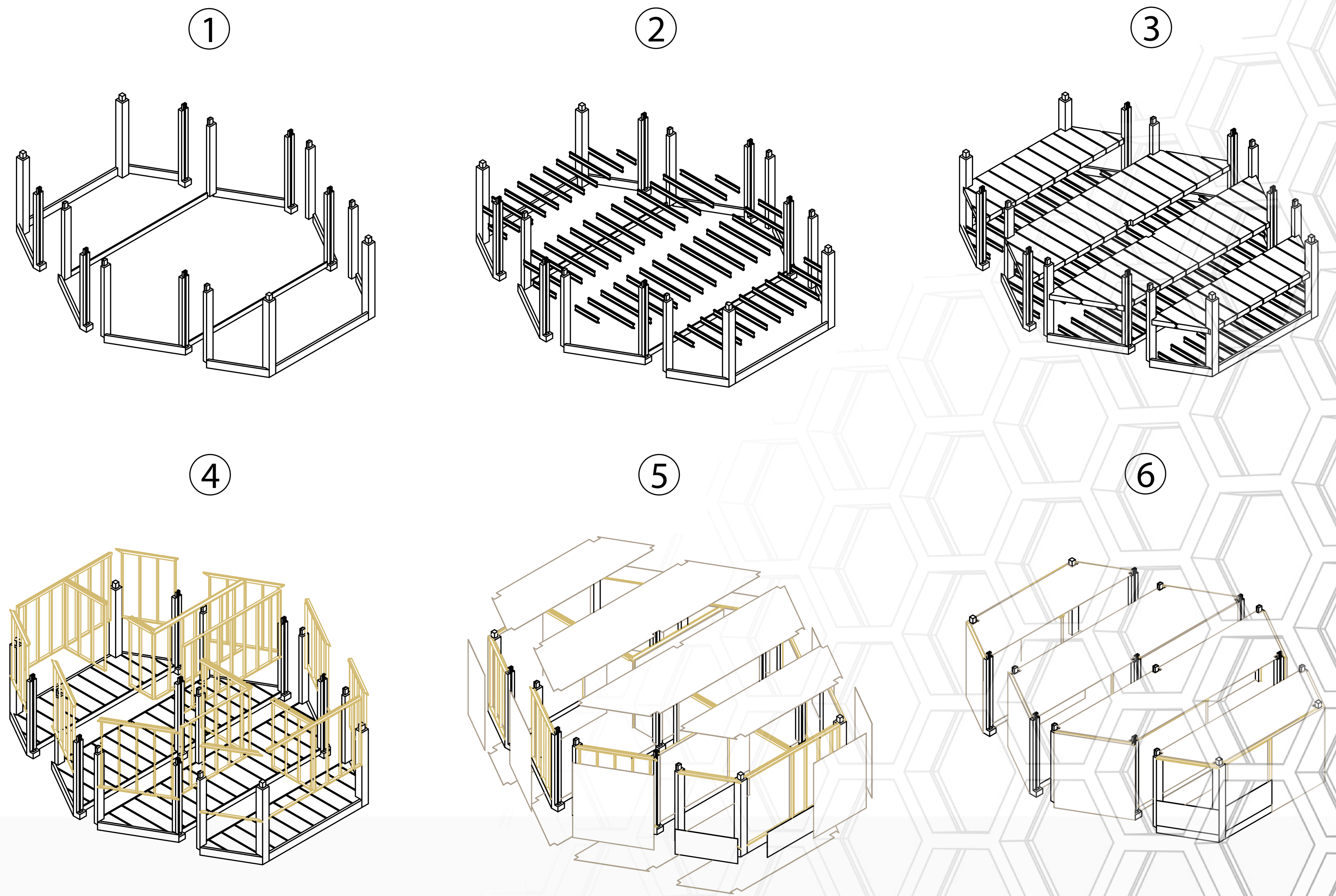
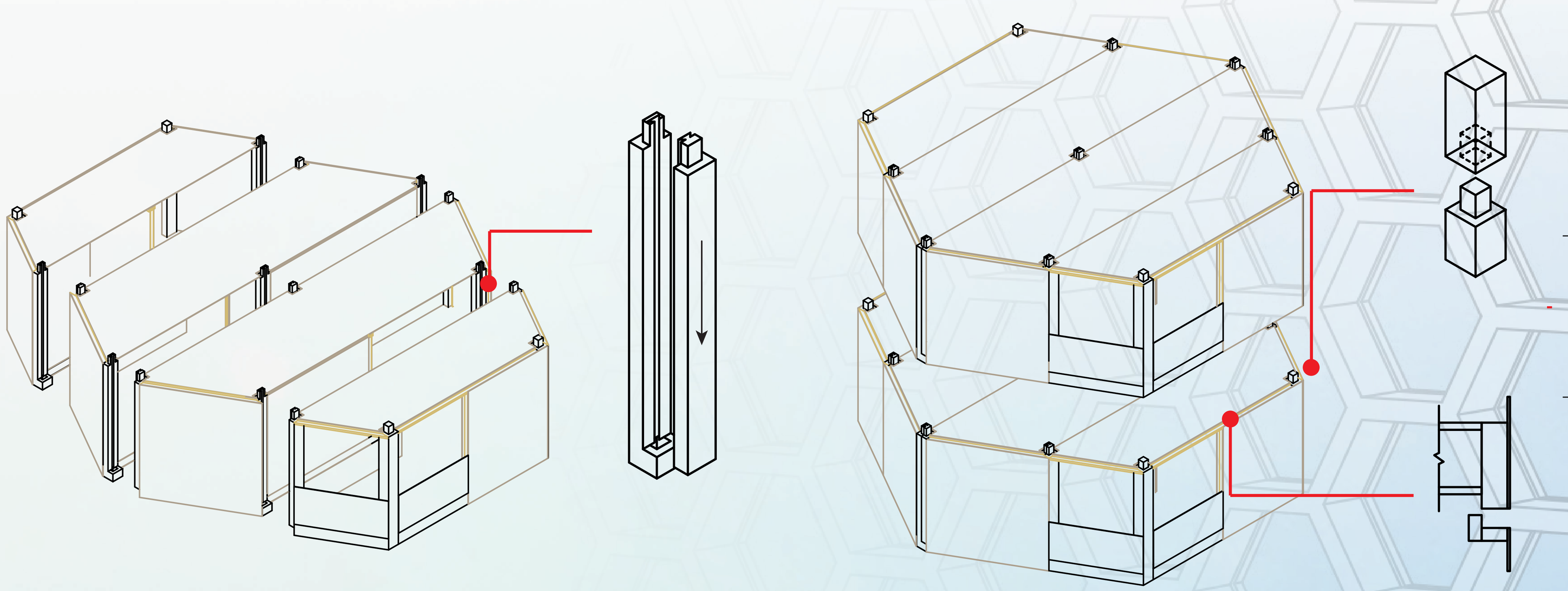
HONEYCOMB HOUSING

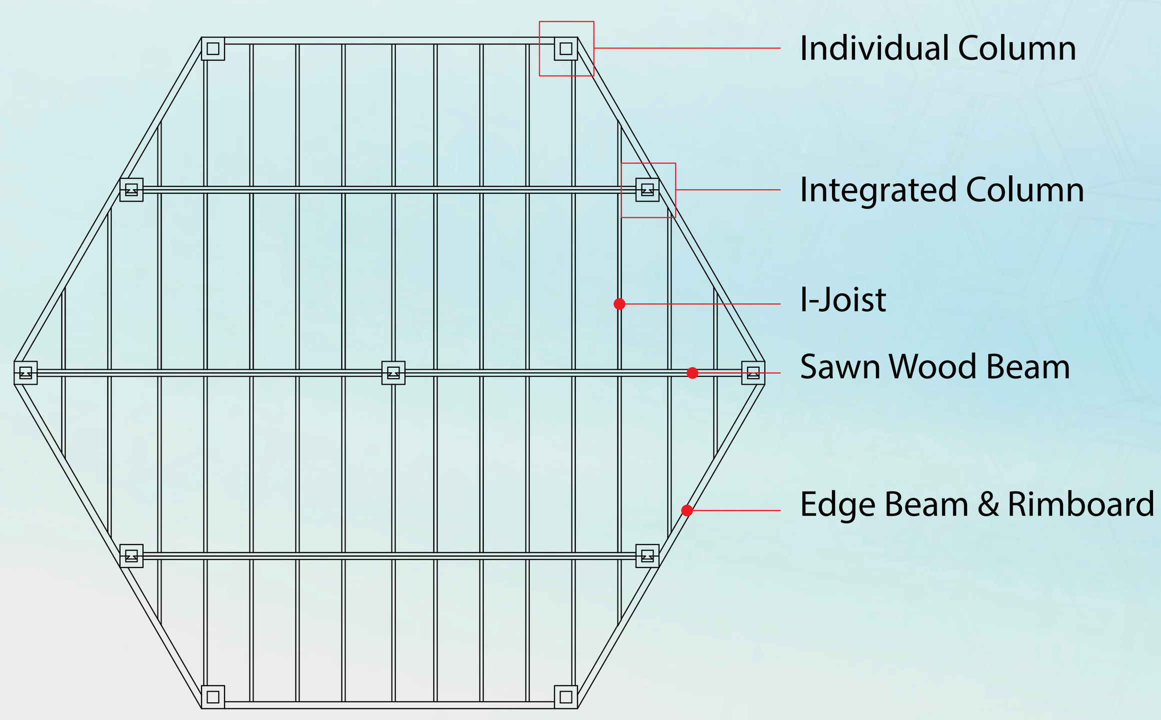
A Future Housing Chioce of Vitality, Sustainability and Flexibility



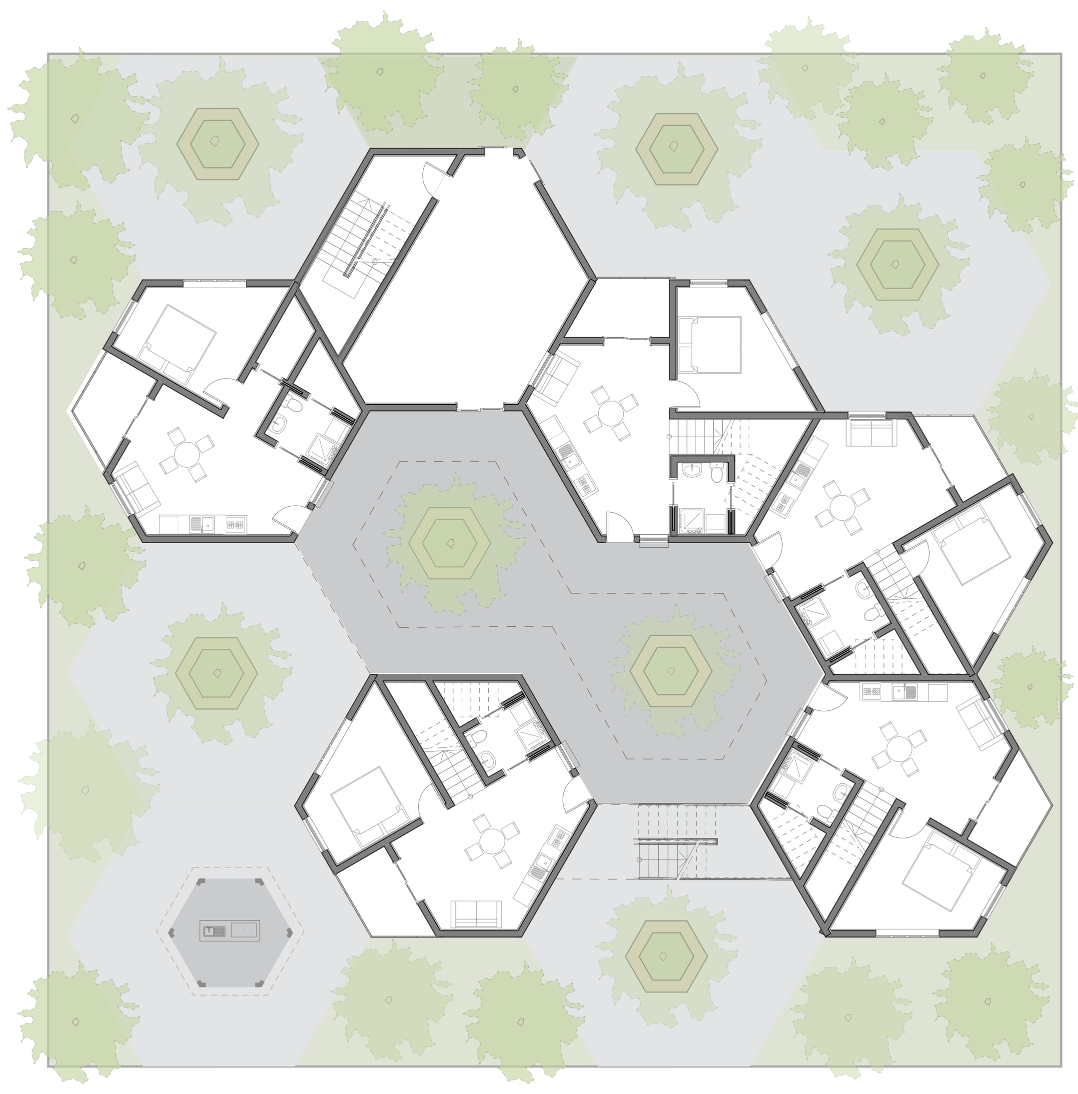
OFF-SITE CONSTRUCTION



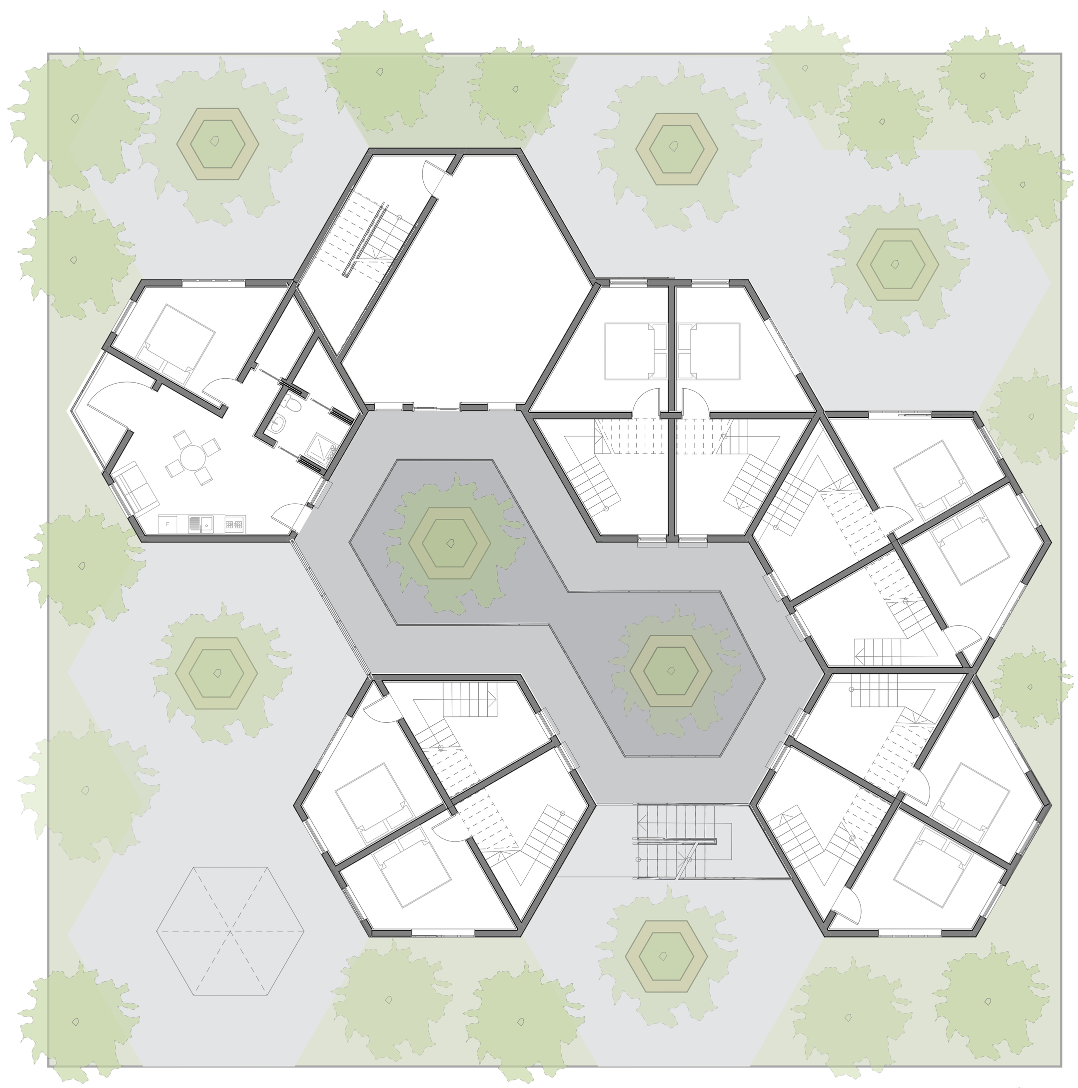
ON-SITE CONSTRUCTION



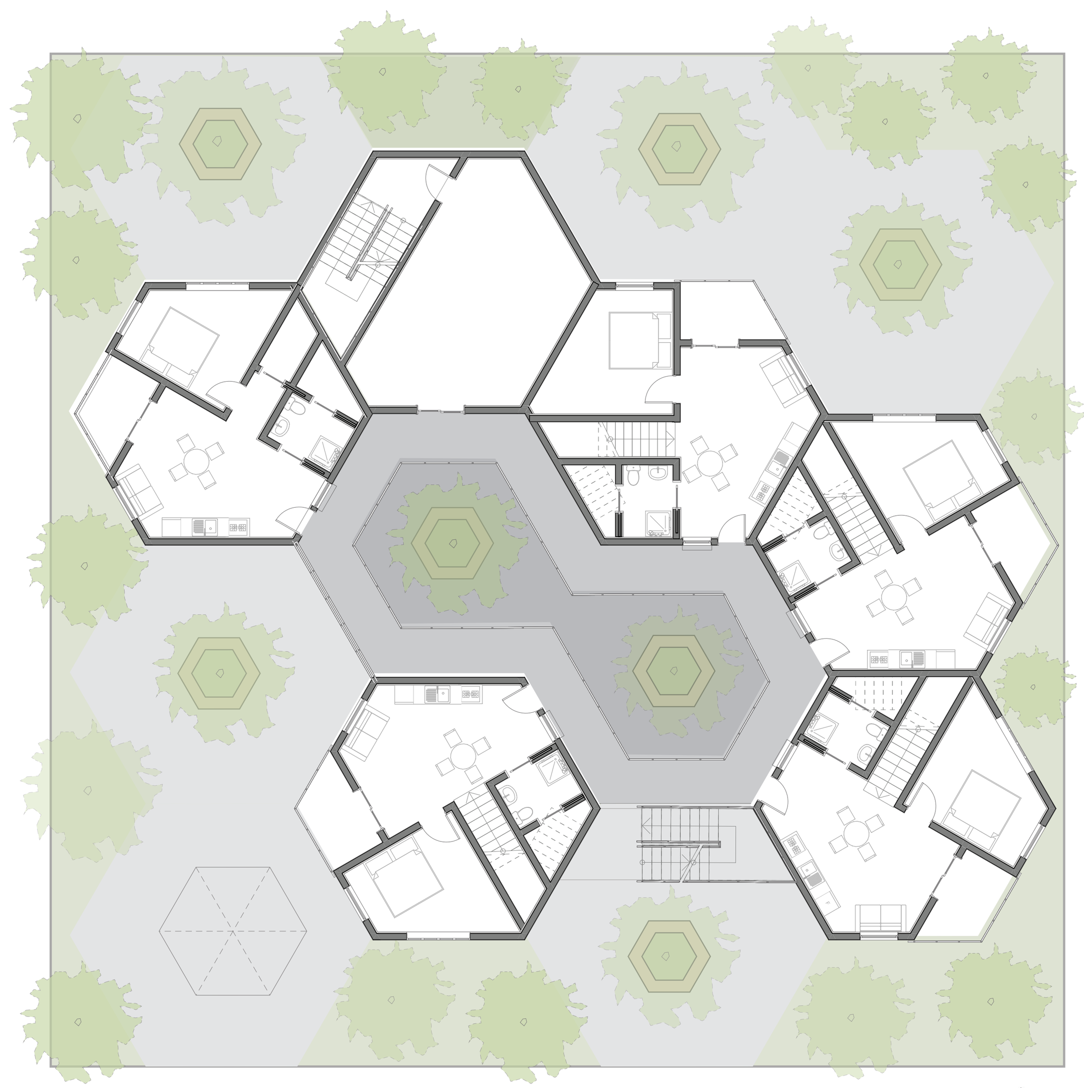
FRAMEWORK STRUCTURE



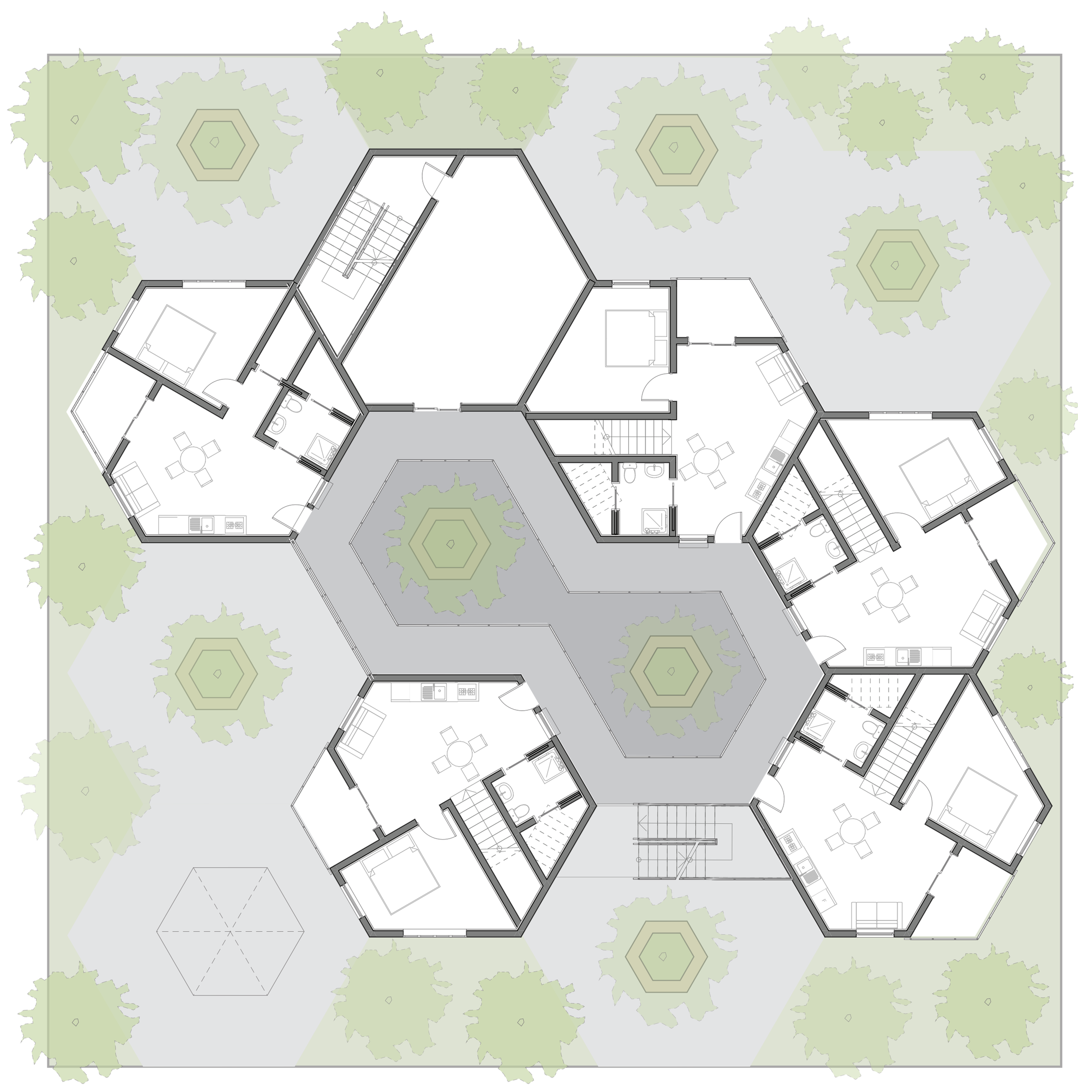
GROUND FLOOR 1 : 200



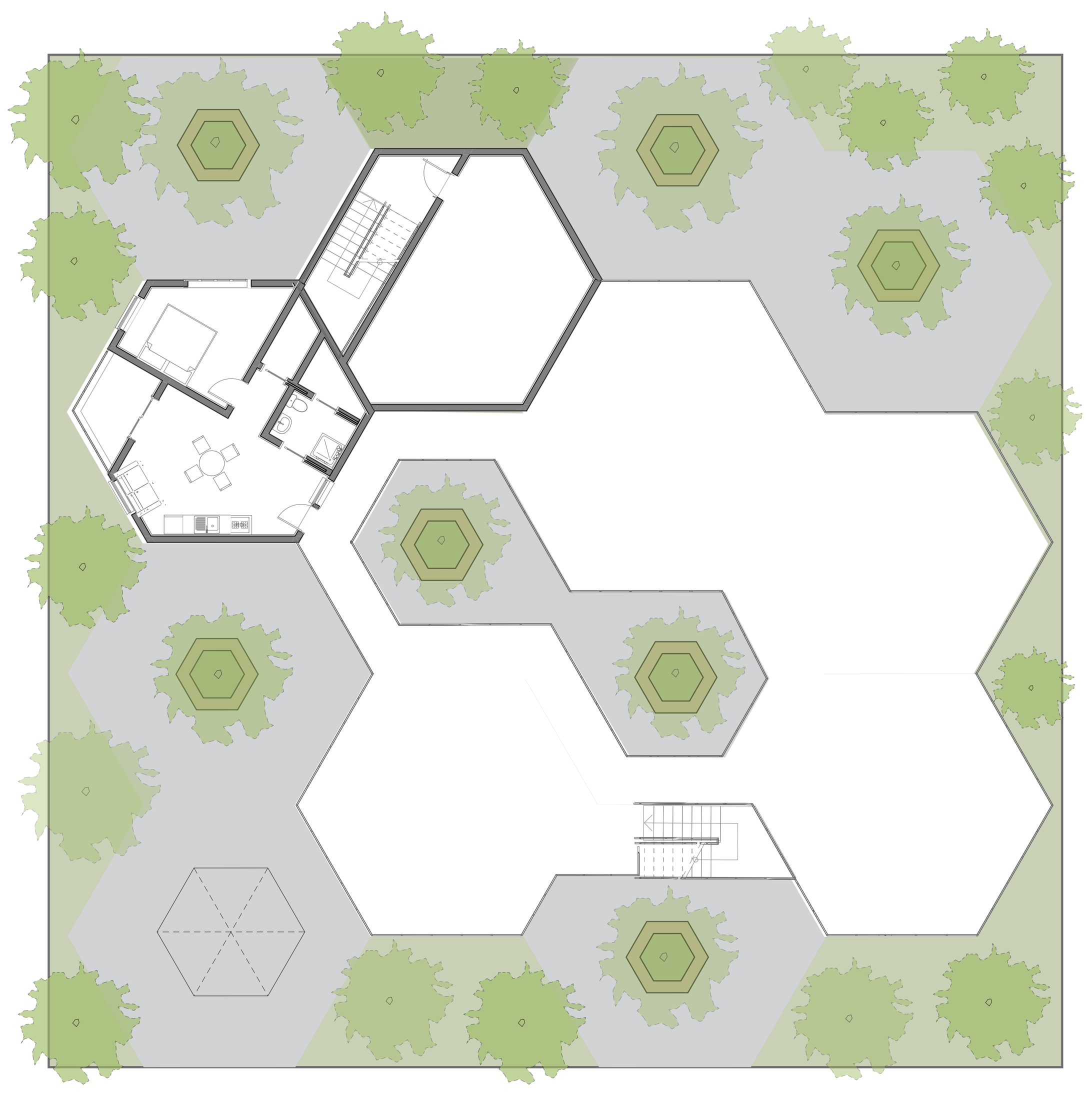
FIRST FLOOR 1 : 200



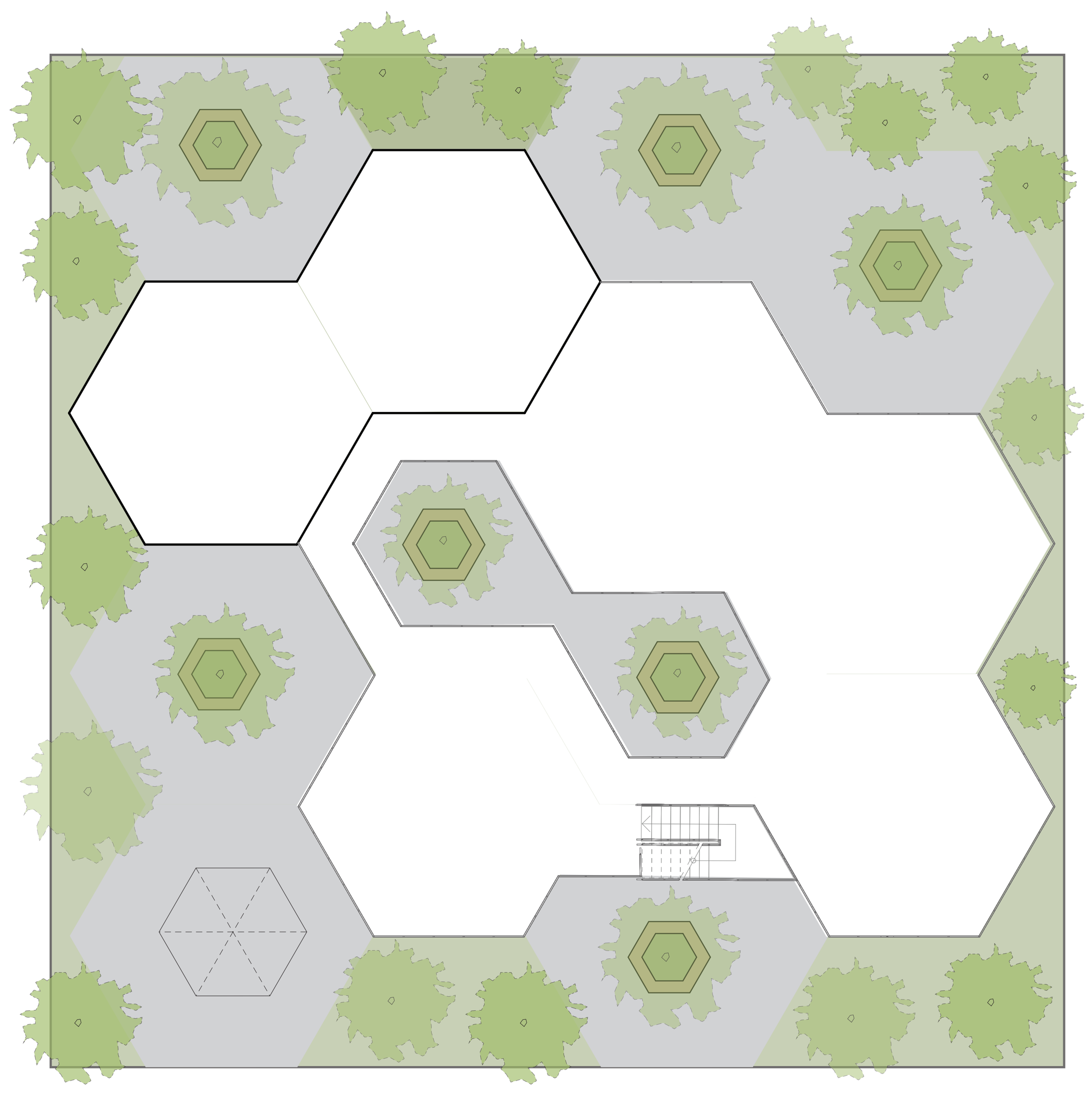
SECOND FLOOR 1 : 200



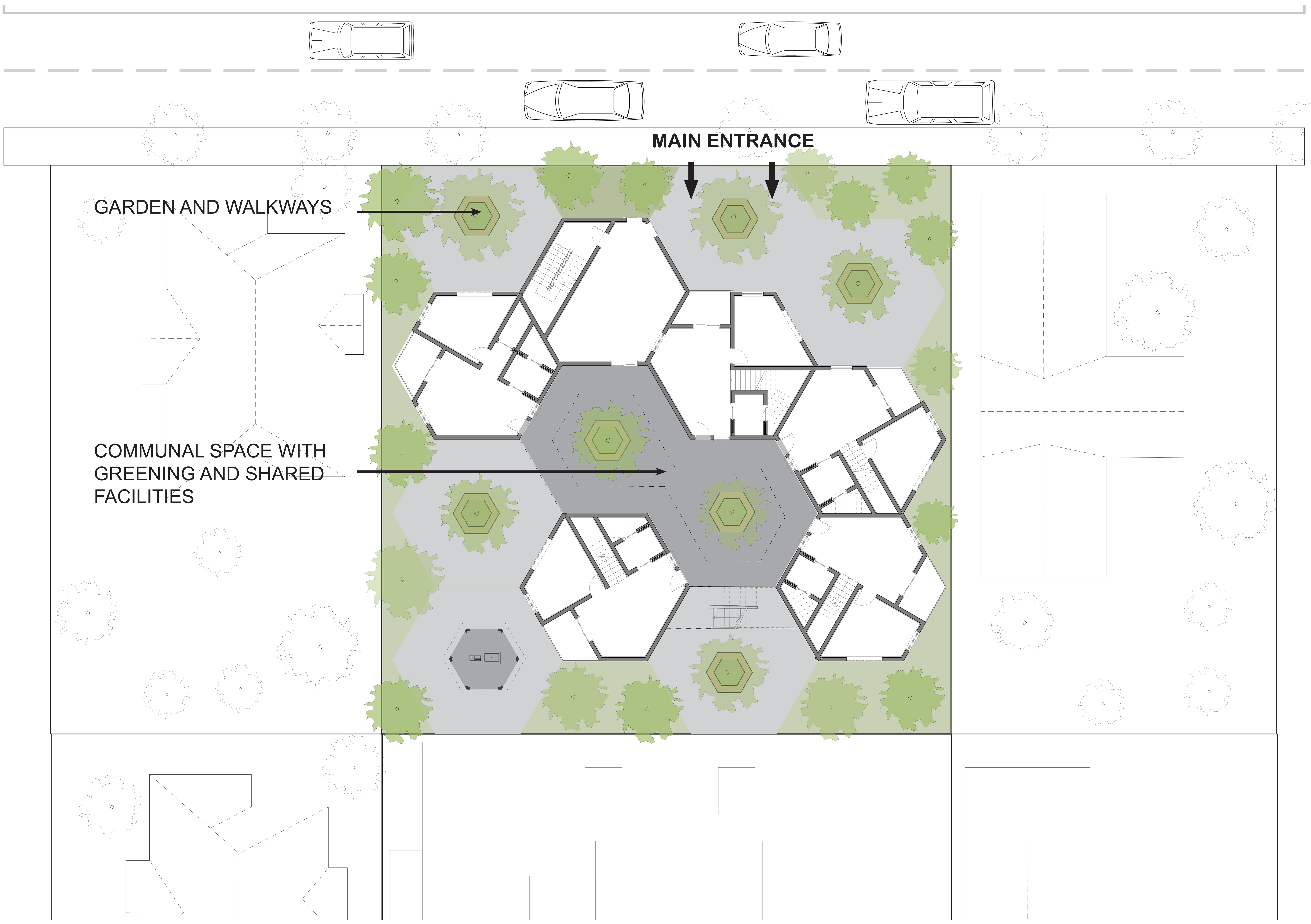
THIRD FLOOR 1 : 200



FOUTH FLOOR 1 : 200

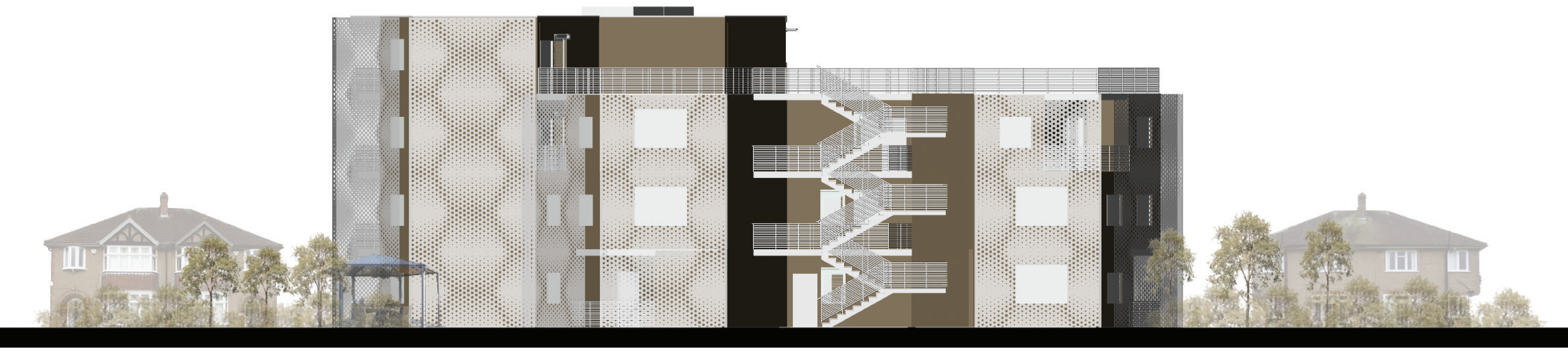


ROOF 1 : 200

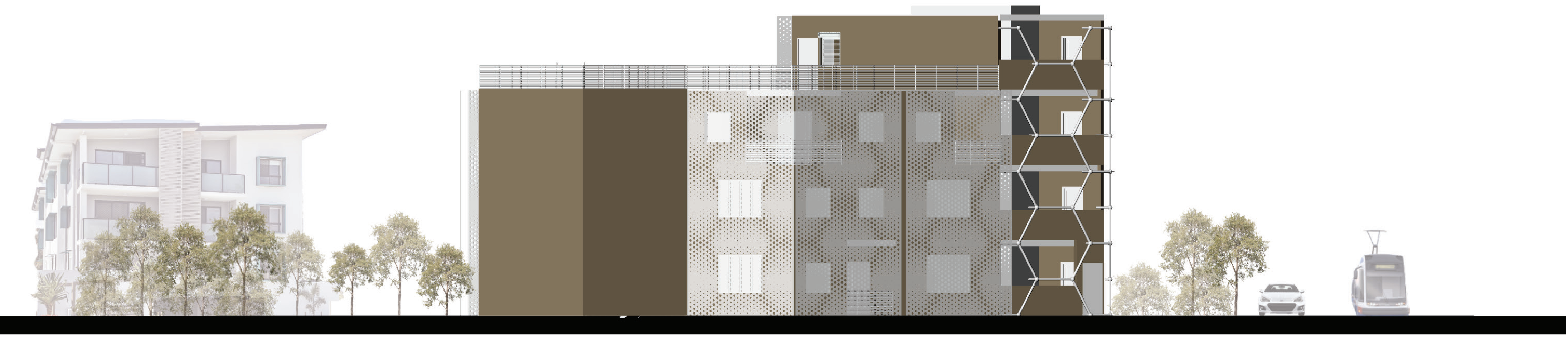


SITE FLOOR 1 : 200

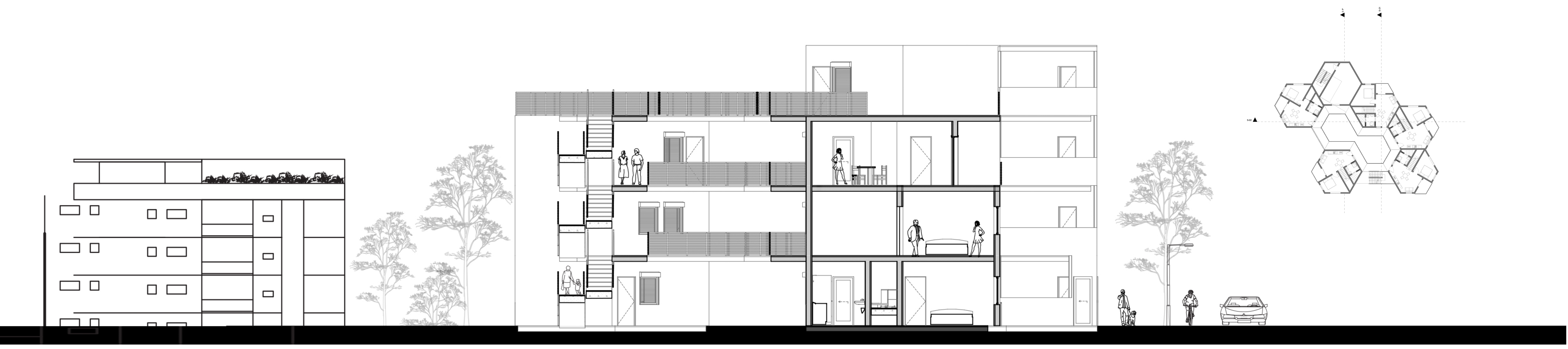
PERSPECTIVE SECTION 1 : 100



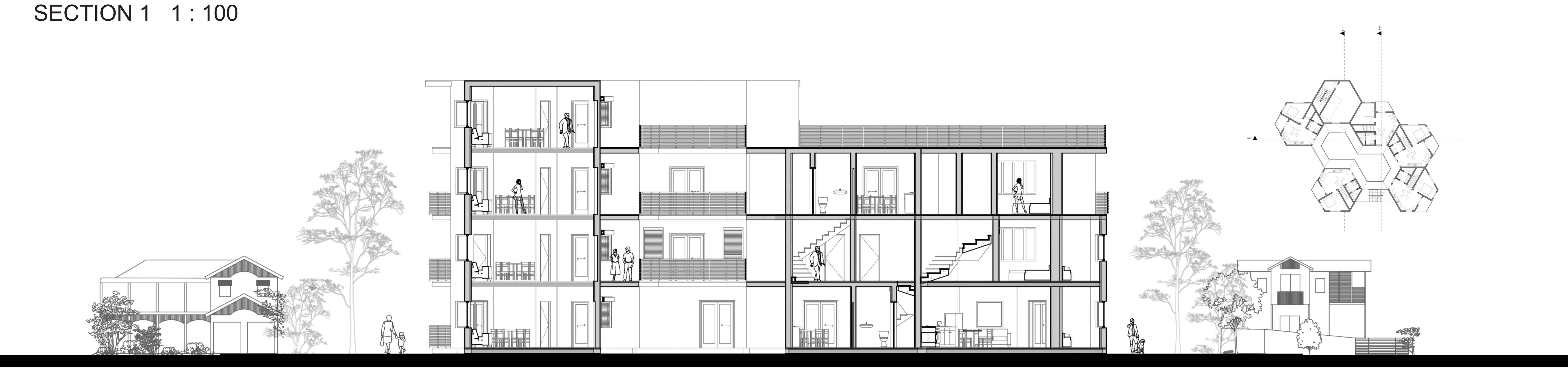
EAST ELEVATION 1 : 100



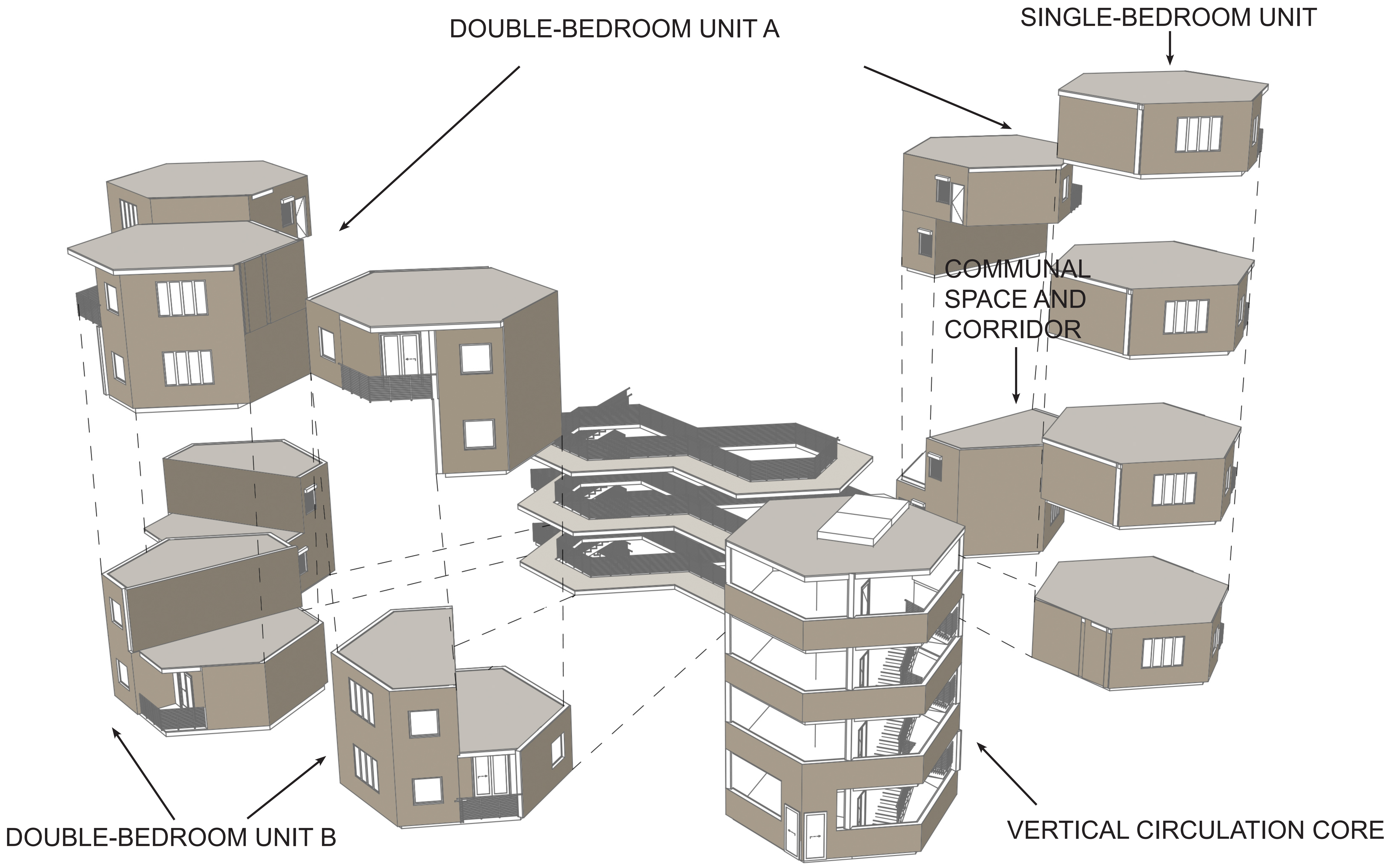
SOUTH ELEVATION 1 : 100



SECTION 1 1 : 100

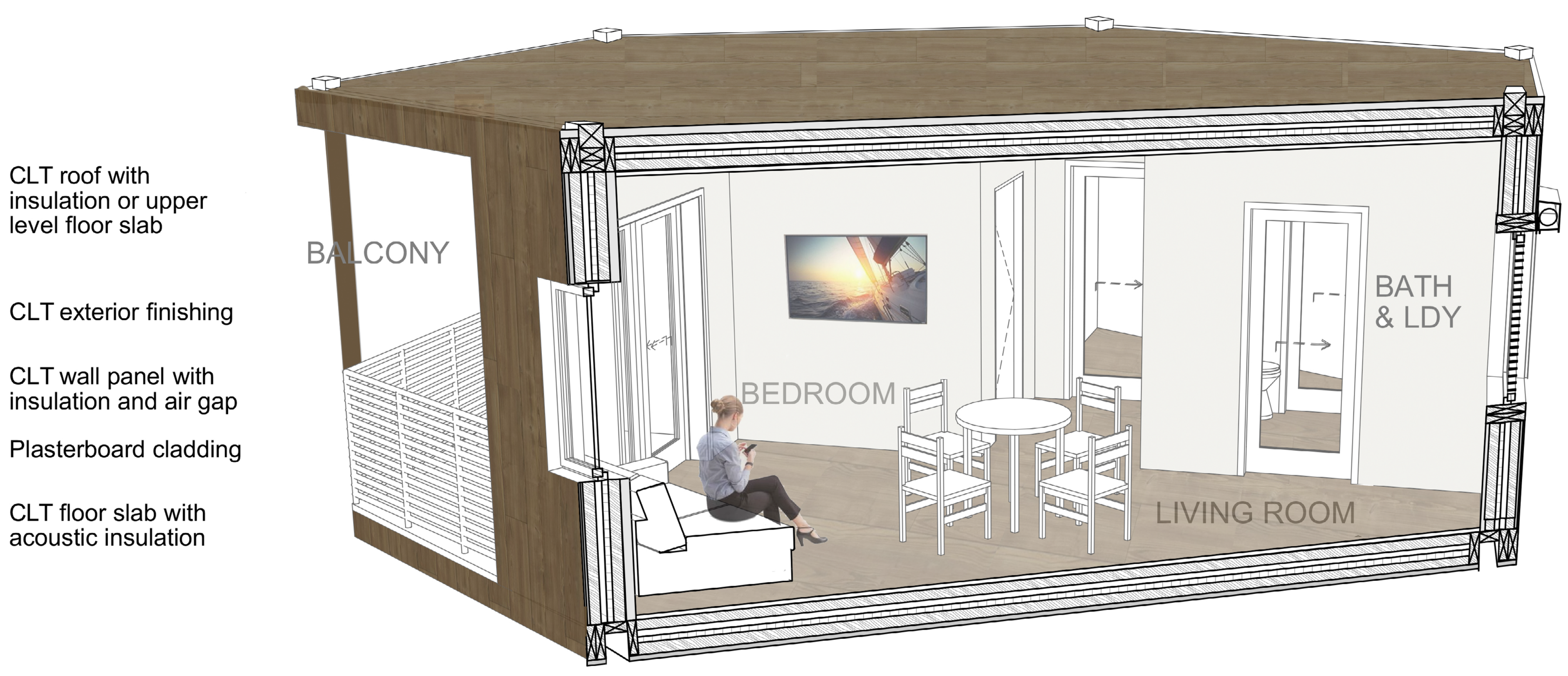


SECTION 2 1 : 100

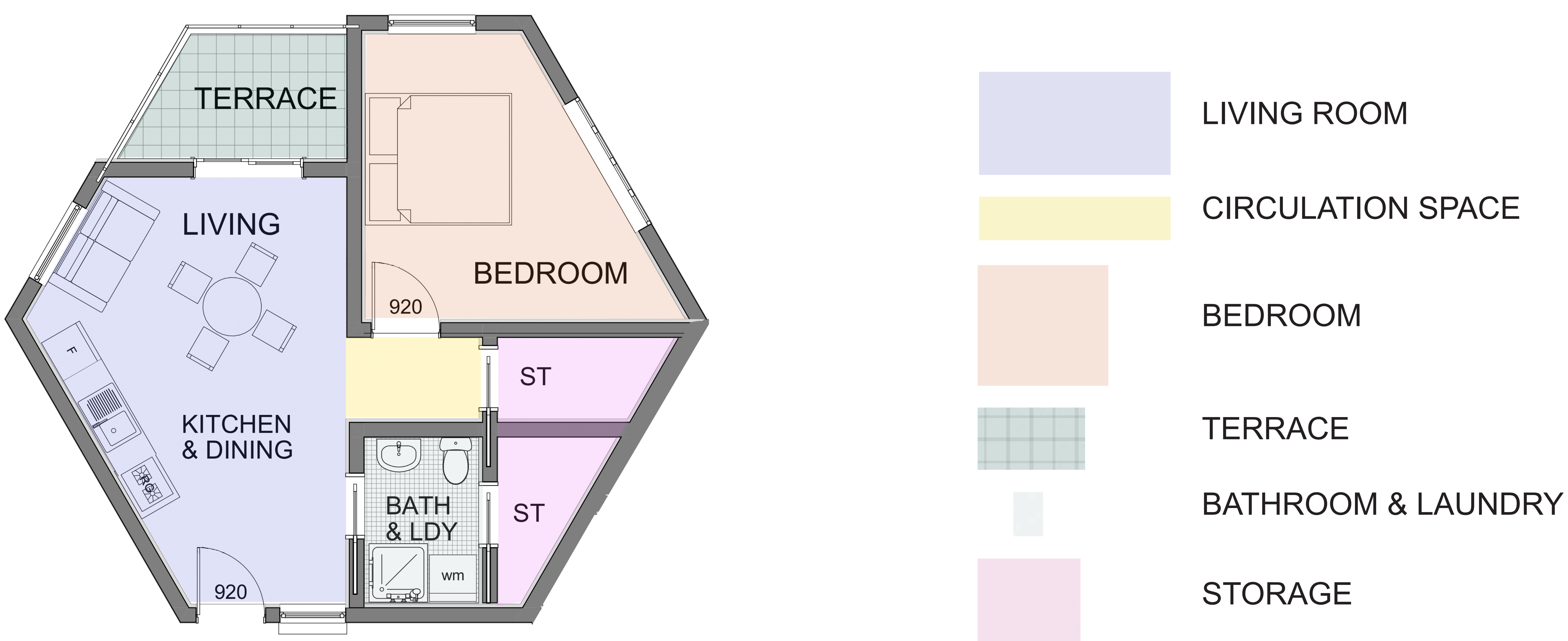


MUDULES ORGANIZATION

ALTERNATIVE ARRANGEMENT OF HONEYCOMB MODULES TO FIT DIFFERENT ENVIRONMENT

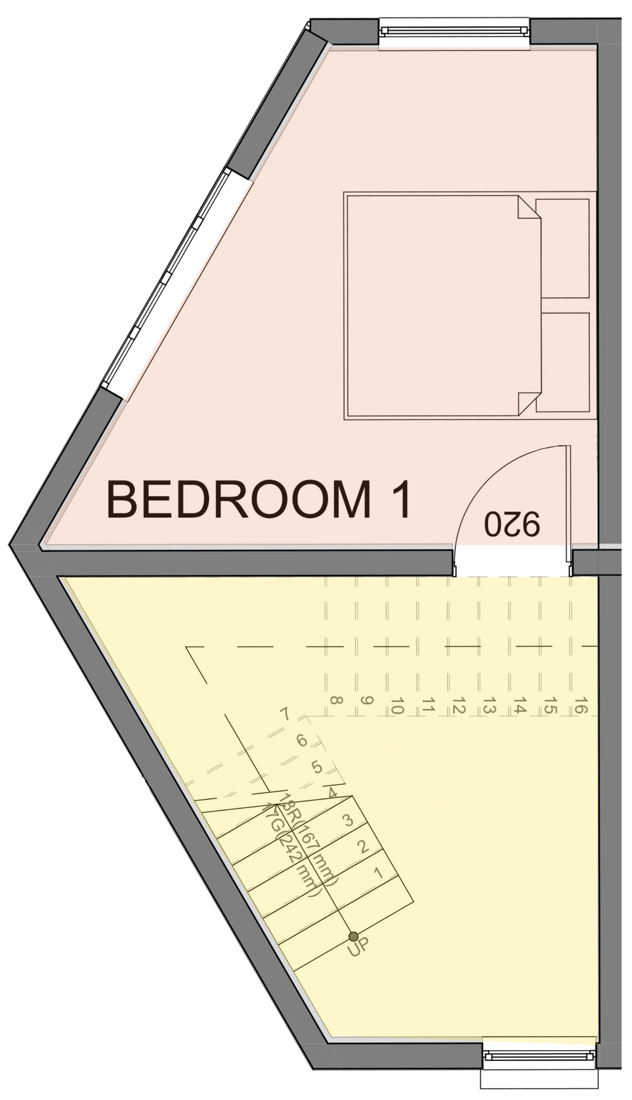


SINGLE -BEDROOM UNIT

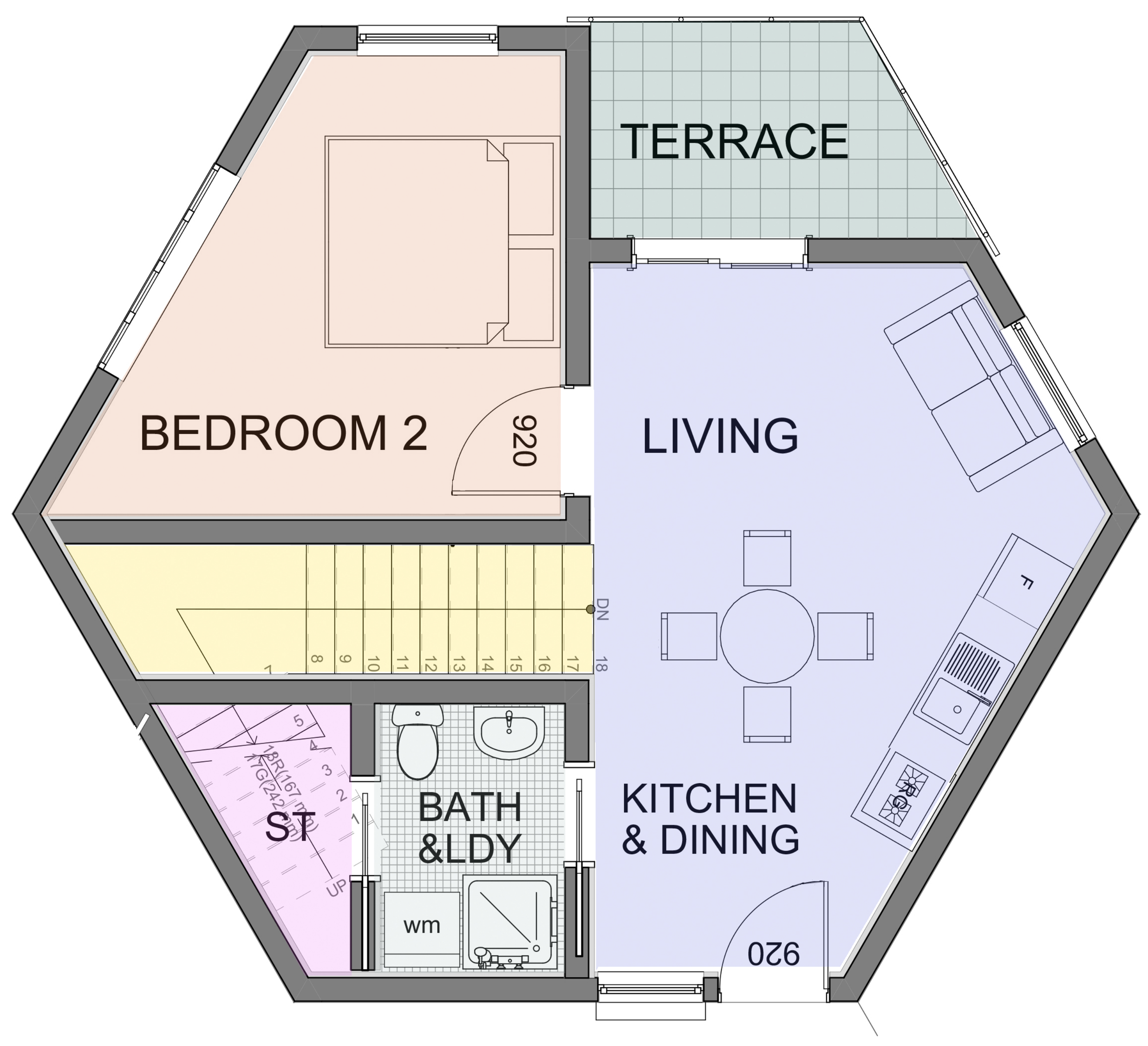


FLOOR PLAN 1 : 50

DOUBLE-BEDROOM UNIT A

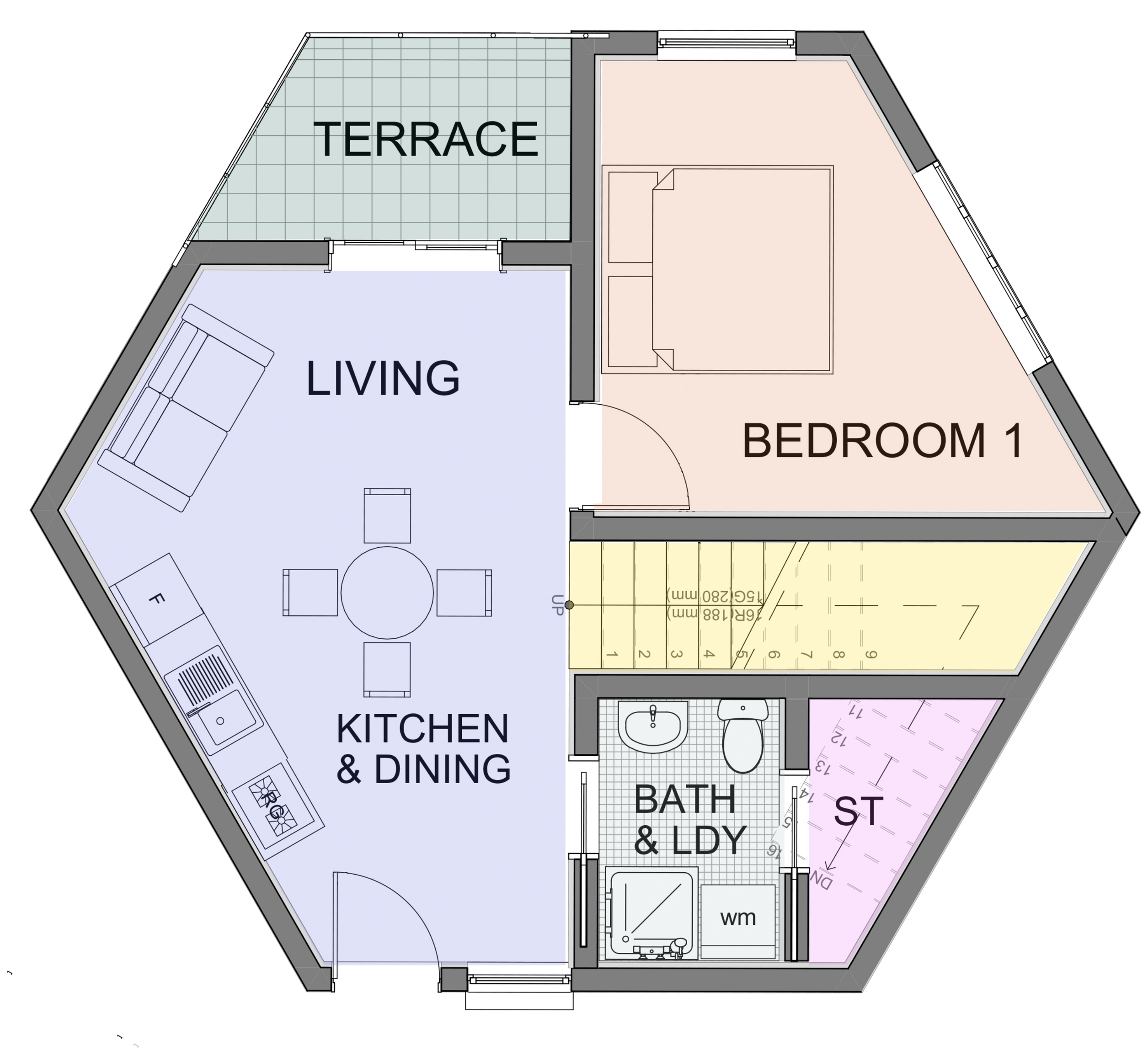


LOWER FLOOR PLAN 1 : 50

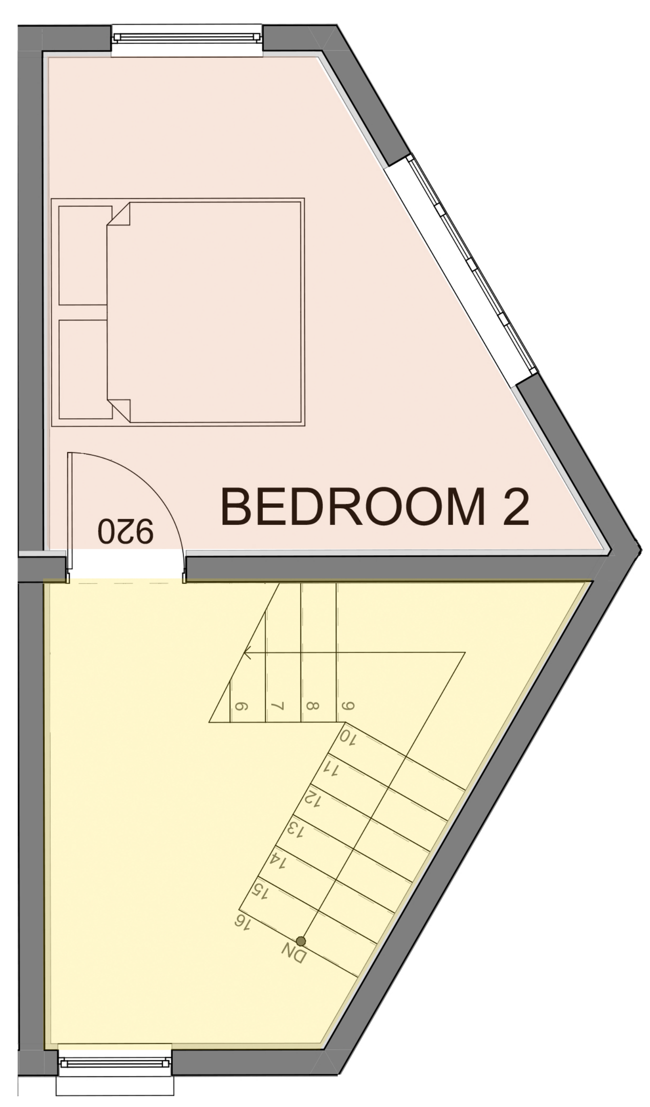


UPPER FLOOR PLAN 1 : 50

DOUBLE-BEDROOM UNIT B



LOWER FLOOR PLAN 1 : 50



UPPER FLOOR PLAN 1 : 50

CHALLENGE CUP 2020-

Honeycomb housing

NEW GENERATION OF AFFORDABLE ACCOMMODATION:

- Vitality
- Sustainability
- Flexibility

The incisive issues can be resolved

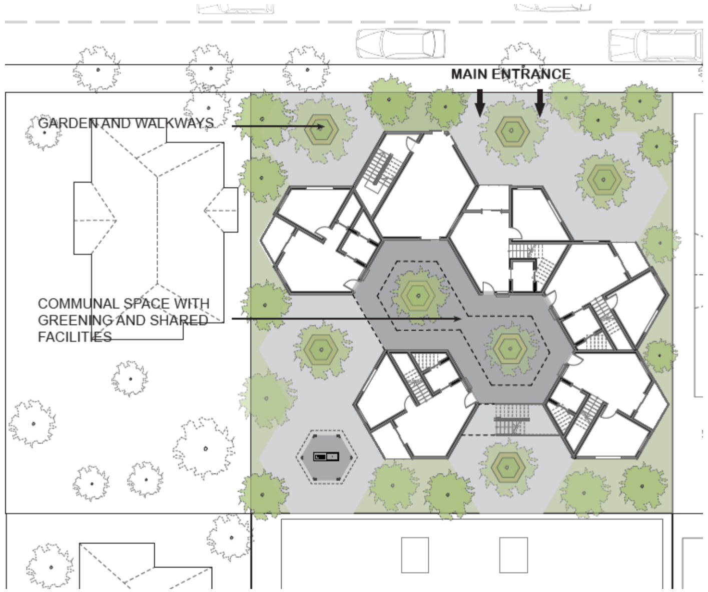
- architecture construction pollution and natural environment
- housing shortage and increasing accommodation requirements

by the new construction method and architectural design of Honeycomb housing.

VITALITY

- Innovative hexagonal form: challenge the traditional
- Impression of viewer & users of this building: creativity and new look toward the life
- Entertainment: plenty of communal spaces and greening can be created in this neighborhood and on the roof top.

  Useful in the Covid-19 situation



Site plan

Bio-inspiration – honeycomb
Reference 1

Perspective section

Reference 1 : https://www.123rf.com/photo_127194119_stock-vector-cute-honey-sweet-background-honeycomb-banner-vector-cartoon-flat-illustration-.html

SUSTAINABILITY

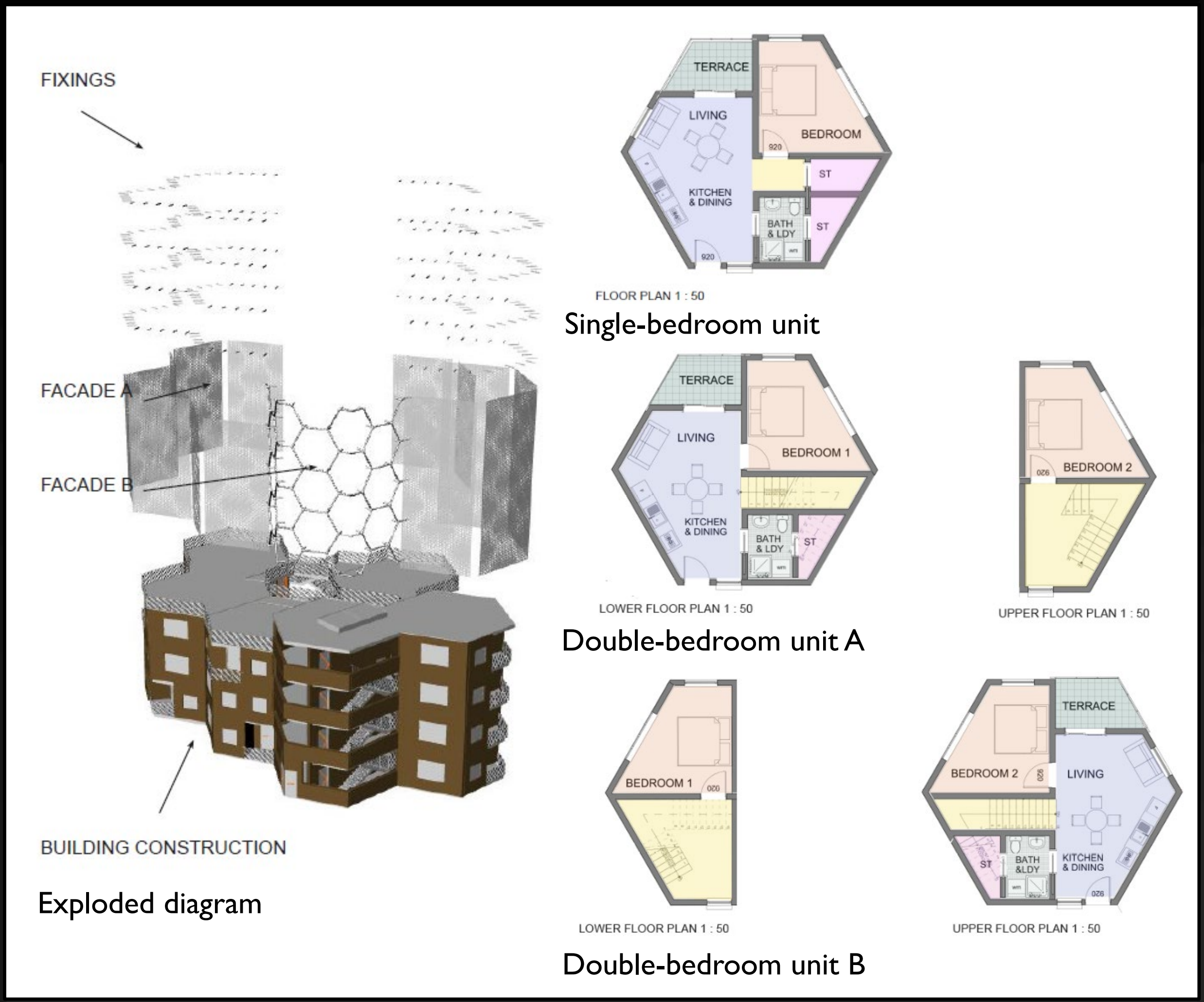
Hexagonal building form：

- Strong bearing capacity
- High material efficiency & cost saving potential

Hexagonal plans：

- Six-side form would achieve mix-mode building.

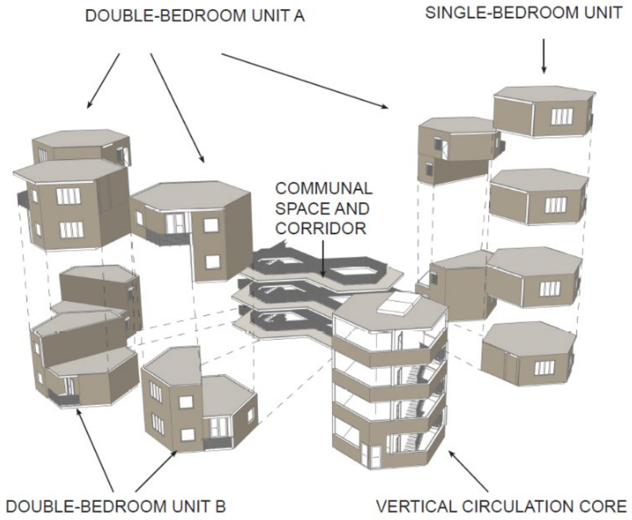
It can increase the ventilation and natural sunlight to come into the interior



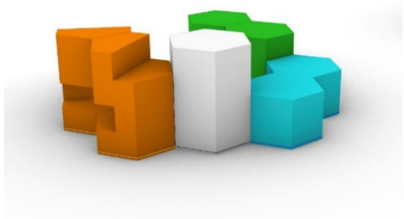
FLEXIBILITY

- Six-side structure provides more possible and combination of the organization of modules
- Different organization could be created to adapt to different requirement of different sites

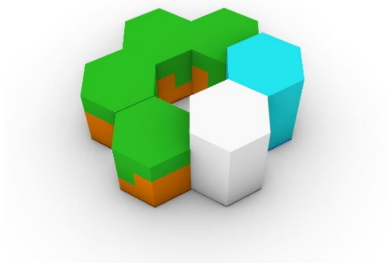
  Such as orientation, landscape, sunlight & ventilation and number of capacity.



Module Arrangement for this site



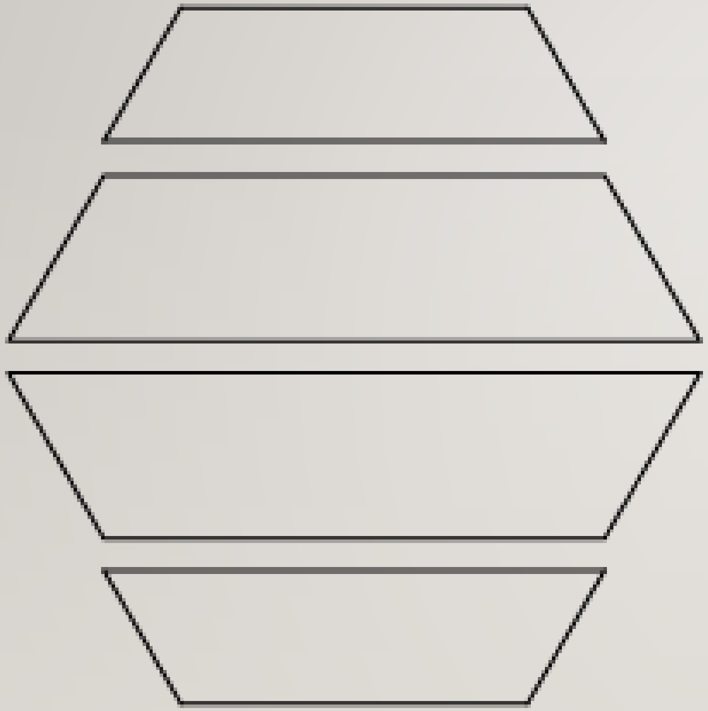
Alternative Arrangement 1



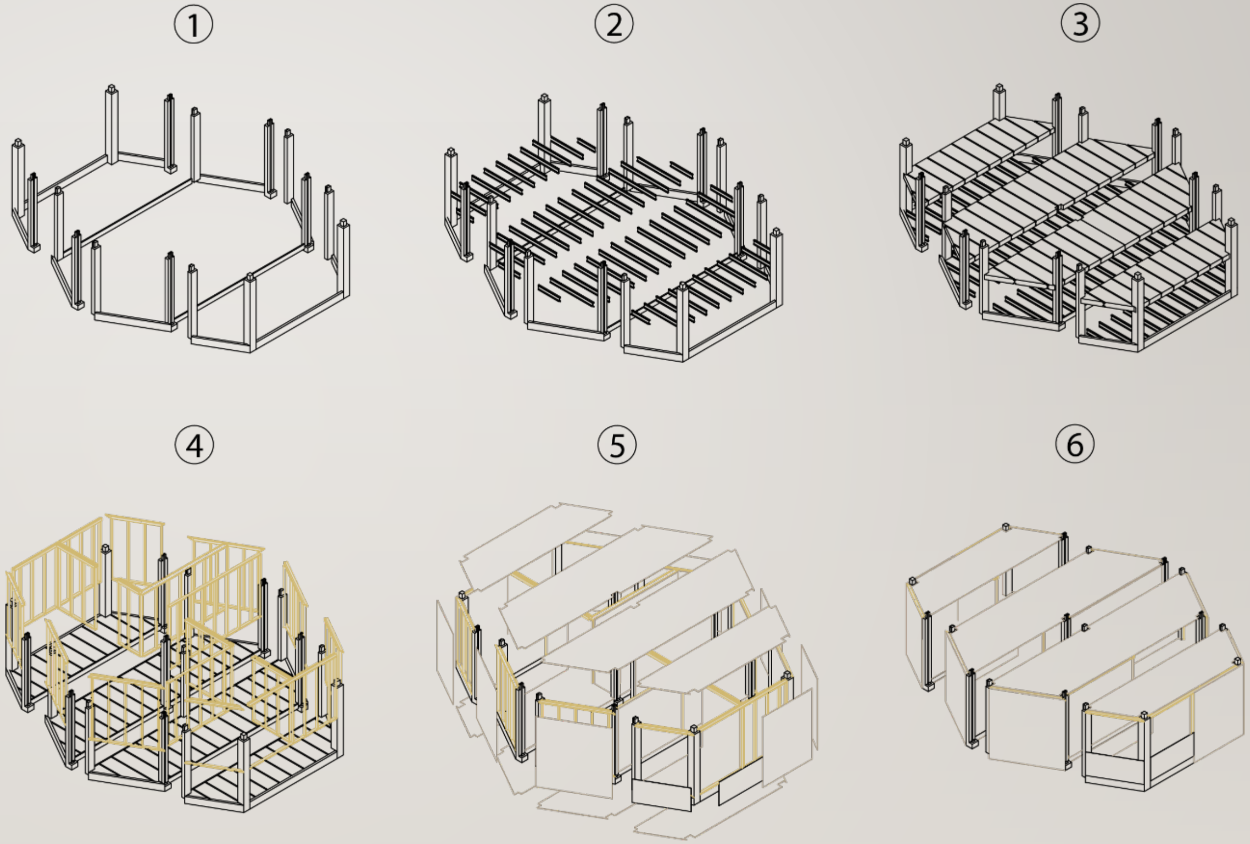
Alternative Arrangement 2

ENGINEER

Modularization



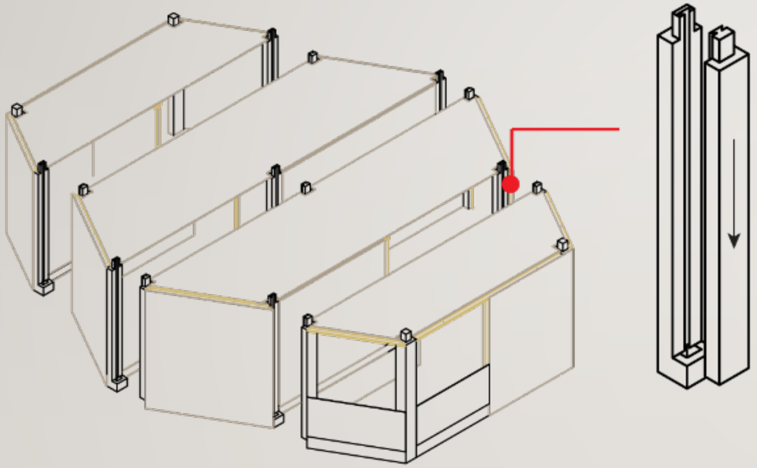
Cutting Pattern



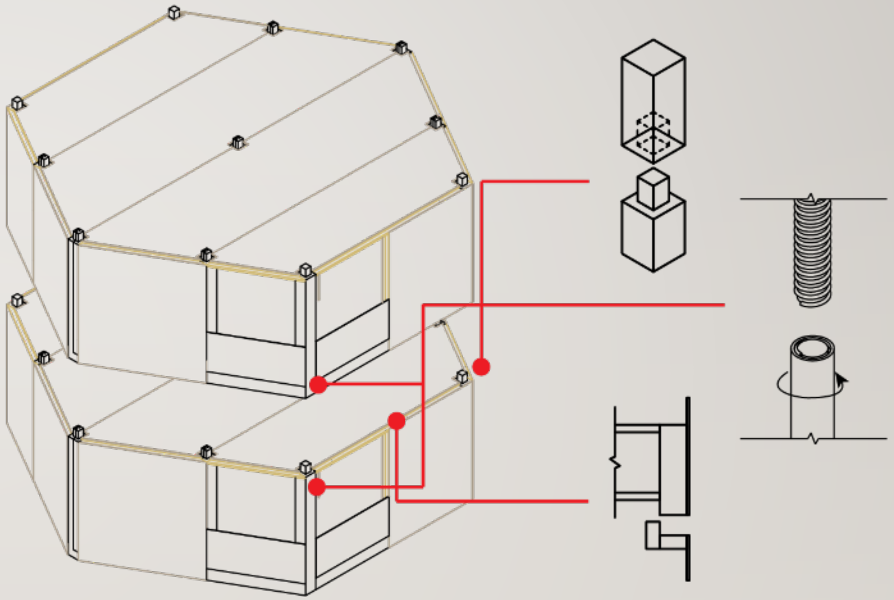
Modular Manufacture

ENGINEER

Installation



Modular Sliding



Vertical Alignment

ENGINEER

Material and Capacity Check

Smart Material

- GLT (Column)
- I-joist (Beam)
- Plywood (Panel)
- SIPs (Floor / Wall)
- Sawn Wood (Primary Beam)

ULS Check

Column Axial	Beam Moment	Connection Shear
104.72 kN	2.78 kNm	4.32 kN
GL 8 GLT	MPG 10 Sawn Wood	M 15 Sherpa

SLS Check

	Column Side Sway	Beam Sag	Floor Sag
Displacement	1.23 mm	2.05 mm	2.24 mm
Criteria	≤ 6 mm	≤ 16 mm	≤ 12 mm

LIFECYCLE ASSESSMENT

Material Acquisition & Manufacturing, Transport, Assembly and Use

Our Design Model

Embodied energy of approx. 124 GJ

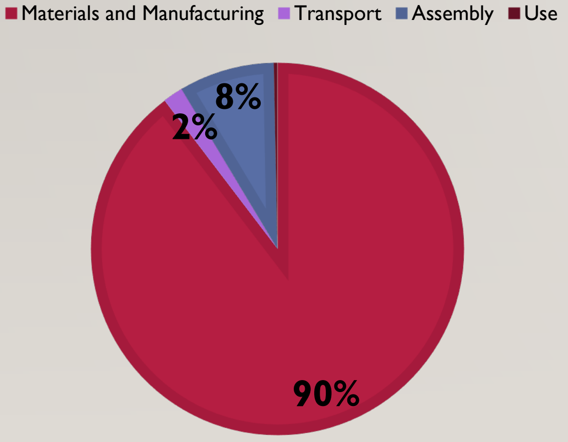
Embodied CO_2 emissions of approx. 7 tonnes

Conventional Construction Model

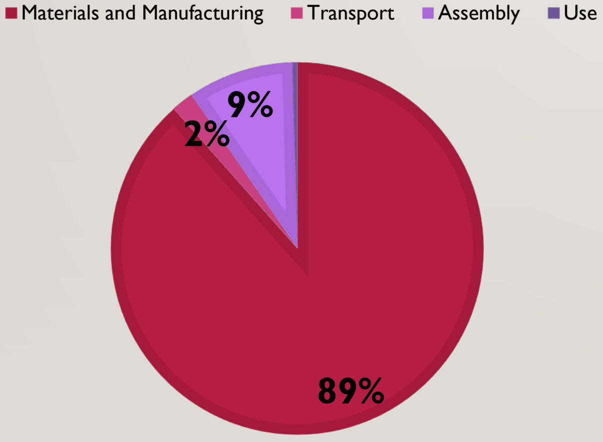
Embodied energy of approx. 307 GJ

Embodied CO_2 emissions of approx. 49 tonnes

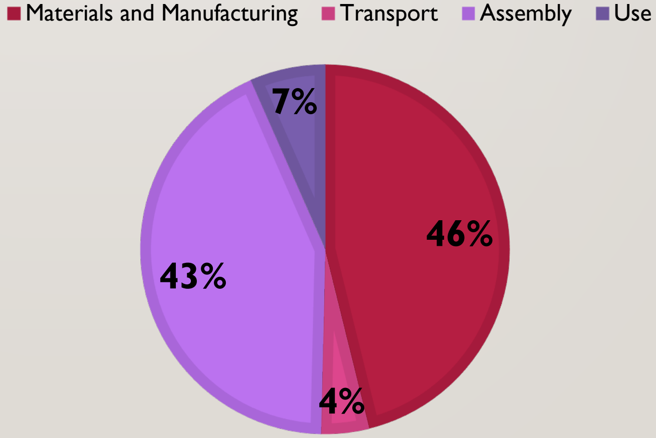
EMBODIED ENERGY (%)



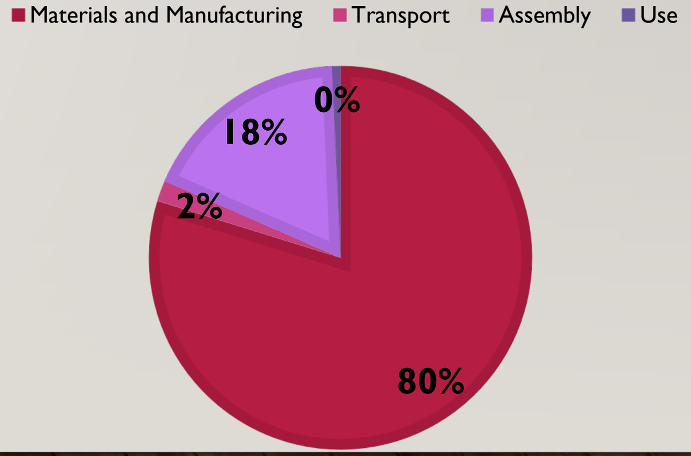
EMBODIED CO2 EMISSIONS (%)



EMBODIED ENERGY (%)



EMBODIED CO2 EMISSIONS (%)



BUDGET EVALUATION

Lifetime Capital Costs

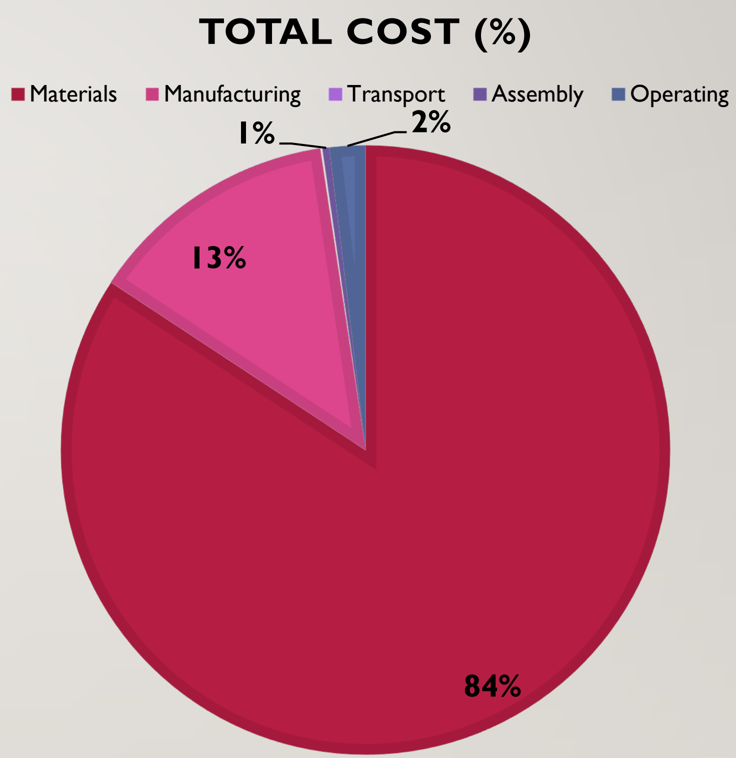
- Material Acquisition = $ 750,429.26
- Manufacturing = $ 118,832.00
- Transport = $ 1,275.00
- Assembly = $3,200.00

Lifetime Operating Costs

- Use = $ 16,768.51

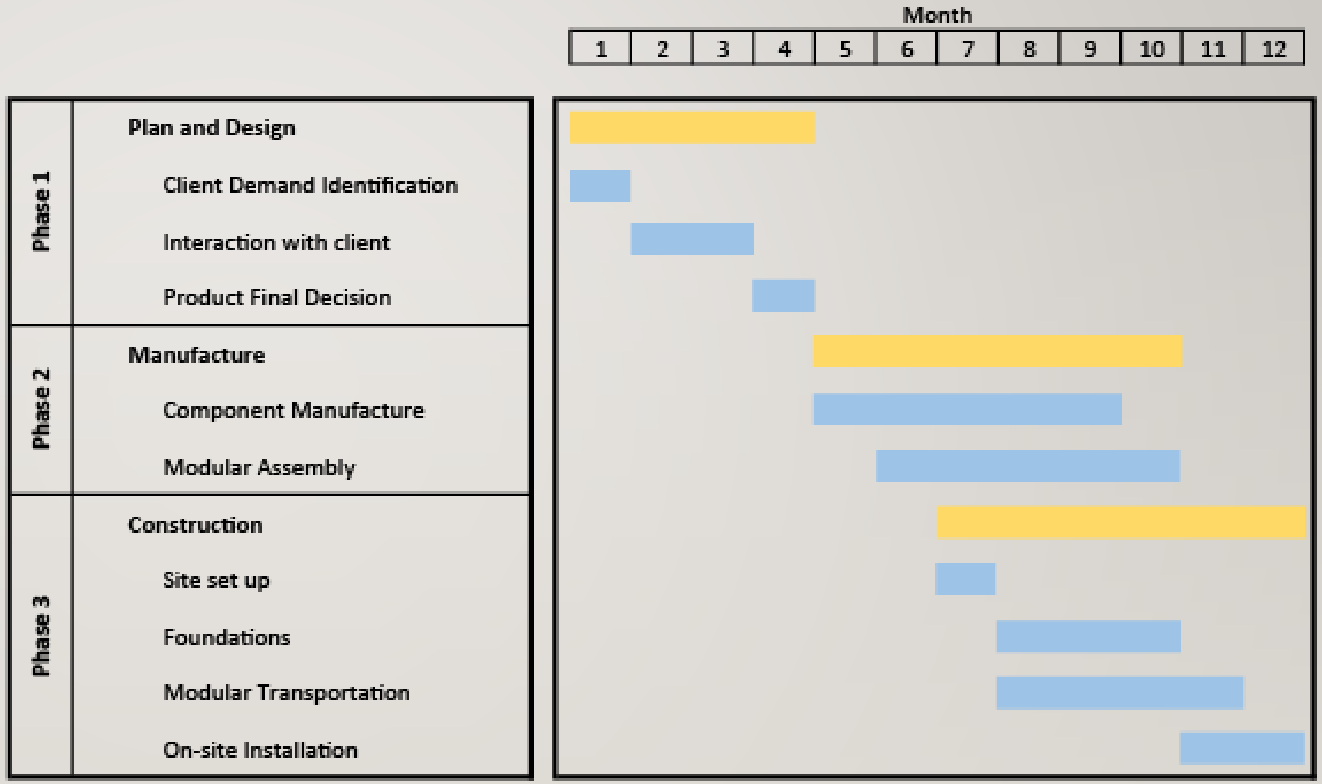
Total Cost

- $890,504.77



PROJECT INNOVATION

- Automation
- Smart Construction
- High Quality and High Speed
- Sustainable
- Deconstruction
- Response to Climate Change



Honeycomb Housing Concept Design Validation Report

Executive Summary

Honeycomb housing provides an innovative choice for affordable accommodation with Vitality, sustainability and flexibility. It challenges and surpasses the conventional residence by its unique and creative construction form and architectural design. In its new interpretation of affordable housing, the conflict of natural environment and construction pollutions as well as the unbalance between housing shortage and increasing accommodation requirement in the society will be alleviated. The vitality of this project is presented in the innovative hexagonal form which is bio-inspired by the honeycomb, a masterpiece of nature. The appealing shape with its freedom leaves viewer an impression of creativity and reminds the users of this building to have a new look for the life. With the arrangement of this unique shape there is lots of communal spaces is created in the neighborhood and on the roof top. Therefore, the users of this building could have more entertainment space when they have to keep social distance and unable to go out, especially in this Covid-19 situation. The sustainability of this project is demonstrated in the overall form and layout of this building. The hexagonal shape has strong bearing capacity, high material efficiency and cost saving potential. In this project, we designed three kinds of modules: Singe-bedroom unit, Double-bedroom unit A and Double-bedroom unit B. With the six-side plans the ventilation and sunlight which comes into the interior are greatly increased, in comparison with the traditional four-side plans. The various options and possibility in different arrangements of modules maximize the flexibility of this project. Therefore, the whole building can be easily adjusted to different landscape, orientation and numbers of capacity in various conditions. (Of-course it cannot be achieved without the advanced technology of modules prefabrication and off-site construction.)

Modular construction is an innovative technique, and the building system is assembled onsite from a number of volumetric units with reduced schedule, less on-site refuse, declined cost. Therefore, the modularization is also applied in our design. As the dimension of the hexagon layout is too large to be transported though current available vehicle options, the unit is then cut into four modular components. The modular manufacture sequence is specified with all the column, beam, floor wall elements have been manufactured separately. A basic frame is initially located, followed with floor element insertion. Wall and panels are then attached to the frame. Finally, the four components are packaged and ready for transportation. The onsite installation is quite simple. The column components are designed with dovetail geometry, which allows the modular components to attach together by the column sliding along the rail, from top to bottom. When the bottom modular unit is finished, another modular unit

would be lifted on the top and aligned through the two designs: the column mortise and tenon joint and the edge beam extension. A thread and sleeves that attached besides the columns are then manual assembled to provide vertical restraint between two modular. The structure material almost utilize the high-performance engineer wood product like GLT for column, I-joist for beam and plywood for panel. Structural insulated panels as a light-weight insulation prefab component are also used as floor and wall. Sawn wood material is only used for primary beam. Based on the material and geometry assumption, a simple SPACEGASS numerical model is developed. After comparing different load combinations, some critical internal values are given. Based on the given results for ultimate limit state analysis, the grade classification of material is then determined. For the serviceability limit state check, it could be seen all the main parameters satisfies the criteria according to code, which shows a good engineering performance for our structure design.

The Lifecycle Assessment (LCA) provides an evaluation of the embodied footprint (energy and CO_2 emissions) of the building system across each stage of its proposed 50 year design life:

- Material Acquisition and Manufacturing
- Transport
- Assembly
- Use

The LCA uses a parallel model to compare the proposed pre-fabricated design with a residential development that uses traditional construction techniques. The results of the LCA estimate that the aggregate embodied energy of the prefab design is 124 GJ per hexagonal module, and embodied CO_2 emissions are 7.5 tonnes per module, in which the major contributions derive from the Material and Manufacturing stage. For the conventional construction model, less durable building components and higher energy materials, transportation processes and on-site assembly processes result in greater embodied energy and emissions totals of approximately 307 GJ and 48.8 CO_2 tonnes. Across its lifecycle, the proposed residential housing concept has design considerations, which reduce its embodied footprint and make it more sustainable.

From a cost perspective, the bulk of the project's budget is directed towards the initial capital outlay, which primarily involves material acquisition and preliminary manufacturing this building concept. Unlike conventional construction, however, there are significantly lower on-site assembly and transportation expenses for this project, because building components are hauled to the site in complete modules from a single off-site facility. In addition, the chosen building materials have low replacement rates, hence operational expenditure is minimal. The total expenditure for this project is approximately 890,000 AUD.

Overall, in the manufacture stage, our project proposes an automated production line with digital tool and control system, allowing the real-time interaction with clients and high manufacture quality. For the construction sector, modularization provide a smart solution for building industry, tackling the global problem like labor shortage and housing demand. The high building performance and sustainability could also be seen based on the LCA evaluation. The structure is also designed for deconstruction, allowing the reuse and recycling to the end of its life. The typical climate change in Melbourne is the super-hot weather, such that the building façade and roof garden could somehow relieve the heat transfer pressure to provide a sustainable living environment. The project programme is then plotted as the apartment could be completed in one year from client stage to construction stage.

1. Introduction

This project, Honeycomb Housing, represent a new generation of affordable accommodation. Its vitality, sustainability and flexibility provide a new interpretation of affordable housing. The incisive issues of architecture construction pollution and natural environment, as well as, housing shortage and society can be resolved by the new construction method and architectural design of Honeycomb housing.

Fig. 1 Honeycomb housing

2. Design Concept

2.1.Honeycomb Form

In terms of architectural design, the Honeycomb project also reverses tradition by adopting a biologically-inspired hexagonal form. According to the studies, it is found that the honeycomb structure has strong bearing capacity and exquisite structure, which saves materials to the greatest extent.

2.2.Alternative Module Organization

In addition, the six-side structure provides many different combinations for the connections of different Modules. This structural diversification brings a variety of possibilities for dealing with different sites and different environments and building deformation.

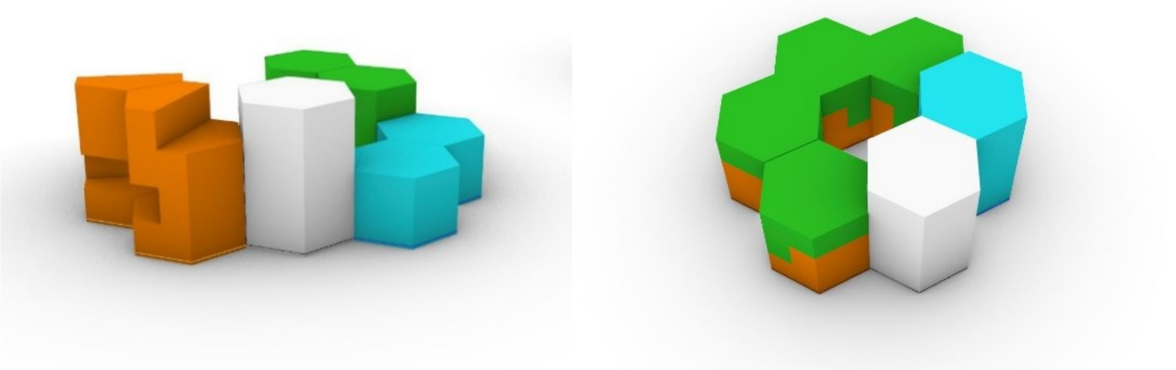


Fig. 2 Alternative example of module organization

3. Architectural Design

3.1.Modular Organization

This project provides 4 Single-bedroom units, 8 double-bedroom units, as shown in Fig. 3. Three different modules were produced to provide house types with different size requirements: Single-bedroom unit, Double-bedroom unit A and Double-bedroom unit B. the rationality of internal layout is revealed in this hexagonal structure.

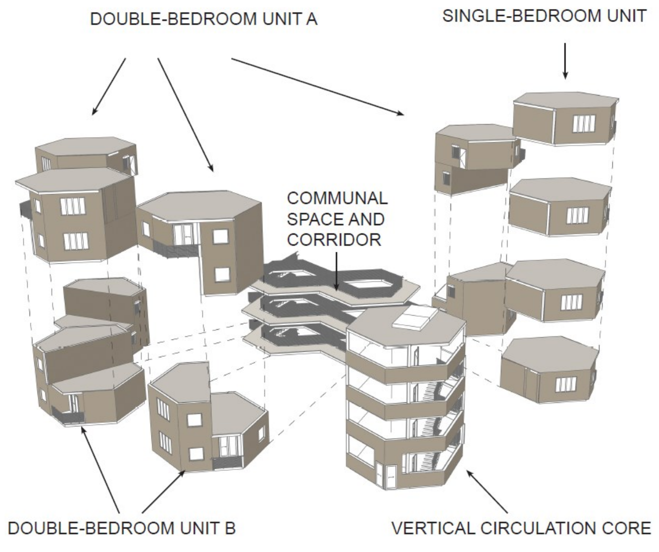


Fig. 3 Organization of modules

3.2.Interior Design

In this project, there are living room, bedroom, kitchen and dining, laundry and bathroom, storage room and terrace in each of module types, shown in Fig. 4. Two Double bedrooms are made into A double-layer structure. Under the stairs hidden storage space, there is the living environment more spacious and comfortable and with higher comfort. Based on the size requirements of NCC, these interior layouts provide users a comfortable as well as quality life.

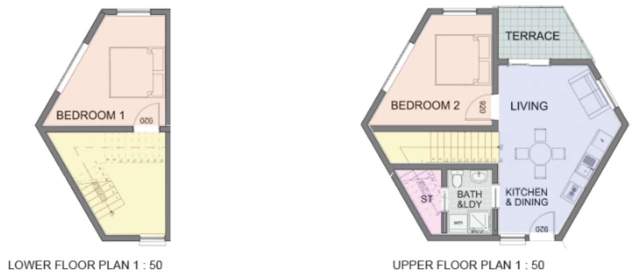


Fig. 4 Interior design layout

3.3.Building Façade

The facade for building is quite direct and functional. The core language of façade is using the honeycomb hexagon idea continuously on our facade. The type of facade can be divided into two types, solid and void. For solid honeycomb hexagon, which made in aluminum, this solid panel provides privacy and safety to residents. The holes on the panel form the hexagon shape and get bigger when it gets close to the window. This will provide sunlight to interior space and also shading main wall panel under the summer sunlight. Using solid panel can also encourage resident to move out and use the exterior space and communicate with people, which reinforce the connection between people. The void facade is used for public space in this apartment. Although it can be judged as just a frame with hexagon shape, it actually provides variable opportunities to resident to use it. People can use this as clothes hanger or plants climb frame. This is the new type of the space under wisteria frame and a nice place to create memory for residents.

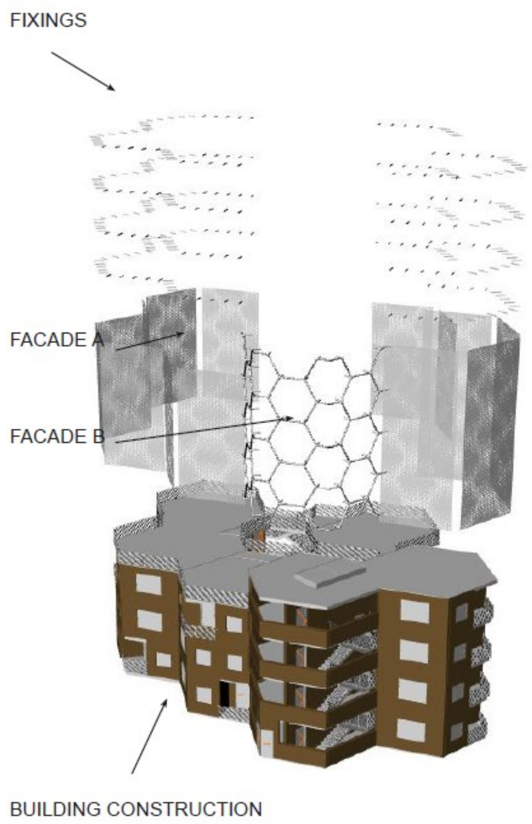


Fig. 5 Construction and building

The transparency of this void facade provides positive ventilation to the apartment courtyard and help improve the air quality in building. Some parts of façade is not covered by the panel and exposing the honeycomb unit material. Such Brutalism design purpose honestly describe the flexibility of our building skin. Residents can exchange or remove the different pattern of panel. It is also important to use this language, which comparing the different material on façade, to represent that even social housing still need to have consideration on aesthetics.

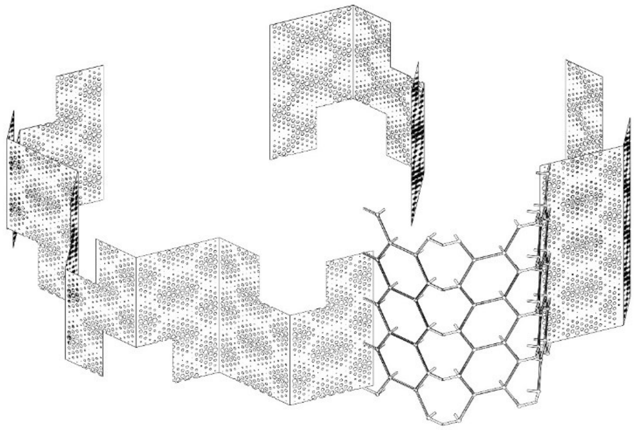


Fig. 6 Two façade types

Fig. 7 Façade on elevation

3.4.Site Adaption

Because of the flexibility of the hexagon, there are different arrangements for different sites. Through the analysis and study of this particular site. We chose the following arrangement to reduce

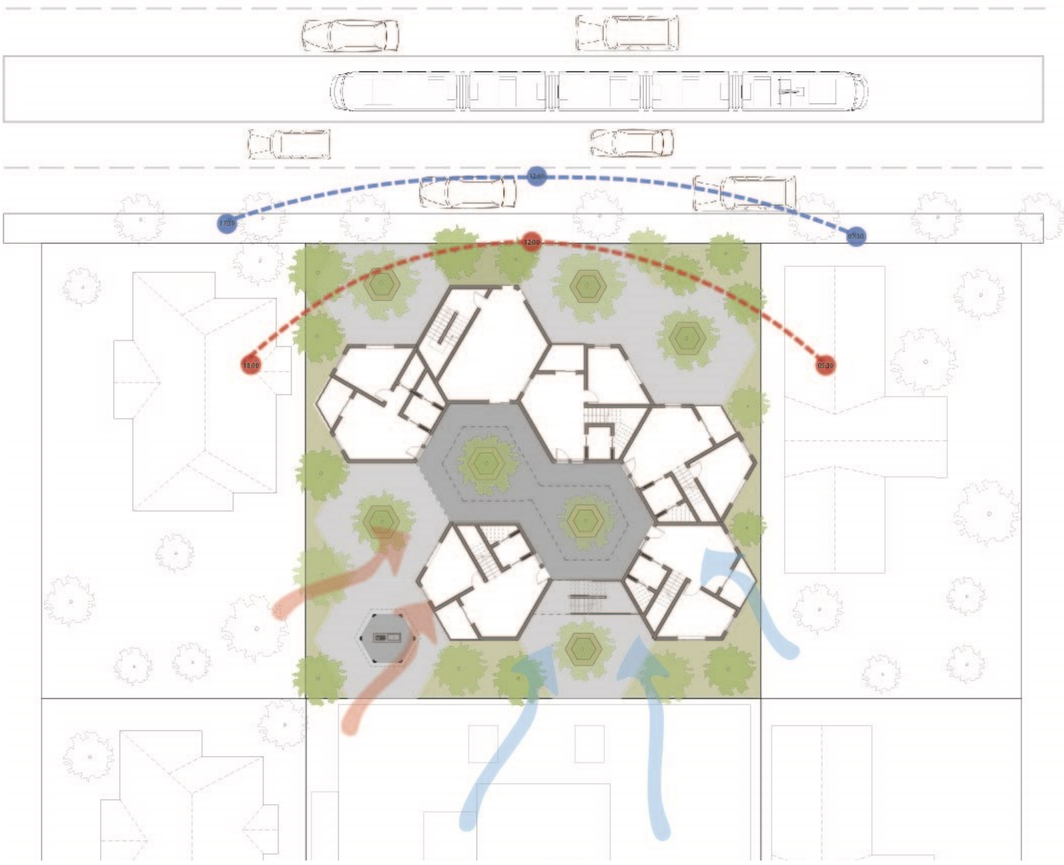


Fig. 8 Site analysis

the direct sunlight from the west, enhance the entry of gentle sunlight from the north, and promote ventilation from the south and west through voids.

Inner city Melbourne is a dense urban environment, hence one of the main challenges of this project was to make urban living just as attractive and liveable as suburban living on this site. Some of the ways we tried to achieve this on the site was to maximise the amenity. Gardens surround the structure on the block. these gardens would hopefully be maintained by the residents and would help to foster a community amongst the people who live in the building. Similarly, vegetable gardens have also be placed on the roof to encourage residents to come up, interact with other residents and appreciate the views of inner-city Melbourne. Barbeque facilities have also been provided for the residents on the site.

On the Site we have also tried to activate the relationship the building could have with the street scape. There are no fences at the front of block to create a welcoming façade and the gardens will hopefully grow out onto the Street. The positive relationship with the streetscape also encourages walkability, active modes of transport and uses of the public tram system

A large amount of vegetation was thought to be important in this urban city setting. We wanted residents to feel like their homes were an escape from the busy city. Greenery can improve one's well-being and create a much more pleasant environment to live in. This is one of the reasons so much of the ground plane and the roof have been dedicated to vegetation. We also propose that there should be hanging gardens in the two central voids so that when people exit and enter their apartments, they are greeted by not just an abundance of sunlight, but also a plethora of greenery so that it feels like you are in a rainforest.

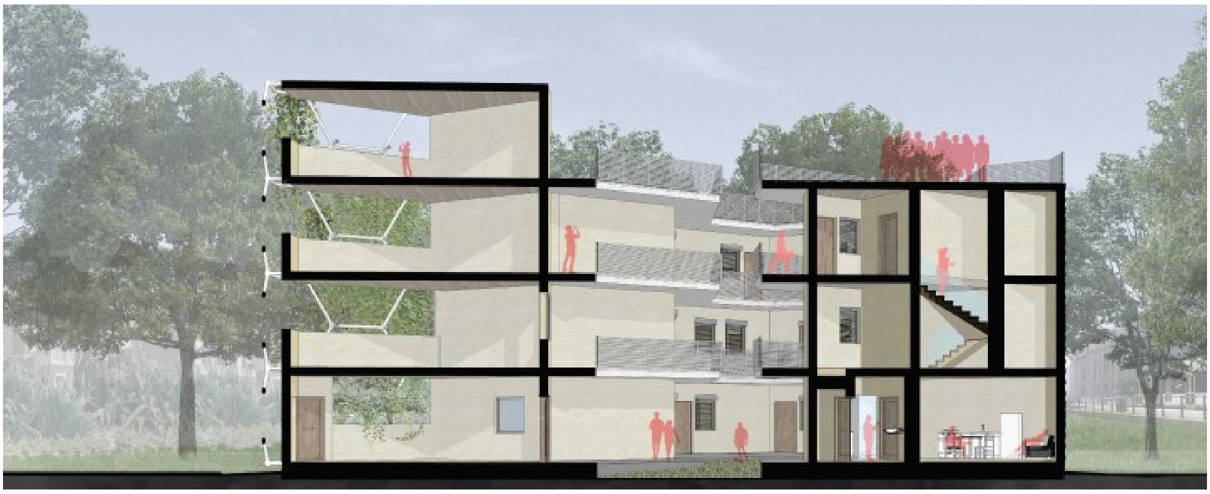


Fig. 9 Building section

4. Engineering Design

4.1.Modularization Concept

Modular construction is an innovative technique where the building system is assembled onsite from a number of volumetric units with reduced schedule, less on-site refuse, declined cost. The off-site prefabrication industry enables the unit product manufactured in higher quality and efficiency with highly equipped industry lines. With a global challenge for housing shortages, labor markets tightness, modulization becomes increasingly popular in construction sector.

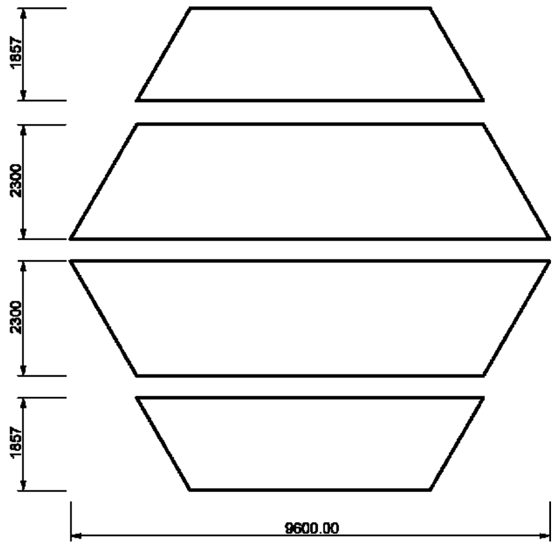


Fig. 10 Modular cutting pattern

The resolution for modular concept design of hexagon shaped unit should be compliant with both the transportation limitation requirement and the architecture interior layout design. Such that a three cut pattern is implemented over each hexagon unit, as shown in Fig. 10. The national heavy vehicle regulation [1] restrict the width of heavy vehicle by 2.5 m and height by 4.3 m. The maximum length 9.6m with two 0.3m façade extensions is below the length requirement constrained within 12.5m.

The above-mentioned cutting pattern illustrated the basic volumetric units for building construction. The structural forming details would then be adjusted for both single and double rooms, with details shown in next section.

4.2.Structural Modular Design

This section would describe the modular design composing of basic structural form, component element configuration, connection design and manufacture sequence. The interior layouts for both room types are similar except for another half second floor for double room. Accordingly, the bellowing description starts with single room, complemented with extra adjustment for double room.

4.2.1. Structural Form

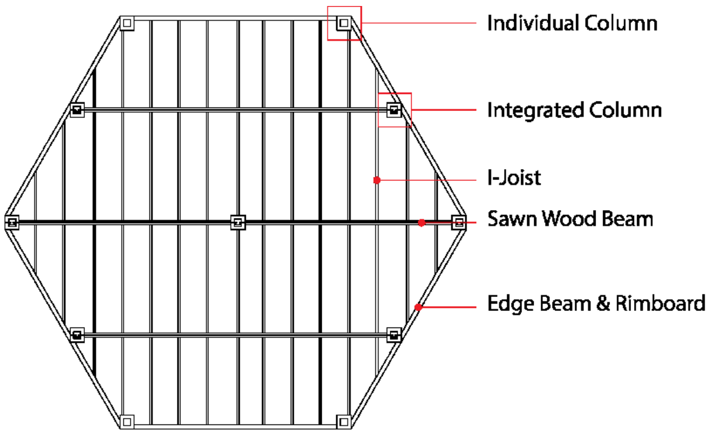


Fig. 11 Frame structure layout

Framework is selected as the fundamental structural form to sustain the building floor and roof loads, with layout configuration shown in Fig. 11. The column elements are mostly located at the corners for each modular unit with one located in hexagon center. The columns as locating between two modular unit are integrated by two half elements, such that four individual columns with 7 integrated columns are designed in the for one hexagon unit. Deep edge beams and sawn wood beams are assembled as the main load transfer element to columns, particularly the edge beam as the exterior hexagon outline extensively performing as rim board for vertically linking purpose between the adjacent modular. The I-joists fill the void space could directly attached with floor and transfer the floor action to the primary beam element.

[Complementary: A void space is cut for double room stair space.]

4.2.2. Component Design

Column-column detail

The column components are 300 mm * 300 mm square section with a central tenon on the top and slot at the bottom. Glulam laminated timber is considered as column material as its higher strength and durability property. The integral columns are additionally manufactured with another connection feature as termed dovetail joint for integrity purpose. The c_2 subassembly slide along the rail on the c_1 element vertically and sit on the stop platform. The dovetail joint and mortise-tenon joint is categorized as integral mechanical attachment, the design eases the assembly process by rail-alignment between each modular unit without any further measurement.

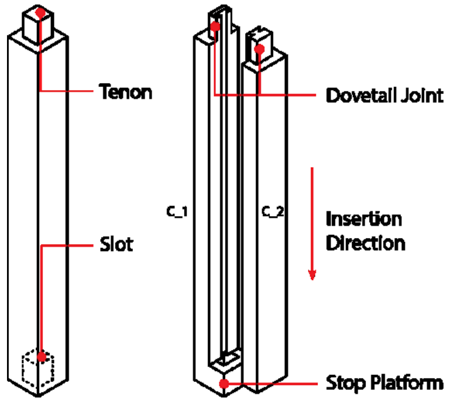


Fig. 12 Column connection

Beam-beam and Beam-column detail

I-joist as secondary beam element is designed to transfer the floor load to the primary beam and edge beam, as both are attached to the column element. The depth of primary beam is consistent with I-joist as 200 mm, with edge beam however having greater depth allowing an extension for alignment purpose and sealing between vertical adjacent modular unit, as all details shown in section 4.2.3. The top-mount I-joist hanger and Sherpa connector integrate the modular structural frame, as connection examples illustrated in Fig.13.

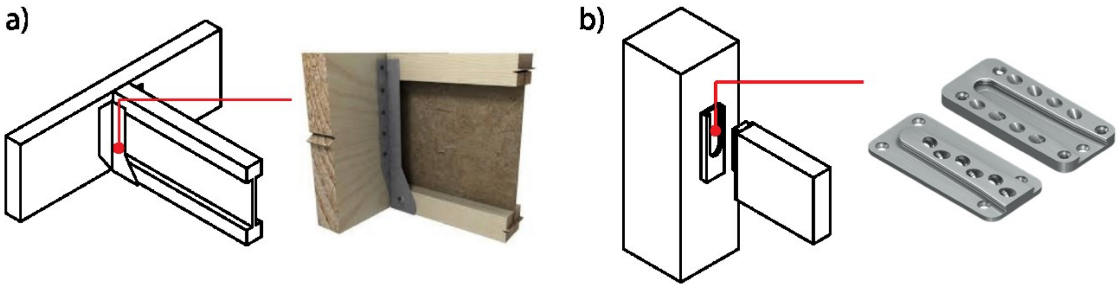
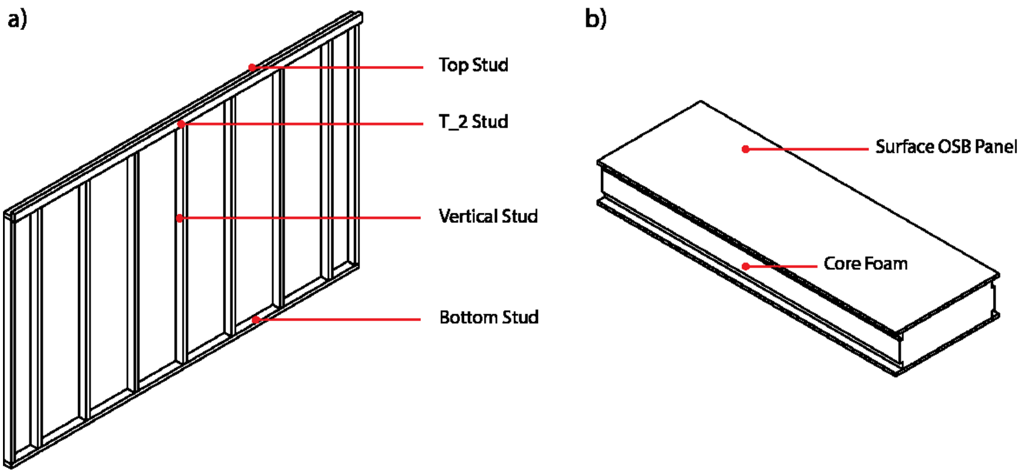


Fig. 13 a) Top-mount I-joist hanger. b) Sherpa

Stud Wall Frame and SIPs

The wall element composing by stud frame and sheeting material is designed for infilled purpose. The vertical studs are arranged with horizontal spacing 600 mm as conventional engineer custom, with the top and bottom studs together forming the frame system. Another top stud termed as t_2 stud is



attached adjacent to top stud interior with 90° rotation, shown in Fig.14, which is designed for aligning the edge beam extension from top modular. The structural insulated panels work as an insulation component and are assembled between both wall studs and floor I-joists.

4.2.3. Manufacture and Assembly

Off-site Prefabrication

The off-site prefabrication should enable the manufacture production line automated and standardized. In current design, the components for examples the column, beam, floor and wall were all manufactured separately with specific geometry and affix, and transported to assembly spot. The factory assembly process is proposed as the column and beam initially located and the floor element attached inside. The stud walls with insulated material are aligned with building layout and screwed into the floor. The exterior and interior panel then covered to the modular and four individual modular components are packaged as ready to be transported.

(complementary: in terms of the double room unit, stairs would also be pre-attached to the modular.)

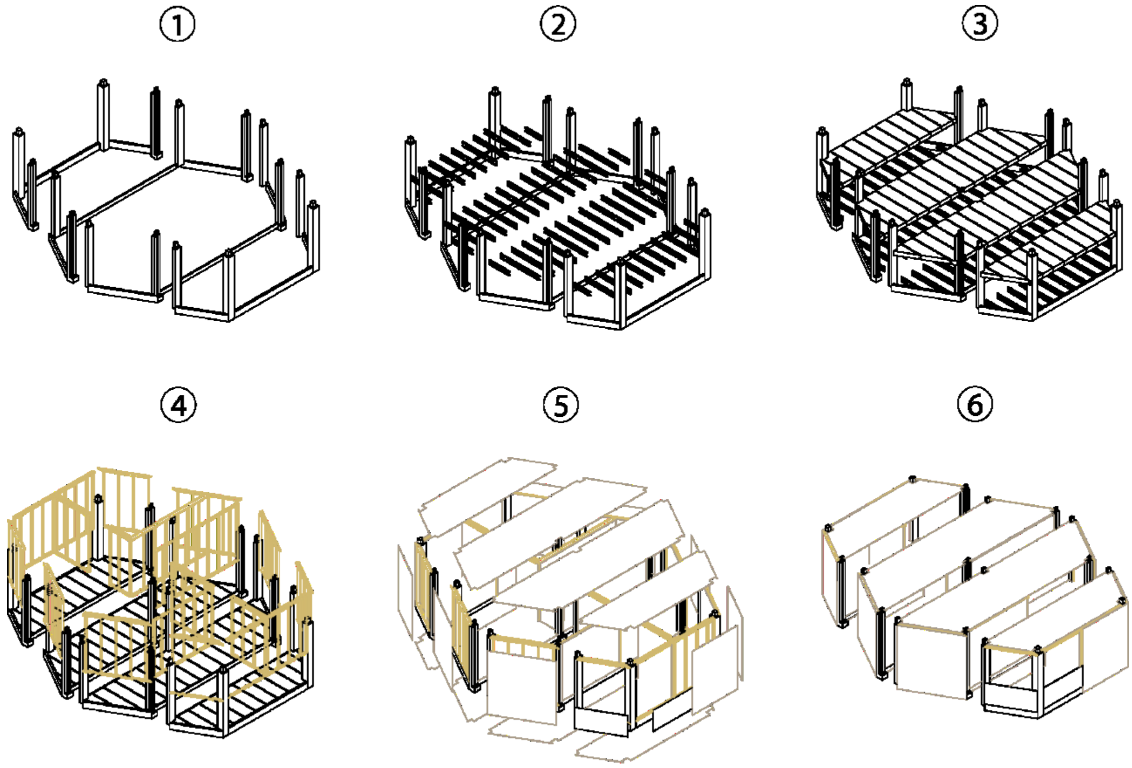


Fig. 15 Off-site modular assembly sequence.

On-site Installation

A fundamental levelling footing would be firstly located on the site by block deck and timber bearer which will not be illustrated in this report. The on-site assembly procedures then follow the exhibited order in Fig. 16 as initially sliding each unit component through the column rail of the adjacent part to integrity a complete hexagon modular unit. The top hexagon will then be lifted above the finished modular following the same sliding sequence, but align the location through the mortise and tenon column joinery and edge beam alignment. A vertical restraint would be provided by thread and bolted connection attached on the column between two modular, which requires simple manual work on tightening. The assembly way gets rid of large manual work and machine operation, easing the on-site construction. Roofing components with gardening was designed as similar pattern but in reduced column length to 1200mm.

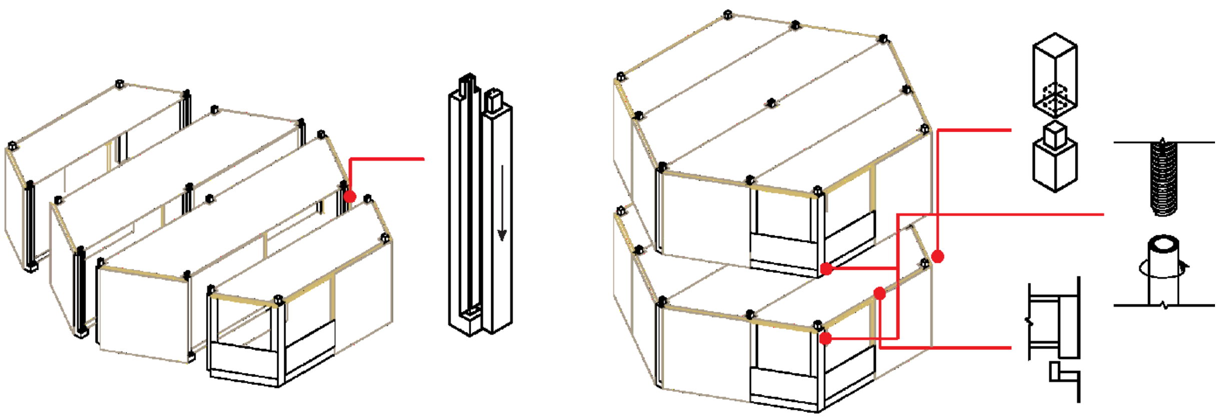


Fig. 16 On-site installation sequence.

4.3.Engineering calculation

The engineering calculation is based on Australia Code AS 1170, supported by SPACEGASS software. The structural form of the proposed apartment is mainly frame structure, demonstrating a great concern on the beam and column capacity check. The overall load values input into SPACEGASS are all listed in Table 1 below based on quantity assumption for the construction materials.

Table 1 Complementary Load Input in SPACEGASS

	Dead Load	Live Load	Wind Load	EarthQuake
Frame Self-Weight	#			
Wall Line Load	95 kg/m			
Floor Load	36.75 kg/m^2			
General Areas		1.5 kPa		
Roof		0.5 kPa		
Wind Load			3.98-4.28 kN/m	
Earthquake				7-7.1 kN

The numerical model only takes one single hexagon column apartment with four floors into account. Considering different load combinations with loading input, the model gave maximum internal load for each main component shown in Table 2.

Table 2 Critical Internal Force of Structural Elements

	Column	Primary Beam	Connection
Axial	104.72 kN (2)		
Shear	6.06 kN (3)		4.32 kN (3)
Bending	9.23 kNm (3)	2.78 kNm (2)	3.99 kNm (1)

Note: The bracket number represent for different loading combination, as (1) for $1.35G$, (2) for $1.2G + 1.5Q$, (3) for $1.2G + \varphi_c Q + Wu$.

Ultimate Limit State Check

Glulam laminated timber material as a high strength engineer wood product, is used for column element. Given the maximum compressive axial force N_c^* for one column as 104.72 kN under different load combinations, the design capacity $N_{d,c} \geq N_c^*$. Based on the basic capacity equation provided in AS 1720.1 $N_{d,c} = \emptyset k_1 k_4 k_6 k_{12} f_c' A_c$ with $\emptyset = 0.85, k_1 = 0.57, k_4 = 1.0, k_6 = 1.0, k_{12} = 1.0, A_c = 90000\ mm^2$. f_c' is then obtained to be larger than 2.4 MPa. The strength of GL 8 is far higher than capacity required.

The primary beam elements are only considered for their bending strength capacity as critical designed load. Given the maximum bending moment M^* as 2.78 kNm under different load combinations, the design capacity $M_d \geq M^*$. Based on the basic capacity equation provided in AS 1720.1 $M_d = \emptyset k_1 k_4 k_6 k_9 k_{12} f'_b Z$ with $\emptyset = 0.85, k_1 = 0.57, k_4 = 1.0, k_6 = 1.0, k_9 = 1.0, k_{12} = 1.0, Z = 1350000\ mm^3$. f'_b is then obtained to be larger than 4.25 MPa. The strength of MGP 10 is far higher than capacity required.

The critical connection shear force is seen between the primary beam and column intersection, as where Sherpa connector is used. M 15 Sherpa connector able to carry the loading within 15-27kN, higher than obtained connection shear design force from numerical model.

Such that, all the components could satisfy the ultimate limit state requirement.

Serviceability Limit State Check

The numerical model only considers one single unit column for analysis, with the critical displacement results and criteria according to AS1720.0 shown in Table.3. The comparison demonstrates enough stiffness for the structure.

Table 3 SLS Check for Element Displacement

	Column Side Sway	**Beam Sag**	**Floor Sag**
Displacement	1.23 mm	2.05 mm	2.24 mm
Criteria	≤ 6 mm	≤ 16 mm	≤ 12 mm

5. Life-cycle assessment (LCA)

This section provides a summary of the energy impact CO_2 emissions of the building system across its 50-year design life including:

- Material Acquisition and Manufacturing
- Transport
- Assembly
- Use

This LCA only considers the materials used for the construction of the building shell, which excludes all the materials used to complete the building (such as bathroom and kitchen fittings, services installation, external/internal finishes and outdoor landscaping), existing urban infrastructure and upstream energy inputs in making the materials (eg. factory/office lighting). In addition, the models do not make an allowance for demolishing or recycling the building and the embodied CO_2 values for timber materials exclude sequestration. The comparative model is assumed to be a free-standing, one-bedroom structure with a lifespan of 50 years. It utilizes more conventional materials and on-site construction methods. Therefore, for a simple comparison, the pre-fab model's life cycle calculations only consider one single-bedroom, hexagonal module from the building system. Furthermore, the LCA assumes both the pre-fab and traditional structures remain at the inner-city Melbourne site for the entire design life.

5.1. Embodied Energy

The process of calculating the embodied energies for the 'Material and Manufacturing' and 'Transport' stages of the life cycle assessment is adapted from Taffese & Abegaz (2019), and the 'Assembly' and 'Use' stages follow the process in Haynes (2013). The aggregate lifecycle embodied energy of the pre-fabricated design model is approximately 124 GJ, and the conventional construction model is approximately 307 GJ. See Appendix D for complete calculations.

5.1.1. Material and Manufacturing Embodied Energy

The proposed building designs are mainly comprised of readily available Australian building materials. For the purpose of simplifying calculations, windows are assumed to be 1200 x 1200 mm, double glazed, air or argon filled (Anderson, 2011), and in the comparative design the pre-cast concrete floor consists of 200 mm T-Beam & infill and the structural wall components are a steel frame and compressed fibre cement clad wall (Milne & Reardon, 2013). Therefore, the total embodied energy across the material acquisition and manufacturing stage of the system is approximately 111,908 MJ for the pre-fab design and 141,625 MJ for the comparison model.

5.1.2. Transport Embodied Energy

The embodied energy for the 'Transport' stage of the structure's life cycle includes the energy required for the transport of recurring components in the use stage. The primary transportation mode for pre-fabricated materials and smaller building components is rigid trucks, which are motor vehicles exceeding 3.5 tonnes GVM, constructed with a load carrying area. Articulated trucks are using to carry larger building components. Assuming the pre-fabrication facility is 50 km from the inner-city building site, the total embodied energy in the transport stage is calculated as approximately 1828 MJ and 12,927 MJ for the pre-fabricated and conventional structures respectively.

5.1.3. Assembly Embodied Energy

The total embodied energy of the assembly stage considers the machinery and tools used in the process. This does not include the embodied transport energy/emissions for human labour or each item of equipment. Therefore, the total embodied energy for the assembly stage of the building design is 10,224 MJ and the comparative design is 132,156 MJ.

5.1.4. Use Embodied Energy

The total embodied energy of the pre-fab building during its service life is approximately 379 MJ. This considers the replacement rate for each material across the 50-year lifespan with the only energy contributions coming from the replacement of windows and plasterboard. In the conventional construction model, the embodied energy through the building's usage phase is approximately 20,127 MJ due to the maintenance of flooring, roof, window and plasterboard components.

5.2.Embodied CO2 Emissions

Using emission factors from various resources, the aggregate embodied CO_2 emissions across the prefab building's entire lifecycle is approximately 7.5 tonnes, and 48.8 tonnes for the traditional construction. See Appendix E for complete calculations.

5.2.1. Material and Manufacturing Embodied CO2 Emissions

The total embodied CO_2 emissions across this period is approximately 6,678 kg and 38,919 kg for the pre-fab and conventional construction models respectively.

5.2.2. Transport Embodied CO2 Emissions

The total embodied CO_2 emissions across this period is approximately 120 kg and 847 kg for the pre-fab and conventional construction models respectively. This includes the CO_2 emitted during the transport of replacement components in the use stage.

5.2.3. Assembly Embodied CO2 Emissions

The total embodied CO_2 emissions across this period is approximately 670 kg and 8,687 kg for the pre-fab and conventional construction models respectively.

5.2.4. Use Embodied CO2 Emissions

The total embodied CO_2 emissions across this period is approximately 30 kg and 327 kg for the pre-fab and conventional construction models respectively.

5.3. Analysis & Recommendations

The embodied energy and CO_2 emissions contributions across the lifecycle of the pre-fabricated building are concentrated in the off-site acquisition and prefabrication of materials (approx. 90%), as shown in Figures C1. Likewise, in the conventional building, embodied CO_2 emissions largely occur in the materials & manufacturing phase (approx. 80%) and an increased amount during assembly (approx. 18%), see Figure C2. Conversely, the conventional structure has a greater distribution of embodied energy across the building's lifecycle including approximately 46% in the materials & manufacturing phase and 43% during assembly, as shown in Figure C2.

Overall, in this LCA, the traditional building exhibits far greater embodied energy and emissions than the proposed prefabricated structure. This can be examined across each lifecycle stage to demonstrate design advantages and further recommendations. The prefab construction requires less transport energy than on-site construction methods because the major building components are hauled directly from a single prefabrication site rather from multiple supplier locations. Furthermore, lower on-site equipment and assembly requirements result in a significantly lower embodied footprint in the assembly phase. The use of materials with higher churn rates also influences the footprint of the overall building system. This is limited to two materials (with low replacement rates and embodied energy/emissions) in the proposed prefab design whereas in the traditional design there are two additional high-energy materials that are likely to require replacement during the building's service life.

The embodied energy and emissions arising from the disposal of building components is not considered in the embodied energy calculations, however, there are elements of the proposed design that aim to make the building more sustainable. This includes modular components that can be re-used at other sites or re-processed for alternative purposes. In addition, this allows modules to be easily separated, which reduces the need for deconstruction equipment. However, this also requires rigid truck transportation, which further contributes to the embodied footprint.

6. Feasibility

6.1. Industry 4.0

The fourth industrial revolution create a new stage for automated industry development. The modern control systems would be embedded into all aspects of industry as clients could get networked efficiently and visibly with product manufacture and provide real-time feedback for promotion. To suit the automation industrialization, the apartment manufacture process would be undertaken through automated control system with digitization tools and robotics. As the similar structure pattern was seen for each hexagon unit, a fundamental digital tool would be firstly designed. All other extension or plug-in would be embedded for alternative options for interior arrangement of the unit to meet different client demand.

The component manufacture process would be highly automated as all the subassemblies geometries are generated from digital tool and output to CNC or robotic machine. Modular assembly process follows the sequence shown in Fig. X under the robotic operation and labelled with installation order, easing for on-site construction.

6.2. Deconstruction

A great concern for construction and demolition (C & D) waste has motivate a new sustainable concept applied in construction industry, termed as design for deconstruction (DfD). Through reusing and recycling the building material economically and environmentally friendly, DfD could increase the utilisation of the material and reduce site waste as well.

The manufacture and assembly of the hexagon structure allow for deconstruction in a easy way without any damage on the modular unit and relocation cost-effectively. Each modular unit could be disaasembled by unscrew the thread connector and lift by crane one by one through the dovetail rail in column.

6.3.Construction Programme

The construction programme for our designed apartment is illustrated in Fig. 17, showing an efficient project progress as work like manufacture and foundation construction could be complemented at the same time. The on-site installation could be seen as only consuming less than two months, which could reduce the environment effect to the surrounding on-site.

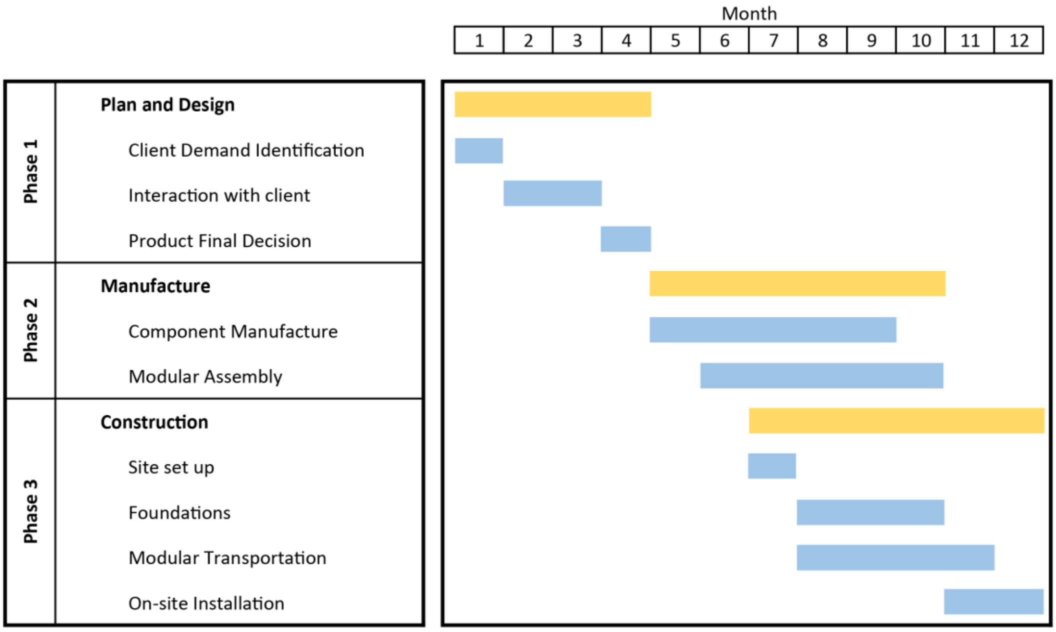


Fig. 17 Construction programme.

6.4.Budget evaluation

The budget evaluation is based on the following assumptions: a) Materials amount considers the entire building structure; b) Operating costs are for the building's 50-year lifespan; c) Assembly costs (i.e. crane hire and use) includes the travel time from its base and the travel time back to base after the lift. It will also include the time it takes the crane to set-up for the lift and to pack up for the lift. Set up may include fixing and supporting outriggers and counterweights; d) Ignore utility connection (e.g. plumbing and electrical) costs. The material costs and capital & operation costs are $ 750429.26 and $ 890504.77 respectively, with details shown in Appendix F.

6.5.Responses to climate emergency

The extreme climate condition in Melbourne is normally the super-hot weather, which could be relieved through the façade design and where heat could be absorbed through the roof garden.

7. Building regulatory

[1] Transportation Regulation: Heavy Vehicle National Regulation

[2] National Construction Code 2016

[3] AS 1170.0, AS 1170.1, AS 1170.2, AS 1170.3, AS 1170.4, AS 1720.1

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Appendix A Earthquake and Snow and Ice Action Consideration

Earthquake action (AS1170.4)

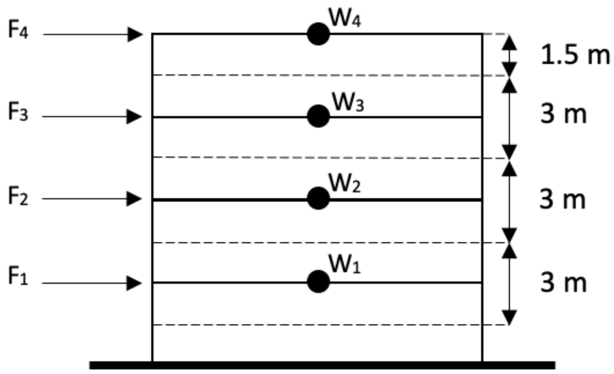
The structure's proposed design life is 50 years of residential occupation with ordinary consequences of failure. Therefore, the structure has an importance level of 2 (Table F1 AS/NZS1170.0) and an annual probability of exceedance for earthquake events of 1/500 (Table F2). The probability factor (k_p) for the annual probability of exceedance is 1.0 (Table 3.1 AS1170.4), and the hazard factor (Z) for Melbourne is 0.08 (Table 3.2). Hence, $k_pZ = 0.08$. The structure's height is 12 metres (four storeys, $h_n \leq 12$) and the site sub-soil class is assumed to be Class C – Shallow Soil, hence the design procedure for this structure shall be in accordance with the requirements for Earthquake Design Category 1 (Table 2.1).

The structure will be designed for the equivalent static forces (F_i) applied laterally to the centres of mass of the levels of the structure, which can be summed to obtain the base shear load (V) at ULS. This is obtained using the seismic weight (W_i) at each level:

$W_i = \Sigma G_i + \Sigma \Psi_c Q_i$ ··· *Clause 6.2.2*

$F_i = 0.1W_i$ ··· *Clause 5.3*

$V = \Sigma F_i$



Considering the structure is for residential applications, the earthquake-imposed action combination factor (Ψ_c) is 0.3. The design procedure (1.3 Appendix) considers the structure as six separate building sections: one single bedroom module, one lift/access module and four double bedroom & communal rooftop modules with the assumptions the slope of design site is negligible (≈1.8°). Also, the calculation of the permanent and imposed action at each level of the structure has these structural considerations:

- Column cross-section = 300 x 300 mm
- Density of columns = 650 kg/m^3
- Unit length weight of I-joist = 9.9 kg/m
- Depth of walls & floors = 25 mm
- Density of walls & flooring = 640 kg/m^3

In addition, the complete earthquake design process for loading at ULS does not consider the access walkways, fire stairs and terrace flooring in the seismic weight calculations. See 1.3 Appendix for full details.

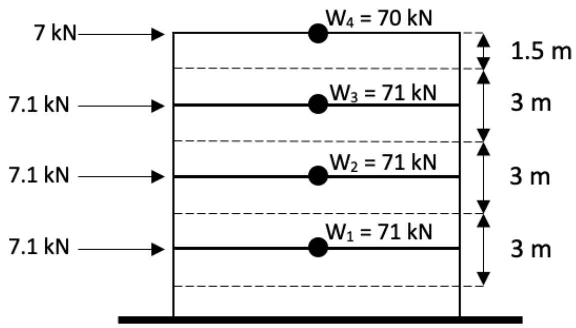
Single Bedroom Module

Equivalent lateral static forces:

$F_1 = 7$ kN, $F_2 = F_3 = F_4 = 7.1$ kN

Base Shear Load:

V = 28.3 kN



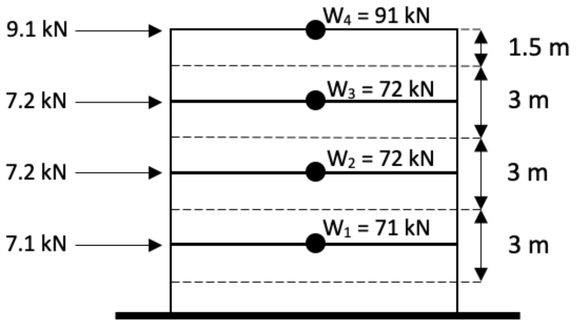
Double Bedroom Module

Equivalent lateral static forces:

$F_1 = 7.1$ kN, $F_2 = F_3 = 7.2$ kN, $F_4 = 9.1$ kN

Base Shear Load:

V = 30.6 kN



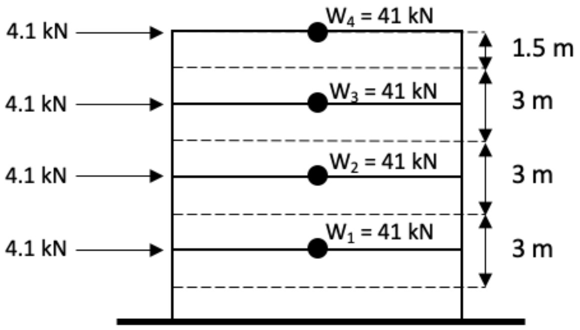
Access Module

Equivalent lateral static forces:

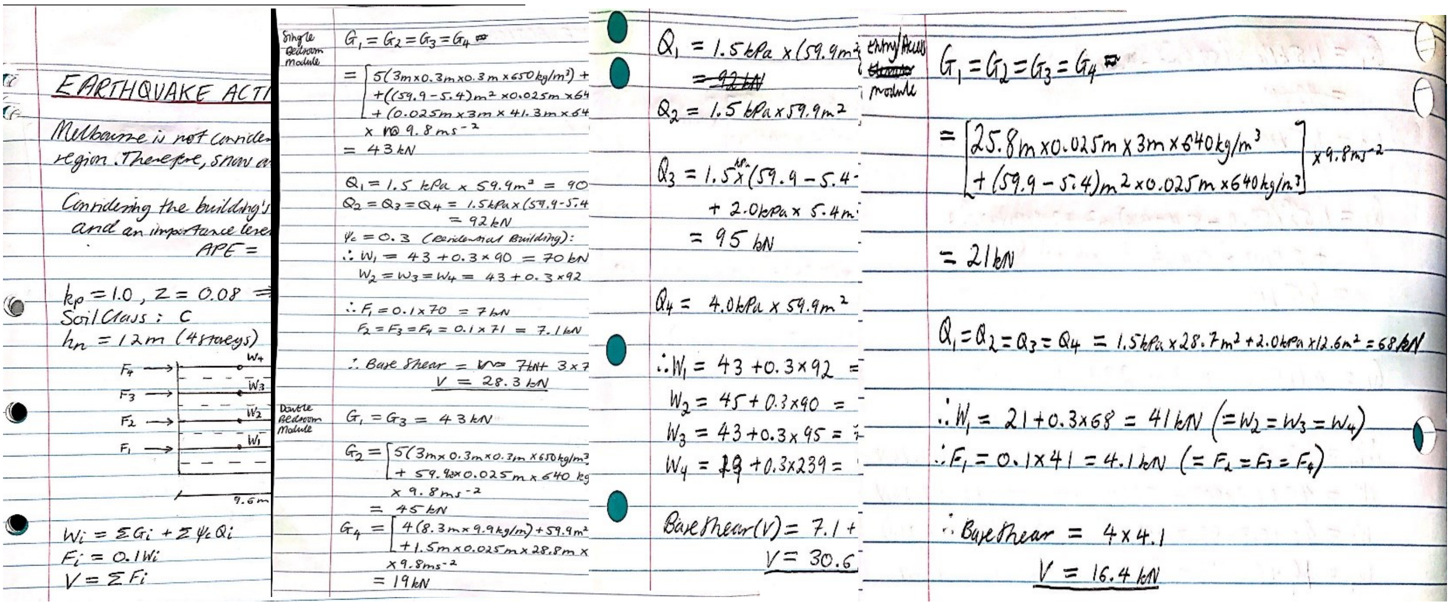
$F_1 = F_2 = F_3 = F_4 = 4.1$ kN

Base Shear Load:

V = 16.4 kN



Therefore, at ULS, the maximum expected lateral force on the base of the structure due to seismic activity is 30.6 kN.

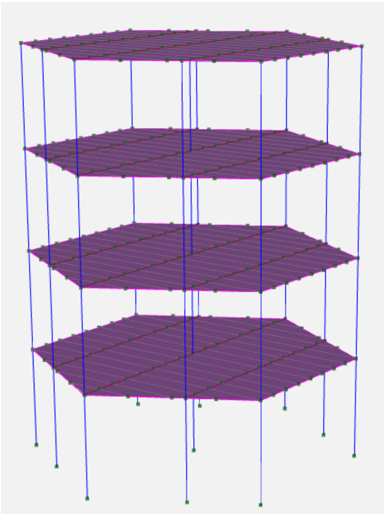
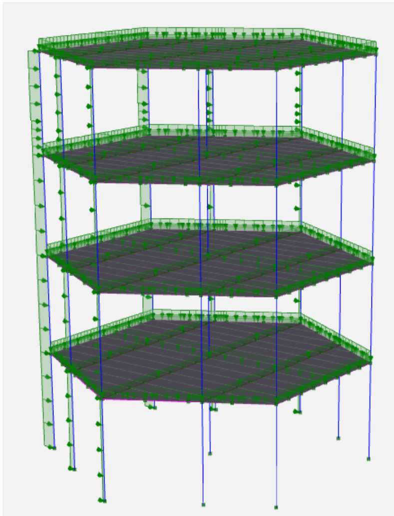
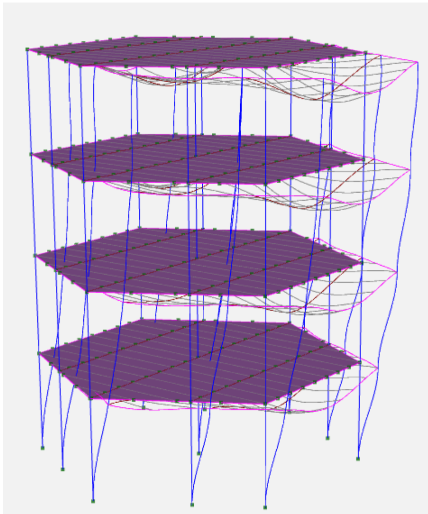


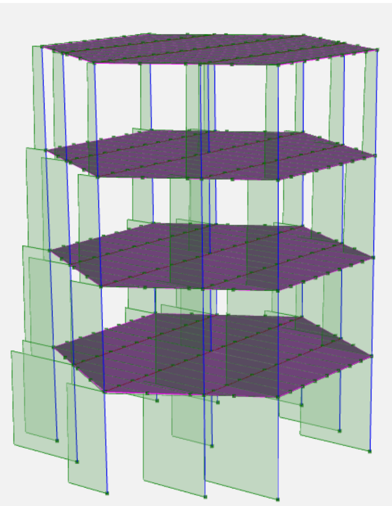
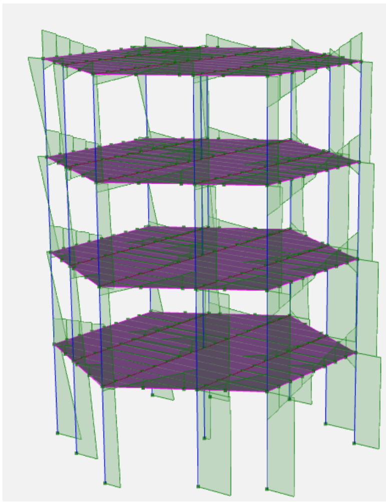
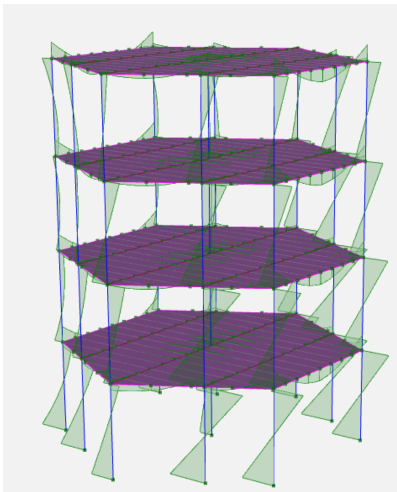
Snow and ice actions (AS/NZS1170.3)

The initial design site in the inner-city suburbs of Melbourne is not considered an alpine or sub-alpine region. Therefore, snow and ice loading is not applicable to the building's structural capacity at ultimate limit state (ULS).

Appendix B SPACEGASS Numerical Model

The numerical model is screen shot under loading combination $1.2G + \varphi_c Q + Wu$, with a) for frame model configuration, b) for loads configuration, c) for displacement, d) for axial load, e) for shear force and f) for bending moment.

a) 
b) 
c) 

d) 
e) 
f) 

Appendix C Pre-Fab versus Conventional construction LCA Comparison

Figure C1 Embodied Energy and CO2 Emissions of Pre-fabricated Design Model

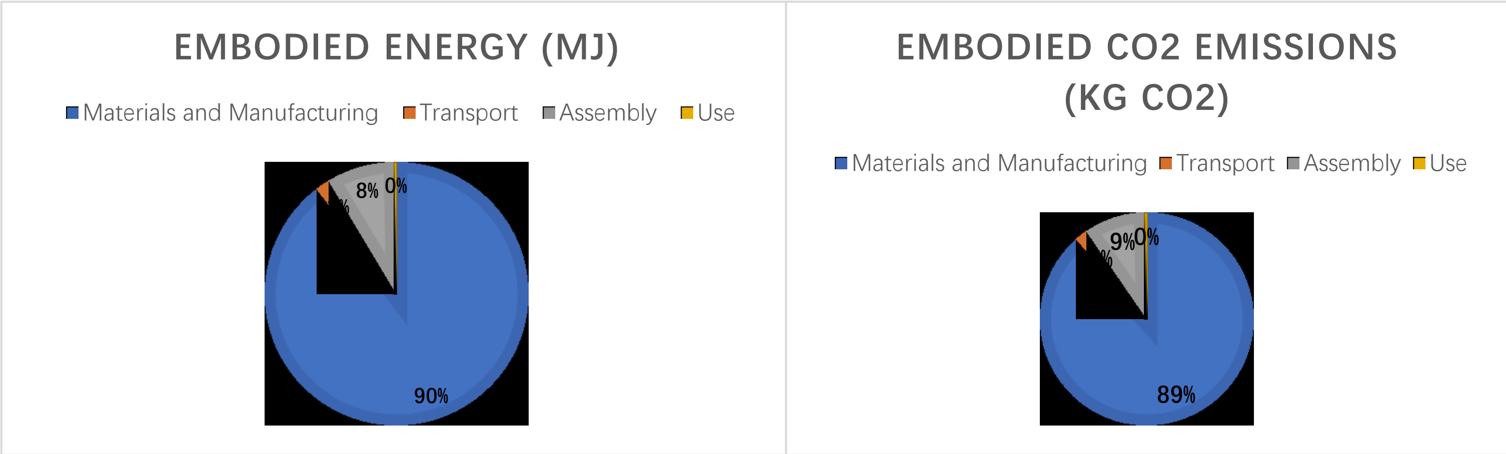
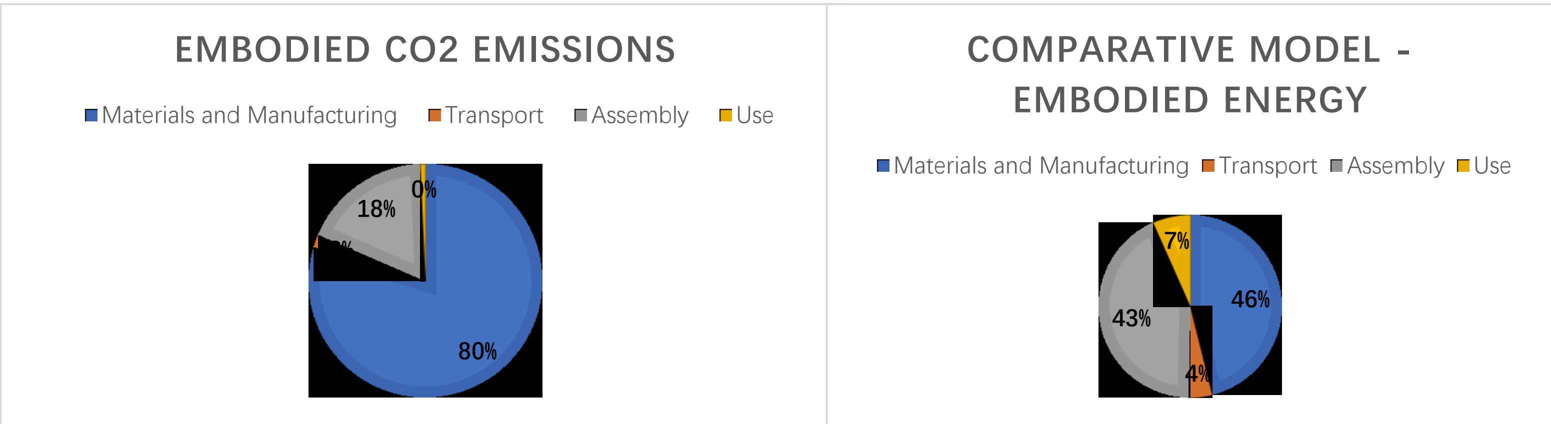


Figure C2 Embodied Energy and CO2 Emissions of Conventional Construction Model



Appendix D Pre-Fab Model Calculation Table

Embodied Energy

Table D1

Materials and Manufacturing (Cradle-to-Gate)				
Component	**Material**	**Embodied Energy**	**Quantity**	**Total Embodied Energy (MJ)**
Column	Glue Laminated Timber (GLT)	11 MJ/kg (Milne & Reardon, 2013)	30 m	19,305
Floor & Wall	Structural Insulated Panel (SIP)	103.6 MJ/kg (Anderson, 2011)	220 m^2	66,097
Wall Stud	Kiln-dried sawn softwood	3.4 MJ/kg (Milne & Reardon, 2013)	420 m	2,313
Wall, Floor & Roof	Plywood Panel	10.4 MJ/kg (Milne & Reardon, 2013)	320 m^2	17,971
Structural Beams (I-Joist)	Oriented Strand Board (OSB), Lamnated Veneer Lumber (LVL)	13 MJ/kg (Milne & Reardon, 2013)	110 m	3,775
Windows	Glass, Timber Frame	230 MJ/window (Anderson, 2011)	4 units	920
Internal Finishing	Plasterboard	4.4 MJ/kg (Milne & Reardon, 2013)	500 m^2	1,437
Process	**Equipment**	**Fuel Efficiency**	**Time Required (Hours)**	**Total Embodied Energy (MJ)**
Assembly	Power Tools and Equipment	2.5 kWh (Haynes, 2013)	10	90
Materials & Manufacturing Total				111,908

Table D2

Transport (to-Site)						
Transport Mode	**Component**	**Hauling Distance (km)**	**Round Trips**	**(L/km)**	**Lower Heating Value of Diesel (MJ/kg)**	**(MJ)**
Rigid Truck	Unit Module	50	3	0.286 (Budget Direct, 2020)	42.6 (Engineering Toolbox, 2003)	1,828
Transport Total						1,828

Table D3

Assembly (to-Handover)					
Process	**Equipment**	**Fuel Efficiency**	**Lower Heating Value of Diesel (MJ/kg)**	**Time Required (Hours)**	**Total Embodied Energy (MJ)**
Install Module	Crane	30 L/h (Haynes, 2013)	42.6 (Engineering Toolbox, 2003)	8	10,224
Assembly Total					10,224

Table D4

Use (to-End of Use)				
Component	**Material**	**Embodied Energy (MJ)**	**Replacement Rate**	**Total Embodied Energy (MJ)**
Column	GLT	19,305	0%	0
Floor & Wall	SIP	66,097	0%	0
Wall	Kiln-dried sawn softwood	2,313	0%	0
Wall, Floor & Roof	Plywood Panel	17,971	0%	0
Structural Beams	OSB & LVL	3,775	0%	0
Windows	Glass, Timber Frame	920	10% (Haynes, 2013)	92
Internal Finishing	Plasterboard	1,437	20% (Haynes, 2013)	287
Operational Total				379

Table D5 Summary

Aggregate Lifecycle Embodied Energy					
Life Cycle Stage	**Materials and Manufacturing**	**Transport**	**Assembly**	**Use**	**Total (MJ)**
Embodied Energy (MJ)	111,908	1,828	10,224	379	124,339

Embodied CO_2 Emissions

Table D6

Materials and Manufacturing (Cradle-to-Gate)				
Component	**Material**	**Embodied CO2 Emissions (kg CO2/kg)**	**Weight (kg)**	**Total Embodied CO2 Emissions (kg CO2)**
Columns	GLT	0.87 (Anderson, 2011)	1,755	1,527
Floor & Wall	SIP	3.51 (Anderson, 2011)	638	2,239
Wall Stud	Kiln-dried sawn softwood	0.86 (Anderson, 2011)	680	585
Wall, Floor & Roof	Plywood Panel	1.07 (Anderson, 2011)	1,728	1,849
Structural Beams (I-Joist)	OSB & LVL	0.96 (Anderson, 2011)	290	278
Windows	Glass, Timber Frame	12 kg CO2/window (Anderson, 2011)	4 units	48
Internal Finishing	Plasterboard	0.38 (Anderson, 2011)	327	124
Process	**Equipment**	**Fuel Efficiency & Emission Factor**	**Time Required (Hours)**	**Total Embodied CO2 Emissions (kg CO2)**
Assembly	Power Tools and Equipment	2.5 kWh (Haynes, 2013) & 0.3 (City of Winnipeg, 2020)	10	27
Materials & Manufacturing Total				6,678

Table D7

Transport (to-Site)						
Transport Mode	**Component**	**Hauling Distance (km)**	**Round Trips**	**Fuel Energy Coefficient (L/km)**	**Emission Factor (kg CO2/L)**	**Total Embodied CO2 Emissions (kg CO2)**
Rigid Truck	Unit Module	50	3	0.286 (Budget Direct, 2020)	2.79 (City of Winnipeg, 2020)	120
Transport Total						120

Table D8

Assembly (to-Handover)					
Component	**Equipment**	**Fuel Efficiency**	**Emission Factor (kg CO2/unit)**	**Time Required (Hours)**	**Total Embodied CO2 Emissions (kg CO2)**
Install Module	Crane	30 L/h (Haynes, 2013)	2.79 (City of Winnipeg, 2020)	8	670
Assembly Total					670

Table D9

Use (to-End of Use)				
Component	**Material**	**Embodied CO2 Emissions (kg CO2)**	**Replacement Rate**	**Total Embodied CO2 Emissions (kg CO2)**
Column	GLT	1,527	0	0
Floor & Wall	SIP	2,239	0	0
Wall	Kiln-dried sawn softwood	585	0	0
Wall, Floor & Roof	Plywood Panel	1,849	0	0
Structural Beams	OSB & LVL	278		
Windows	Glass, Timber Frame	48	10% (Haynes, 2013)	5
Internal Finishing	Plasterboard	124	20% (Haynes, 2013)	25
Operational Total				30

Table D10 Summary

Aggregate Lifecycle Embodied CO2 Emissions					
Life Cycle Stage	**Materials and Manufacturing**	**Transport**	**Assembly**	**Use**	**Total (kg CO2)**
Embodied CO2 Emissions (kg CO2)	6,678	120	670	30	7,497

Appendix E Conventional Construction Model Calculation Table

Embodied Energy

Table E1

Materials and Manufacturing (Cradle-to-Gate)				
Component	**Material**	**Embodied Energy**	**Quantity**	**Total Embodied Energy (MJ)**
Floor	Pre-cast Concrete T-Beam	644 MJ/m^2 (Milne & Reardon, 2013)	60 m^2	38,640
Floor	OSB	15 MJ/kg (Anderson, 2011)	55 m^2	13,200
Flooring	Ceramic Tiles	12 MJ/kg (Anderson, 2011)	60 m^2	14,400
Wall	Steel, Cement	385 MJ/m^2 (Milne & Reardon, 2013)	87 m^2	33,495
Windows	Glass, Aluminium Frame	5470 MJ/window (Anderson, 2011)	4	21,880
Roof	Timber, Terracotta, Plasterboard	271 MJ/m^2 (Milne & Reardon, 2013)	60 m^2	16,260
Wall Stud	Kiln-dried sawn softwood	3.4 MJ/kg (Milne & Reardon, 2013)	420 m	2,313
Internal Finishing	Plasterboard	4.4 MJ/kg (Milne & Reardon, 2013)	500 m^2	1,437
Materials and Manufacturing Total				141,625

Table E2

Transport (to-Site)						
Transport Mode	**Component**	**Hauling Distance (km)**	**Round Trips**	**Fuel Energy Coefficient (L/km)**	**Lower Heating Value of Diesel (MJ/kg)**	**Total Embodied Energy (MJ)**
Articulated Truck	Floor (Concrete T-Beam)	100	1	0.552 (Budget Direct, 2020)	42.6 (Engineering Toolbox, 2003)	2,352
Rigid Truck	Floor (OSB)	50	1	0.286 (Budget Direct, 2020)	42.6 (Engineering Toolbox, 2003)	609
Rigid Truck	Flooring	50	1	0.286 (Budget Direct, 2020)	42.6 (Engineering Toolbox, 2003)	1,218
Articulated Truck	Wall	75	1	0.552 (Budget Direct, 2020)	42.6 (Engineering Toolbox, 2003)	2,352
Rigid Truck	Windows	25	1	0.286 (Budget Direct, 2020)	42.6 (Engineering Toolbox, 2003)	670
Rigid Truck	Roof	50	1	0.286 (Budget Direct, 2020)	42.6 (Engineering Toolbox, 2003)	2,193
Rigid Truck	Wall Stud	50	1	0.286 (Budget Direct, 2020)	42.6 (Engineering Toolbox, 2003)	609
Rigid Truck	Plasterboard	5	1	0.286 (Budget Direct, 2020)	42.6 (Engineering Toolbox, 2003)	2,924
Transport Total						12,927

Table E3

Assembly (to-Handover)					
Category	Equipment	Fuel Efficiency	Lower Heating Value of Diesel (MJ/kg)	Time Required (hours)	Total Embodied Energy (MJ)
Site Works	Excavator	60 L/h (Haynes, 2013)	42.6 (Engineering Toolbox, 2003)	20	51,120
Floor	Bobcat	12 L/h (Haynes, 2013)	42.6 (Engineering Toolbox, 2003)	40	20,448
Foundations	Concrete Pump	20 L/h (Haynes, 2013)	42.6 (Engineering Toolbox, 2003)	24	20,448
Roof	Crane	30 L/h (Haynes, 2013)	42.6 (Engineering Toolbox, 2003)	30	38,340
Floor, Flooring, Windows, Walls & Roof	Power Tools and Equipment	2.5 kWh (Haynes, 2013)	-	200	1,800
Assembly Total					132,156

Table E4

Use (to-End of Use)				
Component	Material	Embodied Energy (MJ)	Replacement Rate	Total Embodied Energy (MJ)
Floor	Pre-cast Concrete	38,640	0% (Haynes, 2013)	0
Floor	OSB	13,200	0% (Haynes, 2013)	0
Flooring	Ceramic Tiles	14,400	100% (Haynes, 2013)	14,400
Wall	Steel, Cement	33,495	0% (Haynes, 2013)	0
Windows	Glass, Aluminium Frame	21,880	10% (Haynes, 2013)	2,188
Roof	Timber, Terracotta, Plasterboard	16,260	20% (Haynes, 2013)	3,252
Wall Stud	Kiln-dried sawn softwood	2,313	0% (Haynes, 2013)	0
Internal Finishing	Plasterboard	1,437	20% (Haynes, 2013)	287
Use Total				20,127

Table E5 Summary

Aggregate Lifecycle Embodied Energy					
Life Cycle Stage	Materials and Manufacturing	Transport	Assembly	Use	Total (MJ)
Energy Use (MJ)	141,625	12,927	132,156	20,127	306,835

Embodied CO_2 Emissions

Table E6

Materials and Manufacturing (Cradle-to-Gate)				
Component	Material	Embodied CO2 (kg CO2/kg)	Weight (kg)	Total Embodied CO2 Emissions (kg CO2)
Floor	Pre-cast Concrete	0.215 (Sabnis, Mysore, Shashi, 2015)	17,400	3,741
Floor	OSB	0.72 (Anderson, 2011)	688	495
Flooring	Ceramic Tiles	0.74 (Anderson, 2011)	250	185
Walls	Steel, Cement	1.57 (Anderson, 2011)	20,358	31,962
Windows	Glass, Aluminium Frame	279 kg CO2/window (Anderson, 2011)	4 units	1,116
Roof	Timber, Terracotta, Plasterboard	0.74 (Anderson, 2011)	960	710
Wall Stud	Kiln-dried sawn softwood	0.86 (Anderson, 2011)	680	585
Internal Finishing	Plasterboard	0.38 (Anderson, 2011)	327	124
Materials and Manufacturing Total				38,919

Table E7

Transport (to-Site)						
Transport Mode	Component	Hauling Distance (km)	Round Trips	Fuel Energy Coefficient (L/km)	Emission Factor (kg CO2/L)	Total Embodied CO2 Emissions (kg CO2)
Articulated Truck	Floor (Concrete T-Beam)	100	1	0.552 (Budget Direct, 2020)	2.79 (City of Winnipeg, 2020)	154
Rigid Truck	Floor (OSB)	50	1	0.286 (Budget Direct, 2020)	2.79 (City of Winnipeg, 2020)	40
Rigid Truck	Flooring	50	1	0.286 (Budget Direct, 2020)	2.79 (City of Winnipeg, 2020)	80
Articulated Truck	Wall	75	1	0.552 (Budget Direct, 2020)	2.79 (City of Winnipeg, 2020)	154
Rigid Truck	Windows	25	1	0.286 (Budget Direct, 2020)	2.79 (City of Winnipeg, 2020)	44
Rigid Truck	Roof	50	1	0.286 (Budget Direct, 2020)	2.79 (City of Winnipeg, 2020)	144
Rigid Truck	Wall Stud	50	1	0.286 (Budget Direct, 2020)	2.79 (City of Winnipeg, 2020)	40
Rigid Truck	Plasterboard	5	1	0.286 (Budget Direct, 2020)	2.79 (City of Winnipeg, 2020)	192
Transport Total						847

Table E8

Assembly (to-Handover)					
Category	**Equipment**	**Fuel Efficiency**	**Emission Factor (kg CO2/unit)**	**Time Required (hours)**	**Total Embodied CO2 Emissions (kg CO2)**
Site Works	Excavator	60 L/h (Haynes, 2013)	2.79 (City of Winnipeg, 2020)	20	3,348
Floor	Bobcat	12 L/h (Haynes, 2013)	2.79 (City of Winnipeg, 2020)	40	1,339
Foundations	Concrete Pump	20 L/h (Haynes, 2013)	2.79 (City of Winnipeg, 2020)	24	1,339
Roof	Crane	30 L/h (Haynes, 2013)	2.79 (City of Winnipeg, 2020)	30	2,511
Floor, Flooring, Windows, Walls & Roof	Power Tools and Equipment	2.5 kWh (Haynes, 2013)	0.3 (City of Winnipeg, 2020)	200	150
Assembly Total					8,687

Table E9

Use (to-End of Use)				
Compnent	**Material**	**Embodied CO2 Emissions (kg CO2)**	**Replacement Rate**	**Total CO2 Emissions (kg CO2)**
Floor	Pre-cast Concrete	3,741	0% (Haynes, 2013)	0
Floor	OSB	495	0% (Haynes, 2013)	0
Flooring	Ceramic Tiles	185	100% (Haynes, 2013)	185
Wall	Steel, Cement	31,962	0% (Haynes, 2013)	0
Windows	Glass, Aluminium Frame	1,116	10% (Haynes, 2013)	0
Roof	Timber, Terracotta, Plasterboard	710	20% (Haynes, 2013)	142
Wall Stud	Kiln-dried sawn softwood	585	0% (Haynes, 2013)	0
Internal Finishing	Plasterboard	124	20% (Haynes, 2013)	25
Use Total				327

Table E10 Summary

Aggregate Lifecycle Embodied CO2 Emissions					
Life Cycle Stage	**Materials and Manufacturing**	**Transport**	**Assembly**	**Use**	**Total (kg CO2)**
Energy Use (MJ)	38,919	847	8,687	327	48,780

Appendix F Budget Calculation Table

Table F1 Material Cost

Material Costs				
Material	Bulk cost	Quantity	Net Cost	
Glue Laminated Timber	$ 144.32 /m	660 m	$	95,251.20
Structural Insulated Panel	$73.90 /m	4329 m^2	$	319,913.10
Wall Stud (Kiln-dried sawn softwood)	$ 4.75 /m	8232 m	$	39,102.00
Plywood Panel	$ 15.11 /m^2	9900 m^2	$	149,589.00
I-Joist	$ 13.55 /m	2268 m	$	30,731.40
Windows (Glass & Timber)	$ 800 /window	80	$	64,000.00
Plasterboard	$ 5.26 /m^2	9856 m^2	$	51,842.56
Total Material Cost			$	750,429.26

Table F2 Capital and Operating Cost

Manufacturing Costs					
Process	Bulk Cost			Net Cost	
Plasterboarding	$12 / m^2		9856 m^2	$	118,272.00
Window Installation	$80 /h		8 hours	$	560.00
Total Manufacturing Cost				$	118,832.00
Transport Costs					
Transport Mode	Bulk Cost		Round Trips	Net Cost	
Rigid Truck	$	425.00	3	$	1,275.00
Total Transport Cost				$	1,275.00
Assembly Costs	Bulk cost		Time Required (Hours)	Net Cost	
80 Tonne Crane	$320 /h		10	$	3,200.00
Total Assembly Cost				$	3,200.00
Usage Costs					
Material	Net Cost		Replacement Rate	Total Cost	
Windows	$	64,000.00	0.1	$	6,400.00
Plasterboard	$	51,842.56	0.2	$	10,368.51
Total Operating Cost				$	16,768.51
Total Capital and Operating Cost	$	890,504.77			