RETHINKING MODULARITY
Designing a Prototype for Checkered Stacking

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ABSTRACT

Modular prefabrication offers a number of advantages in comparison to conventional construction, including reduced construction time, minimised material waste, reduced labour costs and improved quality control. However, modular construction faces challenges in relation to logistical, spatial and structural issues. Through the development of a modular prototype, this research aims to contribute an innovative modular construction solution, particularly an alternative method of stacking the modules, in order to address these issues.

The prototype draws inspiration from the project Sneglehusene by BIG, which includes the stacking of modules in a checkered pattern. This idea serves as a starting point for the prototype, while developing its concept further.

Keywords: Prefabrication, Modular Prototype, Checkered Stacking

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I. INTRODUCTION

PURPOSE AND AIM

Modular construction, or prefabricated construction, is not a novel concept. It has been a feature of the building industry for several decades. Despite its longstanding presence, the application of this method may not have been fully explored or utilised yet. This thesis is motivated by an interest in these potential improvements.

The decision to focus on prefabricated modular construction stems from its perceived benefits in terms of its construction efficiency. This thesis aims to identify and analyse the potential benefits and limitations of using prefabricated modular construction for urban housing development. It investigates specific areas where prefabrication methods offer improvements over traditional construction. The study aims to provide a balanced view of prefabricated modular construction, showcasing its advantages, while acknowledging the challenges and limitations of this approach. The thesis aims to clarify the circumstances under which modular construction can be most effectively utilised.

Through the design of an innovative prototype, this thesis adresses current logistical, structural and spacial challenges connected to modular construction.

The thesis documents the methodology employed in the design and planning of the prototype. The prototype is tested by making it part of an exemplary building design.

RESEARCH QUESTION

How can stacking modules in a checkered pattern improve modular construction?

The objective is to investigate the application of prefabricated modular construction, specifically the stacking of modules in a checkered pattern, culminating in a prototype design presented through architectural drawings, 3D images, and physical modelling. This supporting booklet accompanies the prototype, detailing the research methodology, analysis of benefits and limitations of modular construction, and the prototype's improvement of modular construction, addressing current logistical, structural and spacial challenges in the field.

Figure 1   Dong, Dortheavey Residence, by BIG Copenhagen, Denmark (Hjortshoj)

METHOD

This section details the methodology used to conduct the research for the thesis, focusing primarily on the development of the design project dealing with prefabricated modules. The methodology is straightforward, combining traditional architectural design tools and theoretical studies to progress from conceptualisation to a tangible prototype.

Conventional drawings

The process began with the use of simple hand drawing and computer aided design software to produce initial sketches and technical drawings. These drawings included basic plans, sections and elevations.

3D Modelling

Software was used to develop the modular prototype in three dimensions. This included generic modelling to explore spatial configurations and external appearances without delving into photorealistic rendering or advanced material simulation, allowing rapid iteration of different ideas and details.

Physical Modelling

A physical model in scale 1:20 was constructed to represent a modular unit in a tangible form. The model provides a basic sense of the spatial arrangement and interface of the modules. The materials and construction techniques for these models were kept simple and did not extensively explore precise details of the module.

Iterations and feedback

The module and building design process followed a basic iterative cycle where designs were regularly reviewed and adjusted based on general feedback from the academic supervisors. This cycle allowed for a gradual refinement of the design, although it was carried out in a relatively straightforward manner without extensive revisions or exploration of alternative approaches.

Theoretical studies

A review of existing literature on modular construction and relevant theory was undertaken. This included reading papers, articles and books that provide a broad overview of the field. The aim was to gather background information on prefabricated modular construction to support the design project.

Reference projects serve as the design inspiration for the prototype. In particular, the project "Sneglehusene" by BIG serves as the starting point and provided the primary conceptual framework for the development of the module prototype. A number of other projects served as sources of inspiration during the course of the thesis. While they did indirectly affect the design decisions made, they were not directly relevant to the thesis and therefore not explicitly mentioned.

The modular design manual by Stora Enso constituted the principal source of inspiration for the design and development of details in modular construction.

Methodology

The methodology employed in this thesis was systematic and focused on integrating conventional architectural design methods and fundamental theoretical research to develop a prototype for prefabricated modular construction. The methodology employed was pragmatic, placing a strong emphasis on the utility of standard tools and processes in architectural design.

DELIMITATIONS

Scope and Focus

This thesis defines its scope in order to maintain a focused and manageable investigation of how stacking prefabricated modules in a checkered pattern can address logistical, structural and spacial challenges in modular construction. To ensure depth and relevance in the exploration, it is imperative to specify the boundaries of this inquiry.

Modularity is versatile and can be applied to many different building applications. To limit the scope for this particular project, the thesis focuses on the design for living spaces for individuals and couples without children, recognising that this demographic is increasingly becoming the predominant group in urban areas.

Material and Construction Techniques

The investigation focuses on timber materials recognised for their durability and minimal environmental impact. The selection of materials and construction techniques is intentionally limited to those that align with sustainability principles and are feasibly applicable in modular apartment design. Advanced or experimental materials, fall outside the scope of this thesis.

Design Parameters

The modular prototype and its design exploration emphasise the design of the structure and floor plan to be easy to construct, transport and install, while following general architectural design principles to create living spaces. The module is developed and iterated according to these parameters. While recognising the importance of other design considerations, such as market viability, wider socio-economic factors and a life cycle assessment, this work does not explore them. These aspects are considered crucial for further research, but are not included in this study in order to maintain a clear focus on design.

Timeframe

The temporal scope of this thesis is also a consideration, as the design, prototyping, and evaluation phases are limited by the academic timeframe allotted for the completion of this study. To conduct research and design exploration on modular construction, a pragmatic approach is necessary, prioritising depth over breadth.

II. THEORY

PREFABRICATION

Introduction

Prefabrication involves the manufacturing of building components in a factory and their subsequent assembly on-site.

The common perception of prefabricated buildings is still heavily influenced by the architecture of the 1960s and 1970s, characterised by the use of serial precast concrete elements, which is linked to an image of lack of design and monotony. However, this perception is challenged by the contemporary wood prefabrication process, which does not adhere to the rigid schemas of the past. Modern software can automate the creation of cutting data for complex buildings, rendering the manufacturing effort independent of the differentiation in workpieces. Today, the design freedom afforded by automated manufacturing is more likely to be problematic than the limitations imposed by prefabrication itself, with major wood constructions often retaining a prototype character (Kaufmann et al., 2017).

Conventional Construction

In comparison to prefabrication, conventional construction methods appear less optimised. Issues are often only realised and resolved on-site, and late changes in planning frequently delay the process (Kaufmann et al., 2017).

The construction is tied to the sequential execution of tasks, vulnerability to weather-related delays, coordination complexities, and unergonomic working conditions, which result in a greater time and cost investment.

The real cost of construction can only be roughly estimated and is not transparent until after construction. These issues can be reduced in the controlled environment of prefabrication (Azari et al., 2013).

Prefabrication

The process of prefabrication involves the transfer of production steps to a workshop, which has the potential to bring various benefits, including the reduction in construction times. Under optimal conditions, the time needed for projects can be decreased by 20–50% in comparison to conventional building methods (Bertram et al., 2019). The manufacturing of building components can be undertaken concurrently with the preparation of the construction site, thereby reducing the overall project duration.

The process of prefabrication necessitates detailed planning, which extends the planning phase and maintains the project in a virtual state for a longer period. Consequently, this delays the actual investment costs for the project's realisation to a later stage, potentially beneficial for the financing of the project over a shorter period.
The fabrication of components under controlled workshop conditions can lead to increased quality of execution and better process control. The benefits of these conditions include being unaffected by weather, reduced distances, consistent availability of team members, materials, and tools, and the ergonomic advantages of an assembly table versus construction scaffolding (Kaufmann et al., 2017).

Prefabrication is based on the principles of standardisation and repetition, which are crucial for achieving economies of scale and enhancing the efficiency of the construction process. This approach enables the efficient production of modules in a factory setting, which in turn maximises productivity (Erixon, 1998; Generalov et al., 2016). Furthermore, the methodical management of materials coupled with a reduction in noise and air pollution at construction sites, contribute to environmental sustainability by minimising waste and disturbances during construction (Salama et al., 2017).

Despite the advantages of prefabrication, the practice is not without challenges, especially logistical issues related to the transportation of the modules (Almashaqbeh & El-Rayes, 2022).

Figure 2 The production in Kalwang (Ott)

Prefabrication Elements

There are three main prefabrication elements with several key differences, which are significant for understanding the diversity and applicability of prefabrication in various contexts.

Linear elements, like beams and columns, are typically used in structural applications where their linear form can be directly integrated into the building's structural framework. The simplicity of linear elements is advantageous for projects that are structurally built upon beams and columns or where structural reinforcement or extensions are necessary. However, the level of prefabrication is limited compared to more complex prefabricated systems(Bertram et al. 2019).

Working with linear elements offer logistical benefits, including compact transportation and the ability to use simpler lifting equipment. Furthermore, they permit certain assembly simplifications on the construction site. However, the method may extend the assembly phase and potentially decrease precision due to on-site assembly conditions (Kaufmann et al., 2017).

Flat elements include panels or wall and slab systems. These can be prefabricated as an open framing or closed with insulation, wiring, external cladding, windows and doors. This method allows for a greater degree of prefabrication compared to linear systems (Bertram et al. 2019).

The prefabrication of flat elements allows for a higher architectural design flexibility in comparison to spatial systems, although the completion of joints may have to be done on-site and ceiling elements typically exclude the floor structure. (Kaufmann et al., 2017).

Spatial elements, also known as modules, involve the prefabrication of entire sections of buildings, including rooms or whole apartments, complete with internal finishes, fixtures, and fittings. Subsequently, these self-contained units can be stacked or linked together on site to form a larger structure. Working with prefabricated modules can significantly reduce on-site construction time, as the bulk of the assembly work is completed off-site. Additionally, it allows for the highest level of quality control, as units can be fully outfitted and inspected in the factory (Bertram et al. 2019).

Modules offer a solution to the limitations of flat elements in construction. All surfaces and connections can be prefabricated to a high quality on a room-by-room basis, reducing assembly time on site. Interior fittings and building services can also be pre-assembled, further streamlining the construction process. Working with modules affects the overall design, including floor plan structure and room dimensions. The dimensions of the rooms are constrained by the transportation routes between the workshop and the construction site. The width of the room cell is the limiting factor. Modular construction is commonly employed for projects with recurring room units, such as hotels and apartment or nursing homes. It also benefits spaces that require complex finishes that can be prefabricated, especially wet areas like bathrooms and kitchens (Bertram et al. 2019). Modules are typically constructed from cross-laminated timber and are elastically supported to prevent sound transmission (Kaufmann et al., 2017).

The Potential of Modules

The successful implementation of modules depends on a number of factors, including the scale and complexity of the project and the ability to standardise design elements. The selection of a linear, flat, or spatial system is largely dependent on the specific requirements of the project, including architectural design and the intended use of the building. Furthermore it is possible to combine multiple systems, using the advantages of the different systems for different use cases or parts of the building.

However, modules offer the highest degree of prefabrication and therefore the highest potential for construction efficiency and time savings.

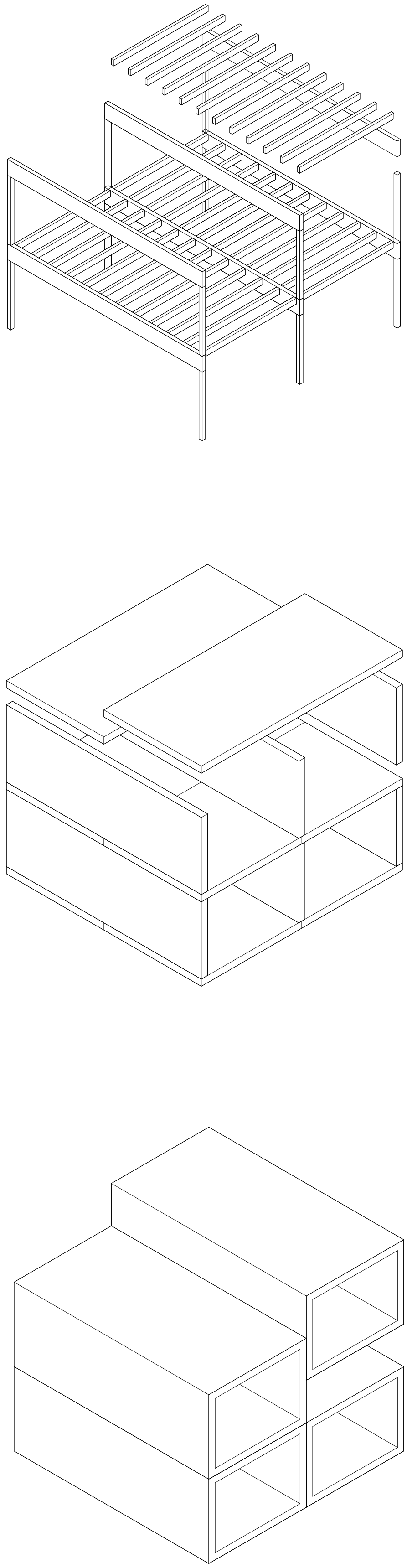


Figure 3 Prefabrication of linear, flat and spatial elements (Kaufmann)

MODULES

Module Transportation

Depending on the location of the project, there are different ways of transporting the modules, by road, rail and water.

The dimensional and weight restrictions of transportation infrastructure and vehicles must be considered. The dimensions and weight of modules are frequently constrained by legal transportation regulations, which vary by jurisdiction and can have a significant impact on the planning and execution of modular construction projects (Salama et al., 2017). The Swedish Transport Agency (TSFS 2009:64) states, that newly built houses and house sections should not have a width that exceeds 4.15 meters and recommends that the transport height should not exceed 4.5 meters, while the length of modules is not directly limited. Oversized modules that exceed standard transport dimensions require special permits, escort vehicles, or even infrastructure modifications, all of which can lead to increased costs and delays.

The transportation distance between the manufacturing facility and the construction site plays a critical role in the efficiency and cost-effectiveness of modular construction. It has been demonstrated that the transportation of modules over long distances can be prohibitively costly, with costs increasing exponentially for modules wider than standard dimensions (Salama et al., 2017). Consequently, the location of manufacturing facilities relative to construction sites is a pivotal factor in determining the overall feasibility and efficiency of modular construction projects. The industry is in broad agreement that the maximum feasible distance for transporting modules from the manufacturing facility to the building site is approximately 200 kilometres (Smith, 2010).

Unlike traditional building parts or linear/flat elements, which can be transported in a flat or compact form, allowing for the maximisation of space and efficiency, modular units are three-dimensional boxes filled with a substantial amount of air. This characteristic inherently leads to inefficiencies in transportation (Bertram et al., 2019). These inefficiencies are not merely about the physical space these modules occupy on a truck or trailer, but also relate to the economic and environmental cost of moving relatively low-density loads over long distances. The size and shape of each module limits the number of units that can be transported per trip, resulting in increased fuel consumption, greater transportation costs, and higher CO_2 emissions. Shipping one square meter of floor space of a module over 250 kilometres costs five times more compared to shipping it in a flat form (Bertram et al., 2019).

Module Installation

Prefabricated components are delivered to the site ready for installation. The culmination of the construction process involves lifting, placing, adjusting, connecting and securing these components.

Typically, the components are transferred directly from the transport trailer to their designated location on the site. The crane lifts and positions each element, while the site crew assists in guiding the elements into place and securing them (Smith, 2010).

To facilitate prefabrication and on-site assembly, the modules must be designed with lifting points, also known as 'pick points'. These points are designed to match the weight distribution of the component, ensuring stability during lifting and accurate placement. In the case of timber modules, a belt strap is commonly used, which requires the modules to have a stronger structure, to prevent breakage during lifting (Lawson et al., 2014). The requirement of a stronger structure leads to manufactures having to oversize the module components to ensure their structural integrity. This leads to higher material costs and a higher demand of space for structural elements, which leads to a reduction of living space and to an increase of the overall cost of the module per m^2.

Improve Transportation and Installation

In the context of modular construction, the geographical distance to manufacturing facilities, the existing infrastructure for transportation, and regional regulatory policies are often beyond the control of project stakeholders. However, the design of the module is a critical domain where planners can exert significant influence. This is where specific design strategies can be employed to simplify the transportation of modular units, thereby mitigating logistical challenges and associated costs.

One such strategy is the optimisation of modular dimensions by adhering to the maximum dimensions permitted under transportation regulations. The adherence to established standards for width, height, and weight ensures that modules comply with the necessary regulations for transportation, thus reducing the necessity for special permits or escorts during transit. This can often entail significant additional expense and logistical planning.

The incorporation of construction materials that offer structural integrity without unnecessary loads reduces the weight of modules. This not only facilitates compliance with weight restrictions but also enhances fuel efficiency during transportation and contributes to a reduction in carbon dioxide emissions.

An efficient use of space within modules is achieved by designing components to serve multiple purposes. When structural elements can also fulfil aesthetic or functional interior requirements, the number of separate components required is reduced. This strategy aids in minimising both the physical dimensions and the weight of each module, further streamlining transportation.

Moreover, optimising the utility of space within each module, ensuring that a smaller volume provides the same degree of functionality, is a critical aspect of design efficiency. Space efficiency is achieved through careful planning to maximise the functional output of every square meter within a module, aiming for an optimal balance between utility and compactness.

In addition to dimension and weight optimisation, the simple reduction of the number of modules in any modular design is cost-effective, provided that the transportation limitations are satisfied. This is because the construction and maintenance costs are increased by the necessity of more modules being connected, as well as the use of more cranes and trucks for transportation (Salama et al., 2017).

Efficiency vs. Adaptability of Modules

When striving for maximum efficiency of the module, it is important to not neglect the ability for the inhabitants to adapt the space. The efficiency of purpose-built spaces may be such that they offer limited scope for future reconfiguration, which could reduce the building's long-term viability if the needs change.

Conversely, designing for maximum adaptability may involve compromises on current space efficiency, which highlights the need for a careful evaluation of priorities and objectives in the planning stage.

The challenge therefore lies in designing modular systems that are both space-efficient and allow for customisation and adaptation of living spaces to meet individual preferences and changing needs. Modular systems should permit a certain degree of customisation and adaptability within their standardised framework.

REFERENCE PROJECTS

SNEGLEHUSENE

The project "Sneglehusene," developed by Bjarke Ingels Group (BIG) in Aarhus, Denmark, features a modular housing concept that distinguishes itself primarily through its checkered facade design. This initiative, finalised in 2022, introduced 93 residential units to the Nye neighbourhood, employing a modular construction technique that makes use of relatively low-cost materials to achieve both affordability and architectural integrity. The project's inception and realisation demonstrate a particular interest in evolving modular housing solutions within a sustainable urban setting. A central aspect of "Sneglehusene" is its repetitive use of two kinds of housing modules, which together form a visually striking checkered pattern on the facade. This pattern is not just an aesthetic choice but serves as a foundational element in defining the project's identity and its approach to modular construction. The advantage of stacking the modules in the checkered pattern is that it results in the creation of vacant spaces in between, which can serve as additional living space, when enclosed by a facade layer. In this way, the same number of modules result in nearly twice as much living space. This approach also directly influences the spatial configuration of the interior, where the stacking of modules results in varying ceiling heights of 2.5 to 3.5 metres, which creates spacious living areas, augmented with floor-to-ceiling windows and private outdoor terraces.

Relevance to the Thesis

The significance of Sneglehusene for this thesis cannot be overstated, particularly when considering the checkered stacking pattern as a guiding principle for the development of the modular prototype. The project establishes a clear starting point for further exploration into how this modular construction technique can streamline the construction process and create functional, desirable living spaces.

The architects do not explicitly state or demonstrate that the modules were prefabricated. Given that the modules are 5.5 metres wide, transporting them would be prohibitively expensive and not at all according to the theme of affordable housing. It is probable that the "modules" were prefabricated as panels and transported to the site, where they were assembled together, making the project appear less modular. This is a missed opportunity to increase the level of prefabrication to standardise this method of building affordable housing.

A disadvantage of this stacking method is the limited accessibility due to the different floor heights between the modules and the open spaces created by the alternating pattern in the checkered design.

In constrast to this project, the modular prototype of this thesis should be accessible, fully prefabricated and transportable to the site.

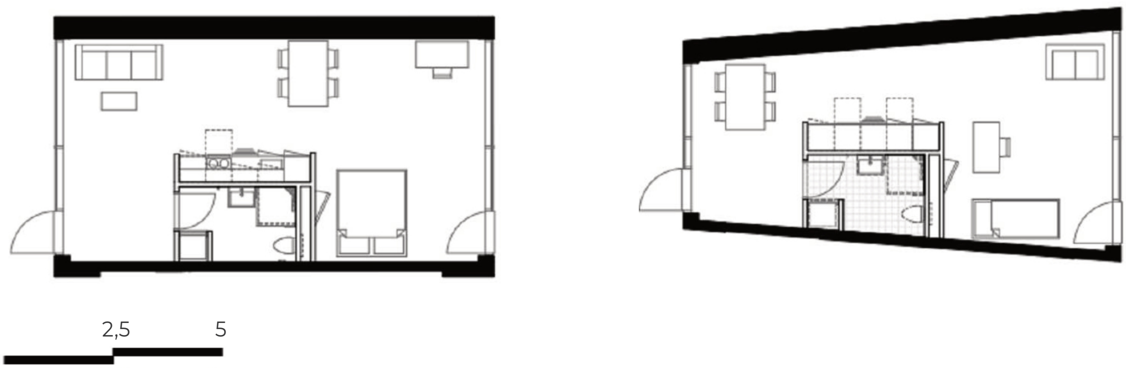


Figure 4 Sneglehusene Plan 1 Bedroom Apartment (BIG)

Figure 5 Sneglehusene Housing (Hjortshoj)

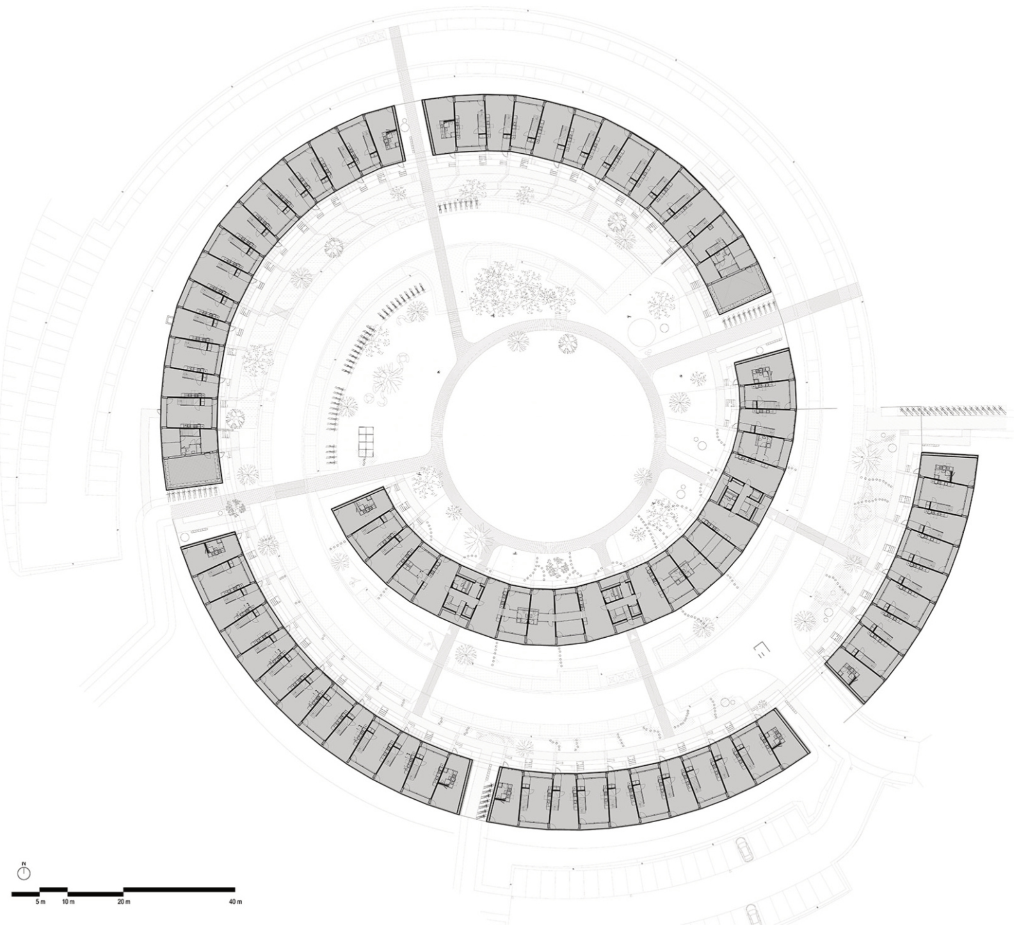


Figure 6 Sneglehusene Ground Floor Plan (BIG)

SVARTLAMOEN HOUSING

The Svartlamoen residential development in Trondheim, Norway, designed by Brendeland & Kristoffersen in 2005, represents a distinctive approach to modern living. It comprises a multi-storey residential building and smaller studio apartments, all constructed with cross-laminated timber (CLT). A notable aspect of this project is the decision to retain the CLT framework exposed, which effectively blends practicality with visual appeal.

This design choice allows the architectural qualities of CLT to enhance the interior spaces, offering a pure and honest display of the construction materials. Beyond aesthetics, the visible wood contributes to a healthier living environment by naturally regulating humidity. This method also showcases a commitment to sustainability, minimising the need for extra materials and finishes. While additional insulation is necessary for energy efficiency, the timber's inherent qualities provide effective thermal and acoustic insulation.

One challenge with exposed CLT is its vulnerability to physical damage over time, such as scratches and dents, which are more challenging to address than with typical wall finishes like drywall or plaster. However, this aligns with the architect's vision, which celebrates the raw beauty of CLT. The material is central to the design narrative, emphasising functionality and the thematic prominence of solid wood construction. The use of CLT creates a harmonious interior, as if the space is sculpted from a single piece of wood, encompassing walls, floors, ceilings, furniture, and doors. The decision to leave the wood surfaces largely untreated minimises chemical use and maintenance while allowing the material to age and develop a patina, which adds character over time. Transparent lacquers are applied only where necessary to maintain the wood's natural look and feel (Brendeland & Kristoffersen, 2009).

Relevance to the Thesis

The utilisation of exposed CLT in modular construction serves to enhance the sustainability and efficiency of the construction process. Exposed CLT simplifies connections and streamlines the prefabrication process, aligning with the overarching aim to build modules more efficiently. The module prototype will follow the design philosophy of Brendeland & Kristoffersen, that values the raw architectural qualities of the material while being environmentally conscious.

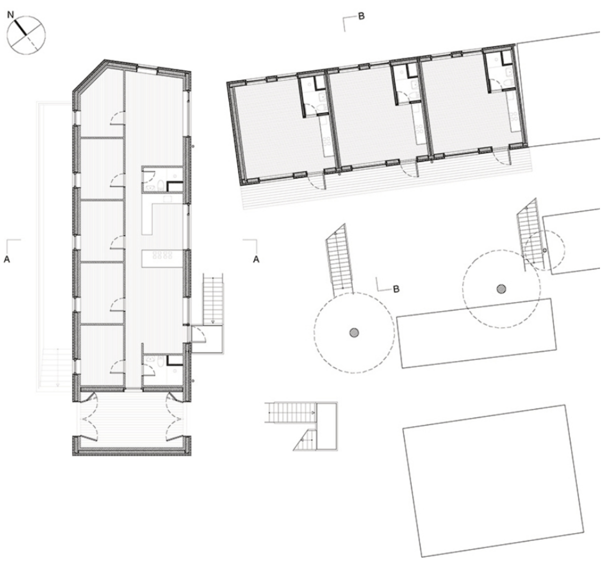


Figure 7 Svartlamoen Ground Floor (Brende. & Kristof.)

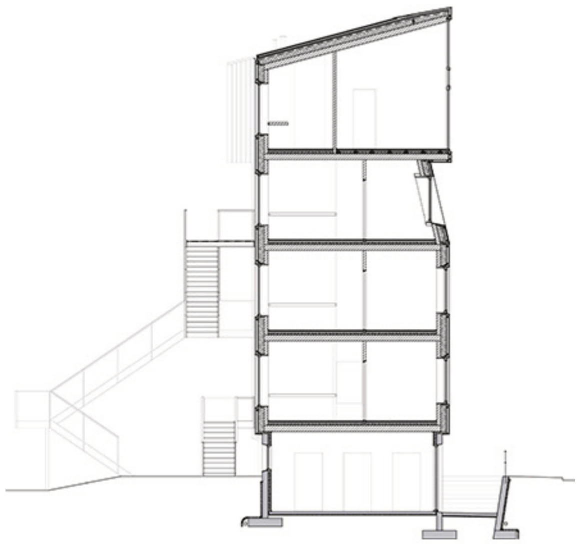


Figure 8 Section A-A (Brend.& Kristof.)

Figure 9 Svartlamoen housing complex (Garcés)

Figure 10 Svartlamoen housing bare CLT walls (Musch)

III. PROTOTYPE

CHECKERED STACKING

The checkered stacking pattern for modular construction presents a compelling solution to several prevalent challenges in the field.

Logistical

One of the most compelling benefits of the checkered stacking approach lies in its logistical efficiencies. The strategic stacking of modules in a checkered pattern allows for a significant reduction in the quantity of modules required without compromising the overall space of the structure. This pattern addresses the inefficiency associated with transporting voluminous modules by focusing modularity on necessary components. This reduction directly translates into a lowered requirement for transportation and logistics, as only half the number of modules needs to be shipped to the site, lifted by cranes, and secured in place. Additionally, this pattern optimises manufacturing facility space, using less space in the factory, allowing for a more streamlined fabrication process which can lead to cost savings and increased production speed.

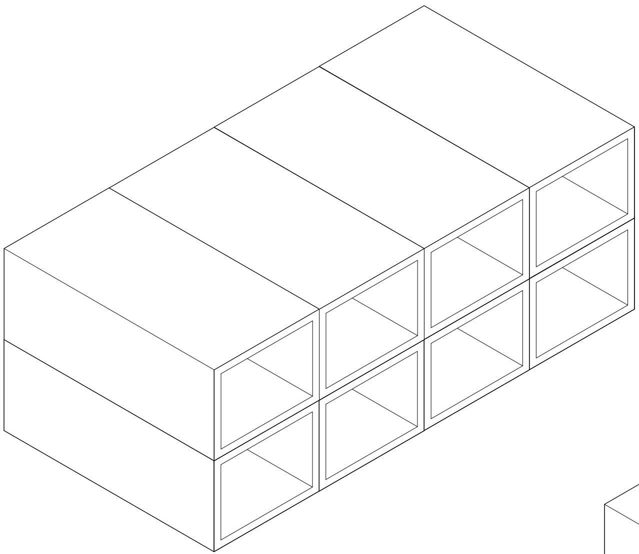
Spacial

From a spatial perspective, the checkered pattern introduces a unique blend of efficiency and adaptability that traditional modular methods struggle to achieve. The open spaces created between stacked modules offer flexibility in design and utility, enabling the inhabitants to use the space freely, which enhances the living environment. This balance ensures that while modules are optimised for their specific purpose – be it residential units complete with fixtures and fittings – the overall architectural plan remains versatile.

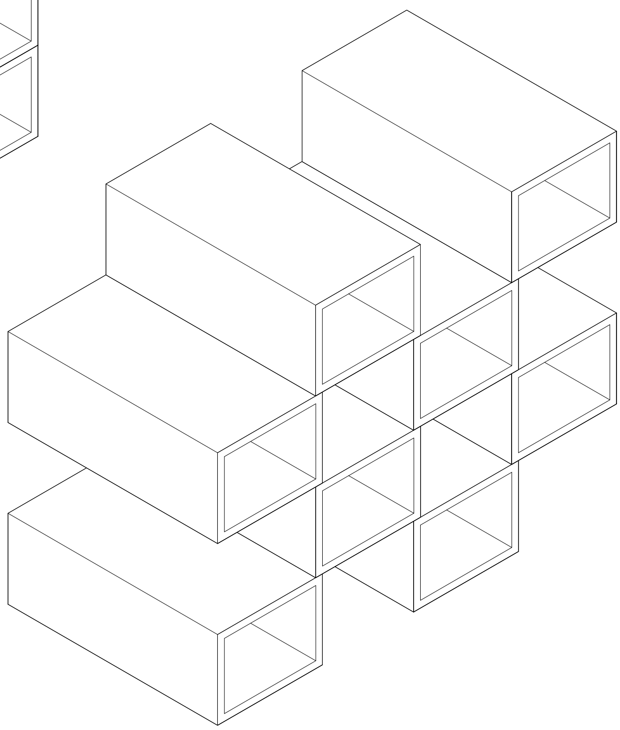
Structural

In conventional modular construction, buildings frequently exhibit two structural layers where modules meet. This double layering of walls and ceilings often presents as a challenge due to increased complexity, cost, and spatial demands. Furthermore, additional structural requirements for modules, to facilitate their transportation and lifting, result in even further cost and spatial demands. However, in the checkered stacking system, this feature is transformed into a significant advantage. Like in traditional construction practices, each wall effectively serves dual purposes, supporting two adjacent rooms, which optimises space. Additionally it also enhances the module's overall stability, because the thickness of the construction layers from two modules are merged into one. This added rigidity is crucial during crane lifting and placement at the construction site, ensuring safer and more reliable installation.

Furthermore, the checkered arrangement possibly improves structural stability by promoting an even load distribution across the structure. This means that loads are shared more uniformly, reducing stress concentrations and enhancing the building's resilience to environmental forces.



8 modules stacked in a
conventional way

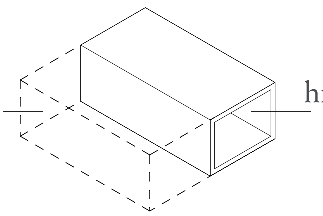


8 modules stacked in a
checkered pattern

STRUCTURAL CONCEPT

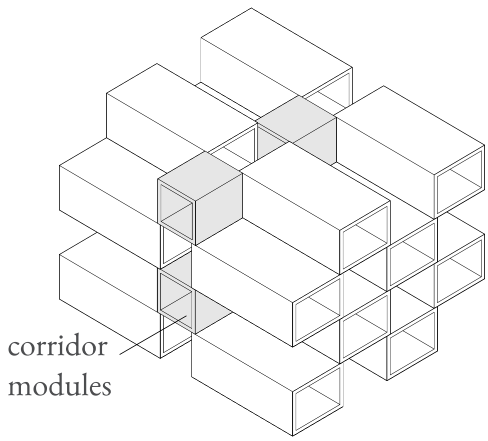
Maximise Prefabrication

Each apartment consists of one module and one open space. To exploit the advantages of prefabrication, the goal is to maximise the degree of prefabrication. In order to attain this objective, it is necessary to classify each room and function into one of two categories: those that require a high degree of manual labour and those that do not. Rooms that require a high degree of manual labour necessitate the installation of long-term fixtures and plumbing, and therefore present a greater potential for prefabrication. Consequently, these rooms should be located within the module, whereas areas requiring minimal prefabrication should be situated within the open space.



Modular Corridors

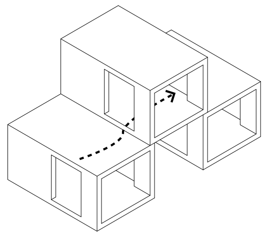
Expanding on the basic checkered stacking system, the idea has been further evolved into a more complex and multi-dimensional concept, that enables the buildings main structure to be entirely built modular. This development introduces a network of corridor modules and an additional layer of apartment modules, intricately woven into the existing checkered framework, enabling the access to all apartments.



The corridors serve not only as transitional spaces but also as structural and space dividing elements, adopting the checkered system themselves. The corridor modules are strategically positioned to weave through open and enclosed spaces, linking adjacent apartment modules and serving as dividing walls in the open areas. Planning the corridors as modules enables the degree of fabrication for the building to be even higher.

Accessibility

Integrating accessibility into the checkered structural system is crucial to improve the inclusivity and usability of these living spaces. The alternating pattern in the checkered design creates varying floor heights between the enclosed modules and the adjacent open living areas, resulting in accessibility barriers, as noticeable in Sneglehusene.



To address this issue, a modification to the corners of the modules is proposed. This design adjustment ensures that when a module meets an open space, the floor heights align seamlessly, removing any potential barriers that could restrict movement between different areas of the apartment. For this, the connection details of the modules have to be adjusted.
The solution is the introduction of a step in the corners of all modules. This facilitates the construction process and ensures structural integrity.

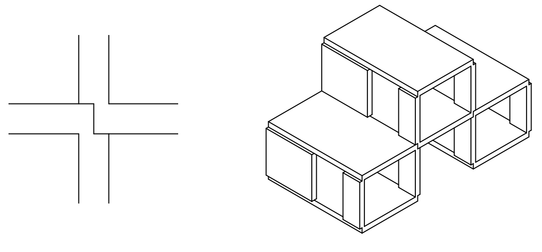
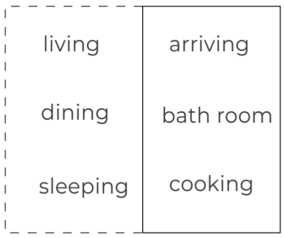


Figure 10 Sneglehusene Housing Interior Step (Hjortshoj)

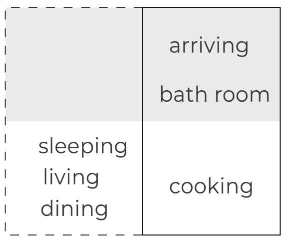
FLOOR PLAN

Organising Functions

The living functions are organised according to the degree of possible prefabrication, which results in the division below. The functions of living, dining and sleeping can be readily accommodated within the open space, whereas those requiring a greater degree of prefabrication are more appropriately situated within the module. Given that the function of arrival involves the main entrance with door, it is advantageous to situate this within the module as well.

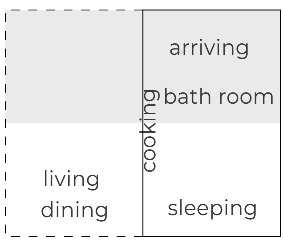


The next step is to categorise the functions according to their requirement for natural light. If the windows were to be positioned on the bottom side, the resulting division would be as follows.

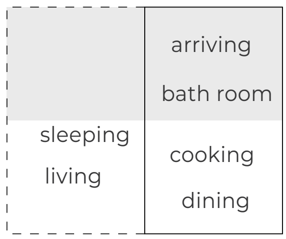


In order to separate the sleeping area from the dining area, there are two possible solutions.

Option 1: The first option is to relocate the dining area to the module adjacent to the cooking area. This is the most intuitive option, and is also the most reasonable solution for small apartments, in which there is no division between the living and sleeping areas.



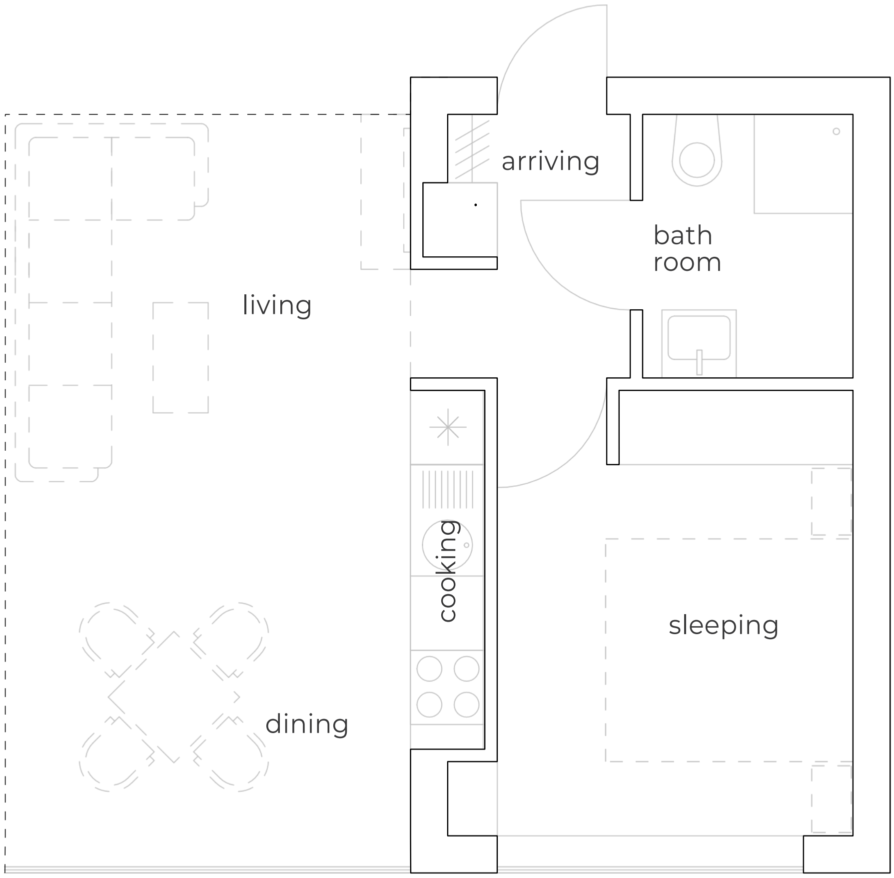
Option 2: An alternative option is to situate the sleeping area within the module, thus creating a more prestigious floor plan in which the living and dining areas are combined. In this instance, the kitchen is built-in into the module and opens towards the open space, creating a separate sleeping area. Furthermore, the incorporation of the sleeping area in the module allows for the inclusion of a built-in wardrobe within the bedroom, thereby optimising the utilisation of space.



Evaluation

Upon careful consideration and implementation of both proposed solutions for the apartment design, the second option was selected for further development due to its superior benefits. This design solution facilitates the inclusion of an entrance area equipped with storage solutions, followed by a compact bathroom. Adjacent to this, the layout features a separate bedroom, which incorporates a built-in wardrobe, enhancing spatial efficiency. The architectural plan further unfolds into an expansive open space, designated for the kitchen, living, and dining area. This communal space is enclosed by full-glazing, ensuring natural daylight reaching deep into the apartment. The design employs furniture not only as functional units but also as structural and spatial dividers, efficiently using the space. The current configuration occupies a total area of 36 sqm, making it a compact living space for individuals or couples.

This is merely the most compact solution, with the module still capable of being planned for a longer length and adjusted accordingly. The module is 4.1 metres, following the width restriction, and has been strategically chosen to facilitate easy transportation, eliminating the need for special permits or escort vehicles.

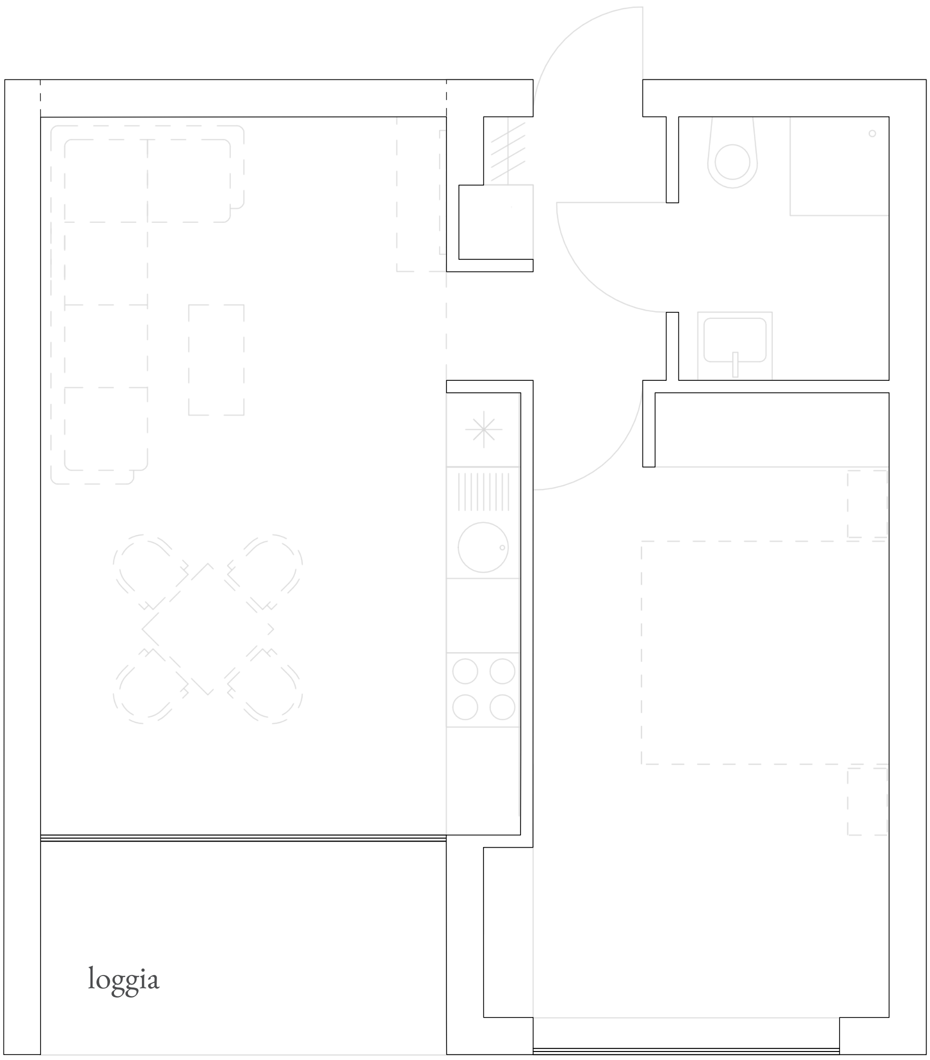


option 1

option 2

Loggia
A loggia should be included into the design, in order to fully utilise the potential of the checkered system. The glazing that encloses the open space can be moved freely to the rear, thus creating an external area. To permit the construction of a deeper loggia, the length of the module was increased.

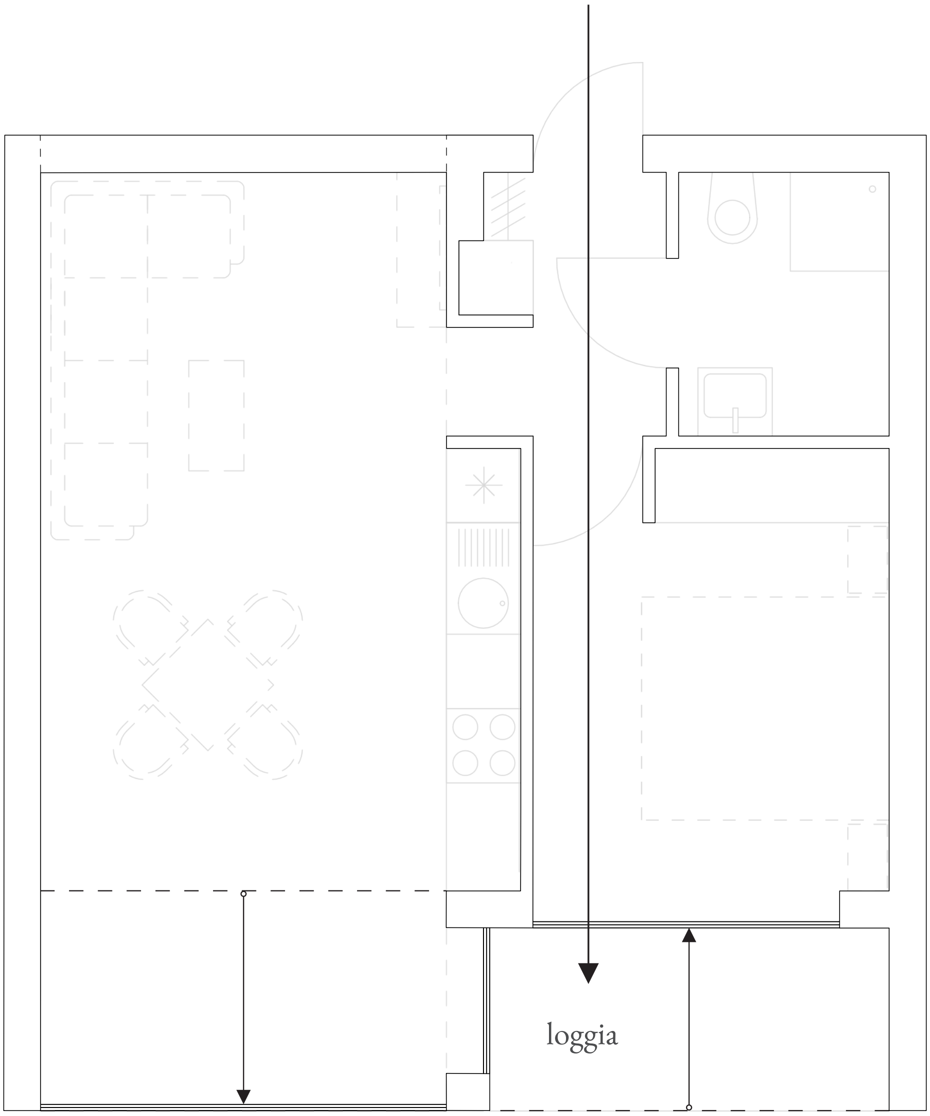
Challenges
The walls surrounding the loggia need to be insulated to eliminate any potential cold bridges. This necessitates additional manual labour on-site, as it is not part of the module and therefore cannot be prefabricated. Another issue is the disproportionately long bedroom in comparison to the living room.



Challenges

Solution

The optimal solution is to integrate the loggia into the module. This methodology permits the prefabrication of the entire loggia, including the insulation and exterior surfaces. This minimises the amount of manual labour on the construction site, as the only remaining step is to install one glazing panel to enclose the open space. This also results in a more balanced distribution of living space between the living room and the bedroom. Furthermore, the loggia can be accessed from both the bedroom and the living room, thereby establishing a clear axis from the entrance to the loggia.

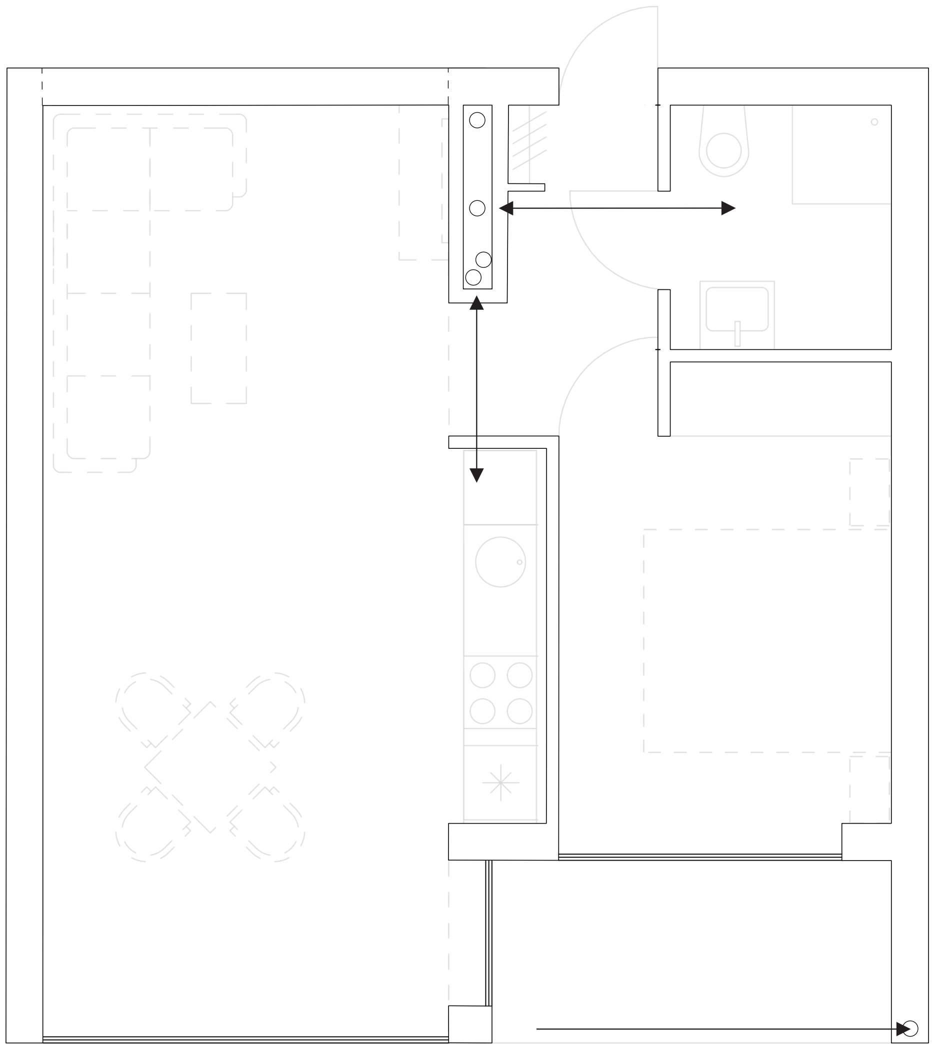


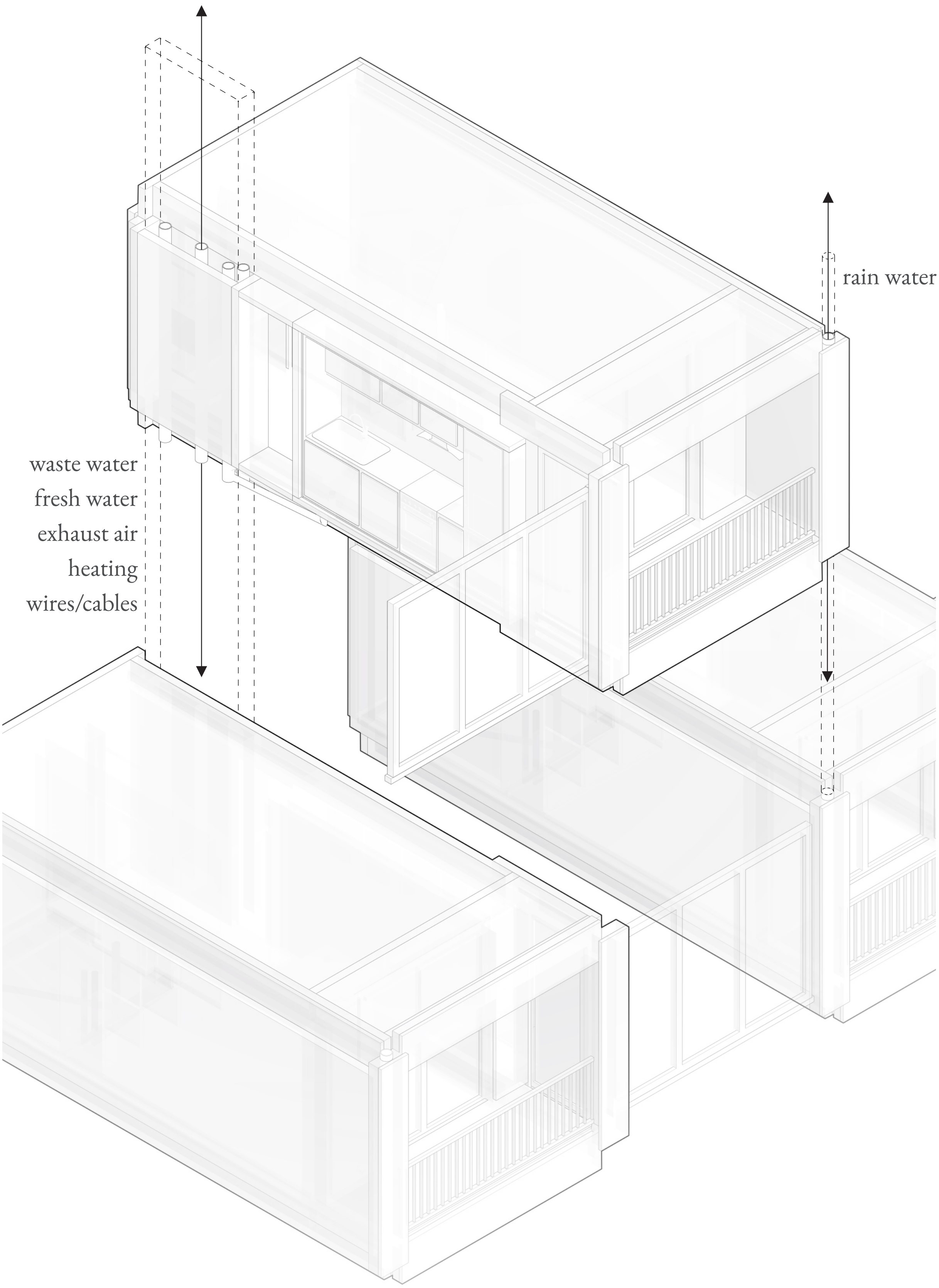
Solution

HVAC

In order to facilitate the routing of pipes and wires from the modules to the technical rooms, it is necessary to incorporate a shaft into the design. The shaft must be situated in the centre of the apartment, between the walls of the modules, in order to ensure that it can be lead vertically throughout the entire building. A suitable location for the shaft would be in close proximity to the entrance. The shaft's proximity to the bathroom and kitchen reduces the length of the pipe pathways.

To accommodate the pipes from the rooms to the shaft, the ceiling must be suspended. Additionally, the module creates a central space in the apartment, beneath and above the kitchen, which facilitates the connection to the main pipes of the shaft. Exhaust air is extracted from the bathroom, while fresh air is supplied naturally through the windows. The rainwater pipe serves to collect and dispose rainwater from the roof and loggia.




rain water
waste water
fresh water
exhaust air
heating
wires/cables

MODULE CONSTRUCTION

Material

The module is made of cross-laminated timber (CLT) for the walls and ceilings and glued laminated timber (GLT) for the beams.

Following the architectural philosophy of Brendeland & Kristoffersen's Svartlamoen housing project, the walls and ceilings are left bare, without any additional finishes, except for the floor and wet areas, where necessary surfaces are added to prevent damage and ensure structural integrity.

Construction

To ensure that the modules can be stacked up to 7 storeys high, the walls consist of two 120 mm thick CLT walls. A layer of insulation is placed between the load bearing structure to provide acoustic insulation.

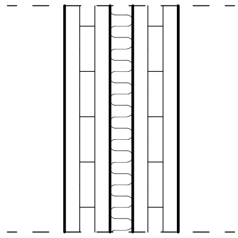
The internal walls consist of single 120 mm CLT walls.

The exterior wall, which includes the walls of the loggia, is a 120 mm CLT wall with 170 mm of insulation to ensure the energy efficiency of the building, covered by a timber cladding.

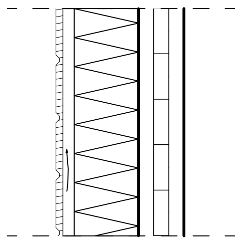
The floor/ceiling consists of a 140 mm CLT slab as the main structural element. This is followed by a generic floor structure with integrated underfloor heating. A suspended ceiling with insulation provides sound insulation between the apartments.

Substructures

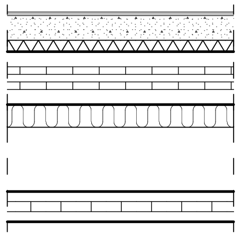
The module is organised into different substructures, which can be constructed separately and mounted together in the workshop, which simplifies the prefabrication process.



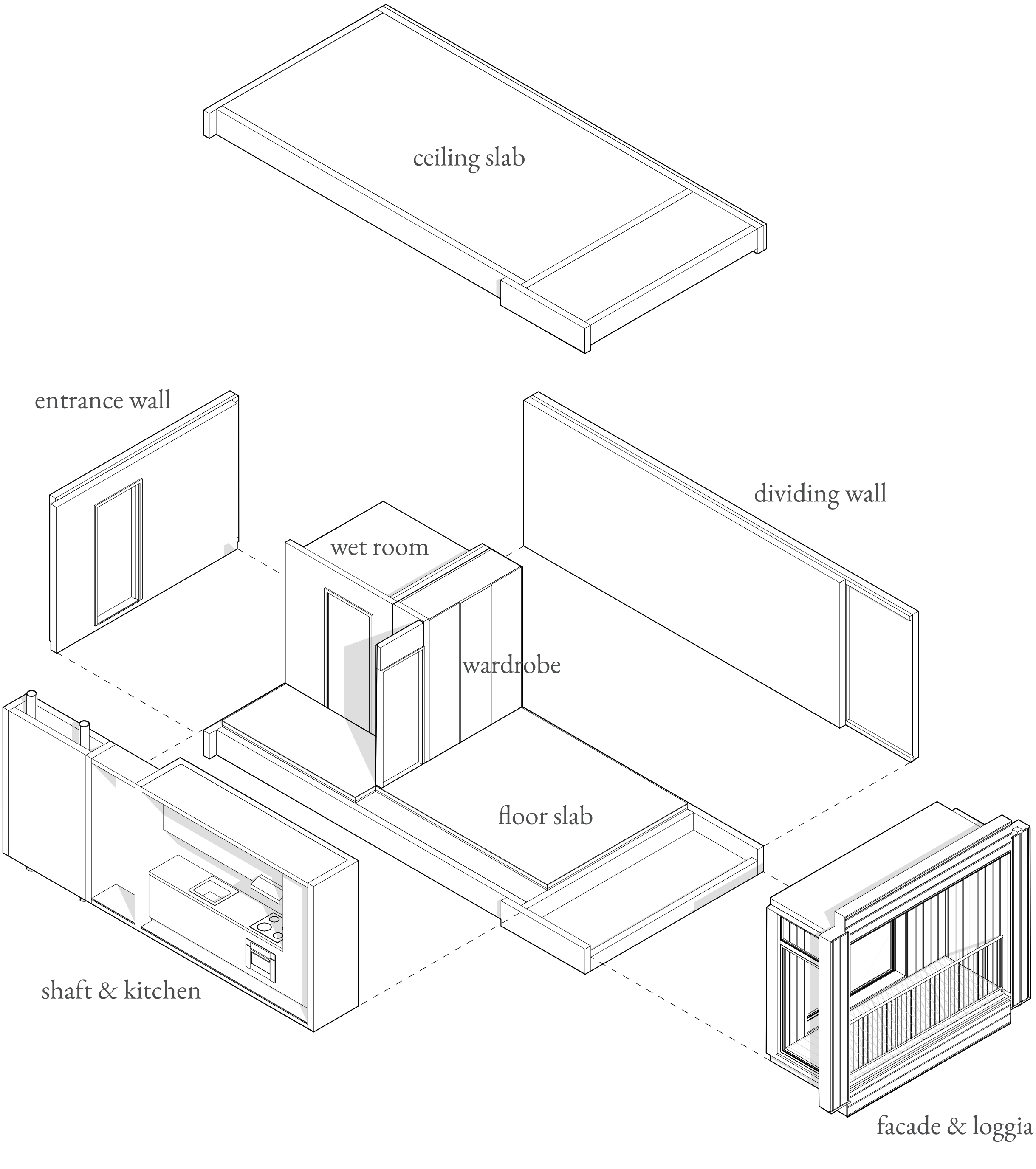
diving wall	300 mm
CLT wall	120
insulation	60
CLT wall	120



exterior wall	340 mm
wooden cladding	20
air gap	30
insulation	170
CLT wall	120

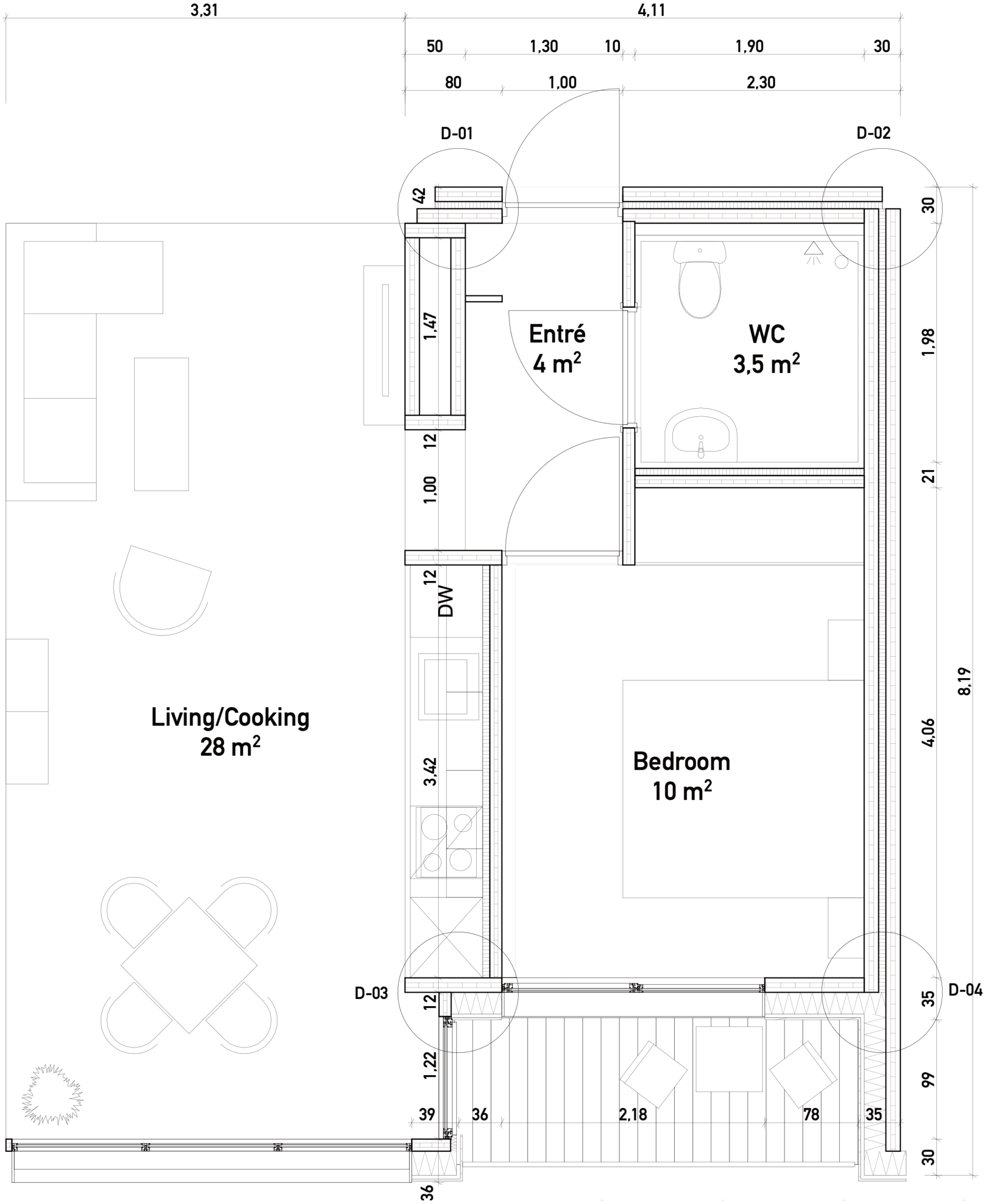


floor/ceiling	555 mm
tiles/parquet	10
cement	65
insulation	30
CLT slab	140
insulation	60
air gap	170
CLT slab	80


ceiling slab
entrance wall
dividing wall
wet room
wardrobe
floor slab
shaft & kitchen
facade & loggia

Floor plan

This is the floor plan of the prototype. This design solution facilitates the inclusion of entrance area equipped with a storage solution. To the right, there is a compact bathroom. The prototype features a separate bedroom, which includes a built-in wardrobe, which also serves as the dividing element between the bathroom and the bedroom. The floor plan further unfolds into an expansive open space designated for the kitchen, living, and dining area. The open space is enclosed by full-glazing, ensuring that natural daylight reaches deep into the apartment. The loggia is accessible from the open space and bedroom. The total floor plan area is 46 m^2.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50
1,30
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1,90
30
80
1,00
2,30
D-01
D-02
42
30
1,47
Entré
4 m²
WC
3,5 m²
1,98
12
1,00
21
12
DW
Living/Cooking
28 m²
Bedroom
10 m²
3,42
4,06
8,19
D-03
D-04
12
35
1,22
99
39
36
2,18
78
35
30
36
0
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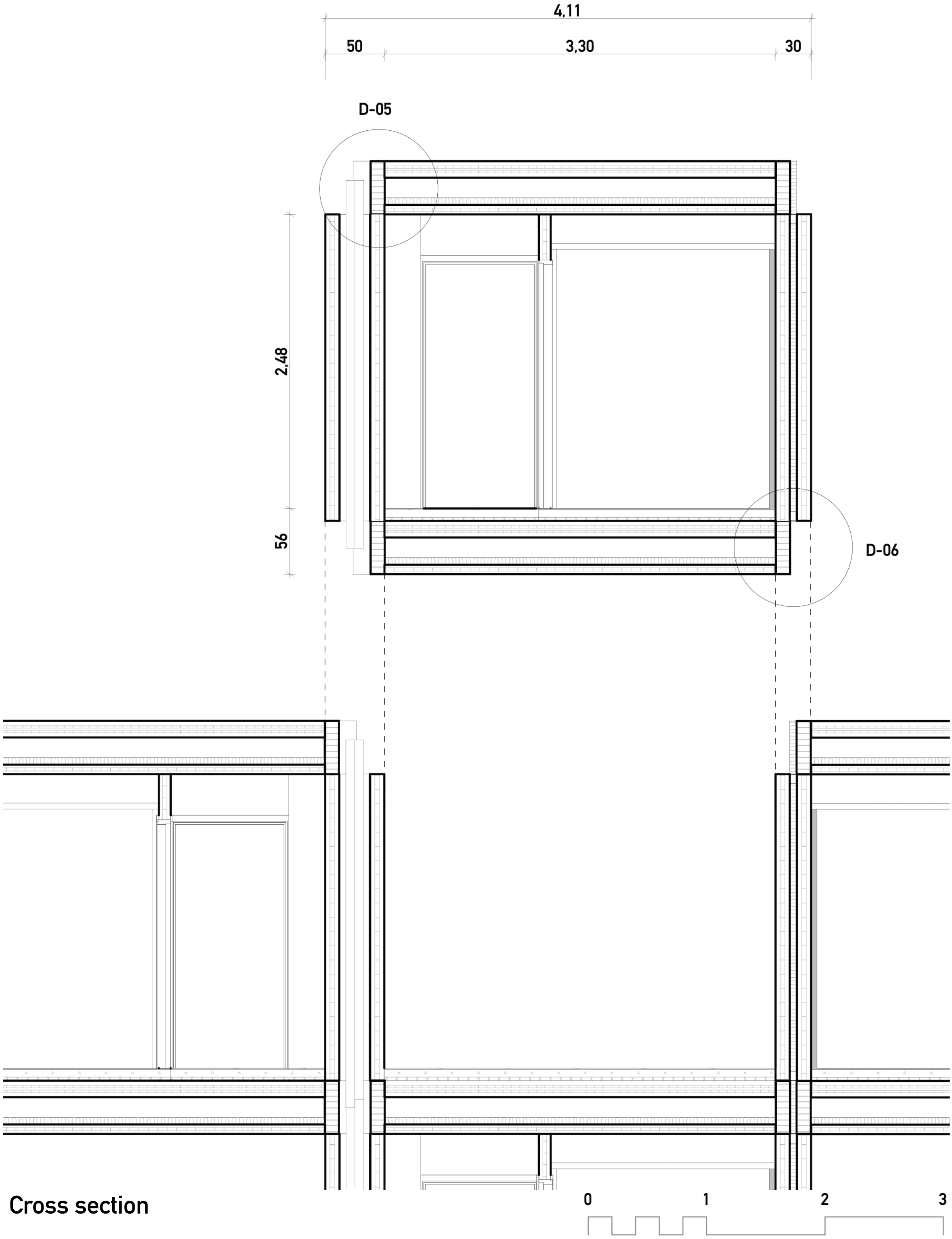
3

Floor plan

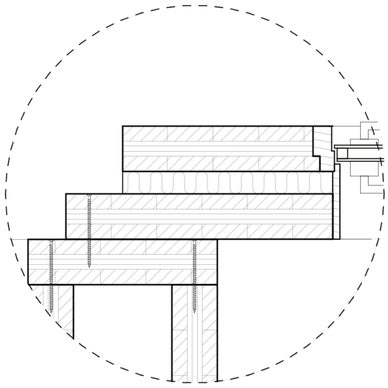
Module

Open space

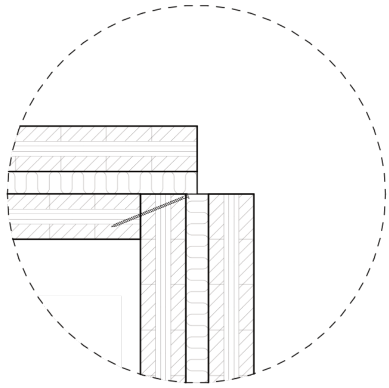
The CLT walls of the dividing walls are connected by wooden slats at the top and bottom of the wall and rest on glulam beams. The protruding wall rests on the glulam beam of the lower module, and so on. The modules can thus be assembled in a building block system.



Cross section



D-01



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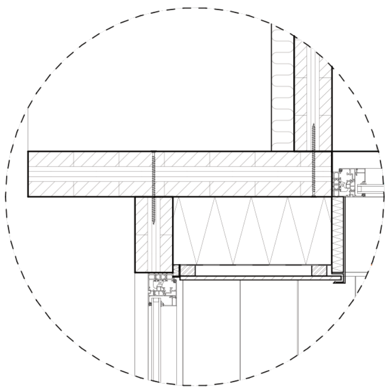

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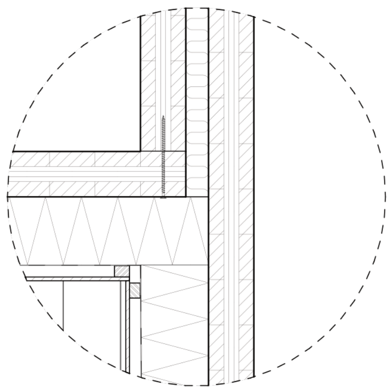

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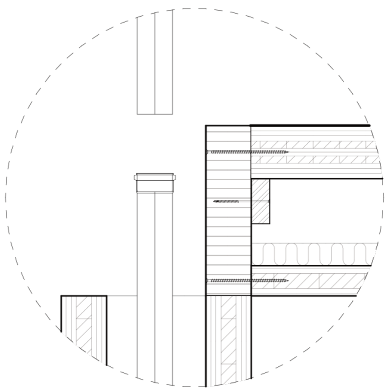

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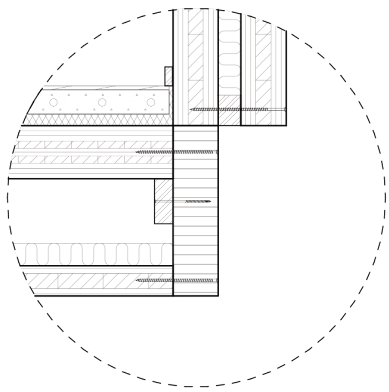

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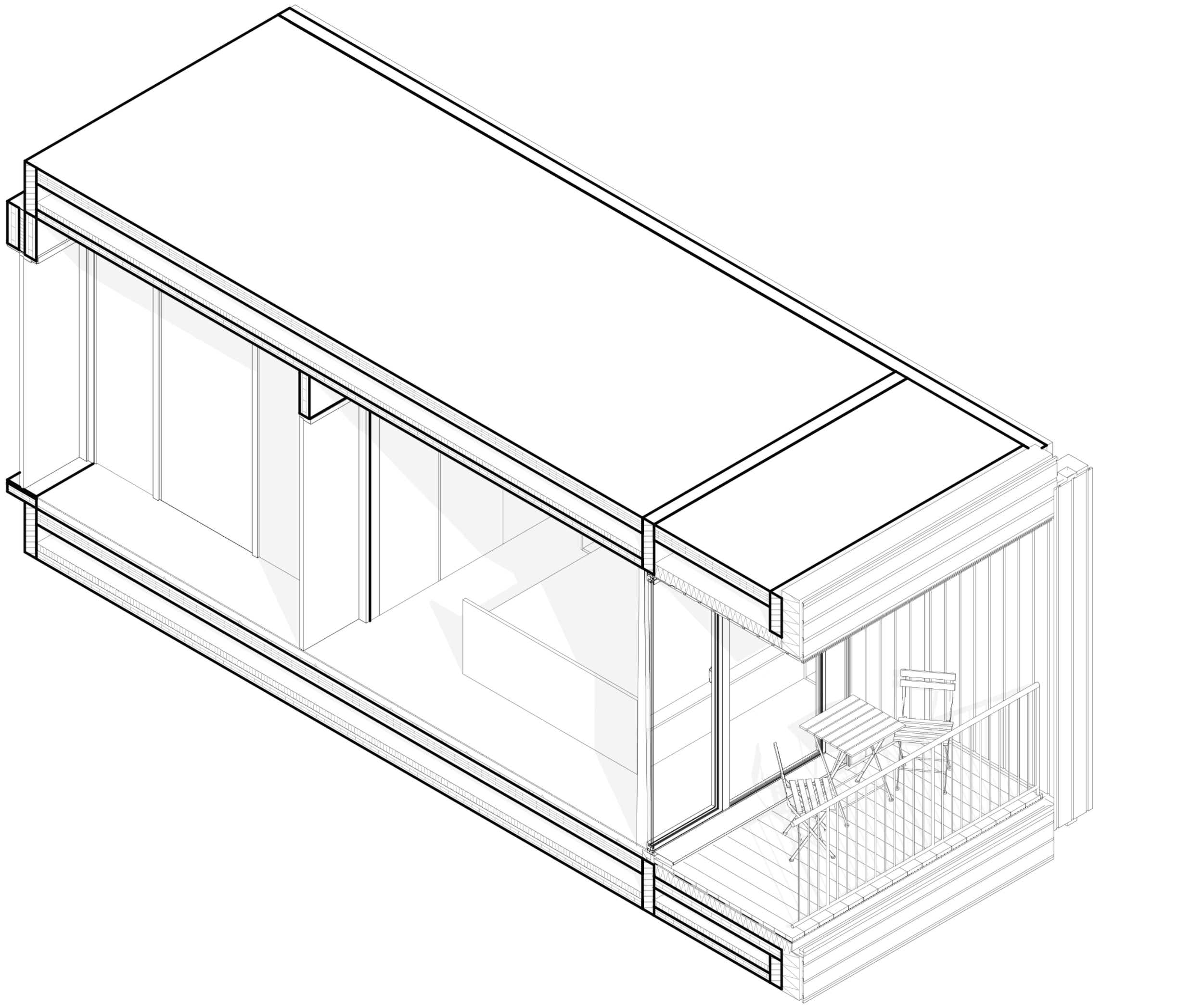
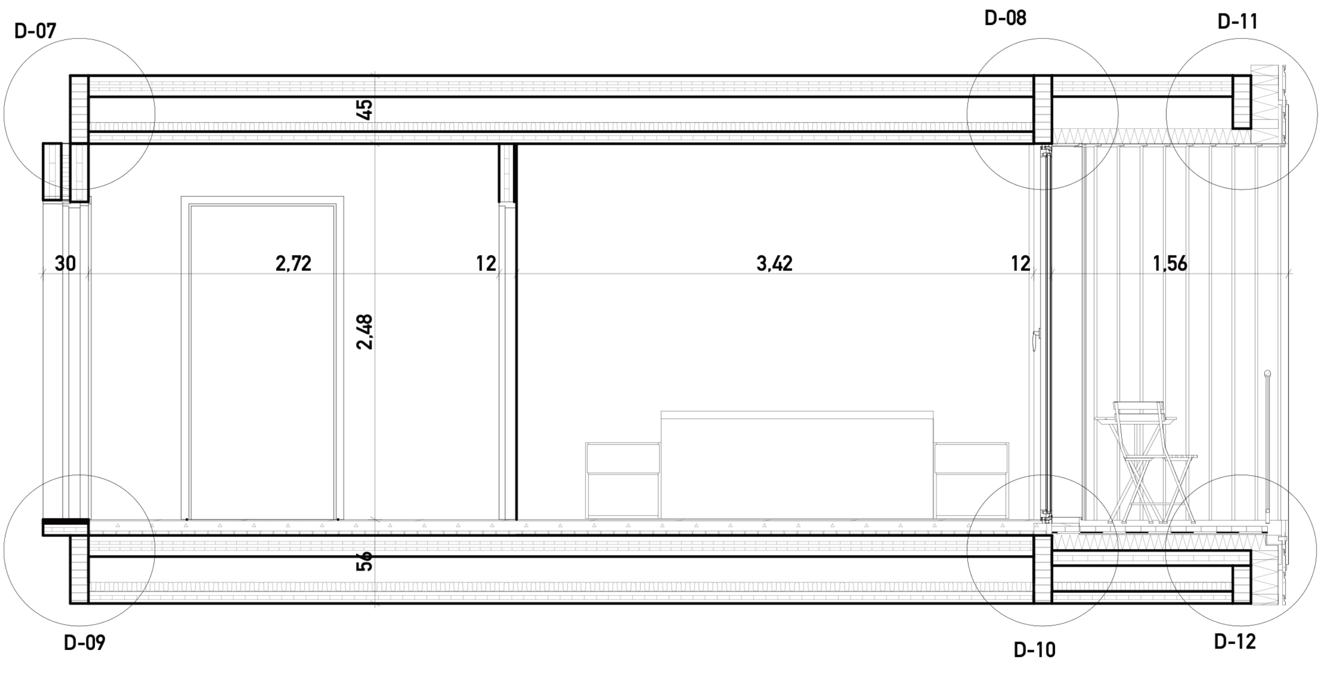
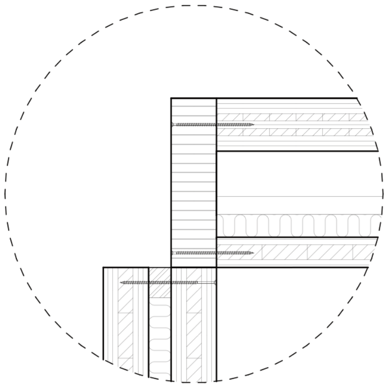




Longitudinal section



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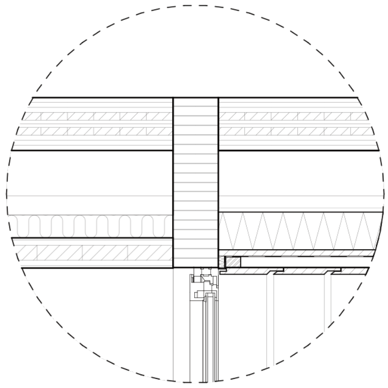

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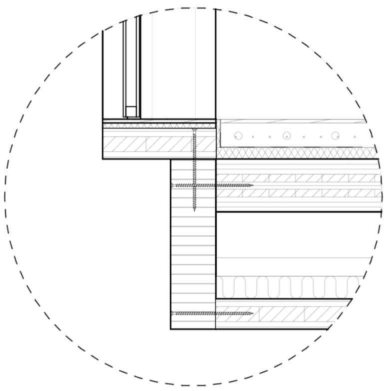

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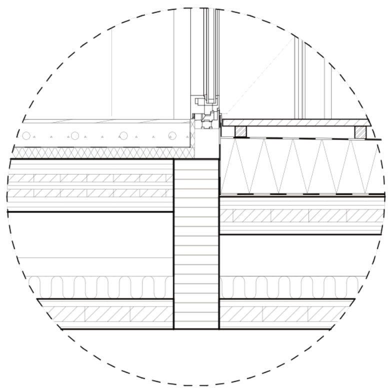

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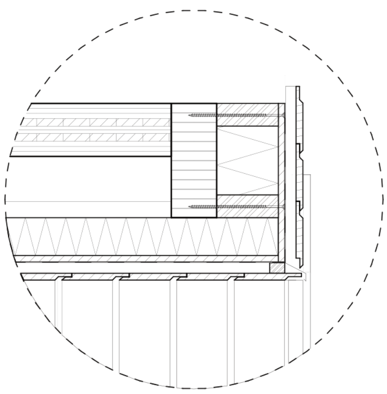

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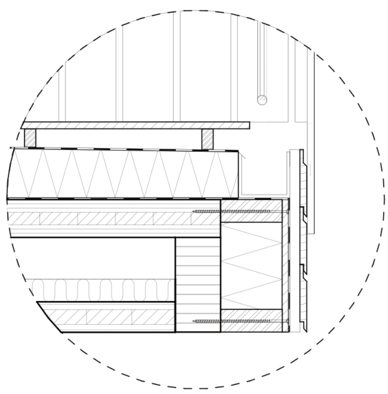


D-12

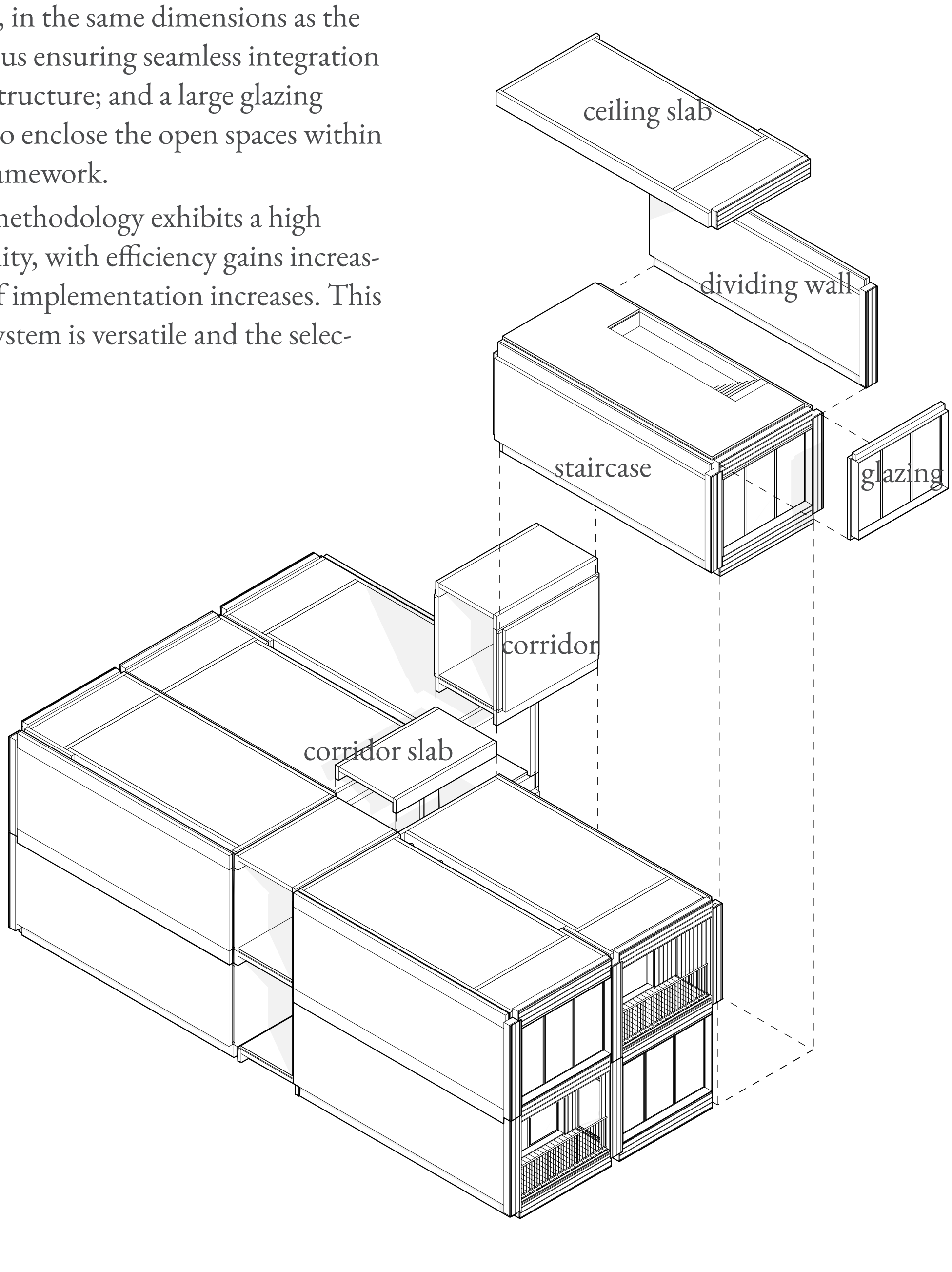
IV. PROJECT

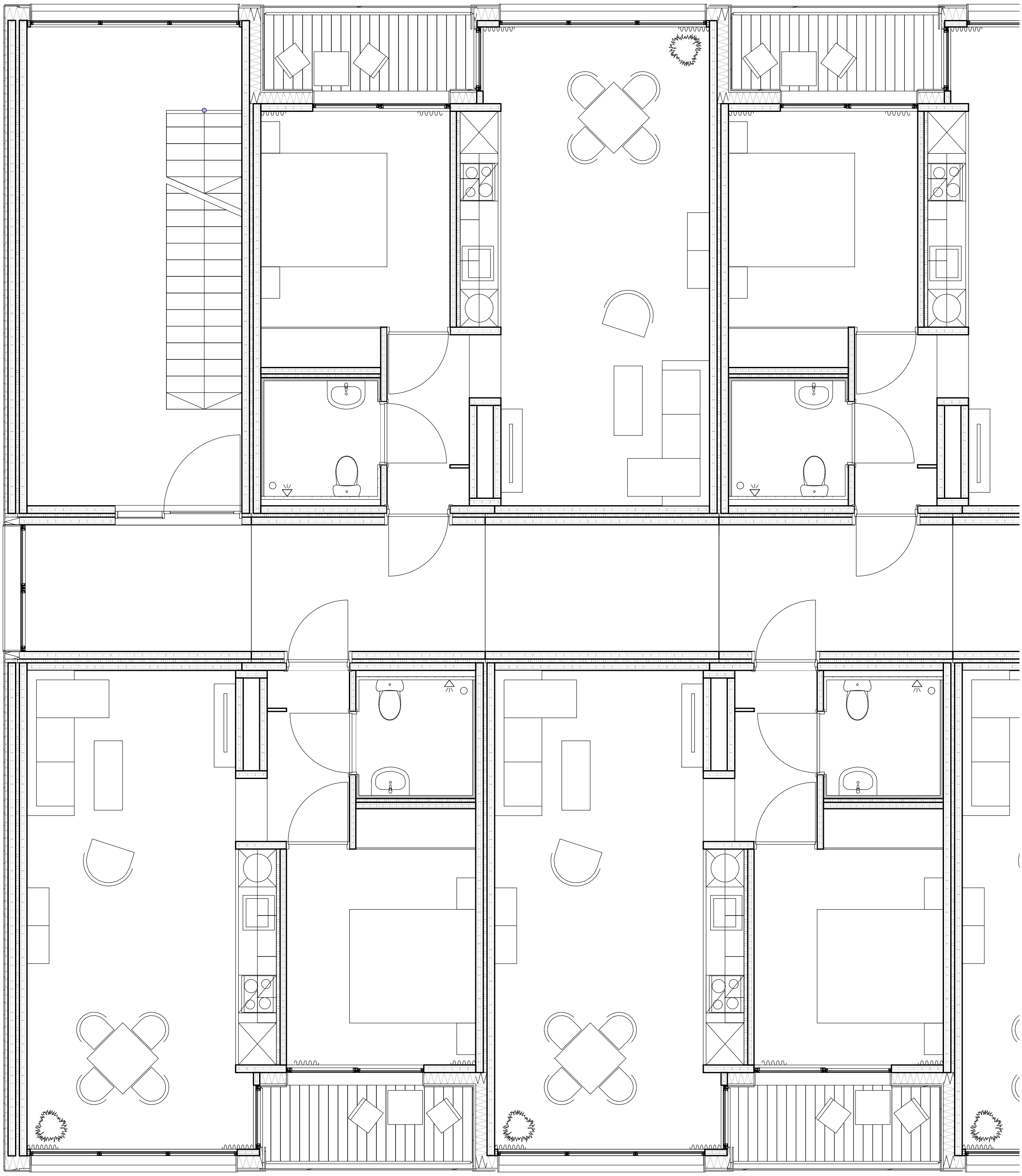
FROM MODULE TO BUILDING

In order to realise the conversion of the checkered module structure into a fully integrated building, it is necessary to incorporate additional modules, walls and slabs. These components represent only slight alterations of the substructure of the main apartment module. Beyond the main module, there exist five additional elements that can be prefabricated in order to facilitate the structural integrity of the building.

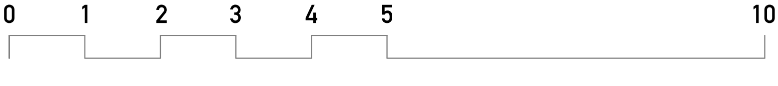
These include: an exterior wall and slabs, which serve to enclose or complete the checkered configuration of the main apartments; a corridor module coupled with a corridor slab that encapsulates the checkered layout of the corridors; a staircase module, in the same dimensions as the main module, thus ensuring seamless integration into the overall structure; and a large glazing panel, designed to enclose the open spaces within the checkered framework.

This structural methodology exhibits a high degree of scalability, with efficiency gains increasing as the scale of implementation increases. This building block system is versatile and the selection of foundation can be adapted based on the specific conditions of the site. It is even possible to build upon pre-existing structures. The building can support any roof type, though a flat roof is probably the most efficient option, as there is no need for an additional structure for its support. The building's structural shell can then be enveloped by insulation and a facade layer, thereby completing the construction of the entire building. The building is scaleable, which means its length is free to choose.





Floor plan



Section, Elevation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PROJECT SITE

Gibraltarvallen

As the project site, Gibraltarvallen was chosen. The site is currently used as a parking area and is adjacent to the Gibraltar guesthouse. Its surrounded by an assortment of residential, educational, and commercial structures, in a mix of architectural styles, including modernist educational buildings within Chalmers University and residential blocks in the Johanneberg area, which are characterised by their functionalist design language from the early to mid-20th century.
The typical buildings along Gibraltargatan are averagely six-storys high and in uniform orientation, in alignment with the street. Gibraltargatan is the main street to the east, which facilitates significant vehicle traffic. Vehicle access to the site is straightforward, possible from both the southern and northern directions, through the surrounding parking areas. Pedestrian and cycling infrastructure is present but varies in quality across the site, indicating room for enhancement to promote non-motorised mobility.
The site comprises a mixture of flat terrain and gently sloping hills. A number of alleys of mature trees are situated between different parking lot sections and Gibraltargatan, with existing greenery concentrated along street edges and in scattered green pockets. The green buffer alongside Gibraltargatan serves as a soft edge between the busy roadway and the parking lot.

Opportunities and Constraints

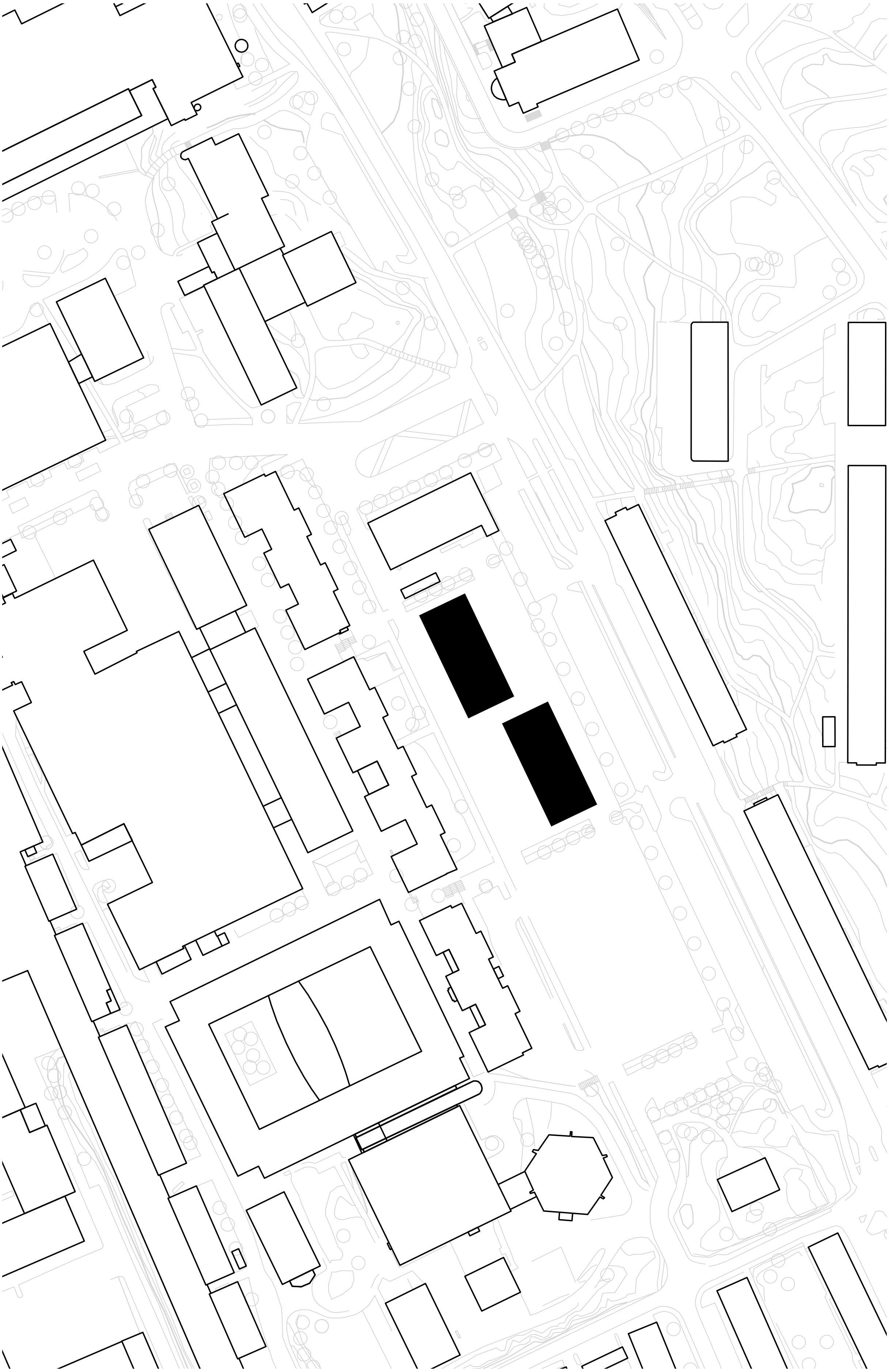
The area is characterised by a high level of activity during weekdays, largely due to the presence of the university, which attracts students, faculty members and visitors. Residential areas of Johanneberg, while quieter, contribute to a steady flow of local foot traffic and community engagement. Weekends see a notable decline in activity within the academic zones, presenting an opportunity to explore mixed-use developments that can sustain vibrancy throughout the week and the proximity to Chalmers University offers the potential for collaborations with research facilities and student housing. The existing green spaces have the potential to be developed into a cohesive network of public parks and green corridors, enhancing recreational options. The redevelopment of underutilised plots and surface parking areas presents an opportunity to create high-density, mixed-use zones that can cater to the academic population and local residents alike.
Traffic noise and pollution along Gibraltargatan could detract from the quality of pedestrian environments, necessitating noise mitigation and green buffer interventions. Furthermore, the limited existing vegetation and green public spaces require thoughtful planning to ensure that open spaces are integrated into new developments.

Redevelopment

Gothenburg has planned for the redevelopment of the area, with the intention of introducing new residential units, accommodations for students, service housing, and commercial spaces. This redevelopment plan includes adjustments to the traffic flow, street layouts, and public transportation facilities, with the objective of accommodating the forthcoming changes. Furthermore, Gothenburg has provided a set of guidelines for the construction of new buildings, which are expected to follow these directives closely. The guidelines set out the requirements for the forthcoming developments, ensuring that they meet the city's standards for new constructions within the Johanneberg area.

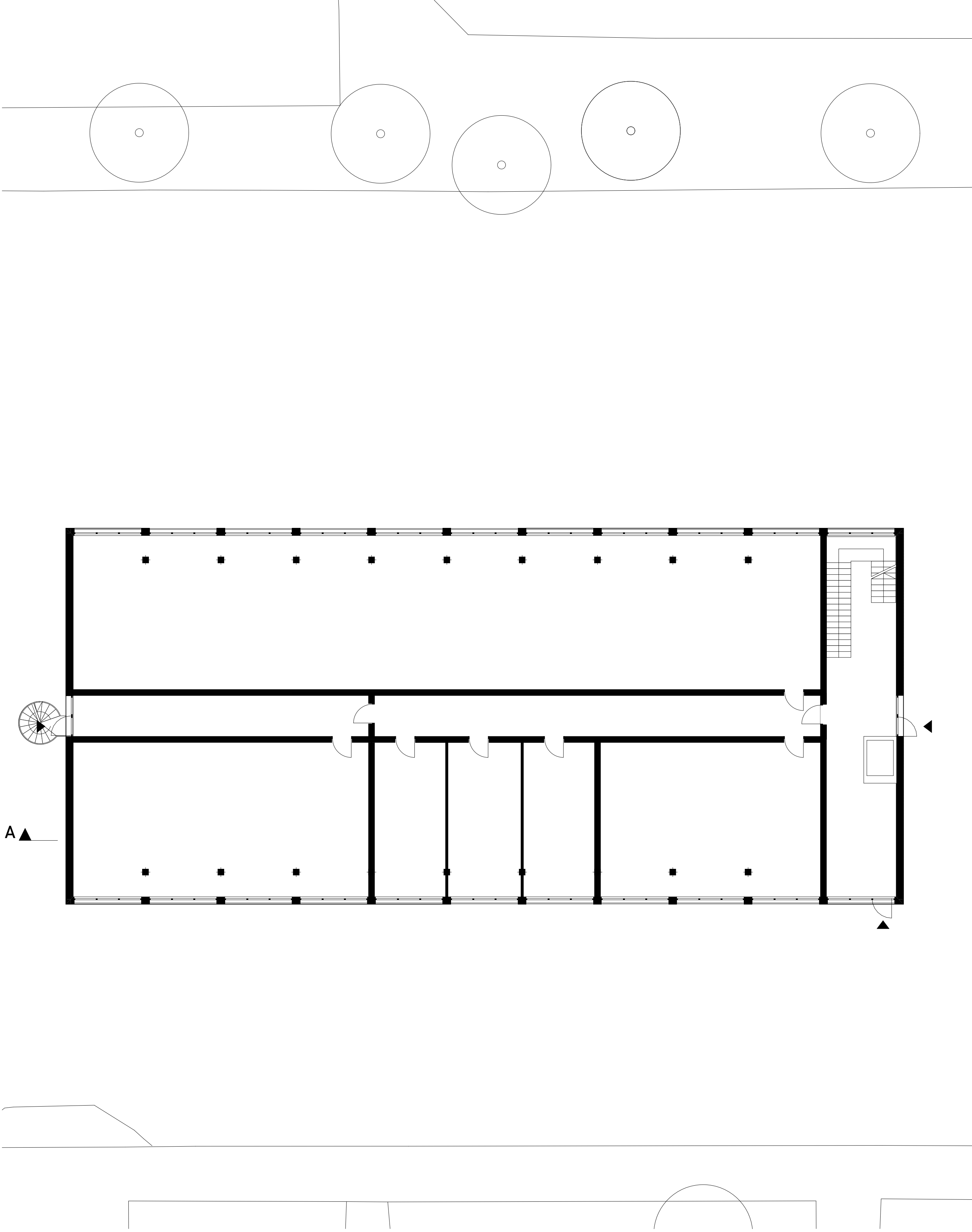
Site and location of the project

The building is planned on the northern parking lot of Gibraltarvallen, next to the Gibraltar Guesthouse, follows the clear axis of the surrounding buildings and is placed next to Gibraltargatan. The alley to the east and the building itself serve as a buffer to the busy road, creating an open but sound protected urban square. The ground floor is not planned modular, creating open spaces for commercial and educational use cases and lifting the residential unit one storey up, thus increasing privacy. The height of the building is 20 meters, matching its surrounding context.

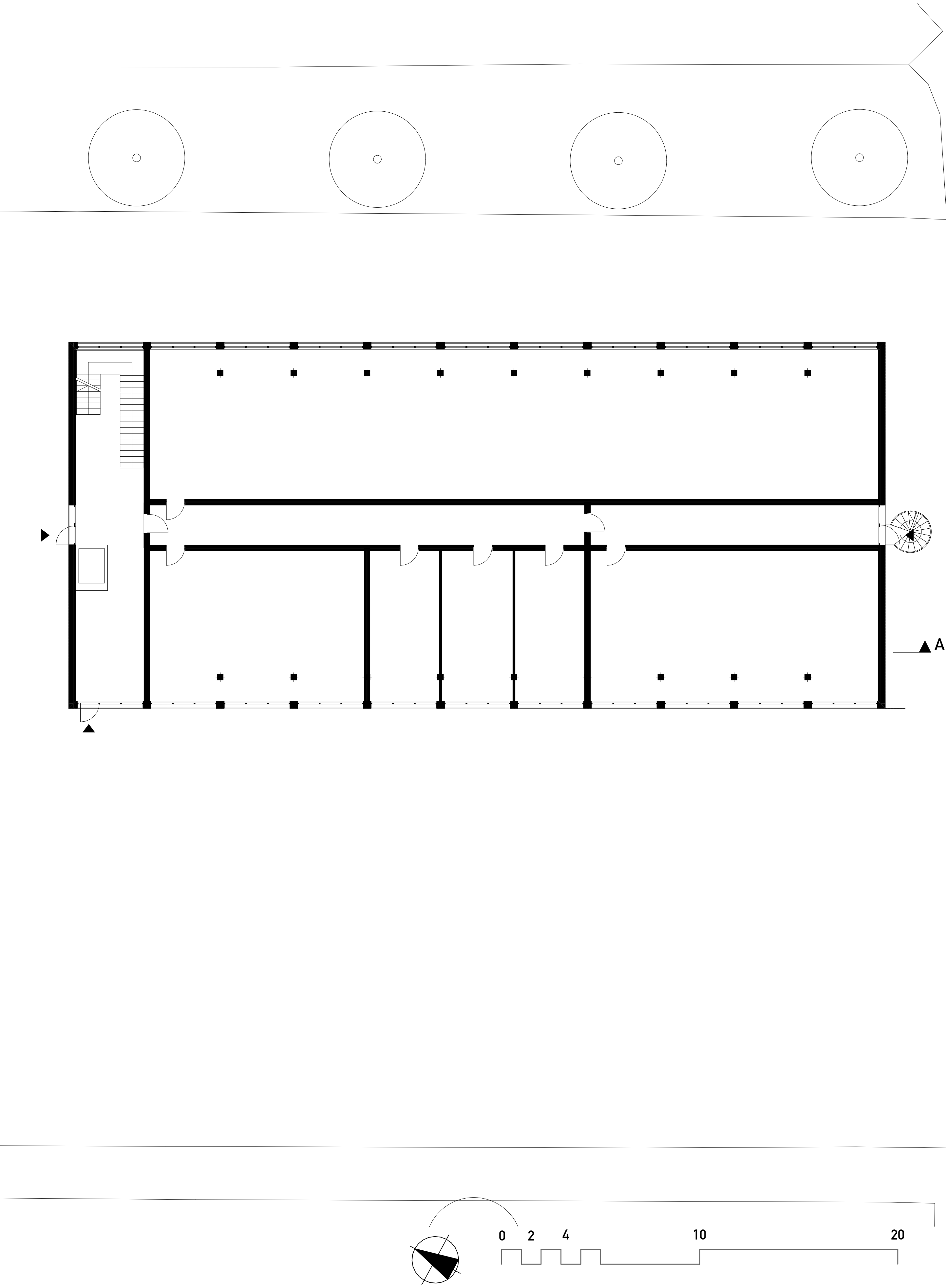


Site plan

BUILDING PLANS



Ground Floor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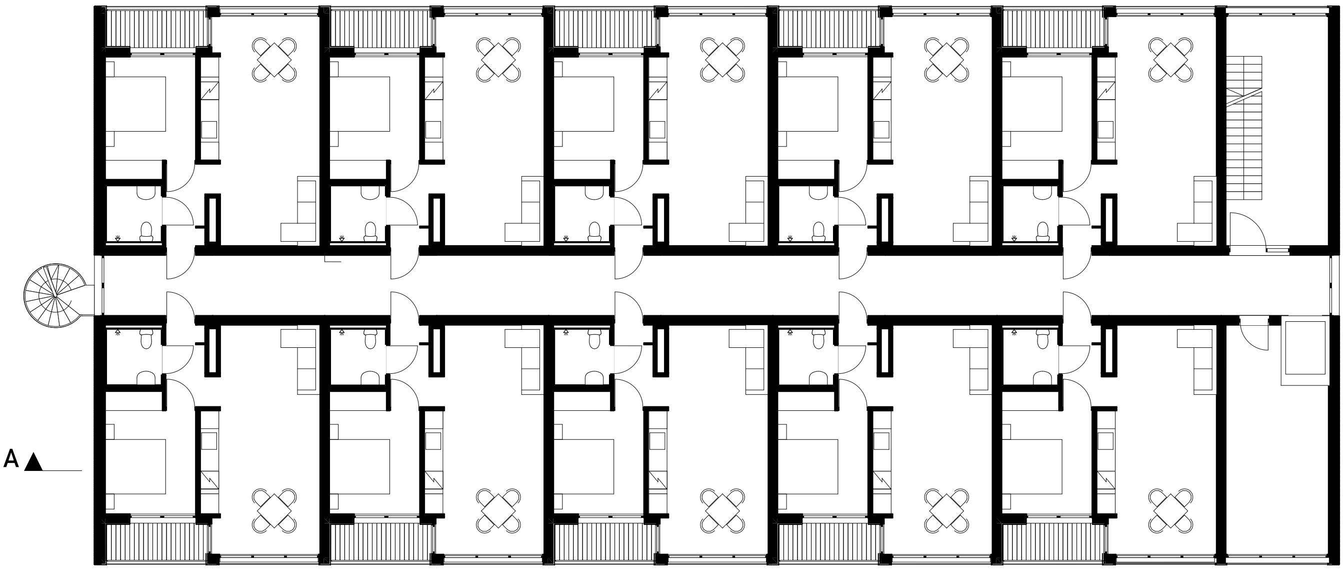
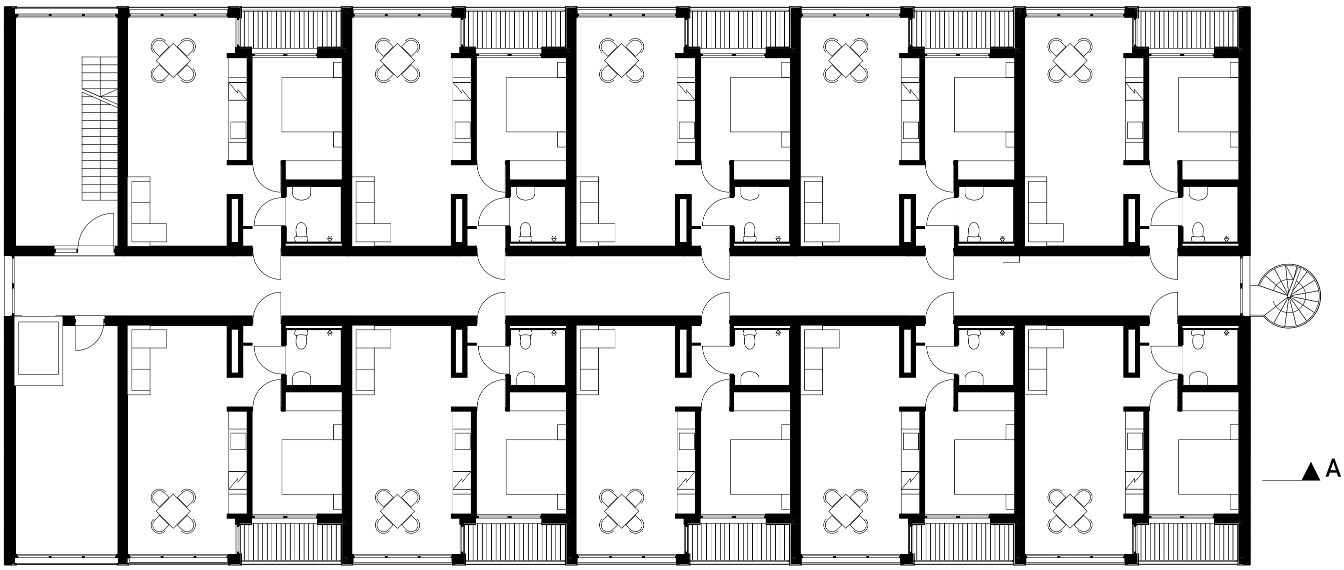


2. Floor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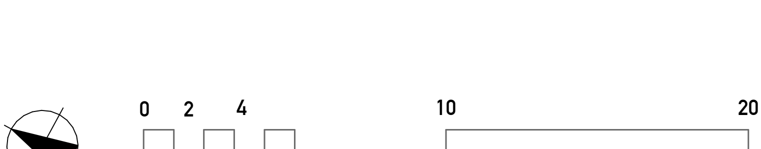
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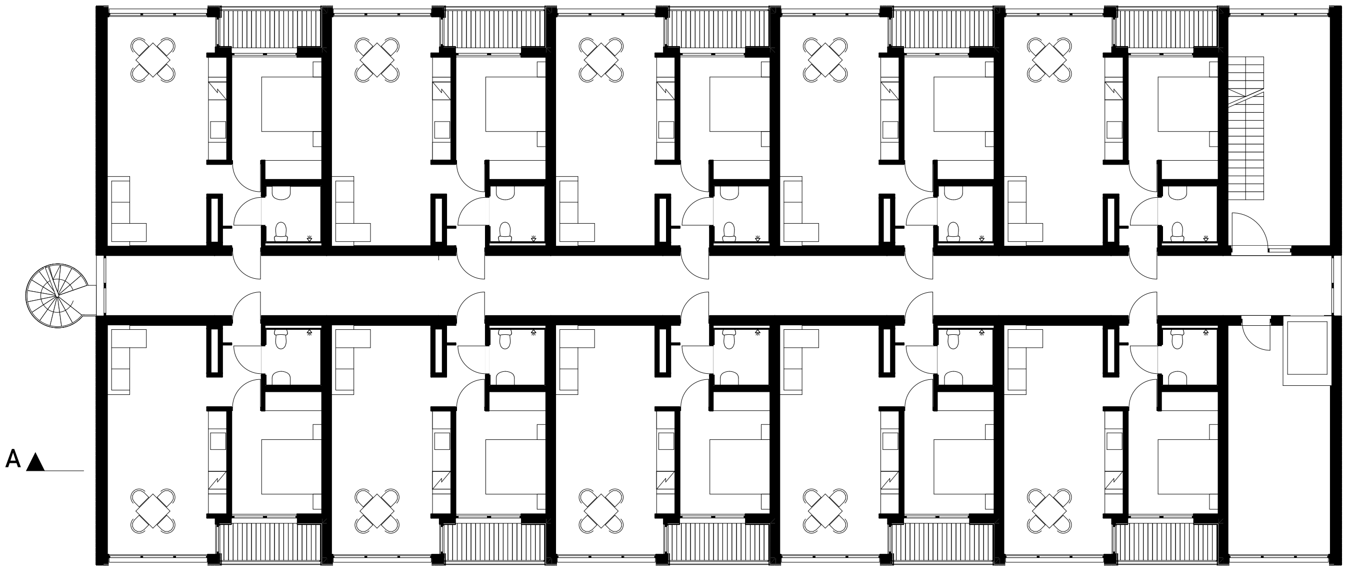
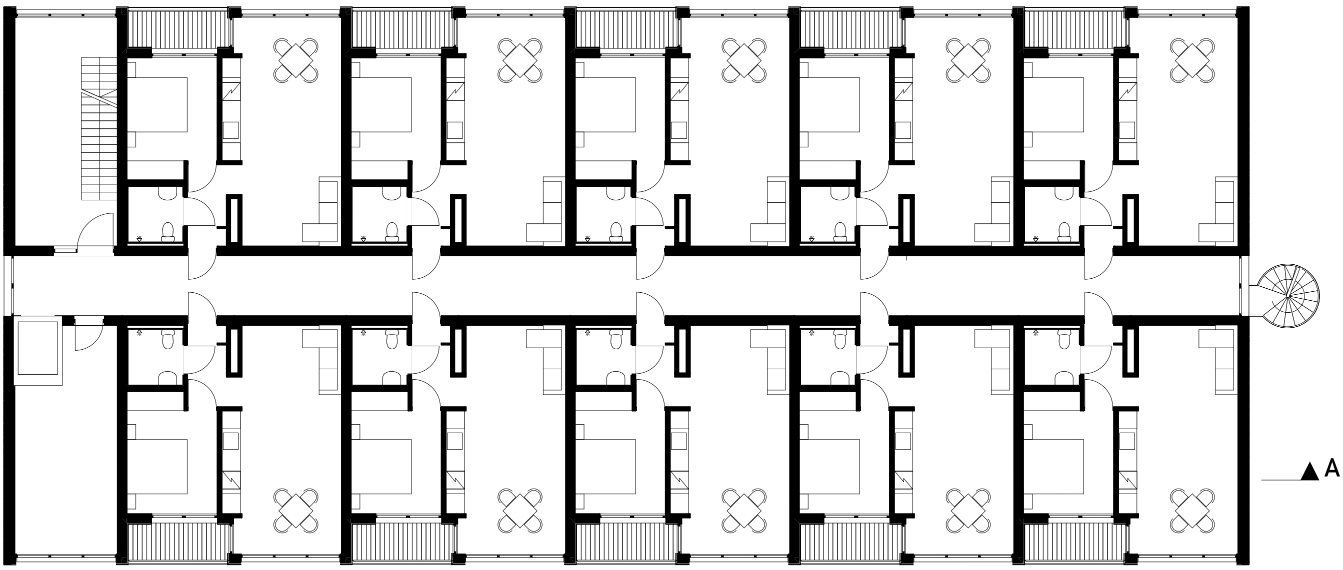


3. Floor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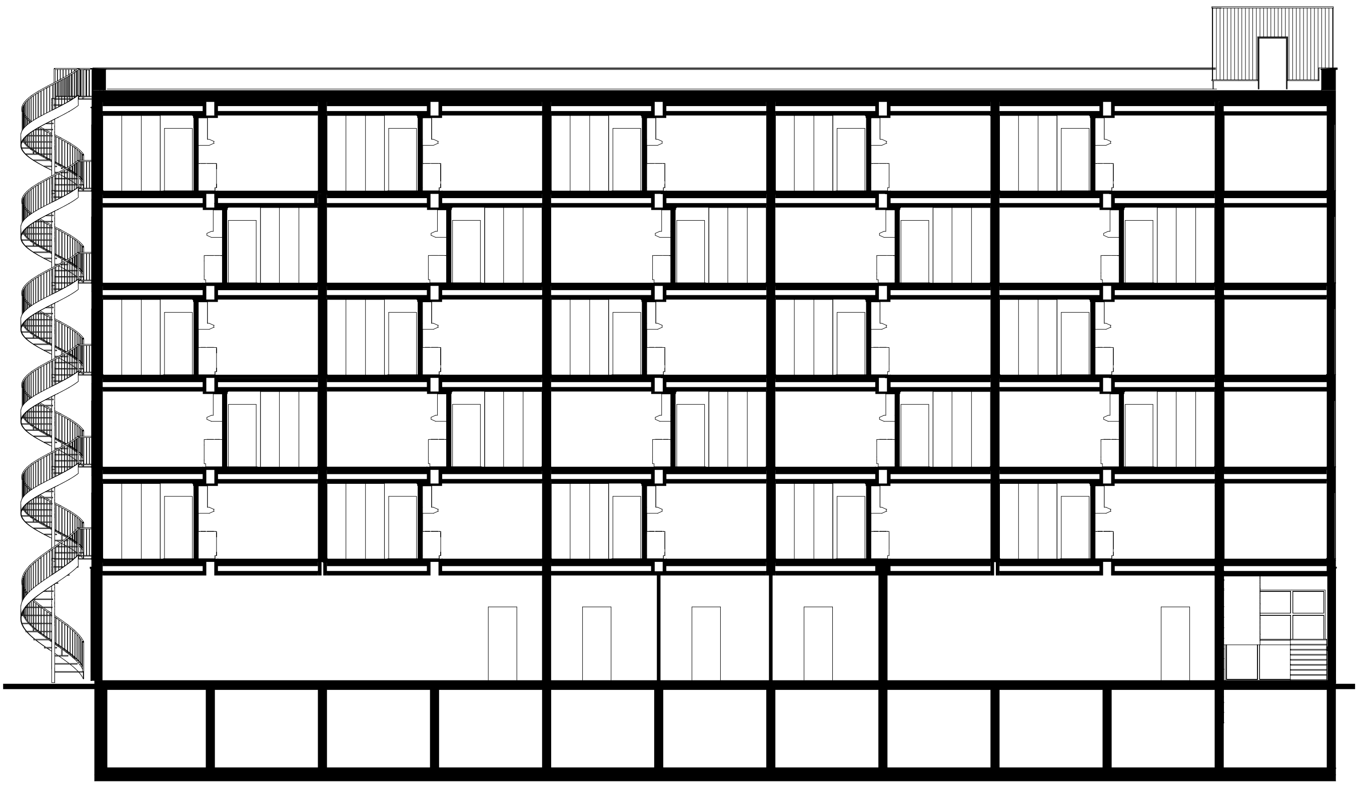
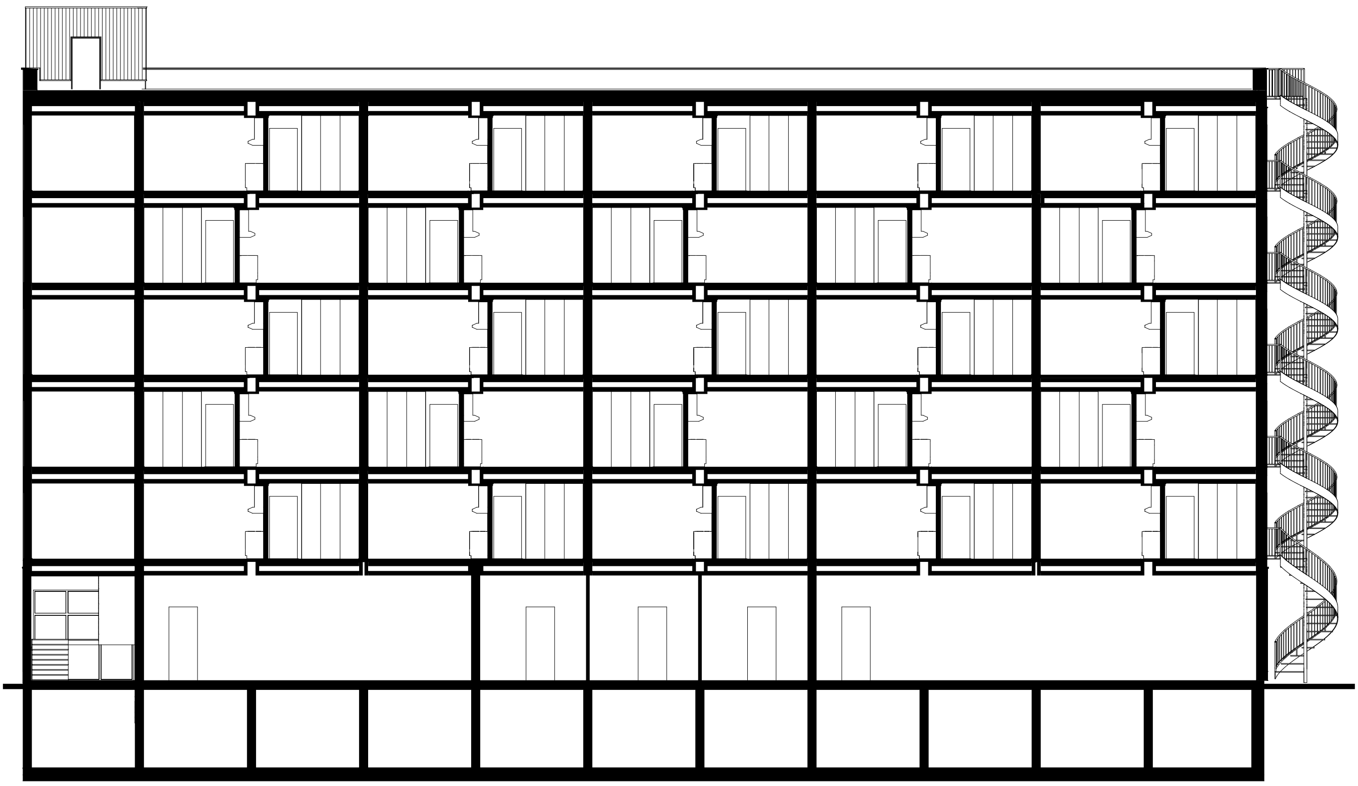
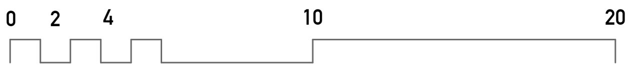


Elevation East, Section A-A

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V

V. DISCUSSION

Discussion

This thesis commenced an exploratory investigation into the potential of modular construction in urban housing, with the development of a prototype inspired by the checkered stacking system conceptualised in the Sneglehusene project serving as the catalyst.

Reflection on the Prototype

The iterative design process has resulted in a prototype that, although detailed, remains conceptual in nature. This critical reflection serves to highlight a significant insight of the thesis: the journey from conceptualisation to a fully realised, feasible modular construction system is full of complexities that transcend architectural design into the realms of engineering and materials science, and modular expertise.

The prototype's development had the ambition to refine and practically apply the notion of checkered stacking to create spatially efficient modular housing. Nevertheless, despite the comprehensive design, the prototype exists in a state of transition between the conceptual and the realisable. The prototype's actualisation in the physical world remains uncertain, thereby highlighting a gap between theoretical innovation and practical application that is often encountered in architectural research.

This uncertainty is not and indication of failure, but rather a reflection of the thesis's exploratory ethos. The prototype demonstrates the difficulty of crossing the threshold between innovative design and the practical limitations of modular construction. Although the prototype may not be immediately realisable, it serves as an exemplar of the potential of modular construction to evolve and adapt to contemporary urban challenges.

If the prototype is realisable, the advantages and challenges would have to be reevaluated by an expert. But according to my own research, the prototype has significant logistical, structural and spacial advantages.

Role of Experts and Freedom of Design

The decision to develop the prototype without direct input from modular construction experts was a double-edged sword. This approach permitted unlimited creative exploration, unconstrained by the immediate limitations of current construction practices. This freedom was instrumental in pursuing bold and innovative design solutions that challenge conventional modular construction paradigms.

However, this approach also entailed navigating the complex landscape of modular construction without the guidance of expert knowledge, which might have provided a more solid foundation for the prototype in. Upon reflection, the integration of expert consultations could prove beneficial in future iterations of the project. This would enable the blending of creative ambition with pragmatic insights, thereby facilitating the bridging of the gap between concept and construction.

Theoretical Framing

The incorporation of theory at the midpoint of the thesis provided a foundational framework that helped to guide the design towards more grounded solutions. Theory served as a reflective surface, prompting questions regarding the practicality, sustainability, and urban integration of the design, thereby sharpening the focus of the design process.

Site Selection

The selection of Johanneberg was a pragmatic decision, with the objective of contextualising the prototype within a familiar urban setting. Although planning according to the regulations and guidelines as closely as possible, the placement of the project is supposed to serve as a proof of concept, showcasing the size and architectural qualites of the modular system.

Although it served its purpose, a more thorough and intentional site analysis could further enhance the prototype's relevance and applicability. This would involve tailoring the design to meet specific urban conditions and challenges.

Presentations and Feedback

The feedback received during the presentation phase was of great value, as it highlighted several aspects that had been overlooked and provided numerous suggestions for improvement.

One significant area of feedback focused on the urban planning of the building, emphasising the need for a better integration within the urban scale to enhance the visual impact on the site. It was suggested that the building should be divided into two parts to avoid a monolithic appearance and create a more aesthetically pleasing structure.

Furthermore, suggestions included the refinement of loggias and the incorporation of cantilevered balconies to extend outdoor areas. These modifications would not only improve the aesthetic appeal but also enhance the building's functionality by increasing daylight in the rooms while providing necessary shading for the open spaces.

Additionally, recommendations were made to experiment with the prototype on different sites, particularly those with existing buildings. This approach would better demonstrate the advantages of the modular construction technique in diverse urban contexts. The feedback included a wealth of reference projects and architects to study, which could provide further inspiration and guidance for the development of the prototype.

Another advice involves mentioning the rationale behind each decision, thereby demonstrating that choices were not merely the most rational but were also informed by thorough reasoning and consideration. Such documentation is essential for validating the project's outcomes and for future reference.

While it was not possible to address all the feedback within the current academic timeframe, these comments and suggestions will be instrumental in guiding the continued development of the prototype. They provide a clear roadmap for further refinement.

Conclusion

This thesis does not conclude the discourse on if stacking modules in a checkered pattern can improve modular construction; rather, it contributes a new perspective to ongoing challenges. The prototype, with all its innovations and imperfections, serves as a catalyst for further investigation. This underscores the importance of a symbiotic relationship between theory and practice, creative freedom and expert knowledge, and conceptual innovation and practical realisation. The thesis thus advocates for a continued evolution of modular construction, with the aspiration of merging architectural imagination with the concrete realities of urban development and modular construction.

VI

VI. REFERENCES

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FIGURES

Figure 1. Hjortshoj, R. (s.d.) Dong, Dortheavey Residence, by BIG Copenhagen, Denmark. At: https://www.rasmushjortshoj.com/architectural-photo-02/dong-dortheavej-residence?itemId=iuagi1q00oqblnl7urk6d540mrthm7 (Accessed on 5 April 2024)

Figure 2. Ott, P. (s.d.) The production in Kalwang (Die Produktion in Kalwang). At: https://www.paul-ott.at (Accessed on 5 March 2024)

Figure 3. Kaufmann, H. (2017) Prefabrication of linear, flat and spatial elements.

Figure 4. BIG. (s.d.) Sneglehusene Plan 1 Bedroom Apartment. At: https://www.designverse.com.cn/en/article/space/444642 (Accessed on 28 April 2024)

Figure 5. Hjortshoj, R. (s.d.) Sneglehusene Housing. At: https://www.archdaily.com/989940/sneglehusene-housing-big/633b29407120027a9adb0700-sneglehusene-housing-big-photo?next_project=no (Accessed on 20 April 2024)

Figure 6. BIG. (s.d.) Sneglehusene Ground Floor Plan. At: https://www.designverse.com.cn/en/article/space/444642 (Accessed on 28 April 2024)

Figure 7. Brendeland, G. and Kristoffersen, O. (2005) Svartlamoen Ground Floor. At: https://hicarquitectura.com/2020/04/brendeland-kristoffersen-svartlamoen-housing-complex/ (Accessed on 5 April 2024)

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Figure 9. Garcés, T. (2020) Svartlamoen housing complex. At: https://hicarquitectura.com/2020/04/brendeland-kristoffersen-svartlamoen-housing-complex/ (Accessed on 28 April 2024)

Figure 10. Musch, J. (2005) Svartlamoen housing bare CLT walls. At: https://hicarquitectura.com/2020/04/brendeland-kristoffersen-svartlamoen-housing-complex/ (Accessed on 5 April 2024)

Figure 11. Hjortshoj, R. (s.d.) Sneglehusene Housing Interior Step. At: https://www.archdaily.com/989940/sneglehusene-housing-big/633b29407120027a9adb0700-sneglehusene-housing-big-photo?next_project=no (Accessed on 20 April 2024)

STUDENT BACKGROUND

Contact

name:	Paul Müller-Zitzke
email:	paul.muezi@gmail.com

Hello

my name is Paul, I am 24 years old and a final year architecture graduate at Chalmers, originally from Germany.

Before starting my studies, I worked as a carpenter for 3 months which gave me a lot of insight into the practical side of the building process. I completed my Bachelor degree in HAWK Hildesheim in 2022. While studying, I was working part time in the architectural office NGA in Hannover.

Currently I am studying Architecture and Urban Design at Chalmers and will have completed my Master degree in June 2024.

Personal information

name:	Paul Müller-Zitzke
date of birth:	1999, May 29th
nationality:	German

Education

Graduation - gymnasium *Wilhelm-Raabe Schule Hannover*	2018
Internship - carpentry *Holzbau Hurrle Gaggenau*	12 weeks, 2019
Studies - Architecture B.A. *HAWK Hildesheim*	2019-2022
Internship - archi. office *Nehse & Gerstein Architekten*	12 weeks, 2021
Studies - Arch. & Urban Design M.Sc. *Chalmers University of Technology*	2022-2024

Toolset

Archicad	●●●●●
Blender	●●●●
Pixelmator	●●●●●
Affinity Publisher	●●●●●
Affinity Designer	●●●●●
Word	●●●●●
Powerpoint	●●●●●
Excel	●●●
QGIS	●●●
California Pro	●●●●
Rhino	●●●●
Grasshopper	●●●●
Midjourney	●●●
Lookx.ai	●●●●

Volunteering

leadership team *youth group „Free Generation“*	2016-2022

Languages

German	●●●●●
English	●●●●●
Swedish	●●●
Spanish	●

Focus

I would describe myself as a quick learner and I like to use that skill to learn new programs that could improve my workflow and increase my skill set. I like to work efficiently and quickly.

I enjoy working on projects that follow a clear structure or logic. Having studied at a technical university in Germany, I am also interested in drawing details and would like to develop this skill further.

Chalmers University of Technology
Department of Architecture & Civil Engineering
ACEX35 Building Design and Transformation 2024