



Illustration: Naturdorf Bärnau settlement, artist's impression. Courtesy of Andreas Mann, c. 2024.



**Politecnico
di Torino**

Evaluating a 21st-Century Vernacular: Performance and Applicability of Naturdorf Bärnau (Germany), with Reference to the Vegetarian Pavilions in Grugliasco (Italy).

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Abstract

This thesis examines the applicability of Bocco and Habert’s concept of a “vernacular architecture of the 21st century” through the case study of Naturdorf Bärnau, a four-unit experimental holiday housing compound located at the German–Czech border. The conceptual framework defines four criteria for a contemporary vernacular: use of local resources, low environmental footprint, fulfilment of contemporary users’ expectations, and affordability to local communities.

A systemic investigation of the as-built condition was conducted using verified project documentation. A Life Cycle Assessment (LCA), in accordance with ISO 14040 and EN 15978, was performed for modules A1–A4 using the ÖKOBAUDAT (2024-I) database. Climate impacts were determined following the EN 15804+A2 standard, utilizing IPCC characterization factors to calculate Global Warming Potential (GWP). Biogenic carbon storage was assessed separately following EN 16449.

The embodied carbon intensity of the building amounts to 267.60 kgCO₂e/m² (A1–A4), positioning the project below the average range reported for Northern European residential buildings of 310–350 kgCO₂e/m² (One Click LCA, 2021). Material contribution analysis reveals lime-based assemblies as the dominant source of fossil emissions, while the extensive use of timber, sheep wool, and hemp-based components enables the temporary storage of approximately 33,947.9 kgCO₂. Transport impacts remain limited, reflecting geographically constrained sourcing strategies..

Beyond quantitative assessment, the study evaluates the project’s alignment with the four criteria for a contemporary vernacular, examining supply chains, construction processes, and economic flow within the region. The findings indicate that materially coherent, bio-based construction can meet contemporary performance expectations while maintaining regional material legibility and supporting local production networks.

Reflections drawn from the Vegetarian Pavilions in Grugliasco (Italy) during the author’s internship further contextualize the transferability of vernacular principles across different climatic and socio-technical environments. The thesis ultimately argues that a 21st-century vernacular is not a stylistic revival but a performance-driven reinterpretation of local material intelligence within measurable environmental and other frameworks.

KEYWORDS: Life Cycle Assessment (LCA); Vernacular architecture; Bio-based materials; Embodied carbon; ÖKOBAUDAT.

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Statement on the Use of AI-Assisted Tools

This thesis was independently developed by the author. Throughout the research and writing process, AI-assisted tools were employed in a supportive and non-generative capacity. Their use was limited to language refinement, including grammar correction, sentence restructuring, and translation assistance, as well as the organisation of bibliographic references and the navigation of existing research literature.

All academic content, including the theoretical framework, methodological design, quantitative calculations, data interpretation, and conclusions, was produced exclusively by the author. AI tools did not determine, generate, or substitute any element of the original research. Full intellectual and academic responsibility for the content of this thesis rests with the author.

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Chapter 1

Introduction

1.1 Background of the Study

The building and construction sector accounts for approximately 37 percent of global carbon dioxide emissions when both operational and embodied impacts are considered (UNEP, 2023). While significant progress has been made in reducing operational energy demand through improved building performance, the relative contribution of embodied carbon arising from material extraction, production, and construction processes has become increasingly significant. This shift highlights a critical limitation in current approaches to decarbonisation within the built environment.

In response, carbon neutrality has emerged as a dominant framework for addressing emissions across industries, including construction. Rather than eliminating emissions entirely, carbon neutrality aims to achieve a net-zero balance through a combination of emission reduction and compensation mechanisms. In practice, this involves quantifying greenhouse gas emissions associated with a product or system, minimising these emissions as far as possible, and offsetting the remainder through certified environmental projects such as reforestation or renewable energy initiatives (Climate Partners).

However, despite its widespread adoption, the concept of carbon neutrality has come under increasing scrutiny. Concerns have been raised regarding its reliance on offsetting strategies, the variability in its application, and the potential for misrepresentation in both policy and practice. In particular, the material dimension of construction where significant emissions are embedded prior to a building's operational phase remains insufficiently addressed within many carbon neutrality frameworks. This limitation suggests the need for more grounded and material-focused approaches to achieving meaningful reductions in environmental impact.

Standards for Carbon Neutrality

To formalise the concept of carbon neutrality, several international standards have been developed to guide carbon accounting, emissions reduction, and transparent reporting. Among these, PAS 2060, introduced by the British Standards Institution in 2010, established the first widely recognised framework. It defines a structured process involving the quantification of emissions, the implementation of reduction strategies, the offsetting of residual emissions, and the public disclosure of results through a Qualifying Explanatory Statement.

More recently, ISO 14068-1, released in 2023, has emerged as the first global standard for carbon neutrality. It builds upon the foundations of PAS 2060 by placing greater emphasis on emissions reduction prior to offsetting and by introducing stricter requirements for transparency and communication. As a result, PAS 2060 is expected to be withdrawn and replaced by ISO 14068-1 in the coming years (Climate Partners).

While these standards provide important frameworks for managing and communicating emissions, their application within the buildings and construction sector reveals significant limitations. In particular, the focus on achieving net-zero balances may obscure the underlying material realities of construction, where a substantial portion of emissions is generated before a building becomes operational.

The buildings and construction industry, particularly through the production of materials such as concrete, steel, and aluminium, remains a major contributor to global embodied carbon emissions. These emissions arise from processes spanning raw material extraction to final product manufacturing, including energy-intensive activities such as calcination, grinding, and material processing.

Recent estimates suggest that embodied carbon accounts for approximately 50% of total emissions in new buildings (World Business Council for Sustainable Development & ARUP, 2023), a shift widely recognised as a critical challenge in achieving meaningful decarbonisation in the built environment (Chastas et al., 2016).

In response to this challenge, attention has increasingly shifted from operational efficiency to the material basis of construction. Strategies such as reducing material consumption, reusing existing structures, minimising construction waste, and improving circularity are now central to decarbonisation efforts. However, beyond technical optimisation, there is a growing recognition of the need to rethink the relationship between materials, place, and construction practices.

In this context, vernacular architecture offers a relevant and timely framework. Historically, vernacular buildings have relied on locally available resources, climate-responsive design, and low-energy construction techniques, developed through cumulative processes of adaptation and collective knowledge (Rudofsky, 1964; Oliver, 2006). This body of knowledge has been formally recognised as part of cultural heritage, as reflected in the Charter on the Built Vernacular Heritage (ICOMOS, 1999). Rather than representing a reminiscent return to past practices, recent research positions suggest vernacular architecture as a basis for developing contemporary, low-impact building systems. Bocco and Habert (2024) propose a reinterpretation of vernacular architecture for the 21st century, structured around four interrelated principles: the use of local resources, a low environmental footprint, the fulfilment of modern user expectations, and accessibility for most users.

These principles provide a structured framework through which contemporary construction can be critically evaluated, forming the theoretical foundation for this study.

1.2 Case Study Focus: Naturdorf Bärnau, Germany

Naturdorf Bärnau represents one of the most comprehensive recent attempts to apply regenerative and low-impact construction principles at the scale of a contemporary settlement. Located in the Upper Palatinate region of Bavaria, Germany, near the Czech border, the project is characterised by the extensive use of bio-based materials such as hemp-lime, clay plasters, and timber structures, largely sourced from regional supply chains.

Beyond its material composition, the project offers a unique opportunity to examine how vernacular principles can be translated into a modern construction context. Rather than replicating traditional building practices, Naturdorf Bärnau reinterprets them through contemporary design, technical integration, and evolving user expectations.

In this sense, the project provides an appropriate case through which to critically assess the applicability of Bocco and Habert's (2024) conceptualisation of 21st Century Vernacular Principles. By combining quantitative environmental analysis with qualitative evaluation of construction practices and socio-economic dynamics, this study positions Naturdorf Bärnau not merely as an example, but as a test case for examining the extent to which these principles can be operationalised within present-day building systems.

1.3 Research Aim and Objectives

Aim

To critically assess the extent to which Naturdorf Bärnau aligns with the four defining principles of 21st Century Vernacular Architecture as proposed by Bocco and Habert (2024).

Objectives

- 1. To quantify the embodied energy (EE) and embodied carbon (EC) of the case study using Life Cycle Assessment (LCA) in accordance with EN 15978 and ISO 14040 standards.
- 2. To calculate biogenic carbon storage associated with bio-based materials using EN 16449 and IPCC (2021) methodologies.
- 3. To evaluate the degree of material localisation by analysing sourcing origins, transport distances, and supply-chain structures.
- 4. To examine the distribution of economic value within the project by identifying the proportion retained within the regional economy.
- 5. To document craftsmanship, affordability, and users’ comfort, within the contemporary construction context.

1.4 Research Questions

- 1. To what extent does Naturdorf Bärnau align with the four principles of 21st Century Vernacular Architecture proposed by Bocco and Habert (2024)?
- 2. What are the embodied energy and embodied carbon profiles of the project, including the contribution of biogenic carbon storage?
- 3. To what extent does the material sourcing patterns and financial flows contribute to regional economic retention?
- 4. Which design and construction strategies have the greatest influence on the project’s environmental performance?
- 5. How can the findings of this study inform the development of future vernacular and bio-based housing models?

1.5 Methodological Overview

This study adopts a mixed-method approach, combining quantitative environmental assessment

with qualitative evaluation to examine both the measurable performance and the conceptual alignment of the case study with 21st Century Vernacular Architecture principles.

The quantitative component is centred on a Life Cycle Assessment (LCA), applied to modules A1–A4 (material production to transport stage) in accordance with EN 15978 and ISO 14040 standards. The analysis is carried out using material inventories and calculations developed in Microsoft Excel, based on environmental data obtained from the ÖKOBAUDAT database. This approach enables the estimation of embodied energy and embodied carbon associated with the building materials and construction processes

In parallel, biogenic carbon storage is quantified using methodologies derived from EN 16449 and IPCC (2021) guidelines. This allows for the inclusion of carbon sequestration effects associated with bio-based materials, providing a more comprehensive understanding of the project’s carbon profile.

To address the principle of local resource use, material and economic inventories are compiled based on project documentation and supplier data. These are used to analyse sourcing origins, transport distances, and supply-chain structures, as well as to estimate the proportion of economic value retained within the regional context.

The qualitative component focuses on the assessment of vernacular continuity within the project. This includes the observation of construction techniques, the use of traditional or adapted joinery systems, and the evaluation of user-related factors such as comfort and affordability.

Together, these methods establish a structured framework for assessing both the environmental performance and the broader socio-cultural dimensions of the case study, enabling a comprehensive evaluation of its degree of consistency with the proposed vernacular principles.

1.6 Author’s Role and Research Positioning

The author’s involvement in the Experimental Pavilions of Vegetarian Architecture in Grugliasco, Turin, Italy, provides a practical foundation for understanding the behaviour and application of bio-based construction systems. The project focused on the design, construction, and monitoring of low-carbon prototypes using natural materials such as straw, hemp, stone, rammed earth, and timber (Mazelli et al., 2025).

This experience informs the analytical perspective adopted in this study, particularly in relation to material behaviour, assembly logic, and construction practices. While the primary focus of this research is the Naturdorf Bärnau case study, insights derived from the Grugliasco project contribute to a more grounded interpretation of bio-based construction within contemporary contexts.

Rather than serving as a direct object of analysis, the Grugliasco experience functions as a complementary reference point, enabling critical comparison between different approaches to vernacular reinterpretation across varying climatic and socio-cultural conditions.

1.7 Structure of the Thesis

This thesis is organised into seven chapters, each addressing a specific aspect of the research.

Chapter 2 introduces the site, context, and background of the Naturdorf Bärnau project. Chapter 3 presents the theoretical framework and comparative references, with a focus on vernacular and vegetarian architecture. Chapter 4 examines the construction systems and material logic of Building D, forming the basis for the subsequent analysis. Chapter 5 outlines the Life Cycle Assessment methodology and presents the results of the environmental analysis, including material inventories, embodied impact calculations, and

qualitative observations. Chapter 6 evaluates the findings in relation to the four principles proposed by Bocco and Habert, while also incorporating comparative reflections from the Grugliasco project. Chapter 7 concludes the thesis by summarising the key findings, discussing theoretical contributions, and providing recommendations for future applications of vernacular and bio-based construction.

1.8 Expected Contribution

By quantifying the environmental and socio-economic performance of a built project that reinterprets vernacular strategies, this thesis seeks to bridge the gap between conceptual frameworks and measurable architectural practice within the field of regenerative design.

The study contributes to the ongoing discourse on 21st Century Vernacular Architecture by critically evaluating the applicability of Bocco and Habert’s (2024) framework through a combined environmental, material, and socio-economic analysis. In doing so, it demonstrates how vernacular principles can be operationalised and assessed within contemporary construction systems.

Beyond its theoretical contribution, the research provides a structured methodology for integrating Life Cycle Assessment, material sourcing analysis, and qualitative evaluation into the study of bio-based architecture. This approach offers practical insights for architects, policymakers, and local stakeholders seeking to implement low-impact, context-responsive building strategies.

Furthermore, by examining the relationship between material selection, construction logic, and environmental performance, the thesis highlights the relevance of vernacular building principles as a foundation for developing scalable and carbon-conscious architectural solutions.

Chapter 2

Site, Context, and Project Background

2.1 Geographic and Territorial Context

Naturdorf Bärnau is located in the Upper Palatinate region of Bavaria, in southeastern Germany, in close proximity to the Czech border. The settlement is situated within a predominantly rural landscape characterised by low-density development, agricultural fields, forested areas, and gently undulating terrain. This peripheral condition places Bärnau outside major metropolitan systems, reinforcing its identity as a marginal yet contextually rich territory shaped by long-standing interactions between landscape, settlement, and movement.

Despite its contemporary rural character, Bärnau occupies a historically strategic position within Central Europe. The region formed part of an important transregional corridor linking southern Germany to Bohemia, most notably through the medieval Goldene Straße (Via Carolina) connecting Luxembourg to Nürnberg to Prague and even Warsaw. This route functioned not only as a commercial and political axis but also as a channel for the exchange of materials, construction knowledge, and cultural practices across regions.

In this sense, the territorial relevance of Bärnau extends beyond its immediate geographic boundaries. Its position can be understood within what Braudel (1985) describes as a long *durée* spatial framework, where infrastructure and geography establish enduring patterns of economic and cultural interaction over time. The persistence of such routes contributes to the formation of hybrid landscapes, where local building traditions are continuously shaped by both internal conditions and external influences.

The spatial structure of the area today still reflects these historical layers of movement and exchange. The proximity of Bärnau to the German–Czech border, combined with its location along historical trade routes, situates it within a broader network of territorial relationships. These include not only economic connections but also ecological and cultural continuities that extend across national boundaries.

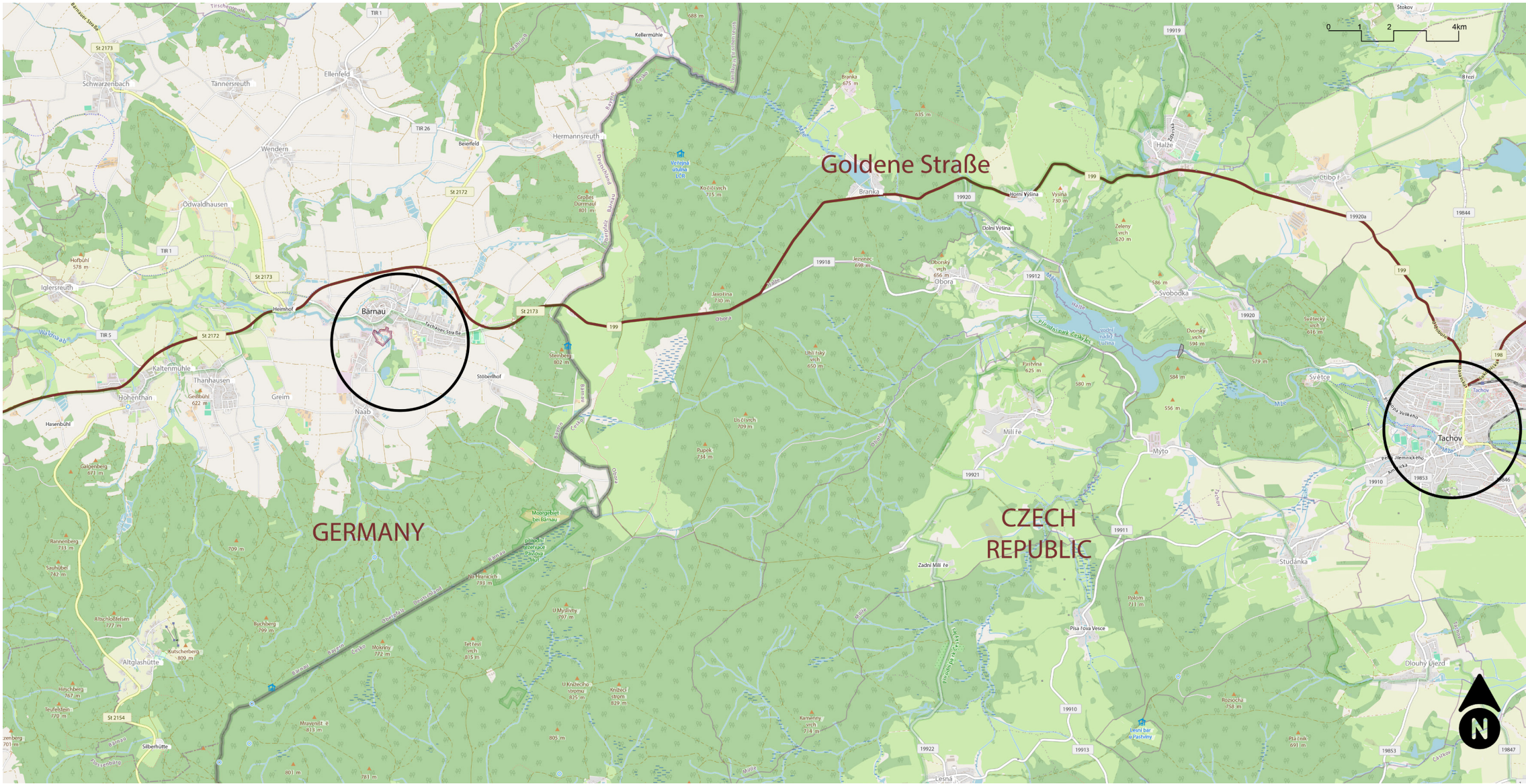


Figure 2.1 – Regional Location of Bärnau in relation to the historic Nürnberg–Prague corridor (Goldene Straße). (Author’s elaboration based on Bärnau’s photo archive and OpenStreetMap.)

This multi-scalar positioning of local, regional, and transnational situation provides a critical foundation for understanding Naturdorf Bärnau as a case study. The project is not merely embedded in a rural setting, but within a historically active landscape shaped by circulation, adaptation, and resource exchange.

As such, it offers a relevant context for examining how contemporary architecture can engage with vernacular principles rooted in both locality and connectivity.

2.2 Historical Background: The Goldene Straße and Vernacular Continuity

The historical development of Bärnau is closely tied to its position along the Goldene Straße (Via Carolina), a major transregional route established in the 14th century under the rule of Emperor Charles IV. Conceived as a political and economic corridor linking the imperial city of Nürnberg with Prague, the route played a strategic role in consolidating power, facilitating trade, and strengthening territorial cohesion within the Holy Roman Empire.

Beyond its administrative function, the Goldene Straße operated as a vital channel for the movement of goods, people, and knowledge across Central Europe. Settlements such as Bärnau, located along this corridor, became points of exchange where regional building practices were continuously shaped by both local conditions and external influences. As noted by Wolters (2015), the Bärnau–Tachov region functioned not only as a transit zone but also as a site of cultural and technological interaction, where craftsmanship, material knowledge, and construction techniques evolved through cross-border exchange.



Figure 2.2 – Trade routes in the late middle ages between Bavaria and Bohemia
Source: Bavaria and Bohemia. <https://hdbg.eu/karten/karten/liste/id/11>



Figure 2.3: The Goldene Straße (Via Carolina), a medieval trade route linking Nürnberg and Prague, situating Bärnau as a historical point of exchange.
Source: Naturdorf Bärnau panel



Figure 2.4 – Old map of the “Goldene Strasse”
Source: <https://www.weiden-tourismus.info/en/leisure-in-the-city-the-region/tips-for-excursions-in-the-upper-palatinate-forest/tourist-routes?utm>



“On September 3, 1343, the village of Bärnau—without having been a market town—was elevated to city status by Emperor Louis the Bavarian and simultaneously granted the right of a “mile of road.” Documentary evidence shows that Bärnau was already the seat of a judge in 1311. Later, a bailiwick was located there. The “Golden Road” trade route from Nuremberg to Prague ran through the city, which was surrounded by walls on a hill and laid out in a slightly oval shape, with the parish church of St. Nicholas at its center”

Figure 2.5 – Button Town Bärnau

Image by: Bärnau City Archives (with author's illustration)

Source: <https://www.baernau-entdecken.de/knopfstadt-baernau/geschichte-und-tradition>

This historical condition contributed to the emergence of a hybrid architectural culture, in which timber structures, clay-based construction, and stone foundations were not employed as stylistic expressions, but as pragmatic responses to climate, soil conditions, and resource availability. These building

systems developed incrementally through processes of adaptation, repair, and reuse, reflecting a key characteristic of vernacular architecture as an evolving practice rather than a fixed typology (Oliver, 2006).

In the contemporary context, this historical legacy is actively reinterpreted through the Geschichtspark Bärnau–Tachov, an open-air museum and research site dedicated to experimental archaeology. The park reconstructs settlement typologies from different historical periods based on archaeological evidence, enabling the study of historical construction methods through full-scale building processes.

Rather than presenting vernacular architecture as a static or purely representational artefact, the Geschichtspark adopts an experimental approach in which buildings are constructed, inhabited, and maintained using historically informed techniques. This methodology aligns with the principles of experimental archaeology, where knowledge is generated through the physical testing of materials, tools, and construction processes under real conditions (Reynolds, 1999). As a result, vernacular architecture is understood not as a finished product, but as a dynamic system of knowledge shaped by environmental constraints, material behaviour, and human agency.

This understanding forms a critical bridge to the present study. By framing vernacular architecture as a process of continuous adaptation rather than a static historical condition, the Bärnau context provides a suitable foundation for examining how these principles can be translated into contemporary architectural practice. The Naturdorf Bärnau project, located adjacent to the Geschichtspark, emerges directly from this lineage, extending the experimental logic of reconstruction into the realm of modern habitation and sustainability.



Figure 2.6: The Geschichtspark Bärnau–Tachov, where historical building techniques are reconstructed and tested through full-scale experimental archaeology

Source: https://www.kreis-tir.de/buergerservice/aktuelles/detail/via-carolina-goldene-strasse-ev-erhaelt-600000-euro-zur-staerkung-des-geschichtspark-baernau-tachov?utm_



Figure 2.7: A house made from clay bricks, clay rendered walls, timber and straw. Source: Naturdorf Bärnau photo archive



Figure 2.8: A pristine condition of a residential typology showing the use of timber without polish aesthetics. Source: Naturdorf Bärnau photo archive

2.3 Landscape, Ecology, and the Green Belt Context

Bärnau is situated within the wider ecological corridor known as the European Green Belt, a transboundary landscape that follows the former Iron Curtain across Europe. Extending over 12,500 kilometres from the Barents Sea to the Black Sea, this corridor represents one of the most significant ecological networks on the continent, characterised by high biodiversity and relatively undisturbed natural systems (Terry et al., 2006).

Following German reunification and the dissolution of the soviet bloc, the former militarised border zone underwent a profound transformation. Areas that had long been restricted from development evolved into spaces of ecological continuity, where limited human intervention allowed diverse habitats to regenerate. In this context, the Green Belt embodies a unique overlap between political history, environmental recovery, and cultural memory, where traces of division have been reconfigured into a shared ecological asset.

The landscape surrounding Bärnau reflects this layered condition. Agricultural fields, forested areas, and open ecological zones coexist within a system that prioritises low-intensity land use and long-term environmental stability. As a result, the territory is not only defined by its natural characteristics but also by regulatory and ethical frameworks that favour conservation, minimal disturbance, and sustainable resource management.

This context has direct implications for architectural practice. Building within the Green Belt requires approaches that minimise ecological impact, including reduced soil disturbance, limited material transport, and the adoption of reversible or low-impact construction systems. These constraints challenge conventional construction methods while simultaneously reinforcing alternative strategies grounded in material efficiency and environmental responsiveness.

In this respect, the ecological logic of the Green Belt aligns closely with the principles of vernacular architecture. Historically, vernacular buildings emerged from a continuous negotiation between human needs and environmental limitations, relying on locally available materials, climate-responsive design, and incremental adaptation over time (Oliver, 2006). The conditions present in Bärnau therefore do not impose entirely new constraints but rather reactivate a mode of building that has long been embedded within the landscape.

This convergence between ecological protection and vernacular logic establishes an important framework for the Naturdorf Bärnau project. Rather than operating as an isolated architectural intervention, the project can be understood as part of a broader territorial system in which environmental sensitivity, material locality, and cultural continuity are structurally interconnected.

2.4 The Naturdorf Bärnau Project

Naturdorf Bärnau is a contemporary architectural intervention comprising four holiday homes located in immediate proximity to the Geschichtspark Bärnau–Tachov. The project was conceived as an extension of the park’s cultural and pedagogical mission, translating insights derived from experimental archaeology and vernacular reconstruction into a contemporary residential setting. In this sense, Naturdorf does not operate as an isolated development, but as part of a broader research-oriented environment in which historical knowledge, material practice, and architectural design are closely interconnected.

Positioned at the interface between historical reconstruction and contemporary habitation, the project explores how vernacular principles can be adapted to meet present-day technical, environmental, and regulatory requirements.



Figure 2.9: The European Green Belt, a protected ecological corridor along the former Iron Curtain, within which Bärnau is situated. Source: Naturdorf Bärnau photo archive.



Figure 2.10: Functional and spatial context of Naturdorf Bärnau in relation to the Geschichtspark and surrounding settlement. The map highlights the distribution of holiday homes, museum functions, workshops, and landscape elements. (Author’s elaboration based on Geschichtspark Bärnau data and OpenStreetMap.)

Rather than reproducing historical forms, the design adopts a reinterpretative approach, in which traditional construction knowledge is critically translated into modern building systems. This aligns with the concept of critical vernacular architecture, where historical techniques are neither replicated nostalgically nor abandoned, but transformed in response to contemporary conditions (Bocco & Habert, 2024).

Materially, the project is characterised by the use of bio-based and locally sourced construction systems, including timber framing, clay plasters, natural insulation materials, and wooden roof shingles. These elements are not employed as symbolic references to tradition, but as performative components contributing to thermal efficiency, moisture regulation, and reduced embodied environmental impact. Their application also depended on craftsmanship and construction techniques that are increasingly uncommon in conventional building practice. The Naturdorf Bärnau site also functioned as a practical training ground where these techniques were taught and rehearsed by small voluntary groups during construction.



Figure 2.11: The Bärnau Nature Village in July 2023: Two of the four houses are almost finished. The first half-timbered house to be built is on the right in the picture. Source:

https://www.dach-holzbau.de/artikel/traditioneller-ab-bund-fuer-fachwerkneubau-3999816.html?utm_

Beyond material selection, the architectural logic of the project is grounded in a broader understanding of circularity and lifecycle thinking. The use of natural materials, reversible construction techniques, and simplified structural systems reflects an intention to minimise environmental impact not only during construction, but across the building's lifespan. In this regard, Naturdorf Bärnau can be interpreted as a contemporary test case for evaluating how vernacular principles traditionally developed through necessity, can inform deliberate strategies for sustainability in modern architecture.

At the same time, the project responds to contemporary expectations of comfort, durability, and usability. The buildings are designed to accommodate modern living standards while maintaining a strong connection to material authenticity and construction logic. This balance between performance and tradition is central to the project's relevance within the framework of 21st Century Vernacular Architecture, where accessibility, environmental responsibility, and user expectations must be addressed simultaneously.

As such, Naturdorf Bärnau represents a critical shift from reconstruction to application. While the Geschichtspark investigates historical building techniques through replication, Naturdorf extends this knowledge into a living context, testing how these principles can operate within current architectural, environmental, and socio-economic systems. This transition from experimental archaeology to contemporary practice forms a key foundation for the analytical focus of this thesis.

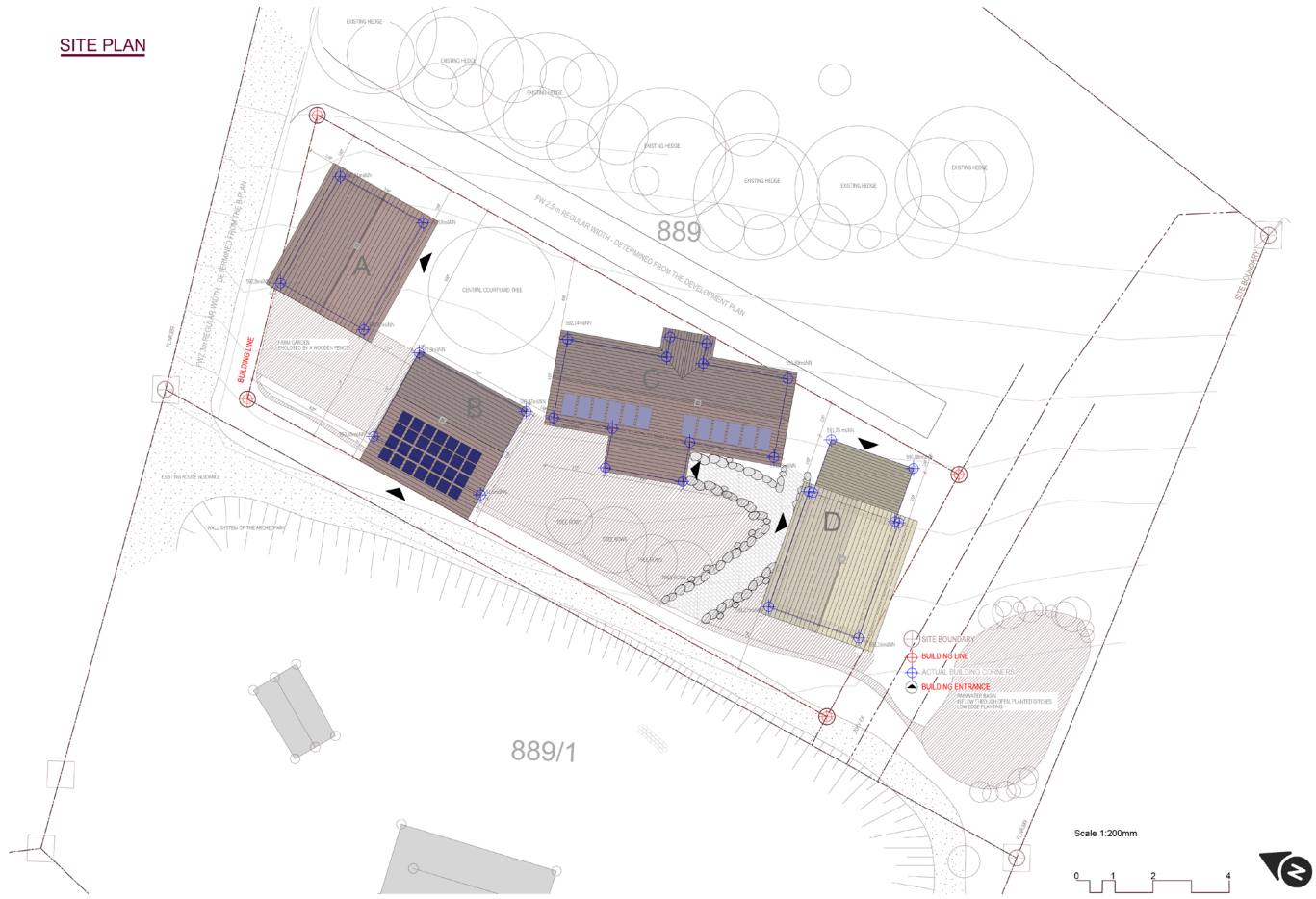


Figure 2.12: Site plan of Naturdorf Bärnau showing the spatial arrangement of Buildings A–D and shared external areas (Scale 1:200). Author's drawing based on project documentation.

2.5 Scope of Analysis and Focus on Building D

While Naturdorf Bärnau is conceived as a coherent architectural ensemble, this thesis adopts a focused case study approach by concentrating on Building D, a single unit that was the first to be completed. It is located at the eastern edge of the site and characterised by its wooden roof shingles construction. This selection is not arbitrary, but is based on its material clarity, completeness of available data, and its representativeness within the overall typological and construction logic of the settlement.



Figure 2.13: The Naturdorf holiday homes under construction shows diverse use of materials (Labelled A-D from left to right. Source: Naturdorf Bärnau photo archive. <https://www.naturdorfbaernau.de/>

The decision to isolate one building for in-depth investigation enables a higher level of analytical precision, particularly in relation to Life Cycle Assessment (LCA), material quantification, and construction detailing. By limiting the quantitative scope to a single unit, the study ensures greater traceability of data, consistency in methodological application, and reliability of results, which are essential for meaningful environmental evaluation.

At the same time, the broader Naturdorf context is not excluded from the analysis. The ensemble is used as a comparative and interpretative framework, allowing for the examination of spatial relationships, typological variations, and shared construction principles across the settlement. This dual approach—combining site-wide qualitative interpretation with building-specific quantitative analysis—ensures that the study maintains both depth and contextual coherence.



Figure 2.14: Houses C and D of the Naturdorf under construction (Building C and D on the left and right respectively). Sourced from Onetz.de photo archive

From a methodological standpoint, this approach aligns with established case study research strategies, where a single unit of analysis is examined in detail to generate insights that can be cautiously extended to a broader system (Yin, 2018). In this thesis, Building D functions as a proxy through which the environmental, material, and architectural performance of the Naturdorf project can be rigorously evaluated, while remaining grounded in its wider territorial and conceptual context.

Ultimately, this scoped focus directly supports the central research aim of the thesis: to assess the applicability of the “Vernacular Architecture of the 21st Century” framework through a detailed and verifiable case. By anchoring the analysis in a clearly defined unit, the study establishes a transparent and methodologically robust foundation for the environmental and architectural evaluations presented in subsequent chapters.



Figure 2.15: The Naturdorf holiday homes at almost completed state (Labelled A-D from up to down. Source: Naturdorf Bärnau photo archive. <https://www.naturdorfbaernau.de/>

Chapter 3

Theoretical Framework and Comparative References

3.1 Positioning the Theoretical Framework within the Thesis Structure

The preceding chapters have established the geographical, historical, ecological, and architectural context of Naturdorf Bärnau, framing it as a site shaped by long-standing processes of material exchange, environmental adaptation, and experimental reconstruction. While Chapter 2 situates the project within its territorial and cultural setting, it does not yet provide the conceptual tools required to critically evaluate its architectural and environmental performance.

This chapter therefore introduces the theoretical framework that underpins the analysis presented in the subsequent sections of the thesis. Rather than treating theory as a separate or abstract component, the framework is developed as an operational lens through which the Naturdorf Bärnau project can be interpreted, assessed, and positioned within broader architectural and environmental discourses..

The chapter focuses on three interrelated domains. First, it examines the evolving understanding of vernacular architecture, moving from traditional interpretations toward contemporary redefinitions that respond to current environmental and socio-economic challenges. Second, it explores the role of bio-based materials and material cycles in shaping low-impact construction practices, with particular attention to their implications for carbon storage and resource efficiency. Third, it considers the role of experimental architecture as a mode of knowledge production, bridging the gap between historical reconstruction and contemporary application.

In addition, selected comparative case studies are introduced to situate the Naturdorf project within a broader field of architectural practice. These references are not presented as direct precedents, but

as complementary examples that highlight different approaches to material use, construction logic, and environmental responsiveness.

By integrating these perspectives, the chapter establishes a coherent conceptual foundation that links theory to practice. This framework is subsequently translated into an evaluative structure used to assess the Naturdorf Bärnau project in Chapters 5 and 6, ensuring that the analysis is grounded in both theoretical rigor and empirical observation.

3.2 Vernacular Architecture in the 21st Century

Vernacular architecture has long been understood as a form of building practice rooted in local knowledge, material availability, and environmental responsiveness. Early interpretations, particularly those popularised by Rudofsky (1964), framed vernacular architecture as a non-pedigreed and anonymous form of construction, developed outside formal architectural discourse. In this view, vernacular buildings were seen as spontaneous and intuitive responses to climate, geography, and cultural conditions, shaped over time through collective experience rather than individual authorship.

Subsequent scholarship has expanded this understanding by emphasising the socio-cultural and environmental dimensions of vernacular architecture. Oliver (2006) describes vernacular building as a process embedded within specific cultural contexts, where construction techniques, spatial organisation, and material use evolve in response to both

environmental constraints and social practices. From this perspective, vernacular architecture is not defined by stylistic characteristics, but by its capacity to adapt to changing conditions through incremental modification, repair, and reuse.

Despite its historical significance, vernacular architecture has often been marginalised within modern architectural discourse, frequently reduced to a nostalgic reference or aesthetic inspiration. This perception overlooks its underlying logic as a system of resource-efficient and climate-responsive construction. In the context of contemporary environmental challenges, particularly those related to resource depletion and carbon emissions, this logic has gained renewed relevance.

Recent research has sought to reinterpret vernacular architecture as a viable framework for contemporary practice rather than a relic of the past. Bocco and Habert (2024) propose the concept of *21st Century Vernacular Architecture, defined through four interrelated principles*:

- the use of local resources
- a low environmental footprint,
- the fulfilment of modern user expectations, and
- accessibility for everyday users.

This framework shifts the focus from replication to transformation, emphasising the need to adapt traditional knowledge to current technical, regulatory, and socio-economic conditions.

Within this reinterpretation, vernacular architecture is understood as a dynamic and performative system, rather than a fixed historical model. Its relevance lies not in reproducing traditional forms, but in applying its underlying principles—material efficiency, locality, and environmental adaptation—to contemporary building systems. This approach aligns closely with emerging discussions in sustainable architecture, where the reduction of embodied impacts and the integration of circular material flows are becoming central design concerns.

Furthermore, the emphasis on local resources within vernacular systems introduces an important spatial dimension to sustainability. Unlike abstract carbon accounting frameworks, which often treat emissions independently of place, vernacular architecture inherently links material selection to geographic context, supply chains, and local economies. This embeddedness highlights the potential for reducing environmental impact not only through material choice, but through the restructuring of production and distribution systems.

At the same time, the reinterpretation of vernacular architecture must address the demands of contemporary life. Issues of comfort, durability, safety, and regulatory compliance require that traditional construction techniques be adapted rather than directly reproduced. The challenge therefore lies in balancing the environmental and cultural logic of vernacular systems with the technical and social expectations of modern users.

In this context, Naturdorf Bärnau can be understood as a contemporary application of these principles. Rather than replicating historical building forms, the project reinterprets vernacular construction through the integration of bio-based materials, modern construction standards, and evolving user requirements. It therefore provides a relevant case through which the theoretical framework of 21st Century Vernacular Architecture can be critically examined.

This conceptual shift—from vernacular architecture as historical reference to vernacular architecture as an operational framework—forms a central foundation of the present study. It establishes the basis for evaluating how traditional principles can be translated into measurable environmental and architectural performance within contemporary construction practice.

3.3 Bio-based Materials, Material Cycles, and Carbon Storage

The increasing focus on reducing the environmental impact of the built environment has brought renewed attention to the role of materials in shaping architectural performance. While operational energy has historically dominated discussions on building sustainability, the growing significance of embodied carbon has shifted attention toward the processes of material extraction, production, and construction. In this context, bio-based materials have emerged as a key component in strategies aimed at reducing the overall environmental footprint of buildings.

Bio-based materials such as timber, hemp, straw, and clay-based composites are derived from renewable biological resources and are typically associated with lower embodied energy compared to conventional materials such as concrete, steel, and aluminium. Beyond their reduced production impacts, these materials offer the additional advantage of biogenic carbon storage, whereby atmospheric carbon dioxide is absorbed during plant growth and temporarily sequestered within the material for the duration of its use in a building (IPCC, 2021).

However, the environmental performance of bio-based materials cannot be understood solely in terms of carbon storage. Their effectiveness depends on broader material cycles, including sourcing, processing, transportation, and end-of-life scenarios. In particular, the benefits of biogenic carbon storage are closely linked to the duration of carbon retention and the conditions under which materials are reused, recycled, or decomposed. As noted in recent studies, there is still ongoing debate regarding the most appropriate methods for accounting for biogenic carbon within Life Cycle Assessment frameworks, reflecting the complexity of integrating biological

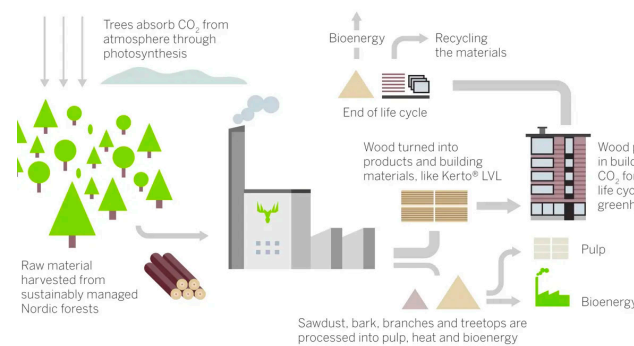


Figure 3.1: Simplified representation of the biogenic carbon cycle in bio-based construction materials, illustrating carbon absorption during plant growth, storage during the building phase, and release or reuse at end-of-life.

Source: https://www.metsagroup.com/metsawood/news-and-publications/articles/carbon-storage/?utm_

processes into standardised evaluation systems (Hoxha et al., 2020).

In addition to their environmental properties, bio-based materials are closely aligned with the principles of vernacular architecture. Historically, construction practices relied heavily on locally available natural resources, not only due to environmental considerations but also because of economic and logistical constraints. This reliance on local materials resulted in building systems that were inherently adapted to their climatic and geographic context, while minimising the need for long-distance transportation and intensive processing.

From this perspective, the use of bio-based materials in contemporary architecture represents not only a technical strategy for reducing embodied carbon, but also a re-engagement with locally embedded material systems. This connection extends beyond environmental performance to include socio-economic dimensions, such as the support of regional supply chains, the preservation of craft knowledge, and the reinforcement of local production networks.

At the same time, the integration of bio-based materials into modern construction presents significant challenges. Issues related to standardisation, durability, fire safety, and regulatory compliance require that traditional materials be adapted and tested within contemporary frameworks. This has led to the development of hybrid systems, where natural materials are combined with engineered components and modern construction techniques to meet current performance standards.

In this context, material selection becomes a critical point of convergence between environmental performance, construction logic, and design intention. Rather than viewing materials as neutral components, they are understood as active agents within a broader system of environmental and socio-economic relationships.

This perspective is particularly relevant for the Naturdorf Bärnau project, where the use of timber, clay, and other bio-based materials reflects both a continuation of vernacular traditions and a deliberate strategy for reducing environmental impact.

By situating bio-based materials within a framework that considers both material cycles and carbon dynamics, this section establishes a conceptual link between vernacular construction practices and contemporary sustainability goals. This connection provides the basis for the Life Cycle Assessment presented in Chapter 5, where the environmental performance of these materials is quantified and evaluated within a defined system boundary.

3.4 Experimental Architecture as Knowledge Production

Architecture is traditionally understood as a discipline concerned with the design and construction of built form. However, beyond its role as a product-oriented practice, architecture can also function as a mode of inquiry, where knowledge is generated through the processes of making, testing, and inhabiting built environments. Within this perspective, experimental architecture emerges as a methodological approach in which construction is not only an outcome, but also a means of investigation.

This approach is closely aligned with the principles of experimental archaeology, where historical construction techniques are reconstructed and tested through full-scale building processes. Rather than relying solely on textual or visual documentation, knowledge is produced through direct engagement with materials, tools, and environmental conditions (Reynolds, 1999). Such methods enable the verification of assumptions regarding construction techniques, material performance, and spatial organisation, while also revealing tacit forms of knowledge that are not easily captured through conventional analytical methods.

The **Geschichtspark Bärnau–Tachov** represents a contemporary application of this approach within the context of vernacular architecture. By reconstructing buildings from different historical periods based on archaeological evidence, the park operates as a living laboratory in which construction knowledge is continuously tested, refined, and transmitted. As noted by Wolters (2015), the project is not intended as a static museum, but as an active research environment where building practices are understood through use, maintenance, and long-term observation.



Figure 3.2: Geschichtspark showing reconstructed buildings from different historical periods based on archaeological evidences
Source: https://www.dach-holzbau.de/artikel/modernes-bauen-mit-natuerlichen-baustoffen-3984646.html?utm_
Photo by: Geschichtspark Bärnau-Tachov

In this context, experimental architecture extends beyond historical reconstruction to inform contemporary design practices. The insights generated through full-scale experimentation, such as the behaviour of natural materials, the limitations of traditional construction techniques, and the interaction between buildings and environmental conditions—provide a valuable knowledge base for reinterpreting vernacular principles within modern contexts.

This research-oriented approach is also evident in contemporary projects that explore bio-based construction through hands-on experimentation. The

Experimental Pavilions of Vegetarian Architecture in Grugliasco, in which the author participated, exemplify this mode of practice. Through the design and construction of full-scale prototypes using materials such as straw, hemp, timber, stone, and earth, the project investigates the performance and feasibility of low-carbon building systems under real conditions of use. These experiments generate practical insights into material behaviour, assembly processes, and structural logic that cannot be fully understood through theoretical analysis alone.



Figure 3.3: A photo of a wall build-up in one of the Experimental Pavilions (Grugliasco) showing the assembly of bio-based building materials (straw, hemp, timber, earth) layered as a wall element.

Source: Author's photo from site participation

Importantly, experimental architecture challenges the separation between research and practice. Rather than positioning knowledge production within academic or laboratory settings alone, it situates learning within the act of construction itself. This approach recognises that building processes involve a combination of explicit knowledge, such as; structural calculations and material specifications and tacit knowledge, including craftsmanship, intuition, and embodied skill.

Within the context of this thesis, experimental architecture provides a critical link between vernacular theory and contemporary application. While vernacular architecture is often understood through historical analysis, and sustainability through quantitative assessment, experimental practice offers a way to connect these domains through material and spatial experience.

Naturdorf Bärnau can be interpreted as an extension of this experimental logic. Building upon the research



Figure 3.4: Construction process of the Royal court on a demonstration site next to the Bärnau History Park with craftsmen using medieval techniques and tools to erect a stone building complex.
Photo by: Geschichtspark Bärnau-Tachov

Source: https://www.dach-holzbau.de/artikel/modernes-bauen-mit-natuerlichen-baustoffen-3984646.html?utm_

environment of the Geschichtspark, the project translates insights derived from historical reconstruction into a contemporary architectural setting. In doing so, it shifts the focus from understanding how buildings were constructed in the past to exploring how these principles can inform present-day construction practices.

This positioning reinforces the role of architecture as both a reflective and generative discipline. By treating construction as a form of inquiry, experimental architecture enables a deeper understanding of the relationships between materials, environment, and human use. It therefore provides an essential methodological foundation for this study, supporting the integration of theoretical concepts, material analysis, and real-world application within a coherent research framework.

3.5 Comparative Case Studies

The theoretical framework outlined in the preceding sections establishes vernacular architecture, bio-based material systems, and experimental construction as key lenses through which the Naturdorf Bärnau project can be understood. However, in order to situate this case study within a broader architectural context, it is necessary to examine comparable projects that engage with similar themes of material locality, low-impact construction, and knowledge production through building.

This section introduces a set of selected case studies that exemplify different approaches to the reinterpretation of vernacular principles in contemporary architecture. These projects are not presented as direct precedents for Naturdorf Bärnau, but as comparative references that highlight varying strategies in the use of natural materials, construction techniques, and participatory building processes.

The selection is guided by three criteria. First, each case engages with bio-based or low-impact material systems, such as earth, straw, or timber, in a manner that reflects a conscious response to environmental constraints. Second, the projects demonstrate a strong relationship between construction process and knowledge production, where building is treated as an experimental or educational activity rather than a purely technical operation. Third, they operate within specific cultural and geographic contexts, allowing for the examination of how local conditions influence material and architectural decisions.

The case studies presented—ranging from the METI Handmade School in Bangladesh to strawbale and timber constructions, and experimental

research in Grugliasco represent diverse interpretations of these shared principles. While differing in scale, context, and programme, they collectively illustrate how vernacular logics can be translated into contemporary architectural practice through both design and construction.

Rather than analysing these projects in isolation, the discussion focuses on identifying recurring themes and divergences that are relevant to the evaluation of Naturdorf Bärnau. These include the role of craftsmanship, the integration of local materials, the relationship between tradition and innovation, and the extent to which construction processes contribute to environmental and social sustainability.

By situating Naturdorf Bärnau within this comparative field, the analysis moves beyond a single-case perspective and establishes a broader basis for interpretation. The insights derived from these examples support the development of a more nuanced understanding of 21st Century Vernacular Architecture, providing a critical backdrop against which the case study can be assessed in subsequent chapters.

3.5.1 METI Handmade School, Bangladesh

The METI Handmade School in Rudrapur, Bangladesh, designed by Anna Heringer in collaboration with Eike Roswag, represents one of the most influential contemporary reinterpretations of vernacular architecture within sustainable design discourse. Completed in 2006 for the Modern Education and Training Institute (METI), the project was conceived not only as a school building, but as a socially and environmentally embedded construction process grounded in local knowledge, labour, and material

grounded in local knowledge, labour, and material resources.

Rather than importing industrial construction systems, the project deliberately relied on locally available materials such as earth, bamboo, straw, and brick. The ground floor was constructed using thick earthen walls reinforced with straw, while the upper level employed lightweight bamboo construction to improve ventilation and reduce structural weight. These material choices were closely linked to the climatic conditions of northern Bangladesh, where thermal mass, natural ventilation, and low-energy construction methods offer significant environmental advantages.



Figure 3.5: The METI Handmade School in Rudrapur, Bangladesh, demonstrating the integration of earthen construction, bamboo structures and other locally sourced materials.

Source: Anna Heringer project archive and project documentation. https://www.zrs.berlin/en/project/meti-school-handmade/?utm_

A defining aspect of the project lies in its participatory construction methodology. Local craftsmen, teachers, students, and residents were actively involved in the building process, transforming construction into a collective learning activity rather than a purely technical operation. According to Heringer, the intention was to ensure that both economic value and construction knowledge remained within the local community, while simultaneously strengthening confidence in traditional building techniques.

This participatory dimension positions the METI School within a broader understanding of architecture as a form of social and material knowledge production. The project demonstrates how vernacular techniques can be adapted and improved through experimentation rather than simply preserved as heritage. For example, modifications to bamboo jointing systems and foundation detailing allowed the incorporation of a second floor and improved durability while maintaining the use of local materials.

Importantly, the METI School avoids romanticising vernacular architecture as a static or purely aesthetic condition. Instead, it reinterprets traditional construction practices through contemporary spatial requirements, educational functions, and environmental concerns. This aligns closely with the principles of 21st Century Vernacular Architecture proposed by Bocco and Habert (2024), particularly in relation to local resource use, environmental responsiveness,

accessibility, and the integration of contemporary user expectations.



Figure 3.6: The METI Handmade School demonstrating the adaptation of vernacular techniques

Source: Anna Heringer project archive and project documentation.

https://www.zrs.berlin/en/project/meti-school-handmade/?utm_

From the perspective of the present thesis, the METI School is significant because it demonstrates how bio-based materials and local craftsmanship can operate simultaneously as environmental, social, and architectural strategies. The project highlights that low-impact construction is not solely dependent on technological innovation, but can also emerge through the reinterpretation of existing material cultures and collective building practices.

Furthermore, the project establishes an important precedent for understanding construction itself as an educational and experimental process. This aspect is particularly relevant to Naturdorf Bärnau and the Geschichtspark Bärnau–Tachov, where knowledge generation similarly occurs through full-scale building, material experimentation, craftsmanship, and the reinterpretation of vernacular systems within contemporary contexts.

3.5.2 Strawbale and Timber Constructions

Strawbale construction represents one of the most significant contemporary developments in bio-based architecture, particularly in relation to low-impact building systems and material circularity (Koh and Kraniotis, 2020). Originally emerging in the late nineteenth century in Nebraska, United States, strawbale construction evolved from pragmatic responses to material scarcity, where compressed straw bales were used as insulating and structural components due to the limited availability of timber and stone. Over time, these systems have been reinterpreted and adapted within contemporary ecological architecture, combining traditional agricultural materials with modern structural and regulatory frameworks (Koh and Kraniotis, 2020).

Unlike purely historical vernacular systems, many contemporary strawbale projects employ mixed construction strategies, where timber structures provide the primary load-bearing framework while strawbale walls function as highly efficient insulating envelopes. This combination enables improved structural reliability, greater design flexibility, and compliance with current building standards, while retaining the environmental advantages associated with natural materials.

A relevant example is the strawbale house constructed by Martin Steiger in the Valdichiana region of Italy. The project combines timber framing with strawbale infill using the GREB construction method, a system developed in Canada that integrates timber, straw, lime-based mortar, and metal joints within a lightweight structural assembly. According to Steiger, the intention behind the project was not only environmental responsibility, but also the creation of a

healthier and more breathable living environment through the use of natural materials.



Figure 3.7: Structure of Martin Steiger's house in Valdichiana using Lunar woodframes, natural insulation materials with lightweight timber structures

Source: La Valdichiana archive and project documentation.

https://www.lavaldichiana.it/casa-di-paglia-valdichiana-martin-steiger/?utm_

The environmental relevance of strawbale systems lies primarily in their low embodied energy, high thermal performance, and capacity for carbon storage. Straw, as an agricultural by-product, requires relatively limited additional processing before construction use and can contribute to reduced lifecycle impacts when locally sourced. Furthermore, the integration of lime and earth-based plasters improves moisture regulation and indoor air quality while maintaining material breathability.

At the same time, these projects reveal the complexities involved in integrating natural materials into contemporary construction systems. Issues such as moisture protection, structural stability, fire resistance, and regulatory compliance require careful detailing and technical adaptation. In many cases, the success of strawbale construction depends not only on material

selection, but also on craftsmanship, construction sequencing, and long-term maintenance strategies.

An important aspect of projects such as Steiger's house is the participatory nature of the construction process. The building was realised with the assistance of friends and collaborators, reflecting a collective mode of construction often associated with vernacular and self-build traditions. This participatory dimension highlights how natural building practices can function not only as environmental strategies, but also as social and educational processes that reconnect construction knowledge with local communities.

From the perspective of this thesis, strawbale and timber systems are particularly relevant because they demonstrate how traditional low-impact materials can be integrated into contemporary architectural frameworks without relying on direct historical replication. Similar to Naturdorf Bärnau, these projects reinterpret vernacular principles through the combination of natural materials and local resource logic with modern structural systems and user expectations.

Furthermore, the emphasis on lightweight bio-based assemblies, reversible construction techniques, and material breathability parallels many of the environmental and architectural strategies observed within the Naturdorf project. These examples therefore reinforce the argument that vernacular principles can remain relevant within contemporary sustainable architecture when adapted through critical and technically informed reinterpretation.

3.5.3 Experimental Pavilions of Vegetarian Architecture, Grugliasco

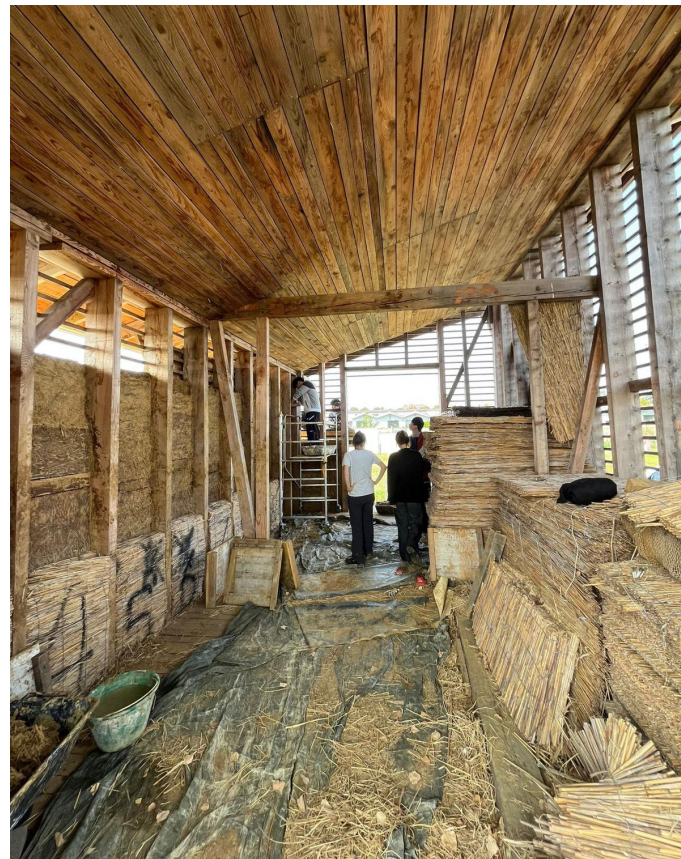


Figure 3.8: Experimental construction process at the Grugliasco site illustrates student participation in the assembly of bio-based building systems

Source: Author's photo from site participation

The Experimental Pavilions of Vegetarian Architecture in Grugliasco, Turin, Italy, represent a research-driven initiative within the Department of Structural, Geotechnical and Building Engineering (DIST) at Politecnico di Torino, led by Professor Andrea Bocco, with principal research coordination by Redina Mazelli, a PhD candidate in Urban and Regional Development. The project focuses on the design, construction, and monitoring of low-carbon prototypes using natural materials such as straw, hemp, stone, rammed earth, and timber. These pavilions are developed through a hands-on, participatory process

in which students and researchers actively engage in self-building, allowing construction to function not only as a means of production but also as a method of knowledge generation.

Unlike the METI School, which is embedded in a permanent social programme, or strawbale housing, which often aims at long-term residential use, the Grugliasco pavilions function explicitly as research-scale interventions. Their primary objective is to explore the structural, environmental, and spatial potential of natural materials such as straw, hemp, timber, clay, and earth-based composites through iterative construction and observation. In this sense, the project aligns closely with the logic of experimental architecture, where the process of building itself becomes a central component of inquiry.

A defining characteristic of the project is its hands-on and participatory methodology. Students, researchers, and instructors are actively involved in all phases of construction, from material preparation and structural assembly to finishing and performance observation. This approach enables the direct engagement with material behaviour, construction sequencing, and environmental conditions, producing forms of tacit knowledge that extend beyond what can be captured through drawings or simulations alone.

Material experimentation plays a central role in the development of the pavilions. By working with minimally processed natural materials, the project investigates issues such as structural stability, moisture regulation, thermal performance, and durability under real conditions of use. The temporary and adaptable nature of the pavilions allows for continuous modification and refinement, supporting an iterative design process in which failure and adjustment are integral to learning.



Figure 3.9: Experimental construction processes at the Grugliasco site, illustrating student participation in the assembly of bio-based building systems

Source: Author's photo from site participation

In addition to its material focus, the project highlights the importance of construction as a pedagogical tool. The act of building becomes a means of transferring knowledge, not only in technical terms but also in relation to craftsmanship, collaboration, and spatial understanding. This educational dimension reinforces the idea that sustainable architecture cannot be fully developed through theoretical analysis alone, but requires direct engagement with materials and construction processes.

From the perspective of the present thesis, the Grugliasco pavilions provide a critical reference for understanding how vernacular principles can be reinterpreted within a contemporary research environment. While vernacular architecture historically evolved through necessity and repetition, projects such as Grugliasco demonstrate how similar knowledge can be generated intentionally through experimental practice.

Furthermore, the project establishes an important link between research-scale experiment and real-scale application. The insights gained from prototyping, particularly in relation to material behaviour, construction techniques, and assembly logic amongst others inform the feasibility of applying bio-based systems within permanent architectural contexts. This transition is directly relevant to Naturdorf Bärnau, where principles explored through experimental reconstruction and prototyping are translated into durable, inhabitable buildings.

In this sense, the Grugliasco project complements the other case studies presented in this chapter. While the METI School demonstrates the social and cultural integration of vernacular practices, and strawbale construction highlights material systems within residential architecture, the Grugliasco pavilions emphasise the role of experimentation in bridging theory and practice. Together, these examples provide a comprehensive framework for understanding how vernacular architecture can be critically reinterpreted and operationalised within contemporary sustainable design.

3.6 Bridging Research-Scale and Real-Scale Experimentation

The case studies discussed in the previous sections reveal a spectrum of approaches through which vernacular principles are reinterpreted within contemporary architecture. While differing in context, scale, and programme, these projects collectively demonstrate that the translation of vernacular knowledge into modern practice is neither linear nor uniform. Instead, it operates across multiple levels, ranging from research-driven experimentation to fully realised, inhabitable buildings.

At one end of this spectrum, projects such as the Experimental Pavilions in Grugliasco function as research-scale interventions, where construction is used as a tool for testing materials, techniques, and assembly processes under controlled yet real conditions. These projects prioritise learning, iteration, and adaptability, often embracing temporary or reversible structures as a means of exploring new possibilities without the constraints of long-term performance requirements.

At the other end, built projects such as the METI Handmade School and strawbale residential constructions represent real-scale applications, where vernacular principles are integrated into permanent buildings designed to meet functional, social, and regulatory demands. In these cases, experimentation is not eliminated, but embedded within the design and construction process, resulting in hybrid systems that balance tradition with contemporary performance standards.

This distinction between research-scale and real-scale architecture highlights a critical challenge; which is how to translate knowledge generated through experimentation into durable and scalable building systems. While research-scale projects allow for flexibility and innovation, real-scale applications require reliability, standardisation, and long-term performance. Bridging this gap involves not only technical adaptation, but also a shift in how construction knowledge is evaluated, validated, and implemented.



Figure 3.10: Naturdorf Bärnau, illustrating the transition from material experimentation to permanent architectural application.

Source: Author's photo from field trip

In this context, Naturdorf Bärnau occupies a hybrid position between these two modes of practice. Building upon the experimental foundation of the Geschichtspark Bärnau–Tachov, the project extends the logic of reconstruction and material testing into a contemporary residential setting. It therefore operates as a transitional model, where insights derived from experimental archaeology and hands-on construction are applied within the constraints of modern building regulations, user expectations, and environmental performance requirements.

This bridging condition is particularly relevant for



Figure 3.11: Comparison between research-scale experimental pavilions (Grugliasco) in Figure 3.5.3 and real-scale implementation in Naturdorf Bärnau

Source: Author's photo from field trip

understanding the role of vernacular architecture in the 21st century. Rather than existing solely as either experimental prototypes or fully standardised solutions, vernacular principles are shown to operate across a continuum of scales and applications. Their relevance lies in their capacity to adapt to different levels of intervention, from small-scale experimentation to broader architectural implementation.

By situating Naturdorf Bärnau within this continuum, the project can be understood not only as a case study, but as a testing ground for the operationalisation of vernacular principles within contemporary

construction practice. This positioning reinforces the central argument of the thesis: that the transition from traditional knowledge to modern application requires an integrated approach combining material understanding, experimental validation, and architectural design.

3.7 Implications for Construction Methodologies

The analysis presented in this chapter highlights that contemporary construction methodologies can no longer be understood solely in terms of technical efficiency or structural performance. Instead, they must be approached as integrated systems in which material selection, construction processes, and environmental impact are closely interrelated.

Across the case studies, a consistent shift can be observed from material-intensive, standardised construction toward approaches that prioritise material efficiency, locality, and adaptability. Bio-based materials such as timber, straw, and earth are not only environmentally advantageous, but also enable construction systems that are lighter, reversible, and more closely aligned with natural material cycles.

At the same time, the role of construction as a knowledge-generating process emerges as a key methodological insight. Projects that incorporate hands-on experimentation and participatory building processes demonstrate a greater capacity to refine material use, improve construction techniques, and adapt to contextual constraints. This suggests that innovation in sustainable architecture is not driven solely by technological advancement, but also by the reintegration of craftsmanship and experiential learning into the building process.

Furthermore, the transition from research-scale experimentation to real-scale application requires the development of hybrid construction systems, where traditional materials are combined with modern structural and regulatory frameworks. This hybridisation enables the translation of vernacular principles into contemporary practice without compromising performance, safety, or usability.

Taken together, these observations point toward a construction paradigm that is material-conscious, context-responsive, and process-oriented. Rather than relying on universal solutions, such an approach emphasises the adaptation of building systems to local conditions, resource availability, and environmental constraints.

These implications form the basis for the methodological approach adopted in this thesis, where material analysis and environmental assessment are used to evaluate how such principles can be effectively implemented within the Naturdorf Bärnau project.

Chapter 4

Methodology: Construction Systems, Material Logic, and Environmental Performance

4.1 Methodological Approach

This chapter defines the methodological framework adopted to analyse the construction systems of Building D of Naturdorf Bärnau. The methodology integrates architectural documentation, material logic analysis, and environmental understanding to evaluate how traditional construction techniques are adapted to meet contemporary performance requirements.

Rather than addressing materials as isolated components, the analysis is structured around construction assemblies, understood as integrated systems in which structure, enclosure, insulation, and finishes interact. This layered approach reflects both vernacular building logic and contemporary performance-based evaluation, and provides the foundation for the Life Cycle Assessment developed in Chapter 5.

The construction systems examined in this chapter are understood not only as technical solutions but as expressions of a material philosophy rooted in breathability, reversibility, and bio-based continuity. This philosophy corresponds closely to the principles advanced by Bocco and Habert (2024) in their framework for 21st century vernacular architecture, which argues for building systems that prioritise local material availability, passive environmental performance, and cultural continuity with established construction traditions. Building D engages these principles through consistent material choices that run from its structural frame through to its surface finishes, and it is within this integrated logic that each assembly is analysed.

4.2 Timber Structural System as Primary Framework

The primary structural system of Building D is a timber load-bearing frame. This choice reflects both the historical building traditions of the Bärnau region and contemporary strategies for low-carbon construction. Timber provides structural clarity, enables dry construction processes, and ensures compatibility with the bio-based infill and finishing materials employed throughout the building.

The timber frame functions as the organisational backbone of the building, allowing to build wall infill systems, roof structures, and floor assemblies without relying on composite or irreversible connections. This structural logic supports adaptability, repairability, and material separation at end of life, making it well suited to the circular and low-impact objectives of the Naturdorf project.

The spatial organisation of the timber grid, documented in Figures 4.2 and 4.3, reflects a clear structural rhythm that is legible across both the ground floor and the upper floor plan. This legibility is not merely aesthetic; it facilitates maintenance, future modification, and the kind of building longevity that is fundamental to reducing embodied carbon over the life of the structure.

Section y-y

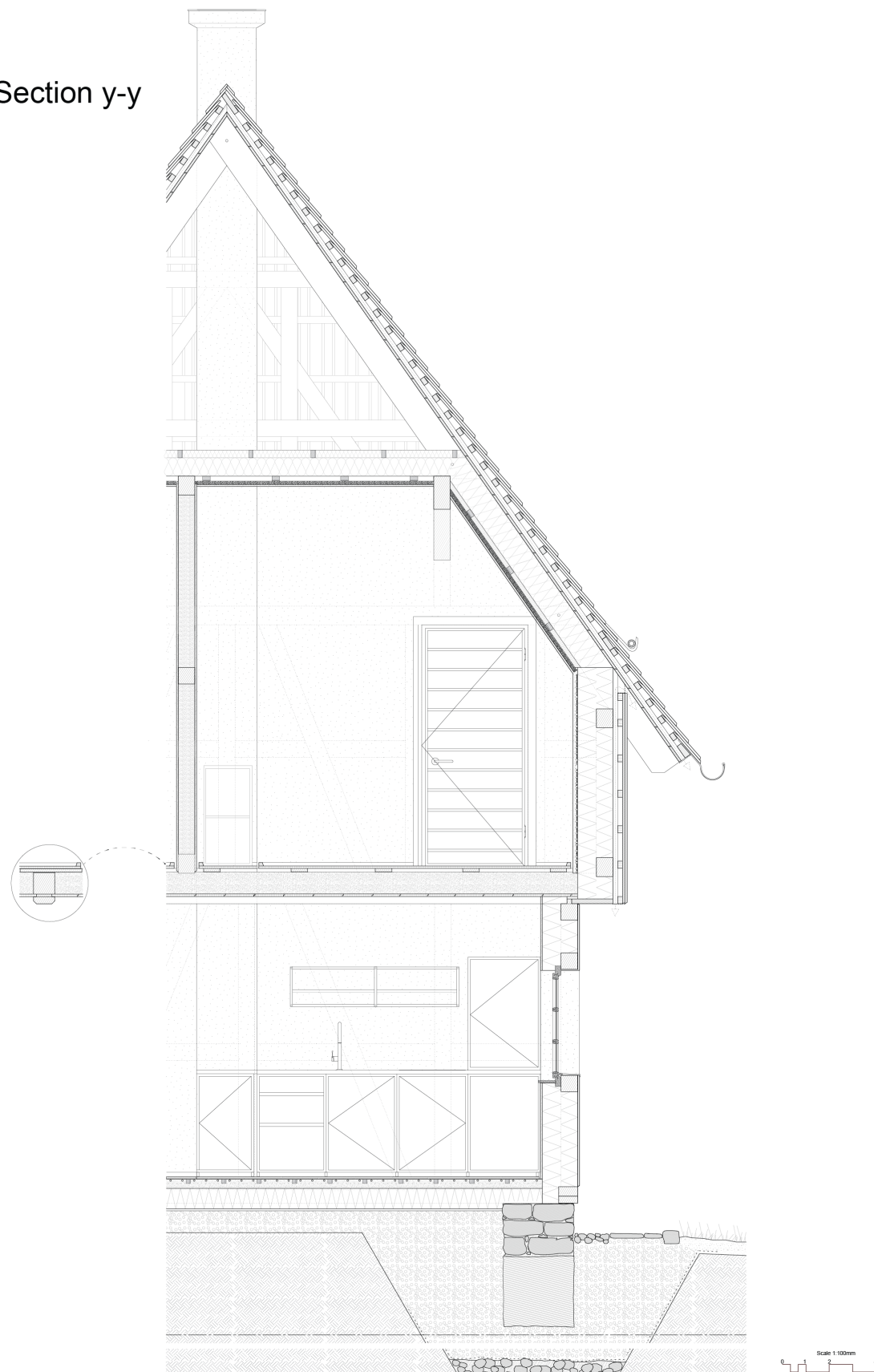


Figure 4.1 – Cross section through the building showing timber frame, hemp-lime wall and other material assembly in illustrating the layered construction system (Scale 1:100).
Source: Author's drawing based on construction documentation and field trip.

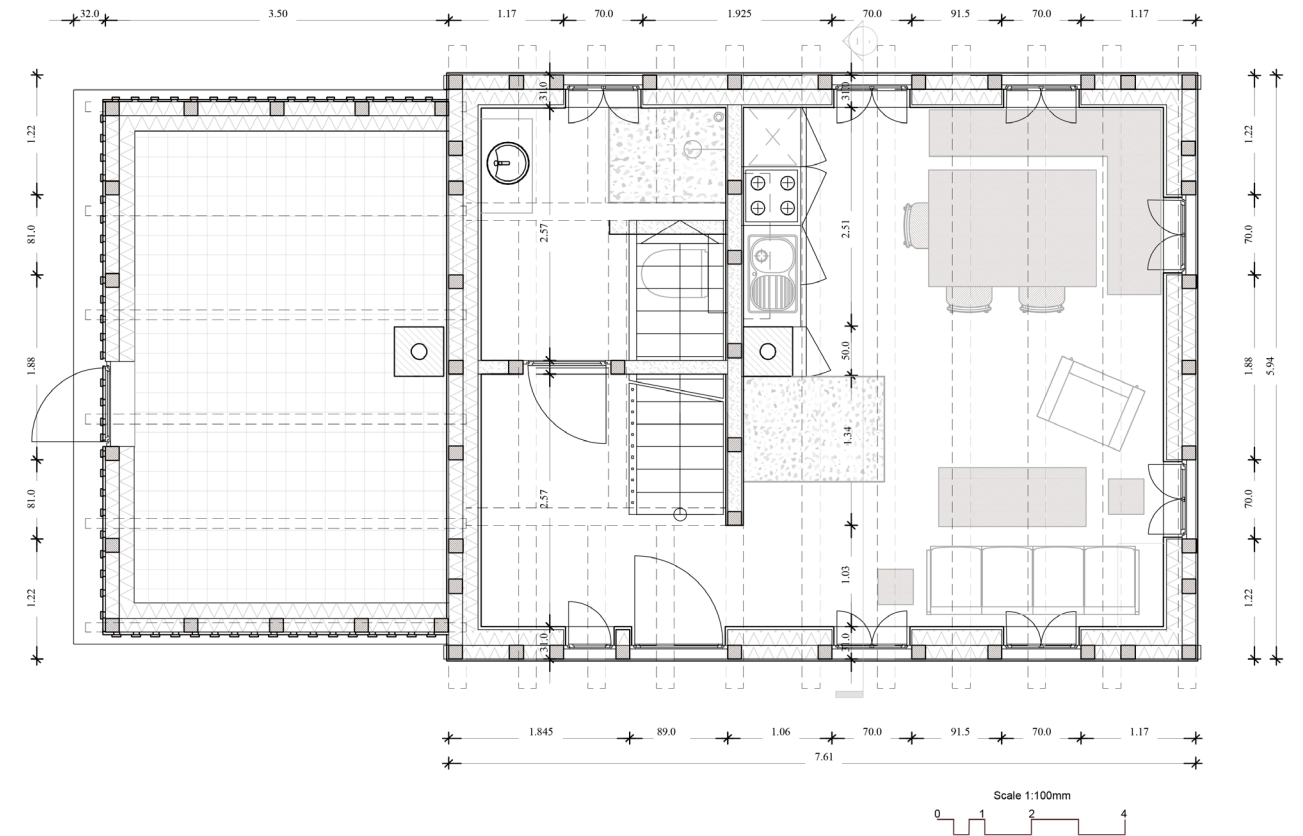


Figure 4.2 – Ground Floor Plan of Building D showing spatial organisation and timber structural grid (Scale 1:100).
Source: Author's drawing based on construction documentation and field trip.

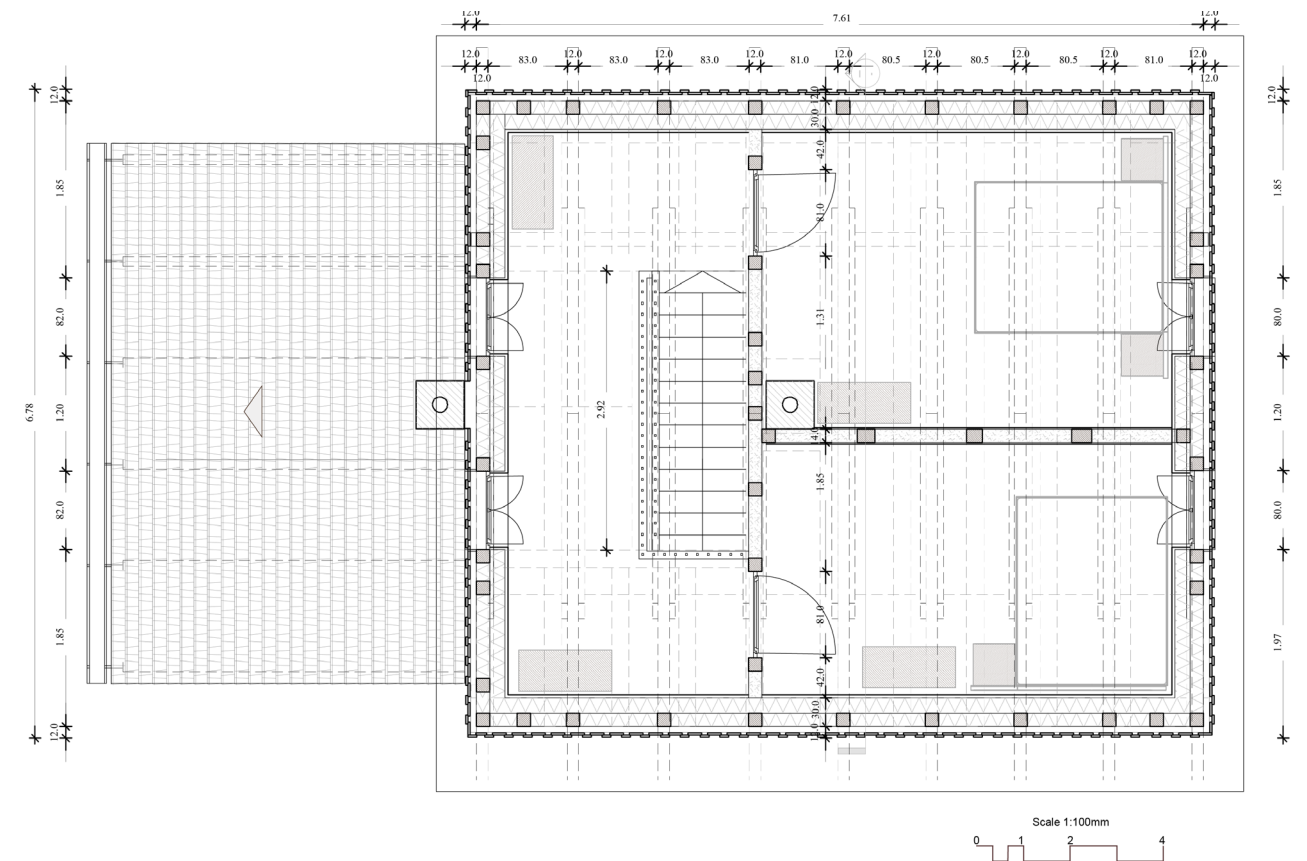


Figure 4.3 – First Floor Plan illustrating the distribution of accommodation rooms and structural grid (Scale 1:100).
Source: Author's drawing based on construction documentation and field trip.

4.3 Roof Construction Methodologies

Two roof configurations are identified within Building D’s roof construction: a warm roof and a cold roof. These configurations occur along the same roof slope, with the upper portion constructed as a cold roof and the lower portion as a warm roof. The warm roof assembly, located at the lower section of the slope, integrates larch shingles, timber battens, a continuous insulation layer composed of sheep wool, and an internal clay-based finish. This configuration provides thermal continuity and minimises heat loss while maintaining vapour permeability throughout the assembly. The sheep wool insulation, totalling 280 mm across the premium and optimal layers, offers thermal performance comparable to conventional synthetic insulation while remaining fully bio-based and reversible.

The cold roof, located at the upper section of the same slope, introduces a ventilated air cavity above the partially insulated layer, enhancing moisture management and prolonging material lifespan by allowing the evacuation of interstitial vapour. Both configurations follow traditional principles of ventilation and layering, adapted through precise dimensional control to meet contemporary thermal performance requirements. The material compositions are detailed in Figures 4.4 and 4.5, with total assembly depths of 468 mm for the warm roof and 307 mm for the cold roof respectively. The use of larch shingles as the external cladding material carries significance from both a cultural and environmental perspective. Larch is a locally available species in the Bavarian region, requiring minimal processing and offering natural durability without chemical treatment, qualities that align directly with the low embodied impact objectives of the study.

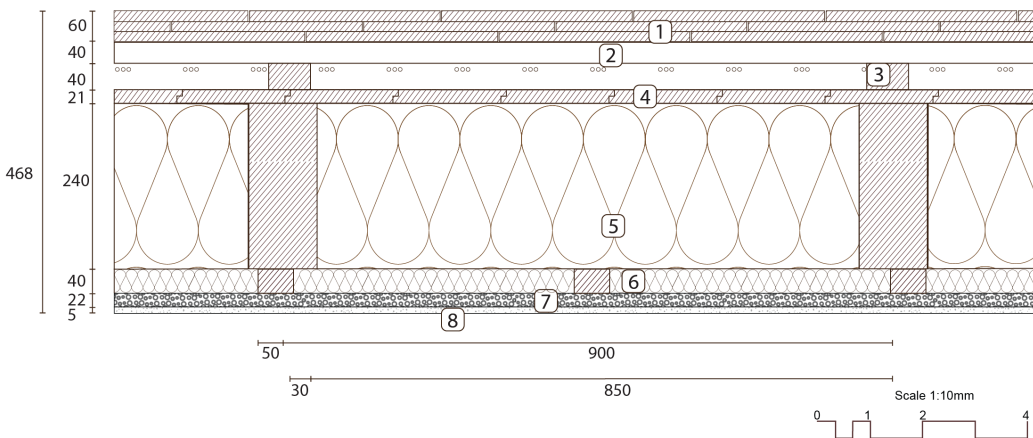


Figure 4.4 – Warm roof detail showing roof geometry and structural layout (Scale 1:10). Author’s drawing based on project documentation.

Warm roof

- ① 60 mm larch shingles (20mm x3 layers)
- ② 40 mm battens 4/6
- ③ 40 mm counter battens 4/6
- ④ 21 mm tongue/groove formwork
- ⑤ 240 mm premium sheep wool insulation
- ⑥ 40 mm optimal sheep wool insulation
- ⑦ 22 mm Claytec clay building board
- ⑧ 5 mm Clay plaster on jute mesh

468 mm

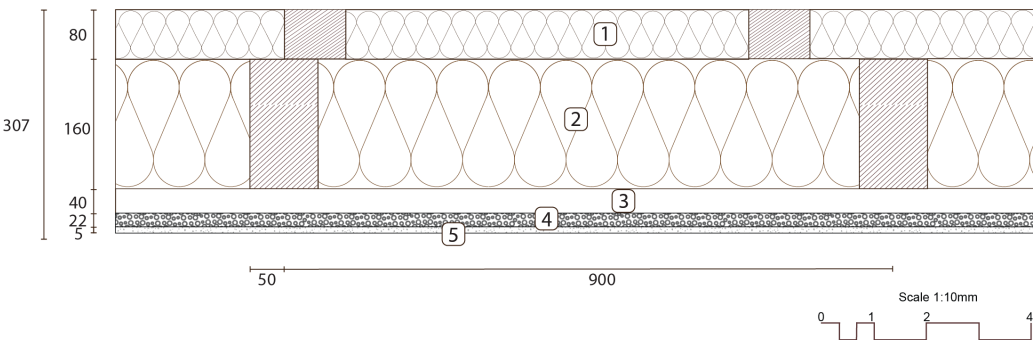


Figure 4.5 – Cold roof detail showing roof geometry and structural layout (Scale 1:10). Author’s drawing based on project documentation.

Cold roof

- ① 80 mm sheep wool
- ② 160 mm sheep wool
- ③ 40 mm air layer counter battens 4/6
- ④ 22 mm Claytec clay building board
- ⑤ 5 mm Clay plaster on jute mesh

307 mm

4.4 Wall Assemblies and Bio-based Envelopes

The external wall assemblies are designed according to principles of breathability, thermal performance, and material compatibility. While variations occur between the upper and ground floor configurations, the underlying logic remains consistent across both.

Upper-floor walls employ timber framing with hemp-lime infill, protected externally by ventilated timber cladding and internally by clay plaster. This configuration balances insulation performance with moisture buffering and avoids the use of synthetic vapour barriers, relying instead on the hygroscopic properties of the materials to regulate moisture movement through the wall section. The total assembly depth is 479 mm, as detailed in Figure 4.7.

At ground level, where exposure to moisture and thermal inertia requirements are greater, lime-based external plasters and clay internal finishes are combined with hemp-lime insulation. This assembly enhances durability and resistance to ground-level moisture while maintaining full continuity with the overall material strategy. The ground floor wall assembly reaches a total depth of 355 mm, as shown in Figure 4.6.

Hemp-lime as an infill material is particularly significant within the context of this thesis. It combines structural containment, insulation, and moisture regulation within a single bio-based system, and its use eliminates the need for separate synthetic insulation layers or vapour control membranes. Its compatibility with both lime and clay binders ensures chemical and physical coherence across all boundary conditions within the assembly.

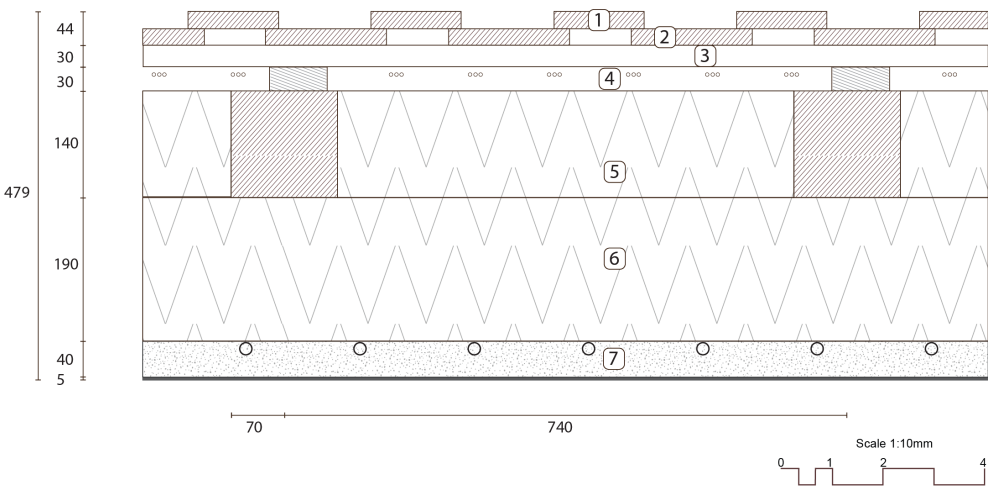


Figure 4.6 – Exterior wall detail (ground floor), showing the timber studs and hemplime infill (Scale 1:10). Author’s drawing based on project documentation.

Exterior wall, upper floor

- ① 22 mm spruce wood panels
- ② 22 mm spruce wood panels
- ③ 30 mm battens 3/6
- ④ 30 mm rear ventilation layer 3/6
- ⑤ 140 mm hemp lime
- ⑥ 190 mm hemp lime
- ⑦ 40 mm clay plaster (basecoat)
- ⑧ 5 mm clay plaster (topcoat)

479 mm

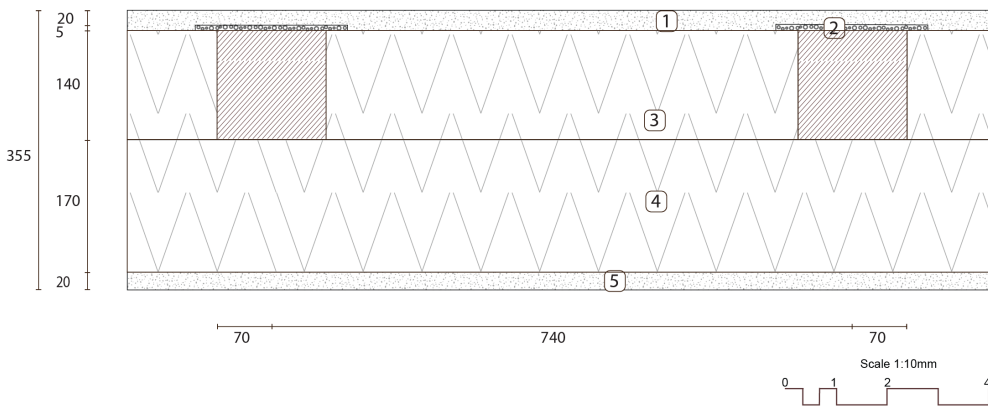


Figure 4.7 – Exterior wall detail (upper floor), showing timber studs, timber cladding, hemplime infill, and heating pipes (Scale 1:10). Author’s drawing based on project documentation.

Exterior wall, ground floor

- ① 20 mm lime render (exterior)
- ② 5 mm reed mats (on timbers)
- ③ 140 mm hemp lime
- ④ 170 mm hemp lime
- ⑤ 20 mm clay plaster (interior)

355 mm

4.5 Intermediate Floors and Acoustic–Thermal Strategy

Intermediate floor assemblies in Building D are designed to address the dual performance requirements of acoustic separation and thermal inertia, functioning as an integrated system rather than as a series of independent functional layers.

The upper floor-ceiling system combines timber joists with a multi-layer infill assembly consisting of a urethane mat for sound insulation applied directly into the joist, a 126 mm clay fill mixed with 10% lime, tongue and groove formwork, and a 70 mm air gap below the ceiling finish. This configuration achieves a total assembly depth of 294 mm, as illustrated in Figure 4.8.

The inclusion of clay-lime mass within the floor system serves two distinct functions. First, it provides acoustic separation between floors by adding mass and damping to the structural system, reducing the transmission of both impact and airborne sound. Second, the thermal mass of the clay-lime fill contributes to indoor temperature stability, absorbing heat during peak periods and releasing it gradually, thereby moderating diurnal temperature fluctuations within the occupied spaces.

The deliberate choice of dry and semi-dry construction techniques throughout the floor assembly preserves reversibility and facilitates future modification or material recovery. This approach is consistent with the broader construction philosophy of Building D, in which assemblies are designed not only for current performance but for long-term adaptability and material separability at end of life.

Upper floor

- ① 34 mm timber skirting
- ② 24 mm timber flooring
- ③ 50 mm support battens
- ④ urethane mat sound insulation (on timber joint)
- ⑤ 126 mm clay fill mixed with 10% lime
- ⑥ 24 mm tongue/groove formwork

294 mm

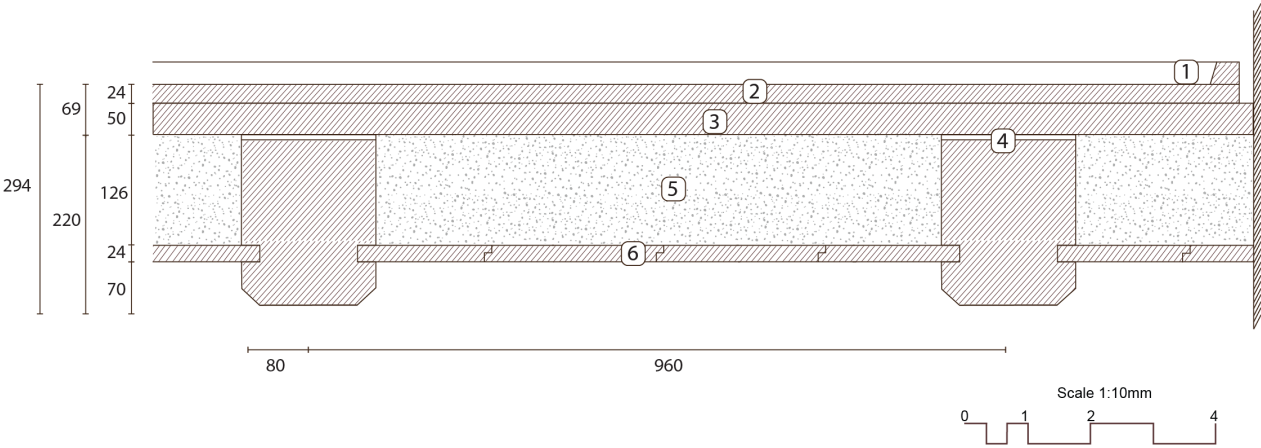


Figure 4.8 – Upper floor detail showing the layered assembly including timber joists, acoustic insulation, and ceiling finish, illustrating the integration of structural support, acoustic performance, and interior finishing within the floor–ceiling system. Author’s drawing based on project documentation.

4.6 Ground Floor

Ground floor assemblies respond to three primary design objectives: capillary moisture control, thermal insulation, and the reduction of environmental impact at the interface between the building and the ground.

In the main floor zone, the assembly consists of a 24 mm spruce timber finish over 80 mm lime screed as a heated screed layer, followed by 190 mm charcoal insulation, 20 mm lime plaster as a levelling layer, 180 mm gravel 16/32 as a drainage layer, a capillary break layer, and compacted soil substrate, giving a total assembly depth of 494 mm. The gravel layer acts as a capillary break, interrupting moisture migration from the ground into the building fabric. The biochar-enhanced insulation layer contributes to both thermal performance and carbon sequestration potential, representing a passive environmental benefit embedded within the construction assembly itself.

Entrance areas employ a differentiated assembly in which natural stone slabs, marble, basalt, or granite, replace the timber finish at the surface level, providing enhanced durability and resistance to concentrated foot traffic. The sublayers maintain full continuity with the main floor strategy, using lime plaster, bound biochar, and a gravel capillary break layer over compacted soil, for a total assembly depth of 480 mm. This differentiation reflects functional requirements without compromising the material coherence of the ground floor strategy.

The decision to use charcoal and lime rather than conventional synthetic insulation at ground floor level is methodologically significant. It demonstrates that environmental performance objectives can be achieved through material systems that are historically rooted, locally available, and chemically compatible with the broader assembly strategy.

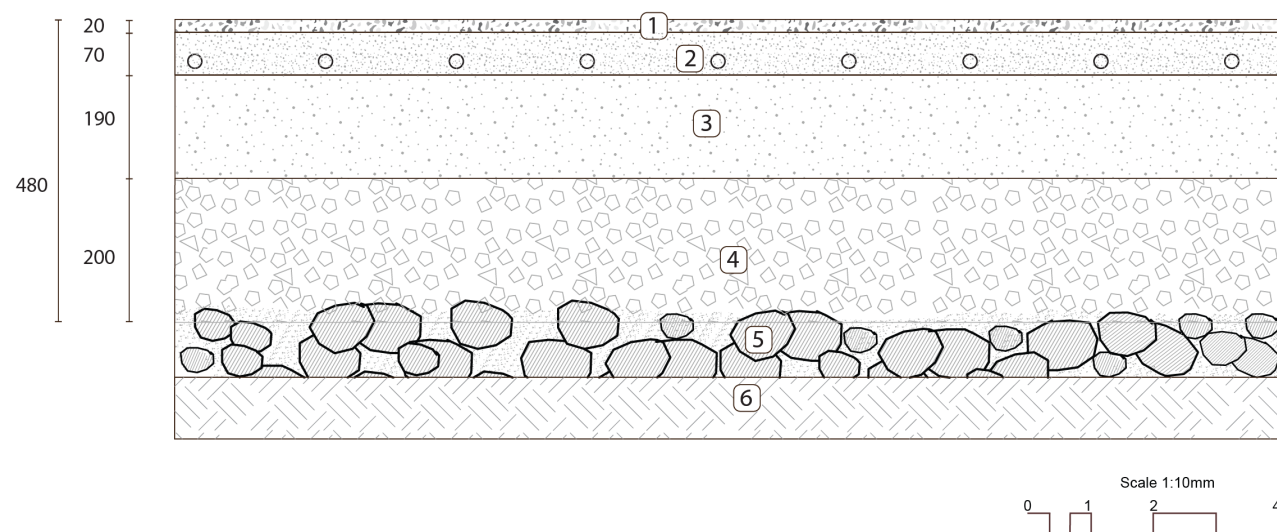


Figure 4.9 – Detail of the entrance floor construction composed of natural stone slabs, lime plaster bedding, bound biochar insulation layer, gravel capillary break layer, and compacted soil substrate. Author's drawing based on project documentation.

Ground Floor Entrance, (LimeCoal+Lime+Granite)

- ① 20 mm natural stone slabs (granite)
- ② 70 mm lime screed
- ③ 190 mm charcoal (bound biochar)
- ④ 20 mm lime mortar
- ⑤ 200 mm gravel 16/32
- ⑥ Capillary break layer
- ⑥ soil

480 mm

Ground floor

- ① 24 mm spruce timber finish
- ② 80 mm lime screed as heated screed
- ③ 190 mm charcoal
- ④ 20 mm lime mortar
- ⑤ 180 mm gravel 16/32
- ⑥ Capillary break layer
- ⑦ soil

494 mm

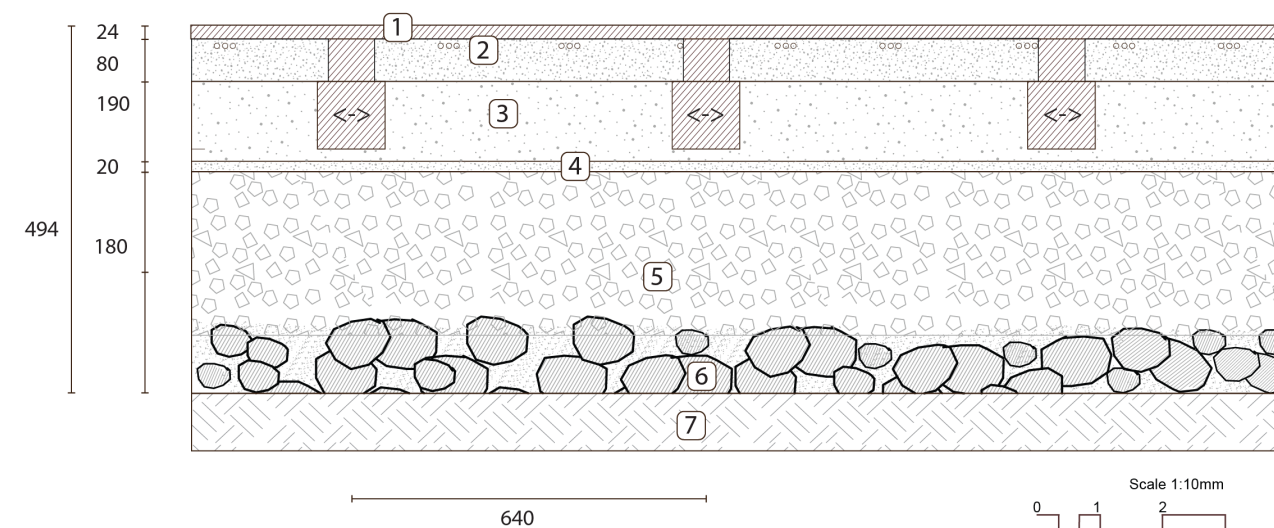


Figure 4.10 – Construction detail of the ground floor assembly consisting of spruce timber flooring, lime screed heating layer, charcoal insulation layer, lime plaster levelling layer, gravel drainage layer, capillary break layer, and compacted soil substrate. Author's drawing based on project documentation.

4.7 Material Cycles and Binder Behaviour as Methodological Tools

A defining methodological component of this thesis is the explicit treatment of material transformation processes, particularly mineral binders. Rather than addressing binders as static materials with fixed properties, they are understood here as dynamic systems whose production conditions, in-use behaviour, and end-of-life characteristics fundamentally affect both construction practice and environmental performance.

Air-lime cycle is analysed here through its complete material transformation, beginning with limestone (calcium carbonate), progressing through calcination to quicklime at approximately 1000 degrees Celsius, hydration to slaked lime, and ultimately returning to a limestone-like state through the process of carbonation. This reversible cycle, illustrated in Figure 4.11, allows air-lime-based materials to

reabsorb carbon dioxide during their service life, distinguishing them from cementitious binders and introducing a time-dependent carbon dynamic that has direct implications for LCA system boundary definition.

The methodological significance of this cycle extends beyond its carbon implications. Lime-based mortars and plasters require lower firing temperatures than Portland cement, remain chemically compatible with timber, straw, and hemp, and allow for repair and reworking without requiring full material replacement. These properties reinforce the coherence of the overall construction system and reduce the likelihood of premature material failure or incompatibility-driven deterioration over the building's service life.

In parallel, the behaviour of hydraulic binders is also examined here through a comparative graph relating clay content, firing temperature, and resulting hydraulicity.

As illustrated in Figure 4.12, increasing clay content and higher firing temperatures shift binders progressively from air-lime behaviour toward natural hydraulic lime (NHL 2, NHL 3.5 to NHL 5), Building cement and ultimately Portland cement. While this transition increases early strength and setting speed, it also results in higher embodied energy, reduced reversibility, and declining compatibility with bio-based materials.

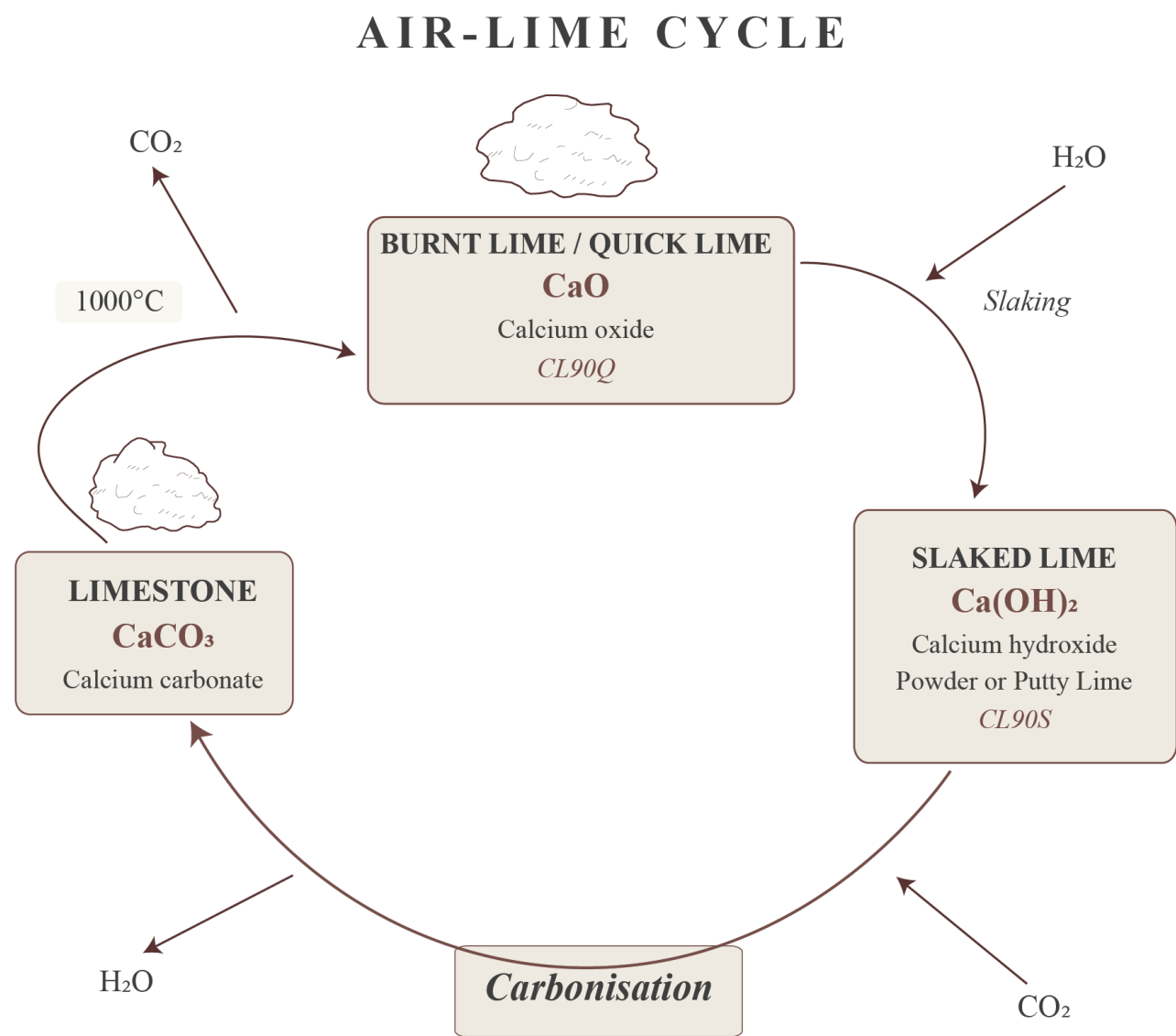


Figure 4.11 – Schematic representation of the Air-Lime Cycle illustrating the conversion of limestone into reactive burnt lime, its hydration into slaked lime, and the eventual re-absorption of CO₂ to return to limestone. This process operates on a closed-loop, low-energy cycle. Author's illustration from site visit.

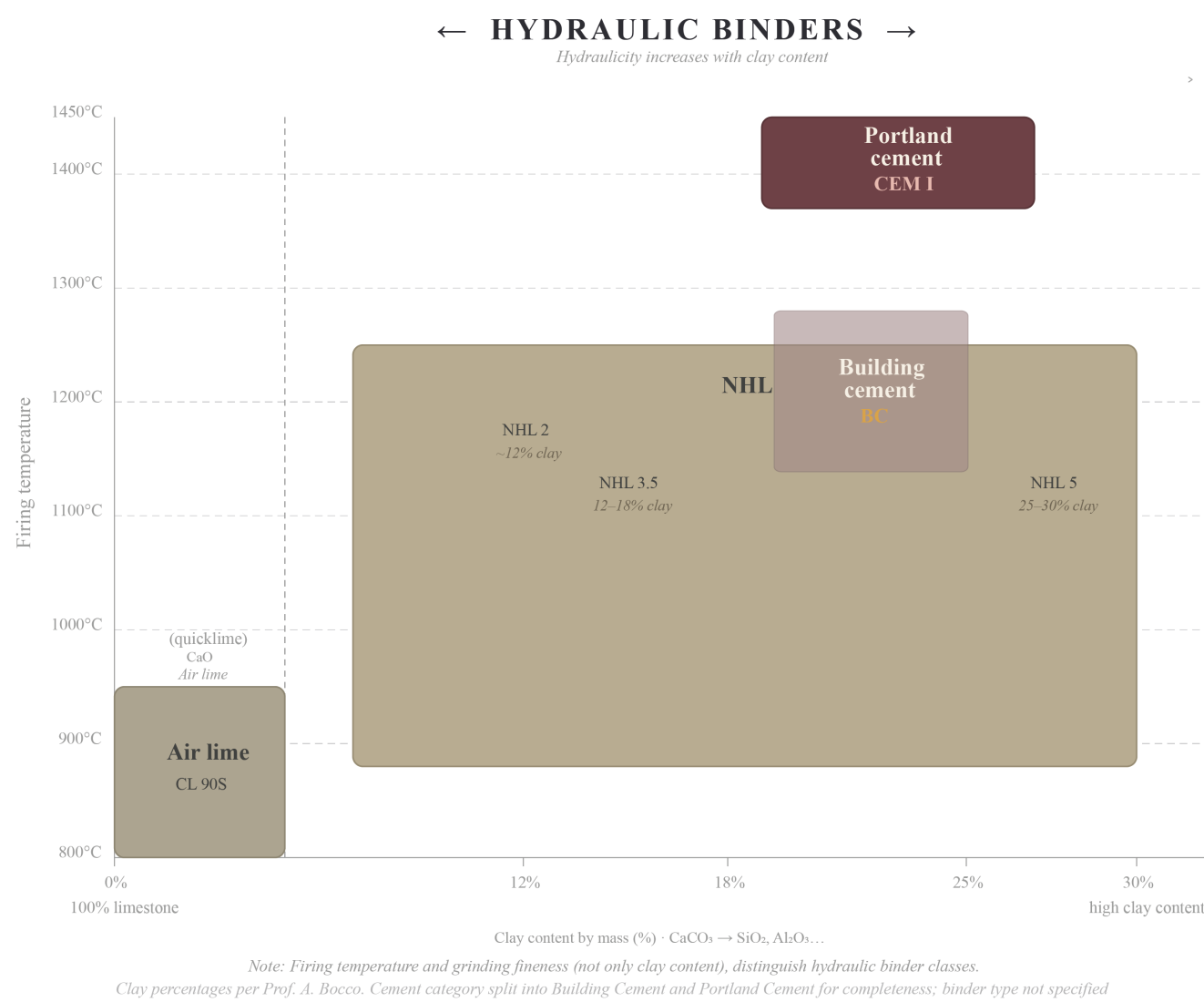


Figure 4.12 – Graphical representation of hydraulic binders illustrating the different heating degrees of limestone into portland cement, and the different output based on the clay content. Author's illustration.

By situating material cycles and binder behaviour at the methodological level, this thesis establishes further clarity for defining the LCA system boundaries developed in Chapter 5. Cementitious binders are therefore treated as environmentally and functionally distinct from lime-based systems in the quantitative analysis that follows, and the carbonation credit associated with air-lime materials is acknowledged as a relevant, if methodologically complex, factor in the overall environmental accounting. As Chastas et al. (2016) note, the embodied energy and embodied

carbon associated with material extraction, production, transport, and construction constitute an increasingly significant share of a building's total life-cycle emissions, a finding that directly motivates the quantitative analysis presented next.

Chapter 5

Life Cycle Assessment: Methodology and Results

5.1 LCA Scope, Functional Unit, and System Boundary

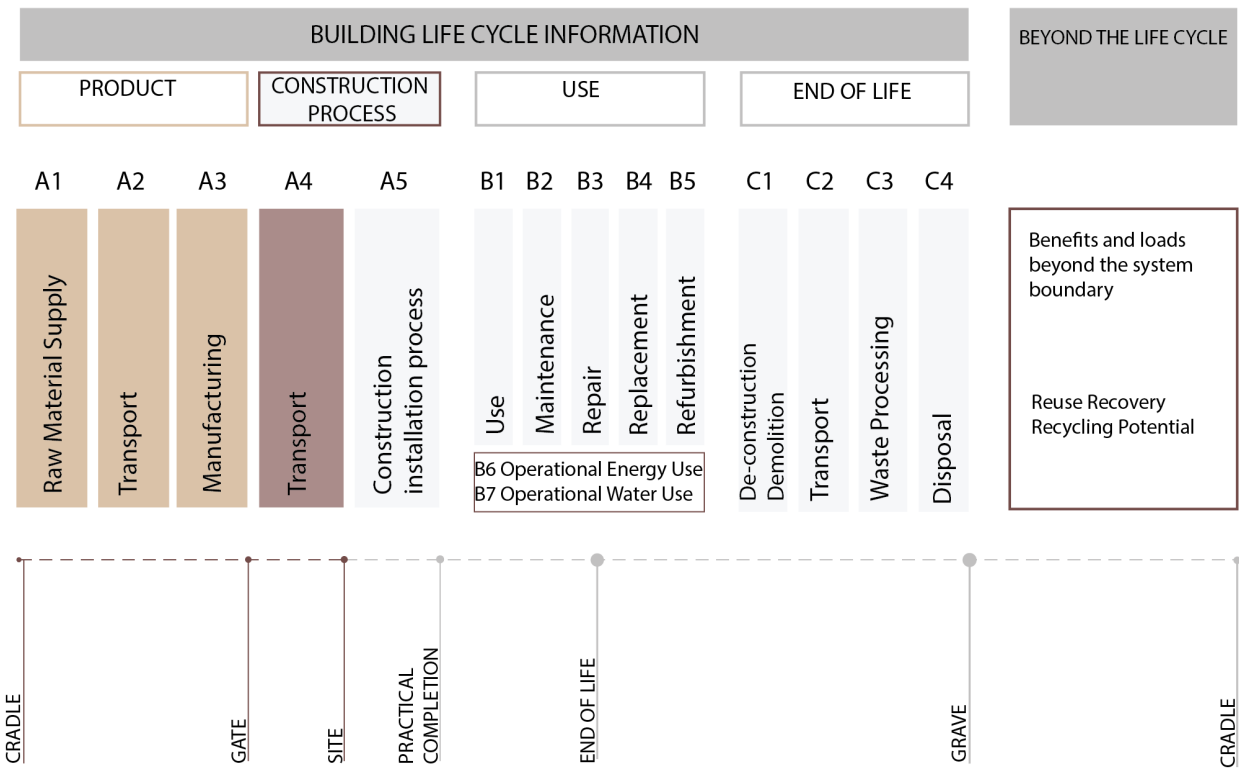


Figure 5.1 – Building life cycle stages according to EN 15978, illustrating the modular structure used for Life Cycle Assessment of buildings. The framework distinguishes product stage (A1–A3), construction process stage (A4–A5), use stage (B1–B7), end-of-life stage (C1–C4), and benefits and loads beyond the system boundary (Module D). Adapted from EN 15978. Source: Author’s illustration.

The LCA is conducted in accordance with the ISO 14040 and ISO 14044 standards, and follows the building-level framework defined by EN 15978. The assessment focuses on the early life cycle stages of the building, specifically modules A1–A4, which encompass raw material supply, manufacturing, and the transport of materials to the construction site. Module A5, covering on-site construction processes, was excluded from the assessment due to the unavailability of site-level data including construction

energy consumption, waste volumes, and disposal routes from the contractors at the time of data collection.

5.1.1 Goal of the Assessment

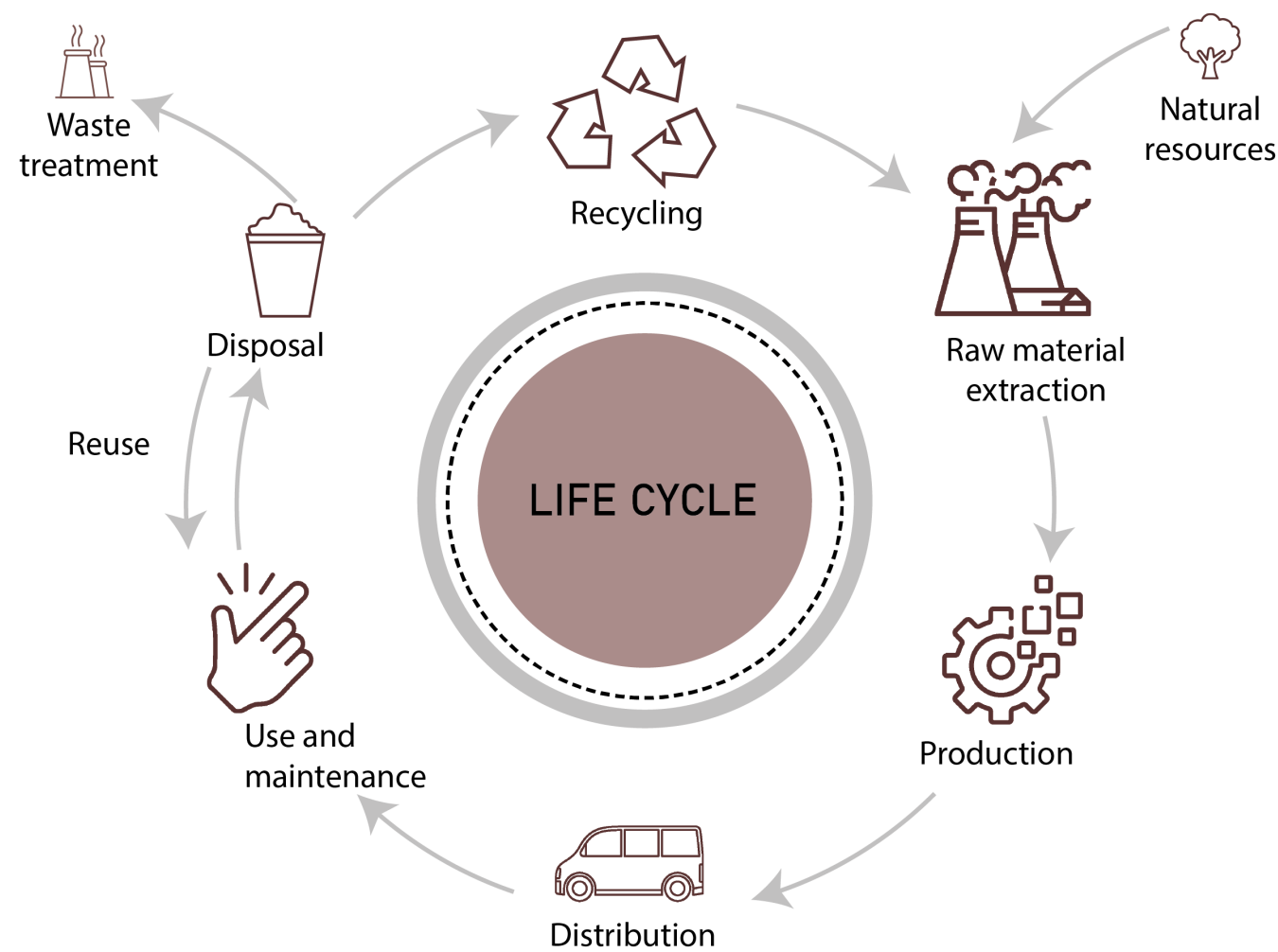


Figure 5.2 – Schematic representation illustrating the main stages of a product life cycle, from resource extraction to production, distribution, use, disposal, reuse, waste treatment and recycling. Source: Author’s diagram.

The primary goal of the assessment is to quantify the embodied environmental impacts associated with the construction of Building D, and to evaluate how material choices, construction techniques, and sourcing strategies influence overall performance.

More specifically, the LCA aims to:

- assess the embodied carbon and embodied energy of the building;

- identify the most impactful construction components and materials;
- evaluate the contribution of bio-based materials to impact reduction and carbon storage;
- verify, through quantitative evidence, the applicability of the “vernacular architecture of the 21st century” criteria in a real-scale contemporary project.

5.1.2 Functional Unit

The functional unit of the assessment is defined as:

One complete constructed residential unit (Building D) of the Naturdorf Bärnau village, at the point of practical completion.

The functional unit includes all permanent construction elements required for the building to be structurally complete and weathertight. This definition allows the assessment to remain directly linked to the as-built condition and to the architectural drawings used for quantity take-off. Temporary construction elements, tools, and equipment are excluded unless they result in permanent material incorporation. Results are expressed primarily in absolute terms relative to this functional unit. For comparability with other studies, supplementary functional units are also reported: embodied carbon per square metre of Gross Internal Area (Building D has a GIA of 76.638 m², calculated as the sum of the upper floor area and ground floor area based on the architectural drawings) and per tonne of building weight.

5.1.3 Reference Study Period

Given that the building has only recently entered its operational phase, the assessment does not include a full operational life cycle analysis. The study therefore focuses on embodied impacts up to completion. A reference study period is not applied in this phase of the research. Future extensions to construction and installation processes (A5) or operational modules (B1–B7) may be considered in subsequent studies once sufficient (performance) data becomes available.

5.1.4 System Boundary

The system boundary of the assessment is defined as cradle-to-gate with transport, corresponding to life cycle modules A1–A4 as defined in EN 15978.

The included modules are:

- A1 – Raw material supply: extraction and initial processing of materials;
- A2 – Transport to manufacturer: transportation of raw materials to production facilities;
- A3 – Manufacturing: production of construction materials and components;
- A4 – Transport to site: delivery of materials from manufacturers and suppliers to the construction site.

The system boundary explicitly excludes:

- A5 – Construction and installation: on-site construction processes were not included due to the unavailability of site-level records (construction energy consumption, waste volumes, and disposal routes) from the contractors at the time of analysis. This limitation is declared in accordance with EN 15978 reporting requirements;
- use phase impacts (B modules);
- maintenance, repair, or replacement activities;
- end-of-life processes (C modules);
- benefits beyond the system boundary (module D), except where biogenic carbon storage is discussed qualitatively.

The choice to limit the assessment to modules A1–A4 reflects the research focus on material choice, sourcing, and construction methodology, which are central to vernacular and bio-based architectural strategies. The declared exclusion of A5 does not undermine the validity of the assessment, as production-stage impacts represent the dominant share of embodied carbon in bio-based construction.

5.1.5 Biogenic Carbon Considerations

Given the extensive use of bio-based materials such as timber and hemp, biogenic carbon storage plays a significant role in the environmental profile of Building D. The accounting of biogenic carbon follows the principles outlined in EN 16449, allowing stored biogenic CO₂ to be reported separately from fossil emissions. Biogenic carbon storage is calculated based on material quantities and carbon content, and is presented alongside embodied impact results to provide a more comprehensive understanding of the building’s climate performance.

5.1.6 Limitations of Scope

By focusing on modules A1–A4, the assessment does not capture long-term operational performance, durability, or end-of-life scenarios. The absence of A5 data represents the principal methodological limitation; however, its exclusion is documented and its potential significance discussed in the interpretation sections. These constraints are consistent with the exploratory and construction-focused nature of the thesis and align with the availability of verified data at the time of writing.

Having defined the scope, functional unit, and system boundary of the assessment, the following section details the quantity take-off methodology and inventory modelling process adopted to translate architectural drawings and construction information into a structured LCA input model.

5.2 Quantity Take-Off and Inventory Modelling Method

The Life Cycle Assessment of Building D is based on a detailed material quantity take-off derived from architectural drawings and verified construction documentation. The accuracy of the assessment depends directly on the reliability of this inventory phase, which translates the built geometry and construction logic into quantifiable material inputs.

The quantity take-off was conducted using as-built architectural drawings, including plans, sections, and construction details. All quantities were calculated manually and organised into a structured spreadsheet provided by my thesis instructor as part of the academic framework for this research (Mazelli, 2025a, 2025b).

5.2.1 Source of Quantities and Drawing Reference

Material quantities were derived from the following sources:

- site plan and building footprint dimensions;
- full building sections;
- detailed section call-outs illustrating wall, floor, and roof build-ups;
- construction notes describing material thicknesses and assembly logic.

Where applicable, dimensions were cross-checked across multiple drawings to ensure consistency. Construction layers were identified individually rather than aggregated, allowing each material to be associated with an appropriate environmental dataset. This approach ensures that the inventory reflects the actual construction logic, rather than simplified or assumed assemblies. Where drawing information was incomplete or ambiguous, quantities and construction details were verified through on-site observation during a site visit to Naturdorf Bärnau and subsequent questions posed to Andreas Mann.

5.2.2 Inventory Structure and Spreadsheet Logic

The material inventory was organised in a structured spreadsheet framework provided by the thesis instructor. This structure follows a component-based logic, grouping materials according to their role within the building system rather than by supplier or trade.

Each entry in the inventory includes:

- material description and product reference;
- material class (e.g. timber, concrete, earth, glass) and material category (bio-based, other natural, other);
- geometric dimensions (length, width, height or diameter, and number of elements);
- calculated volume (m³) and material-specific density (kg/m³ or kg/m²);
- derived weight (kg);

- environmental impact factors from ÖKOBAUDAT (PERT, PENRT, EE in MJ/m³; GWP fossil in kgCO₂eq/m³);
- total impact per flow (unit factor × material volume);
- notes on assumptions, construction-specific considerations, and dataset references.

The predefined headings, dataset codes, and calculation logic of the spreadsheet were retained without modification, ensuring methodological consistency with the academic framework (Mazelli, 2025a, 2025b).

5.2.3 Material Grouping and Level of Detail

Materials were grouped according to major construction elements: foundations and ground interface; structural timber frame; wall infill and insulation systems; floor and roof assemblies; and internal and external finishes. This level of disaggregation allows the contribution of individual systems to total environmental impacts to be identified and discussed. In particular, it enables the isolation of high-impact elements and the evaluation of bio-based materials as carbon-storing components. Construction losses were accounted for where relevant, following information and available documents from the site and standard assumptions embedded within the spreadsheet methodology.

5.2.4 Treatment of Bio-Based Materials

Bio-based materials such as timber and hemp-based products were inventoried using mass- or volume-based quantities consistent with available datasets. Their biogenic carbon content was recorded separately from fossil emissions, following EN 16449 principles. This distinction ensures that carbon storage effects are not conflated with embodied emissions and allows for transparent reporting in later sections of the assessment.

5.2.5 Localness and Transport Distances

Transport distances associated with material delivery to site (A4) were calculated based on known supplier locations and site access routes. Where exact distances were unavailable, conservative estimates were adopted and clearly noted in the inventory. Materials sourced directly on site, specifically excavated clay and cocciopesto, were assigned a transport distance of zero kilometres, as no road transport was required for these elements. Transport assumptions were applied consistently across materials to avoid bias and to maintain comparability within the assessment.

5.2.6 Inventory Validation and Limitations

The inventory represents the most accurate information of the as-built condition based on available documentation and site knowledge. However, minor uncertainties remain unavoidable, particularly regarding construction losses or exact transport distances. The structure of the inventory allows such uncertainties to be identified and discussed explicitly. Any discrepancies in quantities are treated as call

for sensitivity and interpretation, rather than as methodological flaws.

Having established the quantity take-off methodology and inventory structure, the following section describes the mapping of materials to environmental datasets, with particular reference to the Ökobaudat database used for impact calculation.

5.3 Material Inventory and Dataset Mapping (Ökobaudat)

Following the completion of the quantity take-off and inventory structuring described in Section 5.2, each material entry was systematically mapped to an environmental dataset to enable Life Cycle Impact Assessment.

5.3.1 Dataset Selection Criteria

Environmental impact data were primarily retrieved from the German national database ÖKOBAUDAT (2024 edition). The database was selected for the following reasons:

- geographic relevance to the German context of the case study;
- compliance with EN 15804 and EN 15978 standards;
- transparency in impact category reporting, including separate disclosure of GWP fossil, GWP biogenic, PERT, and PENRT;
- coverage of bio-based and earth-based materials, which are central to this assessment.

- compatability with OpenLCA modelling and free access.

Where multiple datasets were available for a given material category, the following hierarchy was applied:

- (1) German production datasets;
- (2) European average datasets;
- (3) generic mineral or timber datasets with clearly defined system boundaries.

This approach ensured consistency while maintaining alignment with the geographical context of the project.

5.3.2 Dataset Matching and Material Categorisation

Each inventoried material was matched individually to the most representative available dataset. Mapping was performed at the material level rather than at assembly level, enabling disaggregation of impacts by material category. The principal categories included:

- lime-based binders: air lime, natural hydraulic lime (NHL5), lime mortar, lime screed, and lime plaster;
- timber: softwood framing elements, battens, beams, cladding boards, and timber shingles;
- bio-based insulation: sheep wool insulation panels and hemplime (hemp shiv + lime binder);
- earth-based materials: clay plasters, compressed earth partition elements, and clay boards;

- minerals: gravel layers, crushed stone backfill, and granite foundation elements;

- glazing elements: flat glass datasets applied per m² of glazed area.

Where no exact dataset was available - e.g sheepwool; a conservative proxy with similar production characteristics was selected. All such proxies were documented within the inventory spreadsheet to ensure traceability.

5.3.3 Treatment of Units and Functional Quantities

Datasets in ÖKOBAUDAT are reported per cubic metre (m³) in the majority of cases, with some materials referenced per kilogram (kg) or per square metre (m²). To ensure dimensional consistency, all material quantities were expressed in units compatible with the selected dataset before impact multiplication. Impact per flow was calculated as:

Impact per flow = Material volume (m³) × Impact per functional unit (per m³)

The resulting values were aggregated per material and subsequently per material category to produce the results presented in Section 5.4.

5.3.4 Transport (A4)

Transport impacts were calculated separately from production datasets for each material group according to the following formula:

Transport impact = Material mass (kg) × Distance (km) × Emission factor (kgCO₂e/kg)

Distances were derived from confirmed supplier locations and conservative routing assumptions. Materials were grouped by transport code into delivery batches reflecting actual logistics. This separation ensured transparency between production impacts (A1–A3) and site delivery impacts (A4).

5.3.5 Data Consistency and Uncertainty Management

Where geometric ambiguity occurred, elements were modelled conservatively to avoid underestimation of embodied impacts. Construction losses were included where applicable following spreadsheet framework assumptions. Given the reliance on secondary environmental datasets, uncertainties related to regional production variability and energy mix remain inherent to the assessment. However, consistent dataset application across all materials ensures internal comparability of results.

5.4 Impact Calculation Workflow (A1–A4)

This section describes the calculation procedure and presents the quantified embodied carbon and embodied energy results for Building D across modules A1–A4.

5.4.1 Calculation Structure

The impact calculation followed a bottom-up aggregation approach structured in four steps:

- (1) material volumes were derived from geometric modelling and quantity take-off;
- (2) volumes were converted to mass using density values from the ÖKOBAUDAT datasets or technical specifications;
- (3) environmental impact factors (expressed per m³ of material) were applied to obtain impact per flow for each material entry;
- (4) impacts were aggregated by material category and life cycle stage. All calculations were implemented within the structured spreadsheet model aligned with EN 15978 module logic.

5.4.2 Total Embodied Carbon (A1–A4)

The embodied carbon (GWP fossil) of Building D was calculated separately for each life cycle module. The production stage (A1–A3) encompasses raw material extraction, transport to manufacturer, and manufacturing processes. The transport stage (A4) accounts for the delivery of all materials from suppliers to the construction site in Naturdorf Bärnau.

The results are as follows in Table 5.1. When normalised by the building area (76.64 m².), the results are:

- A1–A3: 257.29 kgCO₂e/m²
- A4: 10.31 kgCO₂e/m²
- A1–A4 Total: 267.60 kgCO₂e/m²

Table 5.1 — Embodied Carbon by Life Cycle Stage (A1–A4)

Life Cycle Stage	Impact (kgCO ₂ e)	Share (%)
A1–A3 Production	19,718.39	96.15
A4 Transport	789.80	3.85
Total A1–A4	20,508.19	100.00

Values normalised to gross floor area (76.64 m²) correspond to 267.60 kgCO₂e/m². Source: Author’s calculation based on ÖKO-BAUDAT 2024 datasets and contractor’s information.

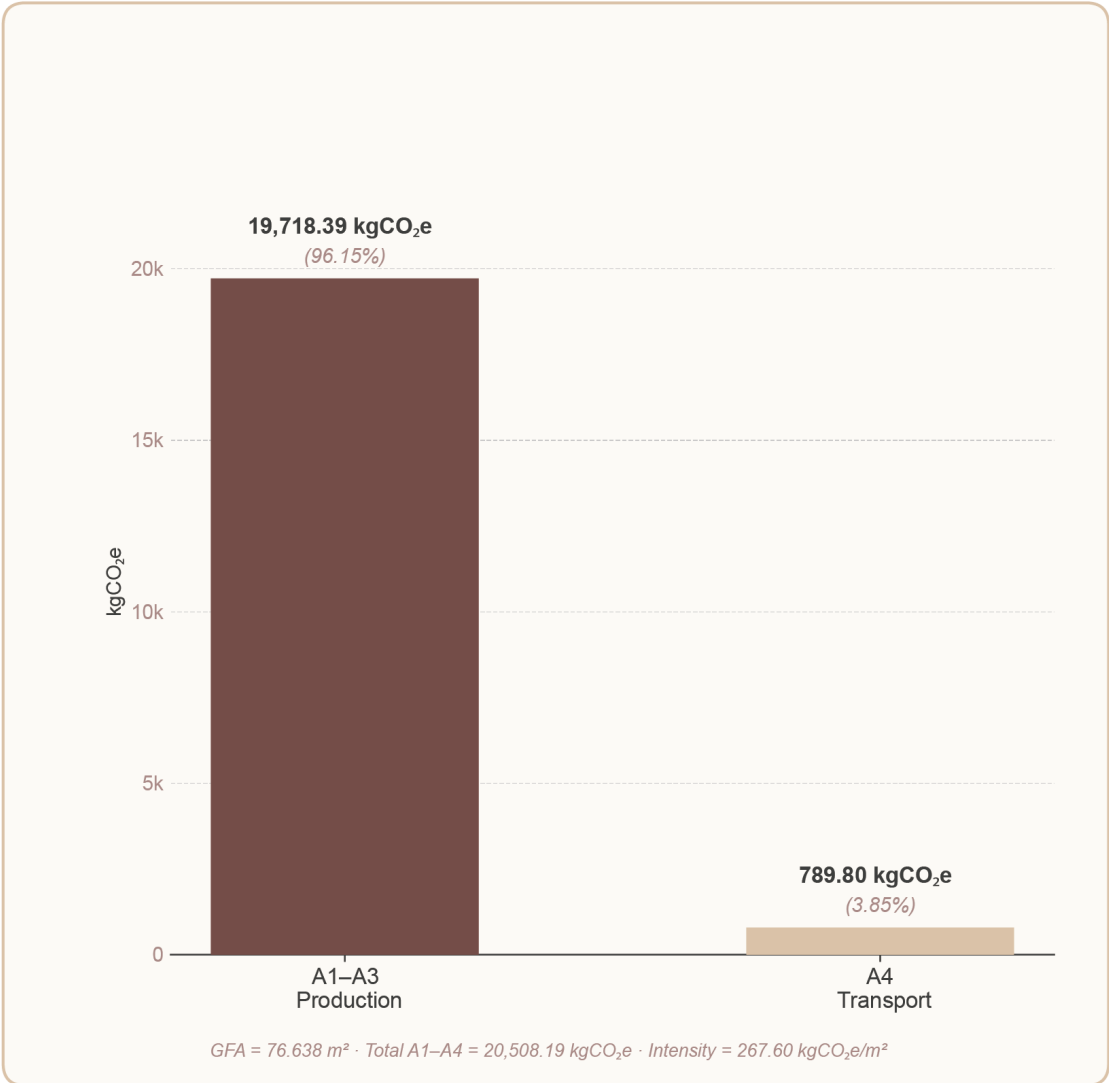


Figure 5.3 – Distribution of embodied carbon across life cycle stages A1–A4 for Building D. The product stage (A1–A3) accounts for the dominant share of total emissions, while transport to site (A4) contributes a minor fraction. Source: Author’s illustration from analysis.

5.4.3 Contribution by Life Cycle Stage

Material production (A1–A3) accounts for 96.15% of total embodied carbon, while transport to site (A4) accounts for the remaining 3.85%. This distribution confirms that production-stage impacts dominate the environmental profile of the building. The modest A4 contribution reflects the geographically concentrated sourcing strategy, with the majority of materials procured from regional suppliers within a radius compatible with local construction practice. This result is discussed further in Section 5.5.6.

5.4.4 Contribution by Material Category (A1–A3)

Disaggregation of production-stage impacts by material category reveals a clear hierarchy of environmental contribution. Lime-based materials account for the largest share at 60.05%, attributable to the calcination process inherent in binder production, while the remaining categories each contribute below at their various percentages as show below.

This distribution is consistent with the material logic of Building D: a hybrid bio-mineral system in which timber provides structural performance, sheep wool and hemp shiv as bio-based insulation, while lime-based binders serve as the principal binding medium in wall assemblies, foundation layers, and surface finishes.

Table 5.2 — Embodied Carbon by Material Category (A1–A3)

Material Category	Impact (kgCO ₂ e)	Share (%)
Lime-based materials	11,840.23	60.05
Timber elements	4,945.80	25.08
Stone / Aggregates	1,268.68	6.43
Earth-based materials	718.29	3.64
Glass	181.81	0.92
Sheep wool	400.11	2.03
Hemp shiv	363.48	1.84
Total A1–A3	19,149.63	100.00

Source: Author’s calculation based on ÖKOBAUDAT 2024 datasets and contractor’s information. Figure 5.4 – Contribution of material categories to A1–A3 embodied carbon for Building D. Lime-based materials account for the largest share, followed by timber. All other categories contribute below 7% individually.

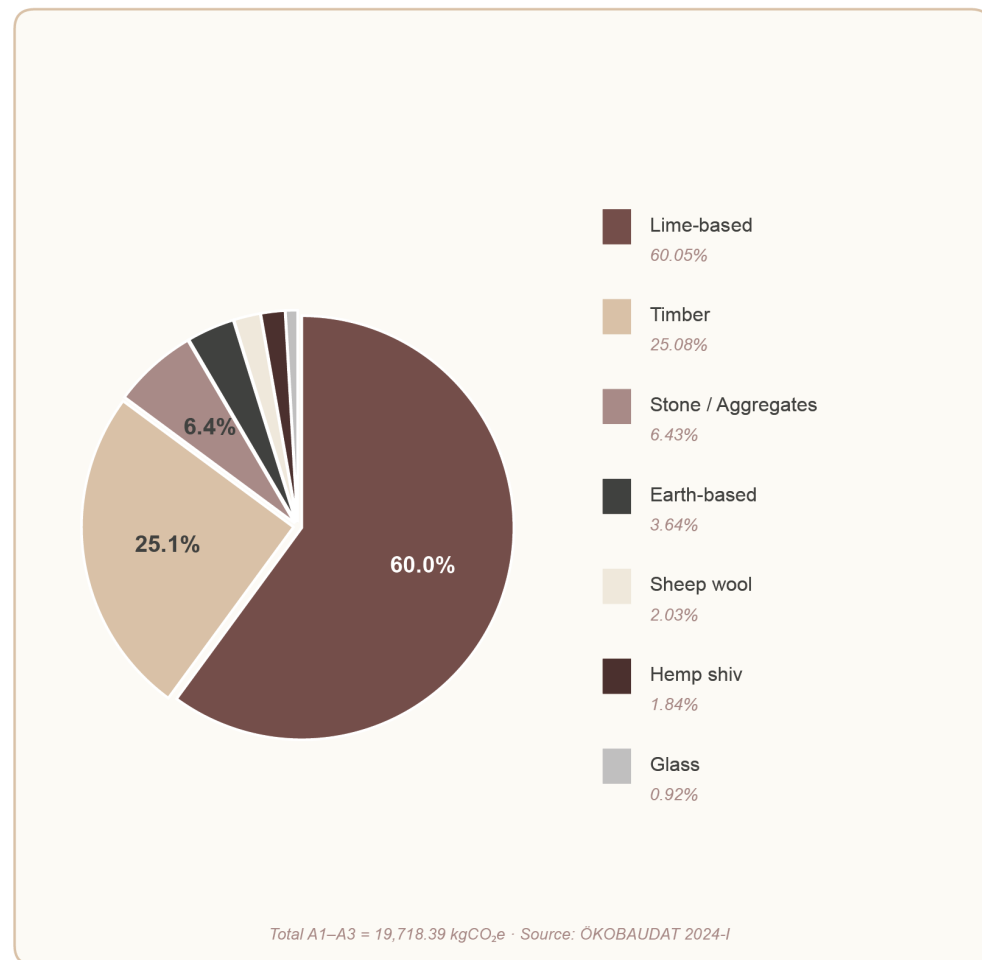


Figure 5.4 – Contribution of material categories to A1–A3 embodied carbon for Building D. Lime-based materials account for the largest share, followed by timber. All other categories contribute below 7% individually.
Source: Author's illustration from analysis.

5.4.5 Embodied Energy Results (A1–A3)

In addition to embodied carbon, total primary energy demand was assessed for the production stage (A1–A3). The assessment distinguishes between renewable primary energy (PERT) and non-renewable primary energy (PENRT), with the sum constituting total embodied energy (EE). This disaggregation follows the reporting framework of EN 15804 and the ÖKOBAUDAT indicator structure.

The results for modules A1–A3 are:

- PERT (Renewable Primary Energy): 359,404 MJ (4,690 MJ/m²)
- PENRT (Non-Renewable Primary Energy): 144,616 MJ (1,887 MJ/m²)
- Total Embodied Energy (EE = PERT + PENRT): 504,020 MJ (6,577 MJ/m²)

The high share of renewable primary energy (approximately 71% of total EE) reflects the dominance of timber in the material inventory. Timber, as a bio-based product, carries a high PERT value because the energy stored within the wood biomass is accounted for as renewable primary energy for material use (PERM) within the ÖKOBAUDAT framework. This does not represent energy consumed in manufacturing, but energy embodied in the material itself as a renewable resource.

The non-renewable primary energy share (PENRT = 1,887 MJ/m²) reflects the fossil energy consumed across production processes, particularly lime calcination, transport, and the manufacturing of glass and metal components. This indicator provides a complementary perspective to embodied carbon and reinforces the observation that mineral binders represent the principal source of fossil energy demand in the building.

5.5 Results, Material Contribution and Key Impact Drivers

Rather than treating embodied carbon as an isolated technical metric, this section interprets the results in relation to material logic, sourcing strategy, and construction methodology.

5.5.1 Dominance of Lime-Based Materials

Despite the lower firing temperature of lime compared to Portland cement, lime remains a mineral binder with inherent embodied carbon intensity.

Therefore, lime in Building D is used as a structural bulk material in the manner of reinforced concrete;

it also functions as a binder in hemplime infill, in lime mortars and renders, and in screed layers.

Its environmental burden is therefore structurally integrated with a broader bio-based system. From the perspective of Bocco and Habert's framework, the high proportion of lime does not contradict vernacular principles. Instead, it reflects the continued reliance on mineral binders historically embedded in regional construction traditions. The question becomes not whether lime is impact-free, but whether its use is proportionate, compatible, and contextually coherent — which appears to be the case here.

This choice is rooted in the cultural and historical premise underlying the wider Bärnau project: the adjacent Bärnau-Tachov History Park reconstructs early medieval Slavic and high medieval settlements native to the Bavaria Slavica region, using original materials and construction techniques documented through archaeological excavation (Geschichtspark Bärnau-Tachov, n.d). Within this regional building tradition, lime, stone, and timber were the principal materials available before the introduction of industrial binders, and the Naturdorf Bärnau project deliberately privileged these historical materials over modern alternatives such as Portland cement or gypsum-based products, in direct continuity with the construction logic of the adjacent reconstructed settlements. The choice of lime over these modern alternatives is therefore not merely a matter of embodied carbon performance, but a considered alignment with the cultural and historical premise that gave rise to the wider Naturdorf Bärnau compound.

5.5.2 Structural Timber and Bio-Based Logic

Timber elements contribute approximately 25.08% of A1–A3 embodied carbon. Given the extensive presence of timber in the primary structural frames, roof systems, intermediate floors, cladding, and battens, this percentage indicates a structurally dominant yet environmentally moderate contribution. Importantly, timber also represents a significant reservoir of stored biogenic carbon, addressed separately in Section 5.6. Its embodied emissions reflect harvesting, processing, amongst several others, while its structural role reduces dependence on high-impact mineral materials.

Within the vernacular framework, timber satisfies multiple criteria simultaneously: local material availability, constructive intelligibility, repairability and reversibility, and compatibility with bio-based infill systems. Thus, while not emission-free, timber reinforces both the material continuity and constructive legibility associated with contemporary vernacular practice.

5.5.3 Contribution of Earth-Based Materials

Earth-based materials contribute approximately 3.64% to production-stage impacts. Clay plasters and compressed earth elements exhibit comparatively low embodied carbon due to minimal processing and the absence of high firing temperature. Their limited share of total emissions reflects low intrinsic impact intensity and the relatively modest volume of earth-based elements within the building’s assembly logic. In Building D, earth is used predominantly in partition walls and as infill in intermediate slabs, applications where mechanical resistance demands are limited;

this reflects a design choice rather than an inherent constraint of the material itself, as earth-based systems such as rammed earth can also serve structural functions when required. This result reinforces the environmental value of low-transformed materials.

5.5.4 Stone, Aggregates, and Foundations

Stone and aggregate materials account for approximately 6.43% of A1–A3 impacts. The relatively modest contribution of mineral aggregates reflects their low intrinsic embodied carbon intensity per unit weight rather than the choice of foundation system in itself, since aggregates such as gravel drainage layers and stone backfill would still be required as infill and drainage elements even with a conventional reinforced concrete foundation. The use of gravel drainage layers, granite footwall elements, and stone backfill nonetheless demonstrates a low-impact adaptation of mineral materials, achieved here without reliance on high-carbon cementitious systems for the foundation structure itself. This strategy directly aligns with the second vernacular principle of low environmental footprint while maintaining structural adequacy.

5.5.5 Bio-Based Insulation: Sheep Wool and Hemp Shiv

Sheep wool and hemp shiv together contribute approximately 3.87% of A1–A3 embodied carbon, with sheep wool accounting for 2.03% and hemp shiv for 1.84%. Both materials are minor contributors in fossil terms, consistent with their role as lightweight, low-processing insulation fills rather than structural or bulk components. Their environmental significance lies less in their fossil footprint and more in their contribution to biogenic carbon storage, discussed in Section 5.6, where both materials act as net carbon sinks. Within the vernacular framework, the use of

locally sourced animal and plant fibres for thermal insulation, in place of synthetic alternatives such as mineral wool or expanded polystyrene, reinforces the principle of material continuity with regional agricultural by-products.

5.5.6 Limited Impact of Transport (A4)

Transport impacts represent only 3.85% of total embodied carbon (A1–A4). This modest share reflects the geographically concentrated sourcing strategy documented in previous chapters. The majority of materials were procured from regional and local suppliers, with several key inputs. Lime, timber, and aggregates were sourced from locations within 100 km of the construction site. On-site materials such as excavated clay and cocchiopesto were assigned a transport distance of zero, further containing the A4 contribution. While transport reduction alone does not define vernacular architecture, the limited transport burden supports the principle of local resource utilisation.

5.5.7 Synthesis: Environmental Coherence within a Vernacular Framework

The embodied carbon profile of Building D reveals a clear hierarchy of impact drivers: mineral binders (lime-based materials) dominate, followed by structural timber, stone and aggregates, earth-based materials, and finally insulation and glazing. This distribution reflects a hybrid material system in which mineral and bio-based components coexist and serve complementary structural and enclosure functions.

The environmental footprint is not negligible; however, it remains moderate when expressed per gross floor area, amounting to 267.60 kgCO₂e/m² for

modules A1–A4. This statement is necessarily relative: without a directly comparable benchmark for buildings of similar typology, climate, and functional unit, “moderate” describes an internal evaluation of coherence between material logic and impact rather than a verified comparative ranking. Within the conceptual framework of Bocco and Habert, the results suggest a strong alignment with the principle of local material use, a moderate but controlled environmental footprint, and a material logic consistent with contemporary performance requirements. Rather than achieving minimal embodied carbon through technological substitution, the project demonstrates environmental moderation through constructive intelligence and material restraint. The embodied carbon results therefore support the hypothesis that vernacular principles, when reinterpreted within contemporary standards, can produce environmentally coherent architecture without relying on industrialised high-carbon systems.

5.6 Biogenic Carbon Storage Assessment

Building D incorporates a substantial quantity of bio-based materials that act as temporary carbon sinks during the service life of the building. This section quantifies stored biogenic carbon separately from fossil-based emissions in accordance with EN 16449 and the reporting conventions of EN 15804.

5.6.1 Methodological Approach

Biogenic carbon storage was calculated for bio-based materials present in the building inventory, specifically structural and finishing timber elements, the hemp shiv component of hemplime wall infill, and sheep wool insulation. Sheep wool was initially approximated using ÖKOBAUDAT hemp/flax insulation datasets; this approximation was subsequently corrected using product-specific Environmental Product Declaration (EPD) data published by the manufacturer (Isolena Naturfaservliese GmbH, 2024), which reports both fossil and biogenic GWP separately for the sheep wool product range used in Building D.

The calculation follows the formula defined in EN 16449:

$$PCO_2 = (44/12) \times cf \times (\rho\omega \times V\omega) / (1 + \omega/100)$$

Where:

- PCO_2 = biogenic carbon stored in the material (kg);
- cf = carbon fraction of the dry biomass (dimensionless);
- $\rho\omega$ = density of the product at given moisture content (kg/m³);
- $V\omega$ = volume of the bio-based material (m³);
- ω = moisture content (%), conventionally set at 12 in accordance with the spreadsheet methodology.

The stored biogenic CO₂ is then expressed as a climate contribution using the static -1/+1 approach per EN 16449:

$$GWPb^{pr} = (-1) \times PCO_2$$

This value is reported separately and is not deducted from A1–A4 fossil emissions.

5.6.2 Timber Carbon Storage

The total timber volume derived from the material inventory amounts to 40.56 m³. This includes all structural framing elements, roof members, floor boarding, cladding boards, battens, window frames, and stair components inventoried as timber.

The following parameters were applied:

- Density ($\rho\omega$): 492.92 kg/m³, consistent with the ÖKOBAUDAT dataset value for the softwood species used;
- Carbon fraction (cf): 0.50, per EN 16449 standard value for dry wood;
- Moisture content (ω): 12 (%).

The moisture-adjusted mass is calculated as:

$$m_{tim}b^{er} = (\rho\omega \times V\omega) / (1 + \omega/100) = (492.92 \times 40.56) / 1.12 = 17,852.3 \text{ kg}$$

Stored biogenic CO₂ in timber:

$$PCO_{2,tim}b^{er} = (44/12) \times 0.50 \times 17,852.3 = 32,729.3 \text{ kgCO}_2$$

5.6.3 Hemp Fraction within Hemplime Assemblies

The total hemplime volume, comprising perimeter wall infill and partition assemblies, amounts to 40.6855 m³. Based on the inventory composition, the wall assemblies consist of 85% lime mortar and 15% hemp shiv by volume. Only the hemp shiv fraction contributes to biogenic carbon storage, as the lime component is mineral-based and does not store atmospheric carbon. Hemp shiv was initially modelled in the inventory using an ÖKOBAUDAT hemp fibre insulation dataset, applied as a proxy in the absence of a dedicated hemp shiv dataset; the biogenic carbon parameters below follow the EN 16449 methodology independently of this proxy, while the fossil GWP correction for hemp shiv is addressed in Section 5.4.4.

The hemp volume is therefore:

$$V_{h}^{e_{mp}} = 0.15 \times 40.69 = 6.10 \text{ m}^3$$

The following parameters were applied:

- Density: 38 kg/m³, per ÖKOBAUDAT dataset for hemp fibre fleece;
- Carbon fraction (cf): 0.47, per reference values for hemp biomass;
- Moisture content (ω): 12 (%).

Moisture-adjusted hemp shiv mass:

$$m_{h}^{e_{mp}} = (38 \times 6.10) / 1.12 = 207.1 \text{ kg}$$

Stored biogenic CO₂ in hemp shiv:

$$PCO_{2,h}e_{mp} = (44/12) \times 0.47 \times 207.1 = 356.8 \text{ kgCO}_2$$

5.6.4 Sheep Wool Biogenic Carbon Storage

Sheep wool insulation totals 550.68 kg across the Premium and Optimal product variants used in Building D. Rather than applying the EN 16449 volume-based formula used for timber and hemp shiv, sheep wool’s biogenic carbon is derived directly from the manufacturer’s EPD (Isolena Naturfaservliese GmbH, 2024), which reports a GWP biogenic value of -36.4 kgCO₂e per m³ for A1–A3, at the EPD’s reference bulk density of 23.26 kg/m³. Converting to a mass basis:

$$PCO_{2,sheep} = |-36.4 / 23.26| \times 550.68 = 861.8 \text{ kgCO}_2$$

This figure is reported on the same positive-stored-carbon basis as timber and hemp shiv in Table 5.4, to maintain methodological consistency across all bio-based materials.

5.6.5 Total Stored Biogenic Carbon

The total stored biogenic carbon within the bio-based materials of Building D is:

$$PCO_{2,total} = 32,729.3 + 356.8 + 861.8 = 33,947.9 \text{ kgCO}_2$$

Table 5.4 — Stored Biogenic Carbon in Bio-Based Materials

Material	Volume (m³)	Density (kg/m³)	Adjusted Mass (kg)	Stored CO₂ (kgCO₂)
Timber (all elements)	40.5636	492.92	17,852.3	32,729.3
Hemp shiv (15% of hemplime)	6.1028	38	207.1	356.8
Sheep wool	—	23.26	550.68	861.8
Total	—	—	—	33,947.9

Calculation method in accordance with EN 16449 for timber and hemp shiv. $\omega = 12$ (moisture content, dimensionless input as per spreadsheet methodology). Carbon fraction: 0.50 for timber; 0.47 for hemp shiv. Sheep wool stored carbon is derived from the manufacturer’s EPD (Isolena Naturfaservliese GmbH, 2024) and converted to a mass basis using the EPD’s reference density of 23.26 kg/m³, rather than the EN 16449 formula.

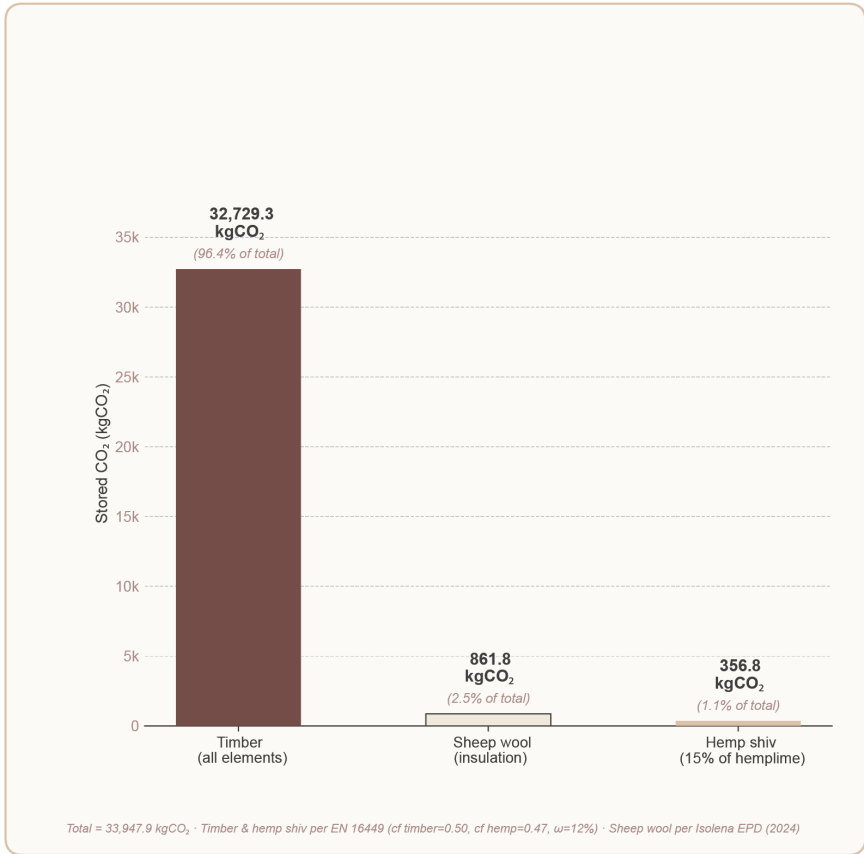


Figure 5.5 – Stored biogenic carbon by material type for Building D. Timber accounts for the dominant share of biogenic carbon storage. Source: Author’s illustration from analysis..

5.6.6 Interpretation of Biogenic Storage

The total stored biogenic carbon (33,948 kgCO₂) exceeds the fossil-based embodied emissions quantified for modules A1–A4 (20,508 kgCO₂e). However, in accordance with EN 15804 and EN 16449 reporting conventions, biogenic carbon storage is reported separately from fossil emissions, stored carbon is not deducted from A1–A4 impacts, and the climatic benefit depends on service life and end-of-life scenarios.

5.6.7 Informative Net Balance (Non-Deducted Reporting)

Table 5.5 — Informative Comparison of Fossil Emissions and Stored Biogenic Carbon

Indicator	kgCO₂
Fossil embodied emissions (A1–A4)	20,508.19
Stored biogenic carbon	33,947.87
Difference (storage – fossil)	+13,439.68
GWPnet (–1/+1 approach: GWPfossil + GWPbio)	–13,439.68

Presented for interpretative purposes only. Biogenic carbon storage is not deducted from fossil emissions in accordance with EN 15804 and EN 16449.

The positive difference indicates that the quantity of carbon stored in bio-based materials exceeds fossil embodied emissions in modules A1–A4. This comparison is presented for interpretative purposes only and does not constitute a carbon-negative assessment, as biogenic carbon storage is dependent on service life and end-of-life scenarios. Long-term retention of structural timber would extend

The stored carbon therefore represents temporary atmospheric sequestration, contingent upon material durability and post-use treatment pathways. Within the framework of Bocco and Habert’s principles, this result reinforces the environmental coherence of a materially bio-based structural system, where constructive logic and material sourcing reduce fossil dependence while enabling significant carbon storage within the building envelope.

sequestration benefits, whereas premature degradation or incineration would reduce the effective climatic benefit of this storage.

Chapter 6

Discussion

6.1 Interpretation of Embodied Carbon Results

The embodied carbon intensity of Building D, calculated at 267.60 kgCO₂e/m² for modules A1–A4, provides a quantitative foundation for evaluating the environmental performance of a bio-based, vernacular-informed construction approach. To interpret this result meaningfully, it must be situated within the broader context of European residential construction benchmarks.

Röck et al. (2020), in a meta-analysis of embodied greenhouse gas emissions across European building typologies, identified a wide range of cradle-to-practical-completion intensities for residential buildings, with conventional construction typically falling between 300 and 600 kgCO₂e/m² for A1–A5 modules. Studies examining timber-dominant and bio-based residential systems consistently report lower values, with several examples falling in the range of 150 to 300 kgCO₂e/m² for the product and construction stage. The result recorded for Building D, covering A1–A4, positions the project firmly within the lower portion of this spectrum, indicating that the material strategy adopted at Naturdorf Bärnau produces an environmental profile consistent with well-performing low-carbon residential construction.

It must be noted that module A5 is excluded from this assessment, as declared in Section 5.1.4. The magnitude of this exclusion cannot be quantified with confidence for Building D specifically. However, related case study research on comparable bio-based pavilions found A5 contributing as much as 20 percent of total A1–A5 embodied carbon (Mazelli et al., in press), substantially higher than is typical for conventional construction, owing to the comparatively low baseline established by stages A1–A4. Given that

Building D similarly relies on minimally processed, low-impact materials, a proportionally elevated A5 contribution cannot be ruled out, and the total reported here should be read as a conservative estimate rather than a complete cradle-to-practical-completion figure.

The dominant contribution of lime-based materials, at 60.05 percent of A1–A3 emissions, is the most structurally significant finding of the results. This result challenges a common assumption in bio-based construction discourse, where timber and hemp-based systems are often presented as universally low-impact. In Building D, the mineral binder infrastructure, though lower in carbon intensity than Portland cement, constitutes a substantial embodied carbon liability precisely because of the volumetric scale at which lime is deployed: as infill binder, as screed, as plaster, and as render across virtually every surface and assembly. This finding reinforces the importance of whole-system inventory approaches rather than material-level assumptions when assessing bio-based construction.

The A4 transport contribution of 3.85 percent further indicates that the sourcing geography of materials was geographically concentrated, reducing logistics-related impacts to a minor share of total A1–A4 emissions. This reflects the regional supply chain logic embedded in the Naturdorf Bärnau project and aligns with the first principle of Bocco and Habert’s (2024) framework, as discussed in Section 6.4.

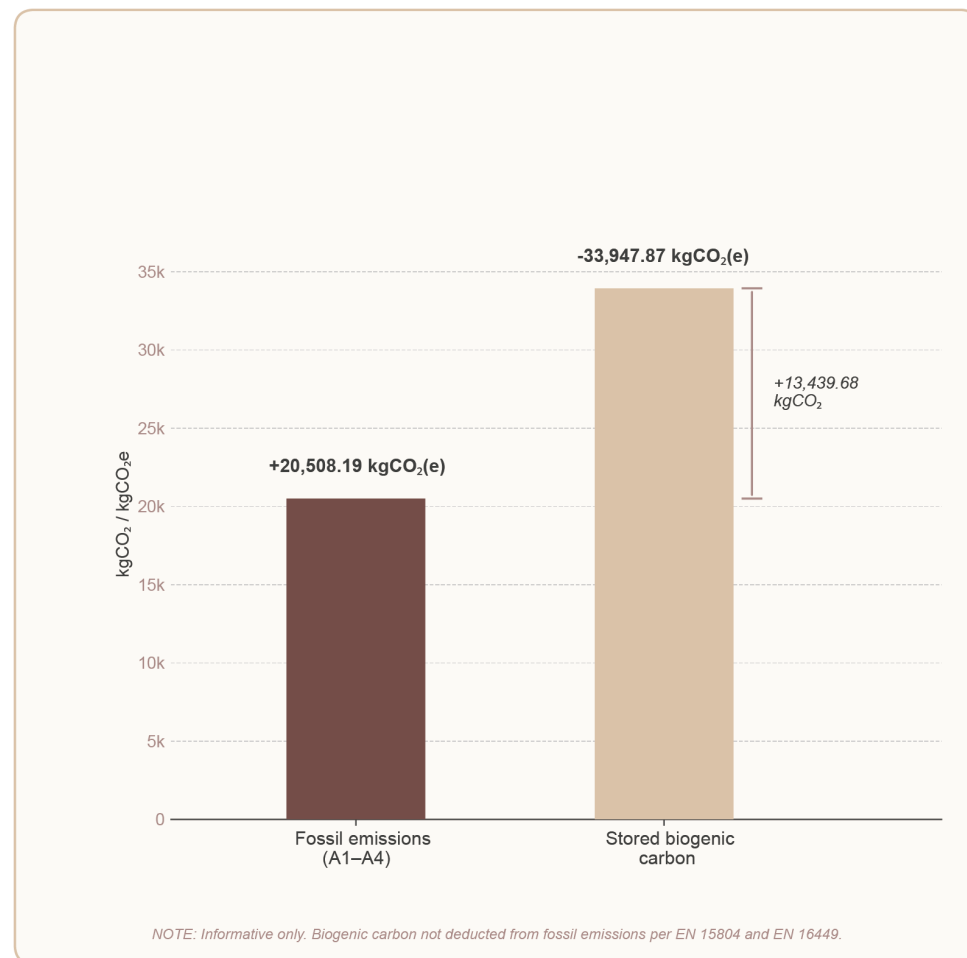


Figure 5.6 – Comparison of fossil embodied emissions (A1–A4) and stored biogenic carbon for Building D. The stored biogenic carbon exceeds fossil emissions, indicating significant carbon sequestration potential contingent on service life. Source: Author’s illustration from analysis.

5.7 Comparison with Related Case Study Research

A related conference paper examining the same case study building reports an embodied carbon intensity of 367 kgCO₂e/m² for modules A1–A5 (Mazelli et al., in press), compared to 267.60 kgCO₂e/m² for modules A1–A4 obtained in this thesis, a difference of approximately 27%. The gap is attributable primarily to the wider system boundary applied in Mazelli et al. (in press), which includes module A5, excluded from

this assessment due to the unavailability of contractor-level construction data (Section 5.1.4), together with differences in background database (ÖKOBAUDAT versus Ecoinvent) and calculation tool. Taken together, these factors indicate that the two results are broadly consistent rather than contradictory, with the residual gap explained by declared scope and methodological choices rather than by inconsistency in the underlying building data.

6.2 Role of Bio-Based Materials and Biogenic Carbon Storage

Building D incorporates bio-based materials across its structural, thermal, and finishing systems in a manner that is not merely substitutive but systemic. Timber constitutes the primary load-bearing frame, the roof structure, the intermediate floors, and the external cladding. Hemp-lime infill functions simultaneously as insulation, structural fill, and moisture regulator. Sheep wool provides thermal insulation in both roof configurations. Clay and lime-based plasters form the internal and external surface finishes across all assemblies. This material redundancy, where multiple functions are served by a single bio-based system rather than by discrete industrial products, is a defining characteristic of the construction approach and is central to its environmental logic.

The calculated biogenic carbon storage of approximately 33,947.9 kgCO₂ quantifies the atmospheric carbon temporarily locked within these bio-based materials at the point of practical completion. This figure exceeds the total fossil embodied emissions associated with modules A1–A4 (20,508.19 kgCO₂e), yielding an informative positive difference of approximately 13,439.68 kgCO₂. This comparison does not constitute a carbon-negative assessment; in accordance with EN 15804 and EN 16449, biogenic carbon storage is reported separately from fossil emissions and is not deducted from embodied totals. Its climatic relevance is contingent on building service life, material durability, and end-of-life treatment pathways.

Nevertheless, the scale of biogenic storage relative to fossil emissions is architecturally and environmentally significant. It demonstrates that the structural decision to use timber at the primary frame level, combined with hemp-based infill across the

envelope, results in a building that functions as a meaningful temporary carbon store over its service life. This is not an incidental outcome but a direct consequence of the material logic described in Chapters 3 and 4, where bio-based materials are understood as active environmental agents rather than passive construction components.

The long-term retention of this stored carbon depends critically on structural integrity and the avoidance of premature timber degradation or combustion. The reversible construction techniques adopted throughout the building, specifically the avoidance of irreversible composite connections and the use of separable assemblies, support material longevity and facilitate the eventual recovery and reuse of bio-based components. This is a further environmental argument for the constructive intelligence embedded in the project beyond what embodied carbon figures alone can capture.

6.3 Thermal Envelope Performance and Passive Comfort

Beyond the embodied carbon assessment, the thermal performance of Building D’s construction assemblies provides a complementary dimension of environmental evaluation. The following analysis draws on verified thermal calculations produced for the principal building assemblies, each assessed against the GEG 2020 (Gebäudeenergiegesetz) reference values applicable to new residential construction in Germany.

Assembly	U-value (W/m²K)	GEG 2020 Threshold	Compliance
Warm roof (sheep wool)	0.15	< 0.16	Compliant
Cold roof (sheep wool)	0.16	< 0.16	Compliant
Upper floor wall (timber cladding)	0.20	< 0.22	Compliant
Ground floor wall (rendered facade)	0.22	< 0.22	Compliant
Main ground floor (charcoal-lime)	0.20	< 0.28	Compliant
Entrance floor (biochar-granite)	0.28	< 0.28	Compliant
Intermediate floor (internal)	0.84	N/A (internal)	N/A

Table 6.1 – Thermal performance of principal building assemblies against GEG 2020 Neubau reference values. Source: Thermal calculations based on construction documentation. verified using the u-wert.net online calculation tool (u-wert.net, n.d.).

All exterior envelope assemblies meet or exactly satisfy the GEG 2020 Neubau threshold applicable to their component type. This is a significant result, demonstrating that a construction system composed entirely of bio-based and mineral vernacular materials can achieve regulatory compliance with current German energy efficiency standards without recourse to synthetic insulation or vapour barrier systems.

The roof assemblies are particularly noteworthy. The warm roof achieves a U-value of 0.15 W/m²K, placing it at the performance level of a three-litre house classification and well within the GEG 2020 threshold of 0.16 W/m²K. The cold roof achieves exactly 0.16 W/m²K, meeting the standard at the boundary. Both results are achieved exclusively through bio-based insulation, using stacked Isolena sheep wool layers of 240 mm and 80 mm respectively in the warm roof configuration, without any synthetic enhancement.

The wall assemblies similarly demonstrate that hemp-lime infill, when applied at the thicknesses documented in Chapter 4, produces thermal resistance compatible with contemporary regulatory requirements. The upper floor wall achieves 0.20 W/m²K against a threshold of 0.22, and the ground floor rendered wall achieves exactly 0.22 W/m²K. Both wall types also incorporate radiant heating within the clay-lime plaster layer, which produces effective U-values of 0.29 and 0.31 W/m²K respectively when the heating system is active. This integration of heating within the building fabric, rather than as a separate mechanical system, reflects a coherent material and environmental strategy consistent with vernacular approaches to passive comfort.

The intermediate floor assembly records a U-value of 0.84 W/m²K. This value is not comparable against a GEG exterior envelope standard, as the floor separates two heated spaces rather than forming a

boundary with the external environment or unheated areas. Its performance is instead evaluated through its acoustic and thermal mass characteristics: a temperature amplitude dampening factor of 9.4 and a heat storage capacity of 120 kJ/m²K indicate significant thermal inertia contribution to indoor climate stability, consistent with the function described in Section 4.5.

Taken together, the thermal envelope performance data confirms that Building D fulfils the third principle of Bocco and Habert’s (2024) framework, namely the fulfilment of contemporary users’ expectations, at the level of quantitatively verified regulatory compliance. This is not merely an assertion of design intent but a measurable outcome documented across all primary assemblies.

6.4 Alignment with Bocco and Habert’s Four Principles

The central evaluative task of this thesis is to assess the degree to which Building D aligns with the four principles of 21st Century Vernacular Architecture as defined by Bocco and Habert (2024): the use of local resources; a low environmental footprint; the fulfilment of contemporary users’ expectations; and accessibility to local communities. The following analysis integrates the quantitative findings of Chapters 5 and 6 with the qualitative evidence established in Chapters 2, 3, and 4.

Principle 1: Use of Local Resources

Building D demonstrates a materially place-based approach through its consistent use of regionally rooted materials. Structural timber corresponds to softwood species common in the Bavarian forest landscape. Lime-based binders reflect a centuries-

long tradition of local mineral extraction and processing documented in the historical analysis of the Bärnau–Tachov region in Chapter 2. Hemp, while increasingly cultivated across Central Europe, was sourced and processed within the supply chains accessible to the Bavarian construction context. Sheep wool insulation under the Isolena brand is produced in Austria, within close regional proximity to the site.

The transport contribution of 3.85 percent of total A1–A4 emissions provides quantitative corroboration of this sourcing pattern. While not all materials can be traced to single-origin local sources without the supplier-level documentation that was unavailable at the time of writing, the consistently low A4 share indicates that long-distance procurement was not a structural feature of the project’s supply chain. The regional economic dimension of this principle, specifically the degree to which financial flows were retained within the local economy, remains a subject for future documentation once supplier-level data becomes available from project records.

Principle 2: Low Environmental Footprint

The embodied carbon intensity of 267.60 kgCO₂e/m² for A1–A4 positions Building D within the lower range of European residential benchmarks, as discussed in Section 6.1. This result is achieved without synthetic insulation, without reinforced concrete structural elements, and without the high-temperature mineral processing systems that dominate the embodied carbon profile of conventional construction.

The dominant impact driver, lime-based materials at 60.05 percent, identifies the calcination-dependent production of mineral binders as the primary environmental cost of this system. This is not a failure of the vernacular approach but a structural condition

of any construction system that relies on lime at volumetric scale. The relevant question is whether this impact is proportionate to the performance delivered, and the U-value data presented in Section 6.3 suggests that it is: the assemblies meet GEG 2020 standards, achieve moisture independence through hygroscopic regulation, and do so without synthetic substitutes. The environmental footprint is moderate, not minimal, but it is coherent.

Principle 3: Fulfilment of Contemporary Users’ Expectations

As demonstrated in Section 6.3, all primary exterior assemblies of Building D meet the GEG 2020 Neubau thermal performance thresholds. The warm roof achieves 0.15 W/m²K, the wall assemblies fall between 0.20 and 0.22 W/m²K, and the ground floor assemblies achieve 0.20 to 0.28 W/m²K. Moisture performance is equally strong: the warm roof and both wall configurations record no condensation or manageable condensation that resolves within short drying cycles. The hygrothermal behaviour of hemp-lime and clay-based materials, which regulate moisture through absorption and desorption rather than vapour barriers, produces indoor climate conditions associated with high user comfort.

The integration of radiant heating within the clay plaster layer of both wall types further demonstrates how traditional material systems can be adapted to deliver contemporary comfort without departing from the underlying vernacular logic. The heated wall surfaces provide low-temperature radiant heat distribution at water temperatures of 30°C, a system well matched to the high thermal mass and high insulation values of the assemblies.

Principle 4: Affordability to Local Communities

The constructive logic of Building D relies on materials and techniques that are, in principle, comprehensible and reproducible within a regional skill ecosystem. Timber frame construction, lime-based rendering, clay plastering, and hemp-lime casting are all techniques with established craft traditions in Central Europe. None of the systems employed depend on proprietary industrial components or specialist technologies that could not be sourced, installed, or maintained within a regionally anchored construction economy.

This affordability is reinforced by the reversible nature of the assemblies. Dry or semi-dry construction techniques, the absence of irreversible composite connections, and the use of materials that can be separated, repaired, or recast without structural consequences all contribute to a building that is not only affordable at the point of construction but remains affordable over time through maintenance and adaptation. In this sense, affordability is understood not merely as a socio-economic condition at the moment of delivery but as a long-term architectural and material quality.

6.5 Regional Material Sourcing and Transport Analysis

Research Question 3 of this thesis asks to what extent the material sourcing patterns and financial flows of the project contribute to regional economic retention. This dimension of the vernacular framework extends beyond environmental performance into the socio-economic logic of construction, examining whether the material choices made at Naturdorf Bärnau produce value that circulates within the regional economy rather than being captured by distant

industrial supply chains. The transport inventory compiled for this assessment provides a verified basis for addressing this question.

Table 6.2 summarises the site-to-supplier transport distances for the principal material categories, derived from the project’s transport inventory documentation.

Material	Source classification	Site-supplier (km)	Notes
Timber (structural, unplanned)	Local	20	Bavarian regional supply
Timber (planned, ceiling/roof)	Local	11	Extremely local
Timber (parquet floors)	Local	20	
Timber window frames	Regional	120	
Larch shingles	Regional	140	Bavarian larch
Lime (Bergmannkalk / Maxit)	Local	28	Mortar, hemplime, renders
Gravels and aggregates	Local	28-35	Scharnagl supplier, Weiden
Granite blocks and slabs	Local	18	Footwall and entrance floor
Clay (site-excavated)	On site	0	Slab infill and ceiling
Clay boards and purchased clay	Local	45	Mixed with site clay
Clay renders and sand	Local	80	Render systems
Charcoal (biochar)	Regional	90	Ground floor insulation
Sheep wool (Isolena)	Regional (Austria)	96	Manufacturer 365 km
Hemp shives	Regional	220	Raw source 700 km; processed regionally
Glass	Local	30	
Pozzolana / trass	Regional / distant	28	Manufacturer 230 km

Table 6.2 – Transport distances from supplier to construction site for principal material categories. Source: Author’s transport inventory based on project documentation.

Material transport distances (site to supplier)

All 17 material categories · Naturdorf Bärnau Building D · sorted by distance

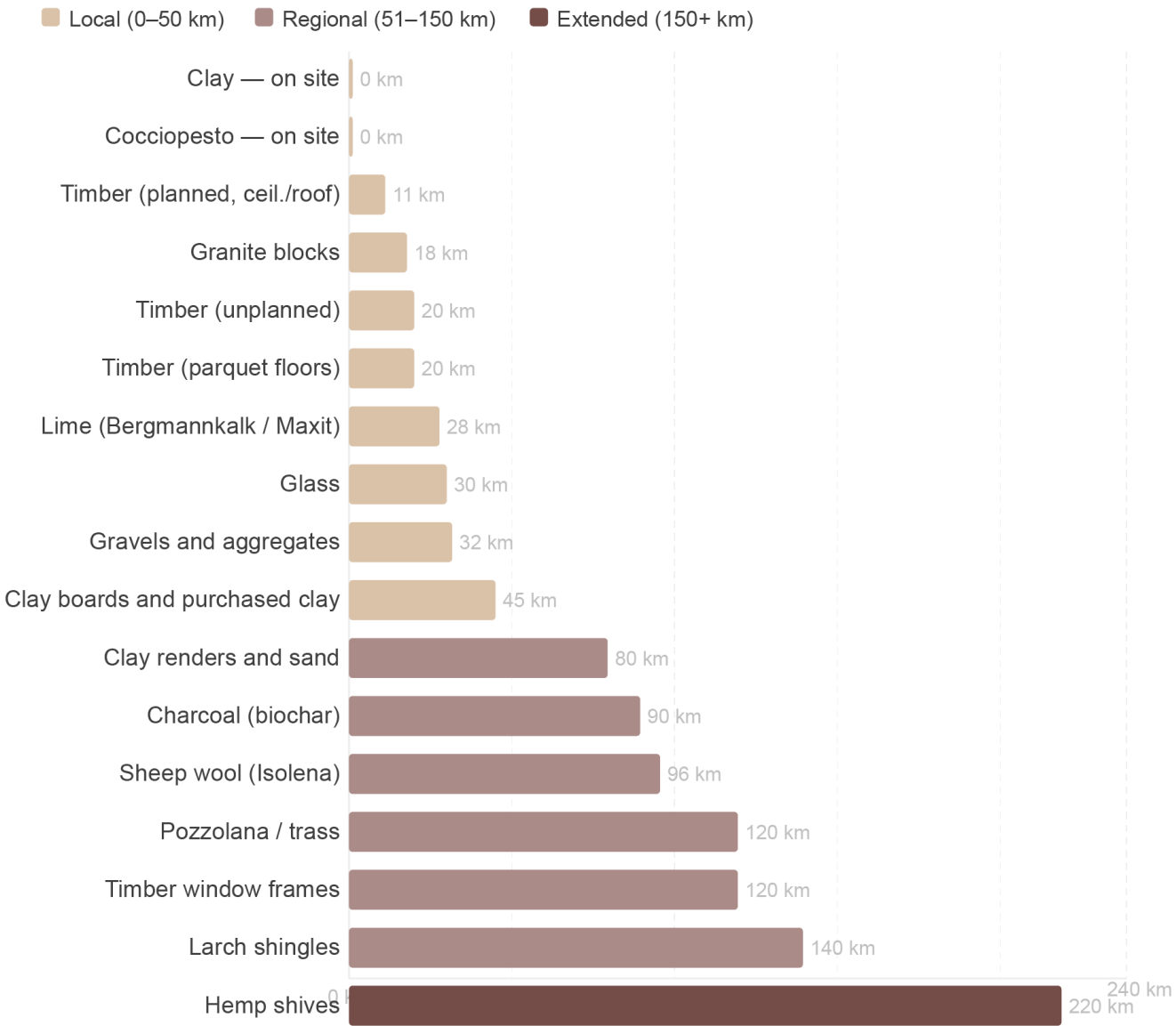


Figure 6.1 – Distribution of material categories by geographic sourcing tier for Building D, Naturdorf Bärnau (n=17 categories). Of the 17 material categories inventoried, 59 percent are sourced within a 50 km local radius, 35 percent within a 51–150 km regional radius, and 6 percent from an extended supply chain exceeding 150 km. Source: Author’s elaboration based on project transport inventory documentation.

The transport data reveals a sourcing pattern that is strongly concentrated within the Upper Palatinate and wider Bavarian region for all primary structural and mineral materials. Structural timber is sourced between 11 and 20 km from the construction site, placing it firmly within local forestry supply networks. Lime, supplied by Bergmannkalk or Maxit, is

delivered from 28 km. Aggregates and gravels originate from the Scharnagl supplier in Weiden, 28 to 35 km distant. Granite for footwall and entrance floor elements travels only 18 km. Most strikingly, clay was excavated directly on site at zero transport distance, a detail that exemplifies the principle of local resource utilisation in its most immediate form.

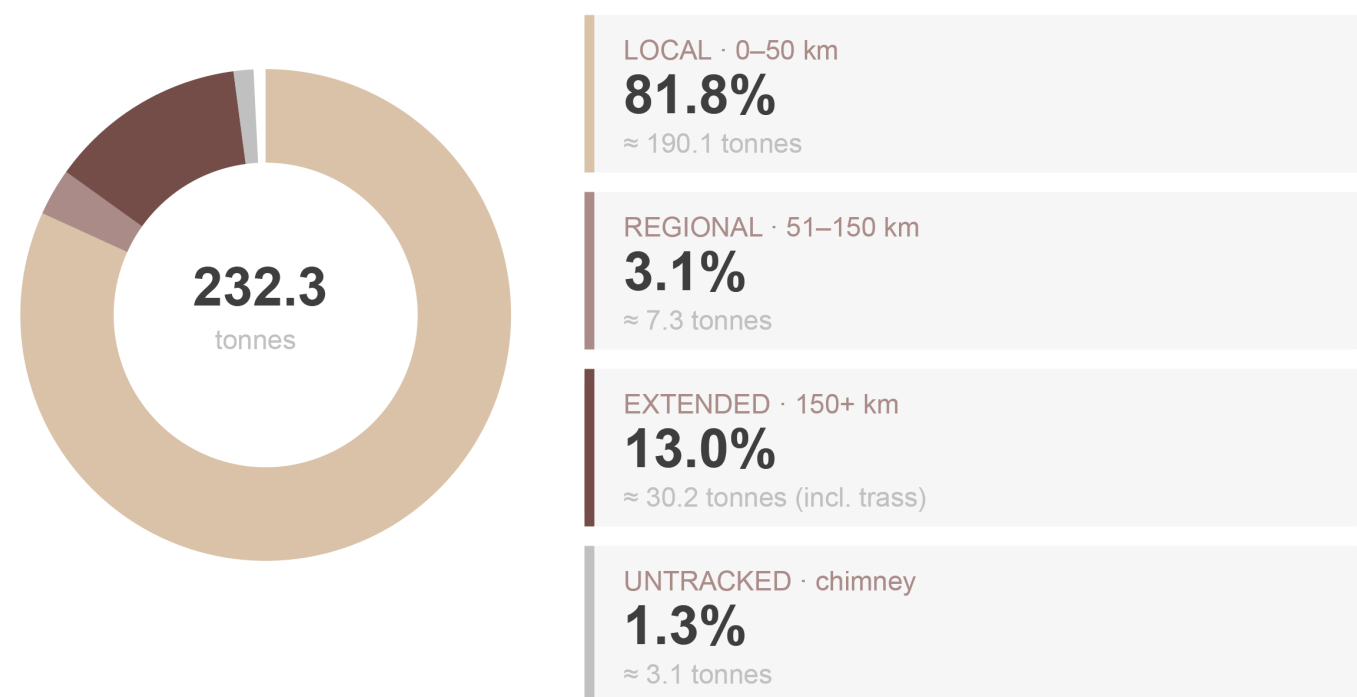


Figure 6.2 – Distribution of material categories by geographic sourcing tier for Building D, Naturdorf Bärnau, by total building weight (232.3 t). Of the total inventoried material weight, 81.8 percent (approximately 190.1 tonnes) is sourced within a 50 km local radius, 3.1 percent (approximately 7.3 tonnes) within a 51–150 km regional radius, and 13.0 percent (approximately 30.2 tonnes, including trass) from an extended supply chain exceeding 150 km. A further 1.3 percent (approximately 3.1 tonnes), associated with the chimney, remains untracked. Source: Author’s elaboration based on project transport inventory documentation

The majority of processed and finishing materials also fall within a regional radius. Charcoal insulation is sourced at 90 km, clay boards at 45 km, and glass at 30 km. Sheep wool insulation, supplied under the Isolena brand from Austria, travels 96 km to site from its point of distribution, with the manufacturing facility located 365 km from the site. This represents the most distant distribution point for a volume material, though it remains within a Central European regional supply context rather than an international one.

Hemp shives present the most complex supply chain in the inventory. The site-to-supplier distance of 220 km is moderate, but the raw material source is documented at 700 km, indicating that hemp cultivation and initial processing occur at a greater geographic distance from the site than is the case for

the mineral and timber materials. This is consistent with the current state of hemp cultivation in Central Europe, where supply chains are still consolidating following renewed agricultural interest in industrial hemp. Hemp’s role in Building D as an insulating infill rather than a structural material means that its extended supply chain, while noted, does not fundamentally challenge the regional sourcing logic of the project.

Pozzolana and trass, volcanic ash additives used in specific mortar formulations, are sourced from Marker Zement GmbH with a supplier-to-manufacturer distance of 230 km. This is the one material category where the production geography departs significantly from the local pattern. However, pozzolana is used in limited quantities relative to the dominant lime and timber volumes, and its contribution to A4 transport

emissions is proportionately modest.

Taken together, the transport data provides quantitative corroboration of the A4 result of 3.85 percent of total A1–A4 embodied carbon documented in Chapter 5. The consistently short site-to-supplier distances for high-volume materials, particularly timber at 11 to 20 km, lime at 28 km, and aggregates at 28 to 35 km, explain why transport contributes so marginally to the overall environmental profile despite the full range of construction materials involved. This sourcing geography directly supports the first principle of Bocco and Habert’s (2024) framework and represents a meaningful economic as well as environmental argument for the regional material strategy of the project.

6.6 Comparative Reflections: Grugliasco and Naturdorf Bärnau

As noted in Chapter 1, the author’s direct participation in the Experimental Pavilions of Vegetarian Architecture in Grugliasco, Turin, provides a practical reference point for interpreting the findings of the Naturdorf Bärnau study. While the two projects operate at fundamentally different scales and with different objectives, the comparison illuminates several dimensions of vernacular reinterpretation that the LCA data alone cannot fully address.

The Grugliasco pavilions function as research-scale interventions, constructed through participatory and iterative processes using natural materials including straw, hemp, timber, clay, and rammed earth. Their primary purpose is knowledge generation through making: material behaviour, assembly logic, and structural performance are investigated under real

conditions rather than simulated environments. In this sense, the pavilions represent the experimental pole of the spectrum described in Section 3.6, where construction is an instrument of inquiry rather than a product.

Naturdorf Bärnau occupies the opposite end of this spectrum, producing permanent, inhabited dwellings that must satisfy regulatory standards, user comfort requirements, and long-term durability conditions. The thermal performance data presented in Section 6.3 is evidence of this transition: the U-values recorded for Building D are not experimental approximations but verified compliance outcomes that meet the GEG 2020 Neubau standard across all primary assemblies. What the Grugliasco experiments investigate as hypotheses, Naturdorf demonstrates as confirmed performance..

The most instructive point of comparison lies in the treatment of material failure and imperfection. At Grugliasco, the iterative nature of the process allows for modification, correction, and learning from assembly errors without consequence beyond the research context. At Naturdorf Bärnau, the same material systems must perform reliably over decades of habitation and variable climatic conditions. The as-built discrepancies encountered during the documentation of Building D, and the methodological adjustments required to account for them in the LCA, reflect precisely this transition from experimental to real-scale conditions. They are not methodological weaknesses but evidence of the friction inherent in translating experimental knowledge into inhabited architecture.

A further point of comparison concerns the role of craftsmanship and tacit knowledge. Both projects depend on construction knowledge that cannot be

fully codified in technical drawings or material specifications. The hemp-lime casting process, the sequencing of lime plaster layers, and the detailing of breathable wall assemblies all require embodied skill developed through repetition and direct material engagement. At Grugliasco, this knowledge is generated collectively through student participation. At Naturdorf Bärnau, it was mobilised through the craft expertise of specialist contractors working within the project’s experimental framework. The continuity of this knowledge, its transmission from research contexts into professional practice, is one of the most practically significant contributions of projects like these to the broader discourse on 21st-century vernacular construction. 492.92

6.7 Sensitivity and Robustness Considerations

The reliability of the results presented in Chapter 5 depends on the stability of several key assumptions embedded in the inventory and calculation methodology. Examining the sensitivity of the total embodied carbon figure to these assumptions provides a basis for assessing the robustness of the conclusions drawn from the data.

The most influential single assumption is the timber density value of 492.92 kg/m³, selected from the ÖKOBAUDAT 2024 dataset as the closest match to the structural softwood species used in Building D, consistent with spruce and pine at structural grade in air-dried condition. This value was chosen in preference to the generic default of 450 kg/m³ to improve alignment between the inventory model and the actual material specification. Given that timber contributes 25.08 percent of A1–A3 emissions and constitutes the largest single material volume in the inventory,

a variation of plus or minus 10 percent in this density assumption would propagate into a corresponding variation of approximately 2.5 percent in total A1–A3 results. This is a modest sensitivity and does not alter the structural interpretation of the findings

The lime-based material datasets carry the greatest potential for result variation, given that lime accounts for 60.05 percent of A1–A3 emissions and ÖKOBAUDAT contains multiple datasets with varying GWP values for lime products depending on production method and geographic origin. The selection of German production datasets over European average datasets, as documented in Section 5.3, introduces a degree of geographic specificity that is appropriate to the project context but means that alternative dataset selections could yield meaningfully different totals. A conservative estimate suggests that an alternative lime dataset selection could shift the A1–A3 total by up to 5 to 8 percent in either direction. This range does not challenge the conclusion that the building falls within the lower portion of European residential benchmarks, but it does indicate that the precise figure of 267.60 kgCO₂e/m² should be understood as the central estimate within a plausible range rather than a precise point value.

Transport distances for A4 were estimated based on known supplier locations and conservative routing assumptions where exact distances were unavailable. Given that A4 constitutes only 3.85 percent of the total, even a doubling of transport distances for all materials would increase total A1–A4 emissions by less than 4 percent, confirming that transport assumptions do not materially affect the conclusions of the assessment.

The biogenic carbon calculation is sensitive to the assumed carbon fraction of 0.50 for oven-dry wood,

derived from EN 16449. This is a standardised value and is applied consistently across timber and hemp fractions. The resulting stored carbon figure of 33,947.9 kgCO₂ is therefore a standardised estimate rather than a species-specific measurement. For the purposes of the comparative analysis presented in Section 5.6.6, this level of precision is sufficient and consistent with the reporting conventions of the standard.

6.8 Limitations of the Assessment

Several limitations of the present assessment should be acknowledged explicitly to ensure that the conclusions drawn are appropriately bounded. The most significant boundary limitation is the restriction of the quantitative analysis to modules A1–A4. Module A5, covering on-site construction processes, was excluded following confirmation from the thesis supervisor that contractor records were not available. This is a documented scope boundary rather than a methodological oversight, and it means the total construction-stage carbon impact of the project is likely marginally underestimated relative to a full A1–A5 cradle-to-practical-completion assessment.

The exclusion of operational modules B1–B7 and end-of-life modules C1–C4 reflects the research focus on construction-stage impacts rather than full life-cycle performance. While this is a coherent and justified methodological choice given the project’s early operational stage and the central research aim, it means that the assessment cannot capture the long-term climatic significance of the biogenic carbon storage, whose value depends entirely on service life duration and post-use treatment pathways. A future extension of the assessment to include operational performance data, once available from the building’s monitoring phase, would significantly enrich the environmental interpretation.

Some material densities were derived from ÖKOBAUDAT dataset reference values rather than from product-specific measurements or supplier data sheets. This is a standard practice in LCA-based research at this scale, but it introduces a degree of uncertainty in the mass-based calculations that cannot be fully eliminated without laboratory-grade material testing. The sensitivity analysis in Section 6.7 provides a framework for understanding the magnitude of the resulting uncertainty.

The financial flows dimension of Research Question 3, specifically the proportion of project value retained within the regional economy, remains only partially addressed. While the transport inventory in Section 6.5 provides verified geographic evidence of regional sourcing for all primary material categories, supplier-level financial records and contract values were not available for this study. A complete economic geography of the construction supply chain, mapping the distribution of expenditure across local, regional, and national suppliers, would require access to the project’s procurement accounts and is recommended as a direction for future research.

6.9 Broader Implications

The findings of this study carry implications that extend beyond the specific case of Building D and the Naturdorf Bärnau settlement. At the level of material strategy, the results demonstrate that hybrid bio-mineral construction systems, combining timber structures with lime-based binders, hemp infill, and earth-based finishes, can achieve embodied carbon intensities in the lower range of contemporary European residential construction without industrial optimisation strategies or high-performance synthetic products. This has practical relevance for architects,

builders, and policymakers working in contexts where regulatory compliance, environmental performance, and material authenticity are simultaneous objectives.

The identification of lime-based materials as the dominant embodied carbon contributor in an otherwise bio-based system highlights a hotspot that has received comparatively limited attention in the low-carbon construction literature, which has focused predominantly on structural systems and insulation materials. Future research should examine the potential for reduced-lime formulations, natural hydraulic lime substitutions, or alternative mineral binder strategies that preserve the hygrothermal and chemical compatibility advantages of lime while reducing process-related CO₂ emissions. The binder behaviour framework developed in Section 4.7 provides a conceptual foundation for this inquiry.

At a broader disciplinary level, the study contributes to an emerging body of evidence supporting the argument that vernacular material intelligence, when critically reinterpreted within contemporary regulatory and performance frameworks, can produce architecture that is simultaneously environmentally responsible, culturally grounded, and technically viable. Rather than treating environmental performance and architectural tradition as competing priorities, Building D demonstrates that they can be pursued as mutually reinforcing objectives within a single coherent material logic.

The implications extend also to the question of transferability. While the specific material assemblies of Building D are calibrated to the climatic, regulatory, and supply-chain conditions of the Upper Palatinate region of Bavaria, the underlying principles of material selection, construction sequencing, and assembly logic are portable across different geographic and

cultural contexts, subject to the kind of critical reinterpretation documented in the comparative case studies of Chapter 3. The Grugliasco pavilions represent one node in a broader experimental network through which such reinterpretation is actively being developed. Naturdorf Bärnau represents another, at the scale of inhabited architecture.

Chapter 7

Conclusion

7.1 Answers to the Research Questions

This thesis set out to evaluate the applicability of Bocco and Habert’s (2024) concept of a 21st Century Vernacular Architecture through the case study of Naturdorf Bärnau, using a combined quantitative and qualitative methodology that integrates Life Cycle Assessment, thermal performance analysis, material sourcing documentation, and architectural interpretation.

The five research questions posed in Chapter 1 are addressed in sequence below, drawing on the evidence developed across Chapters 4, 5, and 6.

Research Question 1: To what extent does Naturdorf Bärnau align with the four principles of 21st Century Vernacular Architecture proposed by Bocco and Habert (2024)?

The study demonstrates a strong overall alignment with all four principles, though with important nuances specific to each. On the first principle, the use of local resources, the transport inventory documents that the primary structural and mineral materials are sourced within a 50 km radius, with timber at 11 to 20 km, lime at 28 km, granite at 18 km, and aggregates at 28 to 35 km. Clay was excavated on site at zero transport distance. The A4 transport contribution of 3.96 percent of total A1–A4 embodied carbon provides quantitative corroboration of this geographic concentration.

On the second principle, the low environmental footprint, the embodied carbon intensity of 267.60 kgCO_{2e}/m² for modules A1–A4 positions Building D within the lower range of European residential benchmarks. The dominant impact driver is lime

based materials at 60.05 percent of production-stage emissions, a finding that complicates the assumption of uniform low impact in bio-based systems but does not undermine the overall environmental argument. The construction system avoids reinforced concrete, synthetic insulation, and proprietary composite cladding, removing the primary sources of high embodied carbon in conventional residential construction.

The third principle, the fulfilment of contemporary users’ expectations, thermal performance analysis of all primary assemblies confirms compliance with GEG 2020 Neubau standards across the entire building envelope. The warm roof achieves a U-value of 0.15 W/m²K, wall assemblies fall between 0.20 and 0.22 W/m²K, and ground floor assemblies achieve 0.20 to 0.28 W/m²K. All results are achieved without synthetic insulation or vapour barrier systems, demonstrating that bio-based and mineral vernacular assemblies can meet regulatory performance requirements at the level of verified compliance.

Lastly, the fourth principle on affordability to local communities, the construction system relies on materials and techniques with established craft traditions in Central Europe. The reversible assembly logic, the absence of proprietary industrial systems, and the use of separable materials all contribute to a building that remains constructively legible, maintainable, and adaptable within a regionally anchored skill ecosystem over its service life.

Research Question 2: What are the embodied energy and embodied carbon profiles of the project, including the contribution of biogenic carbon storage?

The embodied carbon of Building D amounts to 19,718.39 kgCO₂e for modules A1–A3 and 789.80 kgCO₂e for module A4, giving a total A1–A4 figure of 20,508.19 kgCO₂e, equivalent to 267.60 kgCO₂e/m² when normalised by the gross floor area of 76.638 m². Module A5 was excluded following confirmation from the thesis supervisor that contractor records were unavailable; the figures presented represent a minimum baseline for the construction-stage impact. Lime-based materials account for 60.05 percent of A1–A3 emissions, timber for 25.08 percent, stone and aggregates for 6.43 percent, earth-based materials for 3.64 percent, sheep wool insulation for 2.03 percent, hemp shiv insulation for 1.84 percent, and glass for 0.92 percent.

The biogenic carbon storage associated with timber and bio-based insulation components is calculated at 33,947.9 kgCO₂, comprising 32,729.3 kgCO₂ from timber, 861.8 kgCO₂ from sheep wool, and 356.8 kgCO₂ from hemp shiv within hemplime assemblies. In accordance with EN 15804 and EN 16449, this stored carbon is reported separately from fossil embodied emissions and is not deducted from the A1–A4 total. The stored carbon exceeds total fossil emissions by approximately 13,439.68 kgCO₂, though this difference does not constitute a carbon-negative assessment as its climatic value depends on service life and end-of-life treatment pathways. Embodied energy values are not separately reported in this study as the assessment focused on Global Warming Potential as the primary impact category, consistent with the IPCC characterisation factors applied through ÖKOBAUDAT (2024-I).

Research Question 3: To what extent do the material sourcing patterns and financial flows contribute to regional economic retention?

The transport inventory provides strong geographic evidence of regional material sourcing. Of the 17 material categories documented, 10 are sourced within a 50 km radius of the site, 6 within a 51 to 150 km regional radius, and one, hemp shives, from an extended supply chain with a raw material origin of 700 km. The only material reclassified beyond its site-to-supplier distance is pozzolana, whose manufacturer is 230 km from the site despite a short distribution distance, reflecting the limits of simple transport accounting.

The financial flows dimension of regional economic retention remains partially unresolved due to the unavailability of supplier-level procurement records at the time of writing. What the available evidence confirms is that the construction system systematically avoids the high-volume importation of industrialised products from distant markets, which are the primary vectors of economic leakage in conventional construction. A complete economic geography of the supply chain, mapping the distribution of project expenditure across local, regional, and national suppliers, is recommended for future documentation.

Research Question 4: Which design and construction strategies have the greatest influence on the project’s environmental performance?

Three strategies emerge from the analysis as the primary determinants of the project’s environmental profile. First, the choice of timber as the primary structural frame is the single most consequential environmental decision in the building, displacing the reinforced concrete or masonry systems that

dominate embodied carbon in conventional residential construction and enabling the accumulation of 32,729.3 kgCO₂ of biogenic carbon storage. Second, the use of hemp-lime as a combined insulation and infill system eliminates the need for synthetic insulation and vapour barriers, reducing the environmental burden of the envelope while maintaining GEG 2020 thermal compliance. Third, the geographically concentrated sourcing strategy, achieved through consistent use of Bavarian and Upper Palatinate suppliers for high-volume materials, keeps transport impacts to under 4 percent of total A1–A4 emissions.

Conversely, the dominant use of lime-based binders across foundations, walls, floors, and finishes is the single largest source of fossil embodied carbon in the system. The calcination process required for lime production is a structural environmental cost of this construction approach and cannot be eliminated without departing from the material logic that gives the assemblies their hygrothermal and chemical coherence. Future design and material development work should focus on this hotspot: reduced-lime formulations, natural hydraulic lime substitutions, or alternative low-carbon mineral binder strategies that preserve the performance advantages of lime while reducing process-related CO₂ emissions.

Research Question 5: How can the findings of this study inform the development of future vernacular and bio-based housing models?

The findings demonstrate that bio-based vernacular construction, when implemented with material rigour and contemporary technical knowledge, can produce housing that is simultaneously environmentally responsible, culturally grounded, and technically compliant. The study provides a replicable methodological framework, combining manual

quantity take-off, ÖKOBAUDAT-based LCA, EN 16449 biogenic carbon accounting, and verified thermal performance analysis, that can be applied to comparable projects in other climatic and regulatory contexts.

The identification of lime as the dominant embodied carbon driver in an otherwise bio-based system offers a specific and actionable finding for future design development. Projects of this type should invest early in the LCA of their binder strategies, not only their structural systems, as binder volumes at whole-building scale can rival or exceed the embodied carbon contribution of structural materials. The integration of LCA tools at the design stage, rather than as a retrospective assessment, would enable material substitutions and proportioning decisions to be evaluated against environmental criteria before construction.

7.2 Contribution to Architectural Discourse

This thesis contributes to the discourse on 21st Century Vernacular Architecture in three related ways.

The first contribution is empirical. The study provides one of the few published quantitative environmental assessments of a completed, inhabited bio-based vernacular building at the residential scale, conducted against verified as-built data. The embodied carbon intensity of 267.60 kgCO₂e/m² and the thermal performance results across all assemblies offer a documented benchmark against which comparable projects can be evaluated. The simultaneous presentation of fossil embodied emissions, biogenic carbon storage, thermal U-values, and transport distances within a single integrated analysis provides a more comprehensive environmental portrait of this

building typology than studies that address any of these dimensions in isolation.

The second contribution is methodological. The study demonstrates a reproducible approach for evaluating vernacular and bio-based construction within contemporary environmental assessment frameworks, combining EN 15978, ISO 14040, EN 16449, and GEG 2020 compliance analysis in a coherent workflow. The explicit treatment of lime-based binders as dynamic material systems, as developed in Chapter 4, provides a conceptual foundation for future LCA studies that wish to account for the carbonation credit and chemical behaviour of mineral binders rather than treating them as static impact values.

The third contribution is conceptual. By evaluating Naturdorf Bärnau against the framework proposed by its supervising professor, and finding substantiated alignment across all four principles, the thesis provides an evidence-based argument that vernacular material intelligence is not a nostalgic or aesthetic position but a quantitatively defensible architectural strategy. Rather than treating environmental performance and material tradition as competing priorities, the study demonstrates that they can be pursued as mutually reinforcing objectives within a single coherent construction logic. This repositions the 21st-century vernacular not as a stylistic category but as a performance framework with measurable outcomes.

The comparative reflection on the Experimental Pavilions of Vegetarian Architecture in Grugliasco, developed in Section 6.6, further situates the Naturdorf project within an active continuum of experimental and applied bio-based construction practice. It demonstrates how knowledge generated

at research scale, through participatory making and iterative material testing, translates into inhabited architecture through the kind of friction, adaptation, and technical resolution that the Naturdorf project embodies. This continuum is itself an argument for the intellectual seriousness of experimental and vernacular approaches to sustainable architecture.

7.3 Implications for Practice

The findings carry three categories of practical implication: for architects and designers, for policymakers and regulators, and for local stakeholders and communities engaging with bio-based construction.

For architects and designers, the study demonstrates that hybrid bio-mineral construction systems can achieve regulatory thermal compliance and competitive embodied carbon intensity without industrial optimisation. This removes a common objection to vernacular and natural material approaches, namely that they cannot meet contemporary performance standards, and replaces it with evidence that compliance is achievable through material thickness, assembly logic, and hygrothermal coherence rather than through synthetic enhancement. The implication is that architects working in contexts where timber, lime, hemp, and clay are regionally available should treat these materials as viable primary options rather than as marginal or specialist choices. The study also highlights the importance of engaging with LCA at the early design stage, where binder volumes and structural choices have the greatest environmental consequence.

For policymakers and regulators, the study suggests that current thermal performance frameworks in

Germany, specifically GEG 2020, are compatible with bio-based vernacular construction when assemblies are properly detailed and dimensioned. This finding supports the case for regulatory frameworks that recognise hygrothermal performance, vapour permeability, and material reversibility as complementary dimensions of building quality, not merely thermal resistance values. The integration of biogenic carbon reporting into building-level environmental assessments, already enabled by EN 16449, should be further promoted as a way of capturing the full climate significance of bio-based structural systems.

For local stakeholders and communities, the Naturdorf Bärnau project offers a practical model for housing development that preserves regional material and craft knowledge while meeting contemporary living standards. The sourcing data documented in this study demonstrates that a regionally coherent supply chain for bio-based construction is achievable within the Bavarian context, and the accessibility of the construction techniques suggests that maintenance, repair, and adaptation can be managed within a regional skill ecosystem over the building's service life. This has implications for the economic sustainability of rural communities in material-rich regions where conventional construction increasingly imports value from distant industrial supply chains.

7.4 Limitations and Forward Outlook

The present study is bounded by several limitations that define both its scope and the directions in which its findings could be extended.

The LCA is restricted to modules A1–A4, as declared in Section 5.1.4. As discussed in Section 6.1, the magnitude of this exclusion cannot be quantified with

confidence for Building D, and comparable case study research on low-carbon bio-based construction found A5 contributing as much as 20 percent of total A1–A5 embodied carbon (Mazelli et al., in press), substantially higher than is typical for conventional construction. Given Building D's similarly low A1–A4 baseline, the figures presented here should be read as a conservative minimum baseline rather than a complete construction-stage total. The exclusion of operational modules B1–B7 and end-of-life modules C1–C4 reflects the research focus on construction-stage impacts given the building's recent completion and the unavailability of long-term performance data.

The biogenic carbon storage calculation, while methodologically consistent with EN 16449, is based on standardised carbon fractions rather than species-specific or product-specific measurements. The stored carbon figure of 33,947.9 kgCO₂ represents a standardised estimate whose climatic significance depends on service life and post-use material treatment, neither of which can be determined at this stage of the building's life. Future studies that revisit the project after decades of occupation could assess the durability of bio-based components and the retention of stored carbon with greater precision.

The financial flows dimension of Research Question 3 remains partially addressed due to the unavailability of supplier-level procurement data. A complete economic geography of the construction supply chain would require access to the project's procurement accounts, which were not made available for this study.

Three directions for future research emerge from these limitations and from the broader findings of the study. First, a full life-cycle assessment extending to modules B and C, once operational performance data

becomes available from the building’s monitoring phase, would provide a complete picture of the building’s climate impact and enable the full evaluation of the biogenic carbon storage contribution. Second, comparative studies applying the same integrated assessment framework to other buildings within the Naturdorf settlement, and to comparable projects in different climatic and socio-technical contexts, would help establish the generalisability of the findings and the transferability of the material strategy. Third, targeted research into low-carbon lime substitution strategies, particularly the use of natural hydraulic lime, pozzolanic additions, or geopolymers within hygrothermal-compatible assembly systems, would directly address the primary environmental hotspot identified in this study.

7.5 Final Position

This thesis began with a question about whether a contemporary interpretation of vernacular construction could demonstrate measurable environmental performance when assessed through life-cycle methodology. The answer, supported by the evidence developed across seven chapters, is affirmative, and more specifically nuanced than a simple yes.

Building D at Naturdorf Bärnau achieves an embodied carbon intensity of 267.60 kgCO₂e/m², meets GEG 2020 thermal standards across all primary assemblies, sources the majority of its materials within a 50 km radius, and stores approximately 33,947.9 kgCO₂ of atmospheric carbon within its bio-based structural system. These are not marginal achievements. They are the measurable outcomes of a coherent material and architectural strategy that treats locality, breathability, reversibility, and bio-

based structural system. These are not marginal achievements. They are the measurable outcomes of a coherent material and architectural strategy that treats locality, breathability, reversibility, and bio-based continuity not as stylistic preferences but as environmental principles with quantifiable consequences.

At the same time, the study reveals that bio-based construction is not uniformly low-impact. The dominant contribution of lime-based binders, accounting for 60 percent of production-stage emissions, demonstrates that the environmental profile of a material system is shaped as much by its binder infrastructure as by its structural choices. This finding does not undermine the case for vernacular bio-based construction; it refines it. The next generation of projects in this tradition will need to engage seriously with the carbon chemistry of mineral binders, not only the sequestration potential of timber, if they are to push the environmental performance of this building typology toward its lower limits.

Beyond the numbers, the study argues that the 21st-century vernacular is not a nostalgic revival, a stylistic preference, or an alternative niche. It is an evidence-based architectural position, grounded in material intelligence, regional coherence, and constructive honesty, that is capable of engaging contemporary climate metrics without surrendering the cultural and sensory qualities that make architecture more than a carbon calculation. Naturdorf Bärnau demonstrates this not as an aspiration but as a built reality. The task now is to understand it well enough to repeat it.

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