URBAN TECH STUDIES

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FOREST, CITY AND THEIR CARBON CYCLE – QUANTIFICATION OF THE CARBON IMPACT OF DIFFERENT CONSTRUCTION TYPES FOR SCHUMACHER QUARTIER, BERLIN

In cooperation with

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WHAT IS THE MOST SUSTAINABLE WAY TO BUILD USING WOOD?

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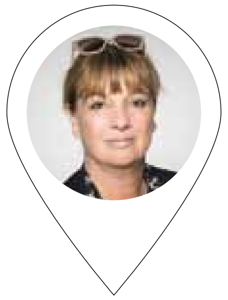


GUDRUN SACK

Managing Director of Tegel Projekt GmbH

Cities around the world are faced with the challenge of meeting the growing demand for building houses in an environmentally-friendly way. Resource-saving construction therefore plays a major role in the construction of the Schumacher Quarter. Over the next 15 years, more than 5,000 residential units are to be built here on 46 hectares, providing more than 10,000 people with comfortable, affordable and sustainable homes.

New concepts and applications will be used in the model quarter. It will become a smart city and sponge city with resource- and climate-friendly infrastructure throughout, as well as a high level of biodiversity and car-free mobility. What's more, it is planned to be one of the largest urban timber construction projects in Europe. Solutions that contribute to its successful construction should serve as a model for many other sustainable neighborhoods in Berlin and around the world.

WOOD AS A GAME CHANGER

The building sector accounts for a significant share of global CO_2 emissions – and building using wood has the potential to be a real game changer on the path to climate neutrality. In addition to being an important carbon reservoir, the building material also offers other benefits: It is ideal for simple construction with loose elements and modules, can be prefabricated with precision and can be quickly assembled on the construction site. The use of computer-controlled planning methods and robotics makes it possible to break new ground in planning and production. This significantly reduces the overall construction time.

USING WOOD FROM THE REGION

In the Berlin-Brandenburg region, we have enough pine wood available to be able to build using wood throughout Berlin over the next 15 years. If we manage the existing monoculture forests in a sustainable way and convert them into resilient mixed crops, this will benefit the entire region. In terms of construction processes, this means we would also become independent of the international timber market, and workflows would also be easier to plan.

RESEARCH WITH DIRECT APPLICATION RELEVANCE

In the one-year research project with students from the Technical University of Berlin under the direction of Prof Galina Churkina, value chains in timber construction were examined systematically, empirically and qualitatively.

Right from the start, the aim was to gain valuable insights for the Schumacher Quarter, to transfer knowledge for day-to-day planning of timber construction, and to develop specifically applicable criteria for this. The study investigates the role of building materials, especially wood, in the context of climate change and the global carbon cycle.

SEARCH FOR THE BEST CARBON FOOTPRINT

Based on the academic discussion as to whether solid timber construction, timber frame construction or even lightweight timber construction is the most sustainable construction method, the idea for this study arose during discussions between Professor Churkina and myself.

This was followed by detailed study and discussion by students of TU Berlin and employees from Tegel Projekt GmbH based on an exemplary block type, a four-story residential building, in the Schumacher Quarter. Tegel Projekt GmbH specified various structures for story ceilings and walls, which were calculated in detail by the study group in relation to their carbon footprint.

The aim was to identify the most climate-friendly construction method by comparing wood and mineral-based construction methods and assessing their contribution to carbon emissions and carbon storage capacity. In addition, each kind of building material was analyzed according to its contribution to carbon emissions during production, manufacture and transport as well as its carbon storage capacity. What was also absolutely exciting for us was the question of whether using regional wood would lead to more climate-friendly building.

PARAMETERS FOR SUSTAINABLE TIMBER CONSTRUCTION

The result is complex, but applicable to any regional context. There is no such thing as a single correct answer to the question "What is the most sustainable way to build using wood?". We still need a detailed view of the specific project, the region, and the supply and value chains there. However, this study provides indications on which parameters to pay attention to in order to implement timber construction in a sensible and sustainable way in the respective region.

GALINA CHURKINA

Professor of Urban Ecosystem Sciences, Technische Universität Berlin

For decades scientists have investigated the capacity of forests, soils, and oceans to act as carbon sinks and offset the enormous release of carbon dioxide associated with the combustion of fossil fuels. These studies have also raised concerns about the future durability of such sinks given that climate change has significantly disturbed those ecosystems. The creation of human-made carbon sinks has recently emerged as a potential supplement to natural carbon uptake and storage.

The growth and urbanization of global populations anticipated over the next several decades will create an enormous demand for buildings and infrastructure, which might become such human-made carbon sinks, if designed with biomass-based materials instead of steel and concrete. Steel and reinforced concrete, the conventional structural materials have high production stage carbon emissions and little or no capacity to store carbon. Their inherent advantages of strength and stiffness come at a significant environmental cost. New and emerging material technologies and building assemblies in timber combine noteworthy structural performance with high carbon storage capacity and low production stage carbon emissions. However what technology to choose if we want to optimize both carbon storage and emissions? What role does the material transport plays in this equation?

The plans to design Schumacher Quartier in Berlin with local timber looked like a perfect case study to explore those questions. In the beginning of 2022 we got together with Gudrun Sack to discuss what timber construction method would be the most optimal for this development in terms of maximizing their carbon storage capacity and minimizing carbon emissions from the building production stage. Together with my students at the TU Berlin we collected necessary data and conducted the pilot assessment shortly thereafter. The first results looked promising so that we decided to follow up with an in-depth study. The Tegel team developed more detailed and complete descriptions of the six possible building assemblies for the Schumacher Quartier and together with another team of TU students we followed up with a comprehensive carbon assessment of those assemblies, which is described in this report. This assessment builds upon the pilot study and is based on an in-depth review of relevant literature, extensive data searches, numerical model, and interviews of experts during our field trip.

ABSTRACT

This study examines the role of construction materials, particularly timber, in the context of climate change and the global carbon cycle. The goal is to determine the most climate-friendly construction type by comparing timber- and mineral-based construction types and assessing their contribution to carbon emissions and carbon storage capacities. Furthermore, each construction material and building part is assessed in terms of its contribution to carbon emissions during production, manufacturing and transport, as well as its carbon storage capacity. Moreover, the study evaluates whether a regional use of timber leads to a more climate-friendly building.

The results show that, on average, timber-based construction types produce around 40 % less carbon emissions in their production than mineral-based constructions. Mineral-based materials, such as limestone, reinforced concrete and brick, have the lowest carbon storage potential. Conversely, timber-based construction types exhibit higher carbon storage potential due to higher amounts of organic materials. The carbon storage in biomass-based buildings ranges from 21.5 kt to 70.3 kt and is therefore about four- to 19-fold higher compared to mineral-based construction types. Furthermore, transport distances play a crucial role in carbon emissions showing that transport emissions highly depend on the weight transported. Transporting lighter materials causes less impact than transporting heavier materials. The highest transport emissions of 14.6 kt are generated by the 'Thoma Wood' construction type, while the lowest transport emissions of 1.9 kt are caused by 'timber frame'. In addition, the choice of transport mode can have a major impact, as transport by rail can reduce transport emissions by 96 % compared to conventional trucks (3.5–7.5 t).

The findings highlight the benefits of using organic construction materials due to their lower carbon emissions and higher carbon storage capacity. These results have implications for sustainable construction practices and suggest that timber-based construction types offer a promising opportunity for reducing the carbon footprint of the construction sector.

This research contributes to the understanding of sustainable construction practices and their potential to mitigate climate change. Future studies could further explore the implementation of sustainable forest management practices and investigate the regulatory frameworks required to promote the use of timber as a climate-friendly construction material.

1 INTRODUCTION

1.1 CLIMATE CHANGE AND GLOBAL CARBON CYCLE

Climate change has been identified as one of the biggest threats to humankind and all living beings on the planet (IPCC, 2023). The main cause of climatic changes on Earth is the in-creased concentration of greenhouse gases in the atmosphere (ibid.). Since the greenhouse gases carbon dioxide (CO_2) and methane are chemically based on carbon inter alia, the carbon cycle is of particular interest in understanding and combating climate change.

The global carbon cycle constitutes a very complex system with stocks and fluxes on various spatial and temporal scales within and between the atmosphere, biosphere, hydrosphere and lithosphere compartments (Carlson et al., 2008; Reichle, 2023). The largest carbon stocks are stored in rocks, followed by the oceans, soils, the atmosphere and the living plant biomass (Carlson et al., 2008). Anthropogenic activities such as fossil fuel combustion, large-scale land-use changes (urbanisation, intensive agriculture and deforestation), as well as resource-intensive consumption patterns lead to the extraction of stored carbon and thus increase greenhouse gas emissions, particularly of CO_2 (IPCC, 2023). Humans are responsible for profoundly altering the carbon cycle by unbalancing the natural stocks and fluxes of carbon (Carlson et al., 2008; IPCC, 2023).

If the emissions of greenhouse gases are not minimised, the effects of climate change will intensify (IPCC, 2023). In order to effectively reduce emissions in the long term, it is necessary to target the sectors with the highest CO_2 emissions. Accordingly, the building sector could be a promising and important starting point. In 2021, CO_2 emissions related to construction, operation and processing of buildings amounted to 37 % of global CO_2 emissions. Nine per cent of these emissions originate from the production of mineral-based construction materials such as steel, brick or concrete alone (United Nations Environment Programme, 2022).

1.2 CONSTRUCTION MATERIALS AND THEIR EFFECT ON THE GLOBAL CARBON CYCLE

Since the industrial revolution, mineral-based construction materials have become the standard for modern construction on a large scale due to their impressive high tensile strength and stability. However, such construction materials have decisive disadvantages: their production and processing require a lot of energy, most of which comes from burning fossil fuels (Dangel, 2017). These issues illustrate the urgent need to transform global building practices and create new pathways for sustainable construction. Therefore, the choice of construction materials and the energy performance of buildings offer great potential for reducing emis-sions (Churkina et al., 2020; IEA, 2022).

As a renewable resource, timber is a promising material for this purpose (Dangel, 2017). Trees store carbon throughout their entire lifespan, thus playing a crucial role in the global carbon cycle by acting as a natural carbon sink. The stored carbon remains within the raw material even when a tree is harvested. Release of carbon to the atmosphere only occurs through aerobic decay or combustion. This usually happens only after decades of timber product usage (Organschi et al., 2016). Therefore, storing carbon in long-living timber products like building parts can potentially increase the urban carbon stock (Lauk et al., 2012). The lifetime of construction timber is generally estimated to be at least fifty years, but it can be even longer if timber is used in a cascading manner (Höglmeier et al., 2015; Neuhaus, 2017). Beyond their ability to store carbon, timber buildings and long-living timber products can also positively impact the carbon cycle through two types of substitution effects. Firstly, increased use of timber-based materials in place of mineral-based materials in construction of buildings would avoid carbon emissions from the production of mineral-based materials like concrete or steel (Bowyer et al., 2012).

Additionally, increasing demand for timber can stimulate forestry, and thus in some forest-rich regions of the world it may prevent forests from being cleared for economic reasons, e.g., for agricultural land (Bowyer et al., 2012; Dangel, 2017).

In conclusion, while the production of mineral-based construction materials releases high amounts of carbon into the atmosphere, timber-based materials can store carbon in the long term, acting as a natural carbon sink when being used in the building sector. Among other advantages of timber construction (short construction times, high degree of prefabrication, low weight and comfortable room climate), this is one of the reasons why construction with biomass-based or low-emitting materials is increasingly recognised as a climate change mitigation measure (Churkina et al., 2020; Hildebrandt et al., 2017).

1.3 FOREST MANAGEMENT

At the same time, there is a need to focus on regional forestry to ensure a sustainable supply of raw materials for timber construction. Globally and across all forest biomes, carbon stored in trees (aboveground biomass and their root systems) accounts for 42 % of the carbon stock stored in temperate forests, the soil for 44 % and dead wood and leaf litter for 13–14 % (Pan et al., 2011). Maintaining the resilience of these ecosystems is therefore important to protect their valuable carbon sink function.

Increasing extreme weather events, such as heat, droughts and heavy precipitation, leave forests more vulnerable to natural hazards such as wildfires, storms and insect infestations (Arnold, A. I. M. et al., 2016; Martínez-Sancho et al., 2022; Palviainen et al., 2020). These events can reduce the ability of forests to absorb and store carbon in the short term as well as increase carbon emissions into the atmosphere. Hence, active forest management is needed to ensure that these ecosystems can cope with climate change and thus keep their natural carbon sink function. Influencing the tree species composition within a forest is one approach to achieve this. Osuri et al. (2020) found that semi-natural and biodiverse forests are less vulnerable to disturbances such as drought than monodominant plantations. Additionally, the total carbon storage poten-tial of broadleaf and mixed forests is greater than that of coniferous (Chen et al., 2016; He et al., 2013). Also, specific management and harvesting methods impact natural carbon storage functions.

'Clearcutting' is a method whereby all trees are felled – the forest switches from being a sink to a source of carbon. In consequence of a clear cut, net primary production drops to zero. Carbon stocks in the soil increase during the first years after clearcutting but start to decrease in succeeding years with growing microbial activity (Ameray et al., 2021).

'Partial cuts' offer another practice whereby not all trees are harvested at the same time. For this management method, the quantity of harvested trees is not specified. The effects on carbon sequestration and soil carbon stocks therefore vary and depend, for example, on the logging intensity and the duration of the forest recovery period. Potentially, managing the forest using the 'partial cuts' method can enhance forest carbon sequestration and positively affect soil carbon stocks (Ameray et al., 2021). The latter can also be facilitated by not harvesting the whole tree, but leaving branches, treetop or bark in situ (Johnson & Curtis, 2001).

The appropriate rate of timber harvesting and the extent of carbon sequestration vary between different forest ecosystems and climatic regions (Ameray et al., 2021). Moreover, they depend on specific biotic and abiotic factors (ibid.).

1.4 DESCRIPTION OF CONSTRUCTION PLANS FOR SCHUMACHER QUARTIER

The present study compares six different construction types, four of them mainly timber-based, using the specific example of the future Schumacher Quartier in Berlin, Germany. Schumacher Quartier is a part of the urban planning project Berlin TXL, which aims at repurposing the former Berlin Tegel Airport. It is located in the eastern part of the former Berlin Tegel Airport site with the coordinates of 52°32'59.8"N and 13°17'52.3"E. The total former airport area ranges within a size of 500 ha, with Schumacher Quartier comprising 48 ha to represent one of the largest urban development projects in Europe (Ambrosius-Groß et al., 2023). The plans for Schumacher Quartier comprise ecological and sustainable construction concepts aiming to build 5,000 apartments for more than 10,000 residents (Figure 1 & Figure 2), half of them built by public housing cooperatives. The proposed construction strategy includes the use of timber as the primary material for buildings to reduce carbon emissions throughout the construction phase and to store carbon within the structures. In a nutshell, the intention of the project developers is thus to minimise the carbon footprint associated with Schumacher Quartier. Plans for Schumacher Quartier incorporate both green roofs on and green spaces between the buildings. The inclusion of green spaces within the built environment contributes to the enhancement of ecological integration and provides habitat to local biodiversity (pers. communication Tegel Projekt GmbH, 2023).

Figure 1

Plan of the Schumacher Quartier, Tegel Project GmbH, Berlin 2023. The black arrow highlights the exemplary four storey building shown in figure 2.

Figure 2

An exemplary four storey building planned for Schumacher Quartier, Tegel Project GmbH, Berlin 2023.

1.5 GOAL AND STRUCTURE

Many studies have shown the advantages of using timber-based materials in the construction sector in order to decrease carbon emissions without deteriorating the natural carbon sink function of forests (Arehart et al., 2021; Churkina et al., 2020; Hart & Pomponi, 2020; Hildebrandt et al., 2017). However, the expansion of timber construction in Germany is still hampered by several obstacles. Practitioners and legislators claim that more knowledge about timber-based materials is needed, that education in the construction sector should focus more on sustainable building and that legal regulations, e.g. on fire protection or emissions of volatile organic compounds in indoor environments, need to be put to the test (Handreichung Holzbauinitiative, 2023; European Environment Agency, 2014). Practical, science-based guidelines are needed to promote the use of timber in the construction sector and to support architects and urban planners in the long-term.

This report analyses six different types of construction considered for the Schumacher Quartier and addresses the following questions:

→ 1. Which construction types are the most climate-friendly in terms of their carbon emissions and storage?

→ 2. Which materials and building parts have the largest contribution to carbon emissions during production, manufacturing and transport, and which store the most carbon?

→ 3. Is the usage of regional timber and raw materials necessarily the most climate-friendly?

The first part of this report introduces the construction types, the Carbon Cycle Assessment (CCA) methodology used for calculations and the relevant data. In the second part, the CCA results are presented and the associated uncertainties are discussed. The report closes with conclusions on the guiding questions and with an outlook for future research.

2 DATA AND METHODS

BASIS AND ORIGIN OF DATA

The data basis for this study was provided in cooperation with Tegel Projekt GmbH. Tegel Projekt GmbH was responsible for the conception of the six construction types that served as the basis for the following investigations. They developed the architecture of the buildings, determined the construction materials and their quantities, densities and mass proportions on which the calculations are based.

The application example refers to a four storey building block with a floor area of 1,276.429 m² per floor and an exterior wall area of 1,935.402 m² (excluding windows), considering an estimated window proportion of 30 % of the total exterior area. Internal walls were not considered in this study. The ceiling area amounts to 3,824.32 m², while the roof area measures 1,274.77 m². The roof is designed to be completely covered with vegetation.

The six construction types, each of which considers exterior walls, ceiling slab and roof for the analysis, can be divided into three categories: mineral-based construction types, light frame timber construction types and mass timber construction types. A table with all construction materials used in the six construction types and their contributions by weight to the entire building as well as the single building parts (walls, ceiling slabs, roof) can be found in the appendices (Table 2).

2.1 COMPONENT STRUCTURES FOR DIFFERENT CONSTRUCTION TYPES

BUILDING SELECTION

For this study, an exemplary building from the development plan of the Schumacher Quarter was selected, which is located in the first construction phase and has a cubature that can also be found in the other construction phases. As shown in figure 2, the building is located in the southern portion of block 9 and is a four storey frame building.

GENERAL REQUIREMENTS AND SELECTION OF BUILDING PART LAYERS

For the example building mentioned above, the masses of the selected superstructures were calculated for all exterior walls, ceilings and roofs. Only the foundation is planned as a reinforced concrete base. For the sake of simplicity, a cellar is not included. Nor has a specific static structure been defined. No structural specifications have been formulated for the wall and ceiling elements. The building is classified in building category 4.

In order to determine approximately realistic values with regard to the wood and building material content, the masses of the wall elements have been calculated with two window cutouts of a standard format per 7m wall section. The superstructures of all versions are selected to meet the same requirements for thermal insulation, fire protection and, if necessary, sound insulation as far as possible (see illustrations below).

MINIMUM REQUIREMENTS FOR CONSTRUCTION OF EXTERIOR WALL:

Facade level	Thermal insulation: 0.16 W/(m²K)
Construction and thermal insulation layer	Fire protection: at least REI 30
Interior lining	Sound protection: Lnw = / Rw = /

MINIMUM REQUIREMENTS FOR FLOOR SLAB:

Floor structure	Thermal insulation: -/- W/(m²K)
Construction and sound insulation layer	Fire protection: at least REI 60
Ceiling cladding	Sound protection: Lnw = <53 dB / Rw = >54 dB

MINIMUM REQUIREMENTS FOR STRUCTURE OF RETENTION ROOF:

Roof structure	Thermal insulation: 0.16 W/(m²K)
Construction and thermal insulation layer	Fire protection: at least REI 60
Ceiling cladding	Sound protection: Lnw = <53 dB / Rw = /

FUNCTIONAL LAYERS

The component structures were selected on the basis of the previously mentioned and presented structural/physical requirements. An economic comparison of the different structures has not been considered in this study, but may be used for a follow-up study.
The system boundaries within the calculations of the constructions are chosen comparably. Although the component of the structural part (construction and thermal insulation level) is the focus of this observation, each structural part was also divided into 3 levels in order to be able to compare the functional layers of the structural part with each other [blue, red, green]. Even varying interior paneling, facade layers, suspended ceiling systems and floor constructions can make a difference to the overall construction when all masses are considered globally.

THE STRUCTURAL PARTS ARE DIVIDED INTO FUNCTIONAL LAYERS AS FOLLOWS

Outer walls
Facade skin,
thermal and construction level,
interior paneling story

Ceilings
Floor structure,
structural and sound insulation level,
ceiling cladding (some with fire protection function)

Roofs
Green roof,
structural and thermal insulation level,
ceiling cladding

All roofs are designed as retention roofs. For the sake of simplicity, the same greening system is assumed in all roof structures. Different on-roof insulation systems were selected to provide further variation (different building material) in the roof structure. Insulations range from compression-resistant wood fiber, to pressure-resistant mineral wool, to XPS and foam glass. The differences in the sustainability of the building materials in terms of production, thermal insulation function and durability become clear on closer inspection.

CONVENTIONAL CONSTRUCTION METHODS

BRICK CONSTRUCTION PAGE 15 | 16

The outer wall is made of chamber-insulated bricks (with mineral wool). Exposed bricks are fixed to a wooden substructure as the facade skin. On the inside, the wall finishes with a lime plaster. The floor slab element is a brick suspended slab consisting of a brick core and strips of grouted concrete with appropriate reinforcement for reinforcement. The floor structure is specified as a floating screed and an impact sound insulating layer of mineral wool. On the room side, a lime plaster is used and the flat roof structure is calculated from prefabricated elements in the form of a tile suspended ceiling. The roof element is also designed as a tile suspension element. An on-roof insulation board made of pressure-resistant rock wool is laid under the retention roof structure.

SAND-LIME BRICK/REINFORCED CONCRETE CONSTRUCTION PAGE 17 | 18

The exterior wall structure consists of a sand-lime brick wall with a fleece-laminated mineral wool board and a special compressed carbon facade panel fixed to a wooden substructure. On the inside, gypsum plaster is used for plastering the wall. The floor slab and the roof structure are selected in accordance with conventional construction methods in multi-story residential construction in reinforced concrete construction. In the floor structure of the story ceiling, a mineral wool board for impact sound insulation is laid under a floating screed. In the room, a lime plaster system is applied to the underside of the ceiling element. The roof receives on-roof insulation made of foam glass.

TIMBER CONSTRUCTION CONSTRUCTION TYPES

LIGHTWEIGHT TIMBER CONSTRUCTION PAGE 19 | 20

A lightweight timber construction system has the advantage of being as resource-efficient as possible, since the belts are made of laminated veneer lumber as an I-Joist system. The belts are made of heavy duty laminated veneer lumber and the joists are made of hardboard. Just like in timber frame construction, the space between the vertical belts is used as an insulation layer and has the advantage over solid timber construction of being able to create slimmer wall structures. The selected wall is formed with cellulose blown-in insulation between the web beams and a wood fiber insulation board terminating on the outside. A ventilated fiber cement board on a wooden substructure is planned as the facade skin. On the inside, an OSB board closes off the insulated steel girder construction and is additionally covered with a clay building board, which fulfills both room-climatic advantages and fire protection functions. The inside of the story ceiling is covered with a soft wood fiber insulation mat. The floor structure results from a weighting system of paperboard honeycombs filled with sand and wood fiber insulation boards. A double gypsum fiberboard panel is attached to a spring rail substructure as a room-side element finish with sound insulation and fire protection functions. In addition to the ceiling structure, the roof has a pressure-resistant on-roof insulation made of wood fiber insulation board and a moisture-variable vapor barrier and wood fiber insulation board on the room side.

TIMBER FRAME CONSTRUCTION PAGE 21 | 22

This exterior wall in the form of a timber frame construction is a typical resource-efficient timber construction with upper and lower frame timbers and vertical studs forming an intermediate space that is ideally used as an insulation layer (cellulose insulation in this case). For reinforcement, the wall is paneled on the inside with an OSB board and closed on the outside with a wood fiber insulation board. The facade skin consists of a rear-ventilated wooden formwork. The selected floor system of the wood joist ceiling consists of a dry screed made of natural stone as a way to improve sound insulation, soft wood fiber boards and a leveling layer of mineralized wood chips. According to the manufacturer, the system is reusable after its service life or can be returned to the material cycle. Between the beams is a wood fiber insulation mat for additional sound insulation. As ceiling cladding, a gypsum fiberboard is mounted on a substructure of spring rods as additional sound decoupling. The roof element differs only in a few points. Mineral wool is selected as cavity insulation and the on-roof insulation consists of a pressure-resistant wood fiber insulation board.

CROSS LAMINATED TIMBER PAGE 23 | 24

A cross laminated timber element (BSP/CLT) as an exterior wall is already a rigid timber element, which consists of laminated timber lamellas. A soft wood fiber mat is formed as the exterior insulation layer between vertically and horizontally formed laminated veneer lumber belts, which is closed to the outside by means of a rigid wood fiber insulation board as a plaster base board and finished with a mineral plaster system. On the inside, the wood remains visible as the wall. On top of the cross laminated timber ceiling, a floor system with a typical dry screed board made of gypsum fiber with a wood fiber insulation board on the underside as impact sound insulation and a resiliently bonded fill as weighting and for sound insulation purposes is laid. The cross laminated timber ceiling element means the wood is visible underneath. An XPS rigid foam board is considered on top as the roof insulation of the BSP ceiling element. In this study, this construction type is referred to as mass timber construction.

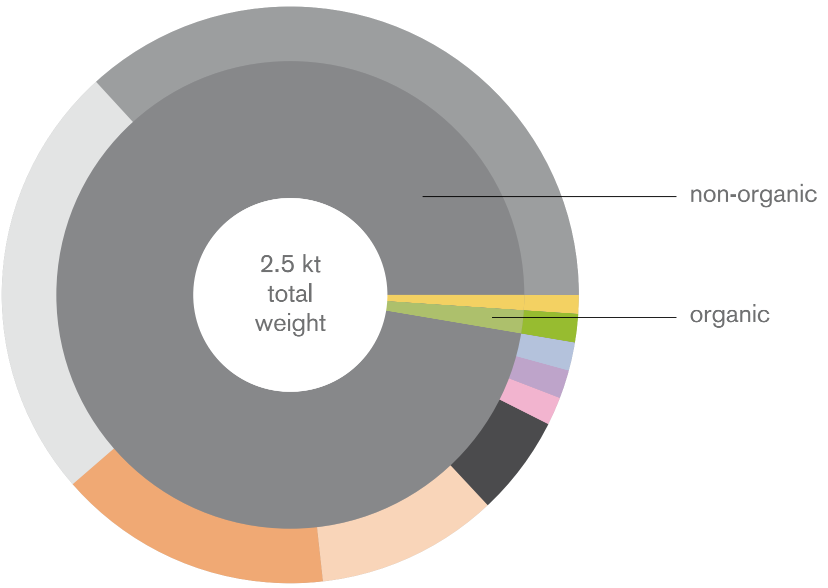
SOLID TIMBER CONSTRUCTION – THOMA WOOD100 PAGE 25 | 26

A solid wood element is selected as the structural element. What sets Thoma-wood apart is the use of moon wood and the connection of the crosswise and diagonally laid wooden boards by pressed beech dowels. This solid wood system is free of glue and adhesives. The solid wood element is constructed with an insulation board on the outside, on which the facade skin (a grooved larch formwork) is mounted by means of a wooden substructure. The wall remains visible inside the room. The floor slab element consists of a floor structure made of various layers of wood fiber insulation board, screed elements and honeycomb filling. The wooden element remains visible inside the room. The roof receives on-roof insulation made of a pressure-resistant wood fiber insulation board.

2.1.1
MINERAL-BASED CONSTRUCTION TYPES

2.1.1.1
BRICK

Conventional brick-based construction has a total weight of 2.5 kt and consists of the two main components brick (37 %) and concrete (25 %), as can be seen in Figure 3. Floating screed used for the ceiling slabs accounts for 18 % of the total weight of the building and intensive substrate light, what is applied to roof, accounts for 8 %. Other non-organic materials are plaster with 5 % and mineral wool, mineral board and rockwool insulation, each of which contributes 2 % to the total weight. In comparison, the weight percentage of organic materials is very low (about 2 %). The rest of the construction material accounts for less than 1 % of the weight.

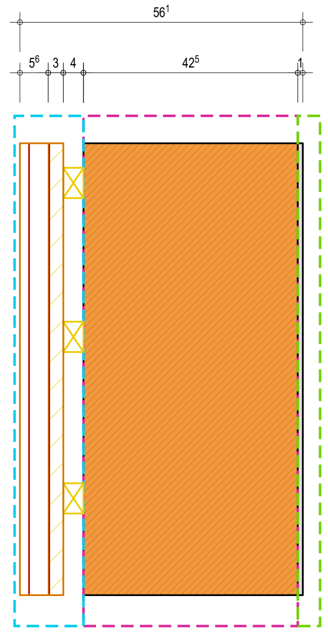


CONSTRUCTION MATERIAL

37 %	brick
25 %	concrete
18 %	floating screed
8 %	intensive substrate light
5 %	plaster
2 %	mineral wool
2 %	mineral board
2 %	rockwool
2 %	timber furnishing
1 %	other materials under 1 % of the weight

→ **Figure 3**
Weight percentage of non-organic and organic materials and total weight of one building of the brick construction. A list of the materials under 1 % of the weight can be found in Table 2.

WALL



outside to inside/left to right | horizontal cut

86 mm Petersen-Tegl-Cover - stone
30 mm counter battens wood
40 mm supporting battens wood

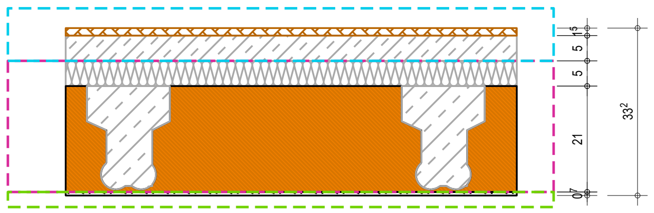
425 mm brickwork Thermoplan MZ7 (mineral wool insulated brick)

10 mm lime plaster

Construction note Petersen-Tegl stone

→ **Figure 4**
Structure of the external wall for the brick construction, Tegel Projekt GmbH, Berlin 2023

CEILING SLABS



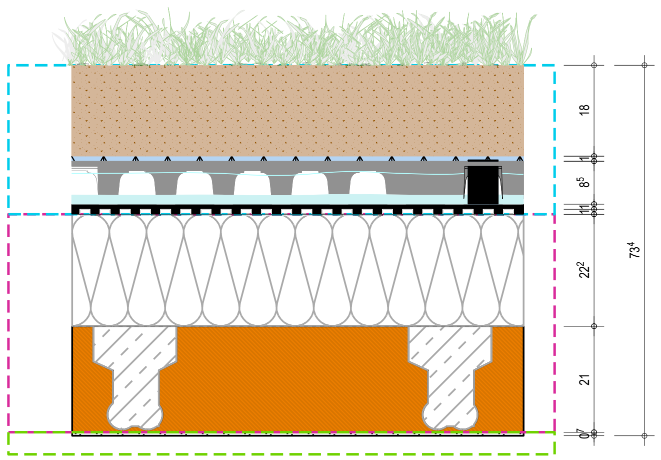
15 mm parquet
50 mm floating screed
0.5 mm separating layer - PE foil

50 mm impact sound insulation mineral wool
210 mm brick element suspended ceiling including concrete filling - casting concrete C25/30 – 38lt/m²
(calculations without steel)

7 mm lime plaster

→ **Figure 5**
Structure of the ceiling slabs for the brick construction, Tegel Projekt GmbH, Berlin 2023

ROOF



180 mm intensive substrate
5 mm absorbent capillary fleece
85 mm retention boxes
5 mm storage fleece
(5.2 mm root protection)
1.5 mm EPDM roofing membrane

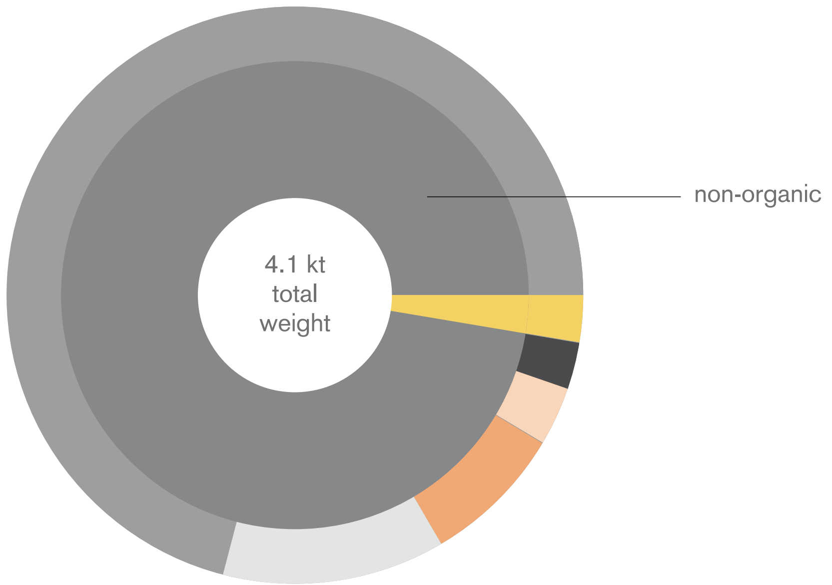
220 mm Rockwool Hardrock 038 (pressure-resistant)
2 mm vapor barrier
210 mm brick element suspended ceiling (without top concrete)

7 mm plaster

→ **Figure 6**
Structure of the roof for the brick construction, Tegel Projekt GmbH, Berlin 2023

2.1.1.2
REINFORCED CONCRETE

'Reinforced concrete' is the heaviest of all construction types, with a total weight of 4.1 kt (Figure 7). This is due to the high proportion of reinforced concrete used in ceiling slabs and roof, making up 62 % of the total weight. In the walls, limestone is the heaviest material and therefore accounts for 14 % of the total weight. Floating screed is only used for the ceiling construction but accounts for 11 % of the total weight. Other materials are intensive substrate light (5 %) located in the roof, plaster (4 %) and others, each accounting for less than 1 % of the total weight (Table 2). Nearly the entire construction type consists of non-organic materials except for a very small proportion.

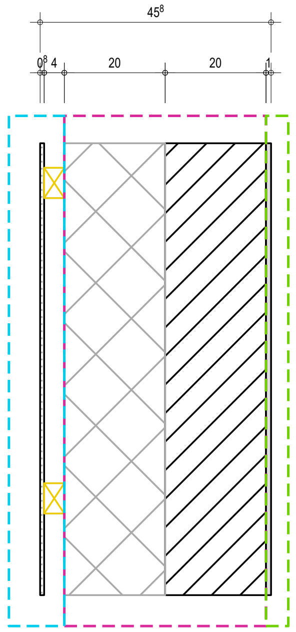


CONSTRUCTION MATERIAL

- 62 % reinforced concrete
- 14 % limestone
- 11 % floating screed
- 5 % intensive substrate light
- 4 % plaster
- 4 % other materials under 1 % of the weight

→ **Figure 7**
Weight percentage of non-organic and organic materials and total weight of one building of the reinforced concrete construction. A list of the materials under 1 % of the weight can be found in Table 2.

WALL

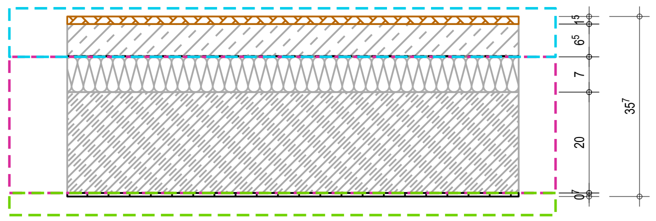


outside to inside/left to right | horizontal cut

- 8 mm Made of Air facade panel
- 40 mm wooden substructure
- 200 mm mineral wool 040 - fleece lined
- 200 mm sand-lime brickwork
- 10 mm gypsum plaster

→ **Figure 8**
Structure of the external wall for the reinforced concrete construction, Tegel Projekt GmbH, Berlin 2023

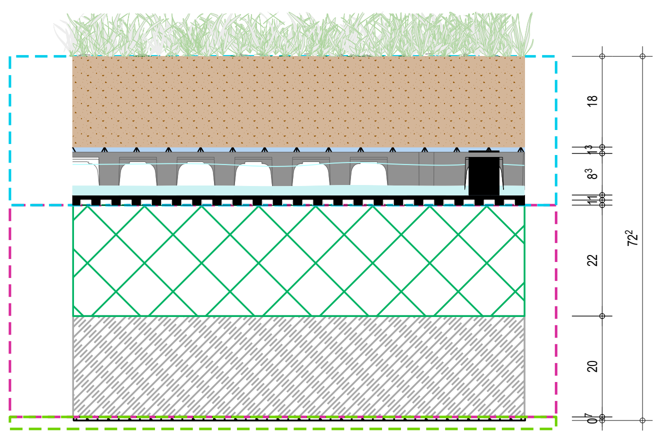
CEILING SLABS



- 15 mm parquet
- 65 mm floating screed
- 0.2 mm separating layer - PE foil
- 70 mm impact sound insulation mineral wool
- 200 mm reinforced concrete ceiling
- 7 mm lime plaster

→ **Figure 9**
Structure of the ceiling slabs for the reinforced concrete construction, Tegel Projekt GmbH, Berlin 2023

ROOF



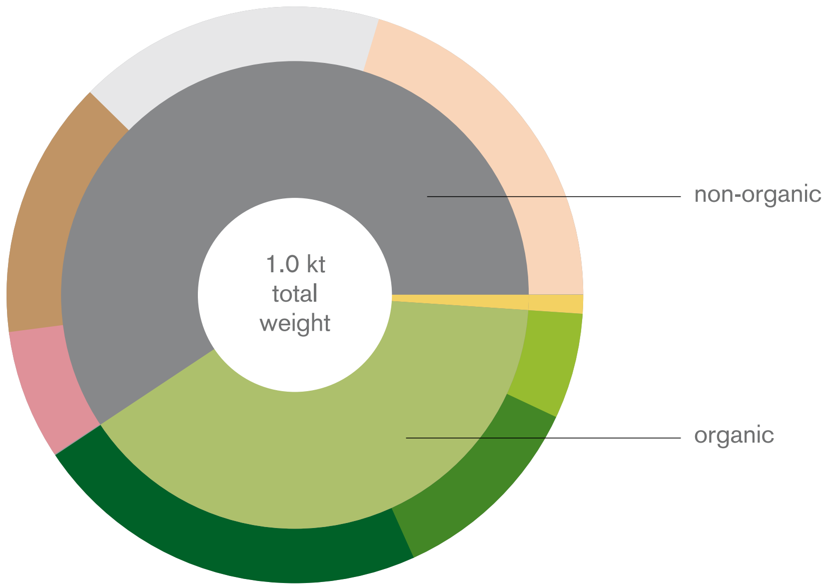
- 180 mm intensive substrate
- 5 mm absorbent capillary fleece
- 85 mm retention boxes
- 5 mm storage fleece
- (5.2 mm root protection)
- 1.5 mm EPDM roofing membrane
- 220 mm FOAMGLAS panel T3+
- 2 mm vapor barrier
- 200 mm reinforced concrete element
- 7 mm lime plaster

→ **Figure 10**
Structure of the roof for the reinforced concrete construction, Tegel Projekt GmbH, Berlin 2023

2.1.2
LIGHT FRAME TIMBER CONSTRUCTION TYPES

2.1.2.1
LIGHTWEIGHT TIMBER

'Lightweight timber' ranks as the lightest construction type compared to all others, with a total weight of 1 kt (Figure 11). In contrast to conventional construction type, lightweight timber is characterized by its high percentage of organic materials, including the combined material groups of timber structure (18 %), timber insulation (14 %) and timber furnishing (7 %). The largest share of non-organic material is accounted for by the intensive substrate light used in the roof, representing 20 % of the total weight of the building. Gypsum fibreboard also has a high weight share of 17 %, followed by dry screed (16 %) and mineral-based boards (8 %). Other materials, each representing less than 1 % of the total weight, are listed in the appendices (Table 2).

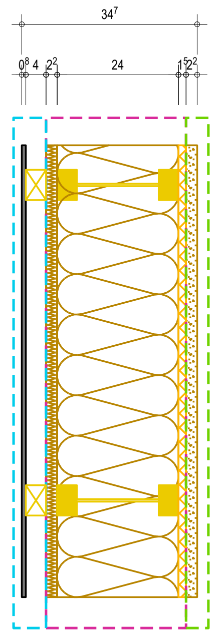


CONSTRUCTION MATERIAL

- 20 % intensive substrate light
- 17 % gypsum fibreboard
- 16 % dry screed
- 8 % mineral based boards
- 18 % timber structure
- 14 % timber insulation
- 7 % timber furnishing
- 1 % other materials under 1 % of the weight

→ **Figure 11**
Weight percentage of non-organic and organic materials and total weight of one building of the lightweight timber construction. A list of the materials under 1 % of the weight can be found in Table 2.

WALL



outside to inside/left to right | horizontal cut

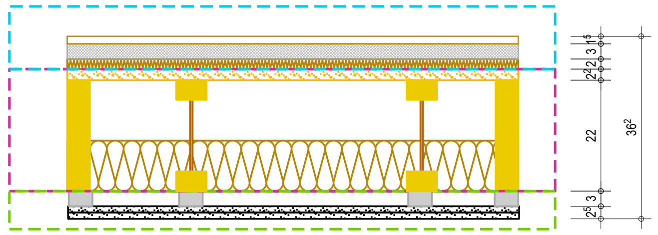
8 mm fiber cement panel
40 mm supporting battens
1 mm wind-proofing film

22 mm wood fiber insulation board STEICOuniversal
240 mm STEICOwall web beam 240 mm
(240 mm cellulose insulation – STEICOfloc)
15 mm OSB board

22 mm clay building board

→ **Figure 12**
Structure of the external wall for the lightweight timber construction, Tegel Projekt GmbH, Berlin 2023

CEILING SLABS



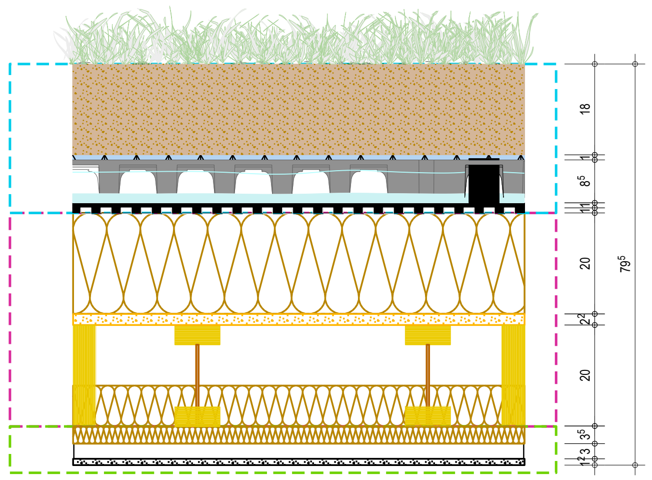
15 mm parquet
30 mm Wolf Phonestar
20 mm impact sound wood fiber insulation board – STEICOtherm

22 mm OSB
220 mm STEICOjoist
100 mm wood fiber insulation

0.2 mm trickle protection
2.7 mm spring rail
25 mm (2x1.5) GF- board (range max. 400 mm)

→ **Figure 13**
Structure of the ceiling slabs for the lightweight timber construction, Tegel Projekt GmbH, Berlin 2023

ROOF



180 mm intensive substrate
5 mm absorbent capillary fleece
85 mm retention boxes
5 mm storage fleece
(5.2 mm root protection)
1.5 mm EPDM roofing membrane

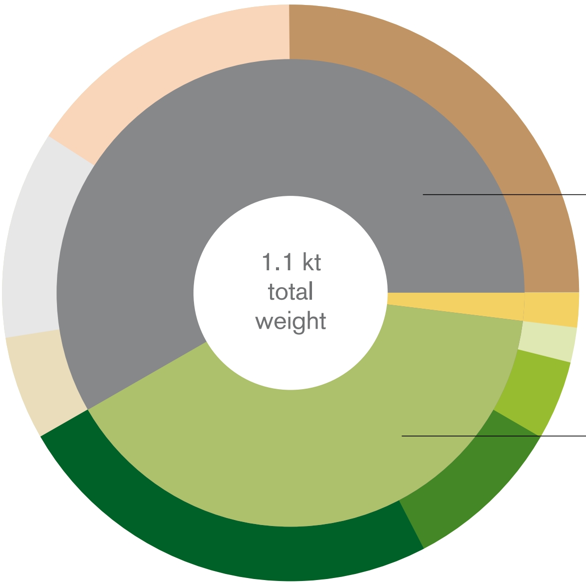
200 mm wood fiber insulation board, pressure-resistant - STEICOroof dry
2 mm vapor barrier
22 mm OSB
200 mm STEICOjoist beam 3.9/9 cm
(80 mm wood fiber insulation mat - STEICOzell)

2 mm STEICOmulti renova - variable moisture vapor barrier
35 mm HFD board STEICOuniversal
27 mm spring rail
15 mm gypsum fiberboard

→ **Figure 14**
Structure of the roof for the lightweight timber construction, Tegel Projekt GmbH, Berlin 2023

2.1.2.2
TIMBER FRAME

'Timber frame' construction is almost as light as the lightweight timber construction type with a total weight of 1.1 kt (Figure 15). Similar to lightweight timber, it holds a high percentage of organic materials, including the combined material groups of timber structure (21 %), timber insulation (10 %) and timber furnishing (5 %), as well as cellulose insulation (2 %). Here, dry screed (24 %) and intensive substrate light (17 %) have the largest shares of non-organic materials in relation to the total weight of the building, followed by gypsum fibreboard (14 %) and fill lime chippings (6 %). Other materials, each accounting for less than 1 % of the total weight, are listed in the appendices (Table 2).

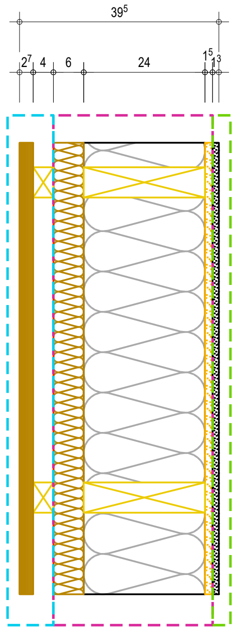


CONSTRUCTION MATERIAL

- 24 % dry screed
- 17 % intensive substrate light
- 14 % gypsum fibreboard
- 6 % fill lime chippings
- 21 % timber structure
- 10 % timber insulation
- 5 % timber furnishing
- 2 % cellulose insulation
- 2 % other materials under 1 % of the weight

→ **Figure 15**
Weight percentage of non-organic and organic materials and total weight of one building of the timber frame construction. A list of the materials under 1 % of the weight can be found in Table 2.

WALL



outside to inside/left to right | horizontal cut

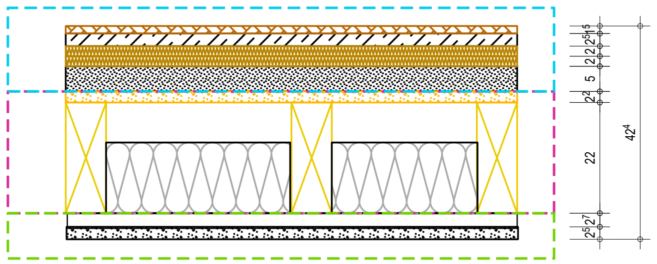
27 mm Larch formwork
40 mm battens (rear ventilation level)
1 mm wind-proofing film

60 mm wood fiber insulation board
240 mm KVH construction
(240 mm cellulose insulation)
15 mm OSB board

1.25 mm gypsum fiberboard (GKF)

→ **Figure 16**
Structure of the external wall for the timber frame construction, Tegel Projekt GmbH, Berlin 2023

CEILING SLABS



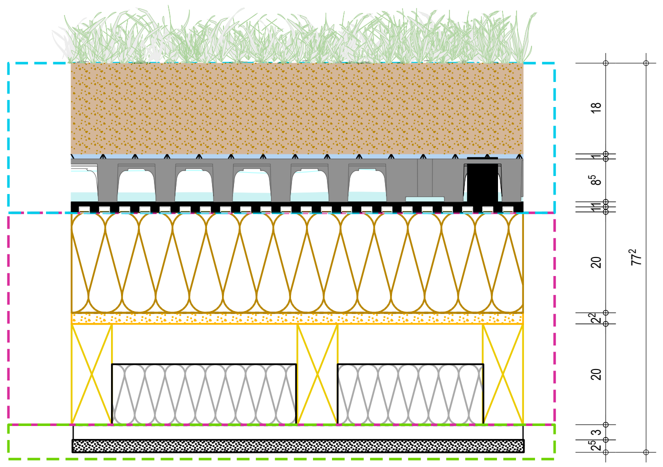
15 mm parquet
25 mm Lithotherm dry coating LW86 Granite (68 kg/m²)
20 mm Lithowood soft wood fiber panel - 5 kg/m²
20 mm Lithowood impact sound panel - 3.2 kg/m²
50 mm LW10 dry filling Cemwood - approx. 16 kg/m²
0,2 mm trickle protection

22 mm OSB panel
220 mm wooden beam 220 x 80 mm
140 mm wood fiber insulation board

0,2 mm trickle protection
2,7 mm spring rail
25 mm gypsum fiberboard 2 x 12.5 mm

→ **Figure 17**
Structure of the ceiling slabs for the timber frame construction, Tegel Projekt GmbH, Berlin 2023

ROOF



180 mm intensive substrate
5 mm absorbent capillary fleece
85 mm retention boxes
5 mm storage fleece
(5.2 mm root protection)
1.5 mm EPDM roofing membrane

200 mm Wood fiber insulation – pressure-resistant STEICOroof dry
1 mm Vapor barrier
22 mm OSB panel
200 mm wooden beam
(120 mm Rockwool Klemmrock 035)

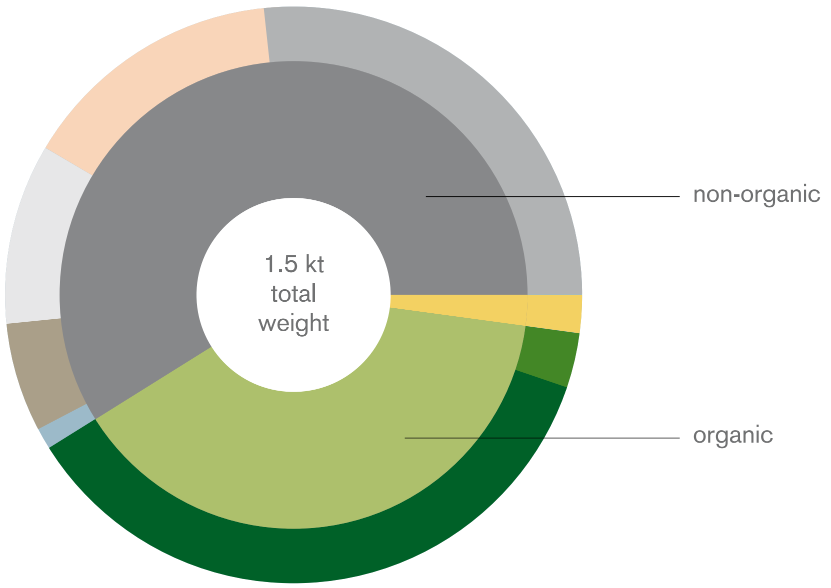
0.2 mm trickle protection
27 mm spring rail
25 mm gypsum fiberboard 2 x 12.5 mm

→ **Figure 18**
Structure of the roof for the timber frame construction, Tegel Projekt GmbH, Berlin 2023

2.1.3 MASS TIMBER CONSTRUCTION TYPES

2.1.3.1 MASS TIMBER

Weighing 1.5 kt, 'mass timber' construction is heavier than the light frame timber construction types (Figure 19). In contrast to mineral-based construction types, mainly biomass-based materials are used for mass timber. The combined material group of timber structure accounts for 40 % of the total weight, with cross-laminated timber (CLT) being the main material and accounting for a large part of the weight. Timber-based insulation accounts for only 3 % of the weight. The largest share of non-organic material in relation to the weight of the building are elastic bonded fill with 26 %, which is used for the ceiling slabs, followed by intensive substrate light (12 %), applied to the roof. Gypsum fibreboard (9 %), tiles (6 %) and mineral plaster (1 %) are further components. Other materials, each accounting for less than 1 % of the total weight, are listed in the appendices (Table 2).

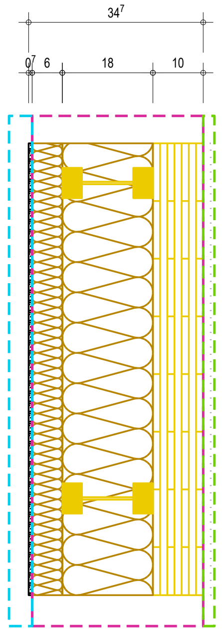


CONSTRUCTION MATERIAL

- 26 % elastic-bonded fill 90 kg/m²
- 12 % intensive substrate light
- 9 % gypsum fibreboard
- 6 % tiles
- 1 % mineral plaster
- 40 % timber structure
- 3 % timber insulation
- 2 % other materials under 1 % of the weight

→ **Figure 19**
Weight percentage of non-organic and organic materials and total weight of one mass timber building. A list of the materials under 1 % of the weight can be found in Table 2

WALL



outside to inside/left to right | horizontal cut

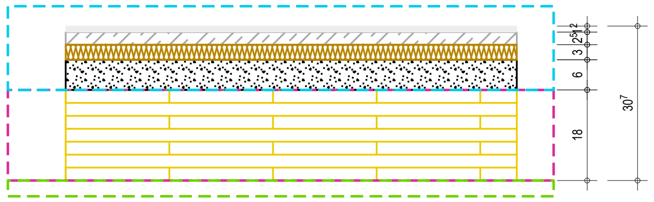
7 mm mineral plaster system

60 mm HFD board STEICOprotect type M
180 mm STEICOjoist beam
180 mm HFD mat STEICOflex 036
100 mm cross laminated timber element

Visible wooden surface

→ **Figure 20**
Structure of the external wall for the mass timber construction, Tegel Projekt GmbH, Berlin 2023

CEILING SLABS



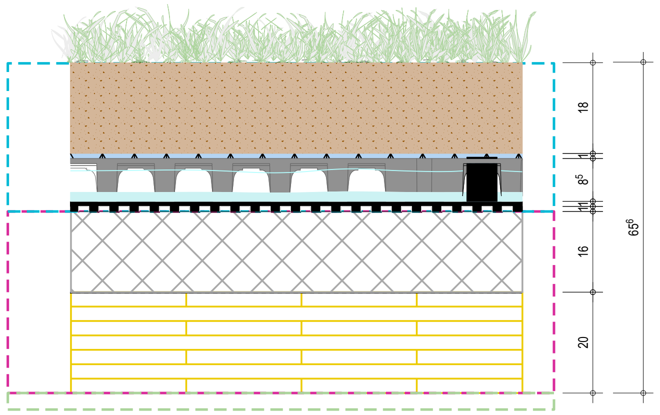
12 mm tiles
25 mm dry coating
30 mm Impact sound wood fiber insulation board
60 mm elastically bonded filling (approx. 90 kg/m²)
0.2 mm trickle protection

180 mm cross laminated timber element

Wood visibility

→ **Figure 21**
Structure of the ceiling slabs for the mass timber construction, Tegel Projekt GmbH, Berlin 2023

ROOF



180 mm intensive substrate
5 mm absorbent capillary fleece
85 mm retention boxes
5 mm storage fleece
(5.2 mm root protection)
1.5 mm EPDM roofing membrane

140 mm hard foam XPS 035 – insulation
5 mm vapor barrier
200 mm cross laminated timber element

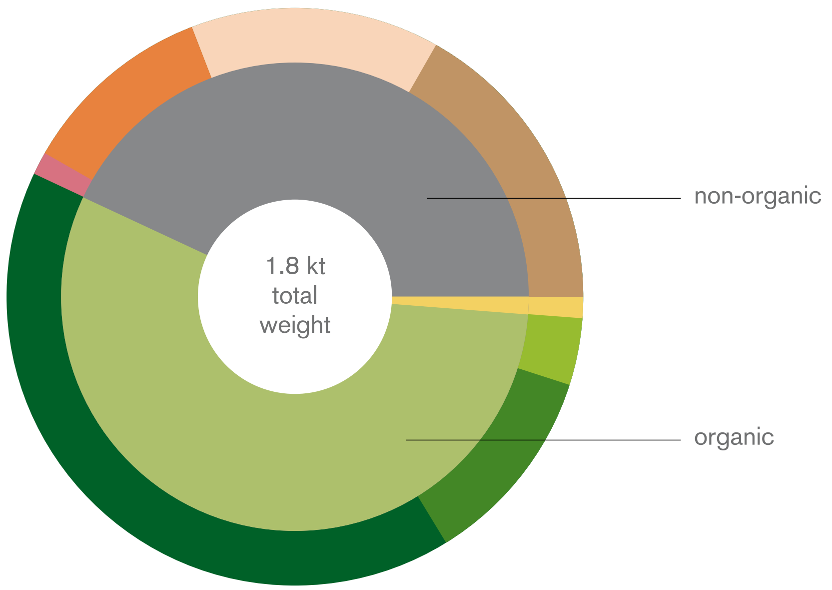
Wood visibility

→ **Figure 22**
Structure of the roof for the mass timber construction, Tegel Projekt GmbH, Berlin 2023

2.1.3.2 THOMA WOOD100

'Thoma-wood' is a special mass timber construction type developed by Thoma Holz GmbH, Austria. This construction type uses no metals, chemicals, wood preservatives or glues. Instead, mechanical connections with wooden dowls connect the building parts (Thoma Holz GmbH, n. d.). According to Thoma Holz GmbH, the harvesting process is optimized by cutting timber during a waning moon. This is claimed to result in denser and more durable timber which is less susceptible to pests, in comparison to conventionally harvested timber (Thoma Holz GmbH, 2020). This assumption is based on the results of a study conducted by ETH Zurich in 2001 (Zürcher, 2001). However, apart from this study, no current sources can be found to support these results.

With a total weight of 1.8 kt, the Thoma-wood construction type is heavier than mass timber (Figure 23). In contrast to all other construction types, most of the construction materials are biomass-based and made from timber, as can be seen from the significantly higher proportion of organic material shown in Figure 23. The aggregated group of timber structure accounts for 44 % and mainly includes the material Thoma Wood100. Timber insulation accounts for 11 % and timber furnishing for 3 % of the total weight of the building. The largest share of non-organic material in relation to the weight of the building is fermacell comb fill with 19 %, which is used in the ceiling slabs, followed by intensive substrate light (11 %) located in the roof, best screed (10 %) and mineral board (1 %). Other materials, each accounting for less than 1 % of the total weight, are listed in the appendices (Table 2).

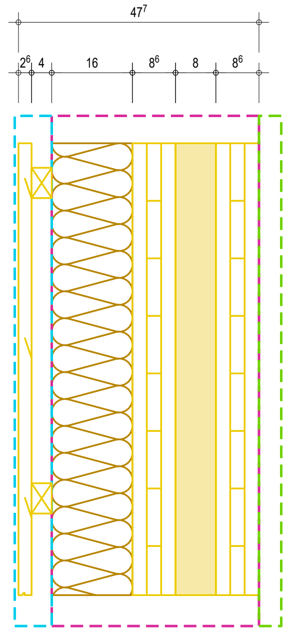


CONSTRUCTION MATERIAL

- 19 % fermacell comb fill
- 11 % intensive substrate light
- 10 % best screed
- 1 % mineral board
- 44 % timber structure
- 11 % timber insulation
- 3 % timber furnishing
- 1 % other materials under 1 % of the weight

Figure 23
Weight percentage of non-organic and organic materials and total weight of one Thoma Wood100 building. A list of the materials under 1 % of the weight can be found in Table 2.

WALL



outside to inside/left to right | horizontal cut

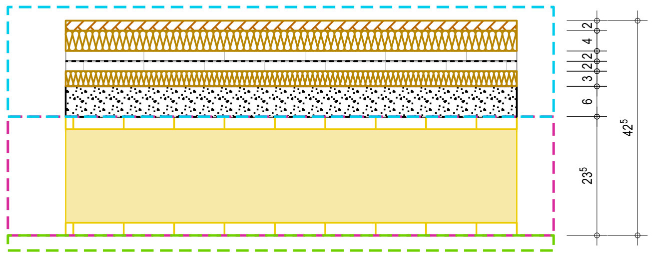
- 26 mm horizontally grooved ventilated larch formwork
- 40 mm supporting battens wood

- 160 mm HFD board bestwood Wall 180 (N+F)
- 85.5 mm crosswise/diagonal vertical board layers
- 80 mm solid wood core - with beech dowel
- 85.5 mm crosswise/diagonal vertical board layers

Visible wooden surface

Figure 24
Structure of the external wall for the Thoma Wood construction, Tegel Projekt GmbH, Berlin 2023

CEILING SLABS



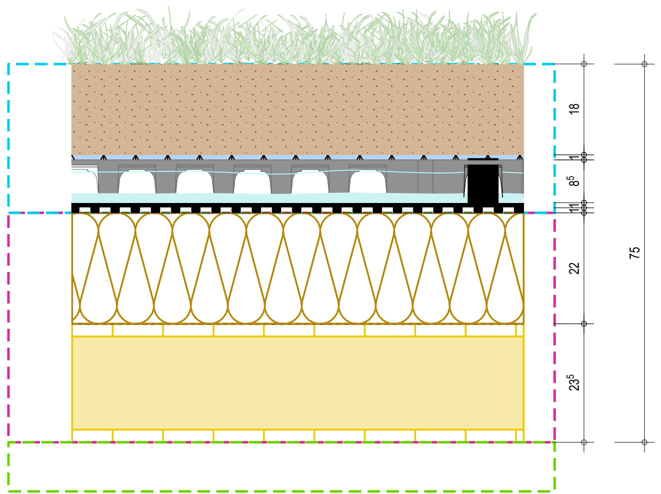
- 20 mm solid wooden flooring
- 40 mm wood fiber insulation board
- 20 mm screed element (glued on the face side) - smoke-proof
- 0.2 mm Kraft paper trickle protection
- 20 mm screed element (moved on gap)
- 30 mm impact sound insulation – Isover Akustic EP1e
- 60 mm Fermacell honeycomb filling in screed honeycomb
- 0.2 mm Kraft paper trickle protection

235 mm Thoma Wood100 ceiling element

Wood visibility

Figure 25
Structure of the ceiling slabs for the Thoma Wood construction, Tegel Projekt GmbH, Berlin 2023

ROOF



- 180 mm intensive substrate
- 5 mm absorbent capillary fleece
- 85 mm retention boxes
- 5 mm storage fleece
- (5.2 mm root protection)
- 1.5 mm EPDM roofing membrane

- 220 mm GUTEX Thermoflat, pressure-resistant
- 2 mm vapor barrier
- 235 mm Thoma Wood100 ceiling element

Wood visibility

Figure 26
Structure of the roof for the Thoma Wood construction, Tegel Projekt GmbH, Berlin 2023

2.2 POTENTIAL MATERIAL SUPPLIERS

The carbon footprint of construction materials usually includes greenhouse gas emissions during production and transportation of raw materials to the manufacturing site or supplier and further to the construction site (Dodd et al., 2021). As some materials consist of several raw materials, knowing the transport distances for each component is important to calculate the total emissions at the production stage. However, there is a partial lack of reliable and transparent data regarding the specific supply chains of construction materials. Furthermore, the final choice of material suppliers is left to the construction developer. Therefore, the analysis performed focuses on the transport emissions of the final material – from the nearest supplier to the construction site in Berlin. In consequence, all transport distances for all material components along the entire supply chain may not have been included in the transport emission calculations, as illustrated in Figure 27 for the example of the material 'reinforced concrete'.

Identifying eligible suppliers, Google Maps entries were filtered based on relevance and selected by their distance to the construction site in Berlin. No further criteria were decisive, except for some cases when specific suppliers were already determined by the Schumacher Quarter project management. This applies to Made of Air GmbH, Pittsburgh Corning Europe NV, Petersen-Tegl A/S, Ziegelwerk Bellenberg Wiest GmbH & Co. KG and Thoma Holz GmbH. The transport distances for material groups for each construction type can be found in Table 1 in the appendices.

Materials and goods in Germany are mostly transported via land. The most common types of transportation include transport by rail, van or truck. Calculations of transport emissions in the CCA assume that materials are carried by road on a motorised vehicle (truck). Trucks have the biggest share in transport of goods in Germany (Statistisches Bundesamt (Destatis), 2023). According to the UK Department for Environment, Food & Rural Affairs (De Wolf et al., 2017) trucks with the smallest capacity (3.5–7.5 t) have the highest CO_2 coefficient. It equals 5.5731×10^{-4} t CO_2 eq t^{-1} km^{-1}. The CO_2 coefficient decreases with the increasing load capacity of the truck: 3.6024×10^{-4} t CO_2 eq t^{-1} km^{-1} for trucks loading 7.5–17 t and 1.7398×10^{-4} t CO_2 eq t^{-1} km^{-1} for trucks with a payload of more than 17 t (De Wolf et al., 2017).

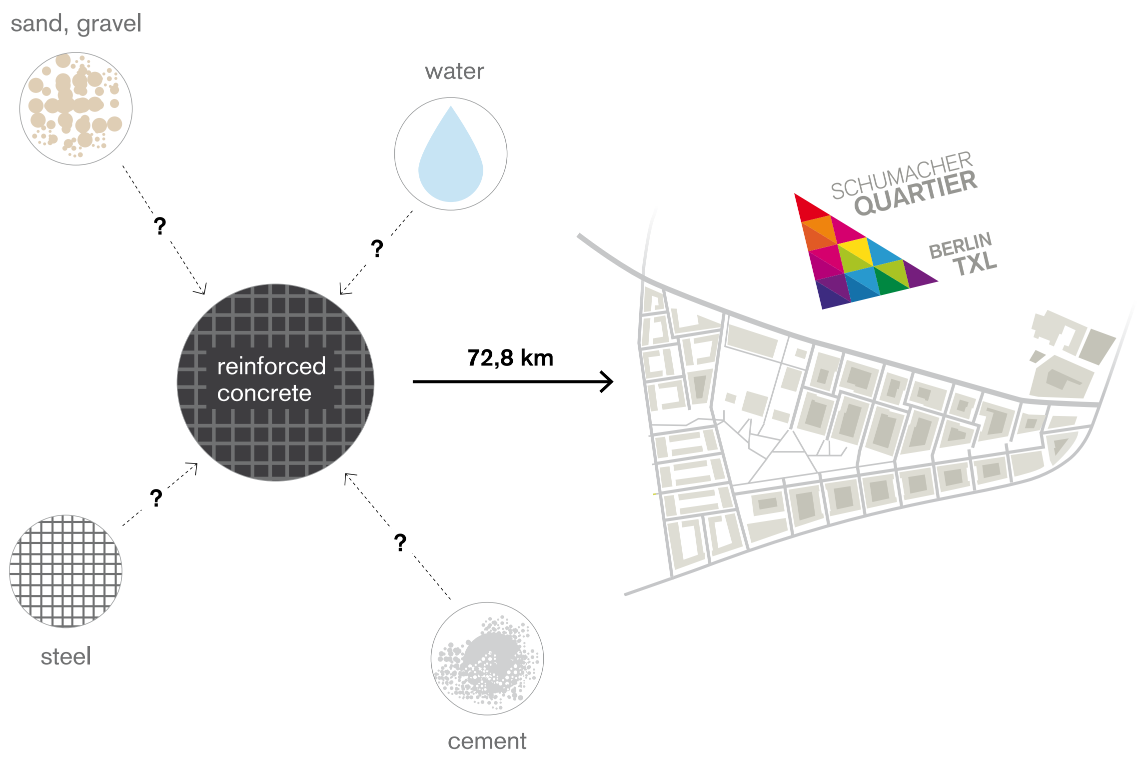


Figure 27
Transport distances for the exemplary material 'reinforced concrete'. Not all components of materials are included in the calculation of transport distances. Here, the example of reinforced concrete is visualised, showing that transport distances of sand, gravel, steel, cement and water are not known in detail.

2.3 DESCRIPTION OF THE NUMERICAL ALGORITHM

To estimate carbon storage and emissions from material production and transport the Carbon Cycle Assessment (CCA) was used, which is an algorithm that simulates the storage and fluxes of carbon within and between the built environment and ecosystems. The numerical algorithm described below is a further development of the methodology, developed and applied for assessing the carbon benefits of a transition to timber construction to meet global housing needs (Churkina et al., 2020). Storage of carbon in materials and associated emissions from materials production were estimated for the entire reference building as well as for its parts, namely exterior walls, ceiling slabs and roof.

Storage of carbon in a building (C_s [t]) is calculated as a sum of carbon storage in different construction materials included in the building assembly using the following equation: $C_S = \sum_i(M_i * B_i * CW)$, where M_i – mass of construction material [t] such as timber, reinforced concrete, brick, etc. included in a building assembly. The masses of materials used in this study are provided in table 3 of the appendices. B_i – biomass fraction of the material [dimensionless]. The fractions used in this study are provided in table 1 of the appendices CW – carbon to biomass ratio [dimensionless].

The calculations are made with a carbon-to-timber ratio of 0.5, which is the global average of 0.476 ± 0.04 (Martin et al., 2018) rounded to the first decimal place, if not provided by respective material data sheets.

Carbon emissions associated with manufacturing materials (C_e [t]) are calculated using the weights of different materials and their CO_2 emission coefficients.
In calculations we assumed that all emissions associated with construction materials manufacturing were CO_2. See the equation below. $C_{ep} = \sum_i(k_i * M_i)$ – carbon emissions associated with production of construction materials, where k_i – the CO_2 emission coefficient [t CO_2 eq./t] of a construction material such as timber, reinforced concrete, brick, etc. The CO_2 emission coefficients used in this study are listed in table 1 of the appendices. In Carbon emissions associated with transportation of materials (C_{et}, [t]) from the closest supplier to the construction site in Schumacher Quarter, Berlin, Germany, were estimated using the equation below. $C_{et} = \sum_i(kt_i * M_i * D_i)$, where kt_i – the CO_2 emission coefficient of different transportation means such as trucks, rail, ship, etc. [t CO_2eq t^{-1} km^{-1}].

It was assumed that all materials for this constructions site are being transported by a truck of 3.5–7.5 t permitted total weight. The CO_2 emission coefficients of this mean of transport are 5.5731×10^{-4} t CO_2 eq t^{-1} km^{-1}.

D_i – transport distances [km] of construction materials estimated for the closest material supplier to the construction site in Schumacher Quartier, Berlin, Germany. Transport distances used in this study are provided in.

To obtain absolute numbers for the entire Schumacher Quartier, Berlin, Germany, the total number of 123 building assemblies was assumed to fit into the construction site.

2.4 DATA INPUTS FOR CALCULATIONS

For the calculations with Python two input tables were created. Table 1 and table 2 list the construction materials for every construction type, allocated to the building parts where they occur and with their weight contribution to the exemplary building (see appendices).

Table 1 contains the construction materials for every construction type with their CO_2 coefficient, biomass fraction and carbon ratio. The definitions for biomass fraction and carbon ratio (carbon-to-biomass ratio) are given in chapter 2.3. All values were researched using mainly the database Ökobaudat from the German Federal Ministry for Housing, Urban Development and Construction Sector (BMWSB, n. d.) and the environmental product declarations provided by the manufacturers for some of the construction materials. If no further information was found, the biomass fraction was assumed to be 1 and the carbon fraction assumed to be 0.5 for biomass-based materials (e.g., timber-based materials), and the biomass fraction and carbon fraction were assumed to be 0 for non-organic materials.

The CO_2 emission coefficient describes the total global warming potential (GWP) of the construction materials. To account for emissions from the production phase, the GWP of life cycle stages A1 to A3 of each material (cradle-to-gate EPD) was used, including raw material supply, transportation to the production site and production itself. As the CO_2 emission coefficient refers to 1 t of construction material, the GWP was divided by gross density or weight per unit area of the material if the reference flow did not already refer to the mass. The mean value was calculated when different values for GWP were available from different data origins.

For some biomass-based materials, especially timber-based ones, the inclusion of the raw material supply resulted in a negative GWP value due to the carbon storage of e.g., timber. Since the CO_2 emission coefficient is only supposed to describe the emissions, carbon storage must be excluded from the GWP. To do so, the mass of carbon contained in the construction material was calculated using

$m_c = M_i * B_i * CW$, where m_c – mass of carbon [t],

M_i, B_i, CW – see chapter 2.3. Description of the Numerical Algorithm.

When hypothetically the carbon from the construction materials reacts to CO_2 the following applies:

$n_c = n_{CO2}$, where

n_c – amount of substance of carbon [mol]

n_{CO2} – amount of substance of CO_2 [mol].

Using the amount of substance, the mass of CO_2 which could form out of the carbon in the construction material was calculated and added to the GWP of the material to eliminate the carbon storage and to determine the CO_2 emission coefficient:

$n_{CO2} = m_c / M_c$, where

M_c – molar mass of carbon [g mol^{-1}], given as 12 g mol^{-1},

$m_{CO2} = n_{CO2} * M_{CO2}$, where

m_{CO2} – mass of CO_2 [t]

M_{CO2} – molar mass of CO_2 [g mol^{-1}], given as 44,01 g mol^{-1},

k_i + GWP + m_{CO2}, where

k_i – see chapter 2.3 Description of the Numerical Algorithm

GWP – GWP [t CO_2 eq. t^{-1}] researched for the different construction materials, including the carbon storage of biomass-based products.

2.5 TIMBER DEMAND

To calculate the amount of harvested timber needed for each construction type, the loss of timber mass during each processing step was considered. The total amount of biomass can be determined via the biomass fraction of the materials set in the input data. For each construction type the following applies:

$m_B = \sum_i (M_i * B_i)$, where

M_i, B_i – see chapter 2.3. Description of the Numerical Algorithm and

m_B – Biomass of every construction type.

To determine the total amount of timber prior to processing, the value for total biomass must be divided by the inverse percentage for every intermediate processing step, starting with construction offcuts.

For each step the following applies:

$m_l - = m_B / P_l$, where

m_l – material before processing step and

P_l – inverse percentage of material loss

Each step is shown below. As timber amount is usually calculated in volume, the weight of timber needs to be divided by its density; for pine the density is given as 520 kg/m^3 (DIN e.V. (ed.), 2003).

Processing steps and occurring material losses:

Processing step	Material loss	Source
Logging of trees	20 %	Estimate referring to Berliner Forsten
Sawmill	15 %	Estimate referring to Binderholz
Construction offcuts	10 %	Own estimation
Density of pine	520 kg/m^3	(DIN e.V. (ed.), 2003)

2.6 EXPERT INSIGHTS

Various research approaches were pursued within the scope of this study to gain comprehensive insights into forest management and timber processing. In addition to analysing existing data and considering relevant literature sources, insights were attained from personal conversations with experts who possess extensive expertise and years of practical experience in this field. These experts were chosen to address specific questions regarding the application, capacity and limitations of timber construction in the Berlin/Brandenburg region.

Direct personal exchange took place in the form of informal discussions, expert interviews and factory visits. The acquired insights were documented and used as an additional source of information for this study. It is important to note that the information presented in this report is derived from personal communication and should be regarded as informal comments of the experts rather than official statements. These insights from the personal conversations serve as a supplement to the methodological approaches, aiming to achieve a more comprehensive understanding of the possibilities and challenges in forest management, timber processing and timber construction. The acquired insights were considered in the discussion and inter-pretation of the results to enhance the applicability and relevance of the study.

3 RESULTS AND DISCUSSION

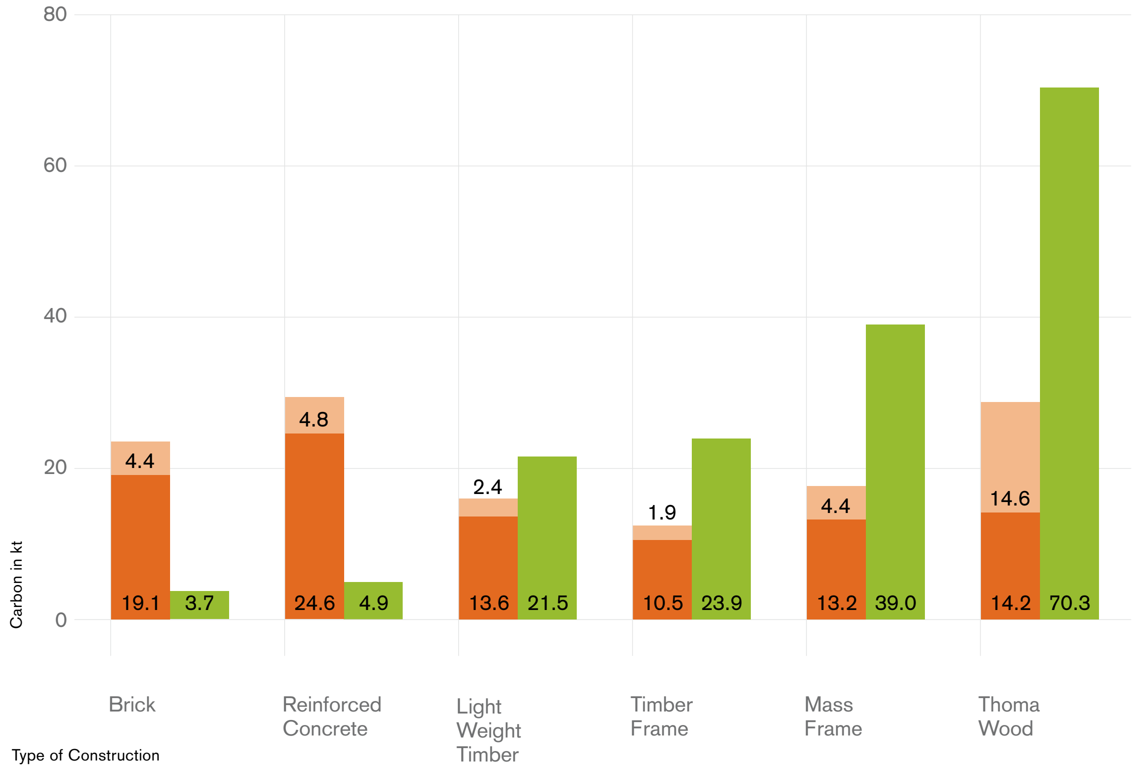
3.1 WHICH TYPES OF CONSTRUCTION ARE THE MOST CLIMATE FRIENDLY?

Future housing and accompanying infrastructures should be built with the lowest carbon emissions possible (Vallenthin et al., 2010). The less carbon emitted during the production and transportation of the materials as well as during construction and operation of the houses, the more climate-friendly they are. Furthermore, a higher carbon storage capacity of a construction material results in a more climate-friendly impact of the corresponding house. The most climate-friendly construction type, according to this report, is therefore defined as the one with the highest ratio of carbon storage per carbon emitted during production. For this ratio, emissions related to transport were excluded as they are very uncertain and can easily be modified by the corresponding construction developer through the choice of supplier.

Figure 28 reveals that mineral-based construction types have the highest carbon emissions from production, with the highest value (24.6 kt) for reinforced concrete followed by brick (19.1 kt). The production emissions of biomass-based construction types are ranked as follows: Thoma-wood (14.2 kt), lightweight timber (13.6 kt) and mass timber (13.2 kt). Timber frame has the lowest production emissions (10.5 kt).

Mineral-based constructions have the lowest storage potential. Brick contains around 2 % organic materials while reinforced concrete contains less than 1 % of organic materials. Thirty-nine per cent of the weight of lightweight timber constructions are organic materials; for timber frame, the figure is 37 %. In these organic shares, 23.9 kt (timber frame) and 21.5 kt (lightweight timber) of carbon are stored. The highest carbon storage capacity can be seen for mass timber construction types, which also have the highest shares in organic materials (Thoma-wood 58 %, mass timber 43 %). Thoma Wood100 stores 70.3 kt carbon, while mass timber stores 39 kt.

The carbon storage per emitted carbon of transport and production is represented by the ratio curves in the right part of Figure 28. The ratio is lowest for brick and reinforced concrete with 0.2 t stored carbon per tonne emitted carbon (Figure 28). The ratio is much higher for timber-based constructions. Per tonne of emitted carbon, 1.3 t are stored in lightweight timber and 1.9 t in timber frame. Mass timber stores 2.2 t carbon per tonne of emitted carbon – only 0.2 t less than Thoma Wood. Finally, Thoma Wood stores 2.4 t carbon per tonne of emitted carbon, thus resulting in the best carbon storage and emittance ratio for transport and production emission.



→ **Figure 28**

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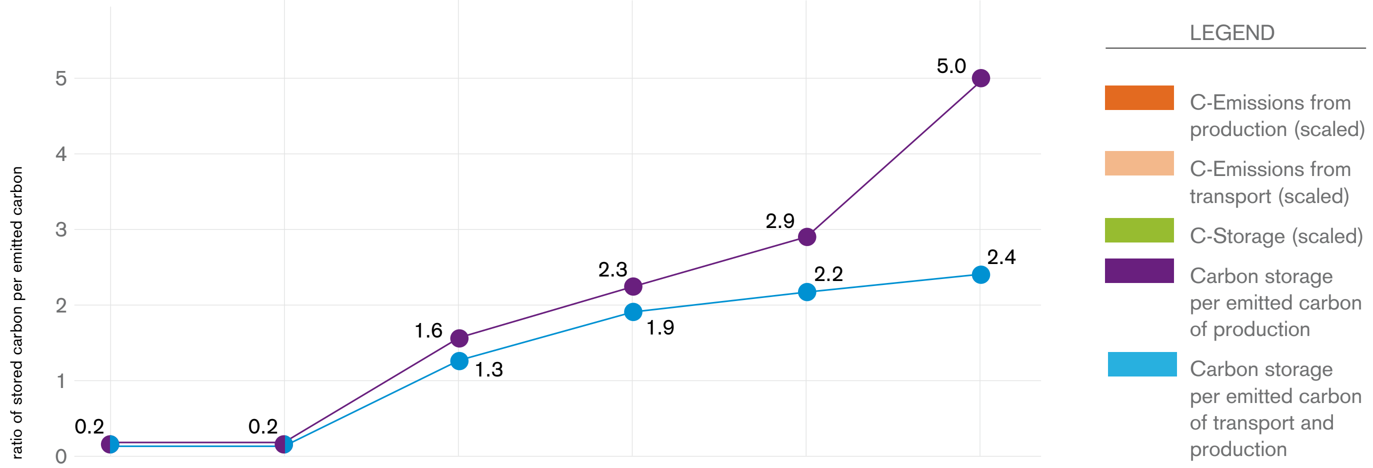


The results show that timber-based construction types are more climate-friendly compared to mineral-based ones. Not only because the emissions of the mineral-based construction types during production are much higher, but also because their carbon storage potential is about four- to 19-fold lower than that of construction types with a higher share of organic materials.

The underlying explanation for the higher ratio values of the timber-based construction types, in relation to the storage potential is as follows: The heavier the proportion of organic construction material, the higher the carbon storage potential.

The Thoma Wood100 construction type is the heaviest of the timber-based ones with a weight of 1808.2 t for one building. Therefore, in total, it has by far the highest carbon storage potential (70.3 kt). This is almost twice the potential of the construction type with the second highest carbon storage potential, mass timber (39 kt), which seems to make it the most climate-friendly construction type. That becomes even more evident considering the ratio of Thomawood without transport emissions (Figure 28, right; see the line in dark blue). It is clearly higher than the ratio including transport emissions (Figure 28, right; see the line in light blue), due to long transport distances for Thoma products. Excluding these transport distances, the ratio of carbon storage per tonne emitted carbon in production for Thoma-products (5 t) is almost twice as high as the ratio for mass timber (2.9 t), indicating the Thoma Wood 100 construction type as the most climate-friendly.

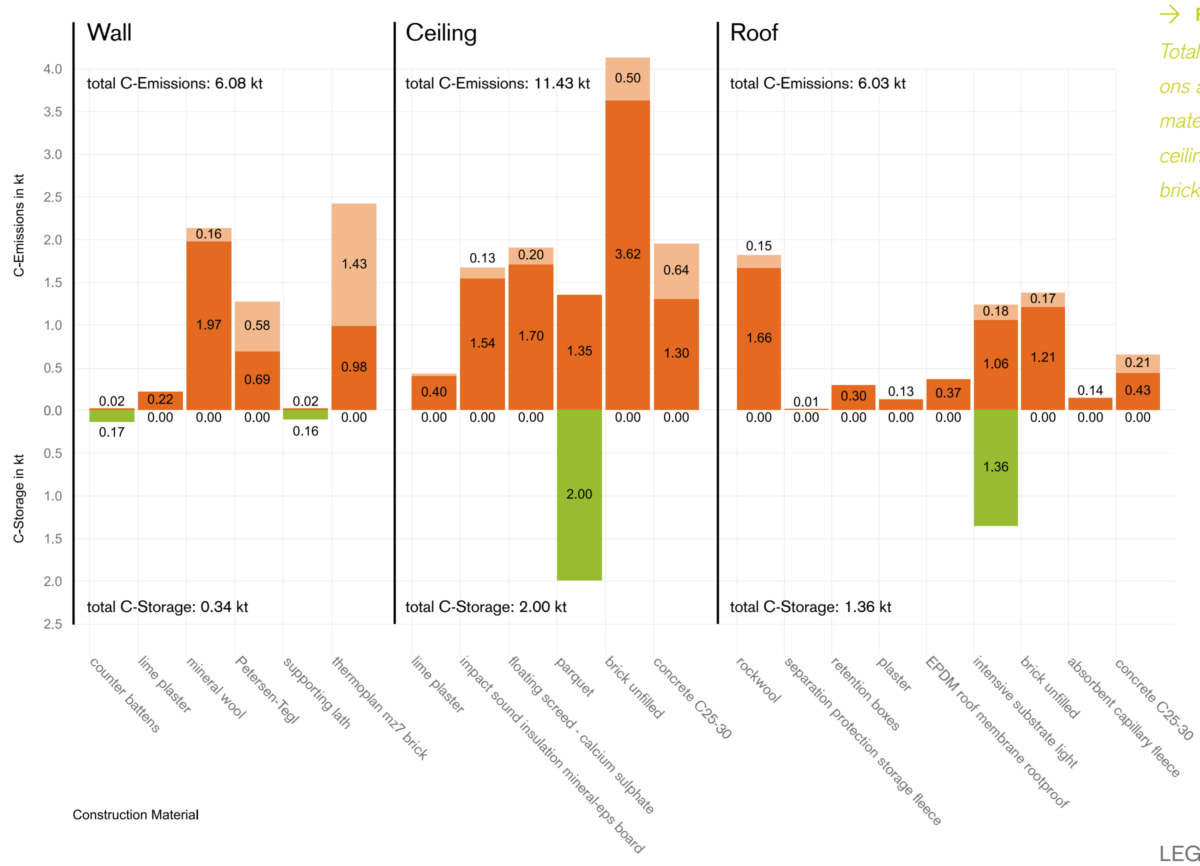
3.2 WHAT MATERIALS AND BUILDING PARTS HAVE THE LARGEST CONTRIBUTIONS TO…

… MINERAL-BASED CONSTRUCTION TYPES?

Brick and reinforced concrete are materials with major impacts on carbon emissions for mineral construction methods. Carbon storage capacity is only noteworthy for parquet and substrate for the green roof (intensive substrate light) (Figure 29 and Figure 30).

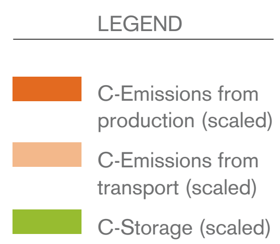
Becoming clear for brick, the sum of carbon emissions outweighs the storage potential by far and over all building parts. Brick materials (especially unfilled brick, as well as Thermoplan MZ7 brick) contribute most to carbon emissions of the entire construction type. Other mineral materials with high energy consumption during production, such as mineral wool and concrete C25-30, also increase carbon emissions. In contrast, only two organic materials store significant amounts of carbon: parquet and intensive substrate light.

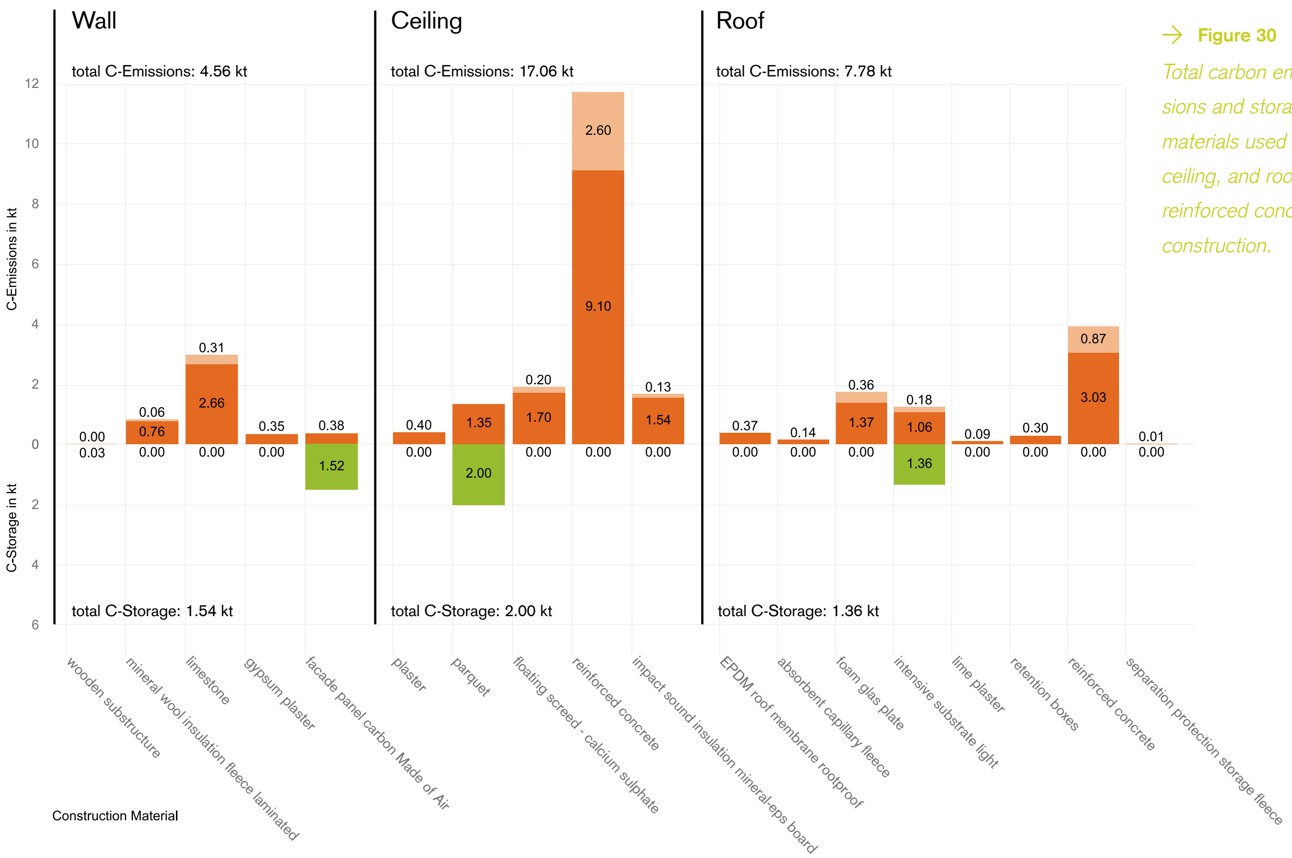
Carbon emissions of most reinforced concrete materials are broadly similar to those of brick, and most are relatively balanced among themselves (Figure 30). However, the total carbon emissions for this construction type rise sharply due to the high proportion of reinforced concrete. These cannot be compensated in any way, not even by the biochar product Made of Air, which binds extremely high carbon contents in the long term through pyrolysis (Made of Air, n. d.).



→ **Figure 29**

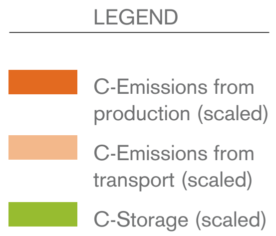
Total carbon emissions and storage of materials used in wall, ceiling and roof of brick construction.

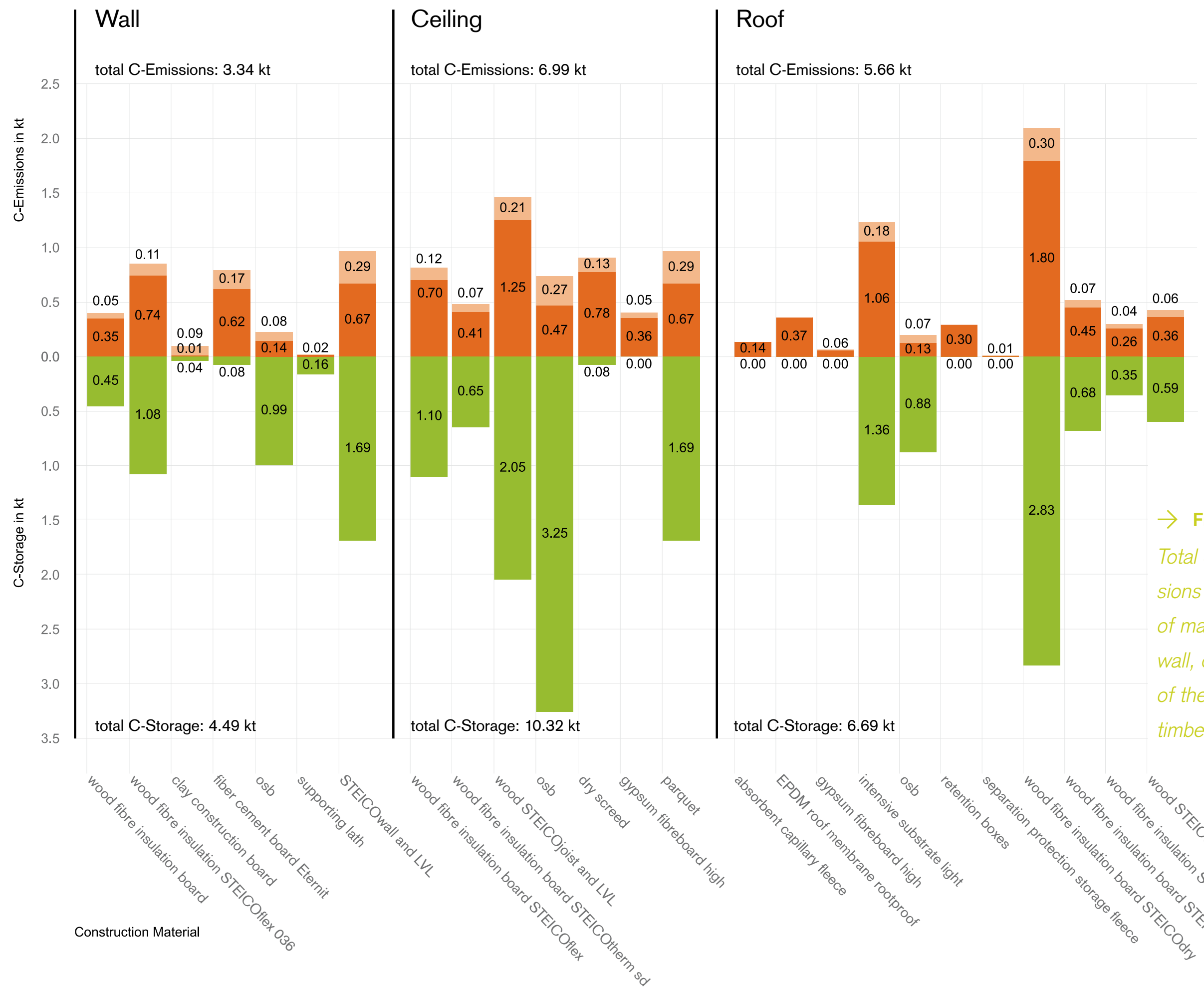




→ Figure 30

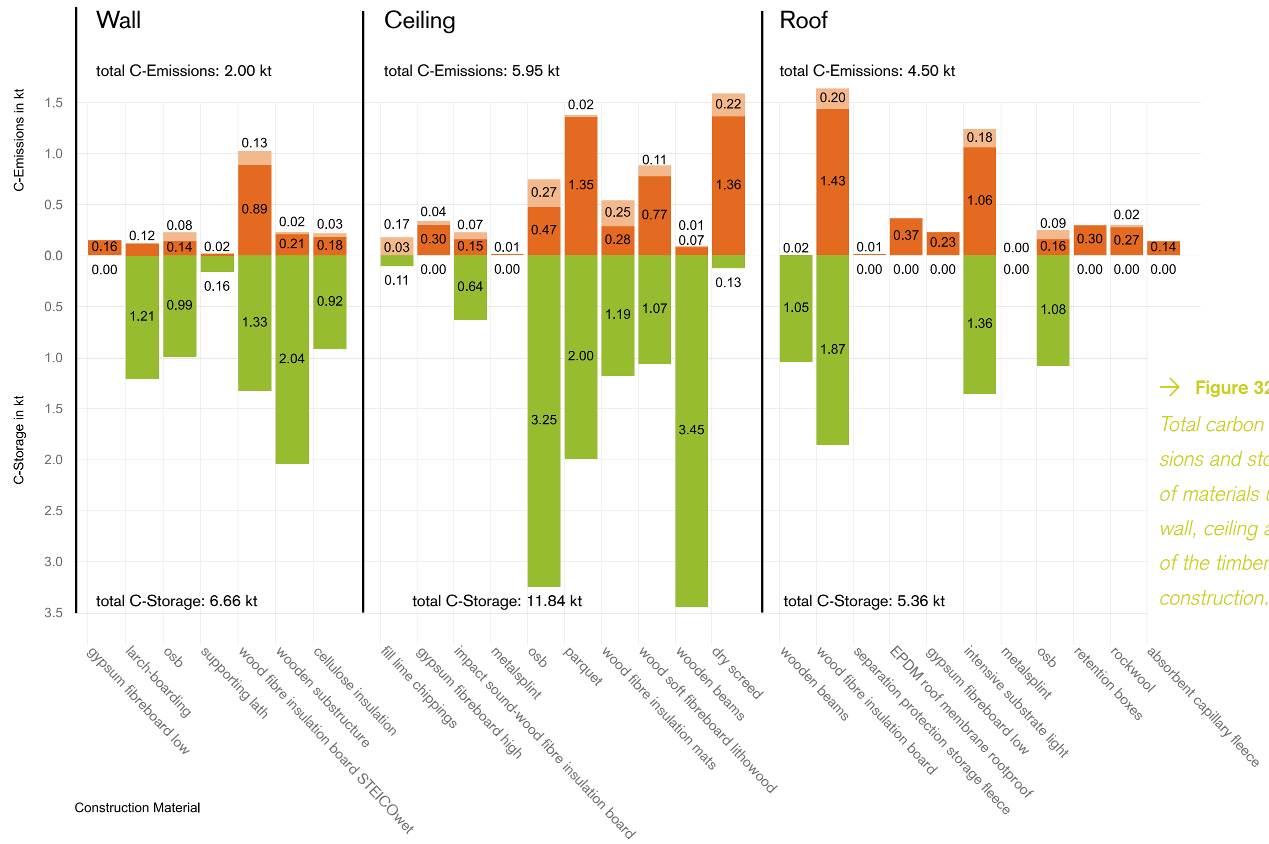
Total carbon emissions and storage of materials used in wall, ceiling, and roof of reinforced concrete construction.





→ Figure 31

Total carbon emissions and storage of materials used in wall, ceiling and roof of the lightweight timber construction.



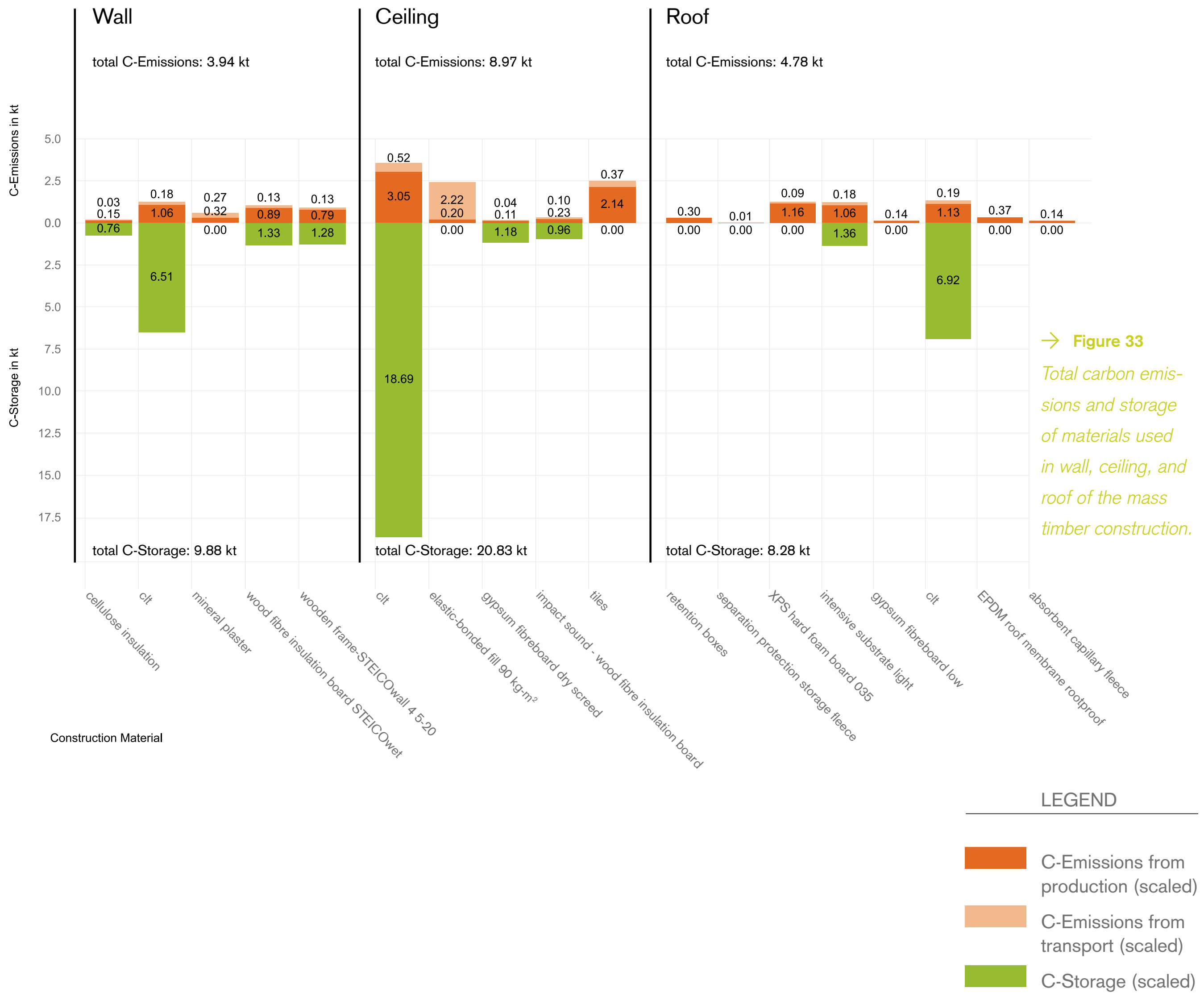
→ Figure 32

Total carbon emissions and storage of materials used in wall, ceiling and roof of the timber frame construction.

… LIGHT FRAME TIMBER CONSTRUCTION TYPES?

The results of carbon emission and carbon storage calculations for lightweight timber and timber frame reveal a quite different picture (Figure 31 and Figure 32). The variations in emissions and storage capacity of the different materials are much more pronounced, so the evaluation appears to be more complex. Although many of the used organic materials have a high carbon storage capacity, these are nearly offset by their high carbon emissions. This applies for example, to wood fibre insulation board STEICOdry, wood STEICOjoist + LVL and wood fibre insulation STEICOflex 036 (Figure 31). Conceivably, the relatively high emissions in these cases are attributable to the occurring transport emissions; however, this would have to be examined in more detail. Thus, high carbon emissions for individual materials may be due to long distances to suppliers, but overall it is likely to be due to the large number of materials, resulting in high transport costs. However, the advantage of the low weight of both construction types must also be considered, which in turn is likely to have a comparatively positive effect on transport emissions.

For timber frame, the high carbon storage capacity of the materials wooden beams, OSB and wooden substructure should be emphasised. Their positive effects on the carbon ratio are less attenuated by emissions than in the case of the materials with high carbon storage in light-weight timber (Figure 32). This results in a higher ratio of stored carbon per emitted carbon for timber frame, which is also reflected in figure 28.

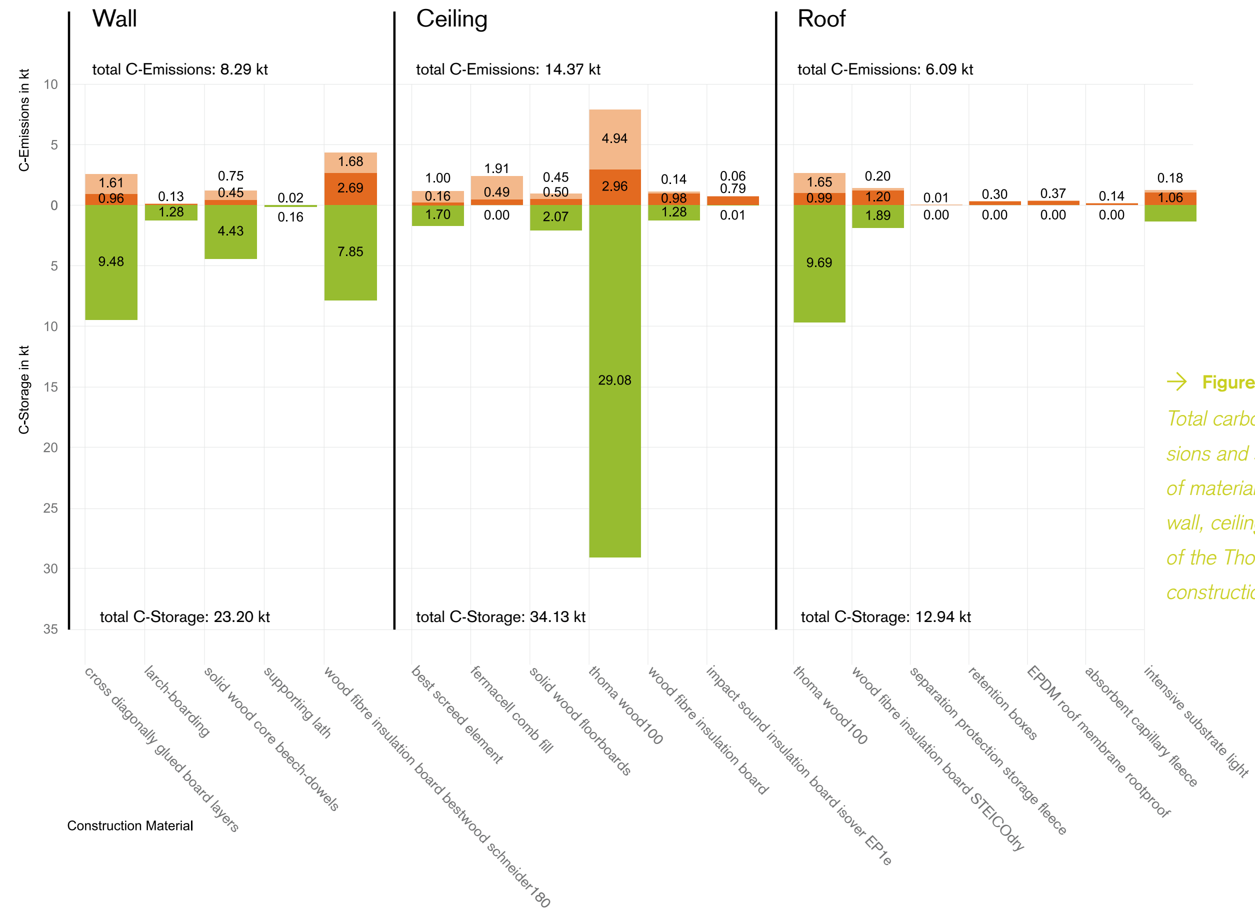


→ Figure 33
Total carbon emissions and storage of materials used in wall, ceiling, and roof of the mass timber construction.

… MASS TIMBER CONSTRUCTION TYPES?

Coming to the assessment of mass timber, the results again show a different pattern. Although carbon emissions are broadly comparable to those of the lightweight timber construction types, outstanding values for the carbon storage of CLT change the overall picture (Figure 33). In consequence, the storage capacity exceeds the emissions by far. Still, by replacing high-carbon-emitting ceiling tiles, potential further reduction in emissions could be possible, which would improve the overall ratio of stored carbon per emitted carbon.

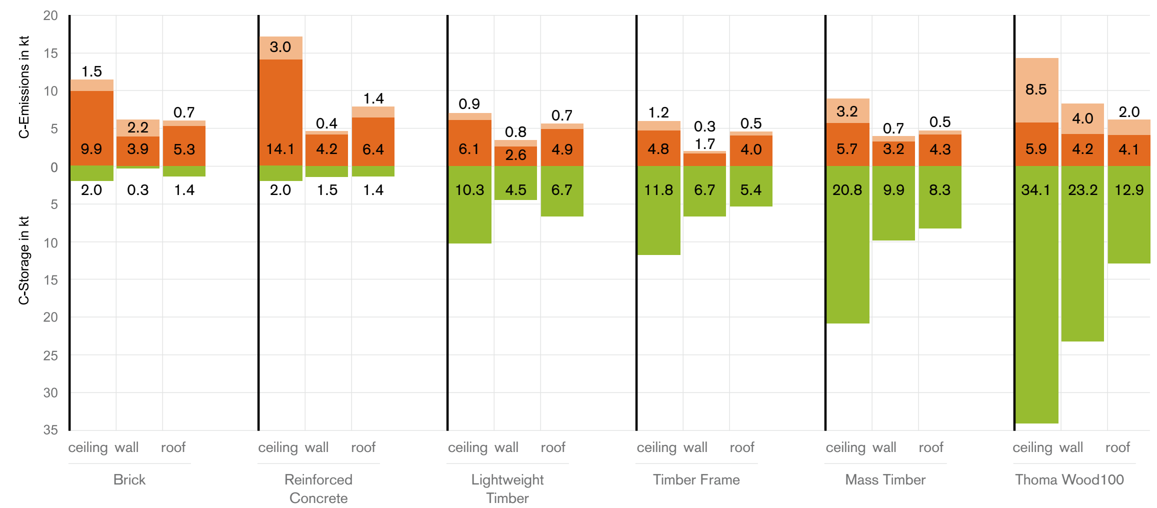
Thoma Wood100 has the highest share (by weight) of organic materials of all construction types; carbon emissions and carbon storage are highest for the materials Thoma Wood100, wood-fibre insulation board best wood Schneider 180 and crosswise/diagonally glued board layers (Figure 34). The carbon storage capacity is particularly high compared to all other materials. Possibly due to the long transport of the material from Austria to Berlin, its carbon emissions slightly mitigate the positive effect on carbon storage.



→ Figure 34
Total carbon emissions and storage of materials used in wall, ceiling, and roof of the Thoma Wood construction.

3.2.1 CONCLUDING REMARKS

In summary, it can be stated that the largest contributions to emissions for the mineral-based construction types arise from the primary structure. For brick this applies to the various types of brick plus concrete, and for reinforced concrete it applies for reinforced concrete and limestone. Regarding the two light frame timber construction types, the carbon emissions are more evenly distributed across



→ Figure 35
Comparison of carbon (C) emissions and C storage per type and part of construction.

the materials due to the broader material mix used.
For mass timber construction types, the ratio of stored carbon to emitted carbon improves due to the high proportions of organic materials with high carbon storage potential. In general, the results underline that the higher the proportion of organic materials, the higher the carbon storage potential of the respective construction type.

Concerning the contribution of the building parts, ceiling slabs have the highest contribution to carbon emissions and storage (Figure 35), likely since the ceiling slab occupies the largest area within the planned four-storey building.

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In general, the results underline that the higher the proportion of organic materials, the higher the carbon storage potential of the respective construction type.

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To assess the contribution of materials to carbon emissions, the energy demand for their production must also be considered. Materials that are energy intensive in manufacturing (e.g., concrete and steel) increase total carbon emissions, especially if used in large quantities, such as in the primary structures of a building. In these cases, carbon emissions could potentially be compensated by replacing energy-intensive mineral materials with organic construction solutions or, if possible, by shifting to renewable energy sources in the production process.

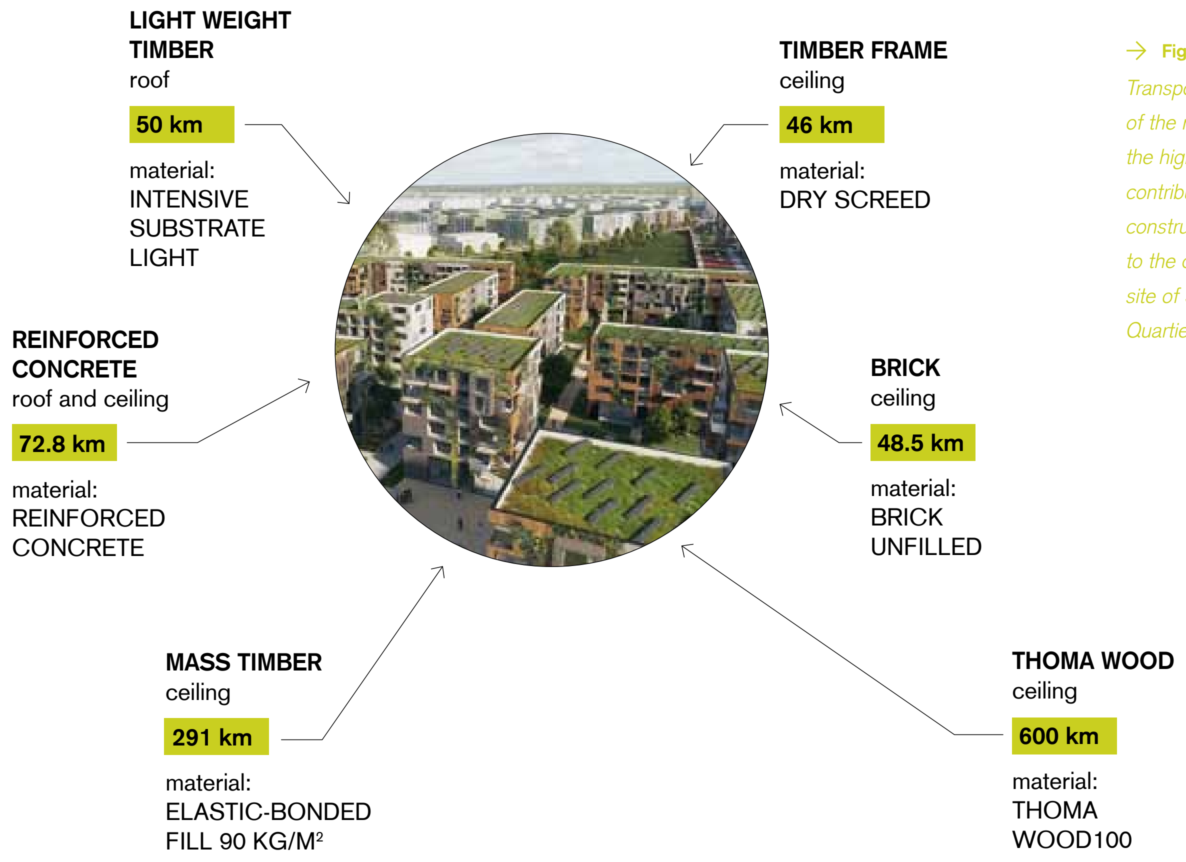
Organic materials with high carbon storage can therefore potentially contribute to the increase of the urban carbon stock. This promises to have positive impacts on the carbon cycle, as it prevents (or at least delays) the release of carbon to the atmosphere, thus potentially mitigating climate change. That especially accounts for multi-storey buildings, which would more efficiently use floor area per capita, prevent further soil sealing and allow for greater carbon storage volumes through i.e. the usage of more timber-based materials (Churkina et al., 2020; Pittau et al., 2022). Additionally, materials with a longer lifetime and especially those more suitable for reusing or recycling positively contribute to the urban stock – called the cascade use of wooden materials (Budzinski et al., 2020). This applies to mass timber and Thoma Wood, as their building parts are less complex in their composition, and therefore, in perspective, better suited for recycling due to their less compounded or glued materials (Dangel, 2017).

3.3 IS THE USAGE OF REGIONAL TIMBER AND RAW MATERIALS THE MOST CLIMATE-FRIENDLY?

Choosing more regional construction materials correlates with shorter transport distances resulting in lower transport emissions. For the Schumacher Quartier project, the term 'regional' was defined as within the limits of the Federal States of Berlin and Brandenburg.
Research on potential material suppliers has shown differences in distribution of producers of various material groups through Germany and nearby countries. Distances vary greatly, from widely used materials such as concrete, for which it is easier to find local suppliers, to very specialised suppliers that require long transportation to Berlin, for instance, products by Thoma Holz GmbH (Table 1 in the appendices). Also, weight, share and quantity of materials vary for different construction types, additionally accounting for a differing relation of carbon emissions to transport distances.

Figure 28 (upper graph) shows the carbon emissions generated during the production of materials (A1–A3) compared to transport emissions of materials from production to the construction site (A4). Thoma-wood has the highest transport emissions with 14.6 kt, mainly due to long transport distances since the timber can only be sourced from a few locations near the company Thoma Holz GmbH, Austria. Furthermore, the transport emissions are almost twice as high as production emissions, resulting in a negative impact on the evaluation of the construction type. The transport distances of the materials for mass timber are comparatively short, which is why the transport emissions of 4.4 kt are about 3.3 times lower than for Thoma Wood. The light frame timber construction types, lightweight timber and timber frame, exhibit the lowest transport emissions with 2.4 kt and 1.9 kt, respectively. Transportation emissions for the mineral-based construction types are 4.4 kt for brick and 4.8 kt for reinforced concrete.
Although both types have the shortest transport distances of their construction materials, their components such as unfilled brick, reinforced concrete and limestone have comparably high weights and shares, which drives up emissions.

The results show higher transport distances lead to higher emissions and influence the climate impact of a construction type, as illustrated by the example of Thoma-wood. Even more decisive than the distance, however, is the weight of the material transported. Figure 36 shows transport distances of the materials with the highest weight contribution for each construction type. It demonstrates that the heaviest components of the mineral-based construction types can be acquired from within distances of 80 km (unfilled brick with 48.5 km for brick; reinforced concrete with 72.8 km for reinforced concrete), whereas the main components for mass timber construction types must be purchased from particular suppliers, therefore resulting in longer transport distances (material elastic-bonded fill with 291 km for mass timber; Thoma Wood100 with 600 km for Thoma Wood).
Figure 37 shows the relation of carbon emissions by increasing transport distance for each construction type. This extrapolation does not display the calculated values for carbon emissions, moreover it aims to illustrate the significance of potential regionality for the construction types with high-weight materials. According to the carbon emissions from production, each construction type has different values as a starting point. Starting from intercept (corresponds to a theoretic production facility within the construction site), the emissions increase with increasing distance. For illustration, 100 km intervals were marked. The different slope for each construction type is decisive: Thus, it is evident that reinforced concrete has the highest relation of carbon emissions to transport distance due to its high weight. Mineral-based construction types are heavier than timber-based construction types, with a total material weight of 4.1 kt for reinforced concrete and 2.5 kt for brick, resulting in significantly higher transport emissions. In contrast, lightweight timber has the lowest slope of carbon emissions per additional km, followed by the rate for timber frame. This can be attributed to the low weight of the materials per building: 1 kt for lightweight timber and 1.1 kt for timber frame. The mass timber construction types have a higher rate of carbon emissions to transport distances than the light frame timber construction types as their materials are comparatively heavy. With a total weight of 1.8 kt, Thoma-wood is heavier than mass timber with a total weight of 1.5 kt, which leads to a higher slope, especially compared to the light frame timber construction types.



→ **Figure 36**
Transport distances of the materials with the highest weight contribution for each construction type to the construction site of Schumacher Quartier in Berlin.

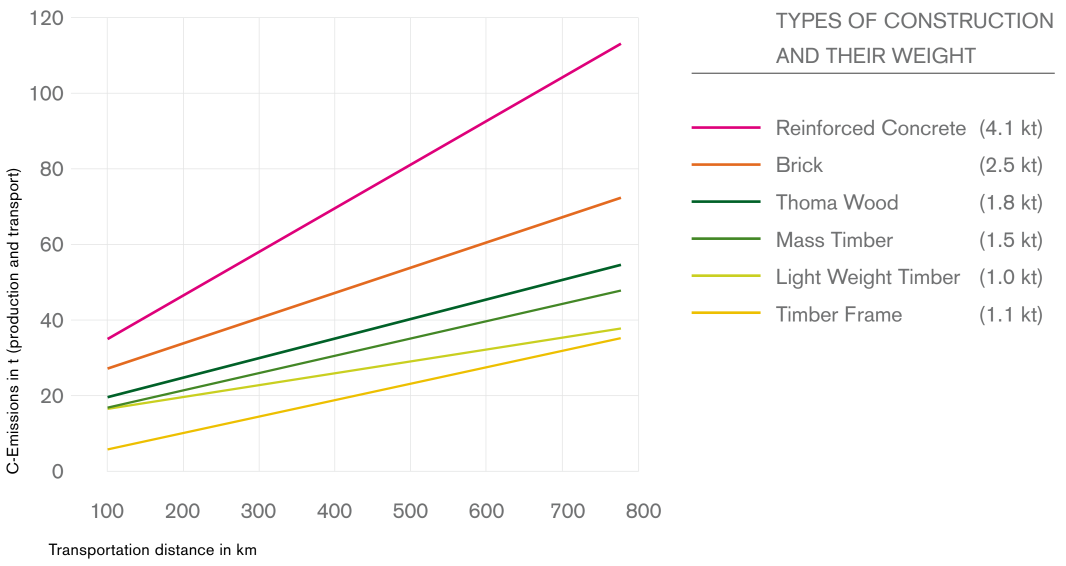


Figure 37
Comparison of slope ratios for C emissions by transport distance for each construction type for one building

The graph also demonstrates that for the same distance from the production site, the use of Thoma-wood materials would emit less than the use of materials for mineral-based construction types. Hence, measures like establishing a regional production site for Thoma-wood in Berlin-Brandenburg could significantly reduce transport emissions and improve the ratio to production emissions.

Therefore, to answer the question of whether the usage of regional timber and raw materials is the most climate-friendly, the type, amount and weight of materials used for a particular construction type must be considered. The results indicate that the lighter the material, the less pivotal regional production is, while for heavier materials the use of regional timber and raw materials becomes more important, as transport emissions are significantly higher. Nevertheless, it can be concluded that the closer the production site, the more climate-friendly it is, as short distances translate to lower relative transport emissions.

Another factor that needs to be considered is the type of transportation. The transport emissions from Figure 28 are a conservative estimate, as the calculation was based on transport by small truck (3.5 t–7.5 t). Other means of transportation, as shown in figure 38, could reduce transport emissions and thus be more climate friendly. Compared to transport with small trucks, the use of standard trucks (7.5 t–17 t) reduces emissions by 36 % and the use of large trucks (>17 t) by 69 % (De Wolf et al., 2017). Train transport, which reduces emissions by 96 %, would clearly be the most climate-friendly option (ibid.). This would be possible, for example, with a supplier of mass timber construction materials who has a railway connection to the production site.

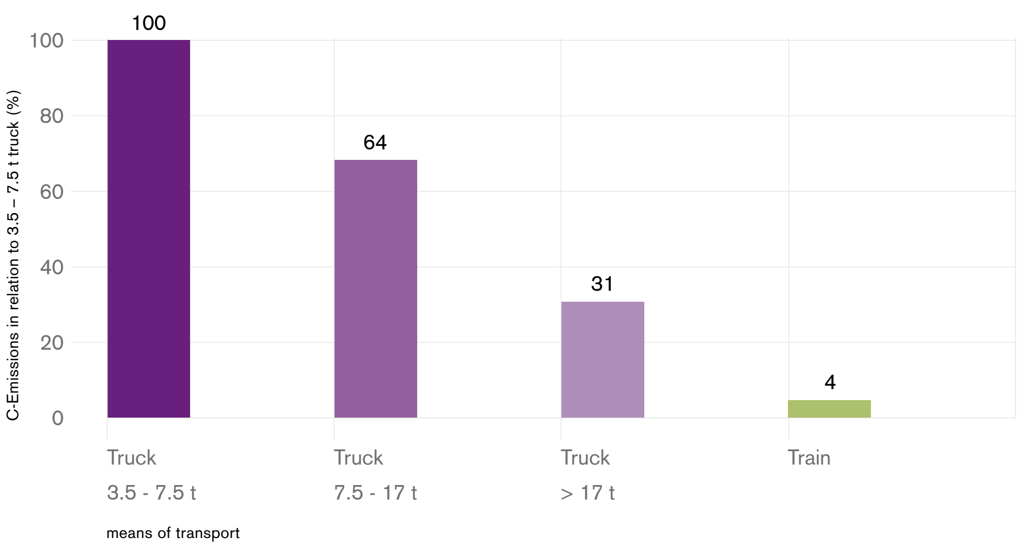


Figure 38
Comparison of C-emissions from different means of transportation. The columns show emissions from the various modes of transportation in relation to the emissions from light trucks used in the analysis.

3.4 CALCULATION OF REQUIRED AMOUNTS OF TIMBER

To assess and evaluate whether Berlin and Brandenburg harvest rates could provide the quantities that are needed to build Schumacher Quartier using a timber-based construction type, the amount of required timber was calculated. As pine accounts for 70 % of the forest area (Ministerium für Ländliche Entwicklung, Umwelt und Landwirtschaft des Landes Brandenburg, 2015),

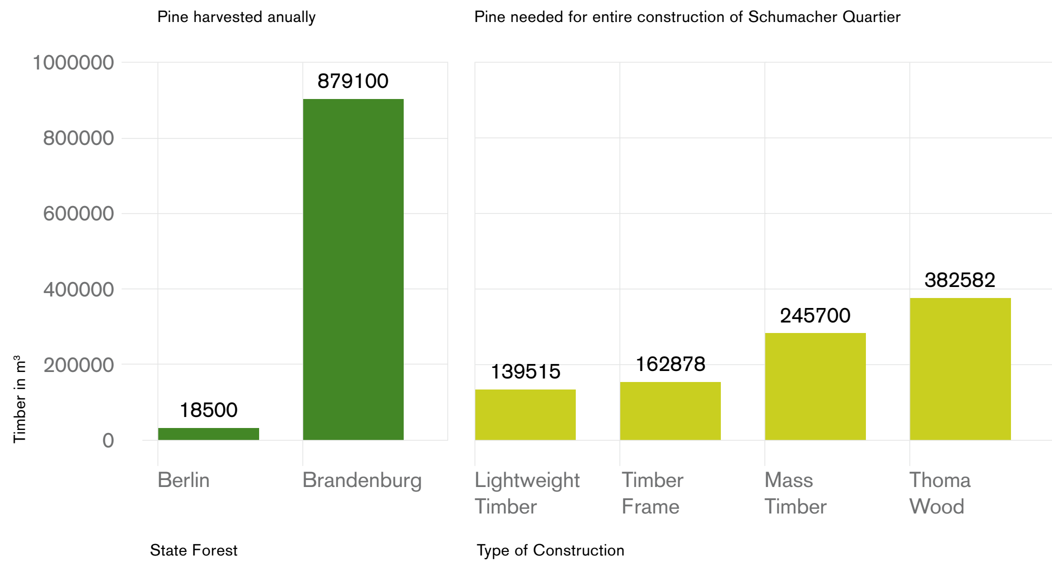


Figure 39
Required amounts of harvested timber for Schumacher Quartier (columns in light green) and annually available harvested timber in Berlin's and Brandenburg's state forests for 2021 (columns in dark green).

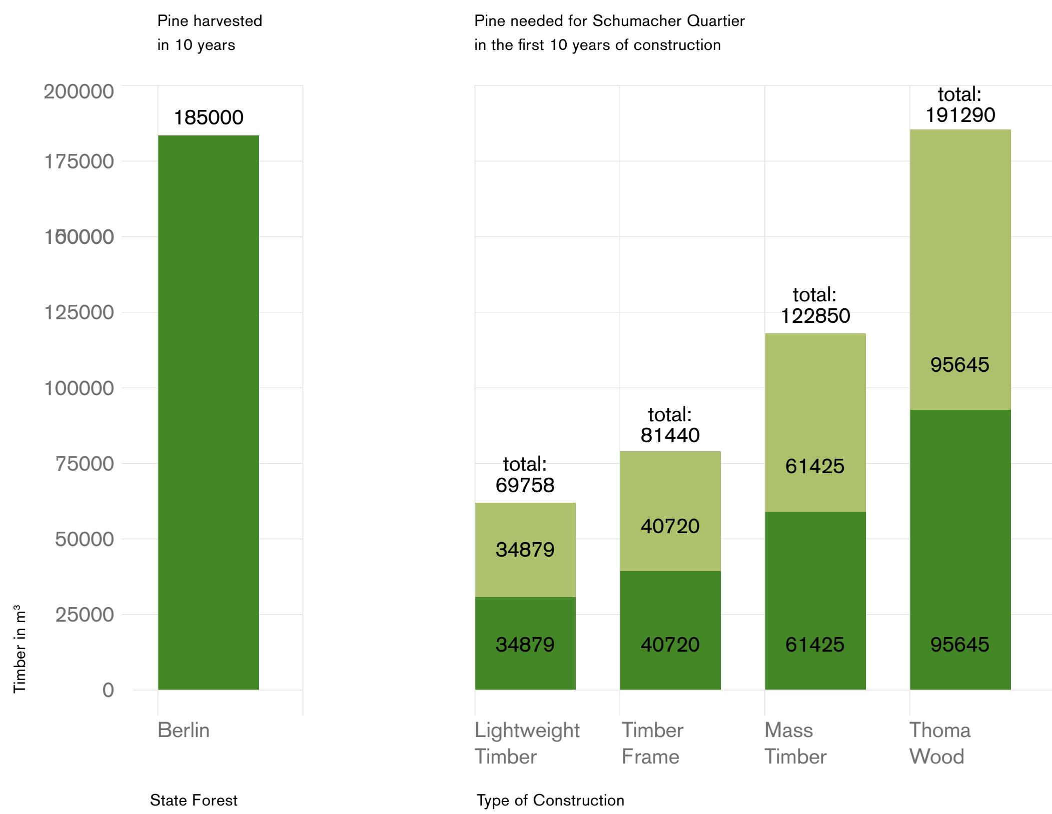
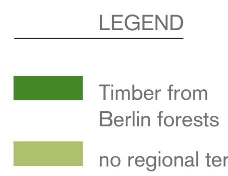


Figure 40
Required amounts of harvested timber for the first 10 years of construction at Schumacher Quartier and available harvested pine over a time span of 10 years extrapolated from 2021 data.



Tegel Projekt GmbH prefers pine as the main timber used in construction. The required amounts of timber were compared to the amount of harvested pine from Berlin's and Brandenburg's state forests in 2021, which is displayed in Figure 39. No private, federal or corporate forests were included in the calculation, as uniform management strategies for forest conversion and sustainable management were only available for state forests. The numbers given represent the amount of pine and larch harvested. Since the share of larch in Berlin and Brandenburg is minimal compared to pine, it was neglected in the calculations. Therefore, only pine will be referred to in the following. Berlin's state forests harvested around 18500 m^3 of pine in 2021 (Destatis, 2022). Annually, this could cover only part of the needs for all timber-based construction types that are discussed for Schumacher Quartier, as those would need between 139515 and 382582 m^3 of timber, depending on the respective construction type. However, Schumacher Quartier states that only half of the total amount of timber is needed in the first 10 years of construction. In addition, the project regulations dictate that only half of the timber must be sourced from Berlin, as this half is being built by housing associations. Therefore, over the first 10 years the timber demand could be met from Berlin's stock, as figure 40 shows.

In addition, the annual average harvest of pine in Brandenburg's state forests (Amt für Statistik Berlin-Brandenburg, 2023) would suffice by far for construction of Schumacher Quartier for all timber-based construction types, as they provide roughly 879100 m^3 of timber annually (reference year 2021).

Climate change implications on forest stands in Berlin and Brandenburg have been recognised by state forests offices and thereby some regenerative practices for forest adaptation are being developed and implemented (pers. communication Berlin State Forestry Office, 2023). One strategy to achieve this consists in the transition from predominant monoculture stands to mixed forest systems. That implies that previously species-pure coniferous stands will be readjusted, resulting in less pine and more deciduous timber being available in Berlin and Brandenburg in the long term, while even more pine can be harvested in the coming decades (pers. communication Berlin State Forestry Office, 2023). Today, industry still considers spruce the most popular tree species for timber construction in the construction industry in Germany (accounting for 85 % of the processed timber).
As most sawmills are specialised in processing of either coniferous or deciduous species only, it might be challenging to adapt the industry to process and use much higher amounts of deciduous timber – at least in the short term (pers. communication Binderholz GmbH, 2023).

3.5 UNCERTAINTIES AND LIMITATIONS

During the extensive work on implementing the calculation of carbon storage and carbon emissions of Schumacher Quartier, some uncertainties occurred, which are discussed in the following.

3.5.1 INPUT DATA

The results are based on materials used for walls, ceiling slabs and roof constructions. They do not reflect the entire building, as e.g., internal walls, staircases, elevator shafts etc. are not included. Results might change by adding the entire range of materials used for construction. Furthermore, the data for the calculation was mainly taken from a database whose data sets were current, but in some cases already one to two years out of date. For the material intensive substrate light, no data on the given gross density was available. In consequence, calculations might possibly overestimate the material's CO_2 coefficient.

The choice of different types of timber can also lead to small variations in the carbon content of timber-based materials (Martin et al., 2018), which could therefore be considered in more extensive studies.

3.5.2 TRANSPORT EMISSIONS

The transport emissions are based on distances between suppliers and Schumacher Quartier in Berlin. As suppliers are not always the producers of a specific material, for some materials transport between producer and supplier might be fully considered neither in the production CO_2 coefficient nor in the final transport distance. It was also not verified whether the assumed suppliers would be able to provide the required quantities of construction materials. Nor were economic aspects taken into consideration.

3.5.3 FURTHER UNCERTAINTIES

This study focusses on carbon emissions from the production and transport of materials. It does not take into account other environmental impacts of the materials used, nor the impacts of the construction, use and end-of-life phases. For the carbon sink function of timber, the full life cycle is essential. A cascade use of timber products is important to enhance its positive impact on the carbon cycle. Additionally, other factors like the energy sources for production or the energy efficiency of the building during their use phase could also be considered in future life cycle assessments of buildings.

Still, quantifying carbon fluxes is considered a good approach to appropriately assess the climate friendliness of different construction types, as the method not only considers carbon emissions, but also assesses the carbon storage capacity of construction materials (Hart & Pomponi, 2020; Heckmann & Glock, 2023).

4 CONCLUSION

5 FUNDING

6 ACKNOWLEDGE-MENTS

7 AUTHOR'S CONTRIBUTIONS

8 LIST OF FIGURES

9 LIST OF TABLES

10 REFERENCES

4.1 RECOMMENDATIONS

The two mass timber construction types demonstrate the best performance in terms of the stored-to-emitted-carbon ratio. The results of the analysis show that the construction type designed with Thoma Wood has the highest carbon-emissions-to-storage ratio (Figure 28). However, the impact of transport emissions due to high distances between timber sources and the respective construction site must be taken into consideration. The transport emissions may vary depending on the mode of transportation, the location of manufacturing facilities and the infrastructure at the construction site. Although Thoma Wood has the best carbon ratio, even when including transport emissions, the climate friendliness could be increased significantly if the transport distances were reduced or if larger trucks or trains were used for transport.

In conclusion, it can be deduced from the present study that the construction types considered can be classified as follows with regard to their climate impact: In first place are mass timber construction types, followed by light frame timber construction types; least climate friendly are mineral-based construction types.

4.2 OUTLOOK

The analysis suggests that the use of timber as a main construction material could significantly lower the negative impact of the construction sector on the carbon cycle. Additionally, the long-term storage potential of carbon within timber-based construction materials can positively contribute to urban carbon stocks. However, a rising demand for timber draws the focus to forest management. Only if timber resources are managed sustainably in economic, social and ecological dimensions can the growing demand for timber be met without negative repercussions. Forest management should consider forests as more than just a timber resource, but as a diverse, sensitive ecosystem. Sustainable forest management should therefore promote a diverse tree composition, active protection of the soil and its carbon stock and sustainable harvesting methods. Furthermore, encouraging the natural regeneration of forests can be a useful approach both to improving resilience to natural disturbances caused by climate change and maintaining important functions such as carbon sink and timber production.

4.3 FUTURE RESEARCH QUESTIONS

Future research could focus on sustainable forest management. Especially on the regional scale of Berlin and Brandenburg, which regulations and frameworks are needed to enhance sustainable forest management is of interest for science and practitioners. If the transition towards more timber-based construction practices is advanced, ensuring sufficient quantities of timber to replace established, mineral-based construction materials could also become an important topic of future research.

5 FUNDING

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7 AUTHOR'S CONTRIBUTIONS

The authors are listed in alphabetical order except FT, CB, GS and GC. GC supported by CB conceptualised this report and supervised it. FT designed the six construction types including the respective quantity density and thickness specifications.

All authors (except CB, GC, GS and FT) researched the material specific values and properties needed for the CCA. All authors (except CB, GC, GS and FT) researched the closest material suppliers. The CCA numerical algorithm was designed by CB and GC. HP provided the method for calculating the CO_2 emission coefficient from the researched GWP values. NK, LM und AN were instrumental in analysing the data and plotting the results. All authors contributed to the writing of the manuscript. LK, AN and BH coordinated and supervised the editing process.

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11
NOTES

APPENDICES

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