TT Professorship Digital Fabrication
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Timber-Clay Composite Slabs

Master Thesis
Department of Architecture
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TT Professorship Digital Fabrication

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Erklärung

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Abstract

Floor slabs are the Achilles' heel of modern multi-storey timber construction. Lacking thermal mass, fire safety and sound insulation, timber construction remains connected to height restrictions and increased energy consumption that can easily outweigh the initial ecological advantages. This project offers an alternative in the form of robotically fabricated timber-loam hybrid floor slabs. By combining the advantages of timber (pre-fabrication potential and structural performance) and loam (thermal mass, fire safety and noise protection) low cost, high performance and sustainability are brought together in one system.

Kurzzusammenfassung

Deckensysteme sind die Achillesferse des modernen mehrgeschoßigen Holzbaus. Ein Mangel an thermischer Masse, Brandfestigkeit und Schallschutz resultieren in begrenzten Bauhöhen und oft erhöhtem Energieverbrauch, der die CO2-Einsparungen aus der Bauphase zunichte machen kann. Dieses Projekt schafft eine Alternative in der Form von robotisch gefertigten Holz/Lehm Hybriddecken. Durch Kombinieren der Stärken der jeweiligen Materialien – die guten statischen Eigenschaften und die Präfabrizierbarkeit des Holzes und die Thermische Masse, Brandschutz und Schallschutz des Lehms – werden Nachhaltigkeit, Performativität und Kostengünstigkeit in einer Konstruktion zusammengebracht.

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List of Abbreviations

AI: Artificial Intelligence

CLT: Cross Laminated Timber

FEA: Finite Element Analysis

GWP: Global Warming Potential

PENRT: Primary Energy Non-Renewable Total

PUR: Polyurethane Adhesive

TES: Timber Earth Slab (brand name of the project)

Glossary

Engineered wood products: a range of derivative wood products which are manufactured by binding or fixing the strands, particles, fibres, or veneers or boards of wood, together with adhesives, or other methods of fixation to form a composite material

Parametic Design: a process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response

Thermal mass: the ability of a body to store thermal energy

Genetic Algorithm: a method for solving both constrained and unconstrained optimization problems based on a natural selection process that mimics biological evolution

1. Introduction

1.1. Goals and motivation

The construction industry holds the sad titles for being both the least innovative (Agarwal, Chandrasekaran, and Mukund 2016) and, by far, the most polluting industry, being responsible for 39% of global CO2 emissions. (IEA 2019) Faced with an overaging workforce (AGC 2019) and the fact that cement production alone accounts for 7-8% of global CO2 emissions (Lehne and Preston 2018), game-changing solutions for a more automated and sustainable way of construction are desperately needed.

However, timber construction comes with its own disadvantages, most prominently fire safety and thermal mass (find more details in section 2.2). While the former issue mainly limits construction height, lack of thermal mass leads to a lack of passive cooling that can outweigh the initial ecological advantages of timber as early as 11 years after completion (Hacker et al. 2008). While there are doubts on the actual environmental impact of timber construction in our climate, it is in any case ill-suited for hot climates (Reilly and Kinnane 2017) where the majority of the world's population is living. With China having used more cement in three years than the USA in the entire 20th century (McCarthy 2014), this is not nearly enough for the biogenous construction movement to have an impact.

In theory, loam perfectly compensates for the disadvantages of timber without compromising the ecological footprint. It is available in abundance, fire-proof, comes with a high amount of thermal mass and conserves timber by keeping it airtight and at a constant humidity level (find further details in section 2.3).

While limited structural abilities and laboriousness have pushed earth out of modern construction practice, the ETH spinoff Oxara (Landrou and Demoulin 2021) has developed additives for clay (Landrou, Brumaud, and Habert 2017) that allow the material to be cast in a fast and simple way. Robotics on the other hand allows for the efficient production of timber geometries suitable for a self-supporting earth infill. In combination, these two technological advances call for a reinvestigation of timber-clay hybrid construction.

Floor slabs are the Achilles heel of wood construction where the lack of noise insulation, thermal mass and fire resistance leads to complicated solutions, including timber-concrete-compound slabs, which compromise the carbon footprint while still offering less performance than reinforced concrete slabs (find more details in section 5). In fact, even the "Einfach Bauen" timber case study house is to be equipped with reinforced concrete slabs given the lack of viable alternatives (Nagler and Jarmer 2018, 152). The timber-clay floor slabs developed in this project aim to provide an attractive alternative that holds an ambitious catalogue of advantages:

- Sustainability: Negative GWP and composed of biodegradable/recyclable materials
- High performance: High thermal mass, sound insulation and at least 60 minutes of fire resistance
- Simplicity: As few materials and working steps as possible to save costs and facilitate easy maintenance and recycling after demolition
- Low Cost: High economic efficiency by material efficiency and a high degree of automation

The process started with sketching out designs and consulting with the architects, civil engineers and industry partners involved in the project. In the second step, the digital design tool was scripted and physical 1:1 prototypes built before re-evaluating, optimizing, finalizing the concept and documenting the research findings.

1.2. Project Structure

The development is inspired by and loosely connected to the TUM "Einfach Bauen" (Nagler and Jarmer 2018) project and was launched as a design studio in the winter semester 2019/20, where the author developed the concept in collaboration with Márton Deme. Its continuation features two parallel theses: This thesis focuses on the general characteristics of the system and the interplay of timber and earth while the thesis of Markus Schneider, submitted on the TUM Chair of Timber Structures and Building Construction, focuses on the statics of the timber structure. The project consortium consists of the TUM TT professorship for Digital Design, Chair for Design and Construction, Chair for Timber Structures and Building Construction, muellerblaustein, Oxara and Jowat.

2. State of the art

2.1. Historical Perspective

In the region of modern Germany, timber and earth look back at a long, shared history. The neolithic longhouse traditionally features a timber construction with non-structural earth infill in a wattle and daub technique (find more details in section 2.3.4) that over the centuries developed into the half-timbered house. With few exceptions, earth as a load-bearing material only appeared in the 9th century AD in the form of cob walling, a primitive low-quality predecessor of rammed earth. Load-bearing earth walls became particularly significant with the 15th- and 16th-century urbanisation and resulting fires and wood shortage. Rammed earth, developed in France, and adobe bricks made their way into Germany on a large scale only in the 18th and 19th century. With earth being conceived as a material for poor people, it was also only in this period that earth construction techniques were first documented. (Schroeder 2019, 13–16) Disastrous urban fires and the industrialisation of brick and concrete production brought a rapid change in the 19th century where the share of timber in construction fell from 90% in 1800 to 30% in 1900. (Libner and Rug 2000) Timber construction had a short come-back between the World Wars, most famously in the Kochenhofsiedlung in 1933 (“Ausstellung Deutsches Holz Für Hausbau Und Wohnung” 1933). A significant number of earth buildings was again erected between 1919 and 1922 (Minke 2012, 11) and an earth construction program launched in GDR after WWII (Schroeder 2019, 19). However, these trends were of very short duration. Earth construction nearly vanished as fire safety concerns in particular meant that timber was pushed out of cities and became a material

Fig 2.1. Half-timbered house

Fig 2.2 Haus Rauch, a modern example of rammed earth architecture

predominantly used in roof structures and temporary or low-quality buildings. (Smith and Snow 2008) Timber and loam re-entered the large-scale architectural discourse in the late 20th century thanks to technical innovation and growing environmental awareness. The first multi-storey timber housing projects were erected in Bavaria in the 90s before the first timber high-rise was finished in 2008. (Kaufmann, Krötsch, and Winter 2017, 12) The development has been triggered by prefabrication-potential and therefore decreased construction time as well as on-site space consumption. (Green and Taggart 2020, 55) While having remained a niche topic, earth construction has found recognition particularly in the works of Hans Rauch, Anna Heringer and Francis Keré. (Sauer 2015, 8) In 2011, the EU passed a regulation stating that buildings have to be composed of sustainable materials and designed for disassembly and recycling, giving further momentum to the movement. (The European Parliament and The Council of the European Union 2011)

2.2. Timber Construction Basics

With timber being a versatile material that can be applied in a multitude of ways, this sub-section examines the qualities and building techniques connected to it.

2.2.1. Material Qualities

Advantages of timber include:

- **Lightness and prefabrication-potential:** The lightness and therefore optimum transportability of the material predestines timber components for off-site prefabrication, increasing accuracy, efficiency and workplace quality. (Green and Taggart 2020, 55; Kaufmann, Krötsch, and Winter 2017, 139–49)

- **CO2 negativity:** With trees absorbing CO2 over their lifetime, timber buildings store carbon before it is again released in the rotting or burning process. Considering that young trees absorb much more CO2 than old trees, utilizing forests for construction can actively slow down climate change. (Green and Taggart 2020, 18)

- **Structural performance:** Timber acts under tension and compression, making it suitable for both horizontal and vertical building components.

- **Versatility:** There is a big catalogue of industrially produced timber composites for many different applications. (Green and Taggart 2020, 19–21)
- **Thermal insulation:** The insulating properties of wood make it ideal for the outer shell of the building. (Keller and Rutz 2012, 47)
- **Positive influence on the interior:** Research has shown that timber surfaces regulate interior humidity and, being soft and warm, have a very high acceptance among users. (Teischinger 2012)
- **Decomposability:** Timber can be thermally utilized or naturally decomposed at the end of its lifetime, therefore leading to no permanent waste.

General disadvantages of timber include:

- **Costliness:** One cubic meter of timber costs roughly four times as much as a cubic meter of concrete, (Cemex 2021; Holzland Stoelger 2021) though this is partly outweighed by generally lower material consumption.
- **Inflammability:** While solid timber burns in a slow and controlled way, it is nonetheless inflammable and therefore hard to implement in high-rise structures. (Green and Taggart 2020, 43–44)
- **Thermal Mass:** While the lightness and low thermal conductivity of timber are in many ways advantageous, they drastically decrease thermal mass and therefore passive cooling. This is a major issue in hot and dry climates as well as typologies vulnerable to overheating such as offices and schools. (Fernandez and Baird 2008)
- **Sound insulation:** Another drawback of low weight is a low level of sound insulation. Timber floor slabs therefore usually feature floating screeds and/or ballast. (Kolb 2010, 270–71)
- **Irregularity:** Being naturally grown, timber comes with dimensional instability and unpredictability towards structural behaviour, though this can be partly compensated by engineered wood products. (R. Brandner et al. 2016)

- **Vulnerability:** While timber components can technically last for hundreds of years, they are vulnerable to pests and mould and must therefore be kept dry. (Wang et al. 2018)

2.2.2. Light timber construction

Light Construction, such as wooden frames and beam floor slabs, is the most material-efficient way of building with timber. However, this technique is also most vulnerable, and a vast number of layers has to be added to ensure spatial enclosure, fire safety, noise protection and thermal insulation, leading to increased fabrication complexity and low thermal mass. (Kolb 2010, 276–82; Kaufmann, Krötsch, and Winter 2017, 140–41)

2.2.3. Solid timber construction

Solid timber construction solutions include log construction and CLT. Featuring better fire resistance (Green and Taggart 2020, 23), noise protection and thermal mass (Perez et al. 2010), solid timber components require fewer additional layers and can be exposed more easily.

Sometimes referred to as the reinforced concrete of the future, CLT is the most widespread solid timber construction material at the moment. (Franco 2019) Consisting of layers of cross-laminated timber boards, it entered the mass-market in the 1990s. While consuming significantly more material than light construction techniques, it utilizes the cheaper, under-demanded sideboards of the stem. (Guttmann 2008)

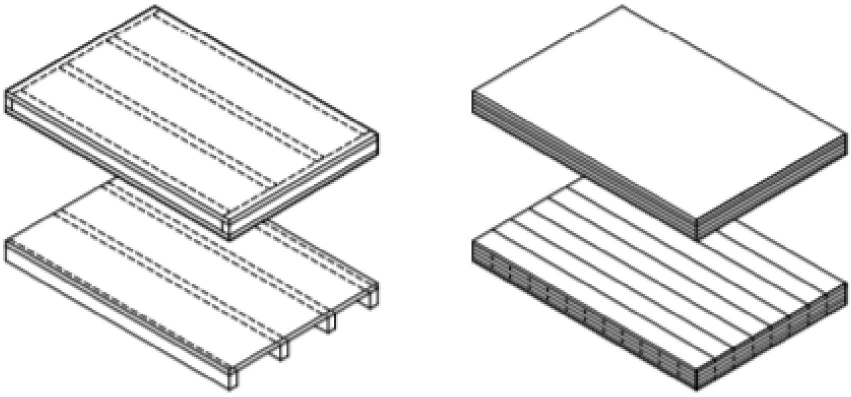


Fig. 2.3 Beam slab vs CLT slab

2.2.4. Hybrid Construction

Timber hybrid construction features a combination of timber and loam, bricks, or concrete to combine the beneficial advantages of two materials.

2.3. Earth Construction Basics

2.3.1. Material qualities

Loam as a building material offers a wide range of advantages and can be found on every continent. 1/3 of the world's population currently lives in loam houses. (World Housing Encyclopedia n.d.) which is not surprising given a long list of advantages:

- **Unlimited availability and reusability:** Loam that is suitable for construction is available in any part of the world and is even likely to be found in the excavation material on site. Since it does not solidify chemically, it can be reused infinitely. (Hestermann and Rongen 2015, 185)

- **Low carbon footprint:** With the material not having to be burned, little CO2 is emitted in the production. (thinkstep 2018)

- **Customizability:** Loam can be used in a multitude of techniques and in combination with many different materials, allowing for solutions with a great variety of consistency, density, strength, and thermal conductivity.

- **Repairability:** Since loam becomes formable once it gets in contact with water, loam building components can easily be repaired or altered by adding or subtracting from the original volume at any point in time.

- **Fire resistance:** Experiments have shown that loam is very resistant to fire, delivering better performance than concrete. (Volhard 2013, 224)

- **Indoor climate regulation:** By offering thermal mass and moisture exchange, loam can keep the air in interior spaces at relatively constant temperatures and humidity levels. (McGregor et al. 2016; Habert 2017) This is not only beneficial to human health; it can decisively prevent mould (Olelenko and Breuss 2020), a severe issue in recent decades as buildings are becoming increasingly airtight.

- **Conservation:** A timber component encased with loam is kept at a constant dry moisture level and is therefore protected from rotting. (Volhard 2013, 69)

- **Non-toxicity:** Neither loam nor any common adhesives to loam pose a threat to human health (Grimm 2019) at any point of the life cycle. (Boltshauser 2019, 152–63)

Despite this long list of advantages, three key disadvantages are responsible for loam being a niche product in the current building industry.

- **Limited structural abilities:** Loam can take nearly no tension and only provides little pressure resistance. Therefore, loam as a load-bearing material can be used only in walls of low-storey buildings and precautions have to be taken if it is to be used in earthquake-prone areas. (Bui, Bui, and Limam 2016)
- **Limited resistance towards water:** While the way loam softens in water is advantageous in many ways, the material is not suitable for building parts in contact with soil (with the exception of a multi-layered rammed earth floor) and should not be used as a load-bearing material in areas susceptible to floods. (Minke 2009, 11)
- **Labour-intensity**: Many loam building techniques are very time-consuming and therefore no longer economical given the cost of labour in the modern construction business. (Minke 2009, 213)

2.3.2. Material basics

Loam primarily consists of clay (< 2µm), silt (2-63 µm) and sand (>63 µm) and achieves its rigidity over friction between the different particles. By adding water, the clay parts dissolve and form a film over the other particles, decreasing friction and therefore making the mixture formable. The water evaporates in the drying process, and the mixture becomes solid. The loss of volume throughout the drying process triggers shrinkage and the evolution of cracks which is why the water content has to be as low as possible. (Minke 2009, 16)

Developing a precise mixture is crucial for a good result. While clay provides formability and cohesion, a too high proportion leads to increased water demand and therefore more cracks. Gravel aggregates may be added to increase structural strength and decrease the water demand while fibres such as straw, woodchips or flax increase tensile strength and can prevent the evolution of large cracks but simultaneously increase the water demand. (Minke 2009, 40) Adding a large portion of organic fibres or light mineral ingredients such as expanded clay or pumice decreases density and thermal conductivity. The water-absorbing characteristics of light mineral ingredients can also be applied for reducing shrinkage down to 0% (Minke 2009, 53), though their limited availability and energy-intensive production compromise the ecological performance. (Pargana et al. 2014)

2.3.3. Load-bearing earth construction principles

Offering only very limited tension resistance, load-bearing loam construction is mainly focused on walls. Rammed earth and adobe bricks are the most common techniques for this purpose. In rammed earth construction, loam with very little water is filled into a formwork where it is compressed in layers of 10-15cm. While laborious, the technique is most resilient and features a visually very distinct layer structure. (Willhardt 2013) To produce adobe bricks, loam is filled into a brick formwork, compressed, dried and stacked analogue to burnt bricks. (Minke 2009, 70–74)

Up to 6 MPa, in most cases around 4 MPa (Minke 2012, 33) of compressive strength can be achieved with these techniques which is only 15% and 10% respectively compared to burnt bricks. (Anton Pech, Hans Gangoly, Peter Holzer 2015, 27) The height of load-bearing earth construction is therefore usually restricted to two storeys. (Volhard 2013, 32) The highest rammed earth house in the world, erected in 1830 in Weilburg, is six storeys high, (Schroeder 2019, 16; Horz 2016).

Fig 2.4. Hainallee 1 Weilburg, the highest pisé house in the world

Another disadvantage of load-bearing earth construction is that in many cases up to 10% of cement is added to the mixture for faster curing, stabilisation against moisture and, especially, compliance with building regulations. (Jeske 2020) Considering that one can easily realise a concrete mixture with 12% cement and that loam walls require additional thickness to compensate for the low compressive strength, this compromises recyclability and leads to the ironic situation of many modern earth walls having a higher carbon footprint than comparable walls made out of reinforced concrete. (Rauch 2020)

2.3.4. Timber/loam hybrid techniques

Timber/loam hybrid construction eliminates many issues of earth construction by applying loam in a non-structural way. Two major techniques are to be presented at this point:

<u>Light loam infill</u>: By adding organic or porous inorganic material, a thermally insulating loam mixture is produced and cast into a timber frame structure. (Volhard 2013)

Wattle and daub: Loam is daubed on a dense mesh of branches (wattle) to form a non-structural spatial enclosure. The technique is not suitable for modern construction because of very limited durability and a very laborious construction process. (Minke 2009, 92)

The main disadvantage against solid earth construction lies in a lack of visibility and architectural expression compared to rammed earth. Example systems include the EcoNest building system (Laporte 2021) which is architecturally inspired by the Japanese Zen and Indian Sthapatya Veda traditions (Volhard 2013, 274–77) and targets single-family home construction in the USA.

2.4. Floor slabs based on renewable materials

The most common floor slab solution is a flat, reinforced concrete slab with a floating cement screed. (Hestermann and Rongen 2015, 365) While not being very sustainable, the system offers high fire resistance, noise protection and thermal mass and therefore serves as the reference system. Find a full evaluation of the different floor slabs in section 5.

2.4.1. Light timber floor slabs

Among other solutions, beams are the traditional way of constructing floor slabs, and remain common today. While being simple and efficient, the system suffers from significant structural height, little sound insulation and high vulnerability to fire and usually must be equipped with additional layers. (Kolb 2010, 276–82)

2.4.2. Solid timber floor slabs

Solid timber slabs, the majority of which are made of CLT, are particularly popular for their fast fabrication process, structural stiffness and increased resistance to fire, making it easier to leave them visually exposed in multi-storey timber construction. (Kaufmann, Krötsch, and Winter 2017, 62)

2.4.3. Timber/Concrete hybrid floor slabs

Concrete has been applied in timber floor slabs since the 1920s with two different directions of development having evolved.

Timber-concrete composite slabs are the most common type in this category and feature a structural system composed of timber in the tension zone at the bottom and 4-12cm of concrete in the pressure zone at the top of the slab. The shear connection between the materials is established with grooves or metal connectors. The advantages of the system lie in increased structural performance, sound protection and better fire safety evaluation. (Kaufmann, Krötsch, and Winter 2017, 64–65)

An alternative approach is to arrange the concrete at the bottom of the slab to increase fire protection and thermal mass. The two major systems are X-Floor (Forum Holzbau 2013) and SwissWoodConcreteDeck. (Meena, Schollmayer, and Tannert 2014; Isopp 2021) In the Woodland Trust Headquarters project by Atelier One, non-structural ripped concrete panels were attached to the bottom of a CLT slab to generate thermal mass. (Dias et al. 2016)

Fig 2.5 LCT One slab

Trying to combine the advantages of the two approaches, one can use beams to span in the main direction and a concrete slab to take compression force and span in the secondary direction. Examples include the slabs in the LCT One building by Hermann Kaufmann (Green and Taggart 2020, 172) and Erne SupraFloor ecoboost (Erne 2021). With installations usually being located between the beams, the effect of the thermal mass is doubtful in this case.

2.4.4. Timber/Loam hybrid floor slabs

In modern construction, loam in horizontal building components is only applied as a screed or as a filling material. Historically, however, there have been several construction techniques for exposed loam-timber hybrid slabs where loam provides resistance against fire and noise. The most noteworthy examples are:

Latia-loam floor slab: Light loam with a high share of organic fibres is wound around a wood log or slat that is then mounted between two timber beams. By arraying the components in close proximity to each other and flattening the loam between from underneath, a continuous surface is achieved. (Volhard 2013, 110–13)

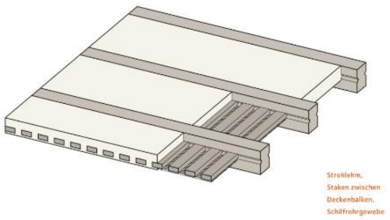


Fig 2.6 Viga-loam floor slab

Viga-loam floor slab: Timber slats are aligned between beams with small gaps. Light loam is cast and rammed from the top using formwork. Alternatively, it can also be cast without formwork and very low viscosity from above while another person at the bottom applies the mass that is dripping down between the boards to the timber slats with a broom. (Volhard 2013, 113–16)

Vaulted Ceiling: Wood beams span in the primary direction while vaults composed of earth bricks close the gaps between the beams. (Minke 2009, 133) The company Casadobe has developed earth brick elements that can be inserted between beams in one piece. (Casadobe 2003)

While especially the first two techniques consume far too much labour time to be applicable in modern construction, their advantages - particularly thermal mass, fire protection, humidity regulation and sustainability - are more relevant than ever.

2.4.5. Earth Flooring Techniques

Historically, there is a wide array of flooring techniques, all of them being connected to a vast number of layers and working steps. With conventional rammed earth floors featuring a thickness of 10-15cm, they are only applicable on the lowest floor of the building. (Sauer 2015, 58–62) However, thinner and lighter alternative floor solutions have been developed since, an overview of which can be found in the following paragraphs:

- Martin Rauch has described a light-clay floor with only 1-2cm thickness and approximately 6cm substructure that simultaneously provides body sound insulation. It is economical to produce. Its disadvantages lie in low thermal mass and the use of casein and glass fibre mesh (Sauer 2015, 63; naturbauhof 2021).

- A loam floor with approximately 60mm thickness and few working steps is currently under development by Oxara but has not reached market readiness yet.

- In the product portfolio of the company Claytec there is a clay terrazzo floor featuring a 60mm base layer, a 20mm top layer and a reinforcing glass fibre mesh between the two layers. While not having to be compressed, the system requires skilled craftsmanship. (Claytec 2018)

- Gernot Minke has developed a light loam floor with a 42mm rammed base layer and 3mm top layer. (Minke 2009, 136)

- Prefabricated loam dry screeds are technically possible and have been found in old Germanic graves from as early as 5 000 B.C. (Böhl 2017, 15) However, they are scarcely available at the moment; only Gernot Minke mentions a small Finish manufacturer producing them (Minke 2009, 82).

2.5. Automation and Innovation in Timber Construction

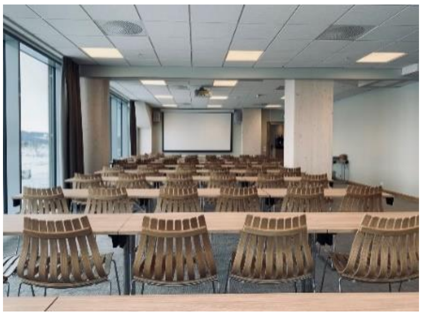
In times of a shrinking and over-ageing workforce, automation promises to reduce labour demand and contribute to a better work environment that encourages young people to join the industry. (Kaufmann, Krötsch, and Winter 2017, 148)

Automated trimming and CNC have been adopted by most large and medium-sized timber companies (Kaufmann, Krötsch, and Winter 2017, 139), though because of the segmentation of the market most German companies do not have sufficient production volume to make higher degrees of automation and industrialisation economically viable at the present time. (Bock and Linner 2015, 75) Outside of mass production, digital manufacturing allows for increasingly ambitious timber construction processes. One example of many is the Swatch Headquarters project by Shigeru Ban. (Skavara et al. 2020, 210–17)

2.5.1. Timber high-rises

At the moment there is a global competition in erecting ever taller timber high-rises with the Mjøstårnet in Brumunddal, Norway, finished in 2019, currently holding the record with 85.4 meters. (Green and Taggart 2020, 50–57) While these projects accelerate industrialisation and automation of timber construction, the results are often compromised by significant concrete use and lack of exposed timber surfaces. (Green and Taggart 2020, 43–44)

Fig 2.7 The interior of Mjøstårnet



2.5.2. Production automation of light timber systems

There is machinery for automating the various steps in the additive production of wall and slab components including automated cutting, storing, stud fitting, blow-in insulation and wrapping. (Orlowski 2019) Major producers include Weinmann (HOMAG 2021), Randek (Randek 2021), MBA (JJ Smith Woodworking Machinery 2021), and Hundegger (Hans Hundegger GmbH 2021). Particularly in the production of prefabricated houses and modularized construction, high levels of automation and production-line like workflows are achieved, though industrial standardisation and modularisation dominate the processes (Popovic 2018).

Fig. 2.8. Weinmann stud fitting station

2.5.3. Production automation of solid timber systems


Fig. 2.9. BUGA pavilion Heilbronn by ICD

Subtractive processes, as usually applied in solid timber systems, are generally easier to automate than additive processes. CNC milled walls and slabs have therefore become a very common practice in timber construction (Willmann et al. 2016). However, while this leads to a high degree of automation, up to 20% cut-off occurs in the process, even further decreasing the already poor material efficiency of CLT (Krötsch et al. n.d.).

2.5.4. Research on the automation of timber construction

In the field of research, particularly the high amount of precision and uniqueness connected to robotic fabrication has been a driving factor.

Fig 2.10. Fabrication of roof truss elements for The Sequential Roof

Gramazio Kohler Research at ETH Zurich has been working on a number of projects, including The Sequential Roof (Apolinarska et al. 2016) and Future Tree (Apolinarska, Lloret-Fritschi, and Fabio Gramazio 2021), for additively assembled timber structures with a high degree of efficiency and geometric freedom (Eversmann, Gramazio, and Kohler 2017).

Fig 2.11. Wood Chip Barn

The Woodchip Barn, built by and at AA London, goes one step further by additively assembling a pavilion based on robotically milled natural logs, allowing for greater variety and material efficiency (Menges et al. 2017, 30–35).

ICD Stuttgart has combined additive and subtractive manufacturing in the production of timber elements for an array of pavilions (Menges et al. 2019). Another research branch is the controlled bending of laminated timber triggered by the humidity of the material, as demonstrated in the Urbach Tower project (Skavara et al. 2020, 50–57).

In the field of additive manufacturing, there are several wood-based filaments for extrusion-based 3D-printing commercially available, though they vary in toxicity (Kam et al. 2019). An alternative approach, currently under development, is to 3D-print textiles composed of laminated layers of solid wood fibres (Leopold, Robeller, and Weber 2019).

Fig. 2.12. Continuous timber fibre placement

2.6. Automation and Innovation in Earth Construction

2.6.1. Automated ramming

To decrease the laboriousness of the rammed earth technique, motorized on-site tools and semi-automated prefabrication techniques have been developed in the 20th century (Minke 2009, 60). In recent years, ramming with industrial robots is increasingly being researched and applied (Rauch 2020; Bick, Bick, and Shaffer 2016).

2.6.2. Material Technology

Oxara, a spin-off start-up of ETH Zurich and partner in this project, is developing additives to eliminate the need for mechanical compression of earth walls altogether (Landrou and Demoulin 2021; Landrou et al. 2016). Instead, the loam mixture can be cast and vibrated analogously to conventional concrete.

2.6.3. 3D printing and digital free shapes

Loam 3D printing works analogously to concrete 3D printing. (Franco 2021) First projects, commonly developed by Wasp 3D and IAAC, include one-storey pavilions and a 3D-printed wall supporting a staircase. (Chiusoli 2019)

Gramazio Kohler Research at ETH Zurich (Fabio Gramazio 2021) has produced a bamboo/loam hybrid wall where a robot assembles a freeform bamboo grid which serves as formwork and reinforcement for Oxara “Cleancrete.” It is part of the MeshMould (Dörfler et al. 2019) project and has not been officially released yet.

Fig 2.13. 3D-printing process by Wasp 3D

3. System Design

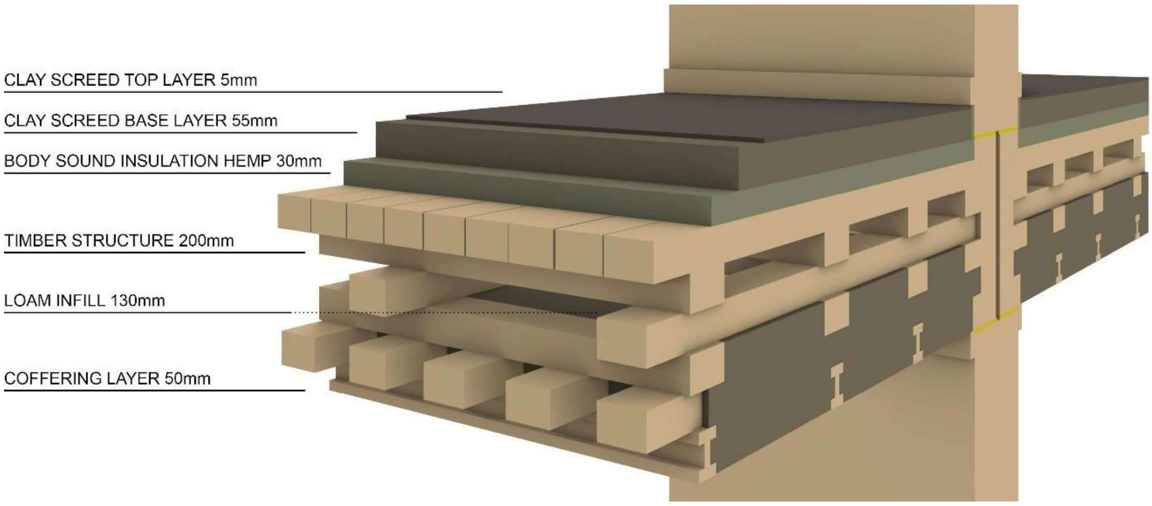


Fig. 3.1. 3D slab section

3.1. Context

The system, which was branded Timber Earth Slab, was developed in the context of “Einfach Bauen,” a TUM project devoted to developing a simple way of building design where the number of layers and working steps, as well as technical installations, are reduced to a minimum. This serves not only to decrease ever-rising complexity in construction but to facilitate maintenance and recycling. (Nagler and Jarmer 2018, 5)

In the course of the project, three student dorms with identical floorplans are to be constructed out of brick, concrete, and timber. The latter building serves as the context of this thesis, featuring four floors with load-bearing CLT walls and prefabricated concrete floor slabs. The default student rooms measure 3.23x6.44 m^2 with all four enclosing walls being load-bearing. The floor slab in a default student room can therefore span in an omnidirectional way and be transported in one piece. It must fulfil 60 minutes of fire resistance and comply with the German norms for noise insulation for floor slabs between apartments. (Hestermann and Rongen 2015, 433) One to two sample floor slabs are to be installed in the building which is scheduled to be erected in 2022 at the TUM campus in Garching.

While the development of the slab focuses on the fulfilment of all requirements posed in this context, it does not limit itself thereto, and instead takes requirements of other potential use cases, such as schools and office buildings, into account as well.

3.2. Basic Idea

Since loam offers high performance on fire protection, thermal mass, and sound insulation, it makes sense for a loam infill to fulfil these functions while timber takes over the structural role. To provide a maximum of thermal mass and fire protection, the infill has to compose the ceiling surface and cannot rest on a support structure since it would have to be fire-proof and would compromise thermal mass. Therefore, the loam infill has to be able to support itself by forming a mechanical interlock with the timber structure. To facilitate an interlock, the timber structure must form a fine-grained grid.

3.3. Structural System

The load-bearing system is composed of a structurally optimized cross-laminated timber grid that ensures structural stability and provides a mechanical interlock for the loam infill. The design must therefore consider both structural optimization and constraints posed by infill and production.

From a structural perspective, the grid combines the advantages of traditional beams and CLT. While beams are very material-efficient and usually come glue-free, CLT slabs provide stiffness, omnidirectionality, high automatization potential, dimensional stability, utilize the cheaper sideboards, and reduce metal connectors. (R. Brandner et al. 2016)

Employing robotics and structural optimization, high material efficiency, low human labour input, utilization of sideboards, omnidirectionality, low glue input, elimination of metal connectors and lateral bracing can be combined in one slab.

3.3.1. Structural optimization

A five-layered grid is recommended for most use cases. The structure spans in two directions though there is a clear main span direction.

Fig. 3.2. Structurally optimized grid

The boards in the primary direction are responsible for resisting momentum forces. It is most efficient to align them densely at the top and bottom of the slab while placing fewer or thinner boards in the centre.

The boards in the secondary direction are responsible for distributing force and are vulnerable to rolling shear. For this purpose, they should be densified in the shear zones and should ideally be four times wider than high. (R. Brandner et al. 2016) In an omnidirectional scenario, they can also transfer momentum forces near their supports allowing for dedensification of the primary boards in those zones.

3.3.2. Constraints posed by the loam infill

To provide sufficient stability for the loam infill, a 40mm minimum should be considered for both layer thickness and gap width. To minimize shrinkage cracks, the centre-to-centre distance between the primary boards of the bottom layer must not exceed 120mm. (find further details in section 6.5.1)

3.3.3. Production constraints

Production constraints are mostly connected to high assembly speed and equal force distribution in the pressing procedure.

Using larger and therefore fewer boards increases assembly speed but can be detrimental to the integrity of the loam infill. 40x60mm boards have turned out to be a very well-working format in this context.

To provide an even amount of pressure in the pressing procedure, parallel layers must feature comparable densities unless temporary support boards are placed to distribute the pressure more evenly.

3.3.4. Wall connection

If vertical load transmission on the supports is not required, there are no special rules for the edge finishing.

Vertical load transmission can be achieved by implementing additional boards. Particularly in multi-storey buildings, cross-grained timber boards must be added to minimize vertical shrinkage (find further details in section 3.7) though there is, unfortunately, a lack of ready-made products on the market. As a beneficial side-effect, the sideboards provide a lost formwork for the infill, reducing labour and material input in the casting process.

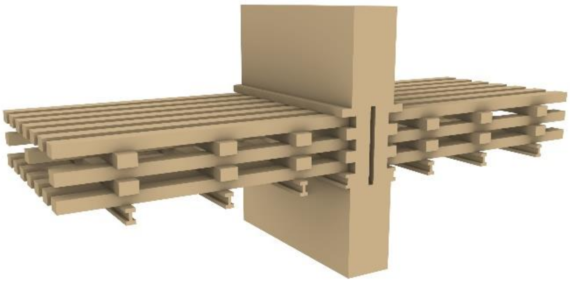


Fig. 3.3. Edge Finish for vertical load transmission

3.4. Infill Functions

The loam infill is responsible for the spatial enclosure, fire protection, and airborne sound insulation. On top of that, it improves body sound insulation and the thermal comfort level by providing humidity regulation and thermal mass.

The bottom two layers of the structural grid must be infilled to achieve sufficient interlock while an additional 4-6cm layer underneath the structural grid provides fire protection and thermal mass. This results in approximately 100 l/m^2 of infill. The other layers can be infilled to increase the level of noise protection. The following sub-points provide a detailed description of the functions and characteristics of the infill.

3.4.1. Fire protection

Loam is classified as a non-inflammable material. However, if organic fibres are included in the mix, there has to be, depending on the exact fibre type, a minimum density of 1200 – 1700 kg/m^3. (Volhard 2013, 224) In the event of a fire, the infill has to thermally insulate the timber structure to keep it under 200° Celsius which is when wood starts losing its structural strength. (Klingsch et al. 2015) A 5cm bottom layer is expected to provide sufficient fire protection for at least 60, likely 90 minutes. (Volhard 2013, 225) If necessary, this duration can be extended by adding light mineral aggregates to the loam mixture to decrease thermal conductivity.

3.4.2. Noise protection

According to the law of Berger, the noise protection volume of a building component increases with its weight (Willems 2020, 68), though multi-layered components can show fundamentally different behaviour compared to mono-layered components. (Willems 2020, 72)

The earth filling is sufficient to protect against airborne sound while the body sound insulation can in any way only be ensured in combination with a floating screed. It is advantageous to at least partly fill up void spaces with a porous material, such as hemp shives, to avoid resonances. (Willems 2020, 75) Physical experiments are required, though, to assess precise values with certainty.

3.4.3. Thermal mass

Providing a very large surface area and being comparably free from obstructions such as furniture, the ceiling is pre-destined for storing and transferring thermal energy.

One has to distinguish between total thermal mass *C* and thermal mass C_{24} activatable in the daily cycle. (Keller and Rutz 2012, 52) A high amount of total thermal mass, which is based on the density combined with a material coefficient, helps saving energy to dampen weather variations and is generally seen as beneficial. (Belfast et al. 2018) A high amount of daily activatable thermal mass, which is additionally influenced by the thermal conductivity of the material, is effective against overheating in summer by storing cold temperature at night. (Gagliano et al. 2014) Research is divided on the question of whether increased activatable thermal mass is beneficial in the heating period, however, and some claim that it can lead to higher energy consumption. (Belfast et al. 2018; Hacker et al. 2008)

As table 1 shows, the weakness of timber lies not so much in total thermal mass as in daily activatable thermal mass. This is because of its low thermal conductivity. Timber is therefore not suitable for most construction projects in non-tropical hot climates. Though not performing as well as concrete, clay provides multiple times higher values on thermal mass than timber. (Keller and Rutz 2012)

To maximize daily activatable thermal mass, the loam mixture is to be as dense as possible. Only when overheating is not an issue is using a light mixture advantageous.

	timber	**clay**	**concrete**
thermal mass (kJ/m^3)	1008	1890	2310
maximum daily activatable thermal mass (kJ/m^2)	44.5	180	220

Table 1: Thermal Mass of different materials
(for clay, a density of 2200kg/m^3 was assumed)

3.4.4. Heating and cooling

It is possible to thermally activate the loam infill, providing an inexpensive and energy-saving means of heating and cooling. Further details can be found in section 7.1.5.

3.4.5. Interior air improvements

As discussed in section 2.3.1., loam improves the interior climate by keeping the air at a constant humidity level throughout the year. This can prevent mould and improves human resistance to diseases in winter. (Minke 2009, 12–13)

3.4.6. Protecting the timber construction

As discussed in section 2.3.1., loam encapsulates the timber structure and therefore expands its lifespan.

3.5. Infill application

3.5.1. Amount of layers to fill

In the average use case, a weight exceeding 250kg/m^2 does not hold advantages that are significant enough to compensate for the additional amount of structural timber needed. With the void of the slab usually providing more volume than necessary for achieving this weight, there are different infill strategies:

1) Using a heavy mixture but filling up only the bottom layers: (recommended) This results in a short drying time, low material cost and a high amount of activatable thermal mass. Disadvantages include less protection for the timber structure, slightly decreased fire safety and potential acoustic resonances in the void space. (Willems 2020, 75)

2) Filling the whole structure with a relatively light mixture. This has the advantage of simplicity and better protection for the timber structure. The disadvantage lies in an increased drying time and less activatable thermal mass. If a non-inflammable classification is to be achieved, either the minimum density requirement for organic light loam must be respected or mineral light loam must be used. The latter, however, comes with a very significant negative environmental impact (Pargana et al. 2014) and decreases the thermal mass activatable in the daily cycle.

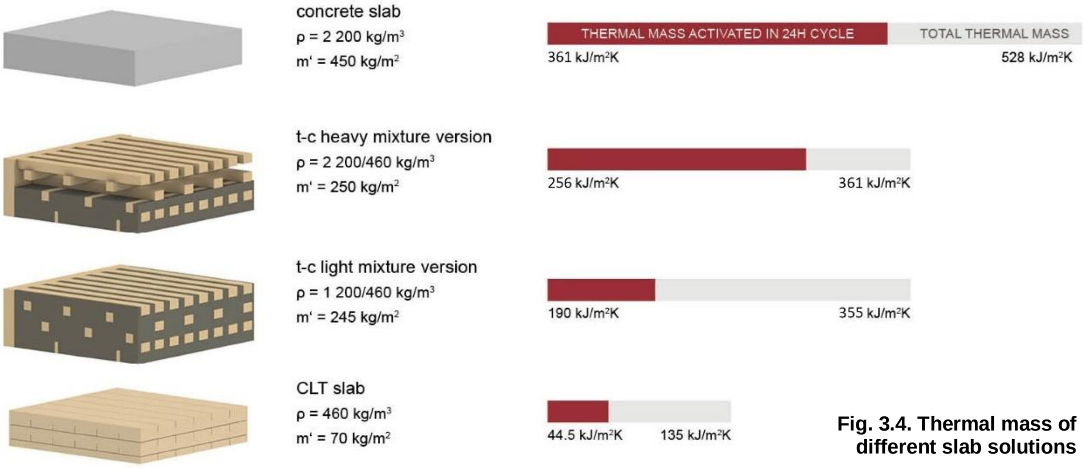


Fig. 3.4. Thermal mass of different slab solutions

3) Hybrid: Trying to combine the advantages of both systems, one can fill the lowest layer with a heavy mixture while using a much lighter mixture for the other layers. In this case, protection for the whole timber structure and a high amount of activatable thermal mass can be provided without having to worry about minimum densities or resonances. The disadvantage lies in a longer drying time and higher material cost

and it yet has to be tested whether the two mixtures can form a well-working compound.

In most cases, including the Garching student dorm, option 1 is the best solution and therefore treated as the default solution.

3.5.2. Coffering

While prototyping has shown that it is not strictly required (find more details in section 6.4.5.), a non-loadbearing layer with I-shaped coffering boards perpendicular to the main span direction may be architecturally desired and can potentially reduce cracks. It can be robotically assembled with the rest of the grid. It is expected not to be a threat to safety under fire in an F60 scenario though this yet is to be validated in experiments.

3.6. Floor structure

The floor structure has to provide a walkable surface and ensure body sound insulation as well as fire protection. Given high thermal mass and fire safety, the recommended solution is to use an earth screed in combination with hemp body sound insulation.

3.6.1. Screed

Given an array of different methods for producing loam screeds (find further details in section 2.2.4), further consultations and experiments yet have to be undertaken to specify an ideal solution.

At the present stage, the most promising approach is to apply a 50mm base layer with the same mixture as the one used for the infill and a wax-sealed 5mm top layer with a loam mixture containing 6% chalk-casein. The wax increases moisture resistance while chalk and casein in a 1:10 mixture provide resistance to abrasion. (Minke 2009, 136) If necessary, a fibreglass mesh can be added between the layers to increase tensile strength. (Claytec 2018)

3.6.2. Body sound insulation

In combination with typical wet screeds, mineral boards protected by a foil are a very common body sound insulation solution in modern construction. (Pfundstein et al. 2007, 22) With earth being breathable (Schroeder 2019, 443), it might be possible to implement a body sound insulation made of hemp fibres without additional foils. However, this yet has to be verified in experiments.

3.7. Specific adaptions for the context

The floorplan of the rooms is slightly parallelogram-shaped, adding another factor of complexity to the robot programming and the production of the slab geometry. Building the grid in an angled way with the individual boards parallel to the walls is the best solution as it provides optimal conditions for the loam infill, lower fabrication complexity and less waste. With all four walls being load-bearing, the structural system is optimized towards spanning in both directions. Since the goal of the “Einfach Bauen” project is to develop buildings with little complexity and low maintenance, no installations are to be included in the slab.

With the other slabs being made out of reinforced concrete, a maximum thickness had to be respected and the individual layers adapted accordingly. To prevent uneven shrinkage, timber boards with vertical grain are to be glued to the side surfaces of the slab.

If the earth screed can be realized as planned, the bathroom walls are to be placed directly on the timber structure and precautions have to be taken inside the bathroom to protect the screed from excessive moisture. Due to fire regulations, a mineral body sound insulation board has to be used.

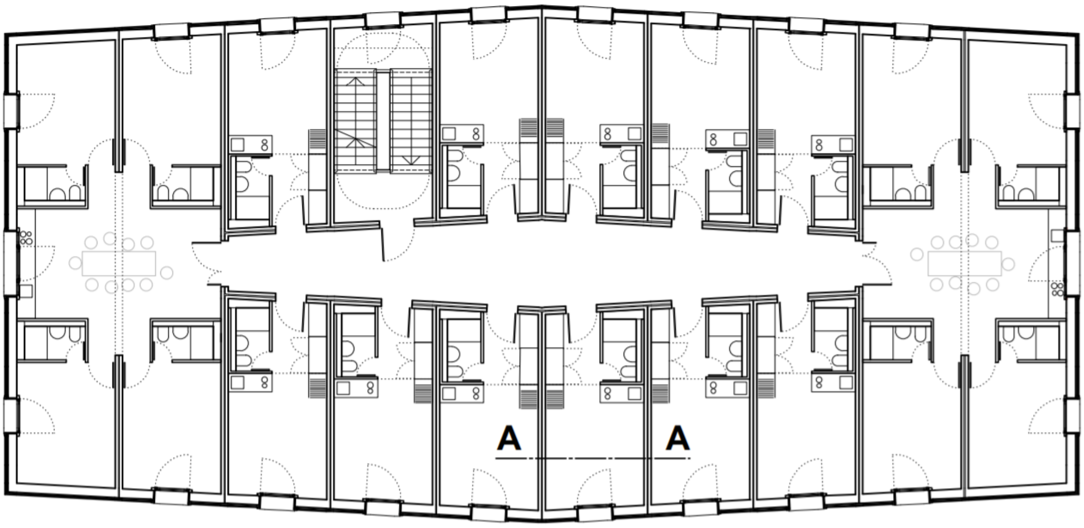
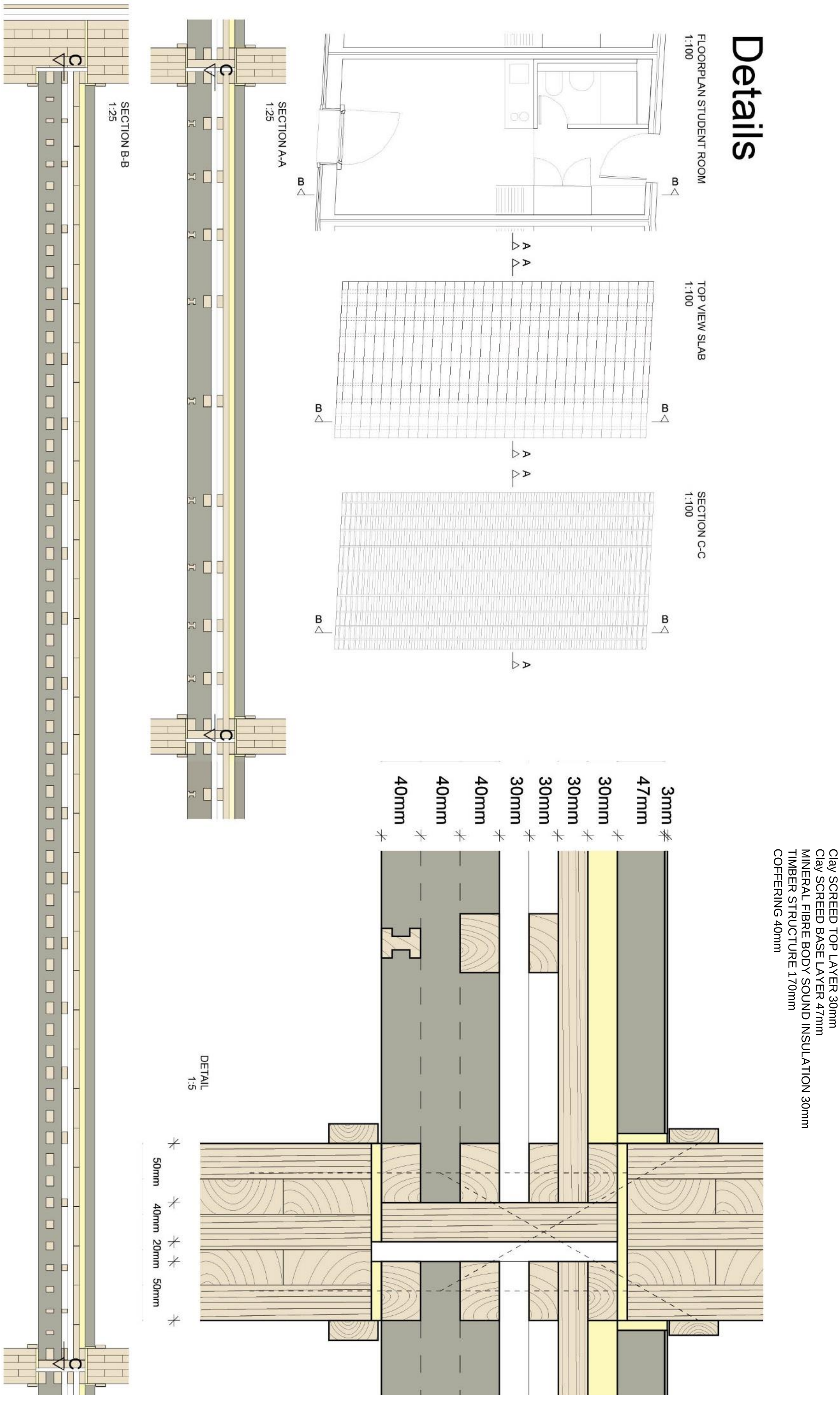


Fig. 3.5. Floor plan of the context builidng

Fig. 3.6. Construction details for the context building



4. Fabrication

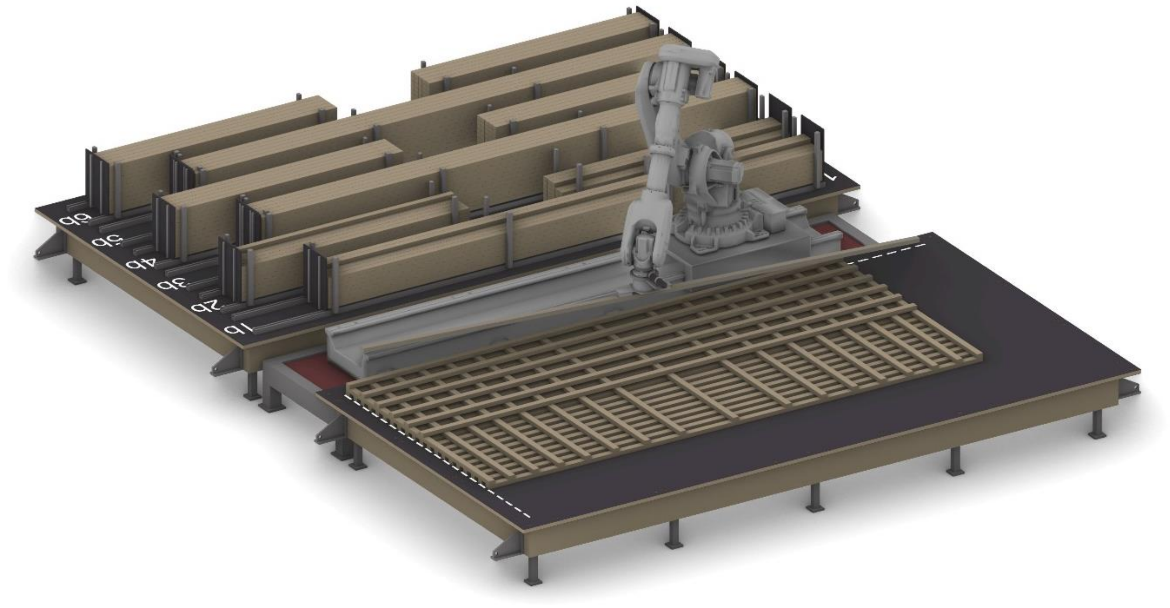


Fig 4.1. Robotic pick&place&glue assembly

While the slab could theoretically be produced manually, digital fabrication makes the process efficient and error-resistant. As discussed in section 2.5., most timber companies do not have enough production volume to make the purchase of advanced automation equipment economically viable. The fabrication concept described in this section was therefore developed around a mobile robot station and based on the assumption that the production environment is equipped only with a low level of automation.

Prefabrication is recommended to be done off-site with both timber companies and precast plants being potential fabrication environments. Timber factories can be advantageous if an automatic trimming machine is available, but one has to set up a vibrating table and casting equipment and mix the loam remotely. Precast plants have the advantages of having equipment for mixing, casting, and vibrating readily available (Bock and Linner 2015, 75), but the timber boards must be pre-cut or a cutting process included in the robotic fabrication.

The process starts in the factory with robotically assembling and pressing the timber grid and casting the infill. After a drying phase, the slab can be installed in the building and the floor system brought in.

4.1. Geometry and machine code generation

The grid is to be created in a parametric way. For this purpose, a software environment consisting of the following elements is required:

- A Geometry Creation Tool that creates the structural grid geometry based on a list of parameters. Parameters include dimensions, number of layers, profile and spacing of the timber boards and edge finish. Find further details and a full list of parameters in appendix A.
- A Finite Element Analysis tool to estimate the structural behaviour of the timber grid generated by the Geometry Creation Tool.
- A Pressure Distribution Analysis tool to analyse the force distribution under pressing and implement support boards if needed. Find further details in section 3.3.3. and 4.4.1.
- A genetic algorithm that finds the optimal parameters for the Geometry Creation tool based on the output of the two Analysis tools.

Input parameters include dimensions of the slab, permissible timber formats, forces and maximum bending and the robotic assembly environment. The output is the floor slab geometry, structural behaviour as well as the machine code for the robot.

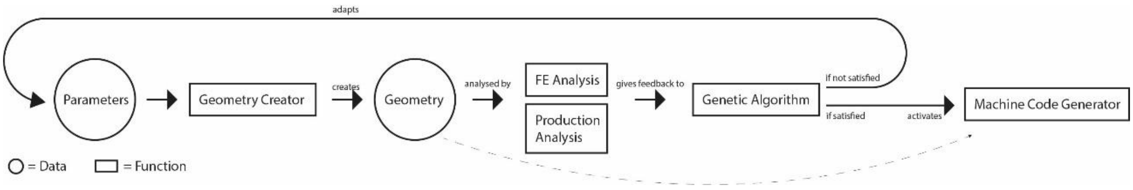


Fig 4.2. Software Pipeline

4.2. Robot Design

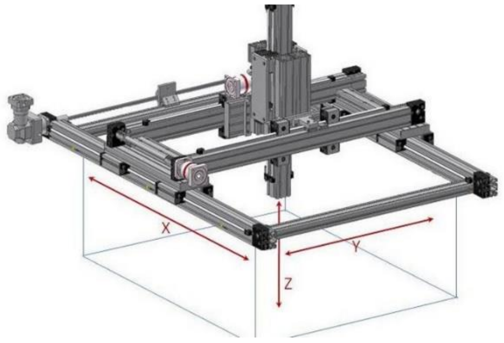


Fig 4.3. Gantry robot

4.2.1. Gantry vs 6-Axis robot

Generally, 6-axis robots (Fig. 4.1) provide more motion versatility and speed (Corporation Keller Technology n.d.) and can be combined with a linear rail to expand the working area while gantry systems (Fig 4.3) are usually cheaper (Crossco

2021) and easier to program (Construction of Buildings on Demand n.d.), provide more rigidity and offer higher payload and larger working range.

Since the assembly only requires simple cartesian motions, the floor slab seems to be destined for a conventional gantry system. However, such a system would have great width and would therefore be hard to ship while current mobile robot stations for construction, such as TIM by ICD Stuttgart (Wagner et al. 2020) and Fabtory by TU Munich, are based on 6-axis robots. Therefore, the assembly procedure has for now been optimized towards one 6-axis robot.

4.2.2. End-effectors

Gripper: Both vacuum grippers and mechanical grippers can be used for the assembly. Vacuum cups feature higher speed and fewer restrictions for the timber board profile. Mechanical grippers have the advantage of higher precision and lower cost. (Bouchard 2014) Since high precision is not crucial in this project, vacuum grippers are primarily recommended.

Glue application: It is recommended to attach the glue gun directly to the robot. Niemes FAS300 in combination with N-Pur100 has been used in comparable projects (Wagner et al. 2020) and is therefore expected to be suitable for this purpose as well. According to consultations with Jowat (Jowat SE 2021), the very small glue surfaces and therefore lower requirements on exact dosage might allow for the implementation of simple dispenser systems or, in combination with a low-viscosity glue, pneumatic press cartridges. Experiments yet have to be undertaken.

Laser distance sensor (optional): Equipping it with a laser distance sensor allows the robot to measure the number of boards on the stack and adapt the picking procedure accordingly. Without it, the stacks always have to be precisely synchronized with the code; a sensor can therefore save time and reduce the chance of accidents.

4.3. General Preparations

4.3.1. Producing the loam mixture

The loam mixture proposed in this thesis consists of five main components:

1) Sludge: Composed of silt and clay, this waste product from gravel production provides the cohesion of the mixture. A small-scale telephone survey revealed

that local gravel companies produce 50 tons of sludge per day on average which suffices for roughly 800m^2 of infill.

2) Aggregates: 0-4mm sand and 4-8mm gravel
3) Fibres: Fibres improve tensile strength and decrease shrinkage cracks. Flax or hemp fibres with 30-40mm length are recommended.
4) Additives: Mineral additives produced by Oxara that mainly serve to reduce the amount of water needed.
5) Water: Key for liquifying the mixture though the amount has to be kept as low as possible. (Minke 2009, 18)

The precise recipe depends on the characteristics of the sludge which has to be analysed before the first application.

4.3.2. Base plate and mobile press

The base plate is designed to be multifunctional and plays a central role in the whole prefabrication process. It provides an even surface for assembly and casting, airtight connection for a flexible vacuum press and stabilisation during the vibrating process. Being composed of a beam structure and a milled coated board, it can be produced in a timber factory.

Fig 4.4. Base plate

A vacuum press consists of a steel frame holding a vacuum bag with a valve. After the frame has been connected to the base plate over the connection bolts in an airtight way, the air can be removed with a pump to create the vacuum. While this device would not necessarily be strong enough for pressing default CLT (Reinhard Brandner 2014), only a fraction of the pressure is needed in this case, thanks to the small size of the glue surfaces.

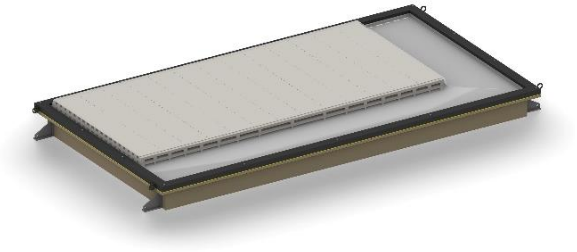


Fig 4.5. Base plate connected of the vacuum press

The connection bolts of the base plate are there to fixate the vacuum press while the stabilisation bolts hold the workpiece and, if required, the side formwork and/or a custom ceiling formwork in place during the vibrating process. The beam geometry on the bottom side is designed to interlock with a vibrating table.

Fig 4.6. Base plate on the vibrating table

4.3.3. Pickup area

There are to be one or two pickup areas with stacks where the robot can pick up timber boards. If a laser distance sensor is attached to the robot end-effector, filling up the stacks in a precise way is no concern; there only has to be a sufficient amount of boards available and the individual board formats must be placed on the respective stacks. Using a mobile base plate with a steel framework for aligning the boards horizontally is recommended. This way, the stacks can be prepared outside of the areas and interruptions in the assembly process thereby minimized.

4.4. Industrial Fabrication Sequence

4.4.1. First grid assembly process

The timber structure is fabricated in two parts with the bottom three layers and the optional coffering constituting the bottom part and the remaining layers the top part. While counter-intuitive, a two-part assembly has an array of advantages including even top surface and therefore a suitable basis for a wet screed, easier casting process, fewer issues with the maximum open time of the glue and more geometric liberty and therefore better structural optimization. The increased geometric liberty stems from the possibility of placing temporary support boards in layers with less density to provide a more even pressure distribution. (find more details in section 3.3.3)

The robot places the glue points, picks the boards from the stacks and places them at their final position. If a layer is very dedensified, temporary support boards can be placed to ensure more even pressure distribution.

After the assembly, the flexible vacuum press is attached to the base plate and the air removed with a pump. Once vacuum and therefore pressing has been established, the compound is to be moved to a different location where it remains under vacuum for at least two hours.

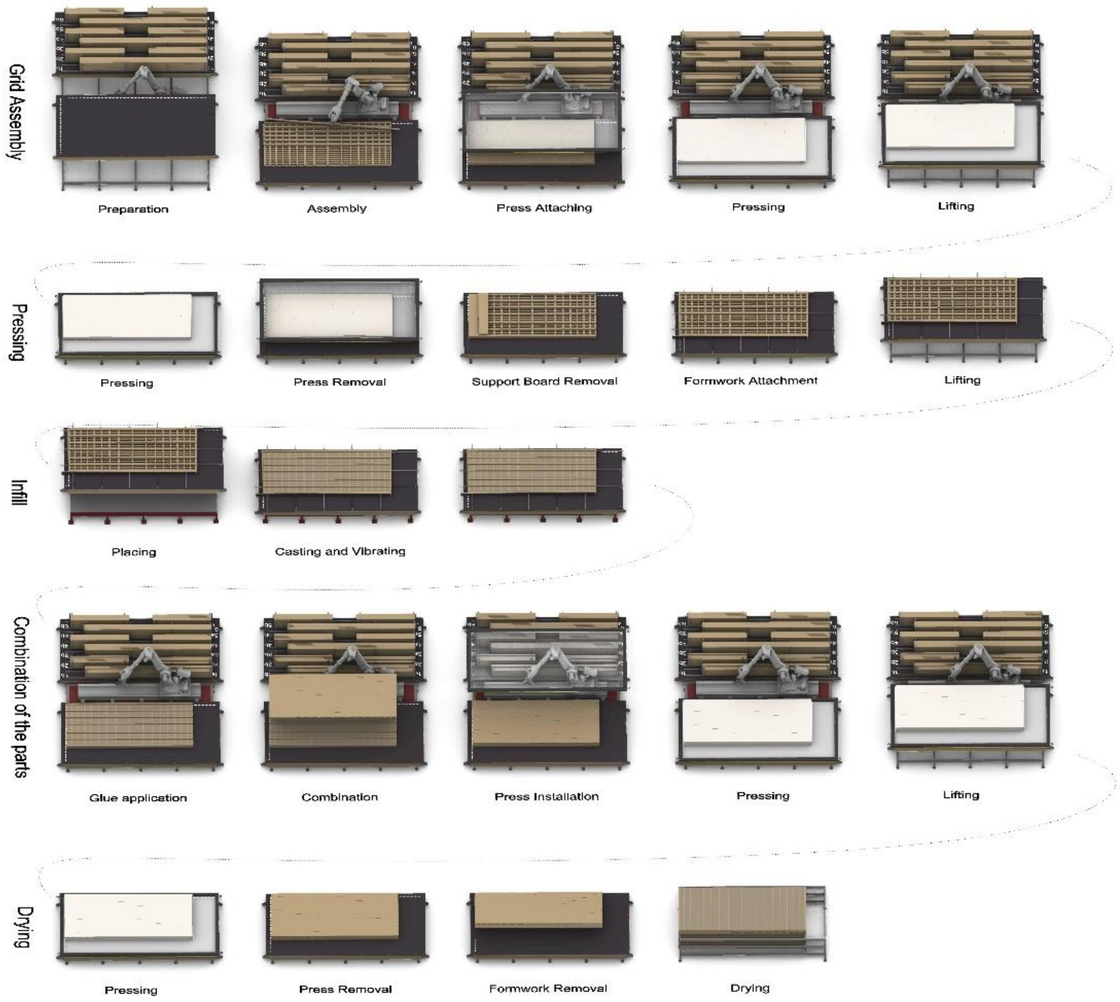


Fig 4.7. Fabrication Sequence

4.4.2. Infill process

After the press and potential support boards have been removed, duct pipes and core activation (if they should be part of the design) can be installed, formwork, if required, applied and the structure fixated horizontally through the stabilisation bolts. The compound is placed on a vibrating table and loam cast into the structure either manually or automatically (Bock 2007) before activating the table densifies the infill. It is important to make sure that the top surfaces do not get in contact with loam since this could have detrimental effects on the glue connections that are to established in the next step.

4.4.3. Second grid assembly process

After the infill process, the two parts of the structural grid are combined into one. The compound is brought back to the robotic assembly area where the robot applies glue points before the two parts are combined and pressed analogously to the first cycle. Thanks to the stabilisation bolts, no recalibration is necessary.

4.4.4. Drying process

The loam needs to dry in a slow and controlled way. Covering the slab with plastic foil or increasing the temperature and humidity of the space crucially slows down the drying speed. Storing the slab outside during drying is not recommended and has to be avoided at all cost if there is a chance of frost. (Schroeder 2019, 280) The slab is to be supported during the drying process since the bending under its own weight would lead to creeping deformation.

Depending on drying speed, the formwork can and should be removed after roughly four days to ensure more even drying. If a vault is to be formed (find further details in section 7.1.2), the slab can be turned around and exposed to bending; if not, it is to be supported continuously. The total expected drying time is three to five weeks.

4.4.5. Surface treatment

By placing the slab in a vertical position or upside down, surface treatment can be applied relatively easily. Loose particles should be removed with a broom while, if there should be cracks, they can be closed by repeatedly humidifying the adjacent loam, putting a clay-based joint sealant into the crack and smoothing the surface with a spatula. (Minke 2009, 123–24; Claytec 2021)

A more distinct texture or increased shininess may be achieved with further treatments; first experiments have been conducted in the course of prototyping (find further details in section 6.5.2).

4.4.6. Transport and mounting

The slab is ready for transport once both timber and loam have dried sufficiently. Timber should feature a humidity of 12% or less (Kolb 2010, 286) while the maximum humidity of loam is expected to lie between 2% and 5%; a precise value yet has to be determined in experiments. Shipping too early could cause creeping deformation (Nagler and Jarmer 2018, 45) of the timber structure and/or cracks in the loam infill.

The slab is to be transported and installed like a conventional timber slab; only the increased weight compared to other timber building components has to be taken into consideration in the dimensioning of the lifting equipment.

4.4.7. Flooring

Analogous to conventional slabs, the floor system is installed on-site. Compared to other wet screeds, the loam screed (find further details in section 3.6.1) has to be applied in two layers with sufficient drying time between the steps.

With the screed being two-layered and loam becoming soft in connection with water, it might even be possible to prefabricate the screed base layer in the factory on a vibrating table. In this case, all there is left on site is to close the gaps between the elements and apply the top layer.

4.4.8. Process output

Robotic fabrication poses the main bottleneck in the process. Assuming that eight 2.5 x 6.0 m^2 floor slabs can be robotically fabricated in one work day, a weekly output of 1 200m^2 of floor slabs is achievable with two robots, 10 vacuum frames, 60 base plates and a vibrating table and casting equipment. Two workers are needed to operate the robots and connect the presses, one to two further workers to handle the work pieces and do the infill. With two 24/7 shift cycles for robotic assembly and two to three default shift cycles for handling and infill, the output can theoretically be maximized to 5 000m^2 per week.

4.5. Optional steps

4.5.1. Applying sludge to the timber structure

Loam sludge is traditionally applied to timber elements in timber-earth hybrid construction to strengthen the bond between the materials and additionally protect the timber structure. (Volhard 2013, 172). According to Lufsky (Bonk 2010, 118–20), the sludge is also likely to reduce the water absorption of the timber structure.

Sludge must not be applied to surfaces that yet are to be glued. The easiest way is to dip the whole structure into a pool filled with sludge.

4.5.2. Trimming

Analogous to CLT production, higher accuracy can be achieved by trimming the edges with a circular saw after assembly. (Reinhard Brandner 2014, 18) This working step is expected to be relatively easy and might decrease the minimum accuracy requirements of the robotic assembly, potentially allowing for higher speeds and lower-quality timber.

4.5.3. Acoustic dampening

As discussed in section 3.4.2., filling up at least a part of the void with porous material such as hemp fibres mats is advantageous from the perspective of noise protection. Unless the material is blown in, it has to be added before the two parts of the timber structure are combined into one.

4.5.4. Use of a static glue gun

In case mounting the glue gun to the robot end-effector is not favoured, a static glue gun can be used as well. The disadvantage is that in the process of combining the upper and the lower part, the glue has to be applied manually.

4.6. Semi-Prefabrication

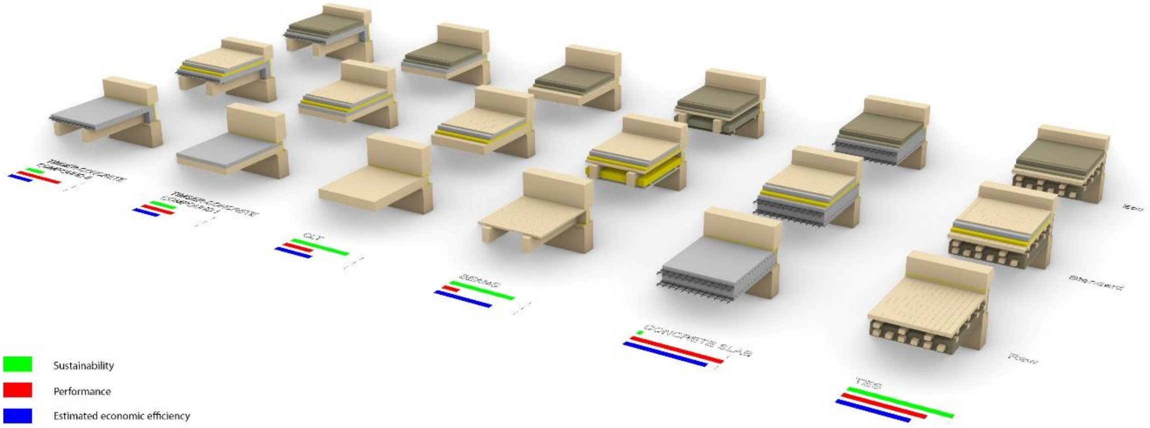
A semi-prefabricated option, where only the timber grid is prefabricated while the infill is cast on-site, was considered in the early phase of the thesis. The approach promised less vulnerability to tension cracks and no risk of transportation damages while being economical thanks to the fact that the formwork can already be mounted in the factory. However, prototyping (find more details in section 6) showed that tension cracks are not an issue at all while casting and densifying in an on-site procedure was more laborious than expected and required a more liquid mix, leading to excessive shrinkage cracks. It became obvious that full prefabrication would cut risk and costs while improving the quality and the concept of semi-prefabrication was therefore dropped.

4.7. Fabrication Process in the context of Garching

The slab is to be prefabricated in the TUM 1:1 Designfactory. The loam is to be mixed with a pan mixer, cast with buckets and compacted with a vibrating needle before the two parts of the load-bearing structure are combined and pressed. After drying the slab in the hall, it is to be transported to Garching and installed in the building which is also where the floor system is implemented.

5. System Evaluation

Fig 5.1. Reference slabs overview



5.1. Evaluation against other floor slab systems

To assess advantages and disadvantages, the Timber Earth Slab (TES) has been evaluated against five other floor slab systems – default reinforced concrete slab, CLT slab, beam slab and two timber-concrete compound slabs – on parameters in three categories: Performance, sustainability, and economic efficiency.

5.1.1. Methodology

For better comparability, each floor slab was analysed in three different configurations: “raw”, “norm” and “eco”. “raw” only features the parts of the slab that are absolutely necessary to form a load-bearing spatial enclosure. “norm” features a typical finishing including floating cement screed, mineral insulation, hardwood floor and, in case of the concrete slab and TES, a plastered bottom surface. “eco” features a more performance- and sustainability-aware option with exposed loam screed and organic insulation material. Parameters were assessed in the following ways.

<u>Performance:</u> Performance parameters include thermal mass, noise protection and fire protection. Fire protection values were calculated according to charring rates and product declarations. The thermal mass values were manually calculated with default formulas. (Keller and Rutz 2012) The values for noise protection were, with the exception of TES and concrete floor slabs, which were, together with improvements gained by floating screeds, calculated according to standard formulas and tables (Hestermann and Rongen 2015, 854–56), derived from sample floor slab systems. (Kolb 2010, 276–83)

Sustainability: While timber and glue consumption were calculated manually based on 3.2 meters span, Global Warming Potential (GWP) and Primary Energy Non-renewable (PENRT) were calculated based on the characteristic values of the materials defined at Ökobau.dat. (Federal Ministry of the Interior; Building and Community 2021). The calculations for the infill were based on values provided by Oxara.

Economic efficiency: Material cost and weight were calculated by adding up the individual components the slabs are composed of. The material prices were evaluated in an internet research. The number of days until the slab has sufficiently dried to work on it are derived from the standard values for concrete building components and floating screeds. Required labour time and potential for prefabrication/automation are rough estimations based on the specific workflows.

5.1.2. Individual results and interpretation (Table 5.1)

While none of the timber slabs can match the performance of reinforced concrete slabs particularly on the field of thermal mass, TES comes close and performs significantly better than the other timber floor slabs in every subpoint. Particularly on the point of thermal mass activatable in the daily cycle, it delivers two to five times better performance. Only one timber-concrete compound slab can match the performance of TES but, like reinforced concrete slabs, loses out in the sustainability category, where TES holds the top position. Only the glue connections and therefore limited reusability of the slab slightly compromise the result.

In the category of economic efficiency, TES again delivers very favourable results, featuring low material costs, high potential for prefabrication and automation as well as little on-site drying time. While further calculations on the eventual costliness of the slab yet have to be undertaken, the data looks promising so far. The only major disadvantages in this field are increased weight compared to many timber slabs in the selection.

5.1.3. Conclusion

Overall, Timber Earth Slab features very favourable results and in many ways combines the advantages of the various slab systems: High performance and low material cost of solid slabs, low environmental impact and high prefabrication potential of timber slabs. Its most significant disadvantage lies in the advanced machinery needed in the construction process.

Category	Unit	Reinforced Concrete				TES				CLT				Beams				Timber-Concrete Compound				LCT One System			
Version		raw	norm	eco	grade	raw	norm	eco	grade	raw	norm	eco	grade	raw	norm	eco	grade	raw	norm	eco	grade	raw	norm	eco	grade
Sustainability																									
timber consumption	kg/m2	-	-		-	28	28	28	1	41	41	41	3	24	25	25	1	27	27	27	1	20	31	31	2
glue consumption	g/m2	-	-		-	60	60	60	2	600	600	600	5	0	0	0	1	300	300	300	4	0	0	0	1
GWP	kgCO2/m2	59	90	67	4	-57	-29	-52	1	-51	-22	-46	1	-51	-6	-34	1	-47	-18	-40	2	-16	12	7	3
PENRT	MJ/m2	373	808	509	5	-133	334	-35	1	-57	387	50	2	-124	343	99	1	24,2	458	120	3	116	556	214	3
disassembly potential		-	-	-	4	-	-	-	2	-	-	-	1	-	-	-	1	-	-	-	4	-	-	-	4
% cradle2cradle	% Vol	0	0	31	5	100	71	100	1	100	66	100	1	99	23	100	2	38	33	80	3	21	12	58	4
Performance																									
fire protection	minutes	90	90	90	1	0	90	90	1	60-90	60-90	60-90	2	-	60	60	3	60-90	60-90		2	30	60	60	2
airborne sound insulation	db	54	73	68	1	27	67	68	2	37	68	68	3	26	65	65	4	42	69	69	2	45	62	62	2
body sound insulation	db	71	43	44	1	89	51	52	2	88	44	46	3	90	49	51	4	85	47	49	2	82	51	53	2
thermal mass 24h	KJ/m2	361	346	416	1	49	186	256	2	59	80	132	4	47	51	56	4	60	81	133	4	192	221	331	2
thermal mass total	KJ/m2	528	682	632	1	50	411	361	2	116	317	268	3	48	221	187	4	210	399	362	2	257	425	388	2
Economic efficiency																									
material cost	€/m2	30	90	53	1	31	96	59	1	104	184	156	4	31	57	89	1	86	142	104	3	41	106	69	1
human labour input		-	-	-	3	-	-	-	2	-	-	-	1	-	-	-	3	-	-	-	3	-	-	-	3
prefab potential		-	-	-	3	-	-	-	1	-	-	-	1	-	-	-	3	-	-	-	3	-	-	-	2
automation potential		-	-	-	2	-	-	-	1	-	-	-	1	-	-	-	3	-	-	-	2	-	-	-	2
on-site drying time	days	28	42	42	5	0	14	14	1	0	14	14	1	0	14	14	1	26	26	26	3	0	14	14	1
weight	kg/m2	460	589	593	4	28	389	393	3	55	305	309	2	24	155	163	1	156	319	334	2	216	317	321	3
thicknes	mm	200	280	290	2	200	330	340	3	120	240	250	1	204	340	360	3	130	240	250	1	260	400	420	4
number of layers		1	4	3	1	2	5	4	1	1	5	4	1	2	8	7	3	2	6	5	2	2	5	4	1

Table 2. Floorslab evaluation

6. Physical Prototyping

Fig. 6.1: Workshop Setup

While first experiments on casting loam into a timber grid in the previous studio phase of the project delivered promising results, they could not proof the concept, given an excessive amount of cracks and an absence of bending. For this purpose, further experiments had to be conducted, assessing the following key parameters:

- **Influence of bending and coffering.** Loam is vulnerable to tension forces and it is therefore crucial to verify whether the system can work under the forces a slab is exposed to. In the process, the cracking behaviour is to be monitored and a potentially beneficial influence of a coffering layer assessed.

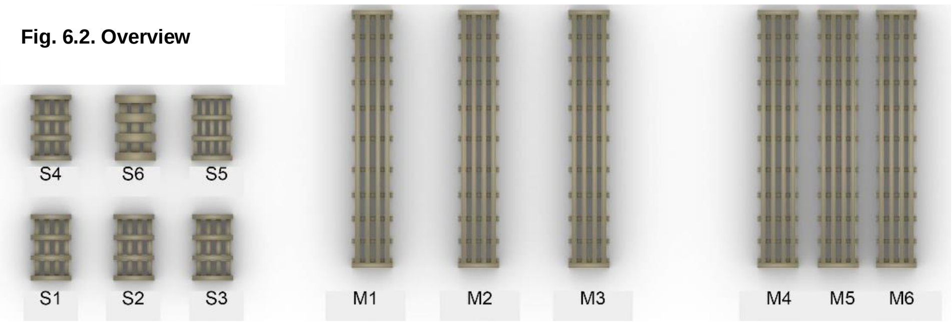
- **Ideal board formats and minimum gap between the boards:** With a layer thickness of 24mm in the previous prototype having resulted in serious cracks, it had to be estimated whether increasing that value to 40-50mm can deliver better results.

- **Drying behaviour:** The humidity curves in different parts of the timber/loam layers had to be documented in order to gain a better understanding of the drying process.

- **Load-bearing capacities of the timber grid:** The structural performance of the timber grid was assessed in four-point bending tests to verify the results of a Finite Element Analysis.

While Julian Trummer and Markus Schneider conducted the prototyping together, the author is primarily responsible for the first two key points which are therefore elaborated on in greater detail in this thesis while details on the latter two key points can be found in the thesis of Markus Schneider. An originally planned robotic assembly of the structural grid could not be realized because of delivery delays of the robot platform.

Fig. 6.2. Overview



6.1. Prototypes Overview

Table 3: Prototypes overview

	Description	Experiment aims	Results	Timber Grid	Infill	Covered by
XS1	20x20x8cm earth brick cast with cotton formwork, treated with water and a soft broom after drying	- Resulting surface of a cotton formwork layer - Assessing the effects of surface treatment with a soft broom after drying	- The surface is very homogenous. - The formwork board underneath the cotton layer stays relatively dry and clean. - Treatment with a soft broom after drying requires surface humidification and leads to a matte and bright surface visually similar to concrete.	no	yes	Julian Trummer
XS2	15x15x40cm earth brick	-Consequences of soaping the formwork surface	- The effects of soaping are comparable to oiling - Even with soaping, the surface cannot be cleaned after exposure to loam			
S1	50x70cm fragment of the bottom three layers with 4x6cm boards and 5x3cm coffering	-Determine the ideal mixture -Assess the ideal timing for removing the formwork	- A recipe with a high proportion of aggregates and minimum added water delivers the best results. - The formwork is not to be removed earlier than four to five days after casting. - Timber cannot be cleaned 100% after exposure to loam.	yes		
S2						
S3						
S4						
S5	50x70cm fragment with 3x5cm boards/coffering	-Determine the integrity of a loam infill in connection with a grid	- 3cm layer thickness leads to serious cracks.			

		composed of 3x5cm boards. -Compare the quality of fibres A and B by filling the grid with two different mixtures.	- Fibres A and B offer comparable crack reduction, though B causes surface damages.			
S6	50x70cm fragment with 4x10cm lamellas and 3x5cm coffering	- Determine the integrity of a loam infill in connection with a grid composed of 4x10cm boards. - Determine the effects of a PVC formwork	- Wide boards/great intervals lead to excessive shrinkage cracks. - Soft formwork can keep the coffering clean but only under ideal circumstances. - A smooth ceiling surface is not necessarily desirable since cracks are perceived to be much more disturbing.			
S7	50x75cm fragment with 4x6cm boards and lost formwork	- Test the use of a vibrating table - Evaluate the characteristics of the type C fibres - Create a visual demonstrator for an option with lost formwork - Test the effects of transporting a prototype in a car ten days after casting.	- A vibrating table increases the speed of the casting process tremendously. - Type C fibres are much less effective in reducing cracks than types A and B. - Cracks can easily be sealed without any visible traces. However, several cycles are necessary to close them for good. - Transportation in a car did not lead to any visible damages.			
M1	312x50cm slab with 4x6cm boards and 3x5cm coffering, infill with fibre type B	- Evaluate the loam infill in its relationship to the timber and its integrity under realistic bending. - Evaluate the behaviour of timber under bending after exposure to wet loam. - Evaluate the quality of fibre type C	-The tension forces in the bottom of the slab during bending do not pose a threat to the integrity of the loam infill. -The timber structure bends more than expected because of creeping deformation caused by the increased humidity. -Fibre type C leads to increased cracking behaviour.			
M2	312x50cm slab with 4x6cm boards and 3x5cm coffering, infill with fibre type C					
M3	312x50cm slab with 4x6cm boards and without coffering, infill with fibre type C	On top of the points from M1 + M2: - Evaluate the influence of coffering layer on the cracking behaviour.	- There are no recognizable tension cracks in the ceiling surface. - There is an increase in shrinkage cracks likely because a coffering layer limits their length.			
M4–M6	312x50cm slab with 4x6cm boards for structural tests, unfilled	- Test the structural strength of the timber grid by 4-point bending tests.	- The structure behaves as expected.		no	Markus Schneider
TH 1-6	10x10x10cm loam cube with a timber piece in the centre. Formwork covered with non-diffusive foil.	Simulate and observe the drying behaviour of the timber structure	- The timber steadily increases humidity in the first weeks after casting.	no	yes	
TL	Analogue to S1-S4 with the side formwork covered with non-diffusive foil.	Simulate and observe the drying behaviour of the loam infill	- The prototype dries evenly in all layers. - The drying speed can be controlled well by covering the prototype with foil and/or spraying water on the surfaces.	yes		

6.2. Preparations

A source of suitable loam had to be found and a well-working mixture developed to be able to perform the eight experiments. A total of eight samples was collected in clay pits and gravel plants around Munich and evaluated by Oxara based on Atterberg limits (White 1949), shrinkage and cohesion. One sample, found in waste material ejected by a filter press of a gravel plant, Dettenbeck Kies, 80km east of Munich, met the requirements. The same plant provided 0-4mm sand and 4-8mm gravel while the industry partner Müller Blaustein sponsored the timber boards.

Jowat provided Jowapur 686.20 to glue the connection points. Although not certified for surface glueing, it was chosen after delays in the delivery of the original product. The company assured that the adhesion of the glue would be sufficient. A spindle press in combination with steel beams served for the pressing procedure.

With the COVID-19 pandemic having compromised international supply routes, the flax fibres used in the experiments came from three different sources: Terre de Lin (Terre de Lin 2021) (type A), Esprit Composite (Esprit Composite 2021) (type B) and Procotex (Procotex 2021) (type C).

6.3. Finding the ideal recipe

6.3.1. Flow tests

Variables in the search for an ideal mixture were the sludge/aggregate ratio, the size of the aggregates and the amount of fibres with the total water content required for liquifying the mix being the main quality criteria.

Table 4: Recipes (unit: kg/l)

Recipe	**1**	**2**	**3**	**4**	**5**	**6**
Sludge	0,8	0,7	0,6	0,8	0,7	0,6
Sand 0-4mm	1,3	1,4	1,6	0,8	0,9	0,9
Gravel 4-8mm	0,0	0,0	0,0	0,5	0,6	0,6
Oxara admixture	0,0096	0,0086	0,0076	0,0096	0,0086	0,0076
Fibres	0,036	0,036	0,036	0,036	0,036	0,036
Added water	var	var	var	var	var	var
Inherent water	0,136	0,119	0,102	0,136	0,119	0,102

Table 5: Flow tests protocol

Experiment ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Recipe	1	1	2	3	4	4	5	6	5	5	5	5
Fibre Amount (g/l)	36	36	37	38	36	36	37	38	37	47	47	47
Fibre Type	A	A	A	A	A	A	A	A	A	A	A	A
Added Water (g/l)	100	125	112	99	125	90	113	125	125	125	135	145
Total Water (g/l)	236	261	231	201	261	226	232	227	244	244	254	264
Avg. Spread (cm)	15,5	20,5	22,2	17,2	28,5	23,7	23,5	23,2	24,2	20,2	21,5	25

Since a normed flow table was not available, an experiment setup had to be developed: A cup filled with loam is put upside-down onto a plate and removed, leaving the loam on the plate. The plate is then manually lifted by roughly 10cm on one side and dropped with force 20 times before measuring the spread. The more spread, the better the flowability.

Experiments 1 – 8 show that gravel significantly decreases the water demand. Therefore, recipes 1-3 were dropped. Experiments 9 – 12 show that increasing the fibre ratio drastically increases water demand and should therefore be avoided.

Experiments 4-8 show that recipes 4-6, which vary in the aggregate/sludge ratio, deliver very comparable values. While Oxara generally recommends a higher aggregate ratio, as in recipe 6, recipe 4 requires significantly less added water. Recipe 5 on the other hand was dropped since its water demand was not lower than the one of recipe 6.

6.3.2. Infill tests

To assess recipes 4 and 6 in detail, four timber grids (samples S1-S4), representing fragments of the lowest three layers of the final slab, were built and filled up with four different mixtures. From each recipe, two mixtures with different viscosities were mixed and cast. The minimum viscosity was estimated by holding a vibrating needle into the mix. As soon as the needle showed an effect in a radius of at least 8cm, the mixture was considered to have reached the minimum viscosity. Recipe 6 thereby required slightly less water than expected, making S3 the sample with the least total water content.

Both mixture 4 and 6 showed satisfying results and verified the feasibility of the concept. There was slightly less shrinkage and cracking in S3 and S4, ultimately making recipe 6 the recipe of choice for further experiments. Increasing the viscosity of the mixture did not significantly decrease voids and it was therefore decided to keep the viscosity as low as possible in the future.

Table 6: Mixtures S1 – S4 (unit kg, total volume: 40l)

	S1		S2		S3		S4	
	total	per l	total	per l	total	per l	total	per l
Sludge	31,3	0,78	31,3	0,78	23,6	0,59	23,6	0,59
Sand 0-4mm	33,4	0,84	33,4	0,84	37,4	0,94	37,4	0,94
Gravel 4-8mm	22,4	0,56	22,4	0,56	25,0	0,63	25,0	0,63
Oxara admixture	0,4	0,01	0,4	0,01	0,3	0,0075	0,3	0,0075
Fibres	0,16	0,0039	0,16	0,0039	0,16	0,0039	0,16	0,0039
Fibre Type	A							
Added water	3,25	0,081	3,7	0,093	3,65	0,091	5,0	0,125
Total water*	8,65	0,216	9,0	0,225	7,65	0,191	9,0	0,225

*sum of added water and water inherent in the sludge

Table 7: prototypes S1 – S4

S1		

S2		
S3		
S4		

6.4. Slab behaviour at full span: M1 – M3

The M1 – M3 prototypes feature a span of 3.12 meters and were built to prove the workability of the solution in a realistic setting. For the system to pass the proof of concept, the integrity of the loam infill and the loam/timber interlock has to remain upright while the slab is exposed to bending forces.

6.4.1. M1 – M6: Timber grid production

While the boards of the S-series prototypes were connected with screws, the M-series was glued to simulate the bending behaviour. A spindle press combined with IPE 120 steel beams served for the pressing procedure. The ideal amount of torque used for fastening the spindles was subjectively estimated based on trials with a pressure sensor. After 15 minutes of pressing, the torque on the spindles was increased to compensate for the compression of the workpiece.

6.4.2. M1 – M3: General methodology

The prototypes were not cast all at once but in intervals of roughly one week in order to be able to find and implement improvements. The bottom formworks were mounted with screws drilled into the bottom primary lamellas to simulate the procedure of a semi-prefabrication process (find further details in section 4.6) while the side formworks were fixated with clamps. The formwork was reused between the cycles.

The required loam volume of roughly 160l was produced with one 80l mixing cycle with a 190l freefall mixer and two 40l mixing cycles with a 50l pan mixer. Because of the weak engine of the pan mixer, water and admixtures had to be added earlier than recommended. Therefore, the resulting mixtures were cast in separate zones of the prototypes to detect potential differences in the behaviour. Once cast, the mixtures were densified using a vibrating needle.

In the early stages of the drying process, the prototypes were covered with foils and the formworks removed after four to five days. In the first weeks, water was sprayed on the surfaces every day before increasing the intervals and aborting the ritual two weeks after removing the formwork.

M1 – M3: General results and observations

In general, the results were better than expected and the loam infill provided sufficient integrity under bending in every single prototype.

In most cases, most visibly in M1, the loam mixtures from the pan mixer showed more cracks than the ones from the freefall mixer leading to the conclusion that sticking to the recommended step-by-step procedure is crucial.

Like in S1 – S6, cracks always appeared on top of and parallel to the primary boards. The geometry makes it impossible for the infill to shrink evenly in this direction and the boards, therefore, pose the weak points. With the infill being able to shrink comparably well in the main span direction, there are nearly no cracks perpendicular to the main span direction.

Casting and vibrating the mixture took 1 ½ hours on average with one person actively casting/vibrating and the other person unloading the mixing machines and carrying the buckets.

Removing the formwork turned out to be more challenging than expected since it is to be removed in a horizontal, sliding way. The holes from the screws on the other hand turned out to be much less significant than expected and could be closed easily.

While the slab showed the expected amount of bending after removing the formwork, the bend increased by more than factor two throughout the further drying process most likely because of creeping deformation of the timber structure caused by increased humidity of the material. (Kolb 2010, 286)

Despite issues in the process (--> M1 process specifics), M1 featured very few cracks at least in the central parts compared to M2 and M3. This is most likely down to the different fibres (type B) used in M1 compared to M2 and M3 where type C fibres were used.

Fig. 6.3: M1 side view

Fig. 6.4. M1 perspective

Fig. 6.5. M2 perspective

Fig. 6.6. (from left to right): M2, M1, M3

6.4.3. M1 specifics

	M1	M2	M3
Base recipe	6	6	6
Added water (kg/l)	0,105	0,091	0,098
Added fibres (kg/l)	0,0075	0,0059	0,0059
Admixture (kg/l)	0,0039	0,0075	0,0075
Fibre type	B	C	C

Table 7: Mixtures used in the M-prototypes

Fibres of type B were used for the infill mixture. The visible timber surfaces were taped to keep them clean.

Errors in the weighing process led to approximately twice as many fibres and half as much Oxara admixture being used, resulting in 15% more water needed to liquefy the mixture in the freefall mixer. Surprisingly, this did not show any major effects in the result.

The side formwork was removed two days earlier than the bottom formwork. This led to the bottom surface drying unevenly in this period with the surface turning out too rough in the centre and too smooth on the sides. The amount and size of voids visible from the sides were lower than in previous prototypes.

There were very few cracks in the centre where the infill had been produced with a freefall mixer but many cracks in the outer part where the infill was produced with the pan mixer. The cracks were at least partly caused by the infill being too humid locally at the point of formwork removal

Fig. 6.7 – 6.9. Ceiling surface of prototypes M1/M2/M3

6.4.4. M2 specifics

The bottom boards were treated with a sludge prior to casting in order to achieve an even surface colour after drying. (--> subpoint surface quality)

Additional flow tests suggested that increasing the amount of fibres of type C by factor 1.5 increases the water demand by only 8%. This led to the decision to increase the share of fibres while keeping the amount of added water on the old level. As a consequence, the mixture was harder to work with and the casting/vibrating process took approximately 2 ½ hours.

After removing the formwork 4 ½ days after casting, it turned out that with one minor exception the loam had spread very well. The surface quality was very pleasing and 4 ½ days therefore specified as the ideal timing for taking off the formwork.

9 days after casting, bright dots appeared on the bottom surface. According to Oxara, these are salt efflorescences, most likely sodium sulphate that formed as a reaction between an unknown substance in the soil and the admixtures. They are harmless and can be wiped off after drying.

6.4.5. M3 specifics

In contrast to M1 and M2, M3 does not feature any coffering boards at the bottom but instead comes with a plain loam ceiling surface. Its main purpose was to evaluate whether and up to which degree the coffering layer can reduce cracks, particularly ones perpendicular to the main span direction.

The loam mixture, including fibres, was very similar to the one used in M2 though approximately 10% more water was added to improve workability. The formwork was removed after 4 ½ days.

The surface featured about the same amount of shrinkage cracks as in M2. There were no tension cracks visible, but the lack of coffering allowed shrinkage cracks to combine to much longer cracks than in case of M2.

6.4.6. M4 – M6 Bending tests

M4 – M6 have undergone bending tests in accordance with DIN EN 408 which are covered in full detail in the thesis by Markus Schneider.

In general, the tests came close to the predictions from the FEM simulations by Markus Schneider which predicted 28 kg/m^2 of material consumption. The performances of the individual prototypes were comparable with each one failing well beyond l/300 bending. The failure occurred, as expected, because of the rolling shear force.

Takeaways include room for optimization against rolling shear force by increasing the board width of the secondary lamellas and/or by aligning them in a diagonal way (--> Outlook).

6.5. Further experiments

6.5.1. Different Board formats

Prototypes S5 and S6 investigate the consequences of using different board formats. While coffering remains unchanged, S5 used 50x30 boards, S6 100x40 boards for the upper two layers. The same loam mixture as in S3 was used. Both prototypes showed a drastically increased amount of cracks.

In the case of S5, all major cracks appeared on the upper side in the areas where the loam layer was locally only 30mm thick. This demonstrated that a minimum layer height of 40mm is strictly required.

S6 showed a high amount of cracks on both the top and bottom side, indicating that the interval of the boards was too high and uneven shrinkage therefore led to more significant cracks. To rule out voids as the cause of the cracks, holes were drilled into the surface after the drying process.

Fig. 6.10. Prototype S5

Fig. 6.11. Prototype S6

6.5.2. Visible Surface Quality

With the exception of S6, all formworks of the S and M series featured an impregnated timber panel at the bottom and planed, untreated wood boards on the sides. S1-S4 showed that untreated wood is to be treated with formwork oil prior to casting.

Experiments on prototypes XS1, XS2 and S6 demonstrate that using a PVC or cotton formwork results in a more homogenous ceiling surface. Putting a layer of cotton into the formwork also has the advantage that the hard formwork may be removed earlier with the loam surface being able to dry more homogenously by breathing through the cotton layer.

architectural intent	formwork materials
Homogeneous	PVC, cotton
Wood grain texture, smooth	Oiled, planed timber
Wood grain texture, rough	Soaped, oiled, or impregnated wood

Table 8:Surface/formwork options

S1 – S4 and XS2 further showed that it is not possible to remove clay from untreated or soaped wooden surfaces and consultations with the company Oli Natura (Oli Natura 2021) suggested that waxes and oils used in furniture protection cannot sufficiently protect the surfaces either. If the original colour of the coffering has to remain, the surfaces must not get in touch with the loam during the casting process. Alternatively, the surface can be painted or stained.

For the purpose of staining, it is recommended to use clay-based sludge. Experiments have shown that this can be achieved by simply mixing soil and water to a creamy substance and applying it to the surface. After drying, the loose particles on top of the surface can be wiped off, resulting in a bright timber surface with the grain texture still visible. If architecturally desired, the same sludge can be applied to the loam surfaces to give them a homogenous cream colour.

S6 is cast with a PVC formwork, giving the loam a much smoother surface and keeping the timber boards clean on most spots. The downside is that because of the smooth surface, cracks are perceived to be much more disturbing. PCV and generally formworks resulting in a smooth surface should therefore only be used if cracks are closed or roughness is achieved through surface treatment.

6.5.3. Prefabrication potential: Vibrating table, transport and fixing cracks

S7 was cast with a vibrating table and transported with a car 10 days after casting to gain a first assessment of a full prefabrication process. Casting with a vibrating table took little time and resulted in a great quality while no visible damages occurred in the transport. The sample was also the first test for fibre type C, showing a drastic increase in cracking behaviour. The cracks could be closed seamlessly with liquified sludge though they resurfaced later in a weaker way, indicating that several cycles are necessary to fix them permanently.

6.6. Conclusion

The most important conclusion is the verification of the technical feasibility of the system. Even under bending, the loam infill keeps up its integrity and concerns about parts potentially falling were falsified successfully. Furthermore, there were many specific insights:

- Full prefabrication is to be preferred with the use of a vibrating table saving a very large amount of working time while bending has turned out to be not an issue at all for the loam infill. Moreover, the slab has to be supported during drying to prevent excessive bending under creeping deformation and mounting/removing formwork is not as easy as expected.

- A minimum gap width and layer thickness of 4cm must be respected at all points.

- Bending is much less critical than shrinkage. To reduce cracks, the bottom primary boards are to have as little interval as possible without violating the minimum gap size. Pipes for thermal activation are likely to fundamentally change this behaviour.

- Cracks can be closed again without visible traces, though multiple cycles might be necessary.

- It is recommendable to use slightly rough formwork to achieve a surface with a certain amount of texture to distinguish the slab aesthetically from concrete slabs. Most importantly, cracks are perceived to be less disturbing in connection with texturized surfaces.

- The coffering layer is not strictly necessary but possible and can take a variety of two-dimensional shapes. It might be aesthetically desirable and makes it easier to mount objects to the ceiling. On the other hand, it is disadvantageous for fire safety and applying a layer of plaster to the ceiling surface, though the latter is not recommended anyway. Both solutions are legitimate; eventually, the decision is to be made by the individual architect.

- The flax fibres do not significantly reduce the density of the mixture which lies at around 2 200 kg/m^3.

7. Outlook

Fig. 7.1. Outlook

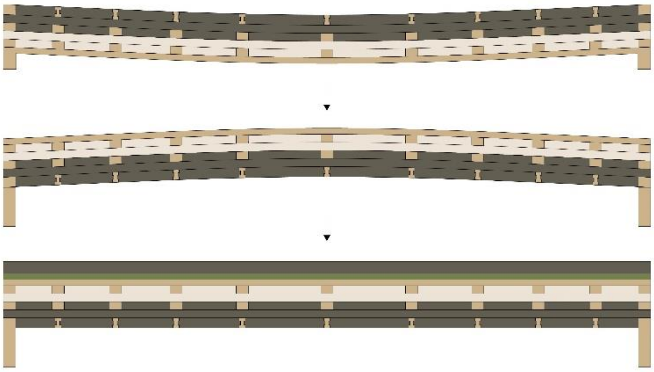
The project is to be continued beyond this thesis as a research project. The next important steps are the robotic fabrication of a 1:1 prototype and the assessment of fire resistance and acoustics in physical tests. These serve as a basis for the implementation of the slab in a real building. Furthermore, there is an array of concepts for the optimization/expansion of the floor slab, an overview of which is presented in this section.

7.1.1. Pre-stressing

The slab may be put under horizontal tension along the secondary direction prior to casting. By slowly relieving the force in the drying phase, shrinkage cracks might be eliminated. The base plate can be utilized for mounting steel cables over which the tension force can be applied.

7.1.2. Pre-vaulting

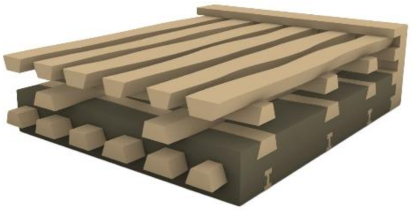
Fig. 7.2. Pre-vaulting



Pre-vaulting can decrease timber consumption by increasing maximum bending or by structurally utilizing the infill by putting it under pressure. For this purpose, the slab is vaulted along the main direction by conducting the pressing procedure on a vaulted surface or by storing the slab upside-down in the drying phase. Once load is applied, the structure becomes flat.

7.1.3. Building with irregular timber

Fig. 7.3. Two-dimensional irregularity



With the timber structure being surrounded by infill, its geometry does not need to be straight. By implementing irregular boards, waste can be reused and cost saved.

Fig. 7.4. Robotic milling of logs at Aarhus school of architecture

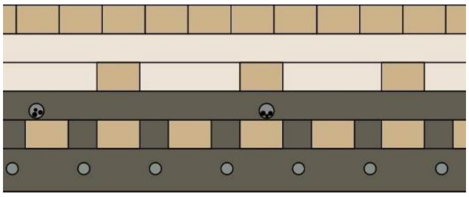
Two-dimensional irregularity as found in the cut-away boards at the very outer part of the timber stem is very easy to implement in the slab. As long as the top and bottom surfaces are plane, the boards can be glued and pressed analogously to the conventional method. Only the alignment of the boards has to be executed thoroughly to ensure a relatively steady gap width. If the boards contain bark, they must be kiln-dried to eliminate potential pests.

Three-dimensional irregularity, as found in timber logs, is much harder but possible to process. As discussed in section 2.5.4., successful research on this field has already been conducted. (Larsen and Aagaard 2020) The logs have to be scanned and the assembly geometry and sequence generated algorithmically. The connection points have to be milled and mechanical connectors might be more suitable than glueing.

7.1.4. Integration of electric/data installations

Duct pipes for hidden installations can be included in the slab in the prefabrication process. Alternatively, cable ducts may be included on the joints and/or next to the supports. This increases reversibility but comes with aesthetic implications that have to be approved by the architect.

Fig. 7.5. Installations



7.1.5. Integration of thermal activation

Integrating thermal activation promises to provide a cheap and energy-efficient way of heating and, if necessary, cooling. The large size of the radiating surface allows for low-temperature systems, utilizing heat sources more efficiently and enabling the use of alternative sources, such as waste heat of servers (Ehlers 2017).

Heating/cooling pipes are to be implemented in the lowest layer and should mainly run parallel to the main span direction. The pipes are expected to have a strong influence on the shrinkage behaviour of the infill and might be utilized for eliminating cracks.

7.1.6. Hexagonal Grid

To increase the stiffness of the slab, which is particularly important in skeleton construction, it is advantageous to align the secondary boards non-perpendicular to the primary boards and not parallel to each other. Expected challenges include higher programming complexity and edge finish.

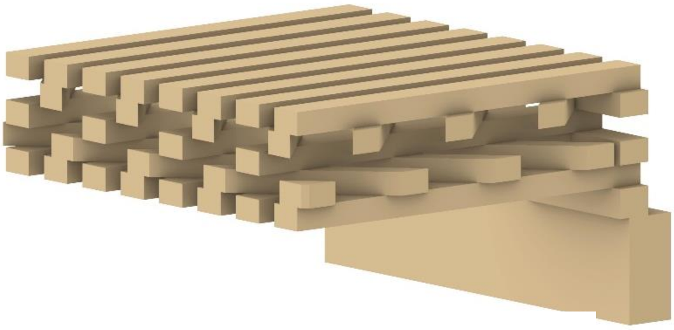


Fig. 7.6. Hexagonal Grid

7.1.7. Potential elimination of beams

Integrating the beams into the structural timber grid or directly placing the slab on columns has been sketched out. Particularly the possibility to implement cross-grained timber boards opens up new potentials in this field. While comparable solutions featuring CLT and steel connectors have already been developed (Maderebner et al. 2017), time gains, fabrication complexity and structural efficiency yet have to be evaluated for this specific case.

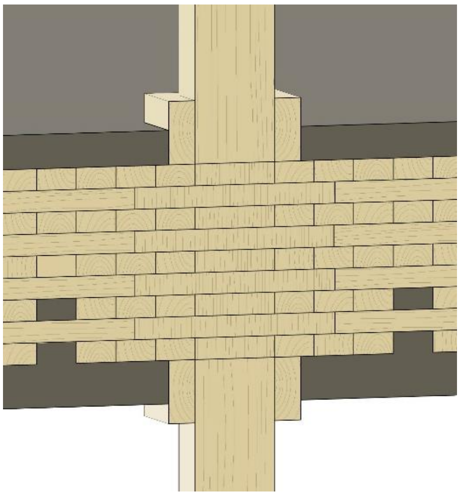


Fig. 7.7. Supporting the slab on columns and transmitting the vertical load

7.1.8. Ornamentation

Instead of parallel coffering, it is possible to align the boards in all imaginable ways to form patterns or images. Short cut-off pieces can be reused for this purpose and an A.I. pipeline can spontaneously generate and fabricate patterns.

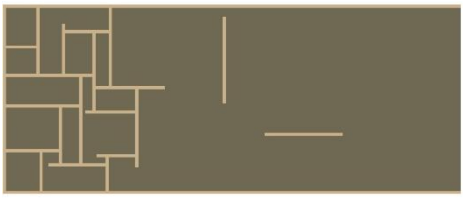
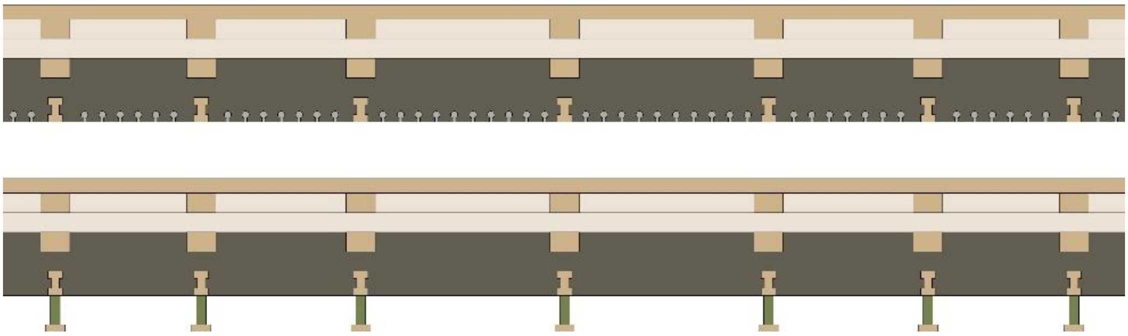


Fig. 7.8. Creating ceiling ornamentation by spontaneously aligning available boards

7.1.9. Integration of acoustic absorbers

Fig. 7.9. Integrated acoustic absorbers



Acoustic absorbers may be attached to the coffering layer to reduce reverberation time in the space without significantly reducing the activatable thermal mass of the floor slab. However, the solution requires additional assembly time while its acoustic impact yet has to be calculated.

Alternatively, sound-absorbing shapes such as holes or small-scale Helmholtz resonators (Dosch and Hauck 2018) may be cast into the loam ceiling surface. This, however, requires additional formwork complexity, particularly in the case of small-scale Helmholtz resonators were pneumatically or hydraulically expandable volumes or lost formworks would be required.

Max Frank GmbH has developed sound-absorbers that can be cast into slabs without significantly compromising the thermal performance. (Max Frank 2021)

7.1.10. Adjustments on the timber boards for a better loam/timber bond

Adjustments on the timber boards may result in a better bond between the different materials and fewer cracks. Promising approaches include:

- Planing the timber boards only on the top/bottom sides. While planing the top and bottom side of the timber boards is essential for glueing, leaving the sides unplaned would not only increase material efficiency but is expected to result in a better bond between timber and loam. However, a stronger bond could also have detrimental effects such as less even shrinkage and experiments are yet to be made.

- Trapezoid boards in the lowest load-bearing layer might provide more stability for the infill.

- Grooves on the bottom of the primary boards might multiply the number of weak points. This could potentially lead to smaller cracks.

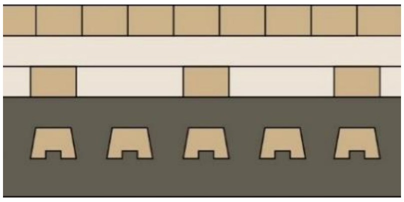
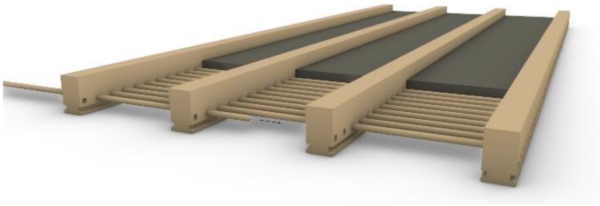


Fig. 7.10. Board adjustments

7.1.11. Hybrid without robotic assembly

It is possible to realize a timber/loam hybrid with equipment available in most advanced carpentries. The geometry is derived from traditional vigia loam floor slabs and adapted to modern construction techniques.

Fig. 7.11. Analogue version



In this case, the loam is held by rods that span between beams. Holes and grooves have to be drilled/milled into the beams with a trimming machine and rods manually stuck through the holes. The rods are to have a diameter of approximately 30mm and be spaced in an interval of approximately 70mm.

Compared to a robotically fabricated slab, the solution requires more assembly time and likely comes with higher material costs. Advantages include less machinery required and better disassembly. Naturally, it is particularly attractive for small-scale projects and settings where robots are not available.

8. Discussion

8.1.1. Use of sand and gravel

While loam does not require cement or burnt material for its production, 60% to 75% of the mixture consists of sand and gravel which are becoming increasingly rare in many regions of the earth. (United Nations Environment Program (UNEP) 2014) While it is possible to decrease their use by utilizing excavation material, it is easier and more reliable to use filtered sludge from gravel plants and add the aggregates. However, with loam being water-solvent, the aggregates can be easily retrieved and reused by liquefying the mixture and running it through a filter press at any point in the future. By offering infinite recyclability, this system is therefore very resource-efficient in the long term.

8.1.2. Use of glue

While it would be possible to use screws or nails instead of glue, the vast amount of connection points would lead to an enormous amount of connectors and therefore high cost and carbon footprint. While glue is toxic and energy-intensive in its production (Messmer 2015), only 1/6 to 1/10 of the amount compared to CLT is needed, the PUR glue used in this project is comparably eco-friendly (Messmer 2015) and not toxic once it has hardened (Jowat SE 2019) and thanks to robotic assembly, human workers are hardly exposed to it.

8.1.3. Reuse after demolition

Because of the glued connections, it is hard to reuse the timber grid in another construction after demolition and the material can only be downcycled to chipboards or be utilized only in a thermal way. However, timber from disassembled buildings normally cannot be reused for structural purposes anyway and usually ends up in downcycling or thermal utilization just as well. (Meinlschmidt, Berthold, and Briesemeister 2013) Moreover, the loam infill conserves the timber structure of the slab by regulating its humidity and thereby significantly increases the life span of the whole structure.

8.1.4. Use of mineral additives

Adding light mineral aggregates such as expanded clay or pumice could reduce the shrinkage down to 0% and therefore eliminate cracks. However, since they do not only decrease thermal mass but consume a lot of primary energy (Pargana et al. 2014), their use should be avoided, and they have therefore been excluded from the concept.

9. Conclusion

The project has presented a great number of promises and has been striving to be no less than the very first floor slab system that successfully combines sustainability, performance, and economic efficiency. However, the concept has only solidified throughout the development process as prototyping has shown that a slab with self-supporting clay infill is realizable and offers a lot of aesthetic potential.

While not all parameters have been assessed yet, there are good reasons to be optimistic that with this slab the aesthetic and ecological sacrifices associated with contemporary multi-storey timber construction can become an issue of the past. Given a high amount of thermal mass, the ecological advantages gained in the construction phase are not outweighed by increased energy consumption throughout the lifecycle.

As development continues, the most pressing goal is to implement the slab in real buildings. Being very suitable for mass-production, little speaks against the system being affordable for everyone, creating a positive impact for both the environment as well as providing better and healthier housing for common people.

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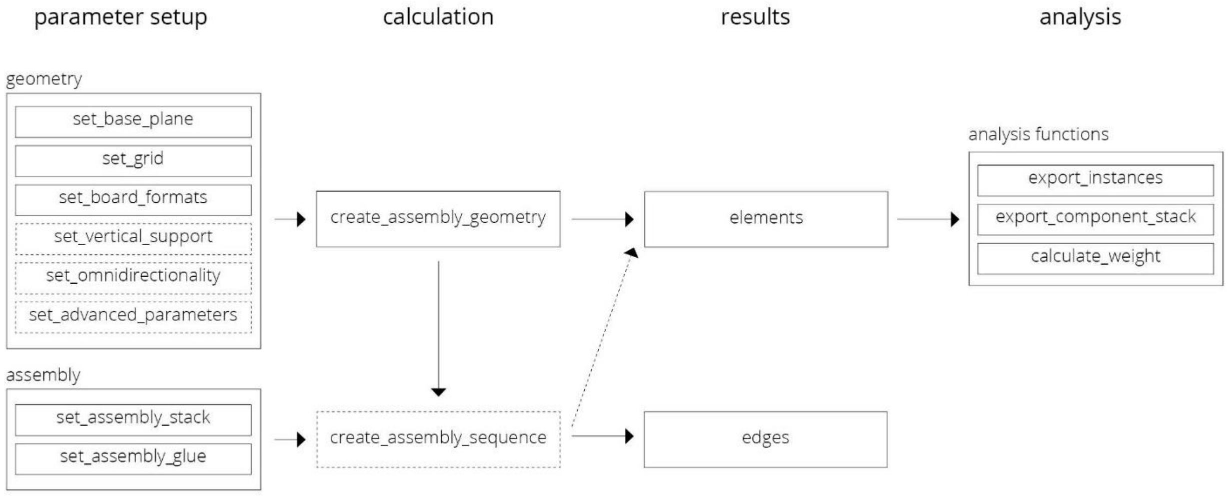
11. List of images

12. List of tables

13. Appendix A: Digital Simulation Environment

The software tool written in the course of this thesis mainly serves for both creating the geometry of the slab as well as planning its robotic assembly. The tool was written in Python 3.8 and executed in Grasshopper and Rhino 6. Compas 0.17.3 and Compas Assembly Information Model acted as key frameworks.

13.1. Overview



The sequence starts off with parameter setup where the properties of the slab and its assembly are defined. Once all parameters have been defined, the calculations can be put underway that return a floorslab composed of single elements which represent the timber boards. Finally, there is a number of analysis tools to export information about the whole slab for further use. The default unit is meters.

13.2. Software Documentation

13.2.1. Assembly Geometry Setup

The assembly geometry parameters serve for creating the basic geometry of the slab without defining glue points or tool frames. The default length unit is meters.

- set_grid(dictionary):
    - “primary_length” and “secondary_length” *float*: Length and width of the (rectangular) slab.
    - “layer_no” *int*: The total number of layers. Should be uneven.
    - “primary_interval” and “secondary_interval” *float*: The default centre-to-centre spacing of the boards in the primary, respectively secondary direction.
    - “secondary_interval_development” *float=1.0*: If at 1.0, the secondary lamellas are spaced evenly according to the default “secondary_interval”. If lower than 1.0, the secondary lamellas become denser towards to edges, if higher than 1.0 the secondary lamellas become denser towards the centre.
    - “skip_centrals” *int=0*: If checked, only every Xth primary lamella on the inside will be created while the rest is jumped. The boards at the ends of the slab are created in any case, though.
    - “gap_min” *float=0.0*: An optional parameter to make sure of a minimum gap width since too narrow gaps can threaten the integrity of the loam infill (find further details in section 3.3.2.).
- set_board_formats(dictionary): All parameters expect a list of two floats [width, height].
    - “prim_board_outside_dimensions” *[float, float]*: Board format of the primary lamellas at the top and bottom layer.
    - “sec_board_inside_dimensions” *[float, float]:* Board format of all secondary lamellas.

  - “prim_board_inside_dimensions” *[float, float], optional:* Board format of the primary lamellas on all other layers. If not specified, these boards receive the values from prim_board_outside_dimensions.

- set_base_plane(dictionary):

  - “origin_frame” *compas.geometry.frame*: Sets the origin frame of the floorslab.

  - “primary_direction” and “secondary_direction” *int, Optional:* Takes 0 or 1. Optional emergency quick fix if the rotation of the workpiece shall be changed. Usually not required.

  - “flip_toolhead_prim” and “flip_toolframe_sec” *boolean = False:* Optional emergency quick fix if the tool head of the robot shall be rotated on the workpiece by 90 degrees in the later process.

- set_vertical_support(dictionary) o*ptional*: Sets up geometry for vertical force transmission on the supports.

  - “prim_vert_sup” *boolean*: Enables geometry for vertical force transmission along the supports of the primary boards.

  - “sec_vert_sup” *boolean*: Enables geometry for vertical force transmission along the supports of the secondary boards.

  - “vertical_support_width” *float*: Specifies the width of the vertical support boards.

  - “vertical_support_interlock” *float*: Specifies the amount of overlap the support boards have with the boards perpendicular to them.

- set_omnidirectionality(dictionary) o*ptional*: Sets up dedensification of the primary boards in the zones where secondary boards can transfer momentum forces. Not applied if not specified.

  - “primary_dedensification” *int:* The number of primary boards by which the geometry shall be reduced on each side.

    - "primary_falloff" *float*: Specifies the width of the area where dedensification shall be applied.

- set_advanced_parameters(dictionary) o*ptional*: Allows for setting up additional boards in the centre and on the sides.
    - "shear_support_length" *float=0.0*: If the "skip_centrals" has been activated, there is the option of not entirely removing those primary lamellas on the inside but substitute them with short boards that go from the supports towards the centre by the length specified in this parameter. By specifying the length, the implementation of these boards is activated automatically.
    - "shear_support_dimensions" *[float, float], optional*: Specifies the profile of the boards for shear support.
    - "primary_inside_support_gap_min" *float=None*: Locally substitutes the value for minimum gap on the inside layers if shear supports are implemented.
    - "momentum_support_length" *float=0.0:* Specifies the length of optional boards that can be placed in the central areas of the outside primary layers in order to increase resistance towards momentum forces. By specifying the length, the implementation of these boards is activated automatically.
    - "momentum_support_dimensions" *[float, float]=None*: Specifies the profile of the boards for momentum support.
    - "primary_outside_support_gap_min" *float=None*: Locally substitutes the value for minimum gap on the inside layers if momentum supports are implemented.

13.2.2. Assembly Sequence Parameter Setup

There are two mandatory dictionaries of parameters to set up the assembly sequence.

- set_assembly_stack_parameters(dictionary):

  - “stack_origin_frame” *compas.geometry.frame*: Specifies the origin frame of the stack of boards from which the robot picks up the lamellas.
  - “max_stack_height” *integer=10*: Maximum number of boards on top of each other in the stack.
  - “max_stack_width” *integer=4*: Maximum number of boards directly next to each other before a gap is made. This measure is meant to increase precision.
  - “stack_bottom_pickup” *float=0.0*: Possible quick fix to adjust the z-coordinate of the pickup frame without changing the origin frame.
  - “stack_col_pickup” *float=0.0*: Possible quick fix to move the pickup frame perpendicular to the board length direction without changing the origin frame.
  - “distance_between_stacks” *float=0.12*: Specifies the width of the gap between two stacks.
  - “stack_full_efficiency” *boolean=True*: If False, the top row of the stack will be filled up in every case, even if this way there are more boards than on the stack than necessary.
- set_assembly_glue_parameters(dictionary):
  - “dryrun” *boolean, optional*: If True, no gluepoints are calculated and the robot assembles the structure without glue.
  - “glue_snake” *boolean=False*: If False, only a simple glue point or line (in case of parallel boards) is created on the connecting surface. If True, a spiralling glue path snake is created to distribute glue more evenly on the surface.
  - “gluepath_width” *float=0.004*: Only relevant if “glue_snake”=True. Specifies the interval of the lines of the glue path snake.
  - “gluestation_default_frame” *compas.geometry.frame=None*: Specifies the frame of a static glue station where glue points/glue lines are applied

to the individual boards before being placed. If None, the robot moves to the gluepoints on the workpiece assuming there is a glue gun end-effector.

- “bending_behaviour” *[float, float]=None*: Optional and only applicable in connection with a static glue station to compensate for the amount of bending under gravity by the board by telling the robot to go higher the further on the edge of the board the glue point is located. The first value describes the width of the gripper in meters, the second value the intensity of the compensation which is recommended to be somewhere between 0.2 and 0.8.
- “bending_calc_includes_lines” *boolean=False*: Optional and only applicable in connection with a static glue gun. Includes gluepaths in the bending compensation
- “safety_distance” *float=0.5*: General safety distance for the assembly in order to minimize risk of collisions between robot and workpiece.
- “safety_distance_gluepoints” *float=safety_distance*: Specific safety distance for the gluepoints where one might want to have less safety distance.
- “flipped_dropframe_distance” *float=None*: Optional and only applicable in connection with a static glue gun. If not None, the robot keeps the board upside down after glue procedure and goes into a position that is on top of the placing point by the distance specified in this parameter and only then flips it down into the default safe frame.
- “sorting_direction” *int=1*: Optional and only applicable in connection with a static glue gun. Specifies X-coordinate (0) vs Y-coordinate (1) to decide on the sorting of the glue point sequence.
- “sorting_flipped” *boolean=False*: Optional and only applicable in connection with a static glue gun. Allows to flip the sequence of the glue gun application.

13.2.3. Calculation

Calculations are triggered with two simple functions.

- create_assembly_geometry(): calculates the floorslab geometry
- create_assembly_sequence() *Optional*: calculates the sequence of the assembly based on the geometry

13.2.4. Individual element parameters

The calculations create a class which represents a floorslab with an array of individual elements which represent the boards. Element parameters are not meant to be set manually but it can make sense to read them out manually. This overview only features a selection of most interesting parameters every single element holds:

- .box *compas.geometry.mesh*: Compas Mesh of the board
- .frame *compas.geometry.frame*: centre frame of the board
- .global_count *int*: total assembly sequence position
- .height *float*: height of the board
- .layer *int*: layer within the slab
- .no_in_layer *int*: assembly sequence position within the layer
- .path *list of compas.geometry.frames*: all frames targeted in the whole path of the element
- .stack_pick_frame *compas.geometry.frame*: frame where the end-effector picks up the board
- .tool_frame *compas.geometry.frame*: frame where the end-effector places the board
- .width *float*: width of the profile

13.2.5. Analysis

After the floorslab has been created, there are three incumbent functions for analysing it:

- export_instances(): Returns an overview of all the different timber boards in the system in the form of a nested list: *[[[profile_width_1, profile_height_1], total_length_1], [length_a, no_pieces], [length_b, no_pieces], ...][[profile_width_2, profile_height_2], total_length_2], [length_a, no_pieces], [length_b, no_pieces], ...]...]*

- export_component_stack(): Returns a nested list of all boards in the order of their assembly: [[board1.width, board1.height, board1.length], [board2.width, board2.height, board2.length], ...]

- weight_calculator(self, protective_clay_height=5.0, density_timber=460, density_clay=2250, fill_limit=None): returns all the important weight-related values in a list.

    - "protective_clay_height" *float, optional*: layer thickness in cm of loam outside of the load-bearing grid – for example under the load-bearing structure where it is usually applied for fire protection or loam screed on top of the slab.

    - "fill_limit" *int, optional*: Specifies the number of layers filled up with loam. If unspecified, all layers are filled up.

    - "density_timber" and "density_clay" *float, optional*: Density of the materials in kg/m^3.

The function returns the information in a list: *[Total Weight, Weight/sqm, Area, Total Volume, Total Timber Volume, Total Clay Volume, Void Volume]*