careful coordination and knowledge that is not yet widespread in the industry.

However, these challenges are not permanent. As demonstrated by the development of other bio-based building materials like CLT, economies of scale and knowledge diffusion can shift the financial equation. If Sweden begins to support the establishment of local producers—particularly those who can utilize local clay resources or waste streams—the cost of raw materials and transportation could decrease significantly.

Furthermore, as regulations begin to internalize environmental costs, conventional materials may face increasing carbon taxes or climate-based disincentives, while low-impact materials like earth could benefit from incentives, subsidies, or fast-tracked approvals. These shifts could fundamentally change what is considered economically viable. Additionally, the upfront investment in earthen construction may be balanced by long-term savings in energy use — due to the material's thermal and hygroscopic performance — and the potential for material reuse at the end of a building's life cycle, advantages that are currently under-recognized in standard cost calculations.

Transportation and Life Cycle Impact

Transportation plays a crucial role in the environmental footprint of building materials, and for earthen construction it can be a decisive factor in determining whether a solution is suitable to a context or not. While earth itself is a low-impact material in terms of extraction and processing, this advantage can be undermined if it needs to be imported over long distances, as is currently the case in Sweden.

This highlights a paradox: a building system celebrated for its low embodied carbon and recyclability can produce a high environmental cost if a local supply chain is not in place.

Moreover, reducing dependency on imported products and associated logistics not only translates into cost savings over time, but it also aligns with the broader push toward resilient, circular construction models, in which materials are extracted, processed, used, and reused within the same geographical context.

At the policy level, transportation-related emissions may increasingly come under regulatory control. As Sweden and the EU move toward carbon accounting across production chains, materials that demand long distance shipping or trucking will likely face penalties or disincentives. In contrast, regionally produced components, especially those that integrate reuse and recycling practices, could gain significant regulatory and market advantages. In this light, the future viability of earthen construction in Sweden depends as much on where the materials come from as what they are.

Conclusion

This thesis has explored the integration of earthen construction into a contemporary, urban Swedish context, proposing an architectural project that operates within a speculative, yet plausible future scenario. While current realities—such as the absence of a domestic earth-building industry and the reliance on imported materials—pose real limitations, they also highlight clear areas for transformation and opportunity.

The introduction of Sweden's climate declaration, despite its current focus on the construction phase, sets the stage for broader life cycle accountability. As regulations expand and begin to reflect the full environmental impact of buildings, materials like unfired earth—offering benefits across the use and end-of-life phases—are positioned to gain recognition. Recent developments such as the inclusion of clay in Swedish building standards signal a shifting attitude in the profession.

However, for earth to become more than a niche material, the issues of scalability, cost, and transportation must be addressed. Industrialization, standardization, and localization of production are all key to unlocking the full potential of the material in a simultaneously high-tech and resource-constrained future. Ultimately, building with earth is not just a return to old techniques, but a re-imagination of future possibilities—a way of building that is materially honest, climatically responsive, and aligned with the values of our time.

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APPENDIX

Life Cycle Assessment – detailed results and material data sources

The tables presented below provide detailed results of the Life Cycle Assessment (LCA) conducted for the final architectural design proposal. The assessment was carried out using the tool One Click LCA, in accordance with the European standard EN 15804+A2 and the Level(s) framework. The LCA encompasses the full building life cycle, including product, construction, use, and end-of-life stages (modules A1–C4), as well as module D, which accounts for potential benefits and loads beyond the system boundary.

The first table summarizes the quantified environmental impacts across a range of indicators—such as Global Warming Potential (total, fossil, biogenic, and LULUC), Ozone Depletion, Eutrophication, Acidification, Abiotic Depletion, and Water Use—presented per life cycle stage and normalized per square meter of gross internal floor area. The second table details the data sources used in the LCA model, including technical specifications, Environmental Product Declarations (EPDs), verification types, and geographic origin.

The material inputs were mapped in accordance with the specifications of the architectural project. In cases where exact matches were not available in the One Click LCA database, the closest available alternatives were selected based on material composition and functional characteristics, acknowledging the limitations of the available environmental data. Together, these datasets support the interpretation of the environmental performance of the proposed design, as discussed in Chapter 04 of this thesis.

Table 1: Life Cycle Assessment Results by Impact Category and Life Cycle Stage (in accordance with EN 15804 +A2 and Level(s))

	Result category	Global Warming Potential total	Global Warming Potential fossil	Global Warming Potential biogenic	Global Warming Potential, LULUC	Depletion potential of the stratospheric ozone layer	Acidification potential, Accumulated Exceedance	Eutrophication fresh water	Eutrophication aquatic marine	Eutrophication terrestrial	Formation potential of tropospheric ozone	Abiotic depletion potential (ADP-elements) for non fossil resources (+A2)	Abiotic depletion potential (ADP-fossil fuels) for fossil resources (+A2)	Water use
		kg CO2e	kg CO2e	kg CO2e	kg CO2e	kg CFC11e	mol H+ eq.	kg P eq.	kg N eq.	mol N eq.	kg NMVOC eq.	kg Sbe	MJ	m3 deprived
A1-A3	Construction Materials	-9,47E+04	7,63E+04	-1,72E+05	4,86E+02	3,69E-03	3,83E+02	3,15E+00	1,05E+02	1,13E+03	2,98E+02	2,28E+04	1,02E+06	4,28E+04
A4	Transportation to site	2,99E+03	2,99E+03		1,01E-01	6,91E-04	4,81E+00	1,97E-01	5,79E-01	6,29E+00	2,65E+00	1,39E+01	6,90E+04	1,13E-01
A5	Construction/ installation process	9,80E+03	5,76E+03	4,00E+03	3,09E+01	3,45E-04	3,32E+01	2,96E-01	1,05E+01	1,18E+02	2,99E+01	1,83E+03	8,62E+04	2,76E+03
B4-B5	Material replacement and refurbishment	9,79E+03	9,68E+03		1,05E+02	8,53E-04	4,28E+01	1,87E-01	1,20E+01	1,00E+02	2,93E+01	2,16E+00	1,41E+05	8,54E+03
B6	Energy consumption	2,32E+05	2,32E+05		5,61E+02	5,29E-02	1,65E+03	2,39E+01	2,17E+02	2,38E+03	6,88E+02	8,67E-01	3,09E+06	3,49E+07
C1-C4	End of life	1,50E+05	3,10E+03	1,47E+05	6,84E-01	5,39E-04	1,89E+01	5,67E-01	8,52E+00	8,29E+01	2,13E+01	1,24E+01	6,32E+04	3,01E+03
D	External impacts (not included in totals)	-2,39E+04	-2,30E+04	-9,55E+02	-3,52E+00	-1,45E-03	-3,89E+02	-3,36E+00	-2,36E+01	-1,34E+03	-6,31E+01	-7,65E-02	-1,66E+05	-9,41E+03
	Total	**3,10E+05**	**3,30E+05**	**-2,09E+04**	**1,18E+03**	**5,91E-02**	**2,13E+03**	**2,83E+01**	**3,53E+02**	**3,81E+03**	**1,07E+03**	**2,47E+04**	**4,47E+06**	**3,50E+07**
	Results per denominator													
	Per gross internal floor area m2 / year	6,13E+00	6,51E+00	-4,12E-01	2,34E-02	1,17E-06	4,21E-02	5,58E-04	6,98E-03	7,53E-02	2,11E-02	4,87E-01	8,83E+01	6,91E+02
	Per gross internal floor area m2	3,06E+02	3,26E+02	-2,06E+01	1,17E+00	5,83E-05	2,11E+00	2,79E-02	3,49E-01	3,77E+00	1,06E+00	2,44E+01	4,42E+03	3,45E+04

Table 2: Data sources - materials

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)	Notes about PCR
Air-dried brick (adobe)	EN15804+A2, ref. year 2023			OKOBAUDAT	4c009f04-44e1-42e3-a32e-4929294debab	ÖKOBAUDAT 2023	EN15804+A2	Third-party verified (as per ISO 14025)	2023	Germany	GaBi	1200.0	EN15804+A2	-
Cellular glass insulation	L = 0.060 W/mK, 10 mm, 2.0 kg/m2, 200 kg/m3, 100% recycled glass, foaming agents: hard coal fly ash and silicon carbide, Lambda=0.046 W/(m.K)		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	200.0	EN15804+A1, EN15804+A2	-
Clay panel	20 mm, 14 kg/m2, 700 kg/m3, EN15804+A2, ref. year 2021			OKOBAUDAT	eb255e58-7955-4d25-a333-4db0340b2864	ÖKOBAUDAT 2021-II (25.06.2021)	EN15804+A2	Third-party verified (as per ISO 14025)	2021	Germany	GaBi	700.0	EN15804+A2	-
Clay panel	20 mm, 14 kg/m2, 700 kg/m3, EN15804+A2, ref. year 2023			OKOBAUDAT	c0915390-0e80-4253-9345-71fd83ef3c99	ÖKOBAUDAT 2023	EN15804+A2	Third-party verified (as per ISO 14025)	2023	Germany	GaBi	700.0	EN15804+A2	-
Clay plaster	900 kg/m3, EN15804+A2, ref. year 2021			OKOBAUDAT	9eae2fed-dba0-4641-b1cc-fd2cc65f2016	ÖKOBAUDAT 2021-II (25.06.2021)	EN15804+A2	Third-party verified (as per ISO 14025)	2021	Germany	GaBi	900.0	EN15804+A2	-

Table 2: Data sources - materials

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)	Notes about PCR
Clay plaster	900 kg/m3, EN15804+A2, ref. year 2023			OKOBAUDAT	422b2446-8a3f-457d-b47b-4728b2869d86	ÖKOBAUDAT 2023	EN15804+A2	Third-party verified (as per ISO 14025)	2023	Germany	GaBi	900.0	EN15804+A2	-
Cross laminated timber (CLT)	470 kg/m3, 12% moisture content, Lambda=0.12 W/(m.K)		Stora Enso	International EPD System	S-P-02033	EPD CLT (Cross Laminated Timber)	EN15804+A1, EN15804+A2	Third-party verified (as per ISO 14025)	2020	Austria, Sweden	ecoinvent	470.0	PCR 2019:14, v.1.0 Construction products C-PCR-006 (to PCR 2019:14) Wood and wood-based products for use in construction	Only with EN15804
Electricity, Sweden, residual mix, 2023			One Click LCA	One Click LCA		LCA study for country specific residual electricity mixes based on AIB 2023 and calculated by One Click LCA, OneClickLCA 2023		Internally verified	2023	Sweden	One Click LCA			
Foam glass aggregate, manufacturer average	0-60 mm, bulk density 191 kg/m3		Foamit Group Oy	International EPD System	S-P-07075	EPD FOAM GLASS AGGREGATE 0-60 mm from FOAMIT	EN15804+A2	Third-party verified (as per ISO 14025)	2022	Sweden, Finland, Norway	GaBi	191.0	PCR 2019:14 Construction products, version 1.11 Published on 2021.02.05, valid until: 2024.12.20.	Only with EN15804

Table 2: Data sources - materials

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)	Notes about PCR
Glued laminated timber (GLT), standard shapes, German average	507.11 kg/m3, EN15804+A2, ref. year 2023			OKOBAUDAT	78bfe151-3cf3-46cb-a1a5-61a79bbd5476	ÖKOBAUDAT 2023	EN15804+A2	Third-party verified (as per ISO 14025)	2023	Germany	GaBi	507.11	EN15804+A2	-
Loose-fill insulation made from wooden fibers for Sealand market (Denmark)	L= 0,036 W/mK, 26-43 kg/m3, avg. density 34.5 kg/m3	Woodfiber AIR	Woodfiber	EPD Danmark	MD-22017-EN	EPD MD-22017-EN | Woodfiber	EN15804+A1, EN15804+A2	Third-party verified (as per ISO 14025)	2022	Sweden	GaBi	34.5	EN15804+A2	-
Natural hydraulic lime (NHL) based masonry mortar	1950 kg/m3	SikaMur®-315 Grout	Sika Hellas ABEE	International EPD System	EPD-IES-0012136:002	EPD EPD-IES-0012136:002 (S-P-12136) SikaMur-315 Grout	EN15804+A2	Third-party verified (as per ISO 14025)	2024	Greece	ecoinvent	1950.0	PCR 2019:14 Construction products, version 1.3.1	Only with EN15804
Natural stone façade cladding	23 mm, 387 kg/m2	Maçonneries massives en pierre de Noyant.	carrières de NOYANT	INIES	INIES_IBSQ20230616_170253,34330	FDES	EN15804+A2	Third-party verified (as per ISO 14025)	2023	France	ecoinvent		NF EN 15804+A2 + NF EN 15804/CN	NF EN 15804+A2 + NF EN 15804/CN
Natural zinc standing seam roofing	0.725 mm, 5.96 kg/m2	Couverture en zinc RHEINZINK-CLASSIC naturel à joint debout (dimensions 250*1000*0,65 mm à 650*1000*0,8 mm)	RHEINZINK FRANCE	INIES	INIES_IQLQ20240530_153926,38567	FDES	EN15804+A2	Third-party verified (as per ISO 14025)	2024	France	ecoinvent		NF EN 15804+A2 + NF EN 15804/CN	NF EN 15804+A2 + NF EN 15804/CN

Table 2: Data sources - materials

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)	Notes about PCR
Non-load-bearing compressed raw earth block wall (unstabilized)	284.11 kg/m2	Parois en blocs de terre comprimée non porteuses d`épaisseur 15 cm, réalisées à partir de blocs de terre comprimée non stabilisés au format 31,5 x 15 x 10 pose en panneresse fabriqués sur chantier par Briques Technic Concept, et de mortier non stabilisé préparé sur chantier.	BRIQUES TECHNIC CONCEPT	INIES	INIES_IBPM20231129_151631, 35905	FDES	EN15804+A2	Third-party verified (as per ISO 14025)	2023	France	ecoinvent		NF EN 15804+A2 + NF EN 15804/CN	NF EN 15804+A2 + NF EN 15804/CN
Rammed earth wall	2000 kg/m3, EN15804+A2, ref. year 2021			OKOBAUDAT	3f9ebd47-f93e-4fee-859a-13700134ee3c	ÖKOBAUDAT 2021-II (25.06.2021)	EN15804+A2	Third-party verified (as per ISO 14025)	2021	Germany	GaBi	2000.0	EN15804+A2	-
Ready-mix concrete, generic	C30/37 (4400/5400 PSI), XC3, 25% GGBS in cement, CEM II/B-S portland-slag cement, 2386 kg/m3		One Click LCA (2024)	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2024	LOCAL	One Click LCA, IDEMAT	2386.0	EN15804+A1, EN15804+A2	-

Table 2: Data sources - materials

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)	Notes about PCR
Ready-mix concrete, normal strength, generic	C28/35 (4000/5000 PSI) with CEM I, 0% recycled binders (300 kg/m3; 18.7 lbs/ft3 total cement)		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2020	LOCAL	One Click LCA	2400.0	EN15804+A1, EN15804+A2	-
Ready-mix concrete, normal-strength, generic	C30/37 (4400/5400 PSI), 0% recycled binders in cement (300 kg/m3 / 18.72 lbs/ft3)		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2018	LOCAL	One Click LCA	2400.0	EN15804+A1	-
Rigid wood fiber insulating panels	L = 0.022 W/mK, R= 6.15 m2K/W, 240 mm, 26.4 kg/m2, 110 kg/m3	STEICOuniversal dry; STEICOduo dry; STEICOintégral; STEICOroof dry; STEICOspecial dry; STEICOtherm dry; STEICOprotect L dry	STEICO SE	INIES	INIES_ICYI20240925_083846, 40347	FDES	EN15804+A2	Third-party verified (as per ISO 14025)	2024	Germany	ecoinvent		NF EN 15804+A2 + NF EN 15804/CN	NF EN 15804+A2 + NF EN 15804/CN
Steel framed glass window with glazing	60 mm, 32 kg/m2		Jansen AG	IBU	EPD-JAN-20230475-CBA1-EN	EPD Janisol Arte 2.0 window width x height: 1230 mm x	EN15804+A2	Third-party verified (as per ISO 14025)	2024	Switzerland	GaBi		PCR Windows and doors , 01.08.2021	Only with EN15804

Table 2: Data sources - materials

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)	Notes about PCR
Wooden cladding and decking, pine or spruce	445 kg/m3, 7-29 mm, 8-18%, moisture content		Stora Enso	International EPD System	S-P-02152	EPD Cladding and Decking by Stora Enso	EN15804+A1, EN15804+A2	Third-party verified (as per ISO 14025)	2020	Estonia, Finland, Netherlands	ecoinvent	445.0	PCR 2019:14, v.1.0 Construction products C-PCR-006 (to PCR 2019:14) Wood and wood-based products for use in construction	Only with EN15804
Wooden cladding profiles from spruce, tongue and groove type, painted	468 kg/m3, 16% moisture content		Derome Timber AB	EPD Norge	NEPD-6422-5685-EN	EPD Derome for Tongue and groove roof-board, Underlagsspon tlucka, spruce, u 16%Product category /PCR:	EN15804+A1, EN15804+A2	Third-party verified (as per ISO 14025)	2024	Sweden	GaBi	468.0	NPCR 015 Wood and wood-based products	Only with EN15804
Wooden door with steel frame	924x2048 mm, 48 mm, 32.2 kg/m2		Daloc Tradorrar AB	International EPD System	S-P-13612	EPD Wooden doors T10 -T25 laminated, laminated with glass pane, painted with wooden frame	EN15804+A2	Third-party verified (as per ISO 14025)	2024	Sweden	ecoinvent		PCR 2019:14 Construction products, version 1.2.5	Only with EN15804
Wooden door, unglazed	40 mm, 7.9042 kg/m2	Swedoor CLEVER-LINE	JELD-WEN	EPD Hub	HUB-2461	EPD SWEDOOR CLEVER-LINE - INTERIOR UNCLASSIFIED DOORS, UNGLAZED EASY, STYLE, EASY EFFECT	EN15804+A1, EN15804+A2	Third-party verified (as per ISO 14025)	2024	Sweden, OCLEPD	ecoinvent		EPD Hub Core PCR Version 1.1, 5 Dec 2023 EN 17213 Windows and doors	Only with EN15804

Table 2: Data sources - materials

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)	Notes about PCR
Wooden entrance door	100 cm x 210cm, 31.09 kg/m2	ST7Ei30	Dieden-Ekodoor AB, Sweden	International EPD System	S-P-07003	EPD Door without glass by Dieden-Ekodoor AB	EN15804+A2	Third-party verified (as per ISO 14025)	2022	Sweden	ecoinvent, GaBi		Construction Products PCR 2019:14 version 1.11	Only with EN 15804
Wooden frame patio door, triple glazed, outward opening	31.8 kg/m2		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA		EN15804+A1, EN15804+A2	-
Wooden frame window, triple glazed, fixed	36.3 kg/m2		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA		EN15804+A1, EN15804+A2	-
Wooden frame window, triple glazed, side-hung	38.2 kg/m2		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA		EN15804+A1, EN15804+A2	-