WHY NOT

PAPER ARCHITECTURE

IN THE FUTURE?

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Master studio 1: EXTREME Archtecture AR1AE011

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The MSc Architecture, Urbanism and Building Sciences (Track Architecture) programme

Introduction

Paper as a sustainable material with advantages such as extremely lightweight, easy to fabricate and recyclable, has been everywhere in our daily life. What if we can recycle waste paper and make it into an environmentally-friendly and high-performance paper architecture?

Through fireproof and waterproof processing, recycled paper can be translated into structures, walls, insulations and facades, which replace the regular high carbon emission materials of ordinary buildings. Owe to the recyclability and sustainability of paper fibers, paper can again be used in new engineered elements at the end of its lifespan. So, actually, paper architecture stores carbon in the whole building life cycle to help deal with the urban heat island effect.

After research of properties and cases, several paper products for architectural prototype are proposed: paper core and paper tube truss for structure, paper honeycomb panel and paper cellulose for high-thermal walls, and molded paper composite for façade.

With this paper design tool, I proposed a design for BK faculty to reduce the Urban Heat Island Effect through the use of innovative materials that could have a complete circular life cycle. In BK's history, it was always changing and breaking through. And as an innovative and experimental faculty, it will need more flexible space in the future. I think it will be a new campus village with living, experimenting and creating for designers and engineers. The different lifespans of paper architecture prototype can satisfy the students' requirements for permanent apartments, semi-permanent experimental space and temporary pavilions.

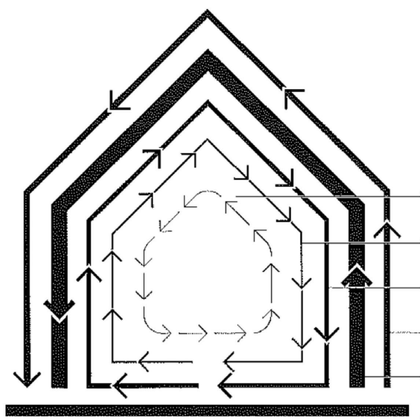
Besides the recyclable features, this prototype has two more noticeable advantages. Firstly, due to the extremely light weight of paper, the partition walls made of paper honeycomb and wood panel can be over 20 times lighter than the concrete wall, which reduces transportation consumption and is more convenient for installation. This provides strong flexibility to the student apartments on this site, and students can freely design and change the space plan. Secondly, due to paper's easy processing and high strength characteristics, it can be manufactured into structural components of free shape and size, providing innovative structural potentials. For example, through the paper winding operation, paper core with circular or convex polygonal cross sections can have 2m maximum diameter and 6m maximum length, the span of paper truss can reach 40m, which has been proven to be temporary building structures in Shigeru Ban's projects. This easy processing characteristic of paper provides the potential for huge lightweight flexible space and aesthetic pavilion space, where students can make digital fabrication and exhibit their design products.

Here we can see the perfect fusion of new paper architecture and this experimental and innovative faculty. As a catalyst, this sustainable, flexible and aesthetic paper architecture definitely will provide a space full of creativity and imagination, inspiring these designers here to think about the future of architecture and environment.

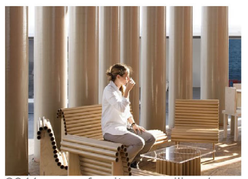
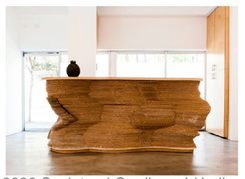
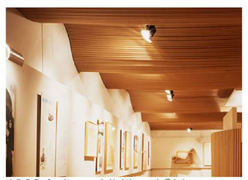
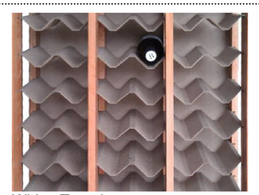
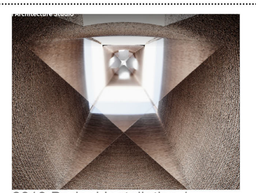
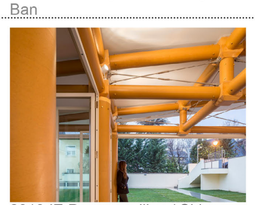
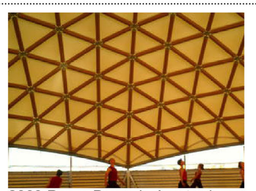
01 Research

01 Research

The potential of paper architecture



Brand's 6S shearing layers theory

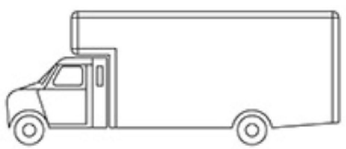
	Paper tube		Cardboard panel		Molded paper	
Stuff Furniture Equipment < 3 years	 2007 paper furniture / paper-less office	 2011 paper furniture pavilion / Shigeru Ban	 2006 Sculptural Cardboard / ball nogues studio	 2014 Semi-transparent paper / stlandsutstillingen	 2008 Paper Chair / Mario Stadelmann	 2018 Paper pulp / Beer Holthuis
Space plan Interior layout (walls,floors,ceilings) 3 - 30 years	 1968 Aalto exhibition / Shigeru Ban	 2014 paper tube wall / Perkins + Wills	 2007 Papercut / dARCH studio	 Honeycomb Wall / ECOCELL fast-building system	 2016 Wallpapering acoustic insulation / Dear Human	 Paper cellulose insulation / ECOCELL
Services Operating system (heating, electricity) 7 - 15 years	 Paper tube for air supply in toilet		 Wiring Trough			
Skin Envelope (facade, roof) 20 years	 1995 Paper log house / Shigeru Ban	 1995 Paper house / Shigeru Ban	 2019 Barjeel Installation / Miskavi Architecture Studio	 2009 Cardboard pavilion / Cambridge University	 2010 Paper composite / Finland pavilion Shanghai EXPO	
Structure Foundation (load-bearing element) 30-300 years	 2013 IE Paper pavilion / Shigeru Ban	 2003 Paper Dome in Amsterdam	 2011 Cardboard Column / Michael Hansmeyer	 2001 Veneer Grid roof house / Shigeru Ban	 2007 Paper composite / Shigeru Ban	
Site Location / Context > 300 years						

01 Research

Advantages of paper

Lightweight

690 kg/m^3 for solid paper
130 kg/m^3 for paper tube
30-90 kg/m^3 for paper honeycomb
3 times ligher than CLT panels / 12 times lighter than concrete panel



easy to transport

easy to assembly

Sustainable

Waste paper can be recycled in manufacturing process and designed into architectural materials and furnitures, which will store the carbon and deal with the urban heat island effect.

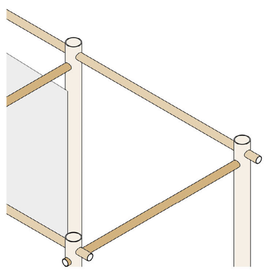
Waste paper

Paper products

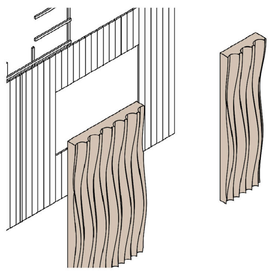
Processing

easy to process

Due to paper cellulose's property, it is easy to process into different shapes and drill holes on the paper product.



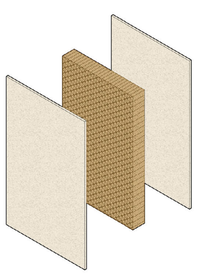
easy to drill holes



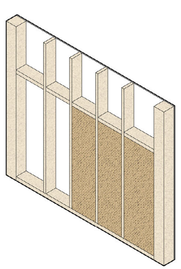
easy to mold

Thermal insulation

Paper cellulose is fiber used in walls and roof cavities to insulate, draught proof.Modern cellulose insulation, made with recycled newspaper using grinding and dust removing machines and adding a fire retardant.



paper honeycomb insulation



paper cellulose insulation

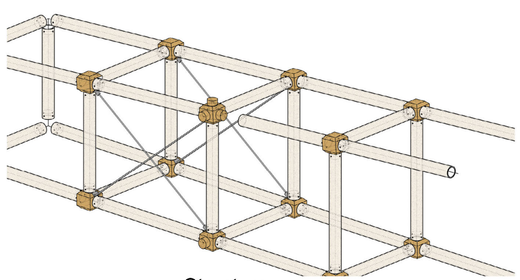
Sound insulation

The sound insulation is low beacuse of lack of mass. The expectation is that through disconnection the values will increase.The porus structure on the paper can help absorb sound. It could control and deaden sound due to the density of the cellulose fibers.

absorb sound

Strength

The paper tubes are usually used in single-story buildings. Being very light weight, the frame needed some kind of lateral bracing in order to resist wind forces.The structure could be strengthened by adding supporting members like wood or cables.
paper tube arch span 25m (case study)
paper tube truss span 15m (case study)

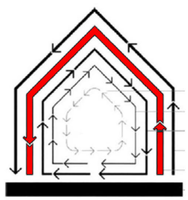


Structure

01 Research

Case studies of paper architecture

Structure — Paper tube



Parameters

length: 20mm-7000mm
Thickness: 2mm-100mm
Inner Diameter: 25mm-1600mm

paper tube arch span 25m (case study)
paper tube truss span 15m (case study)

Strength

The paper tubes are usually used in single-story buildings. The structure could be strengthened by adding supporting members like wood or cables.

Fire resistance

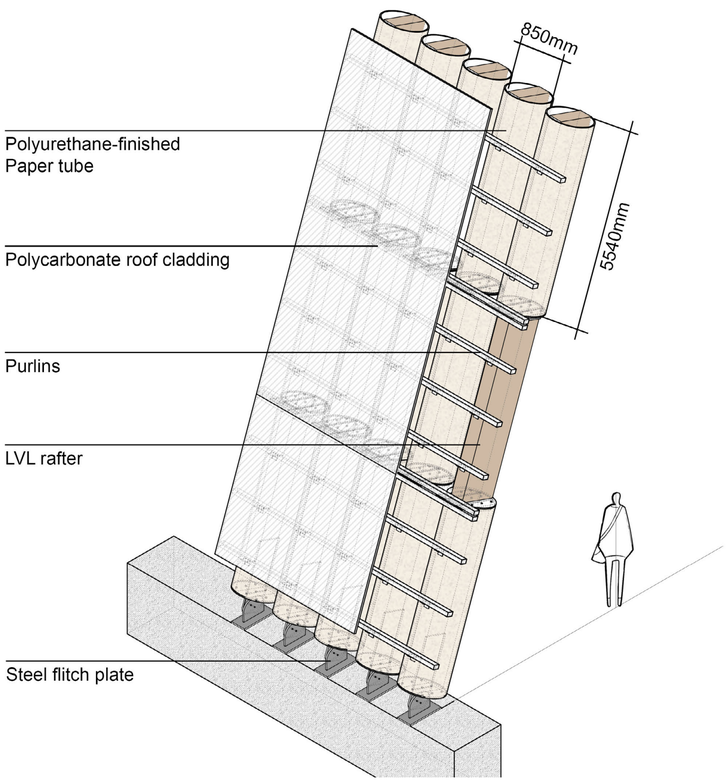
A mineral coating petrifies the raw honeycomb structure and non-bearing walls made of one-layer satisfy fire protection class EI-60(no flames, no smoke, high teperature insulation in 60 mins).

Water resistance

Adding polymer coating like polyurethane can provide water resistance.

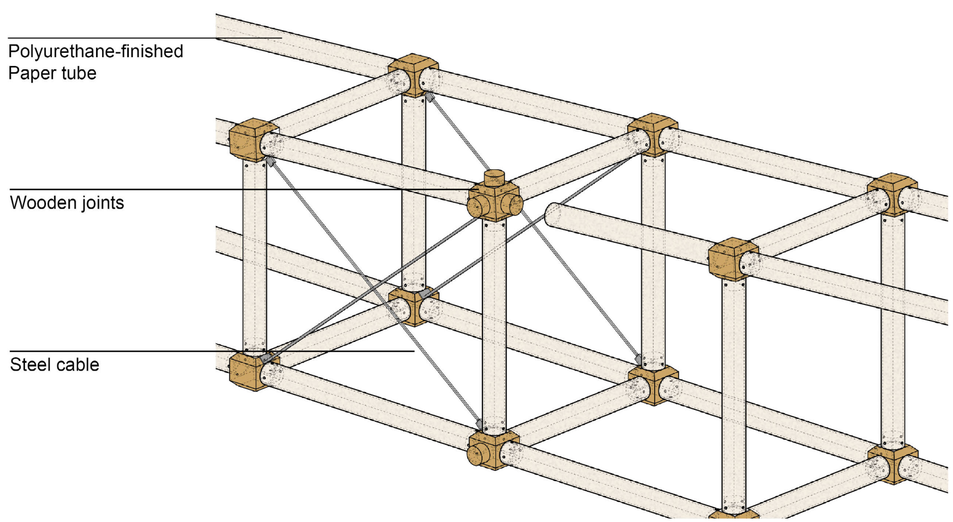
The Christchurch (New Zealand) Cathedral
Shigeru Ban
2013

Because the paper tubes manufactured in Christchurch couldn't provide the stiffness to withstand the high winds in New Zealand, locally sourced LVL rafters are added inside the tubes.



IE Paper Pavilion
Shigeru Ban
2013

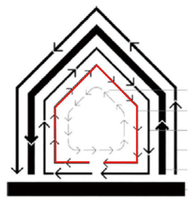
Shigeru Ban designed a system of cardboard roof trusses and columns which were inexpensive to install and can be easily recycled when the building is eventually dismantled.



01 Research

Case studies of paper architecture

Space plan — Honeycomb wall
Paper cellulose insulation



Parameters

Size: 6m x 1.5m
Thickness: 0.15m - 0.35m

Density

The wax cellls characterised by high compression strength.
30-90 kg/m^3 for paper honeycomb
Size: 6m x 1.5m x 0.25m
Paper honeycomb and CLT hyrbid panel：75kg
CLT panel：300kg
Concrete：1500kg

Thermal insulation

The delicate air chambers in the honeycomb can provide thermal insulation.

Sound insulation

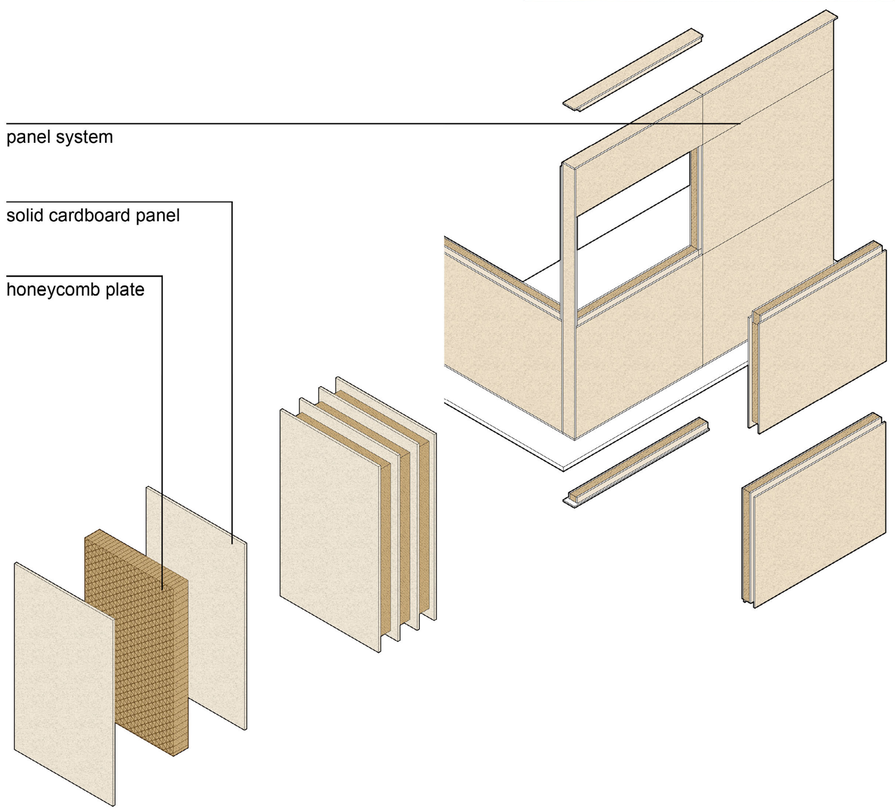
The sound insulation is low beacuse of lack of mass. The expectation is that through disconnection the values will increase.
It could control and deaden sound due to the density of the cellulose fibers and the non-woven manufacturing process.

Flexibility

The finishing profiles and the tongue-and-groove components can be easily removed and reinstalled elsewhere like large LEGO blocks.

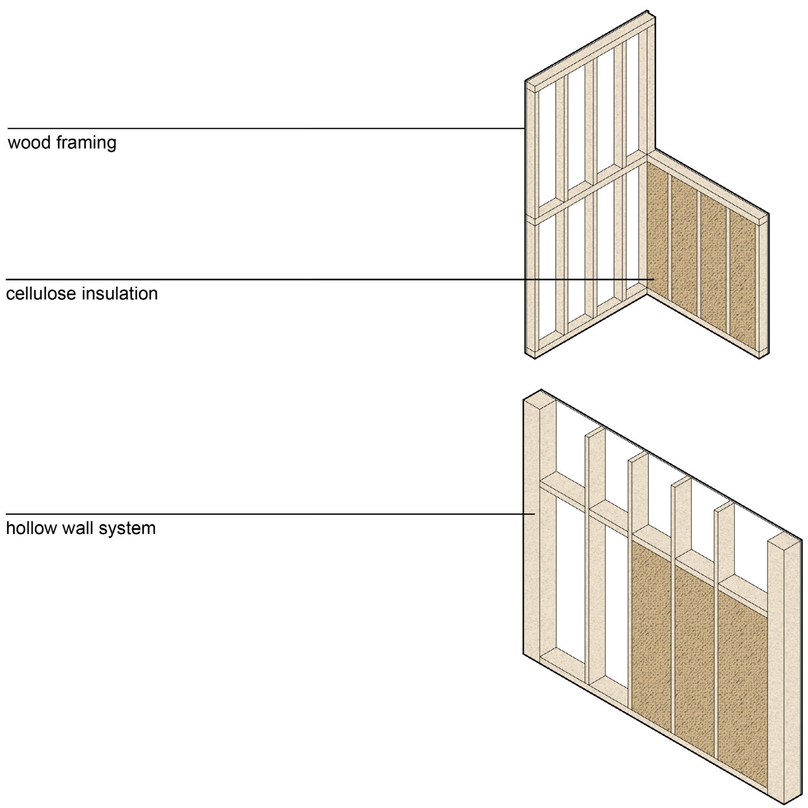
Ecocell
Fredy Iseli

Paper honeycomb plates covered with solid cardboard can be categorised as a panel system.It could be a single, double or trlple-layer sandwiched design.
This system assembles the elements with screw connections using the tongue-and-groove principle.



Ecocell insulation
CMS

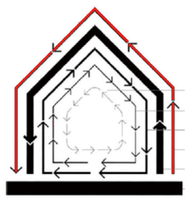
CMS developed ECOCELL insulation, the industry's first cellulose based batts and blankets. They combine ease of installation with superior thermal and acoustical performance.



01 Research

Case studies of paper architecture

Space plan — Molded paper composite



Parameters

It can be molded into any shape.

Fire resistance

The mix of long strands of shredded paper and a sodium silicate gluing agent, which protects against flame.

Water resistance

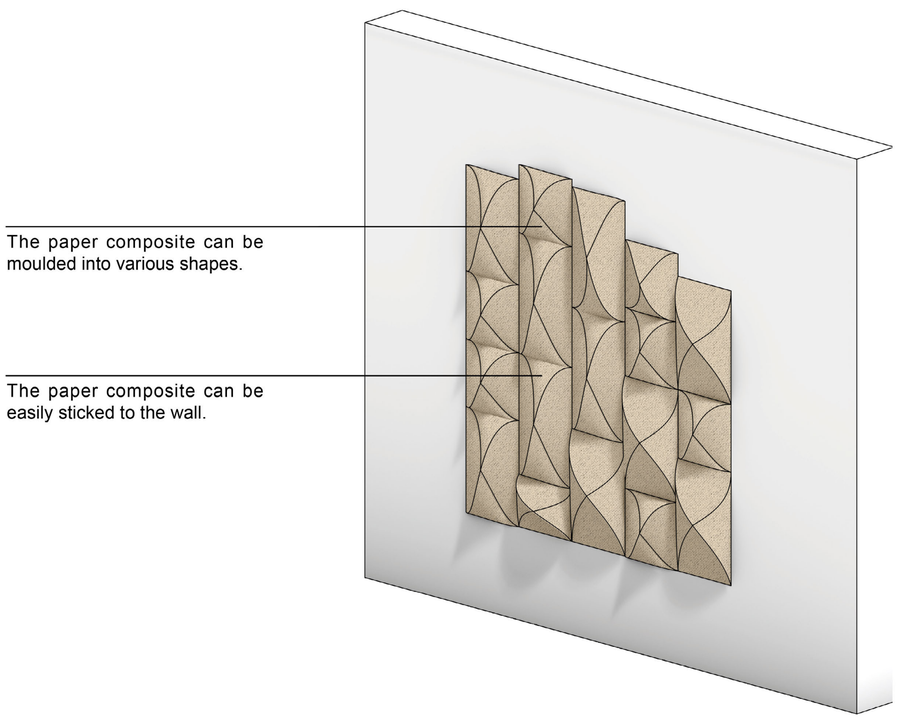
The mix of long strands of shredded paper and a sodium silicate gluing agent, which protects against moisture.

Sound insulation

The porus structure on the paper can help absorb sound.

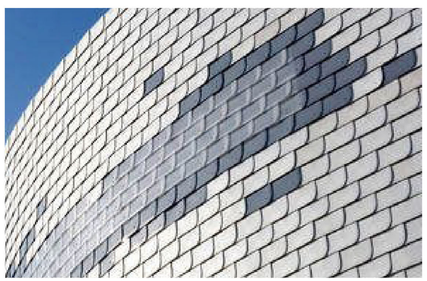
Acoustic wall

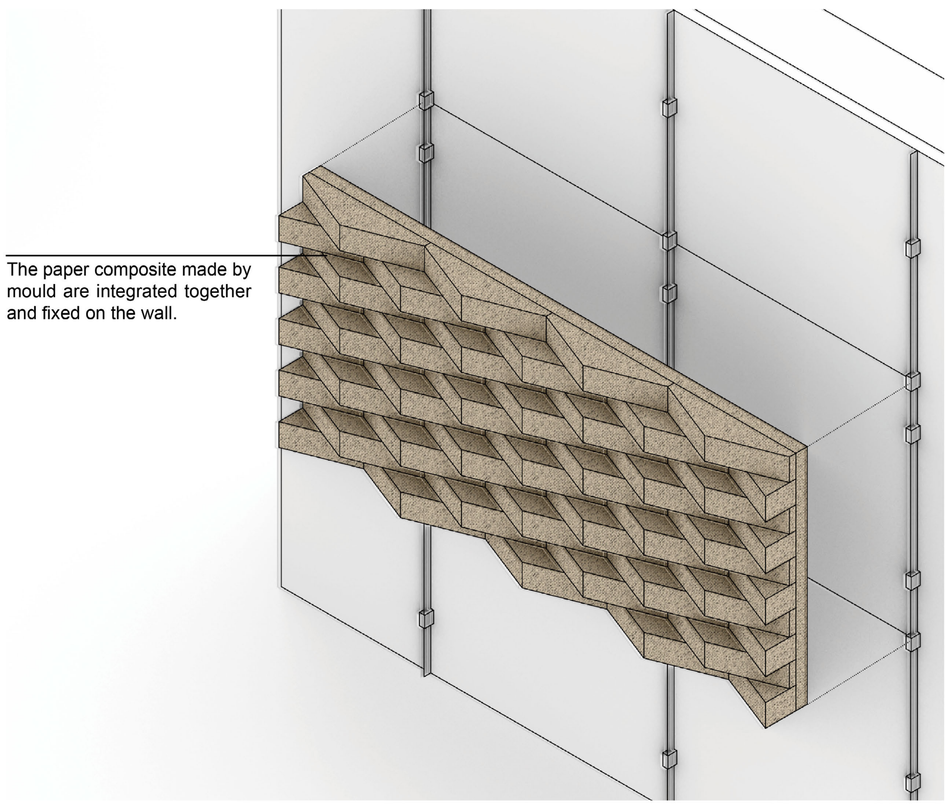
The molded paper units can absorb the sound and can be used as a soundproof wall.



Paper composite facade
2010 Finland pavilion Shanghai EXPO

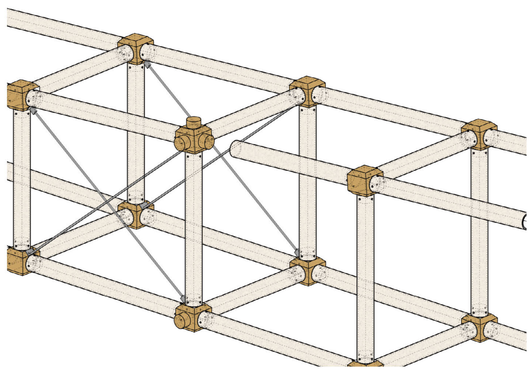
The ratio of 80% paper and 20% sodium silicate is compressed under high temperature at 90°C, which is quick to manufacture and waterproof.



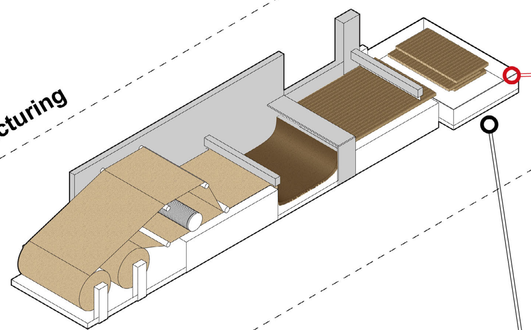


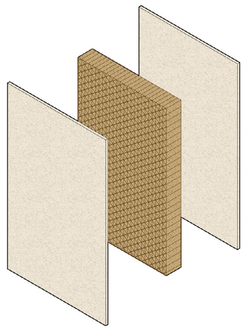
01 Research

Manufacturing of paper

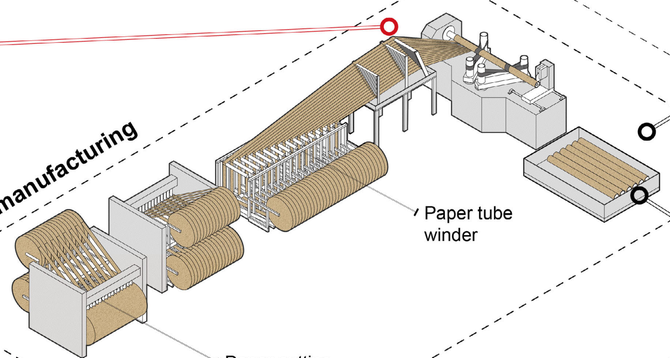


Honeycomb manufacturing

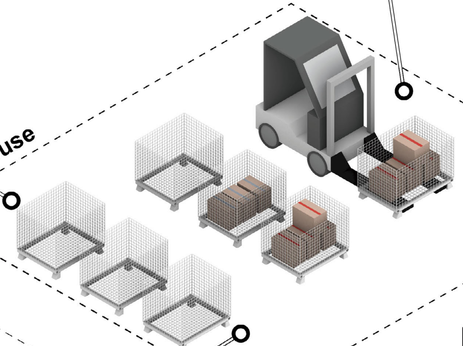




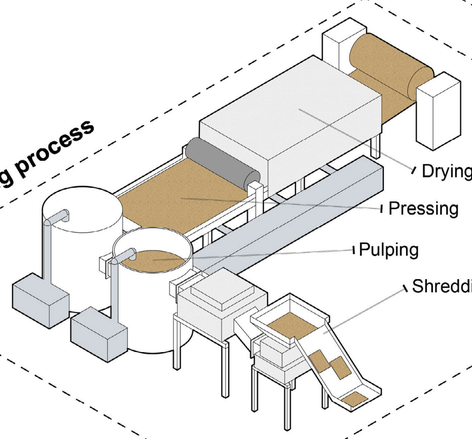
Paper tube manufacturing



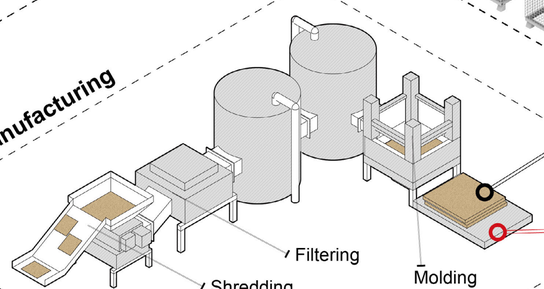
Warehouse

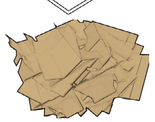


Paper recycling process

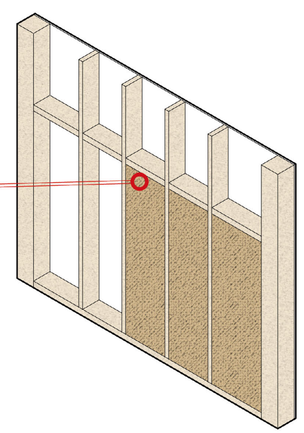


Cellulose manufacturing





Waste paper



02 Design

02 Design

New paper architecture for BK

What's the future of BK city? Living & Experimenting & Creating

BK city and expansion 2008-2009

a new campus village

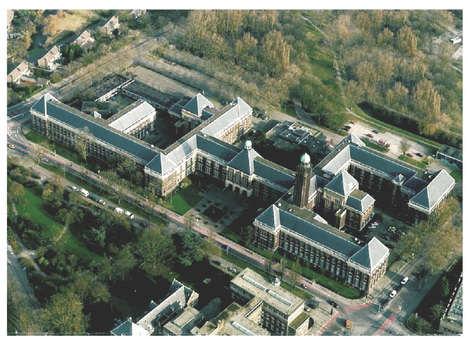
experimental designs

glass house

formal and informal meeting

studying and teaching

Fire on Architecture faculty building

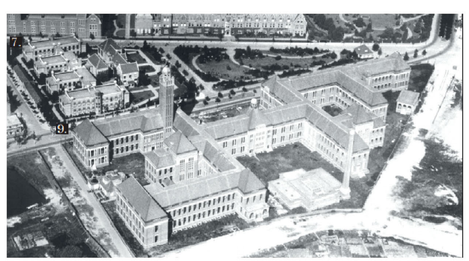


Construction of standalone wing 1974

turning into apartment

Student housing problem

an administrative building

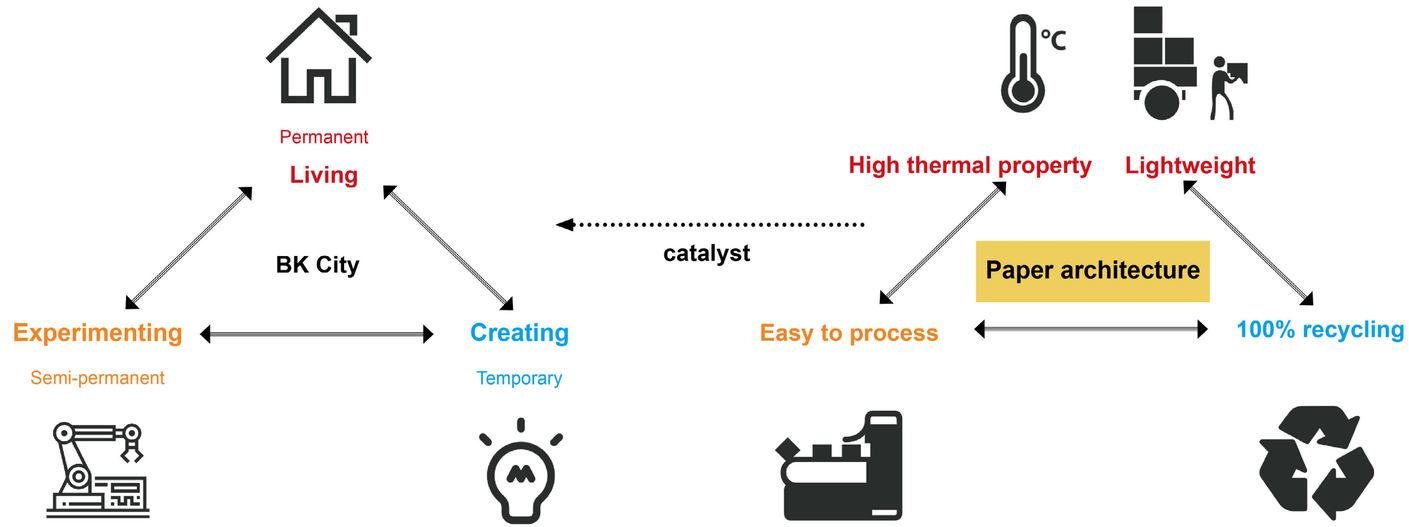


Red Chemistry Faculty 1917

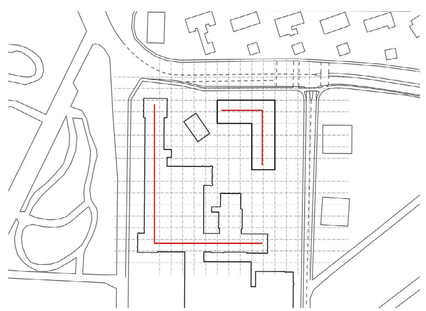
the Faculty of Mathematics

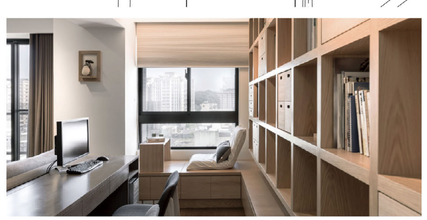
occupied by German oppressors

a light bulb factory

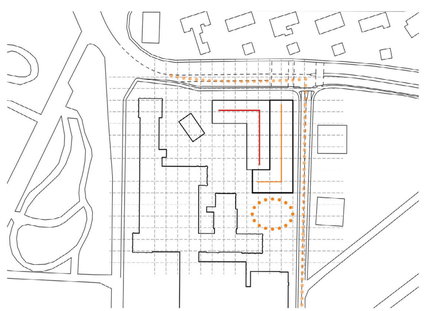


Apartment - Living - Permanent
- a standalone wing echoing BK

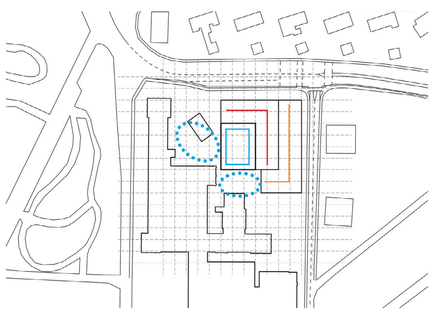




Laboratory - Experimenting - Semi-permanent
- connecting apartment and streets



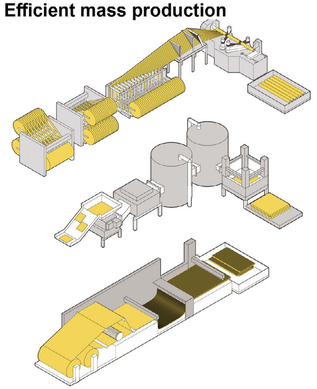
Paper pavilion - Creating - Temporary
- activate BK's public space



02 Design

How to deal with urban heat island effect?

1 **Off-site prefabrication**
Efficient mass production



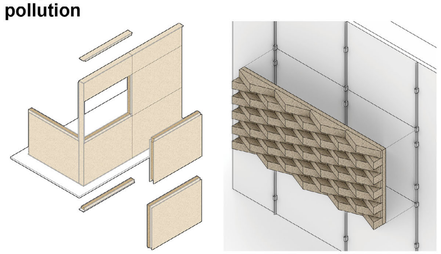
On-site recycling paper fabrication
Reduce material transportation

2 **Much Lighter than concrete / Steel**
Easier for on-site manual construction

Density:

corrugated cardboard:	30-90kg/m^3
hollow paper tube:	132kg/m^3
CLT:	480-500 kg/m^3
Glulam :	500kg/m^3
Concrete:	2,400 kg/m^3
Steel:	8,050 kg/m^3

Dry joint construction to reduce environment pollution



1 Product stage

Raw material supply
Transport
Manufacturing

Wood

From TUD campus

Waste paper

2 Construction process stage

Transport
Construction

Paper Architecture

Store CO_2
in the whole life cycle

3 Use stage

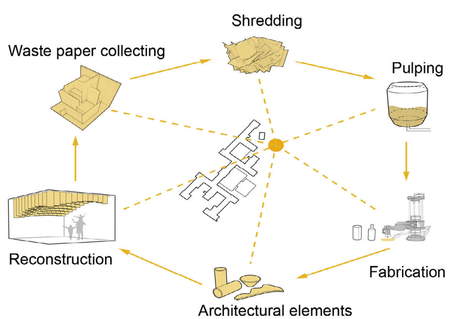
Use
Maintenance
Repair
Replacement
Refurbishment
Operational use of energy
Operational use of water

4 End-of-life stage

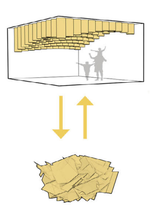
Demolition
Transport
Waste processing
Disposal

Recycling stage 5

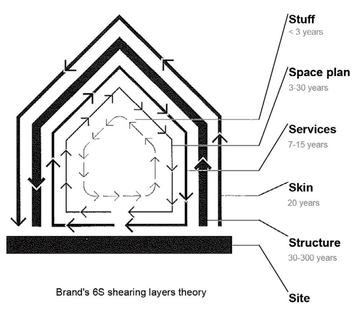
Reuse
Recovery
Recycling potential



5 **Paper:100% recyclable material**



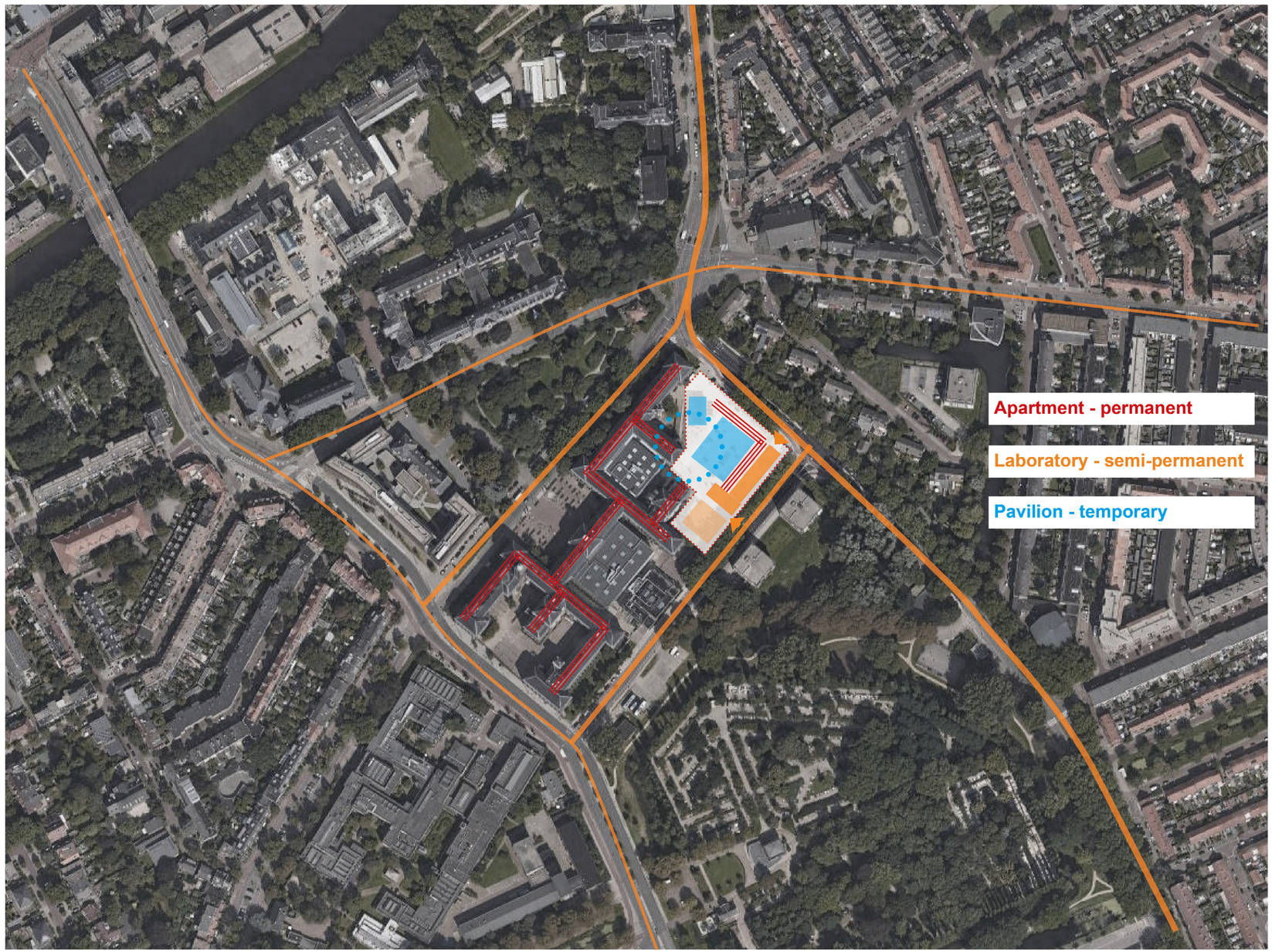
Paper products reuse depending on different lifespans

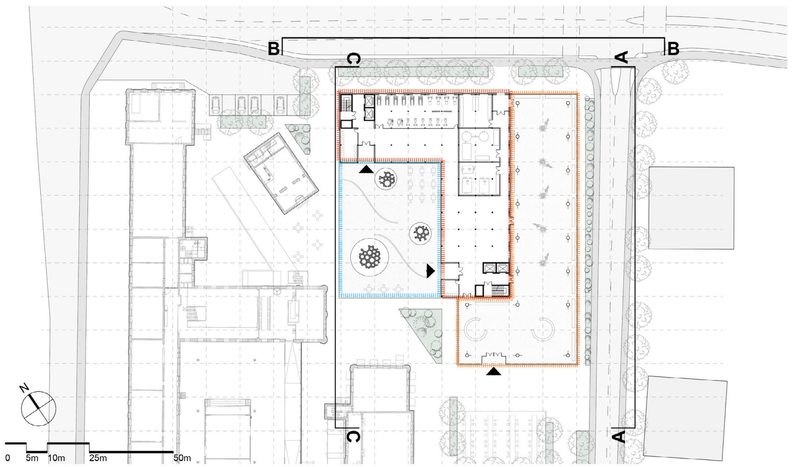


Repair in different layers **3**

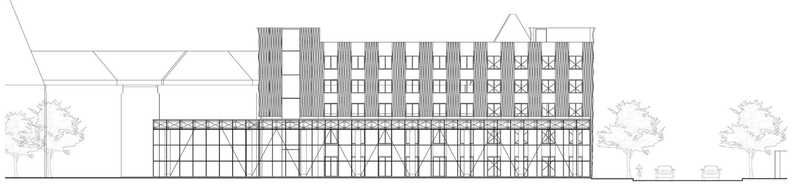
02 Design

Urban context

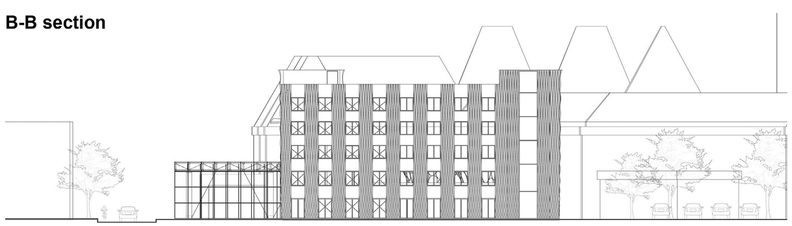




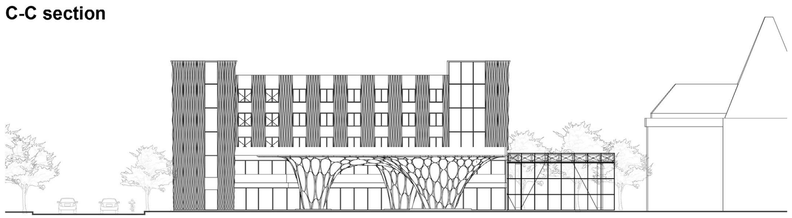
A-A section



B-B section



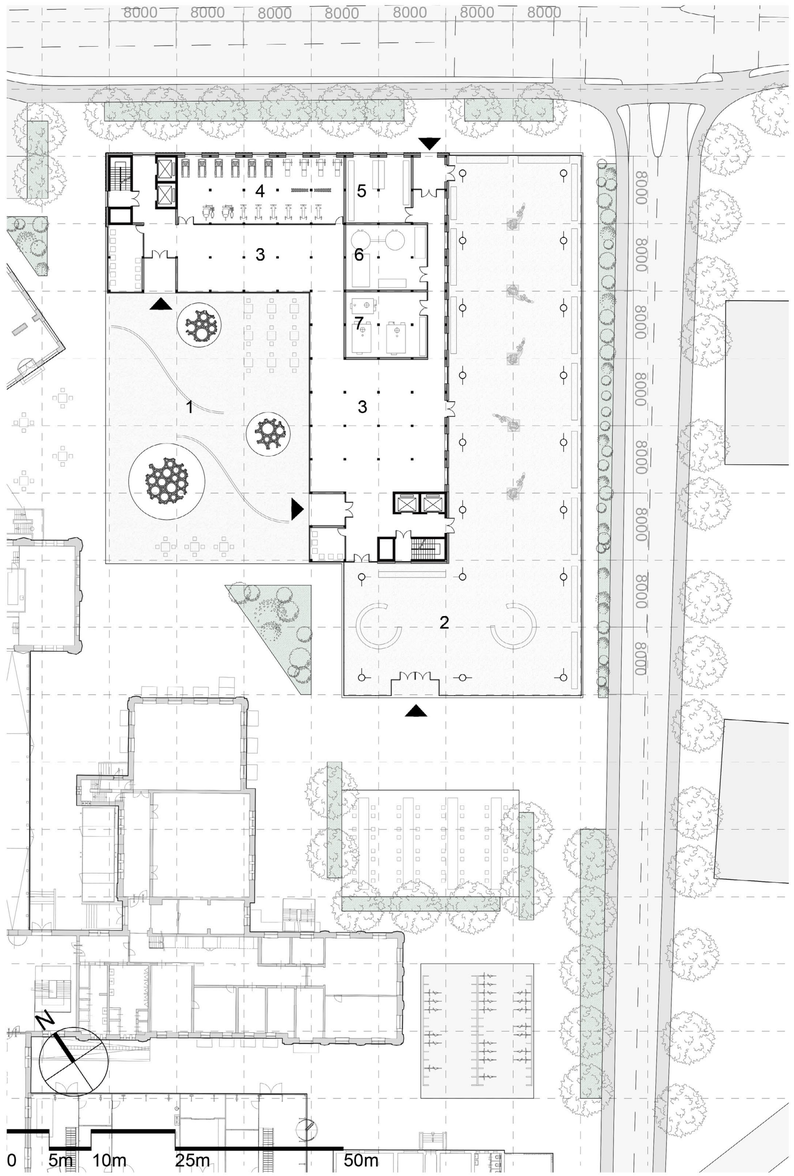
C-C section



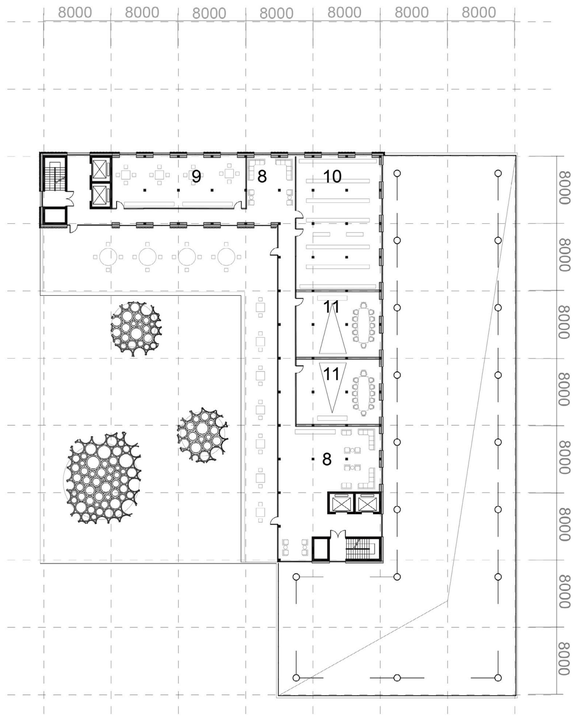
02 Design

Layout and logistics

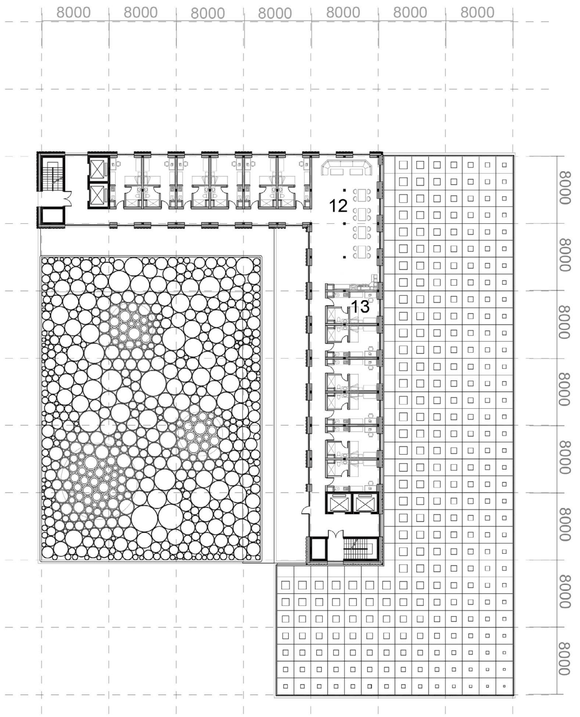
Ground floor



First floor

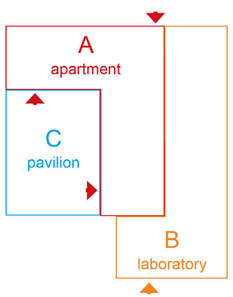


Second floor

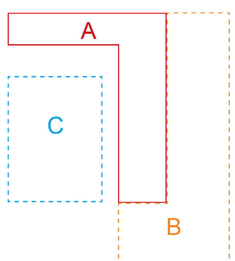


Third floor

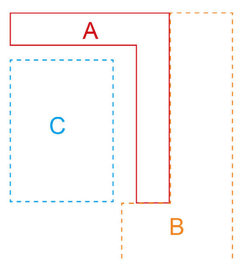
1 Paper pavilion
2 Paper laboratory
3 Apartment
4 Gym
5 Paper collecting
6 Paper manufacturing
7 Heat transfer space
8 public space
9 Study room
10 Library
11 Meeting room
12 Public kitchen
13 Apartment unit



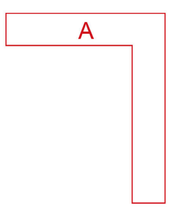
Ground floor



First floor



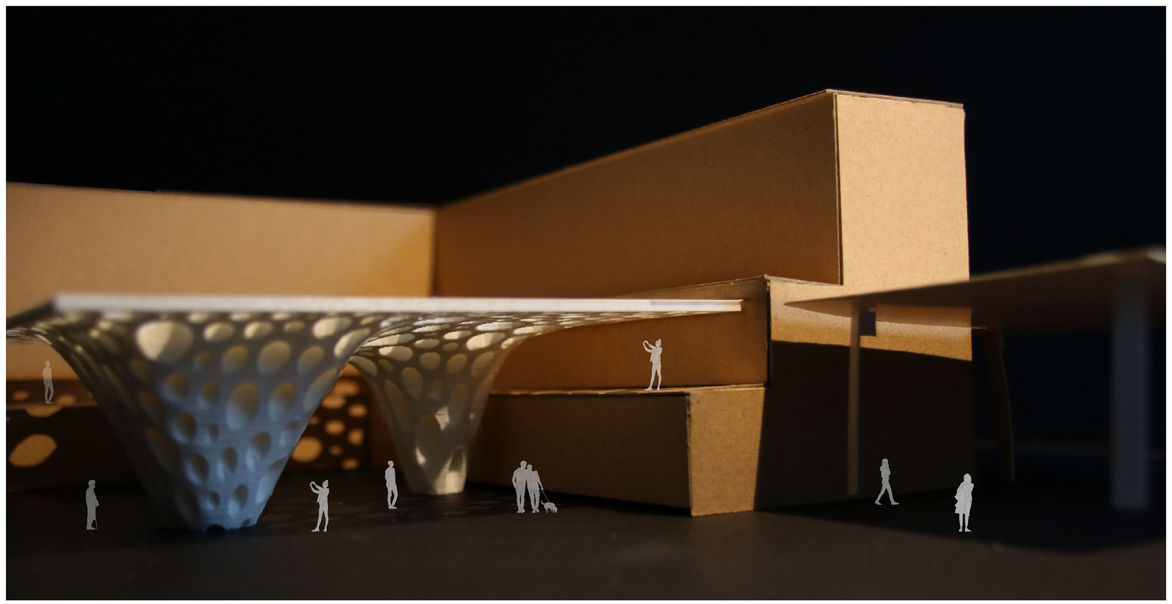
Second floor

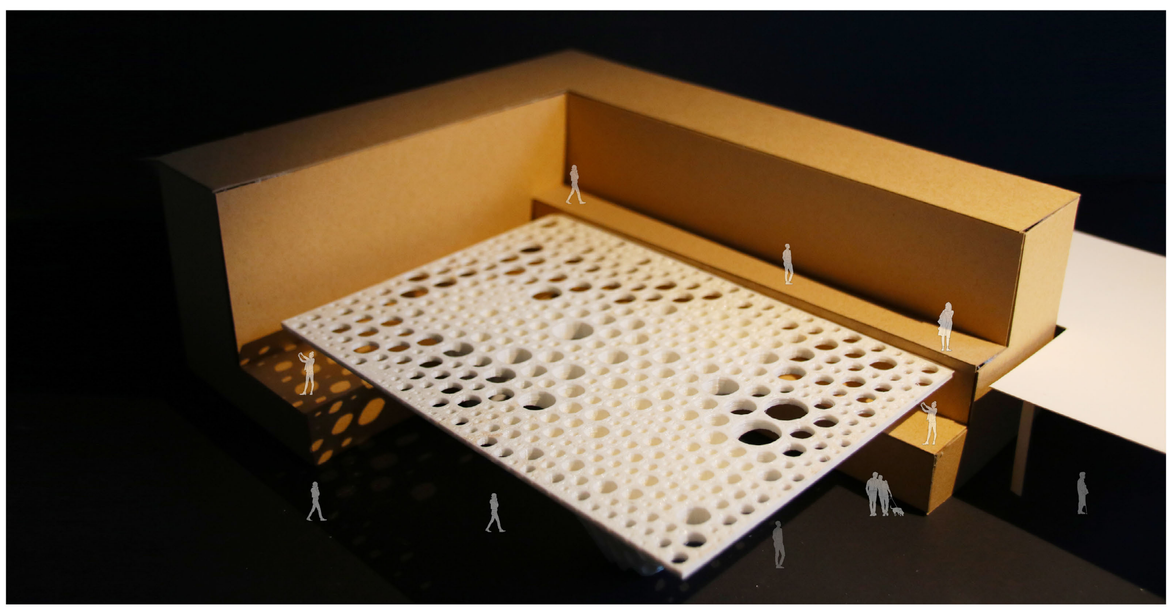


Third floor

02 Design

Physical model



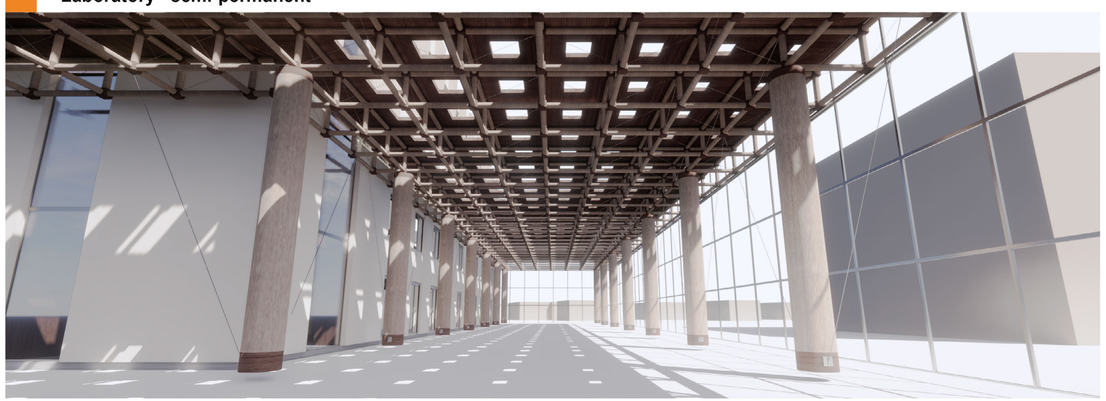


02 Design

Atmosphere

Apartment permanent

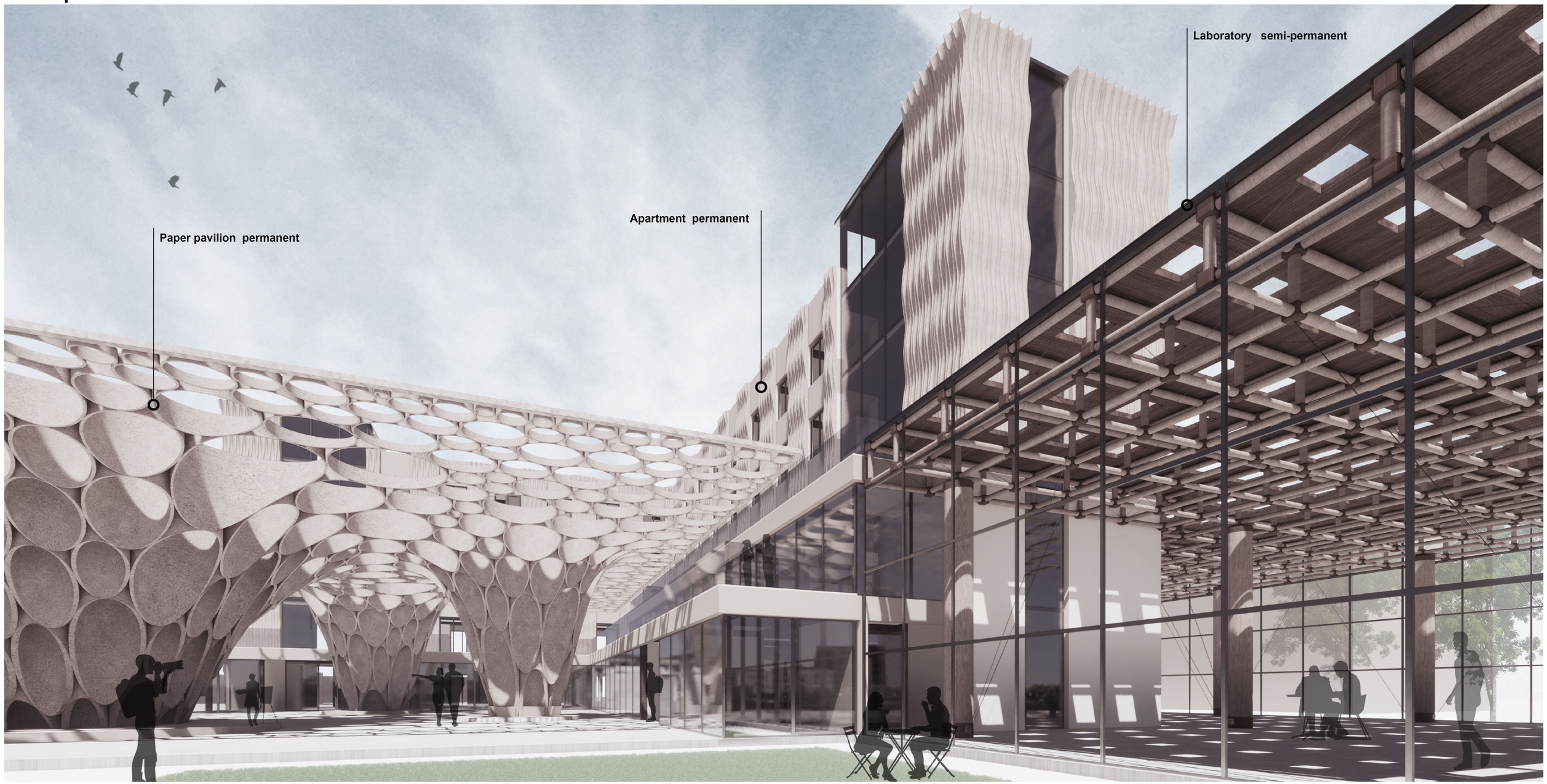
Laboratory semi-permanent



Paper pavilion temporary

02 Design

Atmosphere



02 Design

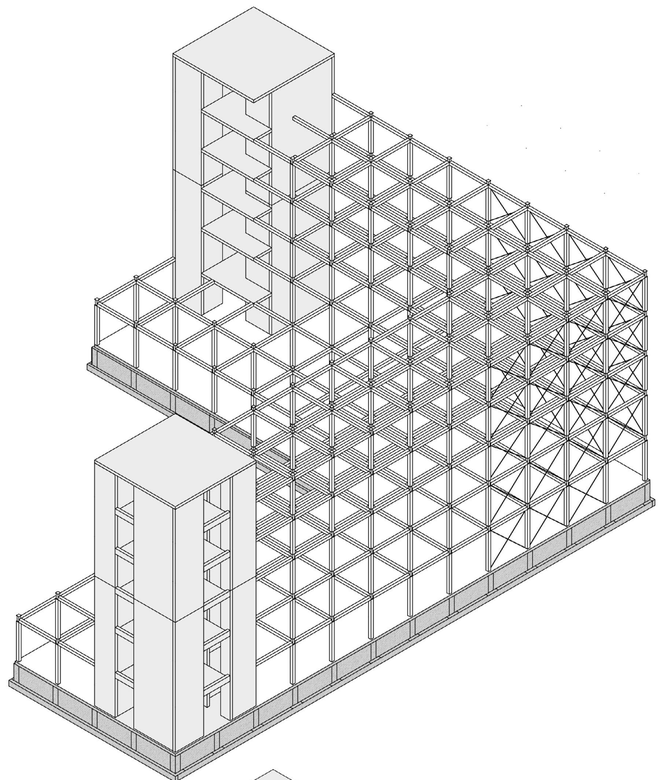
Atmosphere

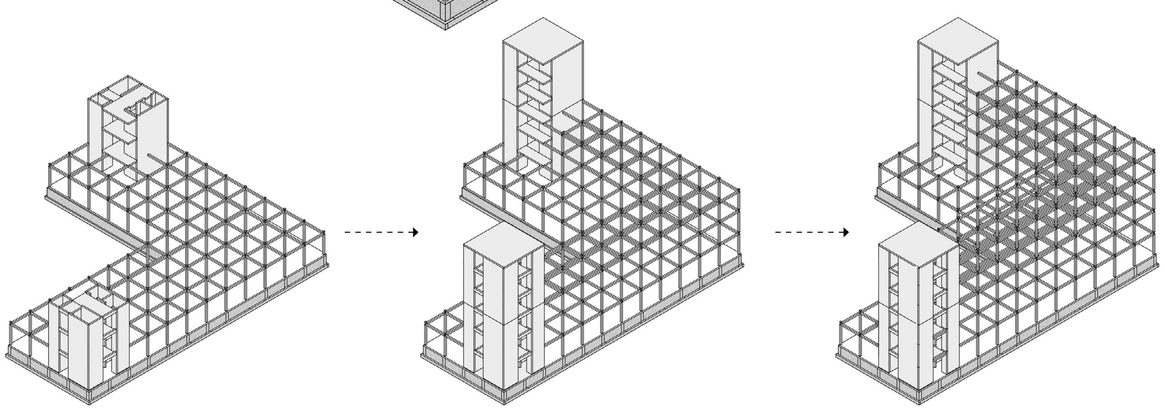
03 Engineering

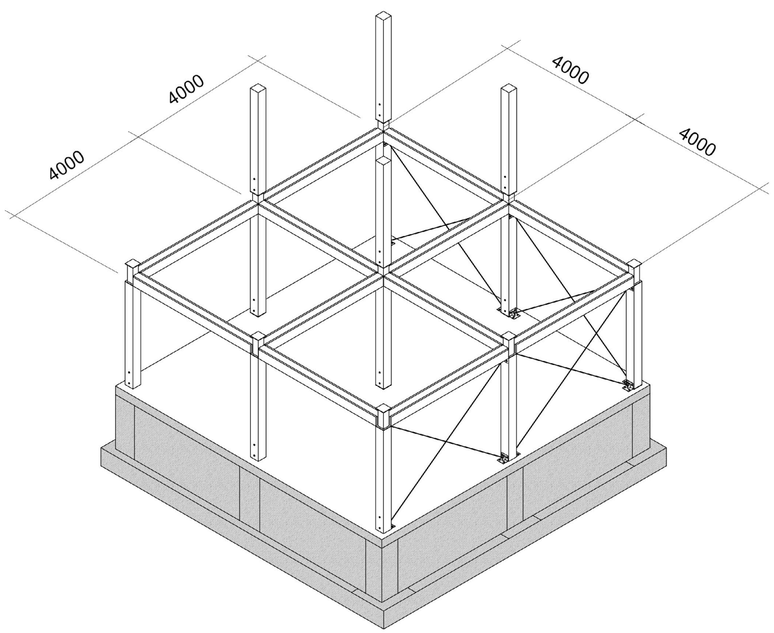
03 Engineering

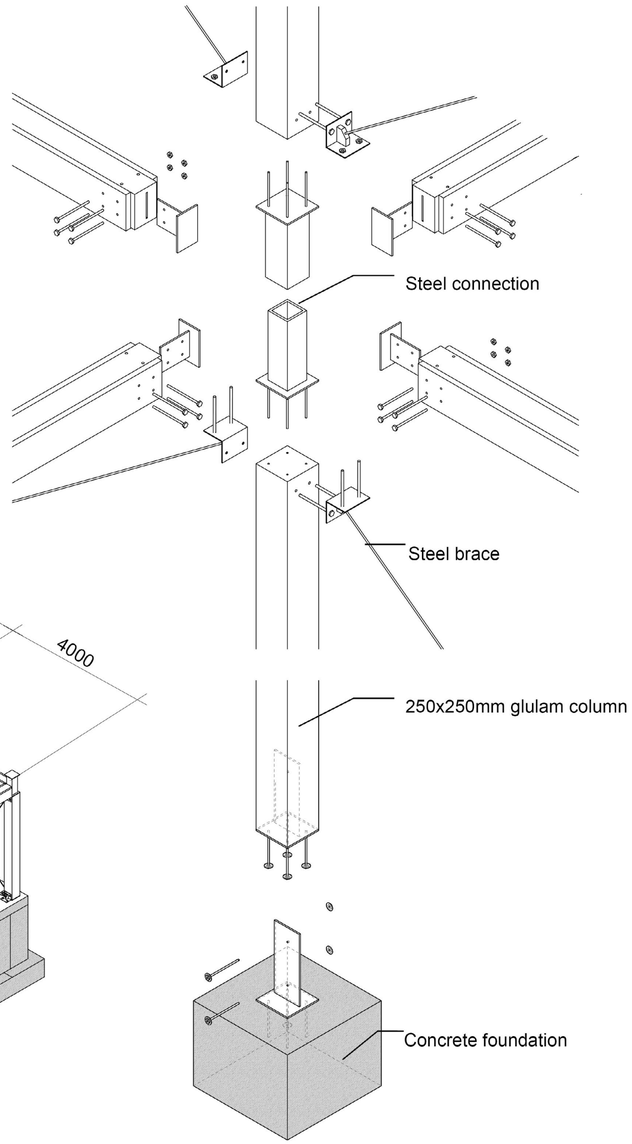
Assembly

- Permanent Apartment Prototype
- Structure





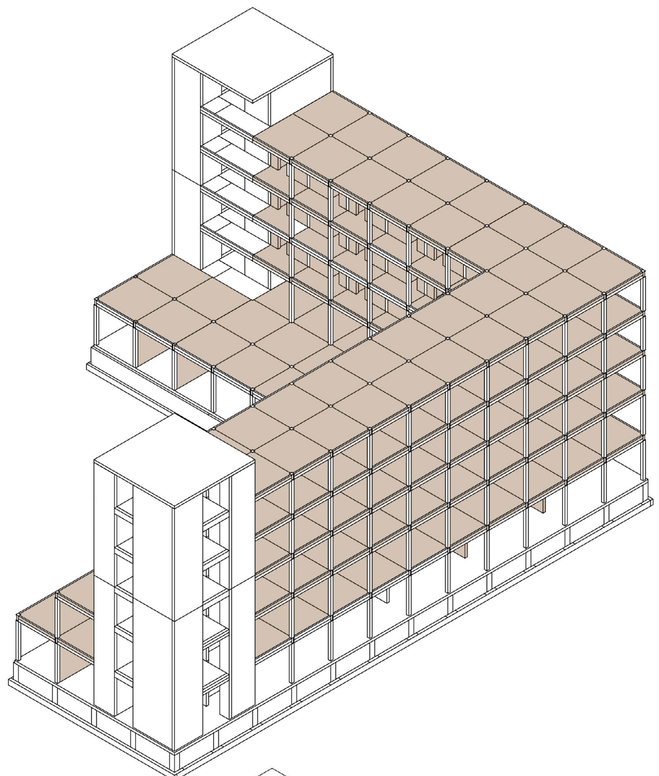


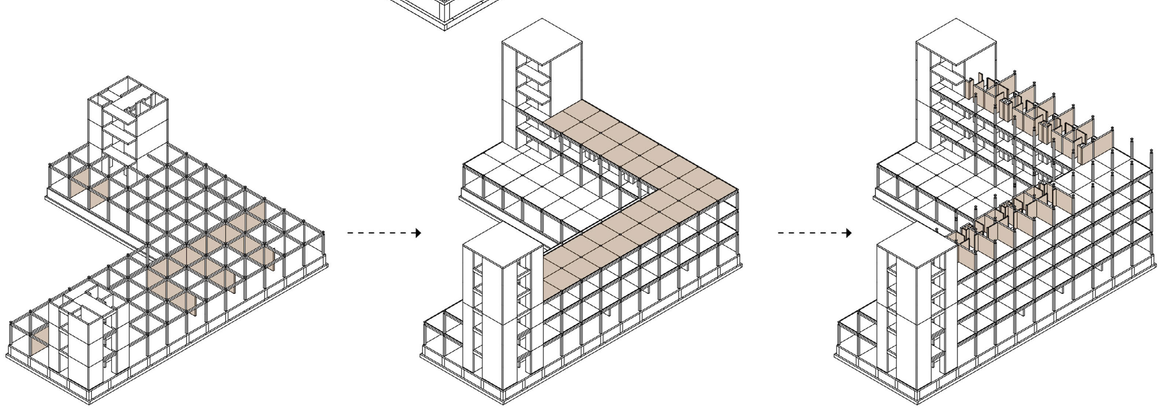


03 Engineering

Assembly

- Permanent Apartment Prototype
- Space plan





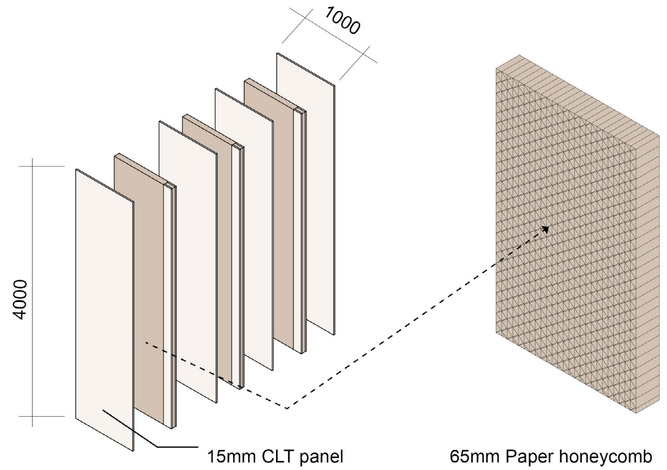
Paper honeycomb & CLT panel wall

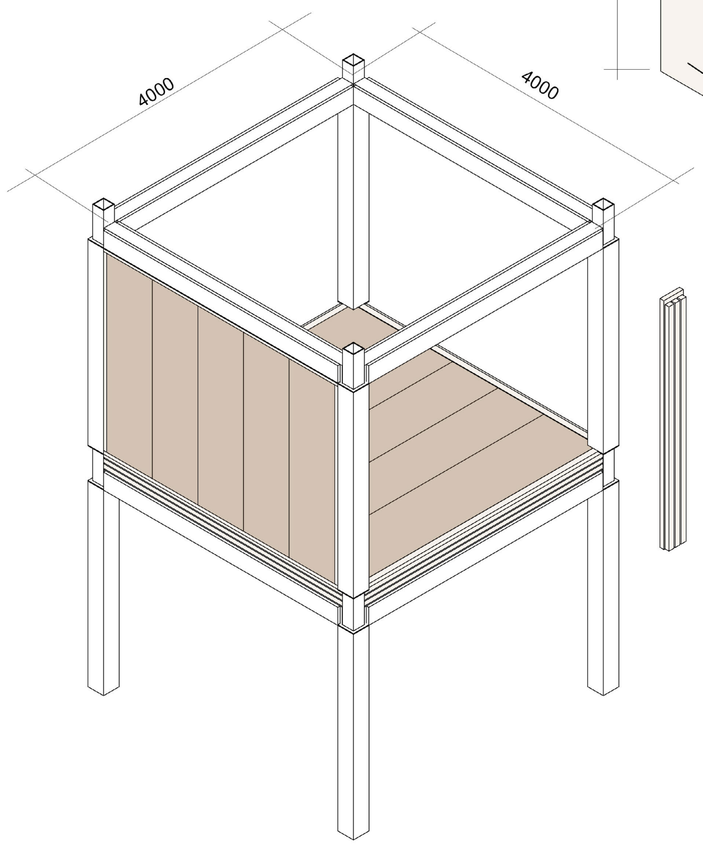
Fire resistance

A mineral coating petrifies the raw honeycomb structure and non-bearing walls made of one-layer satisfy fire protection class EI-60(no flames, no smoke, high teperature insulation in 60 mins).

Thermal insulation

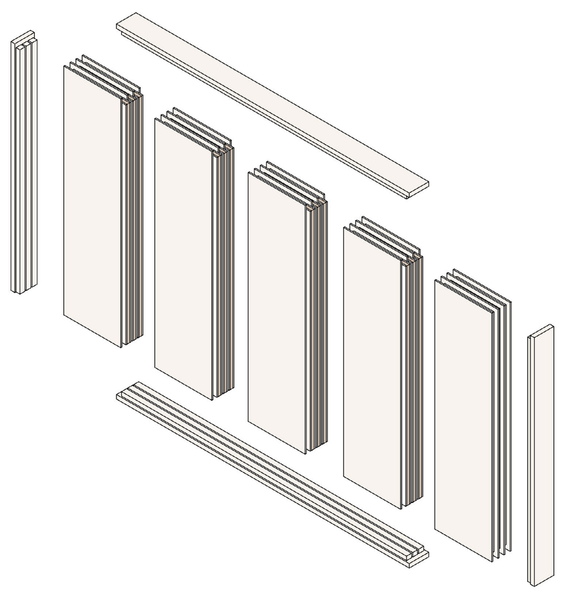
The delicate air chambers in the honeycomb can provide thermal insulation.





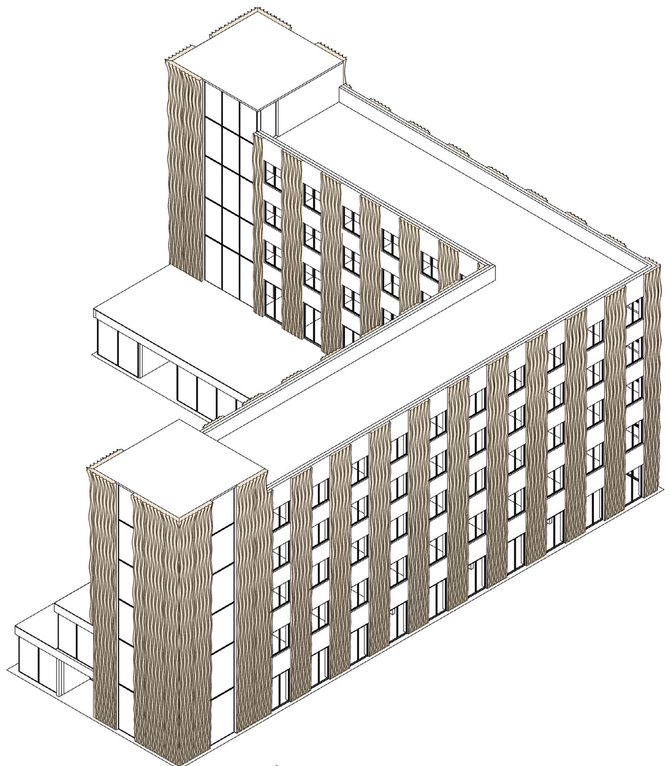
Size: 4m x 1m x 0.25m

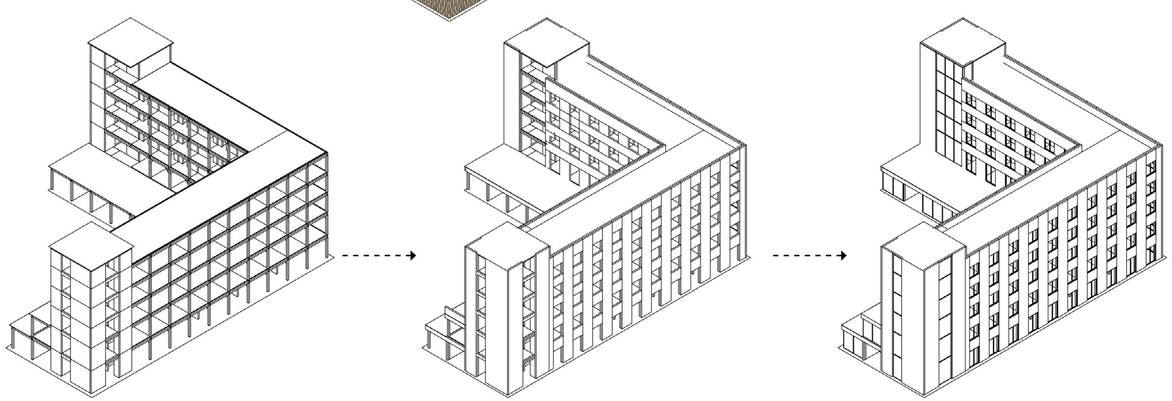
Paper honeycomb and CLT hyrbid panel：50kg
CLT panel：200kg
Concrete：1000kg



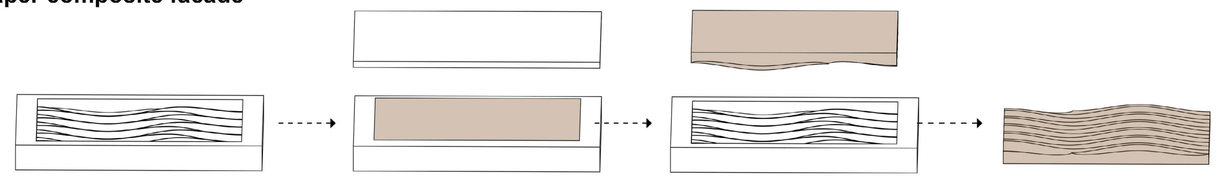
03 Engineering

Assembly
- Permanent Apartment Prototype
- Skin





Paper composite facade



Thermal insulation

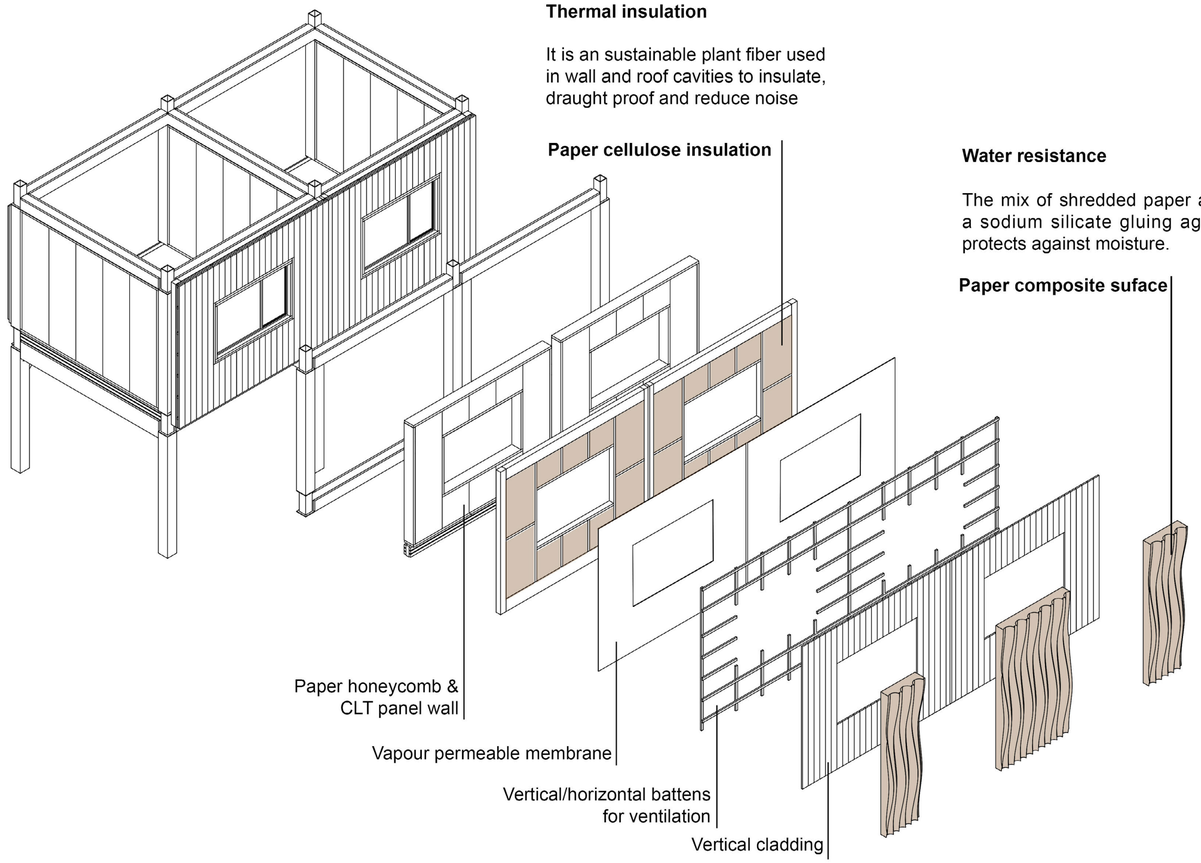
It is an sustainable plant fiber used in wall and roof cavities to insulate, draught proof and reduce noise

Paper cellulose insulation

Water resistance

The mix of shredded paper and a sodium silicate gluing agent protects against moisture.

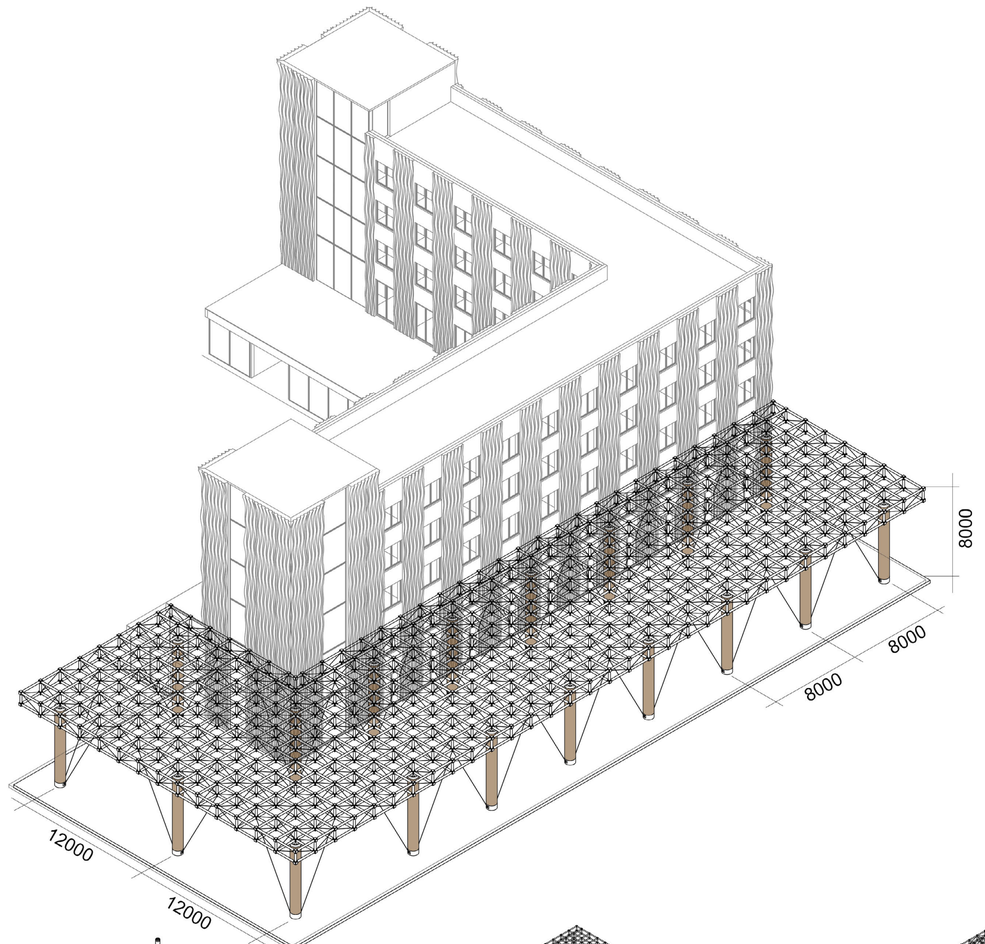
Paper composite suface

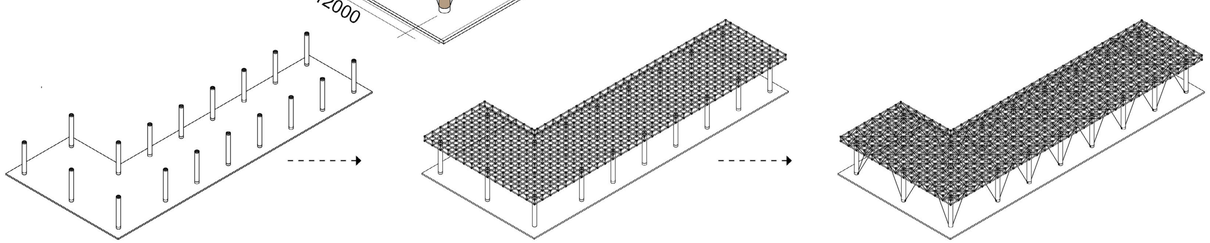


03 Engineering

Assembly

- Semi-permanent Laboratory Prototype
- Structure





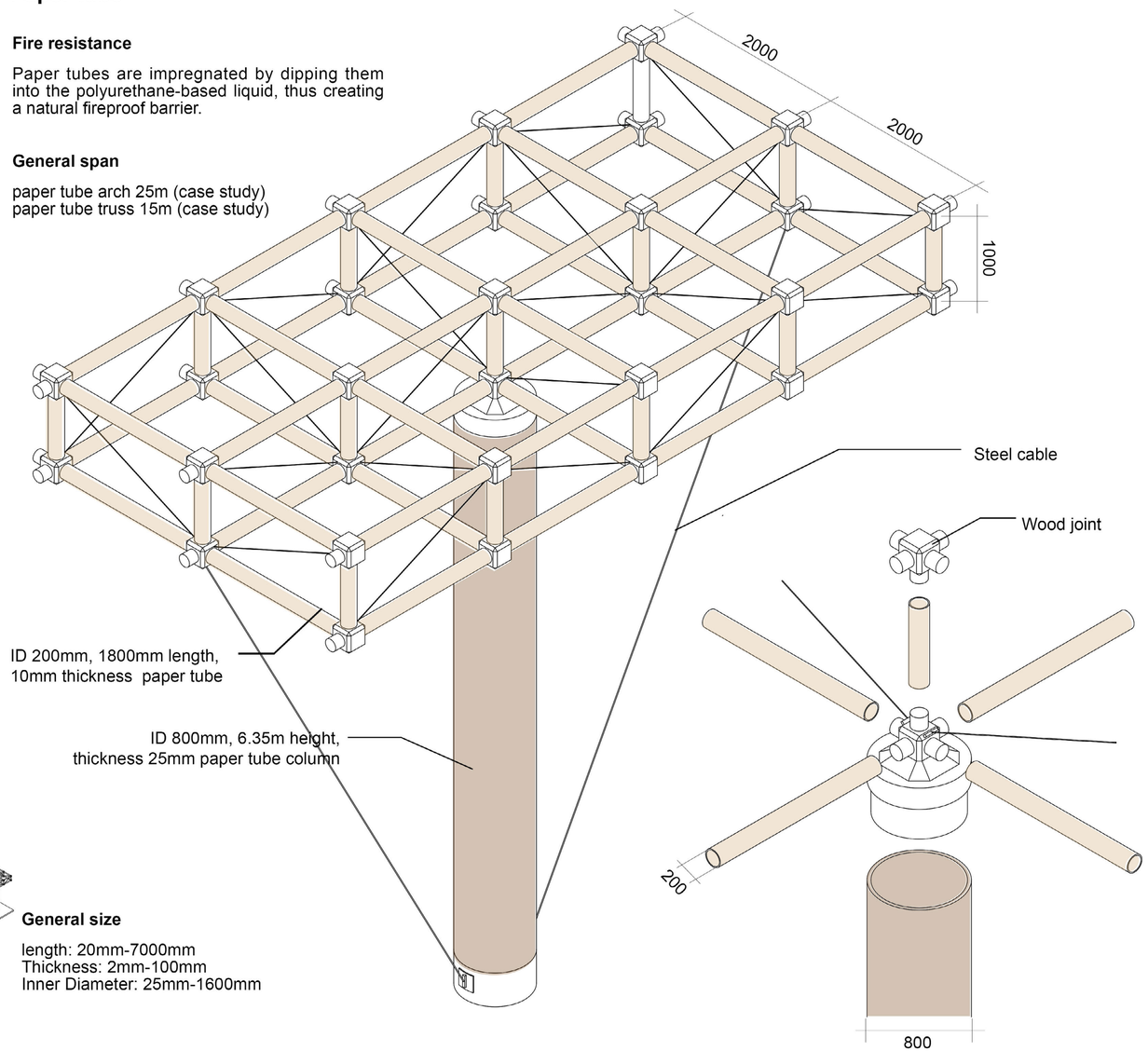
Paper tube

Fire resistance

Paper tubes are impregnated by dipping them into the polyurethane-based liquid, thus creating a natural fireproof barrier.

General span

paper tube arch 25m (case study)
paper tube truss 15m (case study)



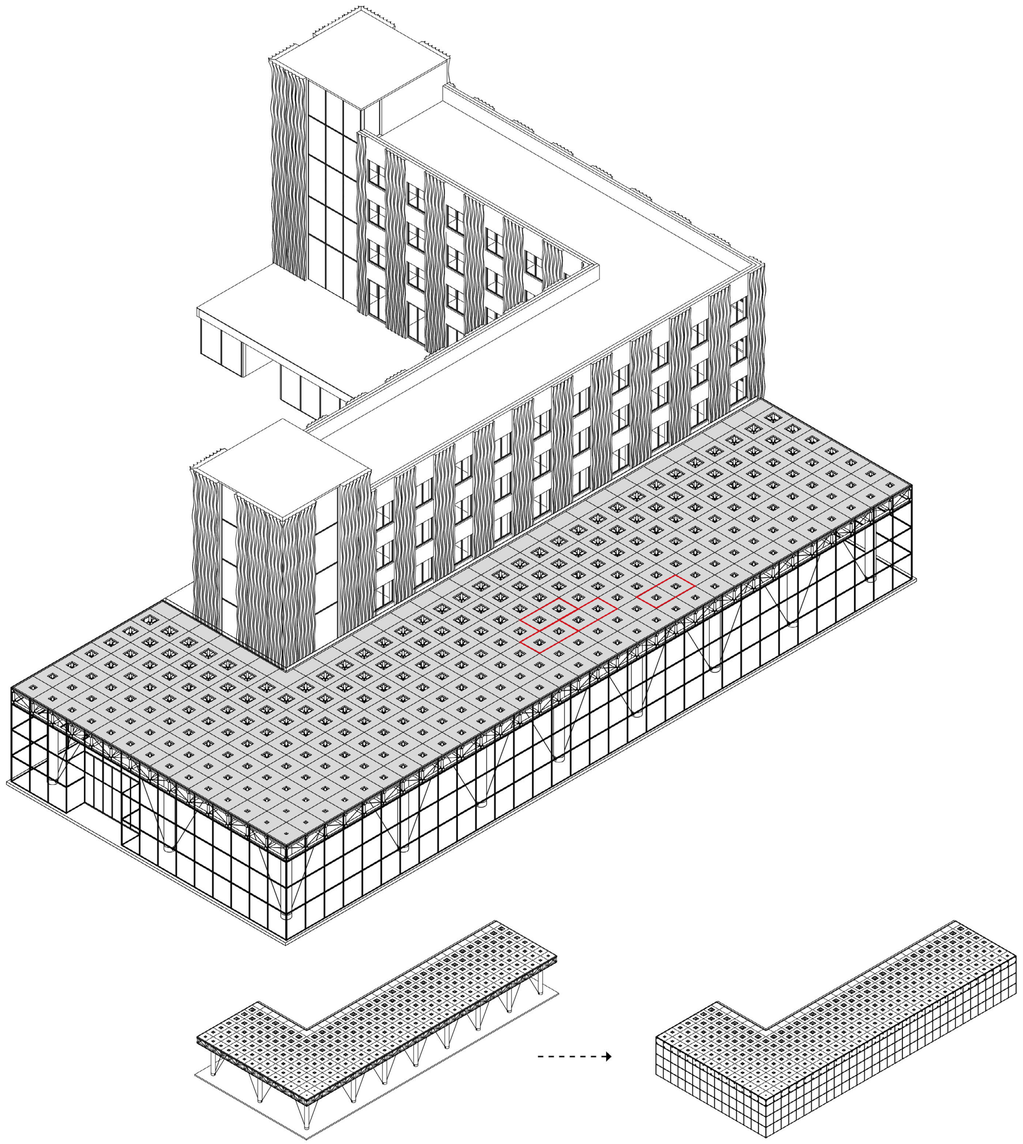
General size

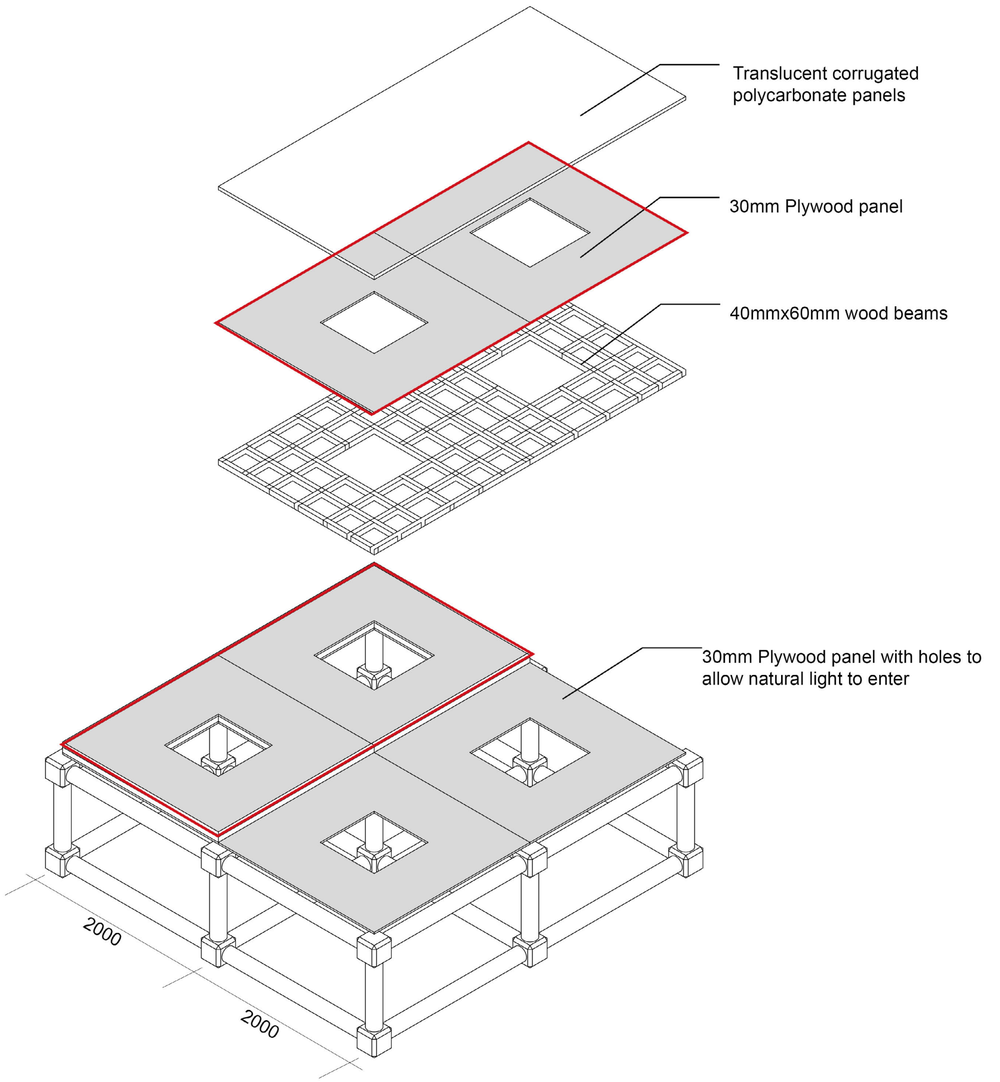
length: 20mm-7000mm
Thickness: 2mm-100mm
Inner Diameter: 25mm-1600mm

03 Engineering

Assembly

- Semi-permanent Laboratory Prototype
- Skin

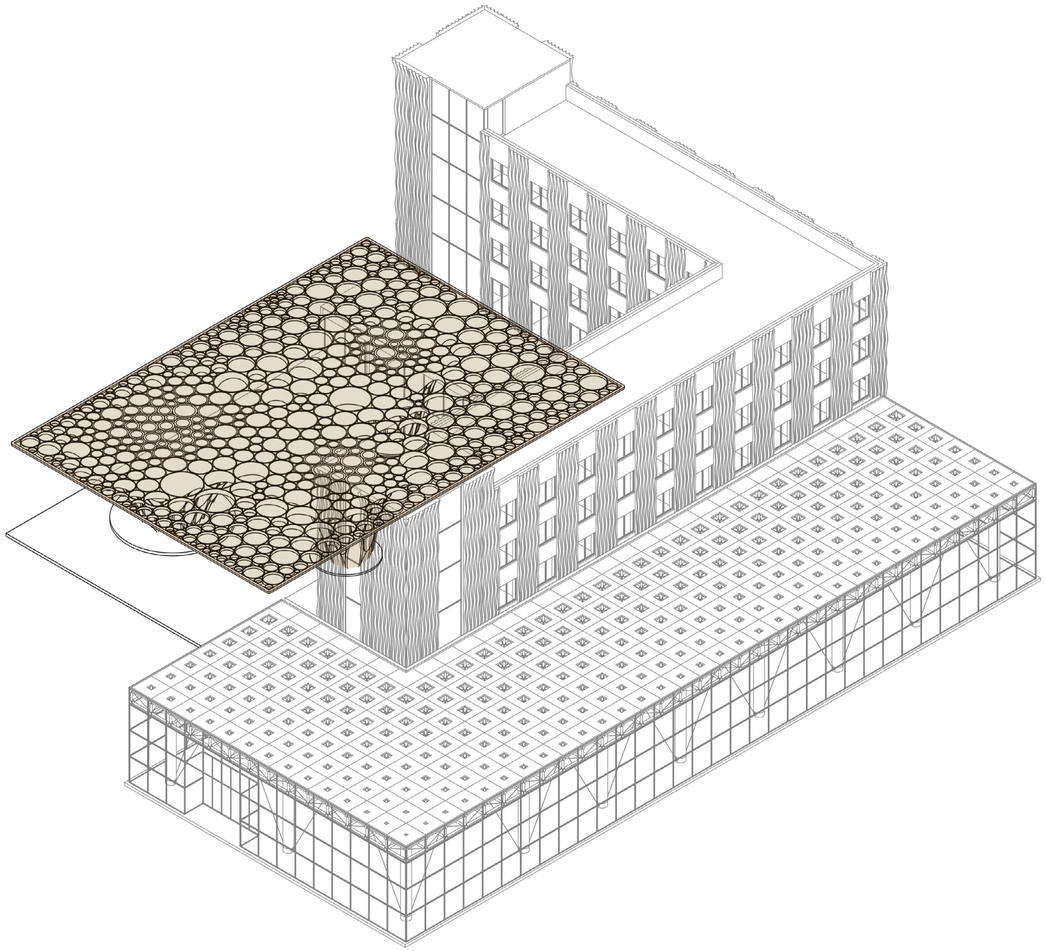


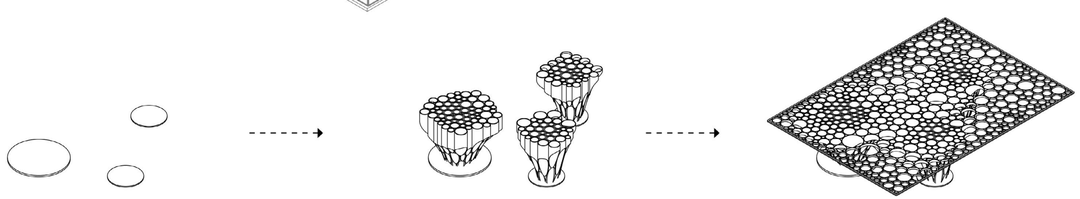


03 Engineering

Assembly

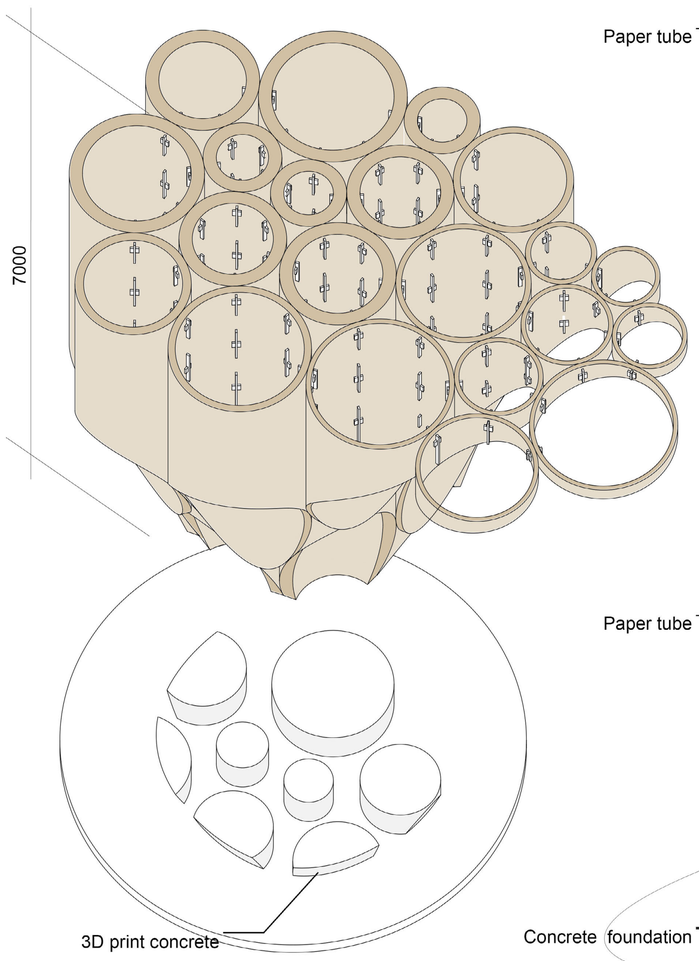
- Temporary Pavilion Prototype
- Structure

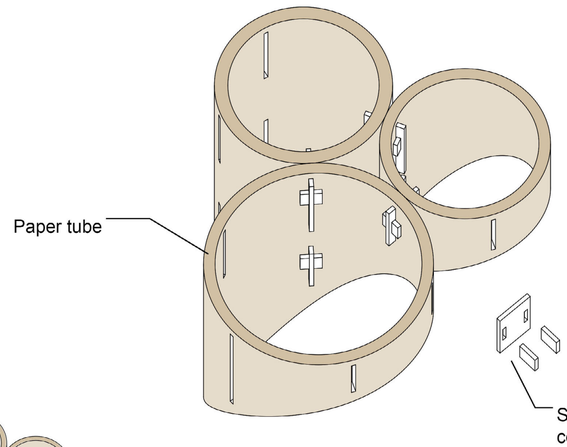


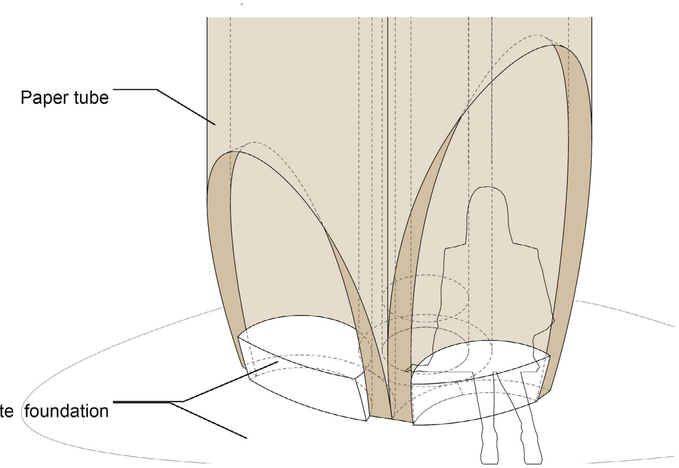


General size

length: 20mm-7000mm
Thickness: 2mm-100mm
Inner Diameter: 25mm-1600mm



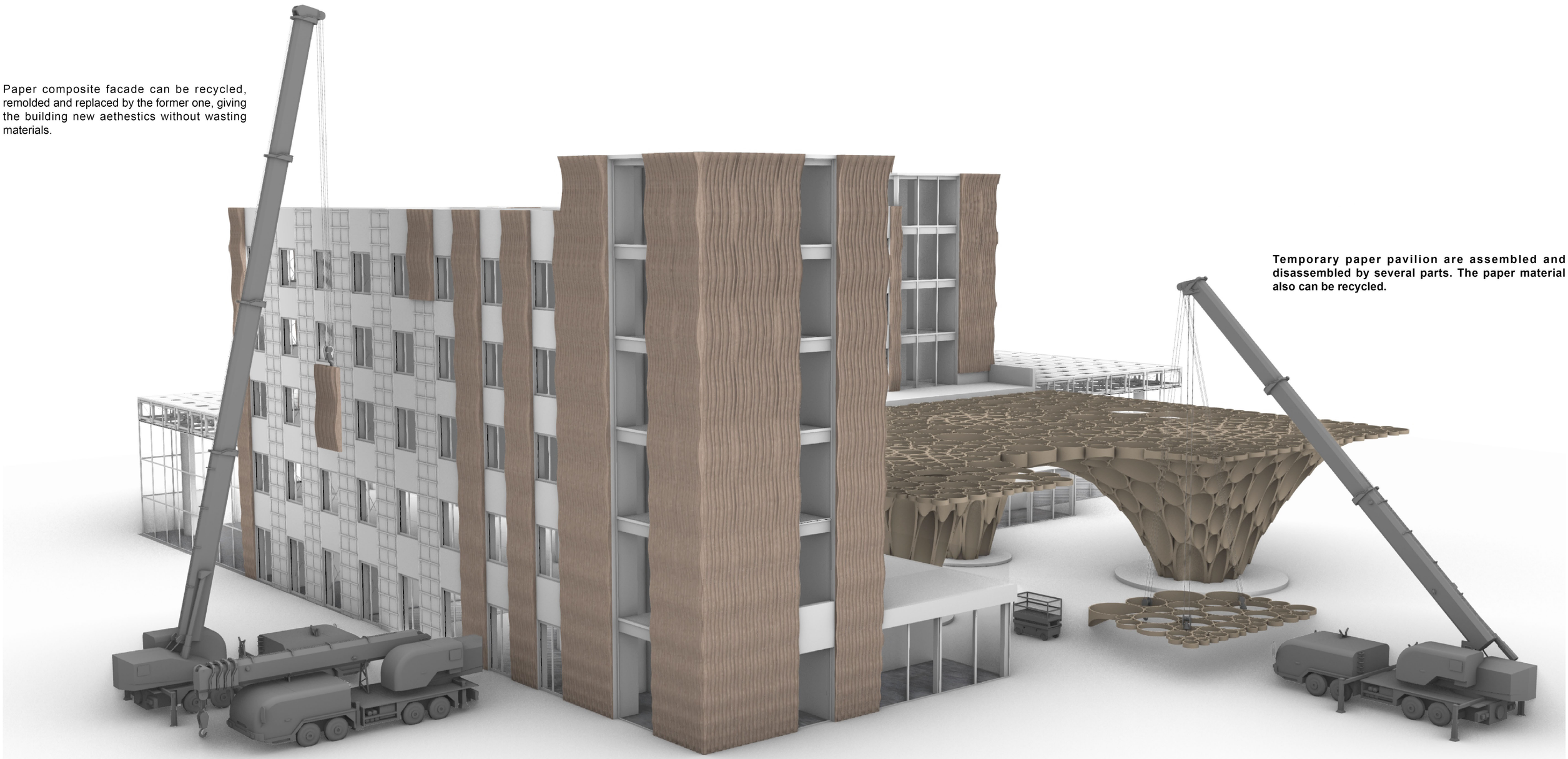




03 Engineering

Maintanence

Paper composite facade can be recycled, remolded and replaced by the former one, giving the building new aethestics without wasting materials.

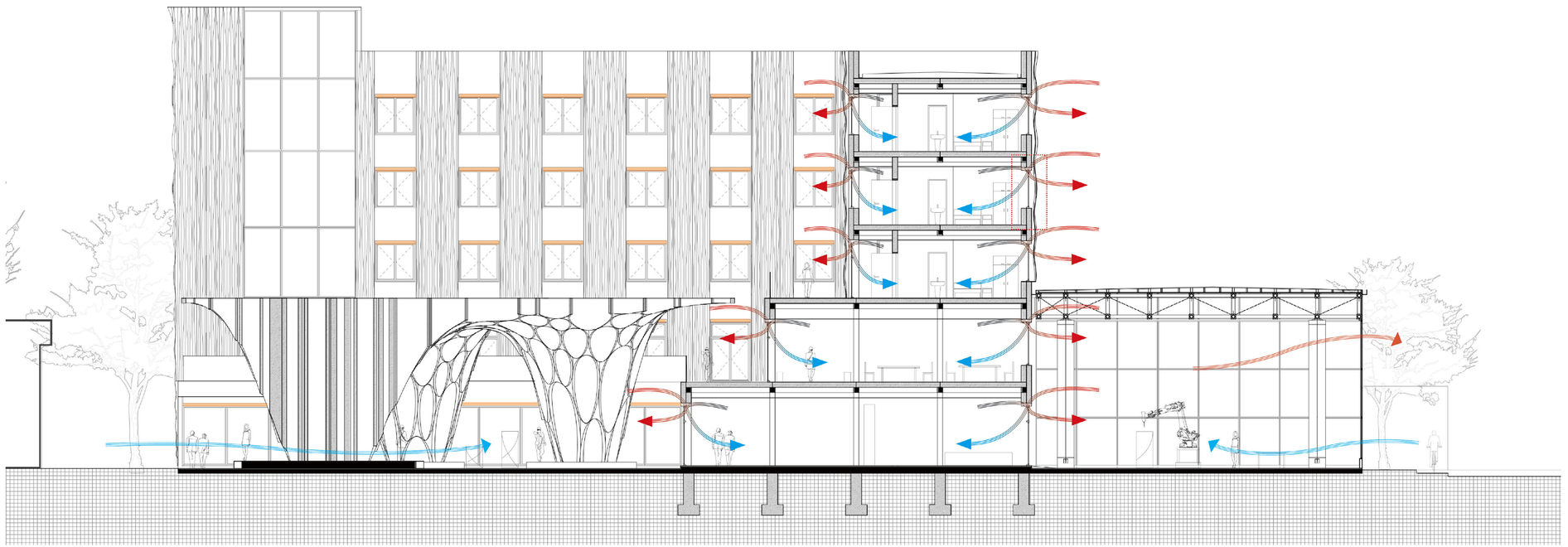


Temporary paper pavilion are assembled and disassembled by several parts. The paper material also can be recycled.

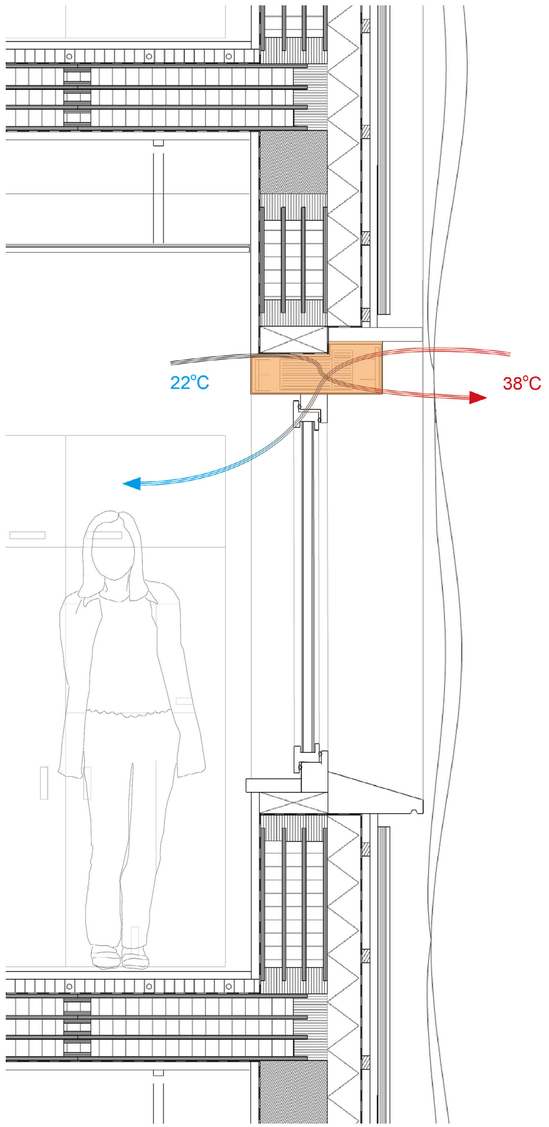
03 Engineering

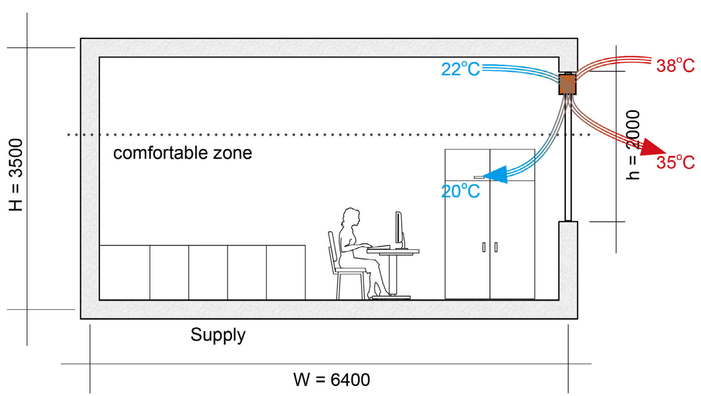
Climate and energy use

- ventilation and energy use in summer

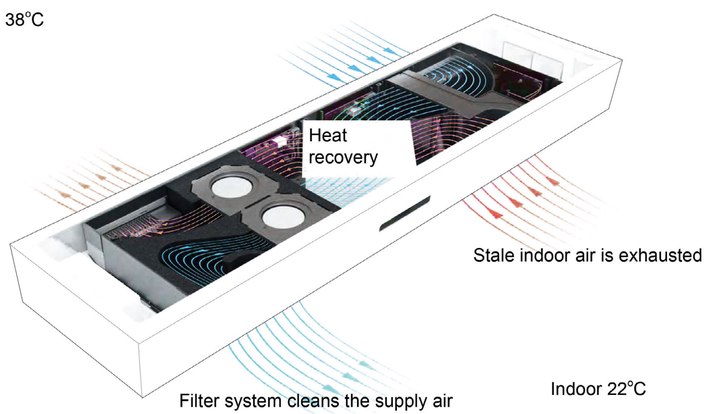


Outdoor 38°C





Decentralized breathing window / summer

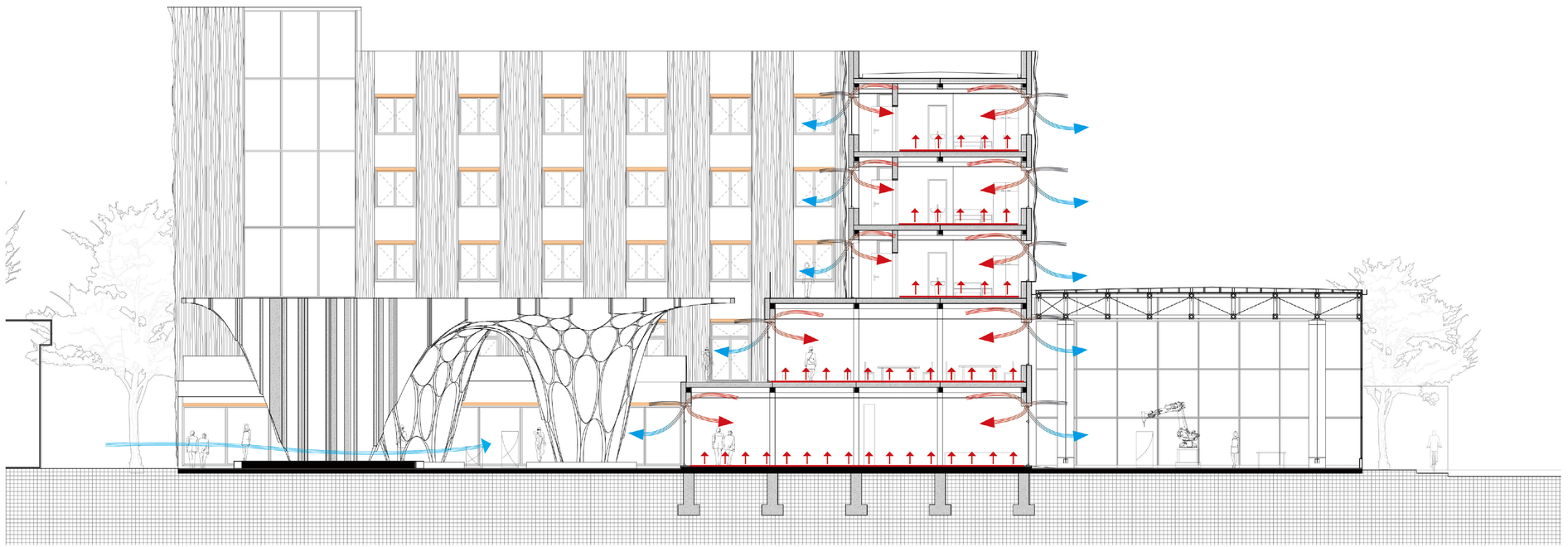


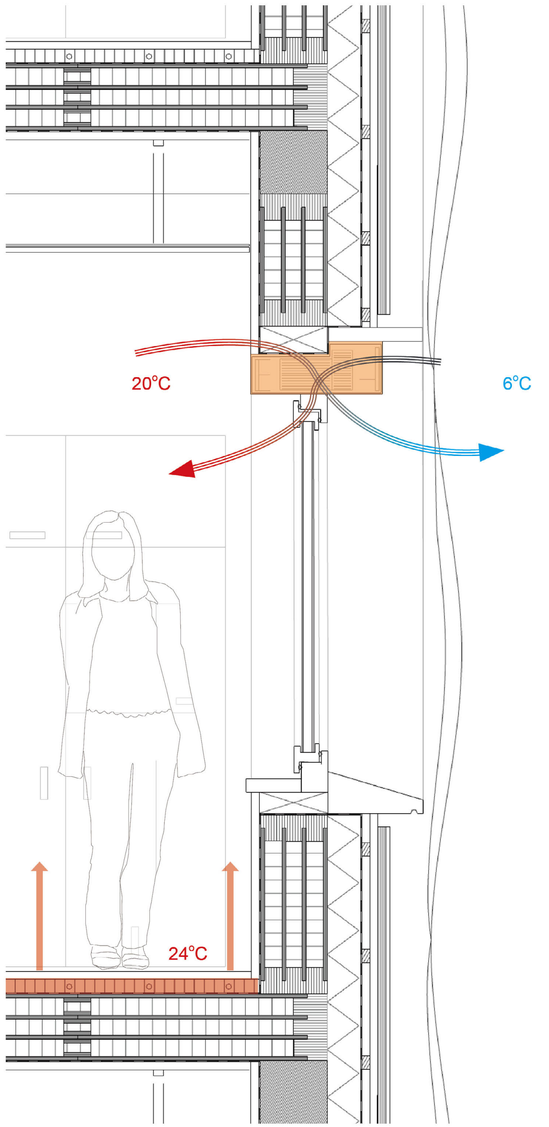
Breathing window system

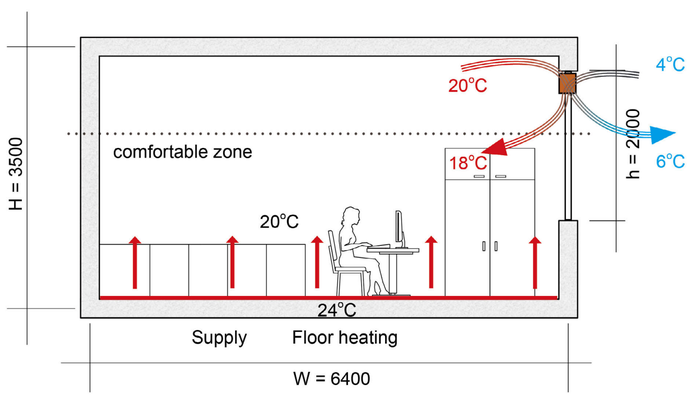
03 Engineering

Climate and energy use

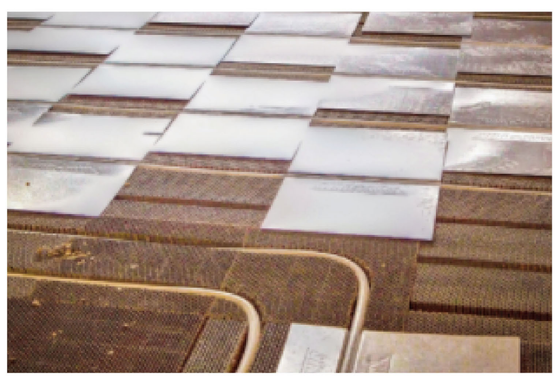
- ventilation and energy use in winter







Decentralized breathing window / winter



Manufactured from 100% recycled paper

Density: 200-250kg/m3
Compressive strength: 10kp/cm2

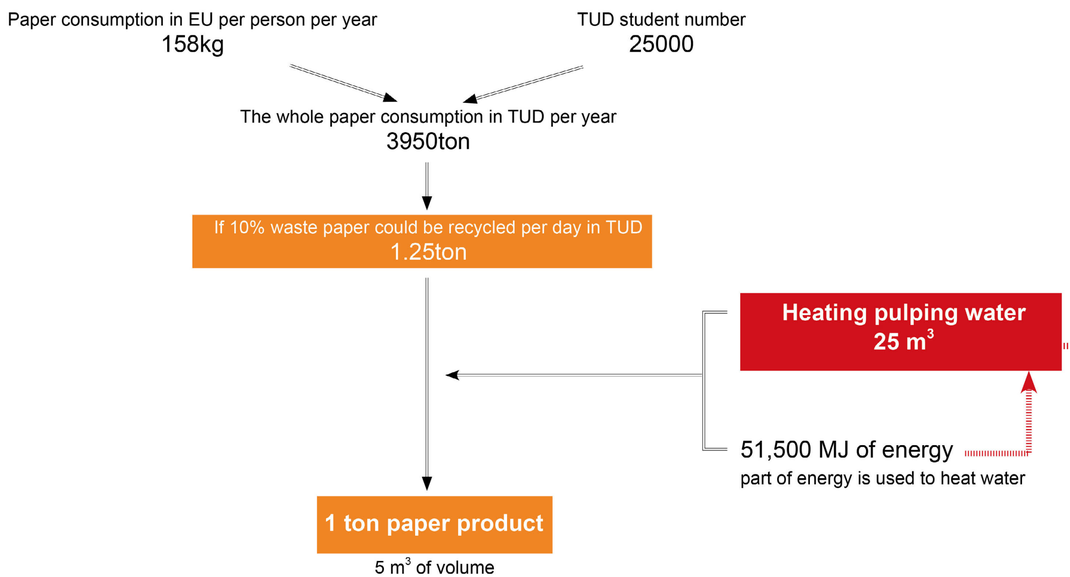
Imbedded heating pipe

03 Engineering

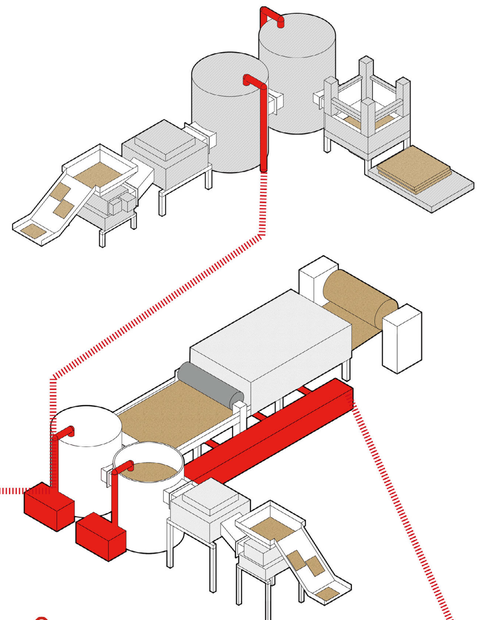
Climate and energy use
- water heat recycling

Paper recycling

Paper consumption in EU in 2016 is 158 kg per person per year. And TUD student number is 25,000. So the whole paper consumption is 3,950 ton. If 10 percent of wasted paper could be recycled, every day 10.8 ton waste paper could be transfered into 8. 5 ton paper product.
Considering the limitation of manufacturing space, up to 1 ton paper product could be made every day.



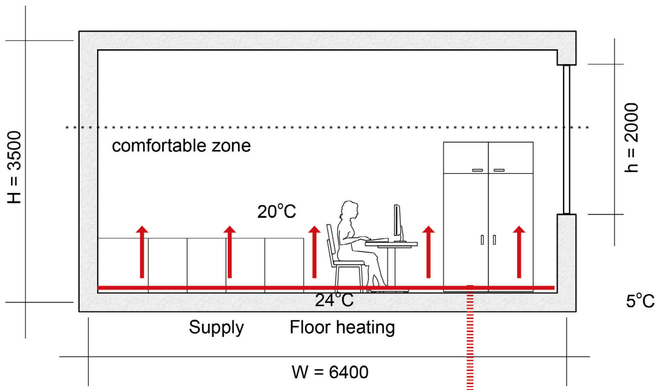
Paper pulping



70°C

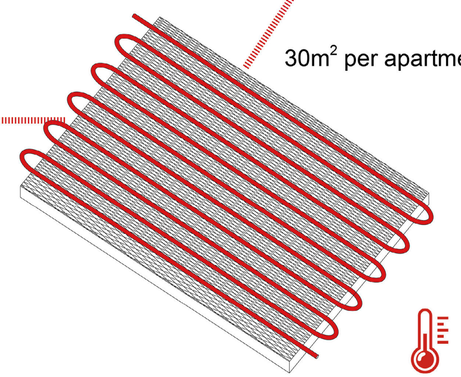
1m³ water = 126MJ energy = 35kW
25m³ water = 875kW
(from 70°C to 40°C)

Apartment heating



Energy transfer hub

875kW
Energy loss 50%
400kW



30m² per apartment unit

40°C

35 apartment unit + 2000m² shared space

100W offers 1m² floor
400kW = 4000m² floor
3900m² (35 apartment unit + 2000m² shared space)

The standard heating index is 50W per m^2, considering the insulation effect, we choose a heat load of 100w per m^2.

The radius of plumbing pipe is 15mm, 1 m^2 floor needs about 5 m pipes. The volume is about 0.1 m^3 of water.

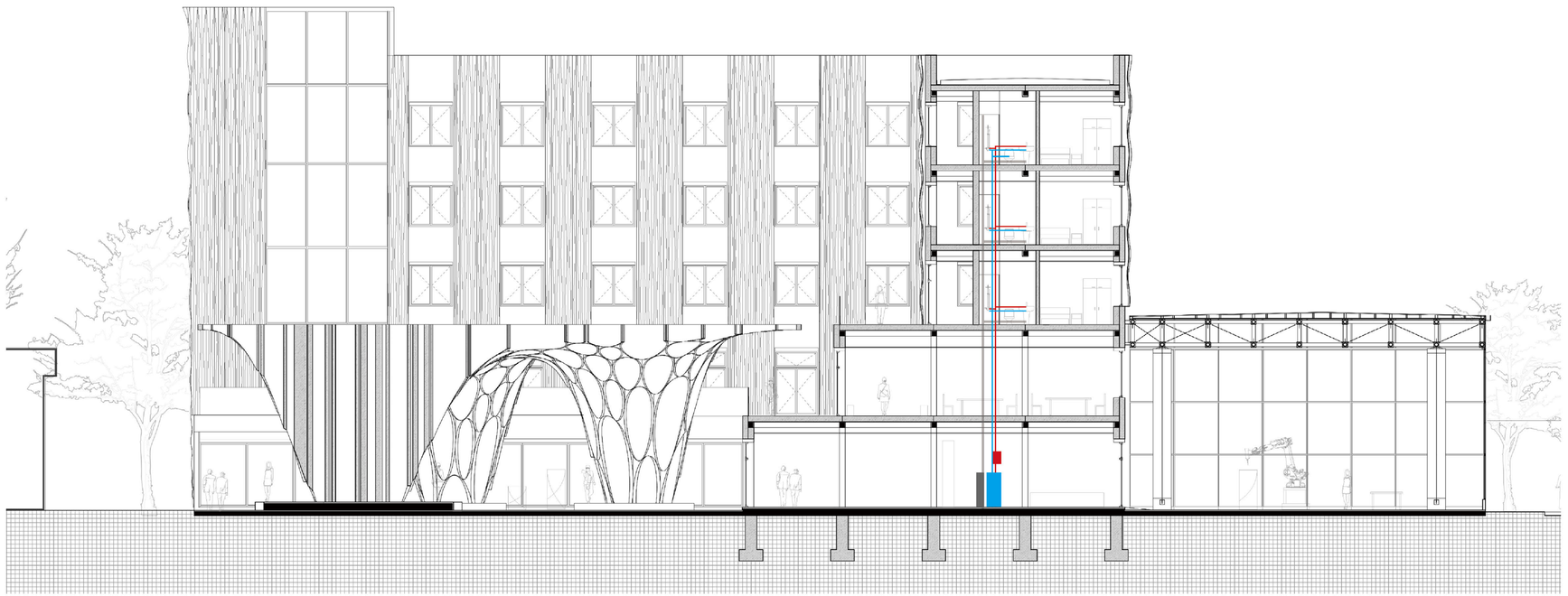
The temperature of water is from 70°C to 40°C when heating the apartment. So 1m^3 water could provide 126 MJ energy.

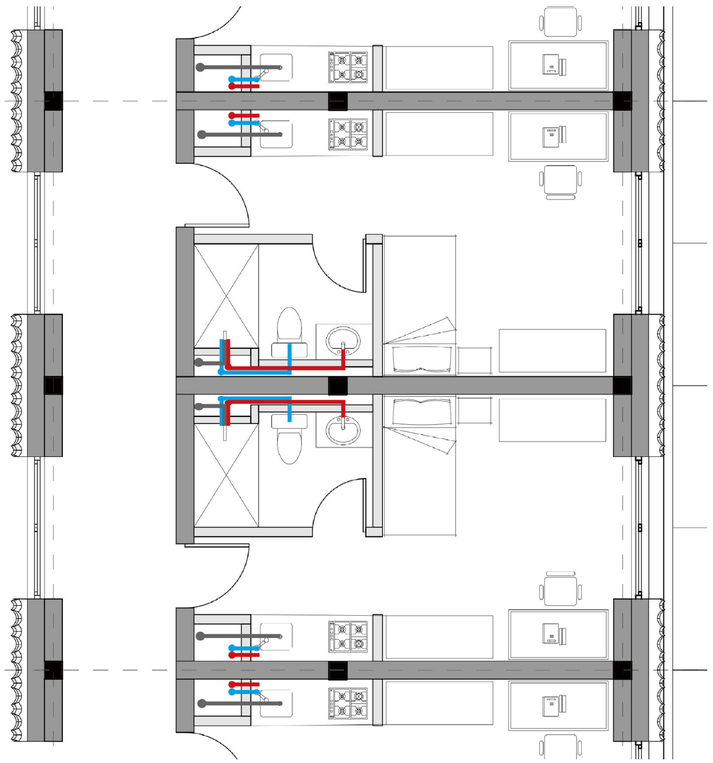
$Q = C_{water} * M_{water} *(t_s - t_e) = 126\ MJ = 35\ kW$

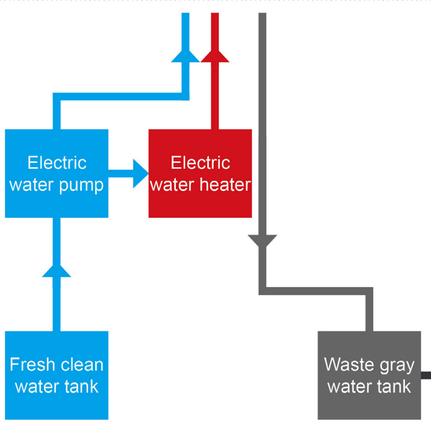
So 25 m^3 hot water could provide 875kW heat and after 50% energy loss in transfer hub, 400KW heat can provide for 4000 m^2 floors (35 apartment units + 2000m^2 shared space).

03 Engineering

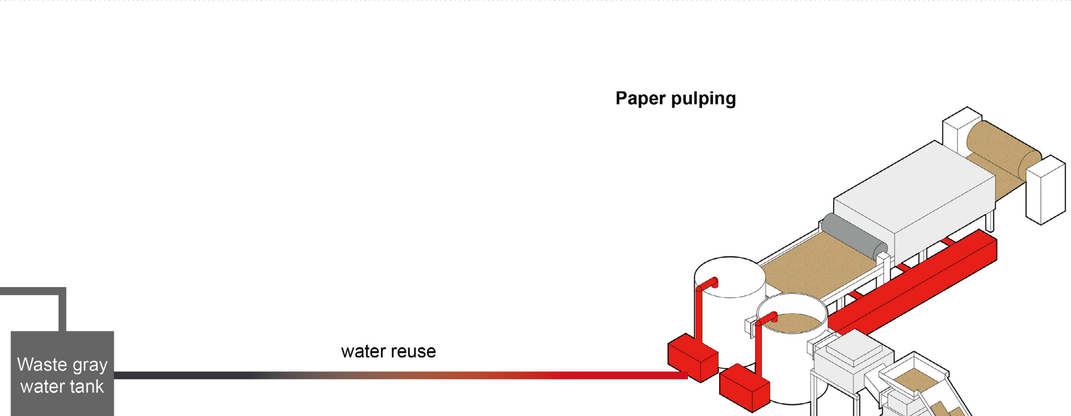
Climate and energy use
- plumbling system







Plumbing system

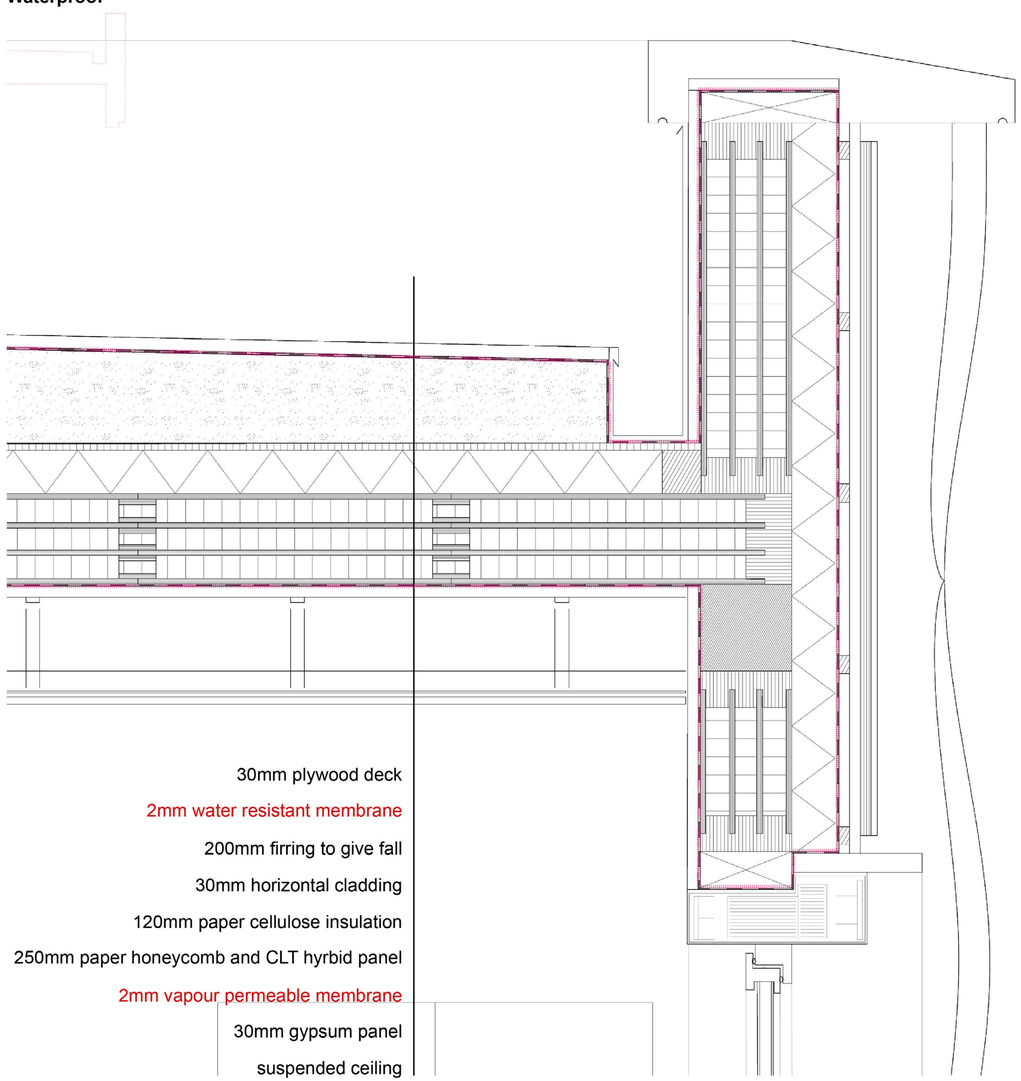


Paper pulping

03 Engineering

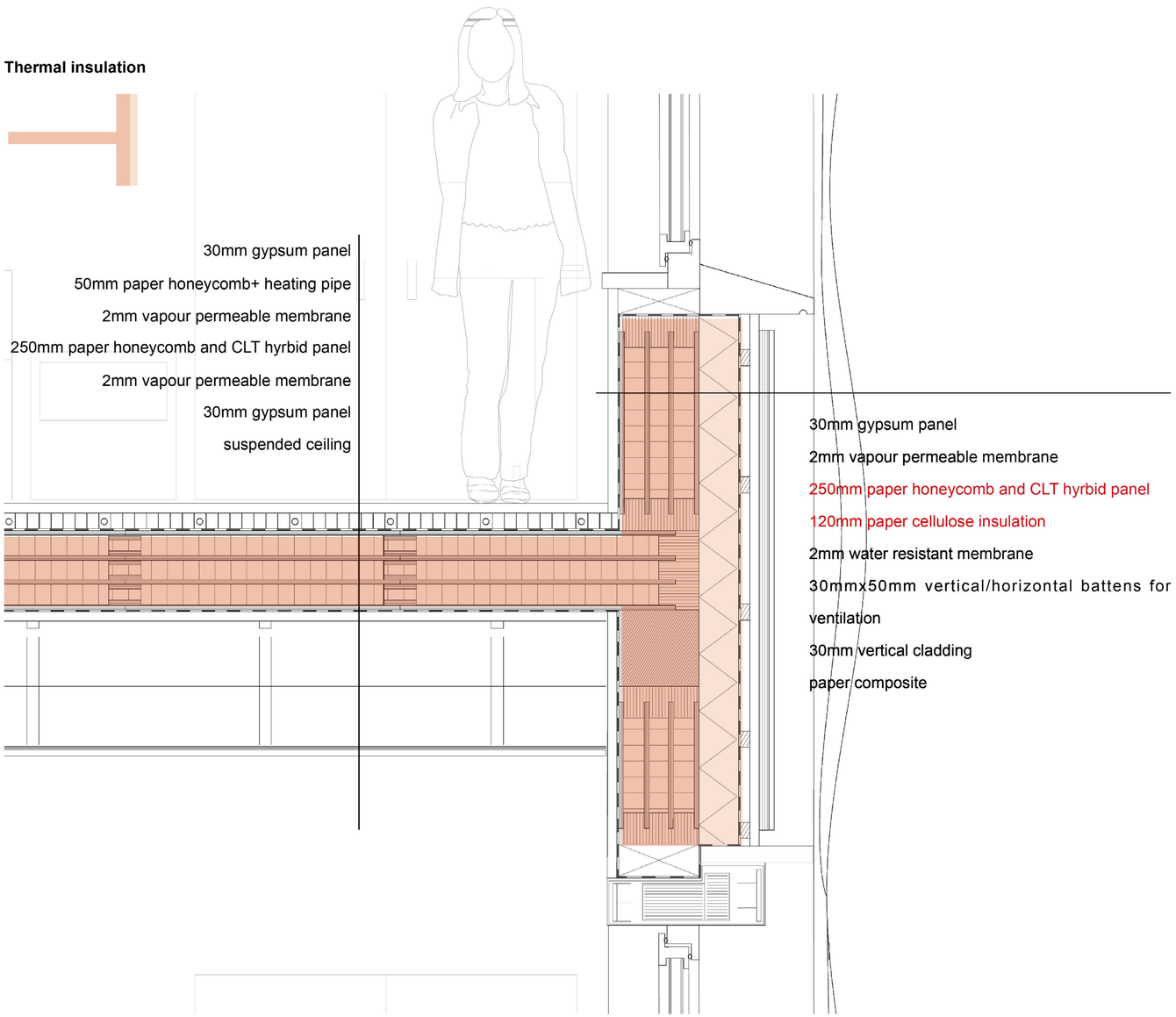
Detail 1:20

Waterproof



30mm plywood deck
2mm water resistant membrane
200mm firring to give fall
30mm horizontal cladding
120mm paper cellulose insulation
250mm paper honeycomb and CLT hyrbid panel
2mm vapour permeable membrane
30mm gypsum panel
suspended ceiling

Thermal insulation

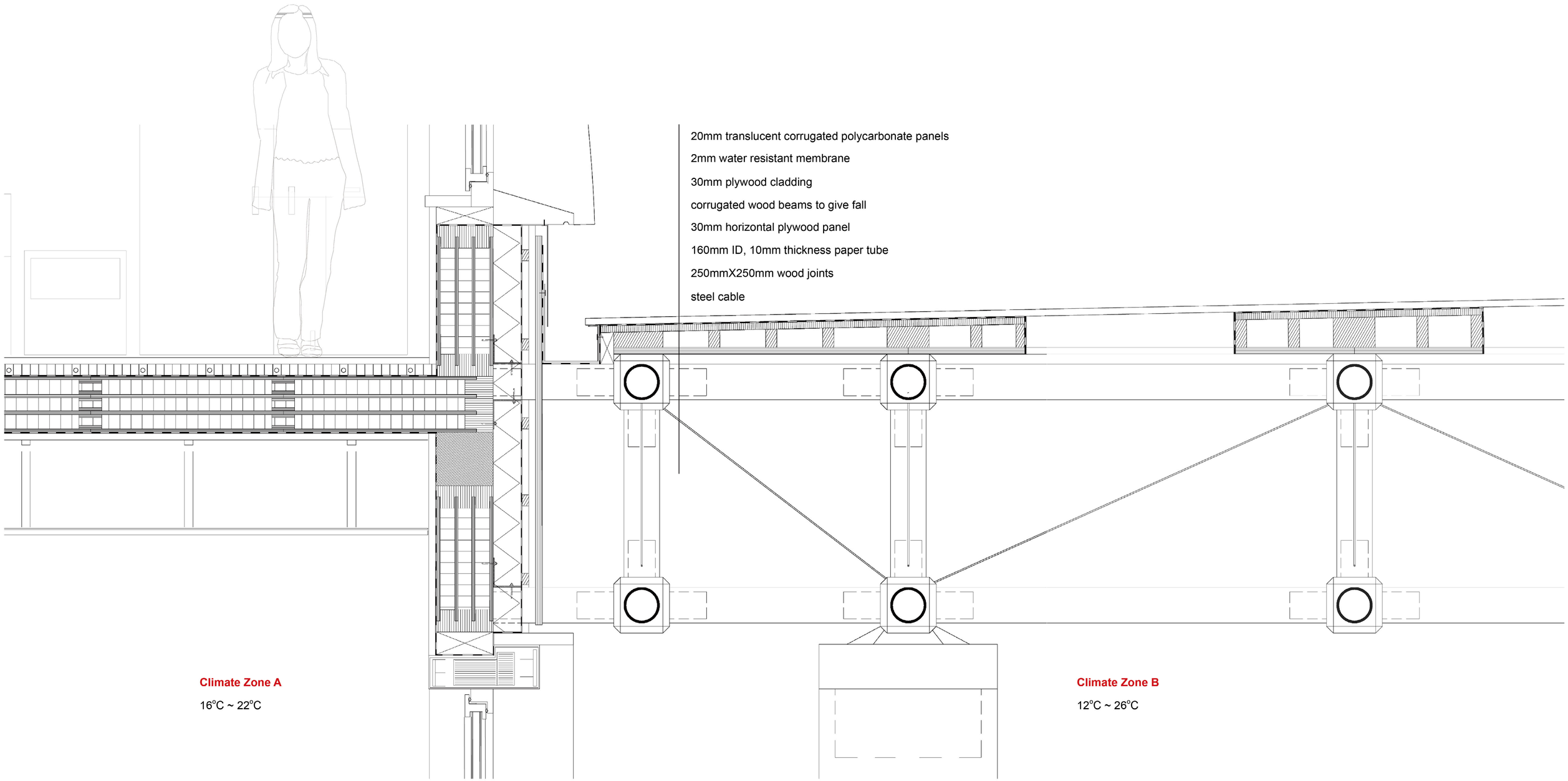


30mm gypsum panel
50mm paper honeycomb+ heating pipe
2mm vapour permeable membrane
250mm paper honeycomb and CLT hyrbid panel
2mm vapour permeable membrane
30mm gypsum panel
suspended ceiling

30mm gypsum panel
2mm vapour permeable membrane
250mm paper honeycomb and CLT hyrbid panel
120mm paper cellulose insulation
2mm water resistant membrane
30mmx50mm vertical/horizontal battens for ventilation
30mm vertical cladding
paper composite

03 Engineering

Detail 1:20



Climate Zone A

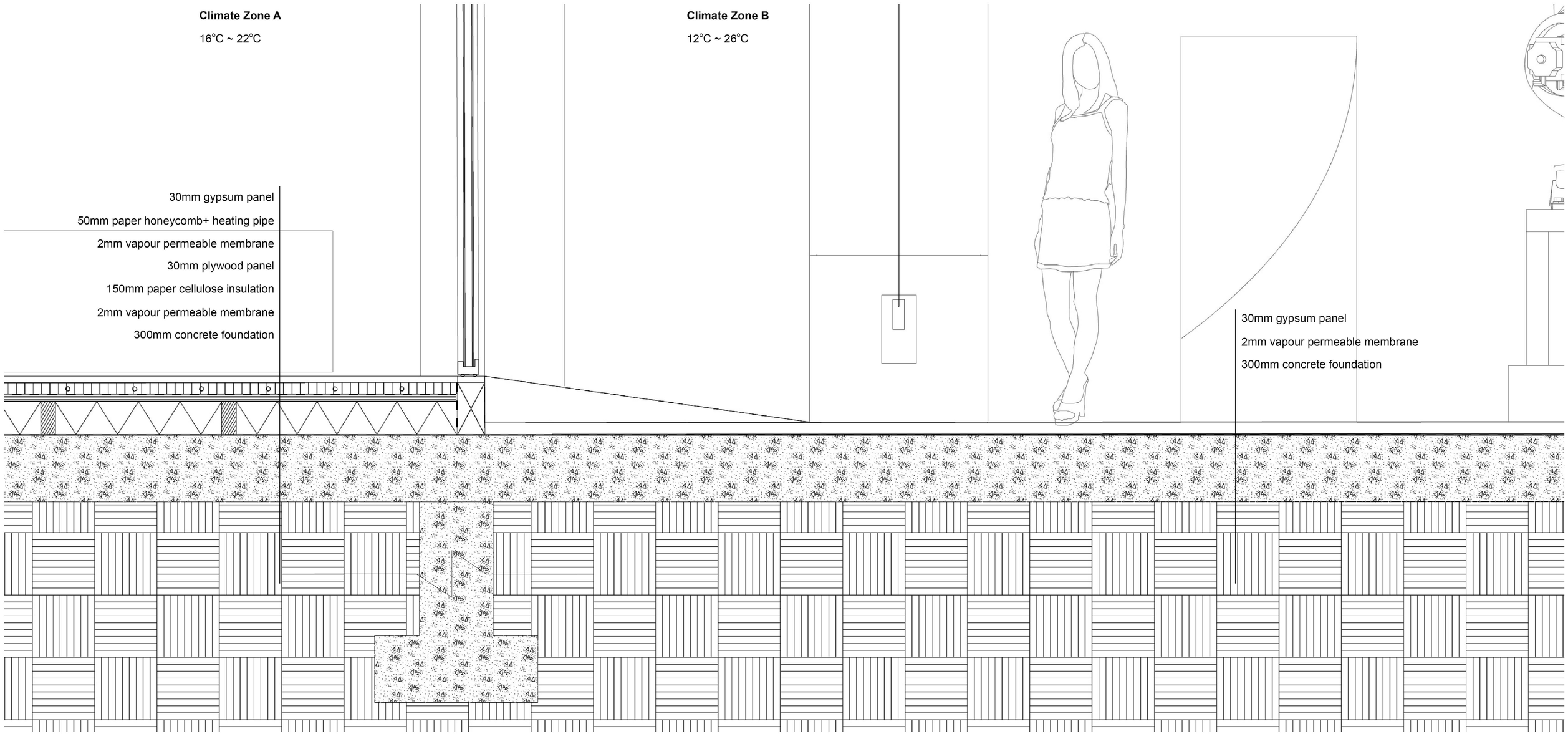
16°C ~ 22°C

Climate Zone B

12°C ~ 26°C

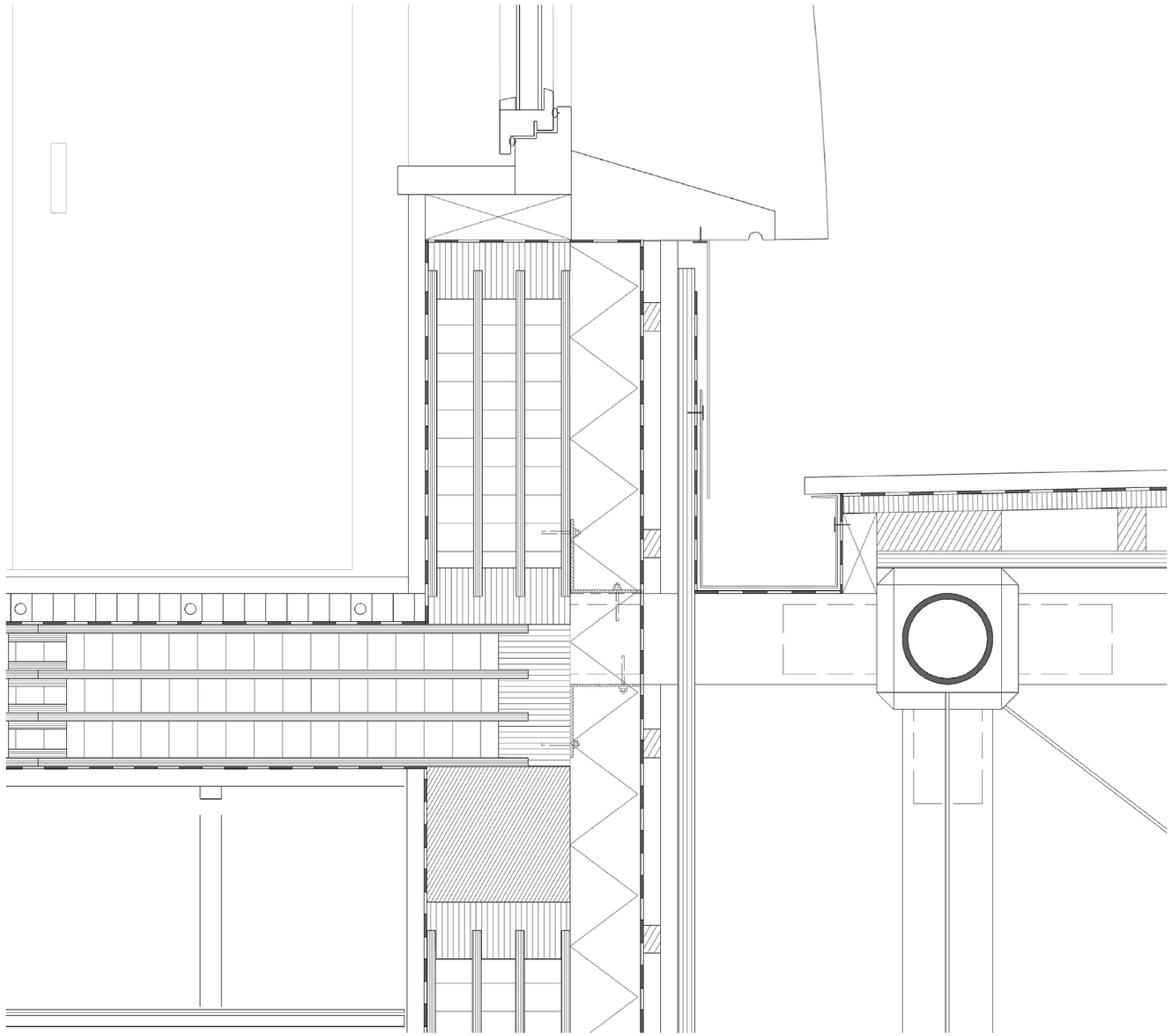
03 Engineering

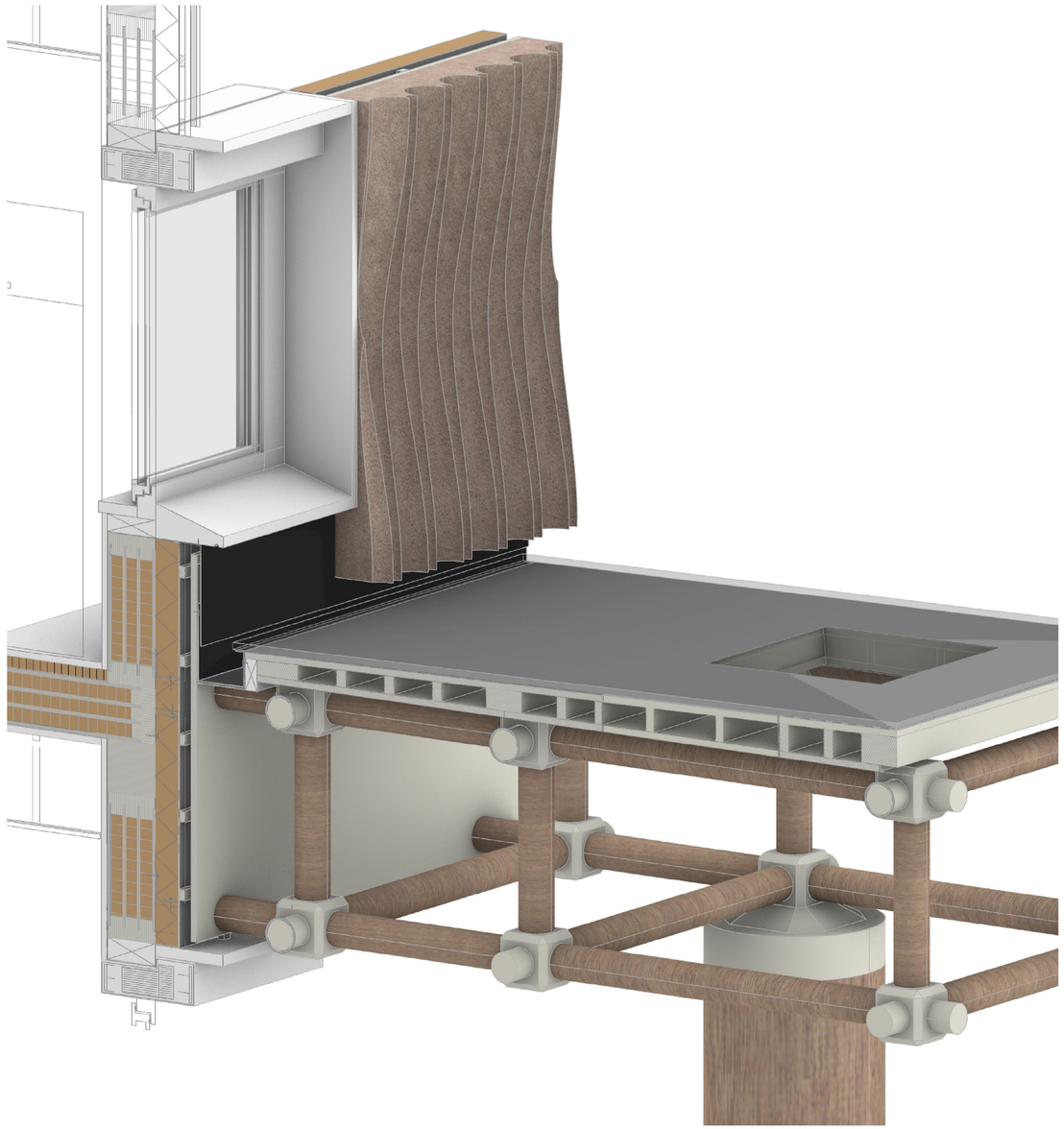
Detail 1:20



03 Engineering

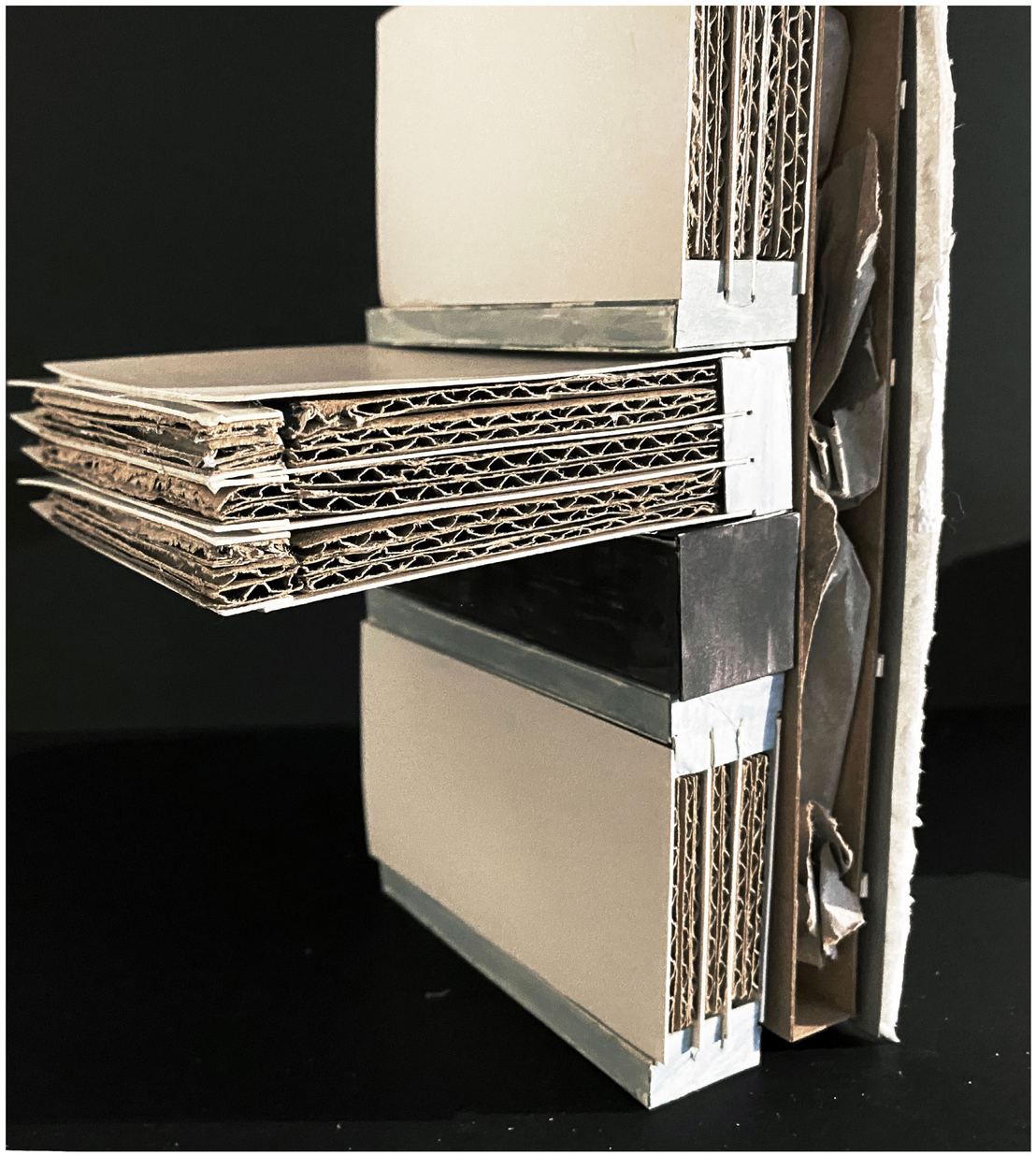
Detail 1:5

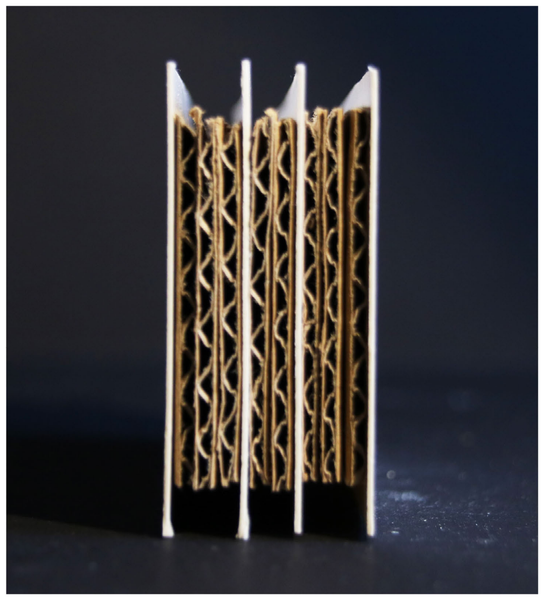




03 Engineering

Physical section model





04 Reflection

04 Reflection

Potential of paper architecture

Property

Fire resistance

A mineral coating petrifies the raw honeycomb structure and non-bearing walls made of one-layer satisfy fire protection class EI-60(no flames, no smoke, high teperature insulation in 60 mins).

Water resistance

Adding polymer coating like polyurethane can provide water resistance.

Thermal insulation

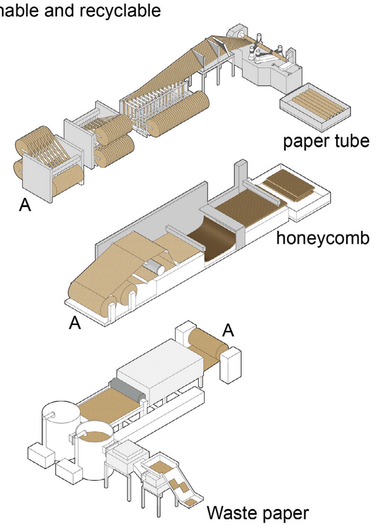
For paper honeycomb and paper cellulose, the delicate air chambers and porous material can provide thermal insulation.

Density

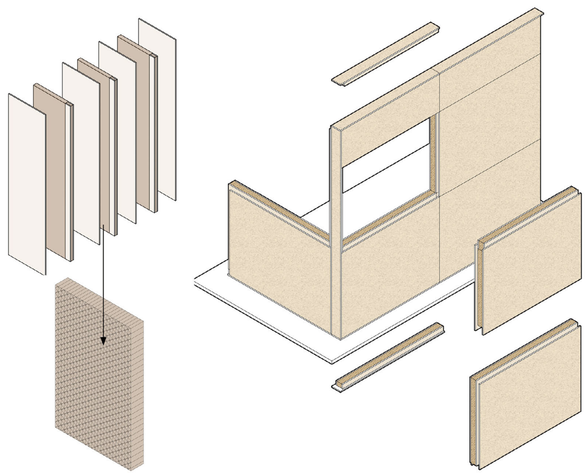
690 kg/m^3 for solid paper
130 kg/m^3 for paper tube
30-90 kg/m^3 for paper honeycomb

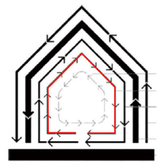
Process

sustainable and recyclable



Product1 : Paper honeycomb & CLT panel wall/floor





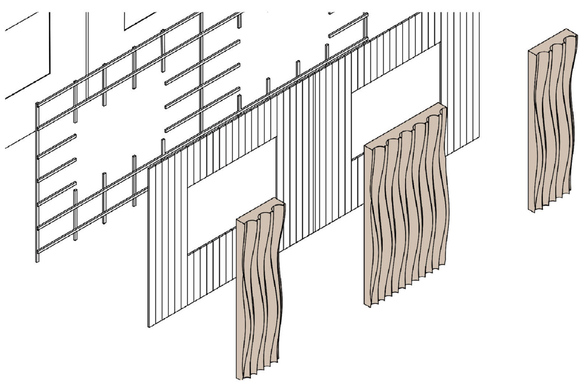
Lifespan
> 20 years

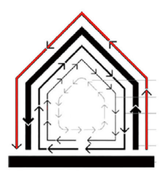
Parameters

Size: 6m x 1.5m x 0.25m
Paper honeycomb and CLT hyrbid panel：75kg

CLT panel：300kg
Concrete：1500kg

Product2 : Paper composite facade



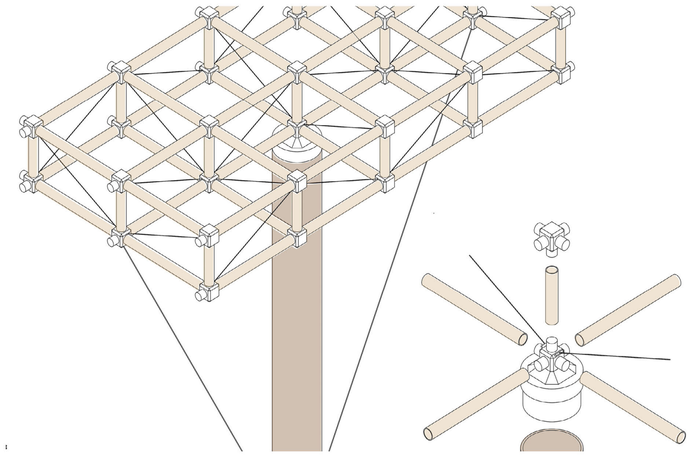


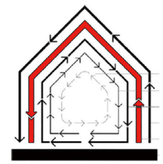
Lifespan
5 years

Parameters

Size: depending on mold/3D printing
Density: depending on the ratio of paper and sodium silicate (80%: 20%)

Product3 : Paper tube truss structure





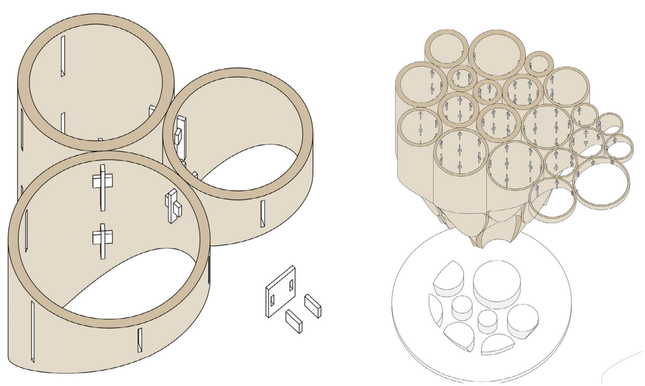
Lifespan
> 30 years

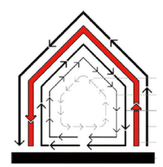
Parameters

length: 20mm-7000mm
Thickness: 2mm-100mm
Inner Diameter: 25mm-1600mm

paper tube arch span 25m (case study)
paper tube truss span 15m (case study)

Product4 : Paper tube pavilion





Lifespan
2 years

Parameters

length: 20mm-7000mm
Thickness: 2mm-100mm
Inner Diameter: 25mm-1600mm

04 Reflection

Unsolved problems of paper architecture

1 Strength

Can paper become a structural material as strong as steel?

Paper as structure, usually has one third of the structural strength of wood, which has been demonstrated in Shigeru Ban's projects. Steel cables and braces have to be added to increase the whole stability.
To increase paper's strength, researches on materials such as paper fibers and additives should be considered.Experiments such as bending strength and tensile strength have to be recoreded to support the building codes.

2 Water resistance

Can paper achieve better water resistance like plastic?

When facing the penetration of water both indoor and outdoor, paper changes its humidity and moisture content, which may cause the damage of strength and thermal property.
To protect paper from water, special plastic coating have to be added on paper product. Different fibers can also be added without limiting paper material's shape and texture.

3 Fire resistance

Can paper meet different fireproof levels in building codes?

Flames damage the paper. Current treatment is to soak paper in a saturated solution of borax. But can paper meet the needs for stricter fireproof requirements. For example, structural fire resistance periods vary between 30,60 and 90 minitues.

4 Lifespan

Can paper materials has longer lifespans?

Existing paper architectures, such as those designed by Shigeru Ban, are usually temporary buildings with a life span of only 5-15 years.
Paper is easy to change its strength and thermal properties when encountering waters, which will reduce its lifespan and increase its instability. However, current measures, such as adding a waterproof layer or adding other materials in pulping process, are extending the lifespan of paper.

5 Sustainability

Can paper be recycled 100%?

Paper fibers can usually be recycled from waste paper products. However, the additives used in paper to improve fire and water resistance now may increase the difficulty of paper recycling. More energy consumption will needed for processing. So, the new methods for seperating pulp and other materials should be considered.

6 Aesthetics

Can paper bring new aesthetics for future architecture?

Because of paper's easy processing and shaping characteristics, it has great aesthetic potential.
Architects have the responsibility to explore innovative paper design methods to expand the possibilities for this material.