PHYLLO STACHYS

EXPLORING THE POTENTIAL OF ENGINEERED BAMBOO

AR3AE100
GRADUATION DESIGN STUDIO
MSc 3/4 Architecture

Mo Smit
Gilbert Koskamp
Pierre Jennen
Robert Nottrot

Luc Thomassen
4553136

CONTENTS

OUTLINE

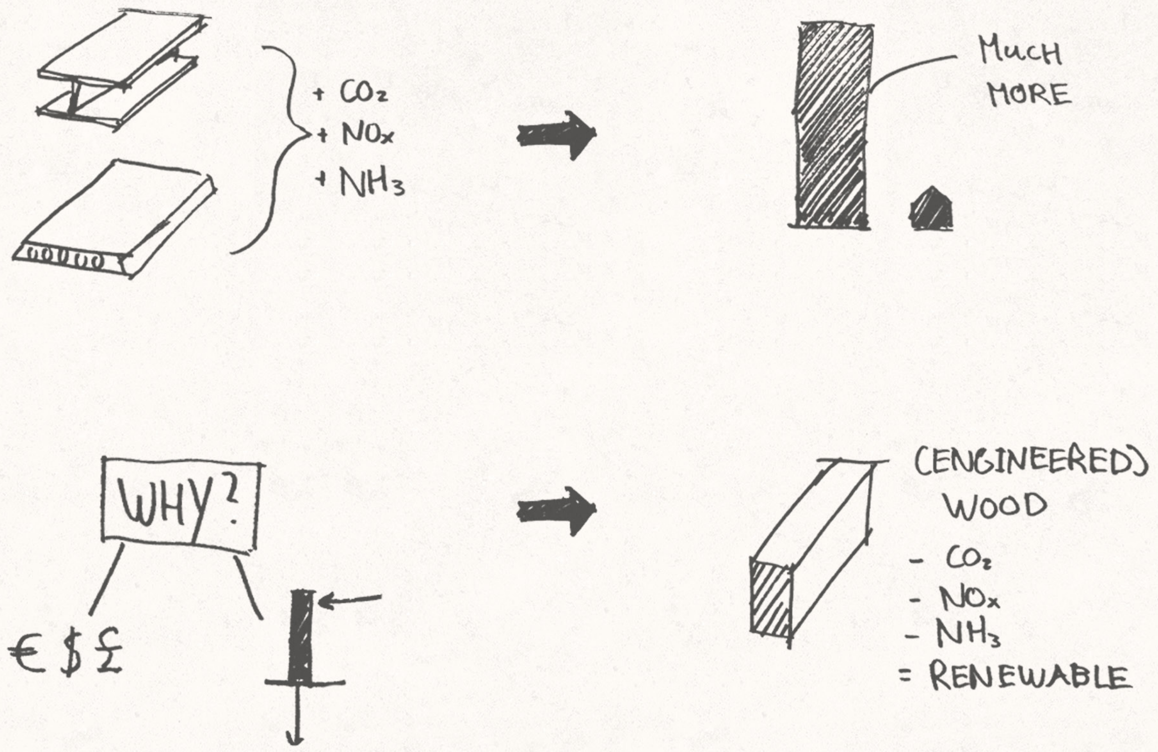
1.

OUTLINE
PROBLEM STATEMENT

High usage of CO2, NOx and NH3 intensive building materials such as steel and concrete.
(Chau et al., 2012)

Highrise structures are responsible for by far the largest part of this material use due to costs and challenging structural properties.
(Chau et al., 2012)

Engineered wood is increasingly used in highrise applications as this is renewable and generally CO2, NOx and NH3 absorbing instead of producing.
(Van der Lugt, 2017)



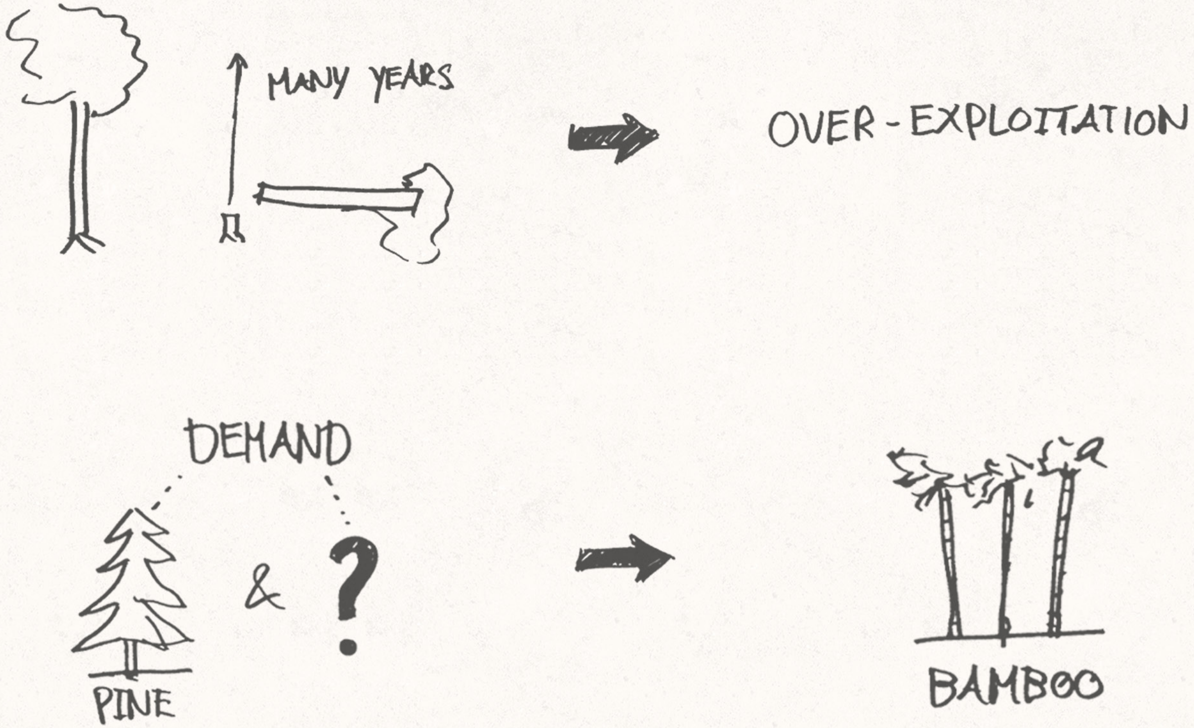
OUTLINE

PROBLEM STATEMENT

Production of wood (although ever increasing) may not able to keep up with projected demand if it were to be used on a similar scale as concrete and steel.
(Arets et al., 2011)

Efforts should to be made to find additional renewable and CO_2, NO_x and NH_3 absorbing building materials that don't compete with softwood production and/or can be used in different use-cases.
(Van der Lugt, 2017)

One such material, showing great potential for structural applications is Moso Bamboo (Phylostacchus Pubescens)
(Van der Lugt, 2017)



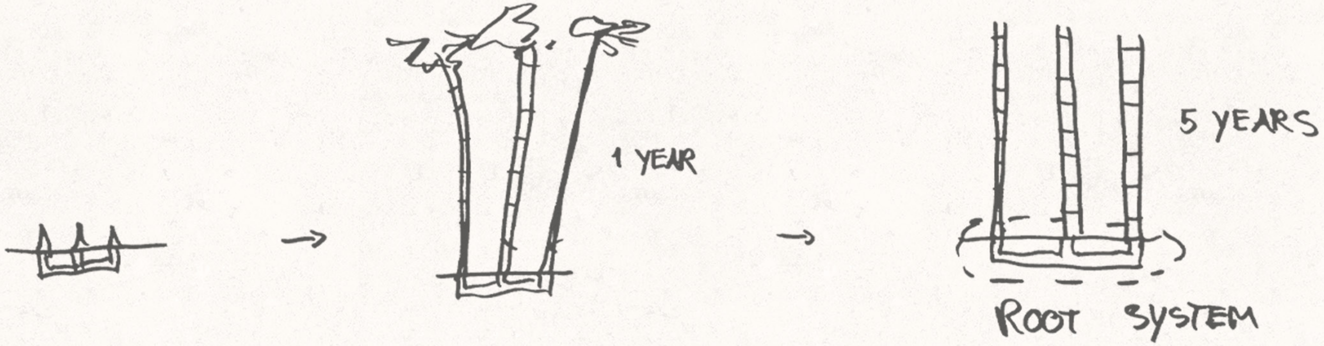
OUTLINE

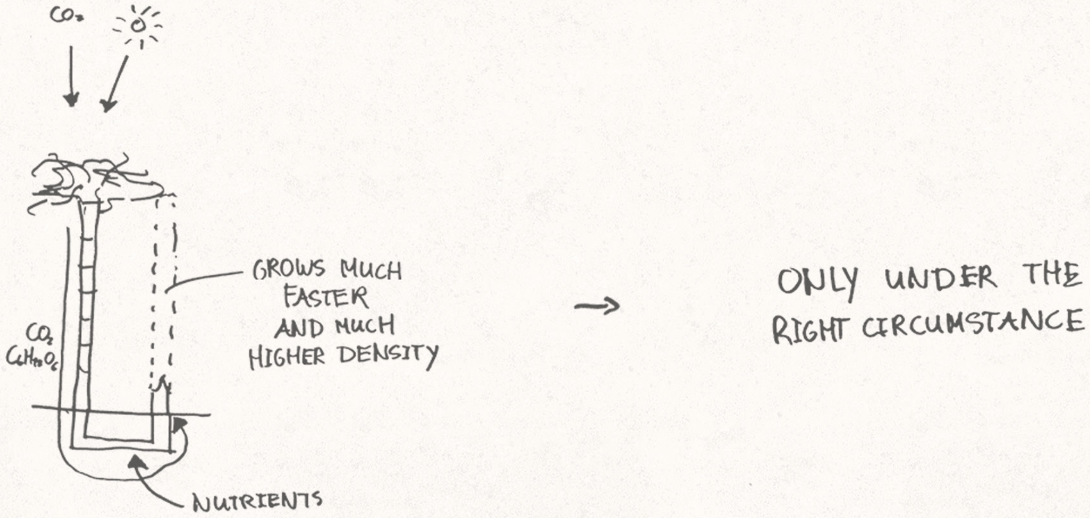
ACADEMIC DISCUSSION

Moso Bamboo can grow increadibly quickly and produce up to 5 times as much biomass as regular pinewood in the same time-period.
(Van der Lugt, 2017)

Underground root system, which uses adult plants as "factories" supplying the young plants with an abundance of CO2 and Glucose, makes bamboo grow fast and at increadibly high density.
(Van der Lugt, 2017)

This can only happen optimally, however, if there is also enoughsunlight and water as well as nutrients in the soil.
(Van der Lugt, 2017)





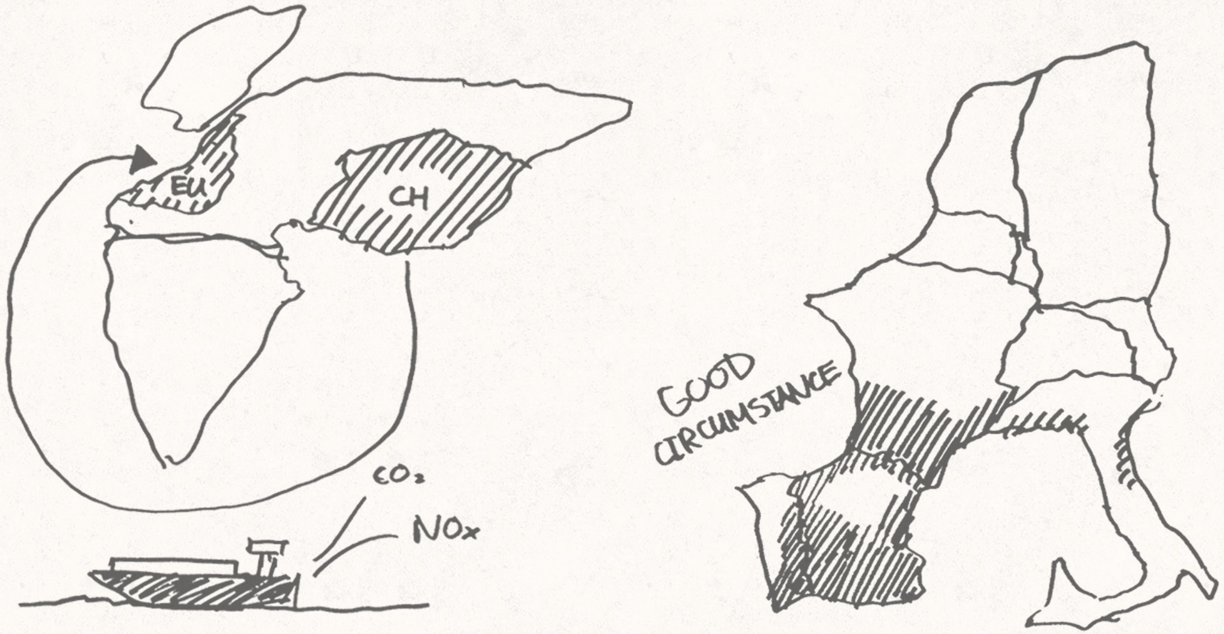
ACADEMIC DISCUSSION

Historically mainly grown in China and shipped to Europe and America. This largely negates the positive properties of using bamboo in these areas.
(Van der Lugt, 2017)

More recently, initiatives have been taken in Florida to grow moso bamboo locally, which have proven very succesful, even at large scale. (OnlyMoso, n.d.)

OnlyMoso grows high quality Moso bamboo in Italy. BambooLogic is currently setting up a production network in Portugal and claims that large parts of Spain, France and Greece are also suitable production locations for high quality bamboo production.
(Onlymoso, n.d.; Bamboologic, n.d.)

The possibility and plausibility of using locally grown bamboo should force us to reconsider using this material in our built enviroment.

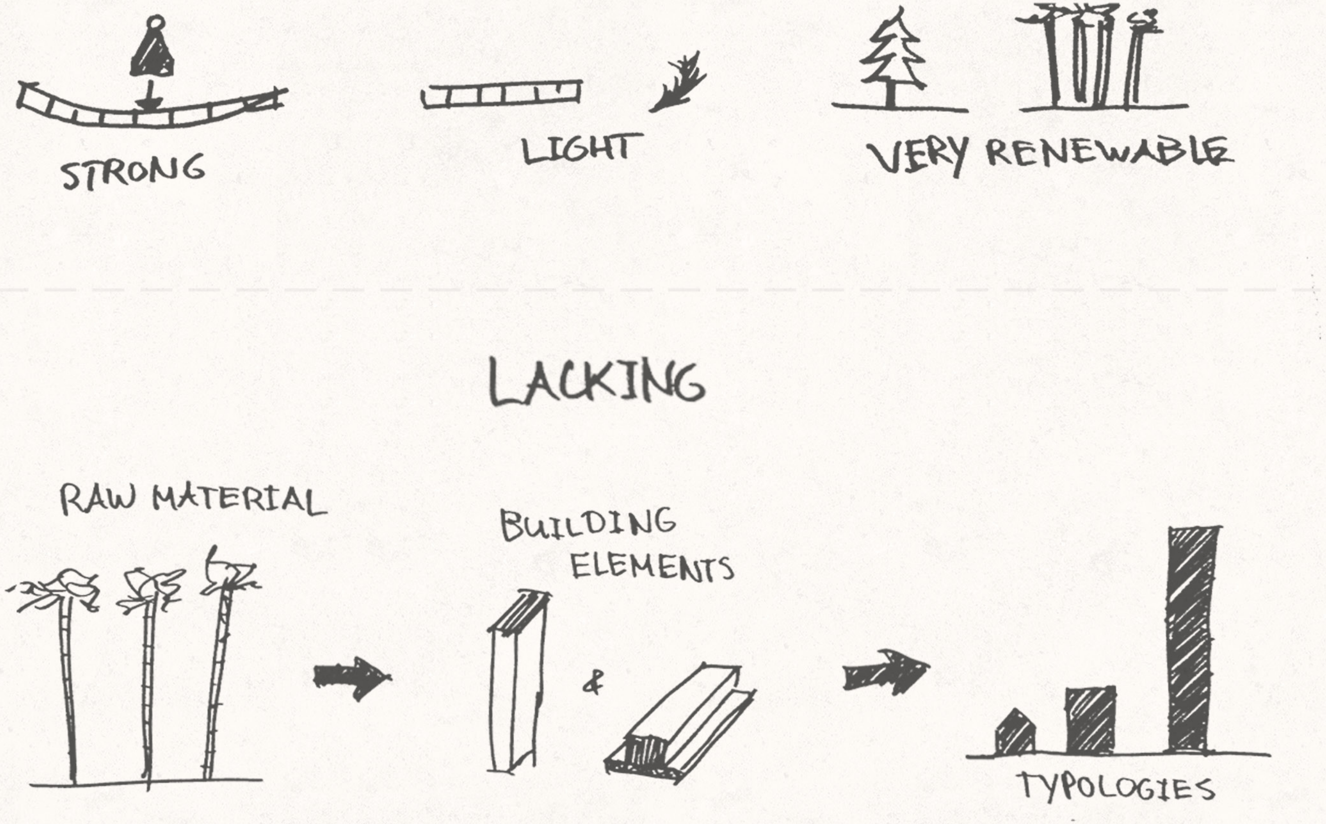


OUTLINE

ACADEMIC DISCUSSION

Although much research is done into the mechanical properties of the material and the possibilities for processing it, there is a severe lack of standardization.
(Van der Lugt, 2017)

No coherent quantification of bamboo building elements' properties, causing every project that applies bamboo to need extensive individual research. This is not feasible on the large scale. What is lacking is a clearly formulated design strategy for optimally applying bamboo-based building elements within different typologies and construction methods.

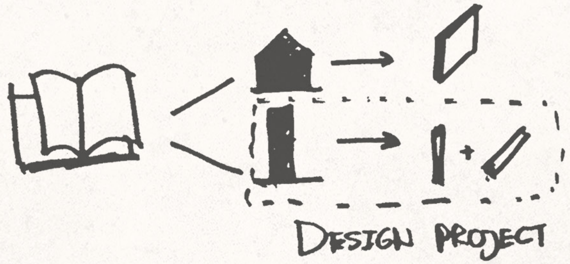


OUTLINE
OBJECTIVE

Research Objective
To improve standardization of bamboo as a building material, by defining a design tool in which standardized bamboo building elements are defined. This is based upon the intended use case of the elements, the chosen construction method and the processing possibilities of the material. To quantify the effects of using bamboo in comparison to other commonly used building materials.
The end result consists of two parts:

1. A research paper, describing the research process and results.
2. A design tool

Design Objective
To demonstrate the possibilities of using Moso bamboo in the European context in order to make high-rise architecture more sustainable. To demonstrate and test the afore mentioned design strategy in a structurally challenging and enviromentally highly impactful typology.



RESEARCH PAPER

2.

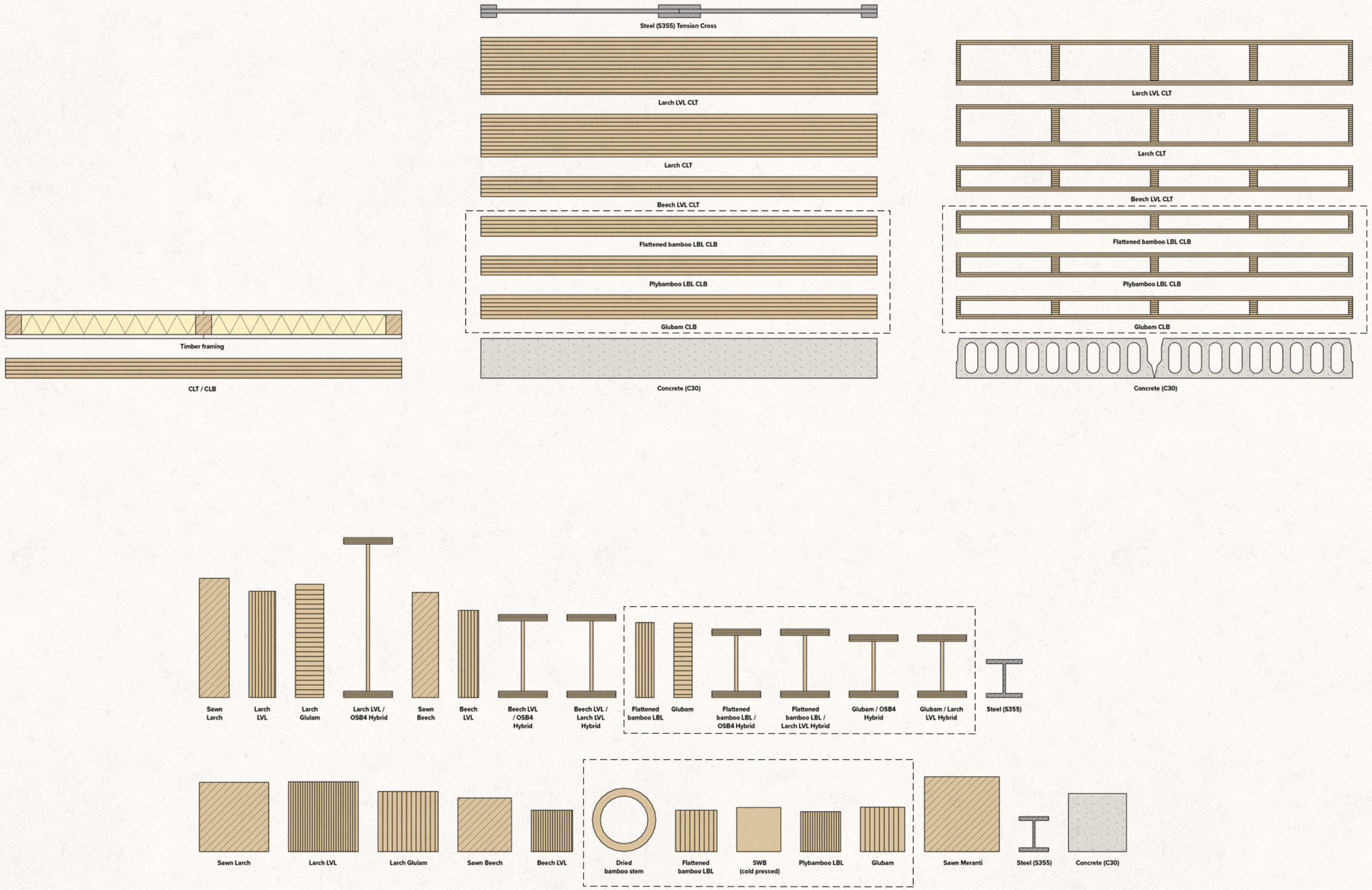
RESEARCH
RESULTS

How can Europe-produced Moso bamboo optimally be engineered into industrialized building elements and implemented in common European typologies?

Moso bamboo can be engineered into a number of forms, each of which is well-suited for a different particular application. The The building elements presented in this study perform excellently when compared to commonly used European wood-based building elements such as Larch and Beech.

In general it can be concluded that for an equally performing building element, bamboo requires less volume, is more cost-effective and far more renewable than common wood-based equivalents. Provided Europe produced Moso bamboo is used, the ECO-cost performance is also on par or better. When Asia produced Moso bamboo is used, the ECO-cost performance is on par with that of European Larch, which is still good (Van der Lugt & Otten, 2006).

Its unrivaled renewability, relatively low cost and excellent mechanical performance can give Moso bamboo a significant advantage over other renewable and non-renewable building materials. As such, large-scale application within European architecture as an alternative to wood-based or unrenewable materials appears viable.



RESEARCH

DESIGN TOOL

RISE OF BAMBOO
RESEARCH PAPER
MSC 3 & 4 (2020-2021)

Appendix 2.1: Design Tool (Page 1 of 12)

Introduction
This design tool was created to assist designers in implementing renewable building materials into their designs by providing them with relevant information, comparisons and conversion charts. It is meant to be used in an early stage of the design process to help the designer make choices with regards to material and building system and see the implications of those choices. It is not to be used for full engineering calculations due to a potential lack of accuracy.

How it works
You will be guided through the document step-by-step and be asked a series of questions. These questions regard the type of project you are working on, as well as the scale and building method. The tool will then suggest suitable building elements to use.

For each building element, there will be three options: the most balanced option, the most sustainable option and the most cost-effective option. When there is no difference between options, they will be merged into one option. Feel free to make your own choice, depending on your priorities.

Upon selecting a building element, you will be referred to a conversion chart. The conversion charts project the data of researched renewable building elements against the data of steel building elements. It was set up so that you can use the common rules of thumb for steel and easily convert them into different materials that perform equally.

Option elaboration
The best balance option contains the best overall balance of characteristics that are relevant for the project scale and construction method. The most sustainable option is a suitable element with the best ECO-cost performance and/or best relative renewability. The most cost-effective option is the most cost-effective, either due to low material cost, fast construction speed or both. The most lightweight option is a suitable element with the lowest relative weight. This option can be especially useful when building on top of an existing building, for example.

Example scenario
I am a designer working on a small house and have decided that I want to make the house as sustainable as possible, but the budget is limited.
I select new-build, because it is a new-build project. The density is low, so I select low-density. I am now presented with the choice of whether I want to use a skeletal building system or a disk building system. The client wants large windows on all sides of the house, so I choose skeletal.

Upon working on the floor-plan, I am interested in the dimensioning of the columns. I see that the most sustainable choice is a sawn Beech column. However, because the budget is limited and I want the columns to be on the slim side, I select the most cost-effective option, which is a Flattened bamboo LBL column.
The design tool refers me to Table 1. Here I can quickly see that the column I have selected needs roughly 6 times the area of a steel column, weights rougly 0,6 as much as a steel column and has roughly 11 times better eco-cost performance.

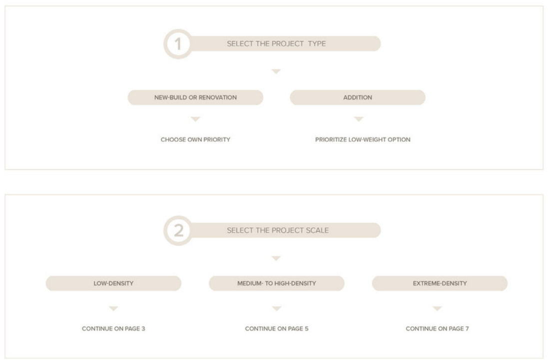
I use a simple calculation and my steel profile app to determine that a SHS-HF 60x60x5 with an area of 1073mm2 is needed. With the data from the tool I can quickly calculate that my Flattened bamboo LBL column needs to be 6438mm2. I take the square root of this to find that the column needs to be a square 80x80mm profile.

I now continue designing with the knowledge that I have selected the most sustainable column for my budget. Additionally, I can prove this to my client using the ECO-cost comparison.

Extra note
Options for facades are exempt from this tool due to the large regional variation in technical requirements. Additionally, facade materials are often largely dependent on the desired architectural expression. Table 5 does, however, also contain data relevant for facades.

RISE OF BAMBOO
RESEARCH PAPER
MSC 3 & 4 (2020-2021)

Appendix 2.2: Design Tool (Page 2 of 12)



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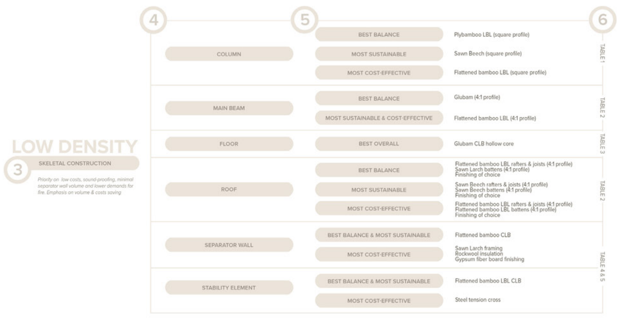
Appendix 2.3: Design Tool (Page 3 of 12)



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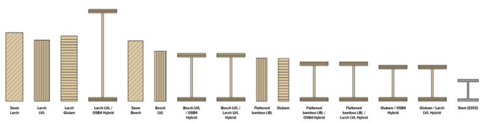
Appendix 2.9: Design Tool (Page 9 of 12)

Table 2 - BEAMS



Beam Type	Relative ECO-costs	Relative Volume	Relative Beam Height	Relative Weight	Relative Renewability	Relative W*
Sawn Larch 4:1	-0,09	9,64	3,13	0,43	1	14,79
Larch LVL 4:1	0,05	7,67	2,8	0,45	1,26	10,5
Larch Glulam (GL28h) 4:1	0,08	8,7	2,98	0,47	1,11	12,68
Larch LVL/OSB4 HEM	0,02	3,03	4,2	0,19	3,58	10,6
Sawn Beech 4:1	-0,16	7,5	2,76	0,68	1,24	10,14
Beech LVL (baubuche) 4:1	-0,01	4,51	2,14	0,46	2,06	4,73
Beech LVL (baubuche)/OSB4 Hybrid HEM	0	2,35	2,18	0,23	3,65	4,92
Beech LVL (baubuche)/LVL Hybrid HEM	0	2,35	2,18	0,22	2,92	4,9
Flattened bamboo LBL 4:1	-0,05	3,8	1,97	0,41	7,8	3,66
Glubam 4:1	-0,03	3,75	1,95	0,42	7,91	3,59
Flattened bamboo LBL/OSB4 Hybrid HEM	-0,02	2,22	1,8	0,23	12,1	3,79
Flattened bamboo LBL/LVL Hybrid HEM	-0,02	2,22	1,8	0,22	11,33	3,8
Glubam/OSB4 Hybrid HEM	-0,01	2,17	1,65	0,23	12,36	3,75
Glubam/LVL Hybrid HEM	-0,01	2,17	1,65	0,22	11,58	3,73
Steel (S355) HEM	1	1	1	1	0	1

* Use Relative W if a steel W value is known due to a higher degree of accuracy

DESIGN

3.

ENGINEERED BAMBOO

LARGE SPANS

Large Spans

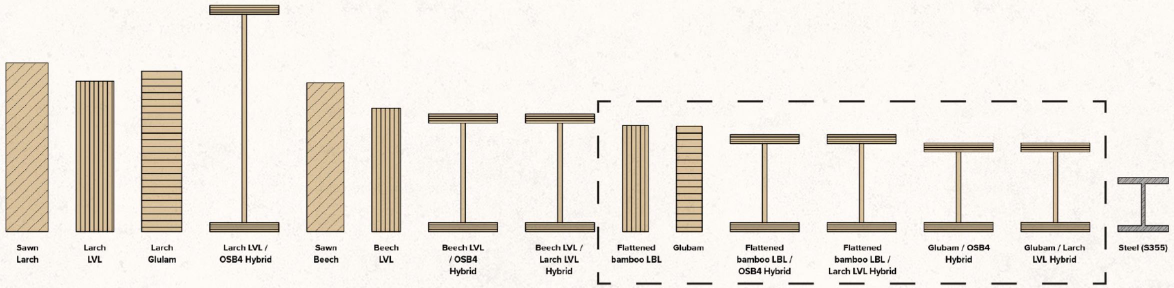
The mechanical properties of Engineered Bamboo are excellent and better than those of concrete or common wood-based products. This allows larger spans, resulting in more efficient space use.

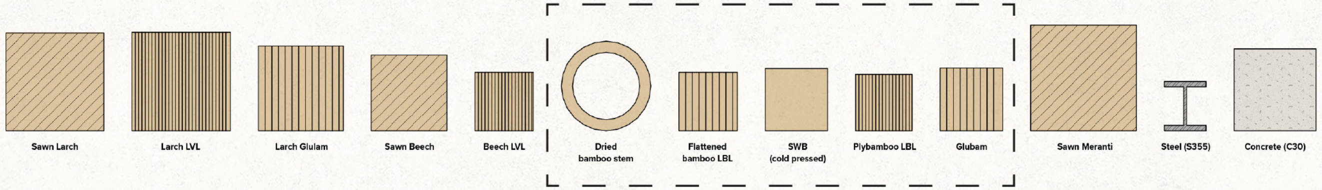
Fibre Direction

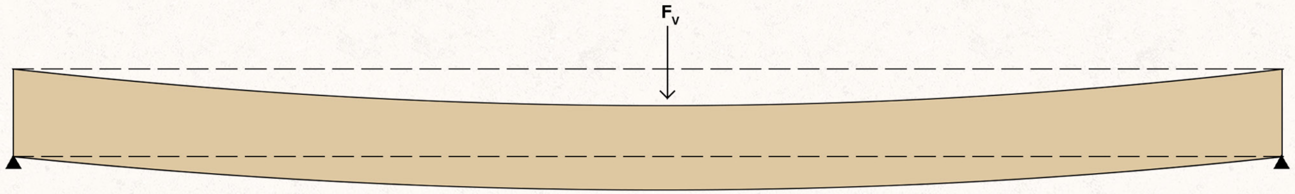
Something to note when using Engineered Bamboo is directional strength, which relates to the direction of the fibres withing the material. Some forms, such as Glubam can be engineered to have multi-directional strength by varying fibre direction in the layup process. Other forms, such as Plybamboo have all of their fibres in the length direction.

Camber

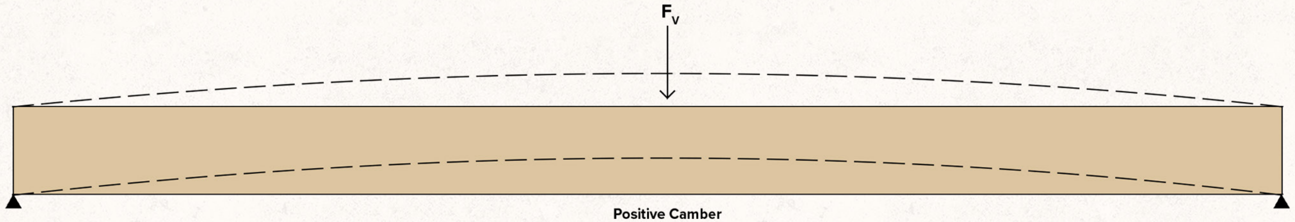
Wood-based products in general and Engineered Bamboo in particular, suffer from low flexural stiffnes. While this can be good for absorbing vibration and wind-loads, beams tend to bend excessively. For this reason, positive camber is implemented in the construction process of the beam. This pre-bends a beam element upwards, so that when the static load is applied, it straightens out.







No Camber



Positive Camber

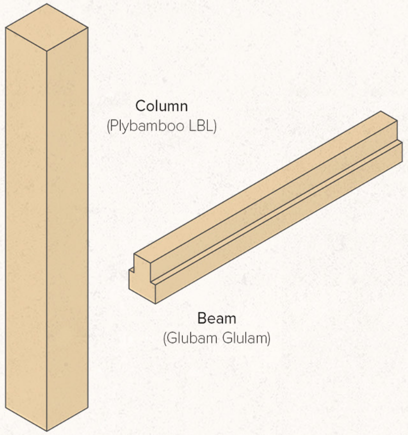
ENGINEERED BAMBOO
JOINERY

Joinery
By applying hidden knifeplate connections, the complex and strong joinery possibilities of steel joints is combined with the easily sawable wood-products to create a strong, complex, invisible and fire-safe joint.

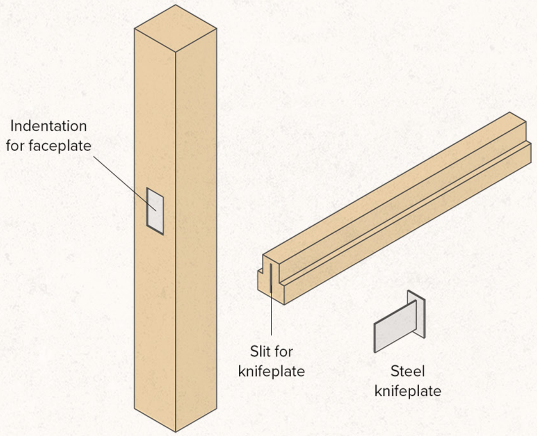
Hidden Knifeplate
A prefabricated steel knifeplate is used as the structural part of the connection. This is connected to the elements using cut out slots and fastened using bolts. Some forms of Engineered Bamboo have a tendency to split on glue layers. For this reason, the boltholes are to be pre-drilled and reinforced with a small metal sleeve in order to evenly distribute the bolt load.

The main advantage of a knifeplate connection is the geometric freedom. The knife part of the connection can go in any direction and even rotate and the Engineered Bamboo element can be sawn at any angle. This makes the connection suitable for all types of complex shapes.

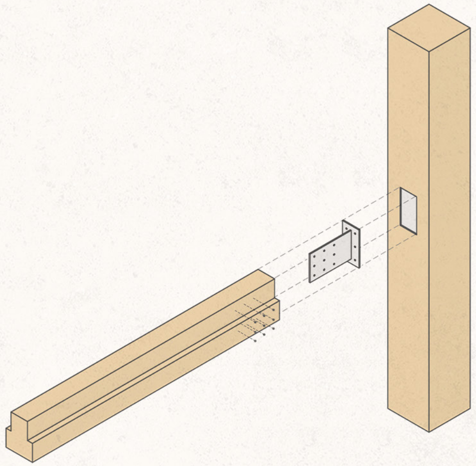
Fire-Safety
Another big advantage of the hidden knifeplate connection is the fire-safety. Wood-based products in general have predictable fire-behaviour with known charring rates. This allows elements and joints to be over-dimensioned to fire-specification. Because the joint is fully enclosed in this over-dimensioned wood, the connection is fire-safe and does not present a point of faillure.



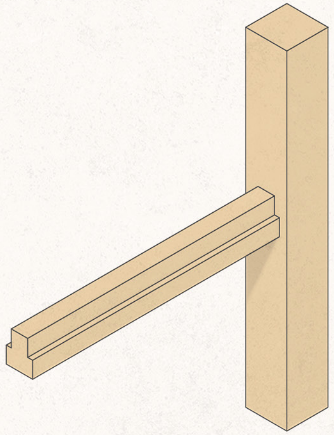
1. Elements to be connected



2. Elements sawn to size & prepared for internal knifeplate connection



3. Elements aligned and fastened with bolts



4. Hidden and fire-safe connection

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JOINERY

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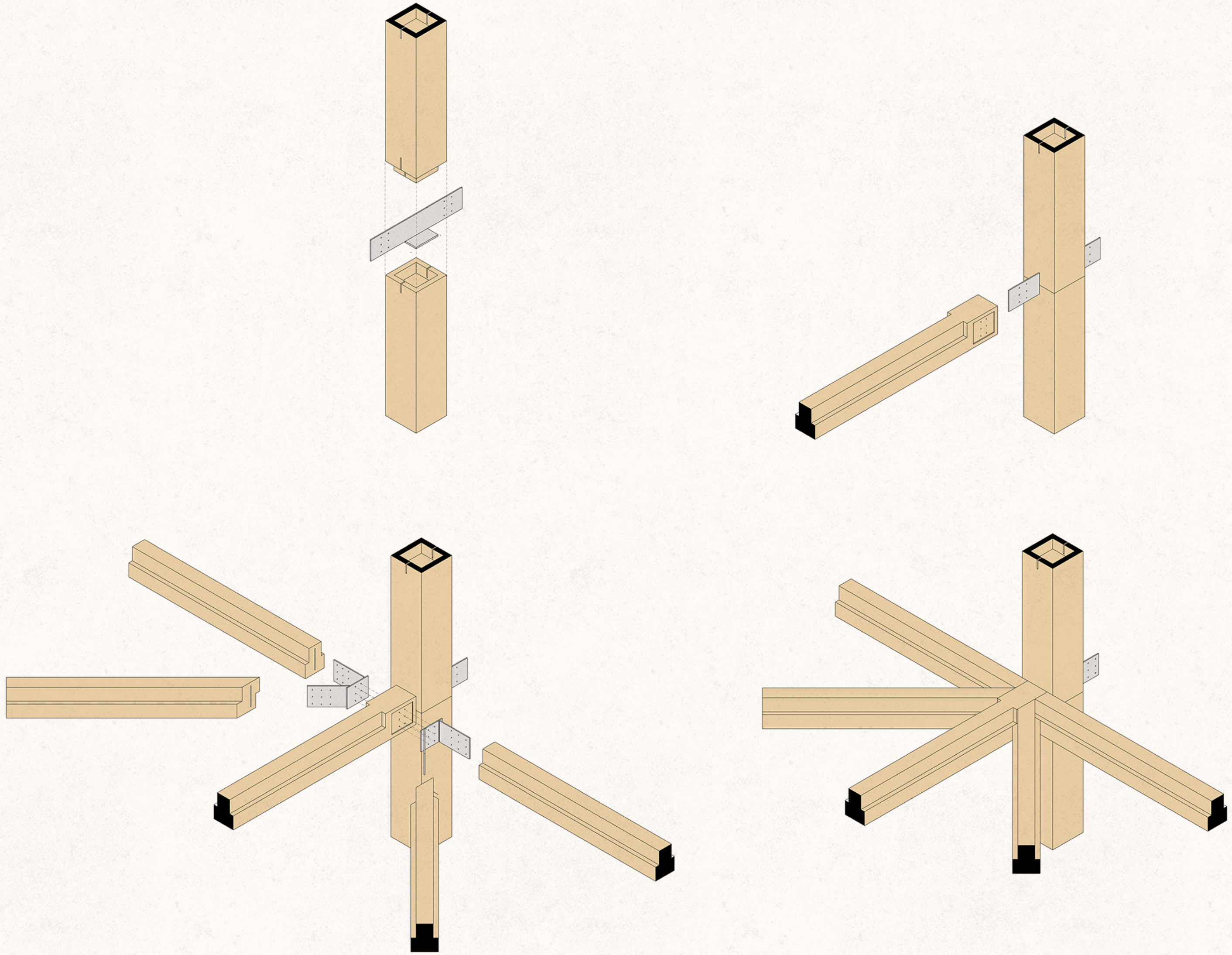


ENGINEERED BAMBOO
DIGITAL MANUFACTURING

A Different Approach To Standardization
Previously, standardization has meant identical. Products are made to identical specification in a factory assembly line to create a standard product time and time again.
More recently, however, strong developments have been made in digital manufacturing. This entails production by a single or set of robots, that can individually perform multiple and more complex tasks. These robots are controlled by software, which can input different data.
What this means in practice, is that elements can be made to size and/or altered in any way, without affecting cost. This is because it is not an assembly line requiring the same step every time. Instead it is a series of computer generated commands, based on 3D model data.

Geometric Freedom
What digital manufacturing allows, when combined with the right material, is full geometric freedom, but not at the detriment of production cost. This opens the door to a host of new types of design, including parametric designs or simply more complex shapes.

Engineered Bamboo
Engineered Bamboo, like other wood-based products is easily editable. It can be cut to size at various lengths and angles and can be CNC milled to create indentations or more complex connections. This material, therefore, combined with digital manufacturing allows nearly endless possibilities with regards to geometry. More easily so than with materials like concrete or steel, which can be difficult to alter.

ETH Zurich Digital Wood Fabrication Robot (2018)
Foto retrieved from: https://www.archdaily.com/891443/eth-zurich-uses-robots-to-construct-three-story-timber-framed-house/5aba4e99f197cce90e0002a9-eth-zurich-uses-robots-to-construct-three-story-timber-framed-house-image

ENGINEERED BAMBOO

COMFORT

Accoustics
Moso Bamboo posesses excellent accoustic properties, very similar to those of mineral wool. Engineered forms of bamboo that keep the fibres relatively unalterd (such as plybamboo or flattened bamboo), maintain these accoustic properties well.

Thermal Comfort
The thermal conductivity of Engineered Bamboo, although not comparable to that of insulation materials, is good. Not only does this help with the energetic performance of the building by preventing heat loss, but it also feels warm to the touch.

Mental Health
Recent studies have shown natural materials such as wood having a positive impact on mental wellbeing and productivity. Applying Engineered Bamboo not only in a load bearing construction, but also as a finishing for users to interact with, can therefore positively contribute to wellbeing.

Impression of Apartment Bedroom

ENGINEERED BAMBOO
ECO-COST

ECO-Cost Neutral Construction
In construction, it is inevitable to use materials with poor ECO-cost performance, such as glass, aluminium, and insulation. However, through the use of Engineered Bamboo and/or many softwood products, this can be compensated, resulting in an ECO-cost Neutral building.

Using ECO-cost data from IDEMAT 2020, mechanical conversion values from the thematic research and volume data from own 3D models, the total volume of materials used was calculated. This allowed for a calculated estimate of total building ECO-costs. The same calculation was conducted for the building in its designed state and for the same building if it were constructed using a more traditional steel & concrete construction.

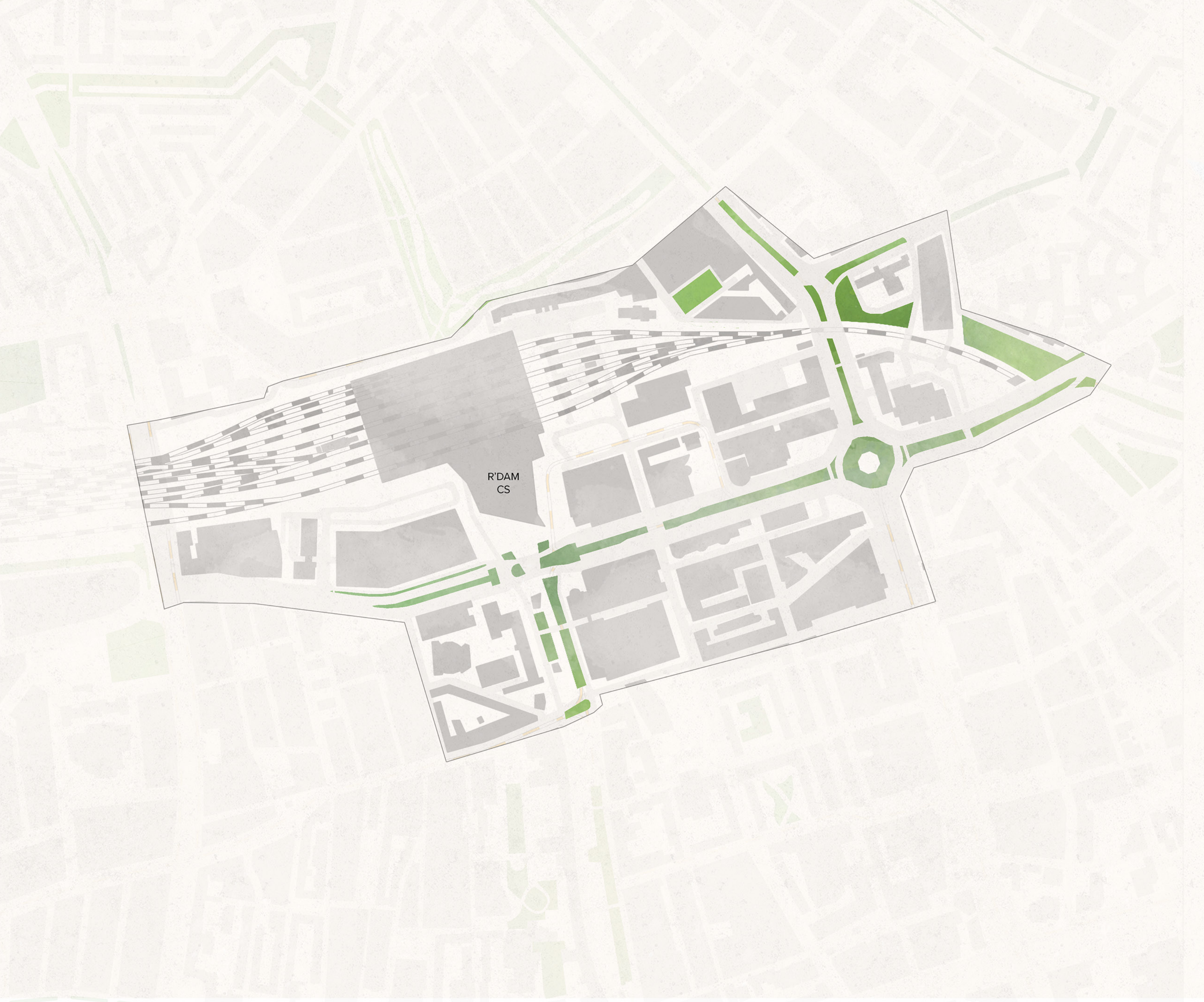
32x REDUCTION IN ECO-COST

LOCATION
ROTTERDAM CENTRAL DISTRICT

LOCATION

ROTTERDAM CENTRAL DISTRICT

Foto's retrieved from Google Earth (2021)



LOCATION
DEVELOPMENTS

The Treehouse
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The Modernist
Retrieved from: https://www.themodernist.nl/media/2019/02/1.hoofdbeeld_CENTRAAL-STATION_1435x910.jpg

Pompenburg
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Schiekadeblok
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LOCATION
DEVELOPMENTS

LOCATION

CONRADSTRAAT

Aerial photo
Retrieved from Google Earth (2021)

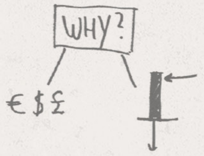
Street level photo's
Retrieved from Google Street View (2021)

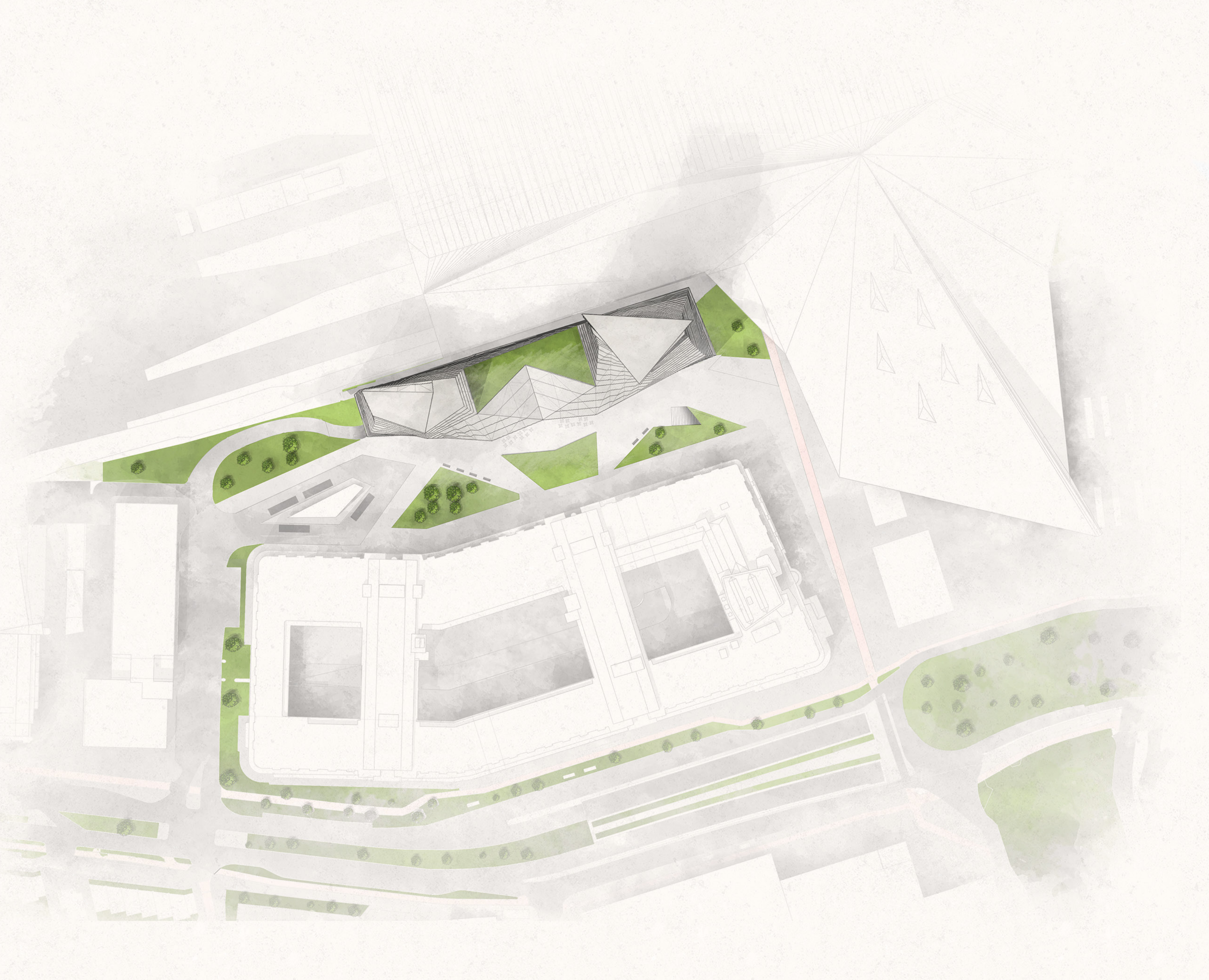
LOCATION
CONRADSTRAAT

Rotterdam Central District (RCD)
Rotterdam Central District is one of the economic hotspots of Rotterdam. Located on the South side of Rotterdam Central Station, the area is characterised by its large buildings and infrastructure.

Unsustainable High-rise
Characteristic for the area are the large high-rise buildings. These are generally office buildings from the 1990s and represent high-rise architecture as is extensively applied globally.

These high-rise buildings contain large amounts of CO_2, NO_x and NH_3 intensive building materials such as steel and concrete, due to costs and challenging structural properties. This makes them far more accountable for unsustainable material use over any other common typology. (Chau et al., 2012)





FORM

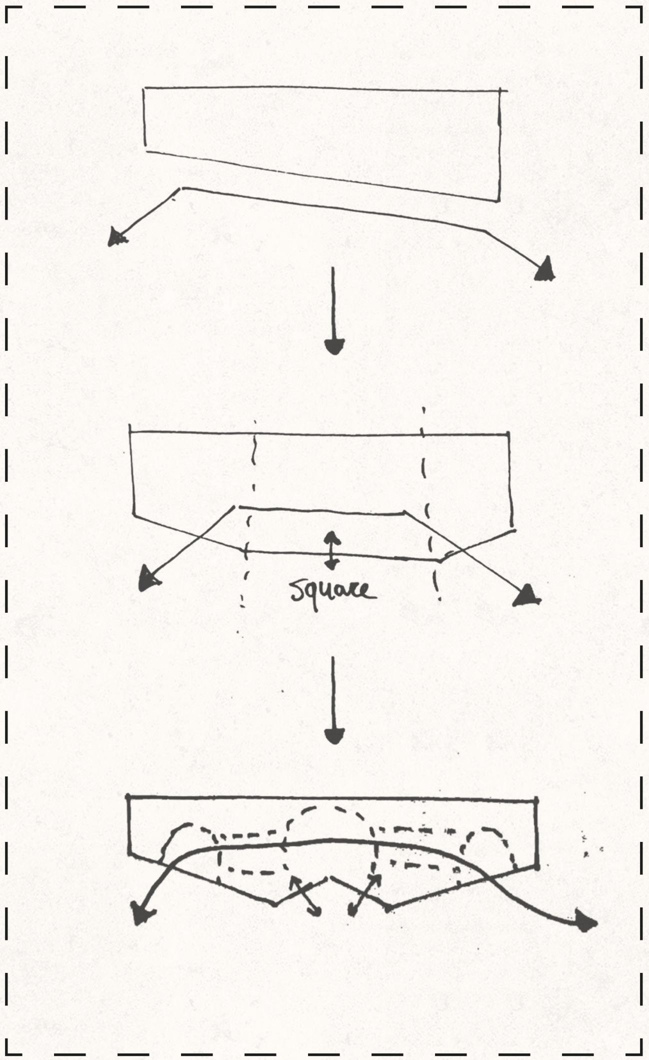
TRANSITION

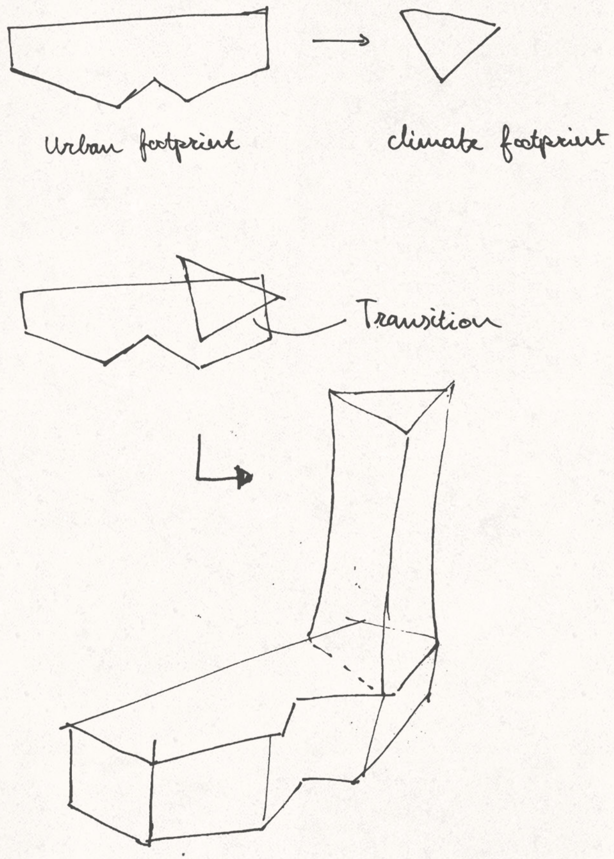
Building Shape

The base building is adjacent to a busy pedestrian walkway between Rotterdam Central station, the buses and the neighborhood to the West of the site.
The building is used to create a protected corridor in order to improve the experience of passer-by. This not only enhances interaction with the building, but it also presents interesting opportunities for neighborhood functions.
Because it is taller than its immediate surroundings, the tower has no such contextual relationship. Its shape, on the other hand, is based on climate principles.

Transition

The concept of a transition arose as a result of the mismatch in footprints between the base building and the tower. It was decided to create an organic transition inspired by the segmented character of bamboo, which was further optimized by balancing design parameters such as depth/width relationship and facade tilt.





FORM

CORRIDOR

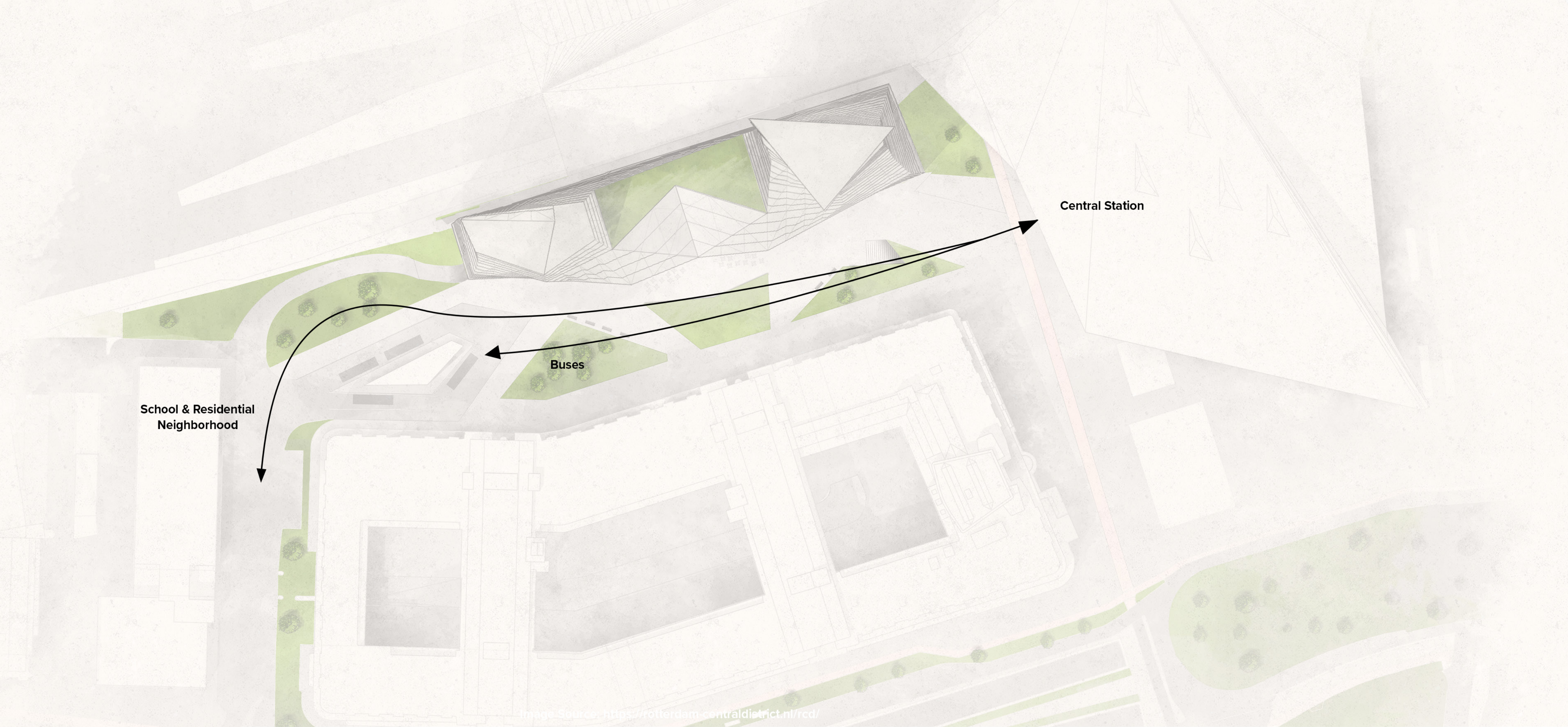
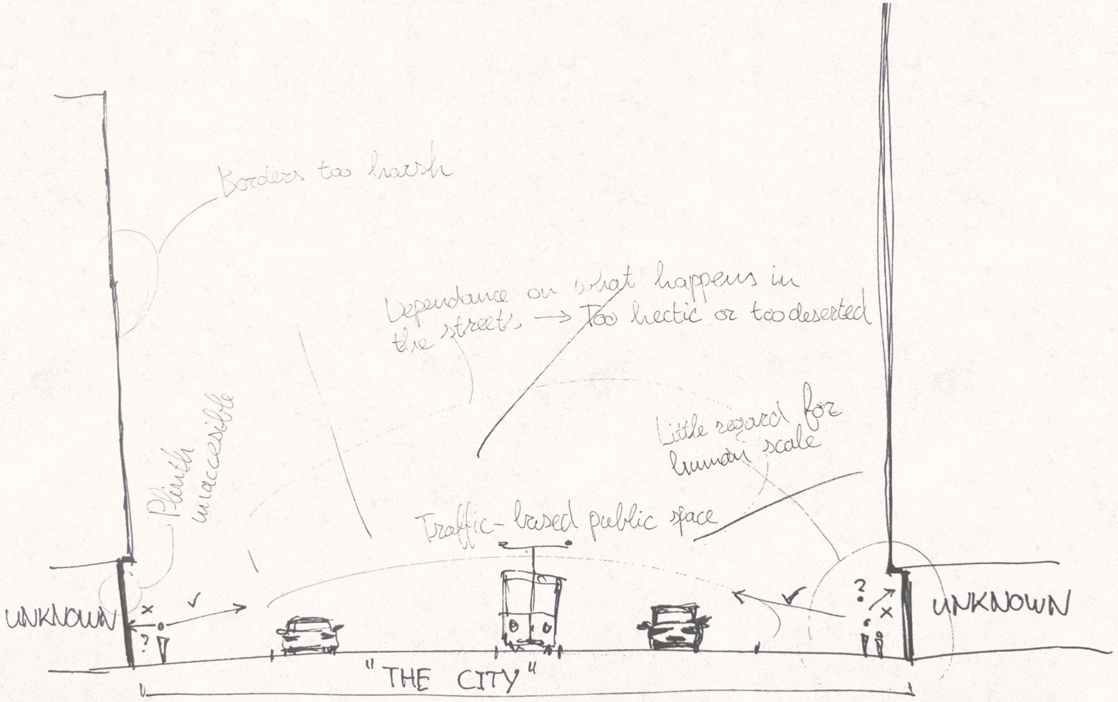
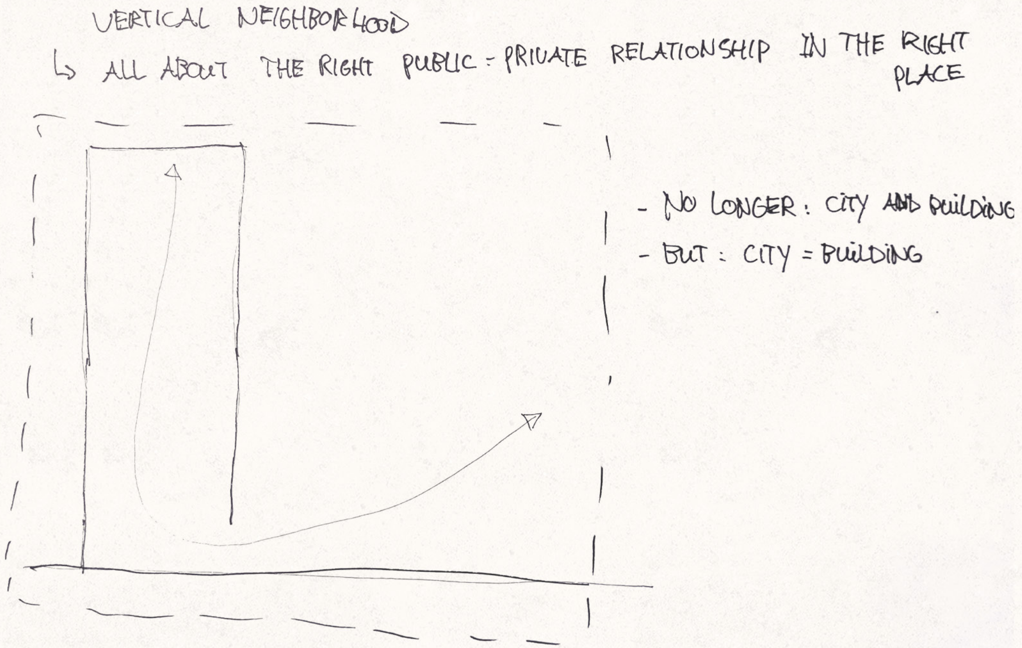


Image Source: https://rotterdam-centraldistrict.nl/rcd/

FORM
CORRIDOR





FORM
CORRIDOR

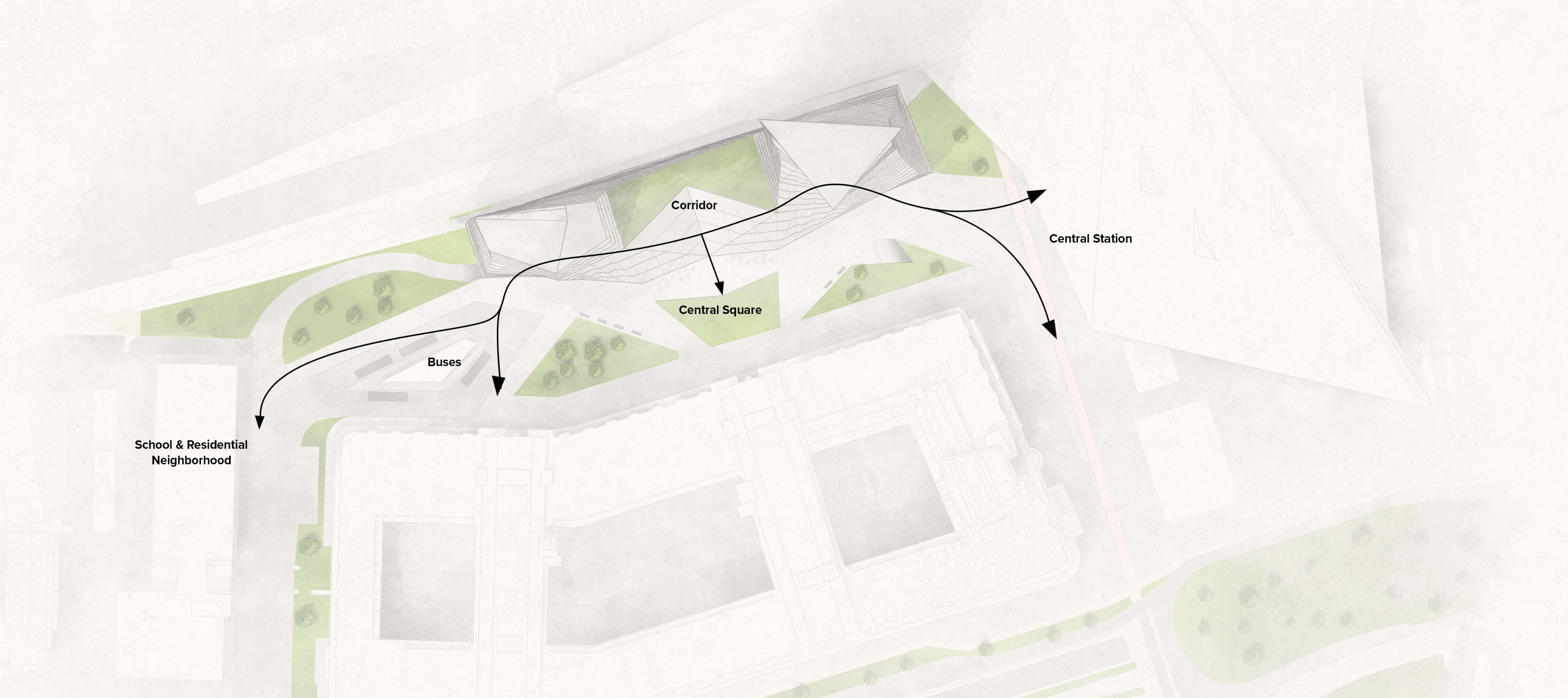
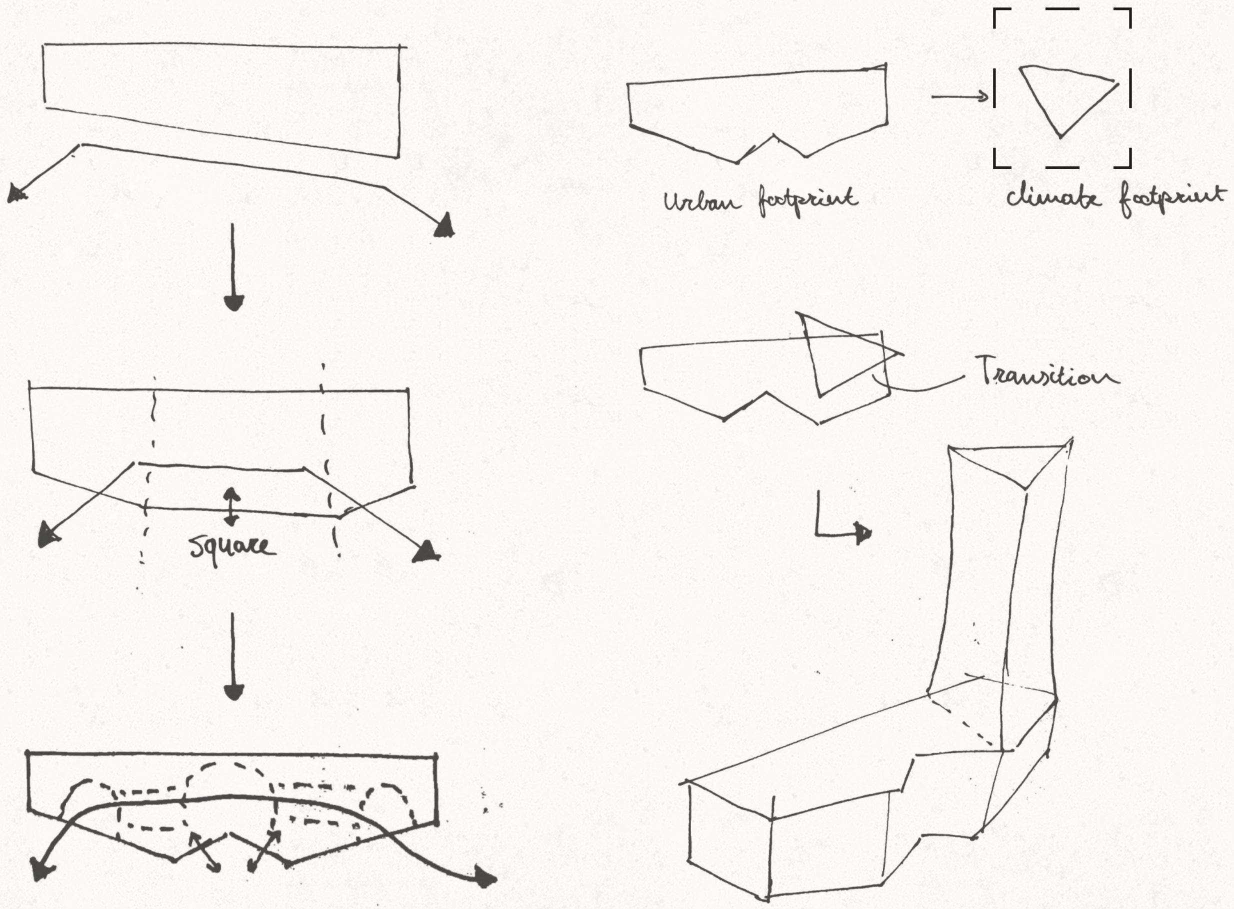


Image Source: https://rotterdam-centraldistrict.nl/rcd/

FORM
TRANSITION

Building Shape
The base building is adjacent to a busy pedestrian walkway between Rotterdam Central station, the buses and the neighborhood to the West of the site.
The building is used to create a protected corridor in order to improve the experience of passer-by. This not only enhances interaction with the building, but it also presents interesting opportunities for neighborhood functions.
Because it is taller than its immediate surroundings, the tower has no such contextual relationship. Its shape, on the other hand, is based on climate principles.

Transition
The concept of a transition arose as a result of the mismatch in footprints between the base building and the tower. It was decided to create an organic transition inspired by the segmented character of bamboo, which was further optimized by balancing design parameters such as depth/width relationship and facade tilt.



FORM
SOLAR ENTRY

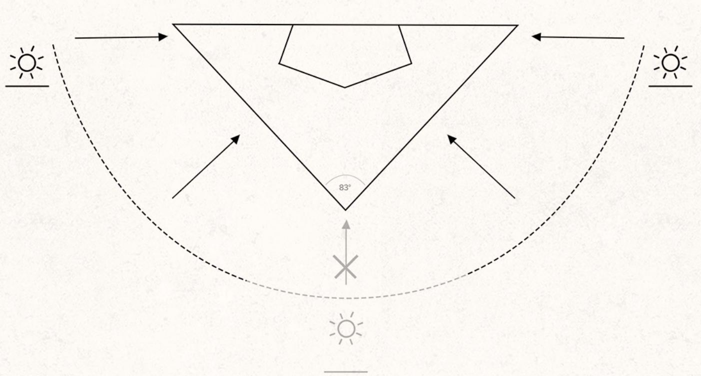
Climate in The Netherlands
The location's climatic parameters were researched in order to formulate what is possible with sunlight entry. KNMI and Meteo.be data were used to determine when and how much the building needed to be heated or cooled, as well as the months and hours during which it needed to be heated or cooled. Blue months are those with an average nighttime low temperature of less than 18 degrees Celsius and an average daytime high temperature of less than 18 degrees Celsius (standard inside temperature). It is critical to have both day and night heating throughout these months. Green months have an average nightly temperature of less than 18° C but an average daytime temperature of more than 18° C. There will be no additional cooling or heating required. Yellow months have daily and nightly average temperatures of at least 18 degrees Celsius. As a result, cooling is required throughout the day as well as at night.

Facade Tilt
A tilt of 6,5 degrees is applied to the facade. This fully reflects high sun angles of 46 degrees or higher. This angle was chosen because it represents the lowest sun angle at midday on August 31th (yellow month). As a result, noon sun angles are totally reflected in summer and are partially allowed in spring/autumn and fully allowed in winter.

Triangular Shape
The triangular shape's purpose is to increase the amount of direct sunlight on the facade plane, whilst also reducing loss area. This is especially important in the blue months, which represent a large part of the year in the Netherlands. The diagrams to the right show the angles required to get as much sunlight as possible during the day. The slant of the facade prevents any additional heat buildup this shape would cause during the warm months. It is therefore paramount that the two are used in conjunction.

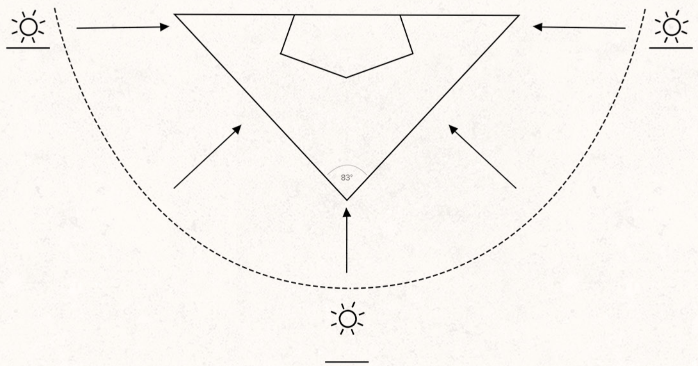
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

SPRING/AUTUMN SITUATION



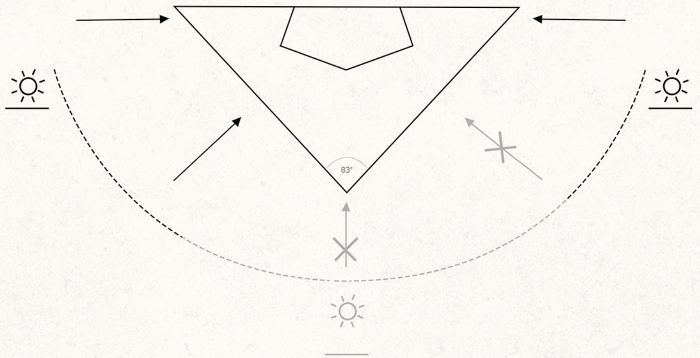
Split up South Facade: Increases effective solar entry during morning and evening, reflects intense noon sun

WINTER SITUATION



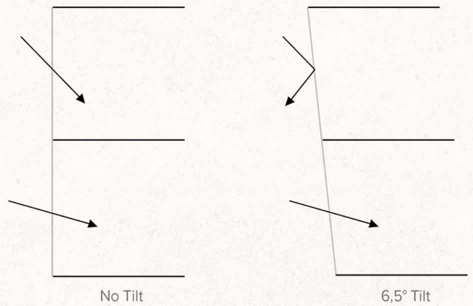
Split up South Facade: Increases effective solar entry, reduces loss area

SUMMER SITUATION



Facade tilt: Fully reflects high sun at midday

GENERAL



Facade tilt: High sun angles are reflected (> 42°). Low sun angles are allowed (< 42°)

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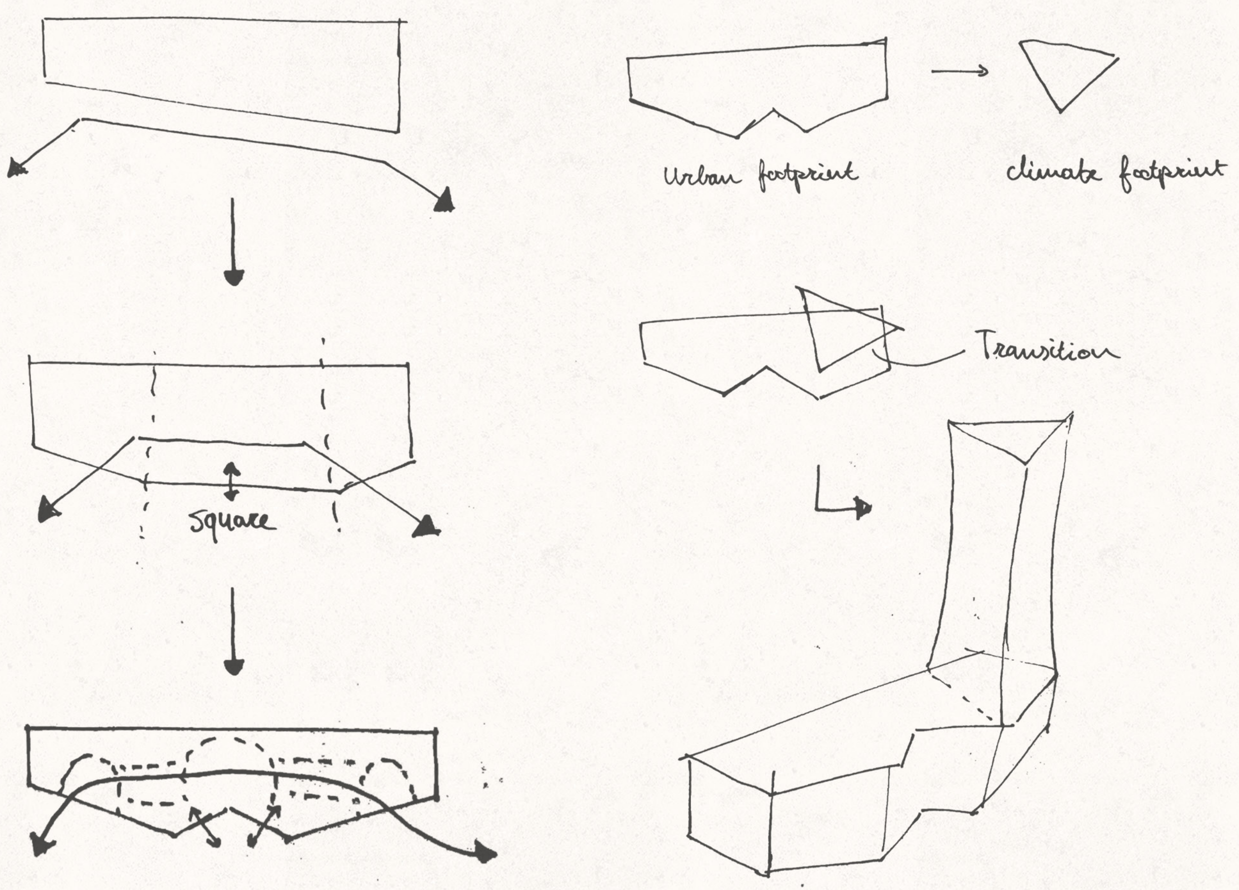

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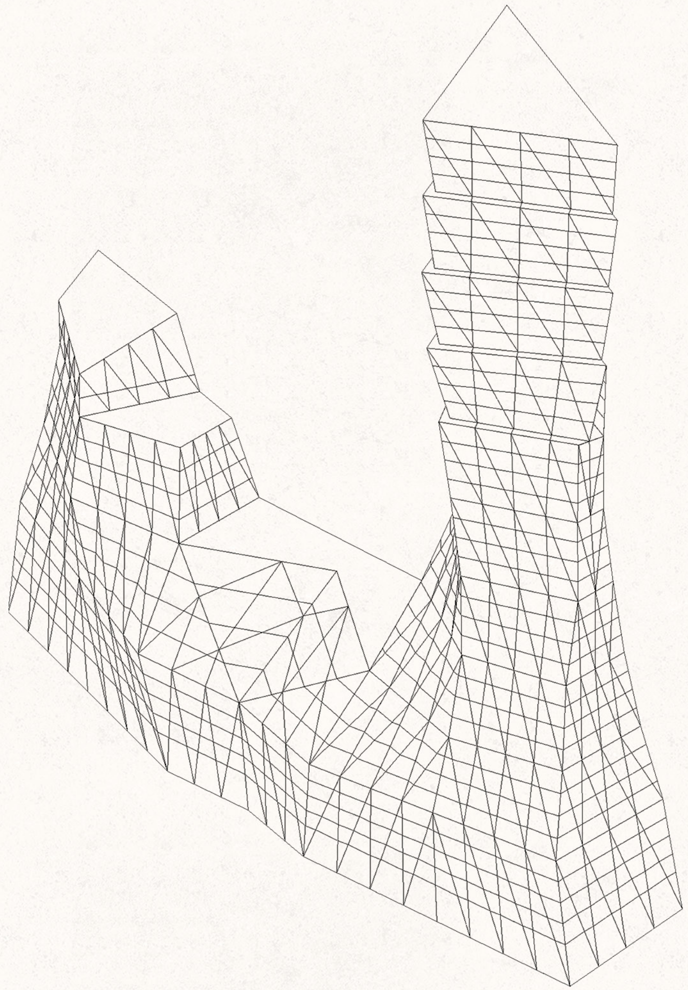
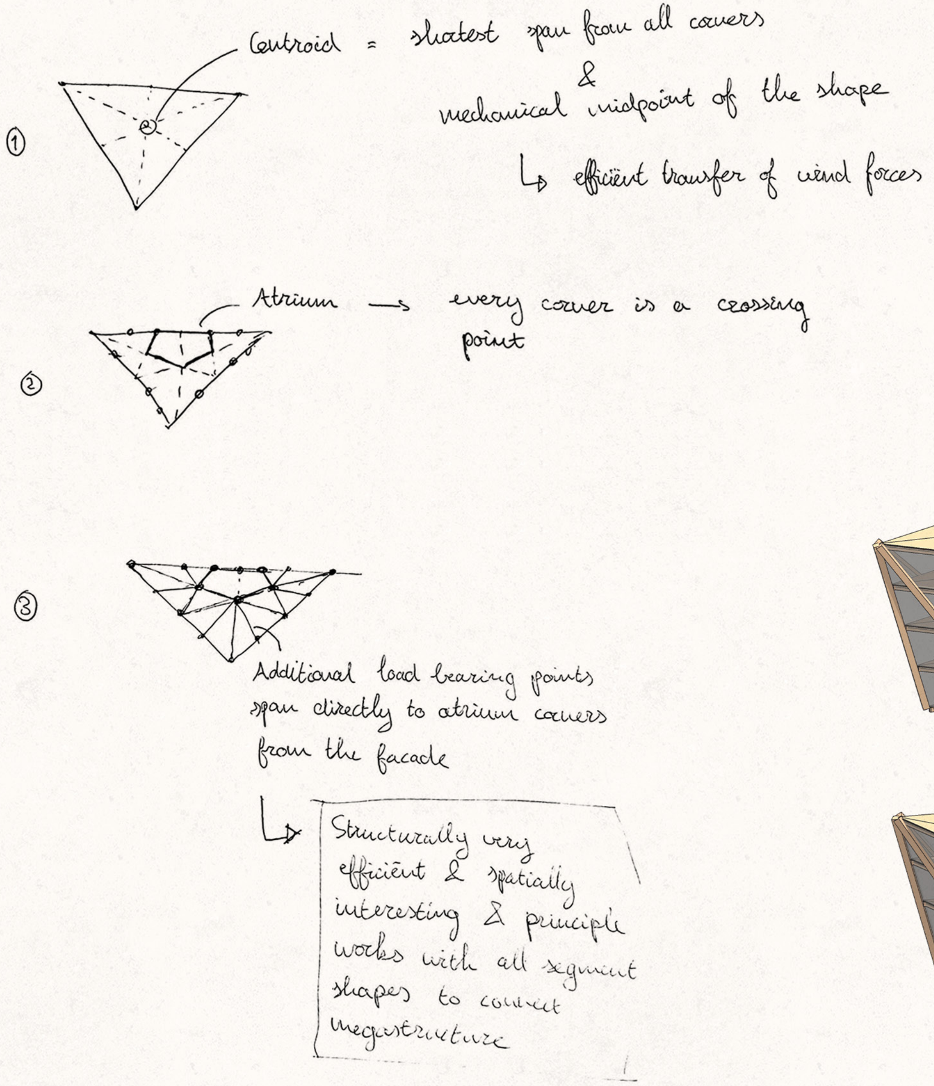


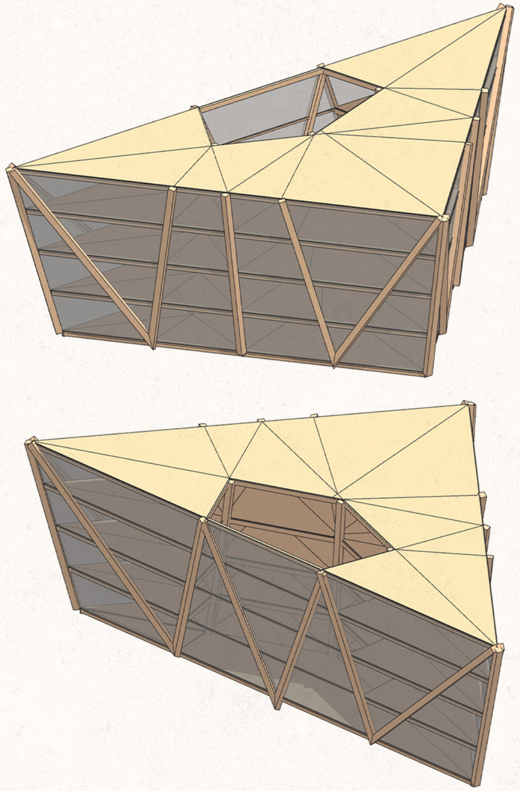
FUNCTIONALITY
GRID SYSTEM

Centroid
The centroid is a geometric property of a shape and represents the exact center of mass, if the shape were to have a weight. By finding the centroid of a shape and drawing a line from it, towards all corners and/or all midpoints, the shape is divided into exactly equal parts.

What this translates to in a grid system is very efficient weight distribution, very efficiënt wind force distribution and an inherent functional hierarchy that is spatially very efficient.

Load Bearing Points
The main advantage of using a grid system that is in line with the geometry of shape, is that the shape itself can form the load bearing structure. This means no additional beam- and column substructure is needed, and beams can span directly from facade to atrium.
This creates complete functional freedom on the inside of the building and as such enables easy future adaptability.





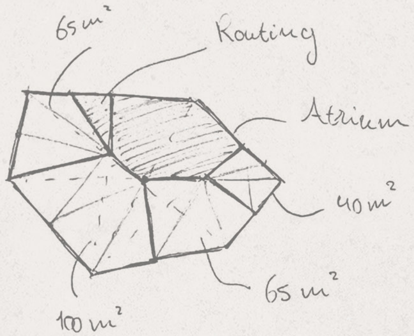
FUNCTIONALITY

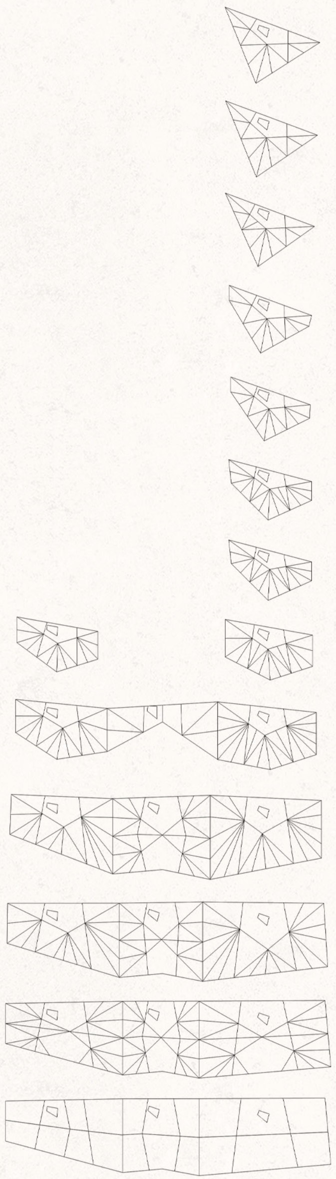
GRID SYSTEM

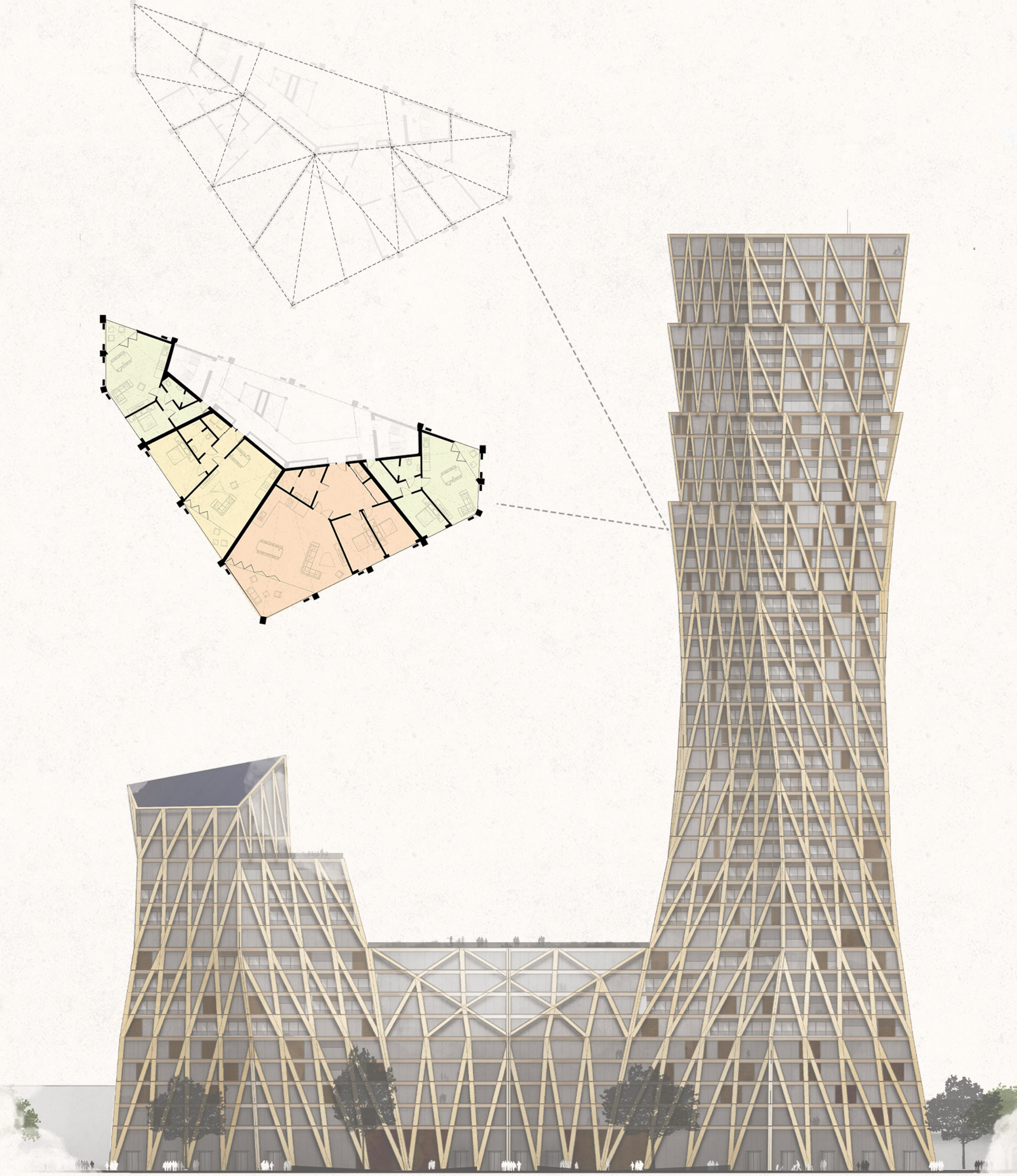
Scale Hierarchy

Although not strictly necessary, the choice was made to use the load bearing grid to define the spatial grid as well. Because of the variations in shape, dimensions and load bearing points, the grid automatically creates a hierarchy of scale, resulting in interesting functional infills. It is made up of triangles of varying depth and width. Their floor area and the practicality of the shape dictate the type of function that can be applied.

For example, small triangles are ideal for a studio appartment, while a large appartment could benefit from more facade area.







FUNCTIONALITY
PROGRAM

Shops & Services
The plinth of the building is fully public and contains shops and services. Examples of such shops and services are supermarkets, café's, health services.
Their function is ideal for the residents of the building itself, but also for passers by and inhabitants of the area.

Restaurant
Just above the second urban layer (> 30 m), is the restaurant. This a large, interesting space, with its own terrace and views of the Rotterdam skyline and the Groothandelsgebouw.

Library & Study Spaces
A large part of the building is made up of a library and study spaces. This is fully public and is integrated with the atrium of the central part of the building. There are multiple schools in the area and a great demand for flexible working spaces. This building aims to respond to that demand.

Flexible Office Spaces
Closely linked to and accessible via the Library space are a number of closed off, quieter spaces. These are to be used as shared office spaces. This kind of space is ideal for startups, internationally operating buisinesses or even students, that require a space for group-work.

Social apartment program
The municipality of Rotterdam indicates a lack of housing for singles, students, starters and low-income housholds. There is therefore a strong demand for studio apartments, social rent apartments and medium size apartments for starters that are reasonably priced.
At the same time, locations in Rotterdam get more expensive, leading to more luxury apartments being built, because they are more profitable from an investment point of view. The program in this building aims to combine the financial viability of luxury apartments with a more social, but less profitable program. It does this through a carefully calculated balance of apartments that can achieve a net profit similar to other buildings in the area (Vestia, 2020; Syntrus Achmea, 2020; Funda, 2020). This not only caters to the societal demand in the area, but also makes the building more viable for investors and thus, realistic.

	Amount	UFA (GBO)	Total UFA (GBO)
Apartments	**123**	-	**12034** m²
Studio	19	54 m²	1026 m²
Social	29	77 m²	2233 m²
Medium	50	99 m²	4950 m²
Large	20	135 m²	2700 m²
Luxury	5	225 m²	1125 m²
Office Space	-	-	**14508** m²
Companies	-	-	6357 m²
Flex-spaces	-	-	8151 m²
Public	**12**	-	**6773** m²
Library	1	2272 m²	2272 m²
Supermarket	1	256 m²	256 m²
Daycare	1	166 m²	166 m²
Gym	1	255 m²	255 m²
Health center	1	248 m²	248 m²
Restaurant	1	420 m²	420 m²
Small Horeca	4	88 m²	88 m²
Roof Garden	1	531 m²	531 m²
Parking	1	2537 m²	2537 m²
Routing	-	2934 m²	2934 m²
Technical	-	88 m²	88 m²
Total	-	-	**36337** m²

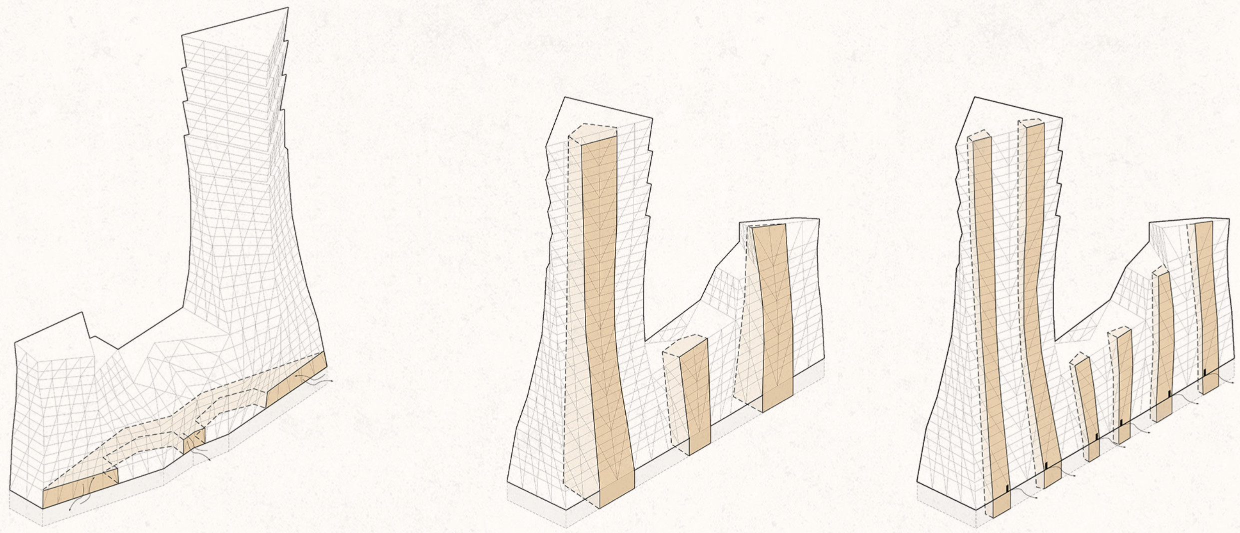
FUNCTIONALITY
PROGRAM

Adaptability
Important to realize is that no functionality can ever be permanent, because society changes and as such, demand for certain functionalities changes.

As such, the building is made to be fully adaptable, with a main structure and substructure that are independant.

Permanence vs. Adaptable
The permanent structure of the building consists of the load bearing shell, the atria (including shafts), the stairwells and the corridor.
The rest of the building can be referred to as infill and is completely changeable. Interior walls can be moved around because they are not in any way load bearing. Ceilings can be adapted to house other installations and the facade behind the exoskeleton can be adapted.

Additional measures that have been taken to account for adaptability are the building's free height of 2,8m or more, the Thyssenkrupp twin elevator system, which can use multiple elevators in one shaft, and the modular facade elements, that can be easily swapped out for a windowed, closed variant or BIPV variant.



FUNCTIONALITY

(SEMI-) PUBLIC

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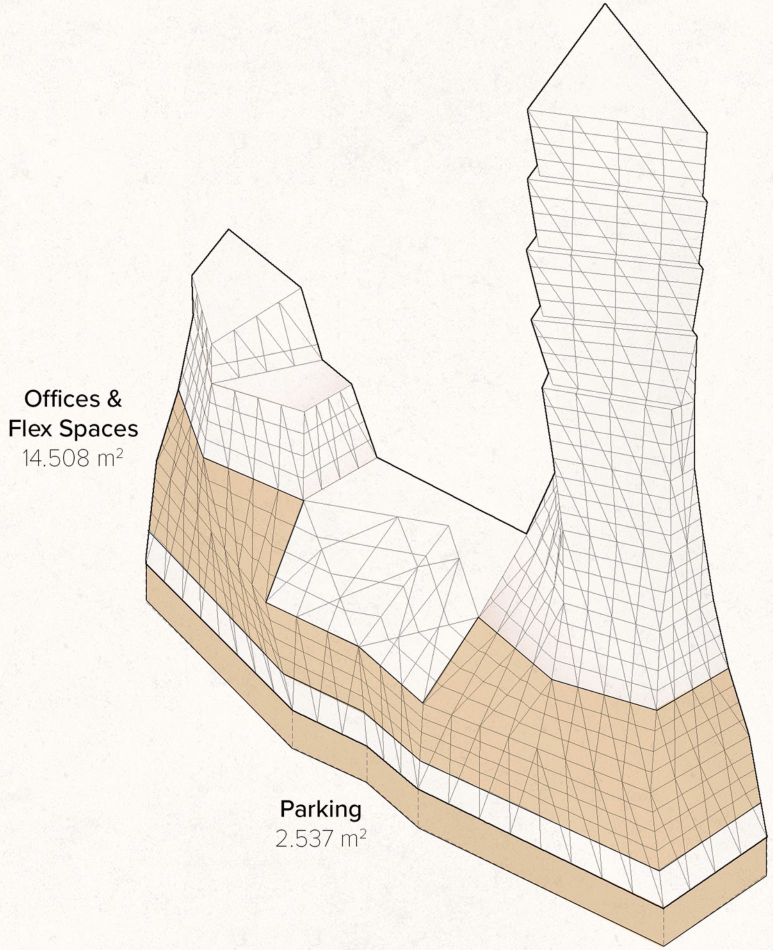

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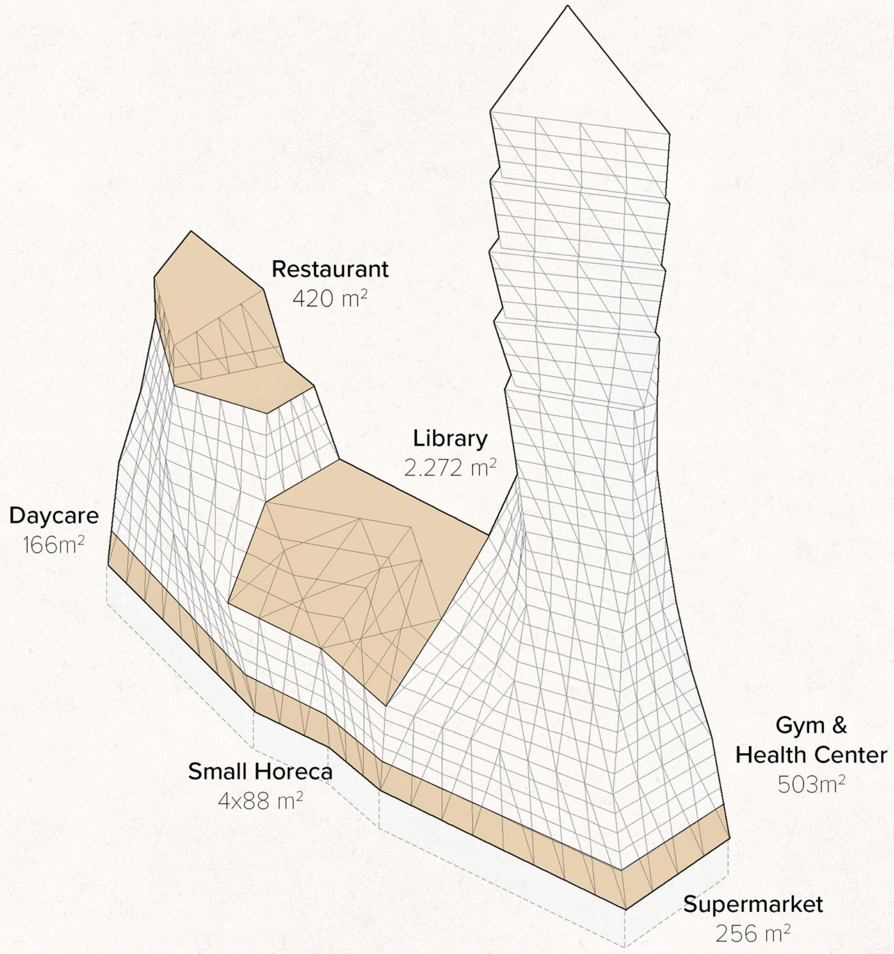

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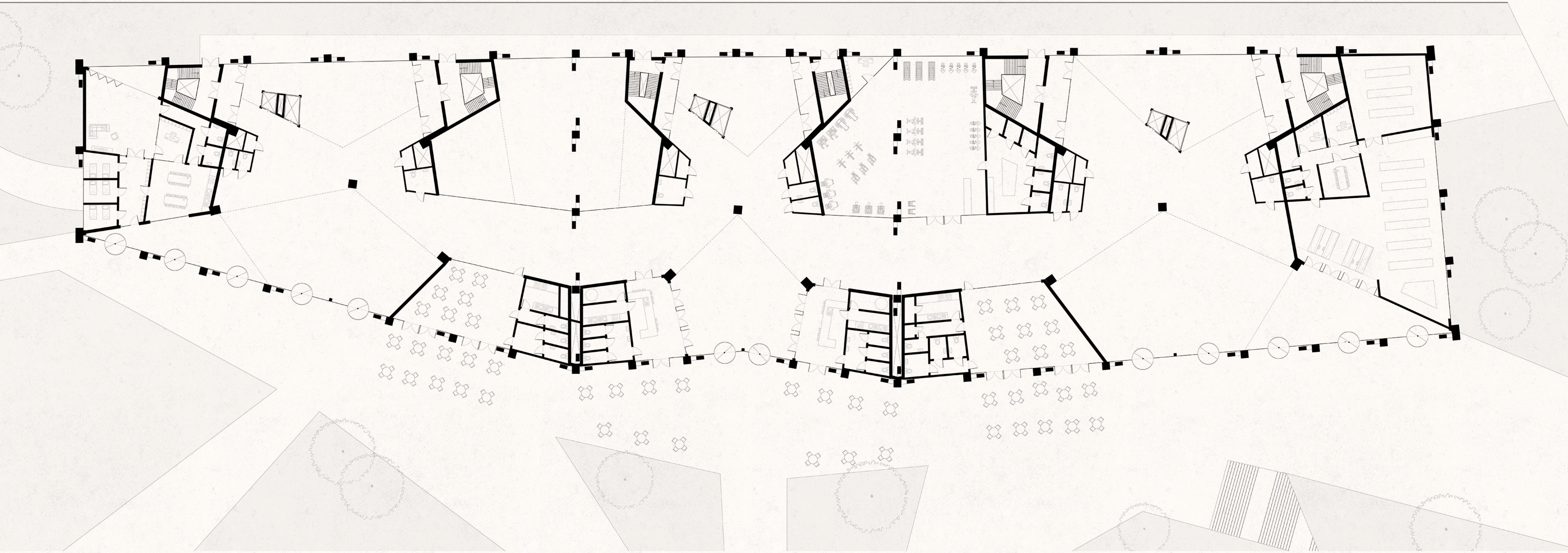
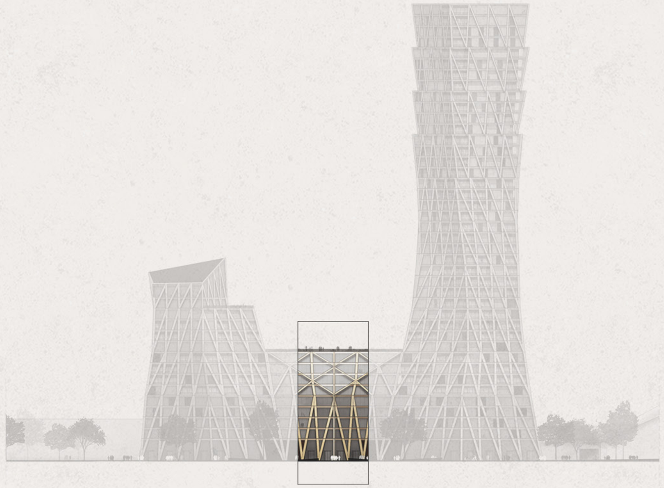
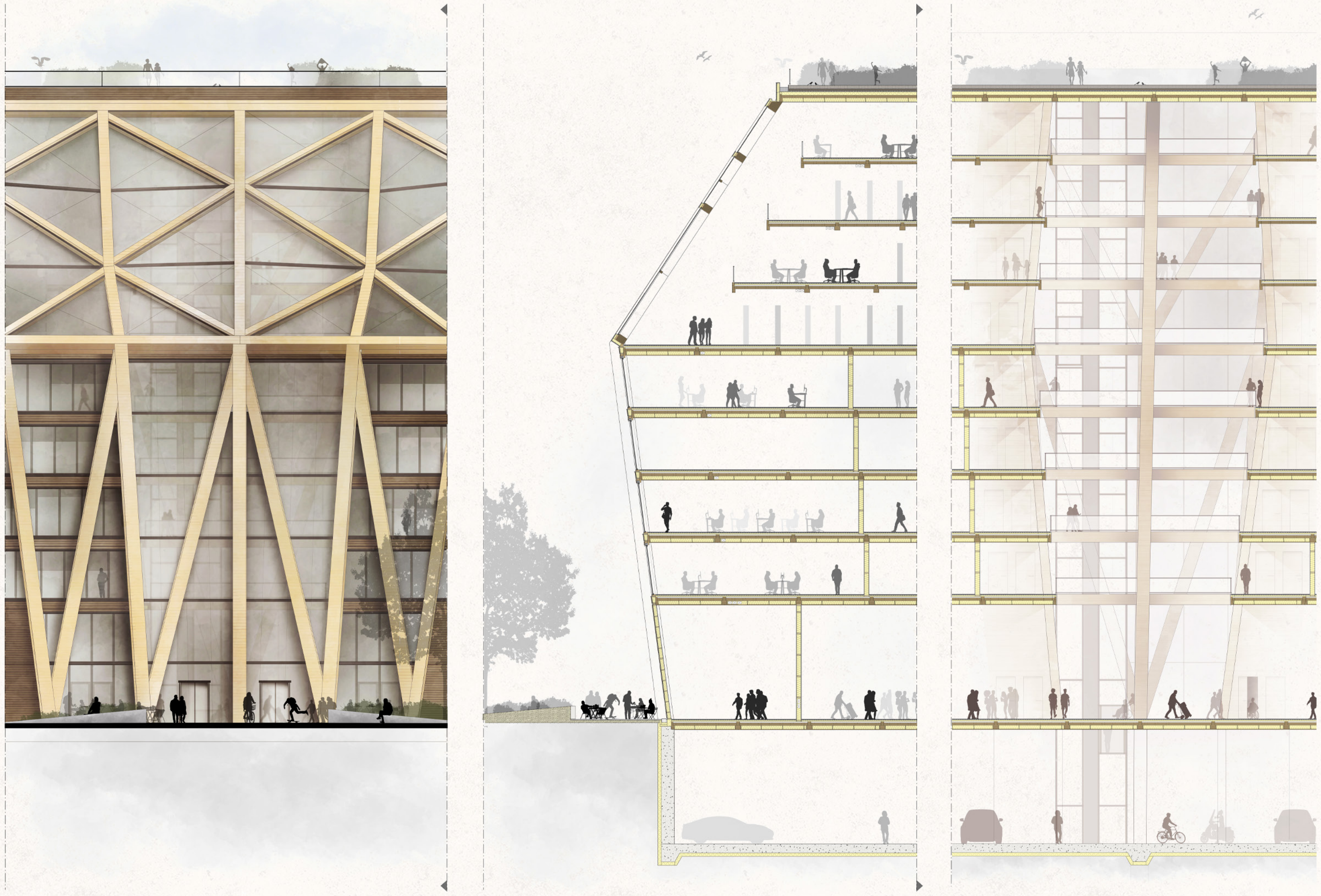


FRAGMENT
CENTRAL ATRIUM

Heart of the Building
The central atrium is not only physically located in the center of the structure, but it also serves as its heart. It is very transparent, and all public functions can be accessed via it or the corridor that runs through it. This makes it an ideal meeting point for all different users of the building. To further establish this meeting function, the public space in front of the atrium is transformed to a small square, featuring small horeca and greenery. Because of the atrium's transparency, there is a strong connection between it and the square.





FRAGMENT

CENTRAL ATRIUM

Roof Garden

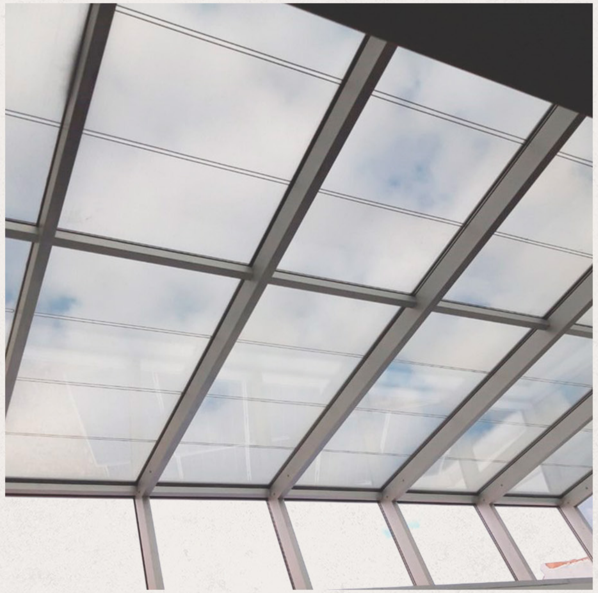
Above the central atrium is the roof garden. This is not a public function and as such not directly accessible via the central atrium. Instead, it is designated for the building's residents in order to offer them with a more serene outdoor space in addition to their balconies. Activities such as BBQ's can be organized here and it provides a safe, demarcated place for children to play. The garden is 31 meters high and features views of Rotterdam and the groothandelsgebouw's roof terrace to the north.

FRAGMENT

CENTRAL ATRIUM

BIPV Panels

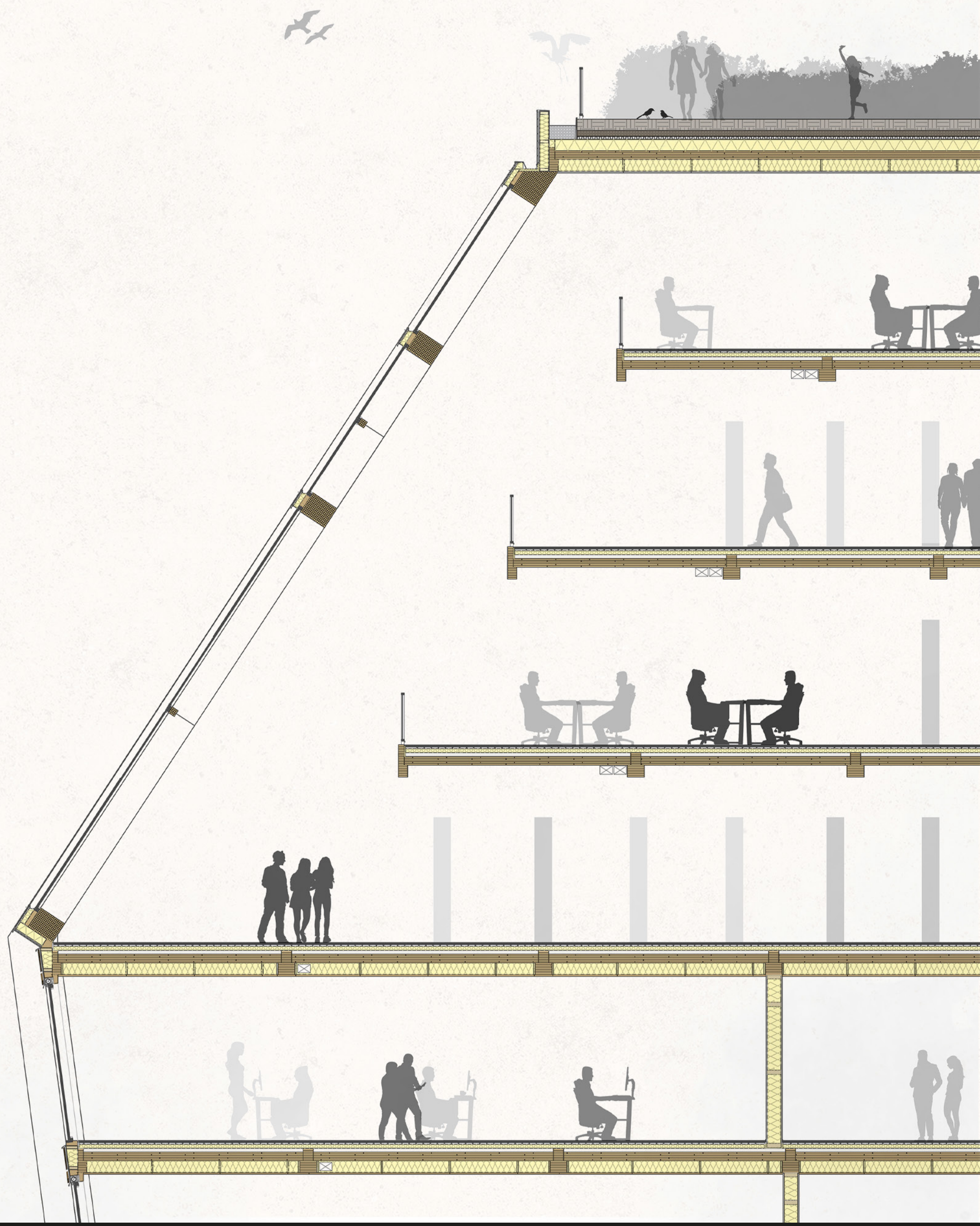
The building makes use of Onyx Solar's fully transparent BIPV panels. These are similar to conventional HR+++ glass and use the same windowframes, but they have a silicon PV layer. They produce electricity and in addition reduce solar heat buildup. The center facade's curtain wall is an example of how these panels are utilised. Depending on their orientation, these panels can also be found in the windows of many of the offices.



Onyx Solar HR+++ transparent BIPV panels

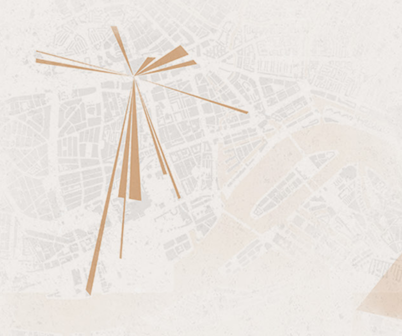
(24Wp/m^2; LTA = 0,7)

Retrieved from: https://twitter.com/onyxsolar/status/1374272125536776193



FUNCTIONALITY
HOUSING

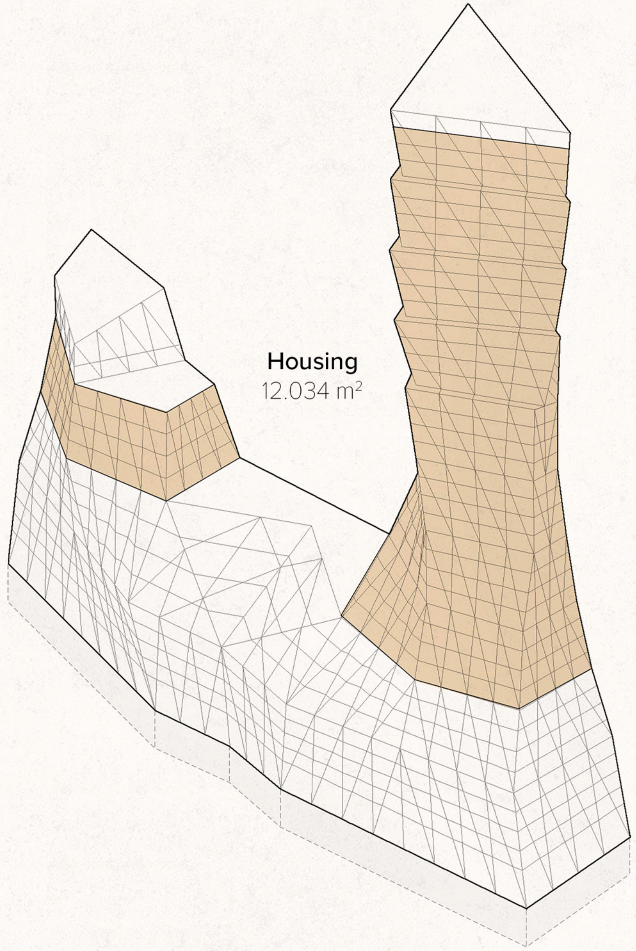
Sightlines
To ensure the best experience of urban living, study was conducted into sightlines towards highlights in Rotterdam. Examples of such highlights are the Erasmus-brug, De Rotterdam, The Euromast and Booimans van Beuningen Museum.
Along with the grid system's dimensioning, results from the sightline study were used to ensure every appartment at 30m or higher contains at least one or more sightlines to a Rotterdam highlight.



30-50 m

50-120 m

120-150 m



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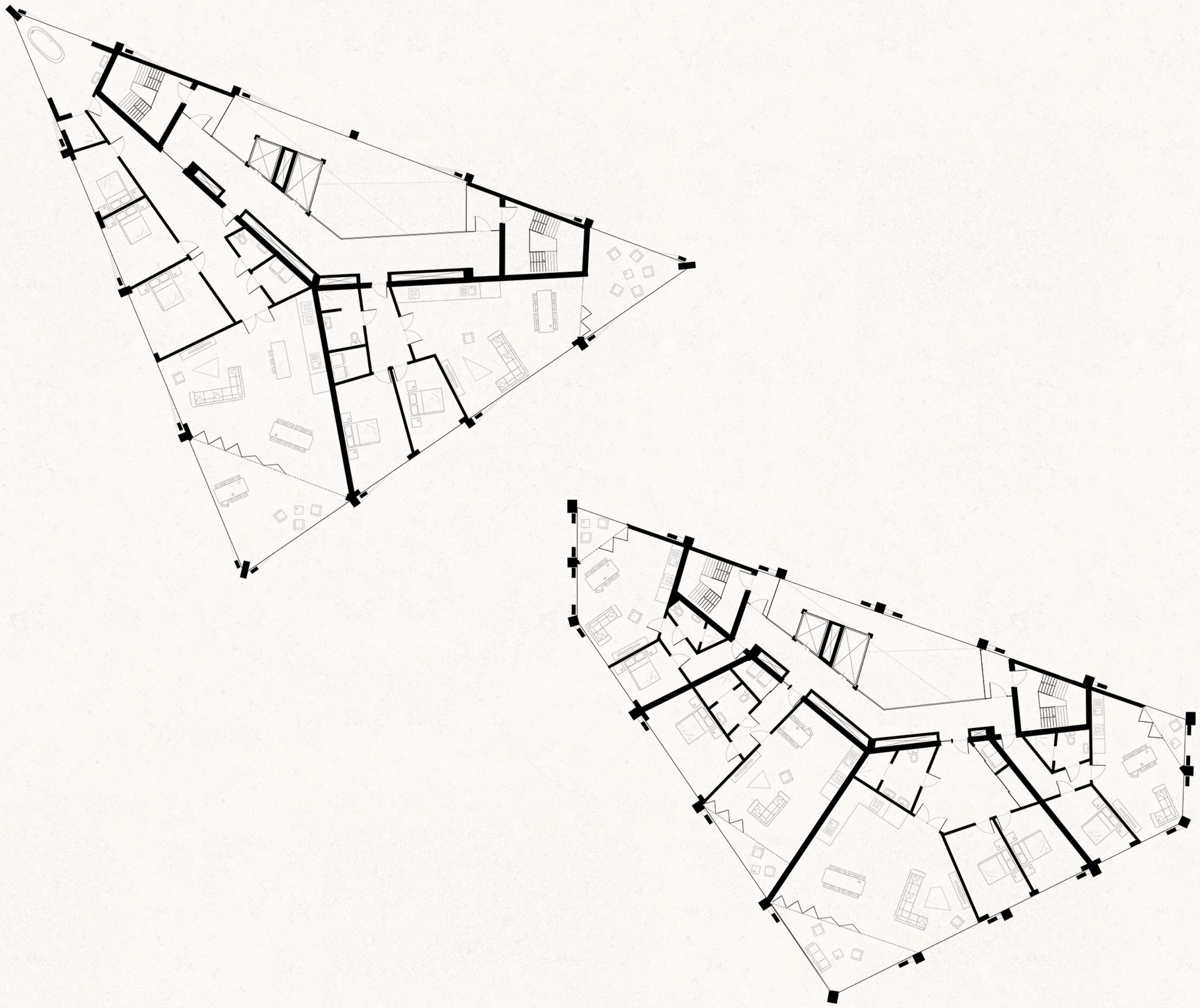
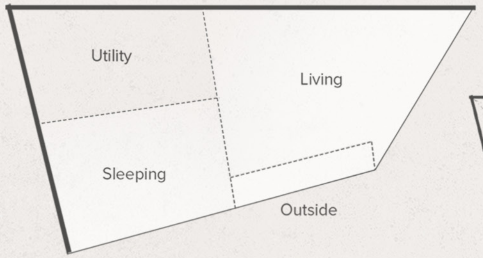
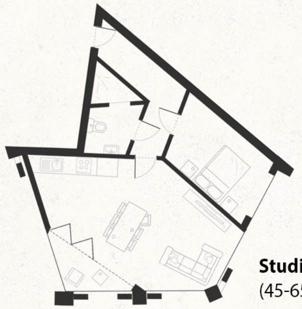


FUNCTIONALITY
APPARTMENT TYPES

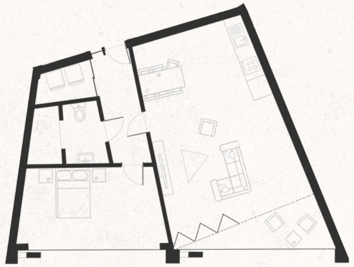
Unique Appartments
Because the geometry and grid of the building vary significantly, each apartment is slightly different. This generates a feeling of individuality for every appartment, but more importantly all facilitates individual choice. Some appartments prioritize large balconies, while others prioritize a bigger bedroom, etc.. Consequently, the building is not only appropriate for a variety of target groups, but also allows for individual expression.

Appartment Elaboration
The general rule is that the amount of light required for each function determines its placement within the shape. This is possible due to the varying depth caused by the irregular geometry. Living is located in an area with little depth and the more facade area, because it requires the most natural light. Sleeping is positioned on the edge of deeper areas to allow for the placement of utility functions that do not require natural light behind them. Thus, the varying depth of the geometry is used as a means to optimize space utilization, resulting in more efficient floor plans than an orthogonal plan of equal area.

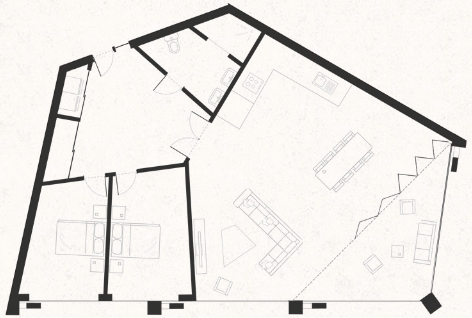


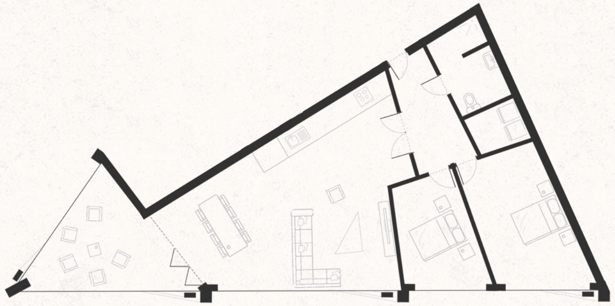


Studio
(45-65 m²)

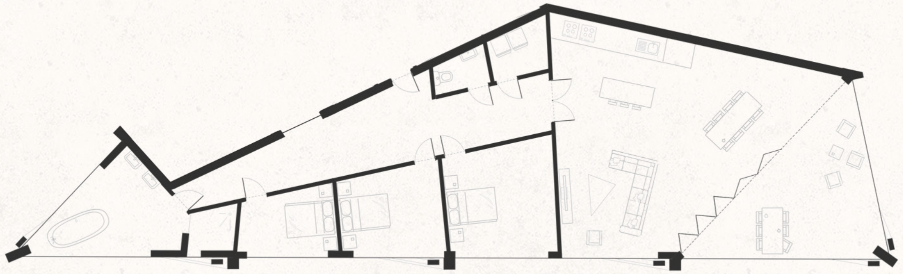


Social rent
(65-90 m²)





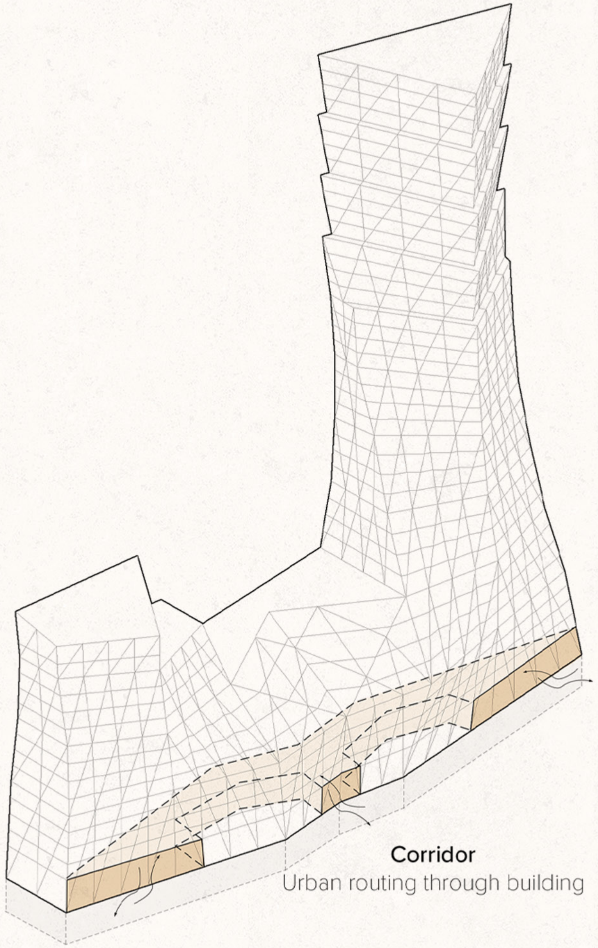
Medium Apartment
(90-120 m²)



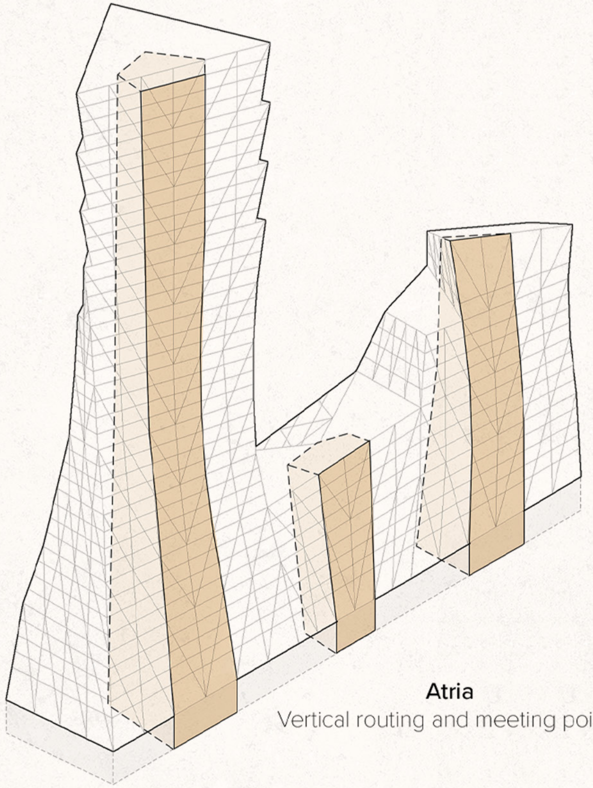
Luxury Apartment
(120-150 m²)

FUNCTIONALITY

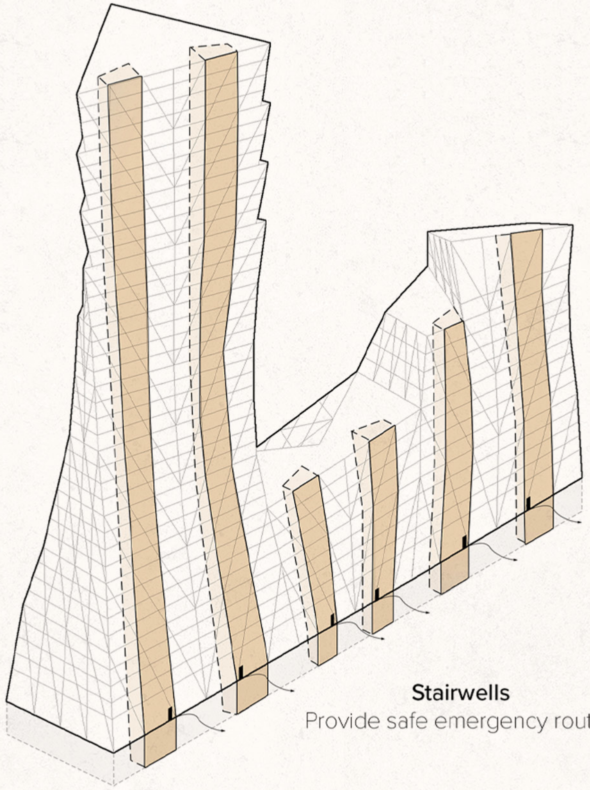
ROUTING



Corridor
Urban routing through building



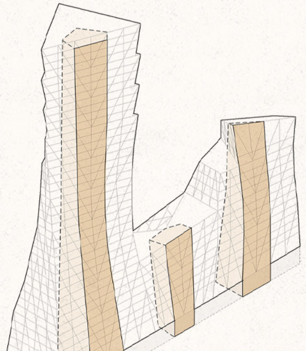
Atria
Vertical routing and meeting points



Stairwells
Provide safe emergency routes

FUNCTIONALITY
ROUTING

Corridor
Urban routing through building



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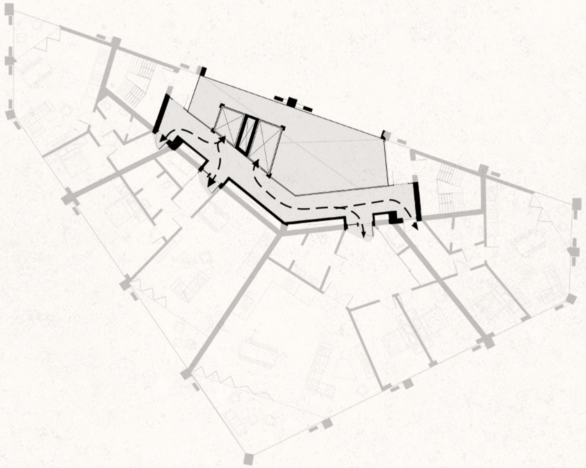
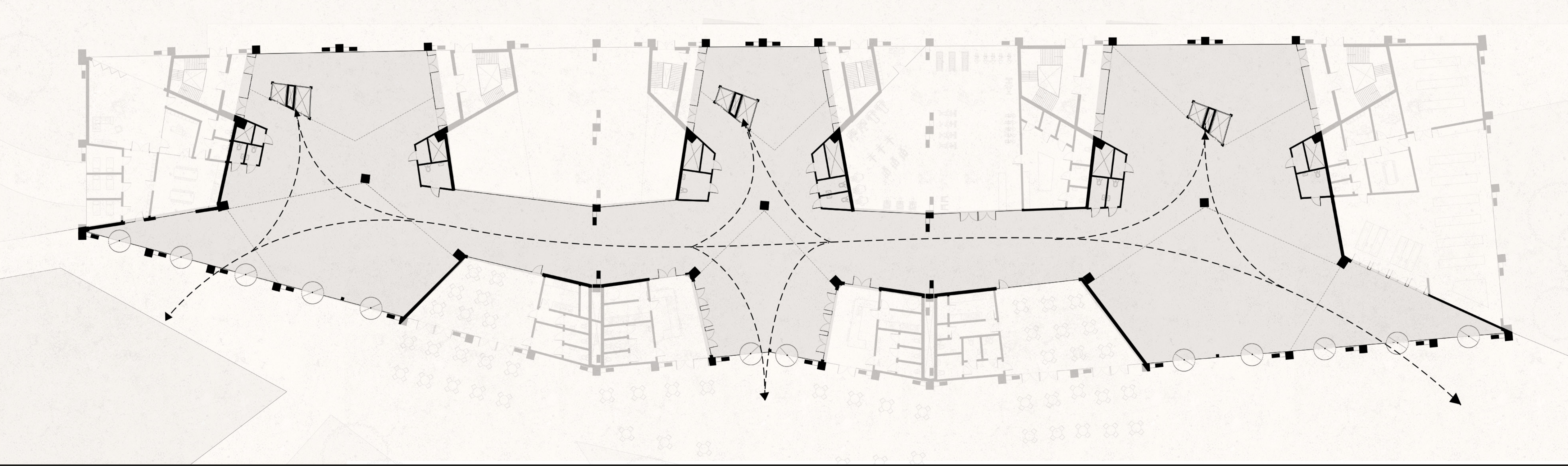
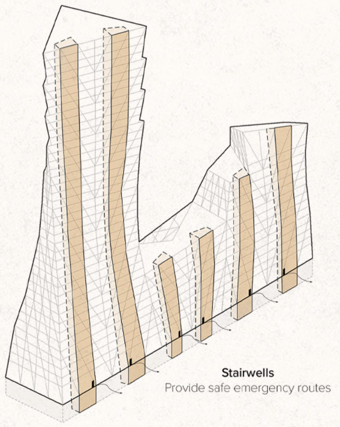
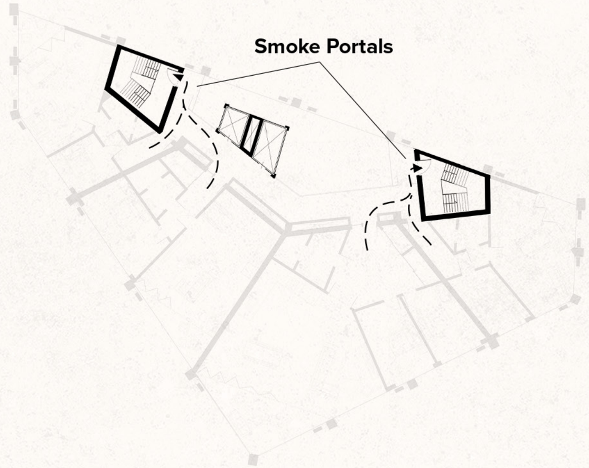
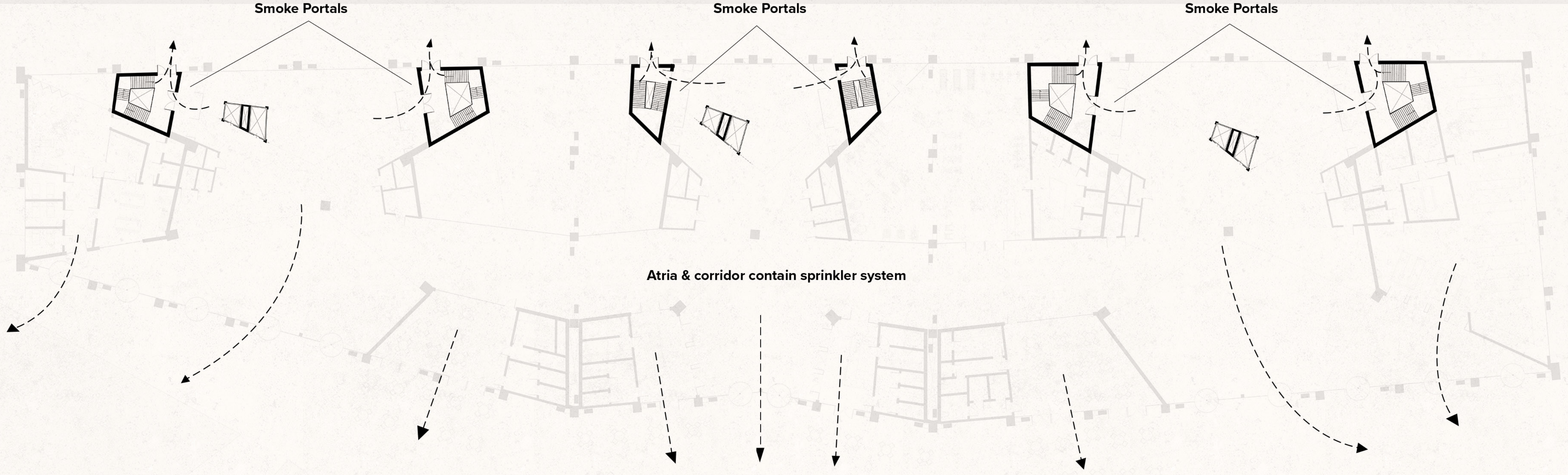




FUNCTIONALITY
ESCAPE





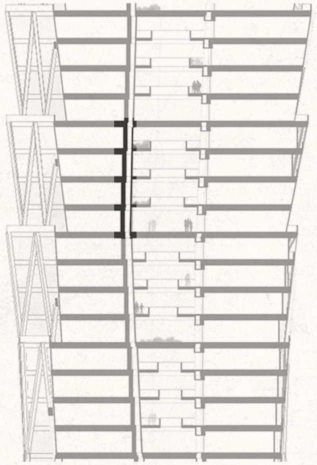


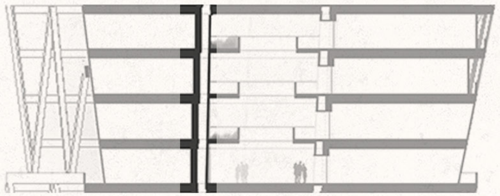
FUNCTIONALITY

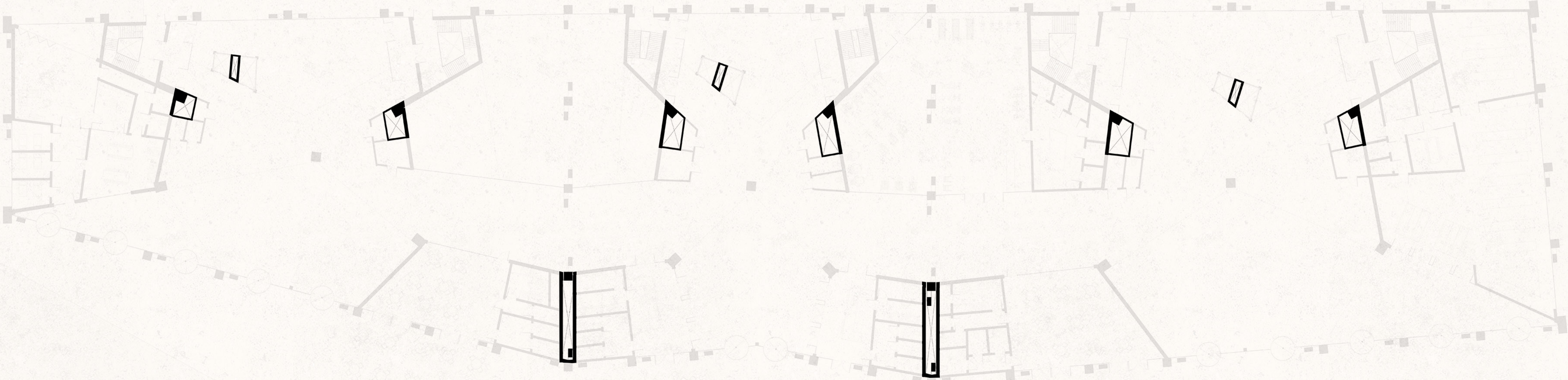
SHAFTS

Integrated Atrium Shafts

By connecting beams to two sides of the atrium columns, an open space is created inbetween the beams. This space is present on every floor, making it an ideal location for a shaft. This shaft is incorporated and exploited as an architectural means by constructing an atrium wall with recessed front doors, to provide a more gradual transition between public and private. No separate shafts are required, creating more useable space.







FUNCTIONALITY
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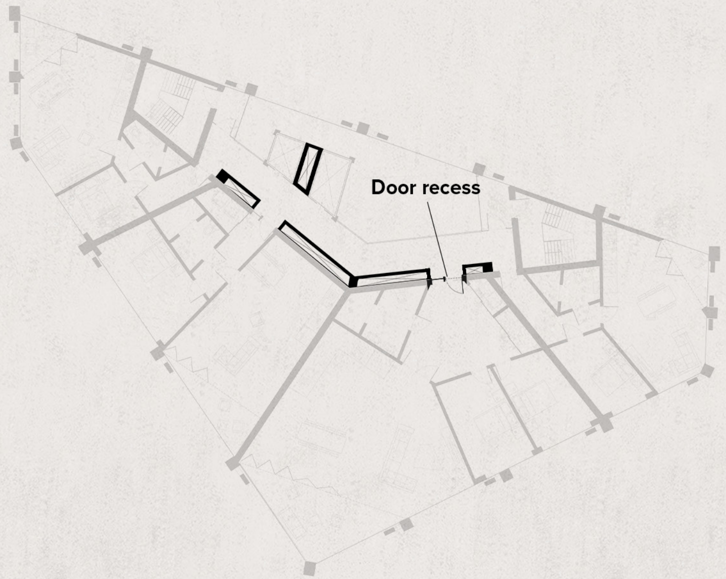
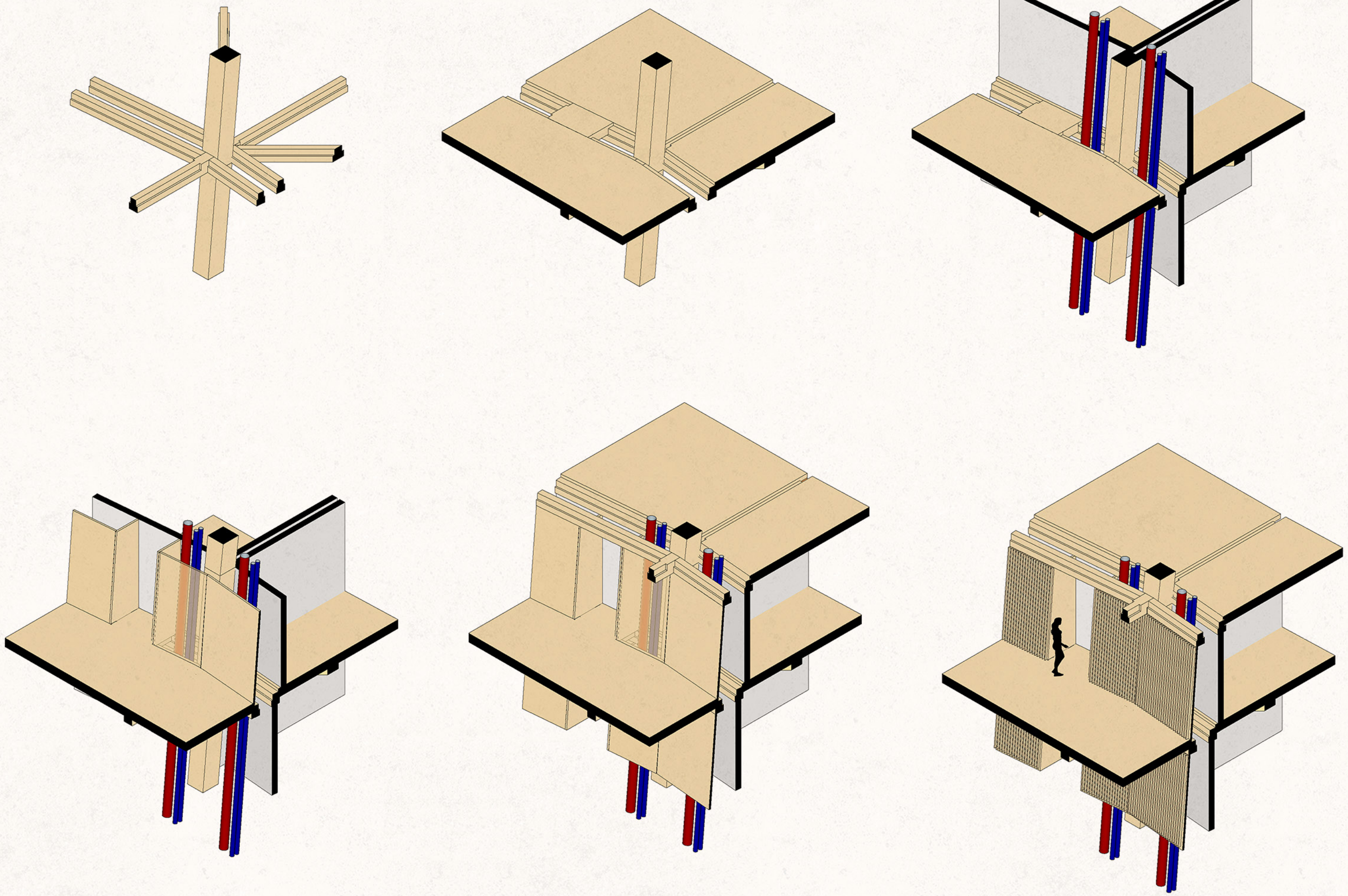
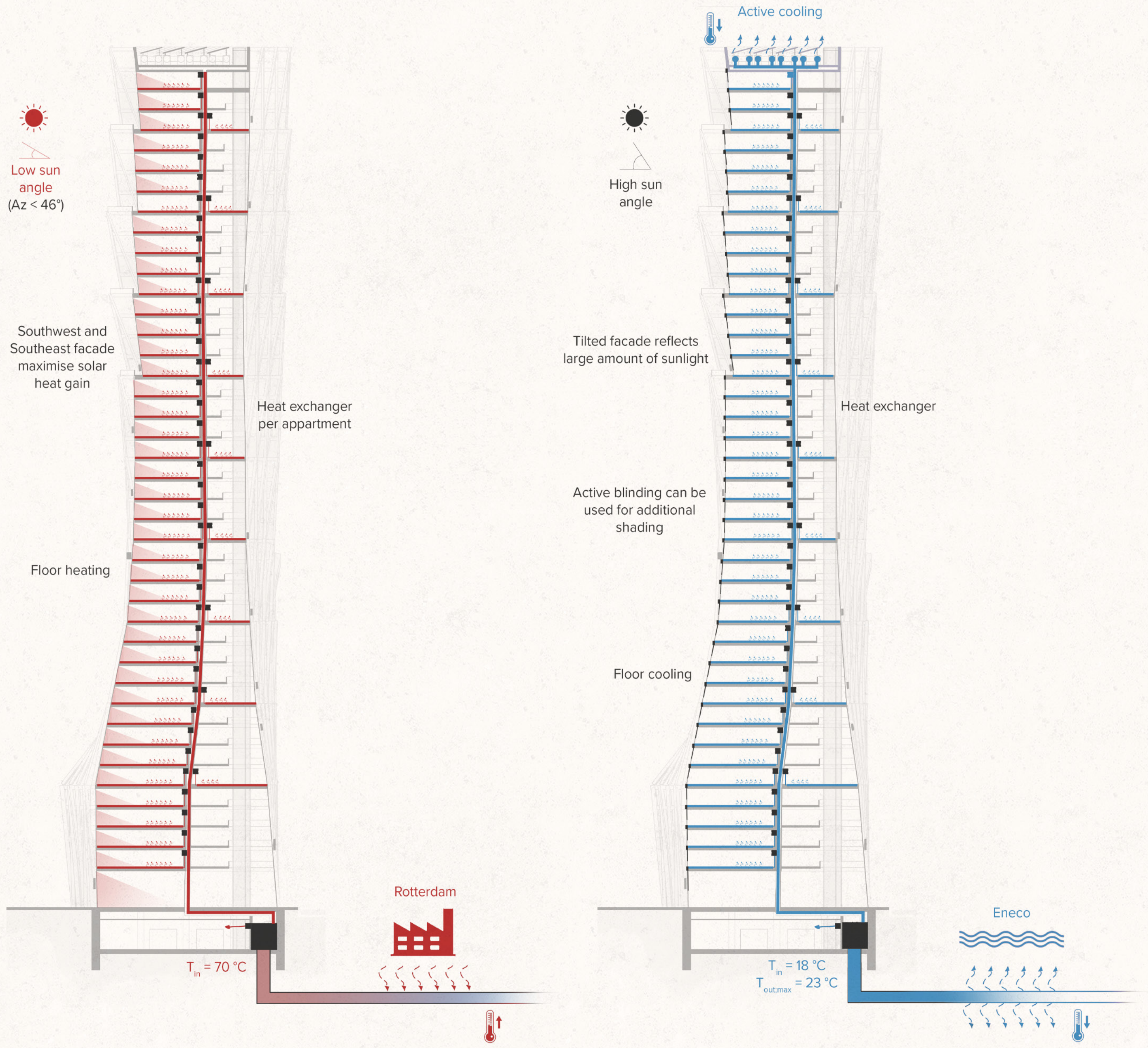




CLIMATE DESIGN
HEATING & COOLING

Winter / Spring / Autumn situation (heating)
Low sun angles are not reflected and the triangular shape makes sure this can happen efficiently without much loss area.
Additional heating of the building happens via Rotterdam's district heating program. The incoming water temperature is very hot at 70 °C and is distributed throughout the building using afore mentioned shafts. Every function has a separate heat exchanger that can retrieve the right amount of heat for the floor heating.

Summer situation (cooling)
The facade tilt causes much of the sun's light to be reflected if the sun angle is high, as is the case during large portions of the day in the summer.
Additional heat is absorbed by the water inside the floor cooling system. This water is then cooled in one of two ways.
Firstly, the Eneco Maas cooling system is used, which allows heat from the building to be exhausted into a water network ending in the Maas river. To prevent the Maas from heating up too much, a maximum output temperature of 23 °C is allowed.
Secondly rest of the cooling happens actively via airconditioning units on the roof.



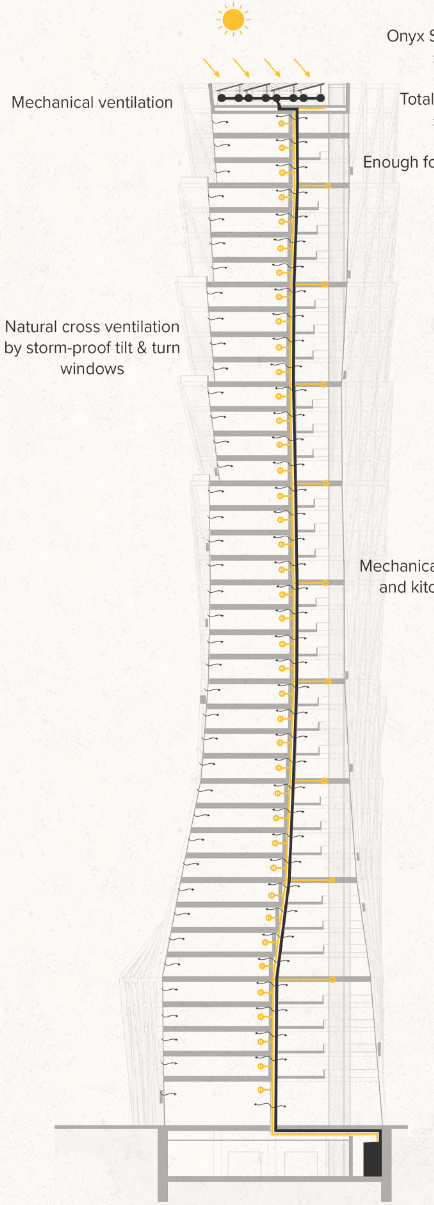
CLIMATE DESIGN
POWER, VENTILATION & RAIN

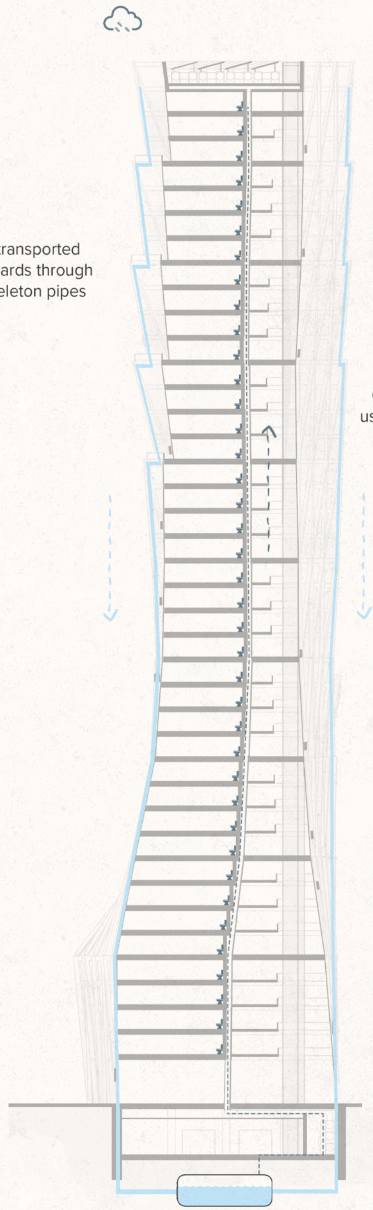
PV Panels
Energy is produced using PV panels on the roof and transparent BIPV panels in the atria curtain walls and office windows. This is enough for roughly 36% of the residential energy consumption, based on average consumption figures per person and climate data from KNMI (2021)

Natural ventilation
Ventilation plays a non-essential role in the cooling and heating of the building and as such, can be largely user-controlled. One way of doing this is through natural ventilation. The windows are Reynaers storm-proof tilt & turn windows, which can be opened even under high wind loads. Additionally, the balcony doors can be opened.

Mechanical ventilation
Functions such as kitchens, bathrooms and restrooms require mechanical ventilation as is the case here. The mechanical ventilation is central, with fans on the roof. It is again distributed through the central shaft system.

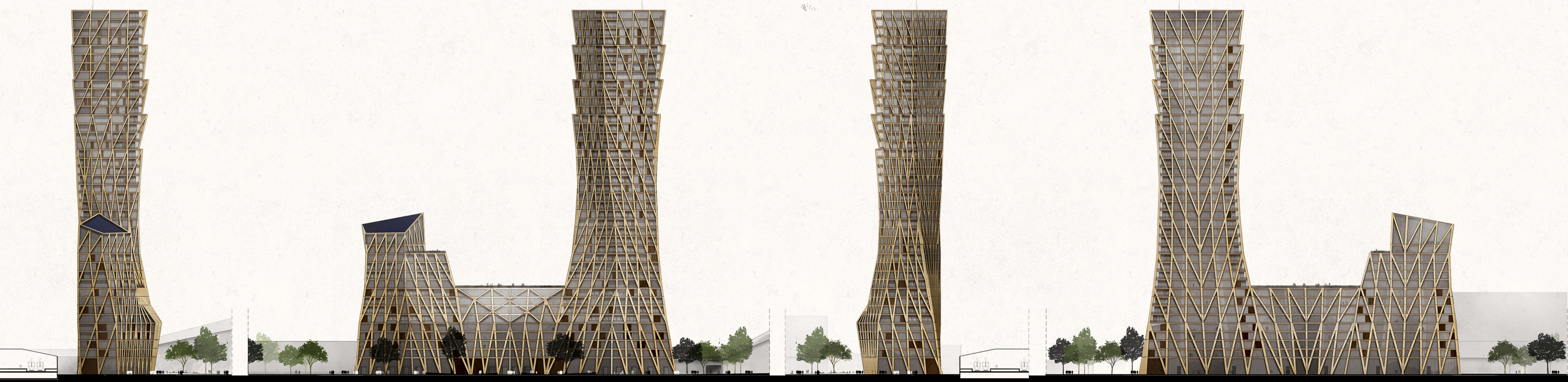
Rain
Rainwater is fed through a piping system inside of the exoskeleton insulation and collected inside an underground reservoir underneath the parking garage. From there it is fed into the technical rooms, where it is distributed to the appartments. This grey water can be used for flushing toilets and accounts for roughly 73% of this, based on data from KNMI (2021) and roof surface area.





FACADE
IMAGE

Contrast
The strand woven bamboo of the exoskeleton differs in color and strip height from the strand woven bamboo of the closed facade. This creates a strong contrast between the two, visually separating megastructure from infill. Because of this visual separation, when the infill is modified, the architectural image of the structure does not change dramatically, preserving its aesthetic quality while being exceedingly adaptable.



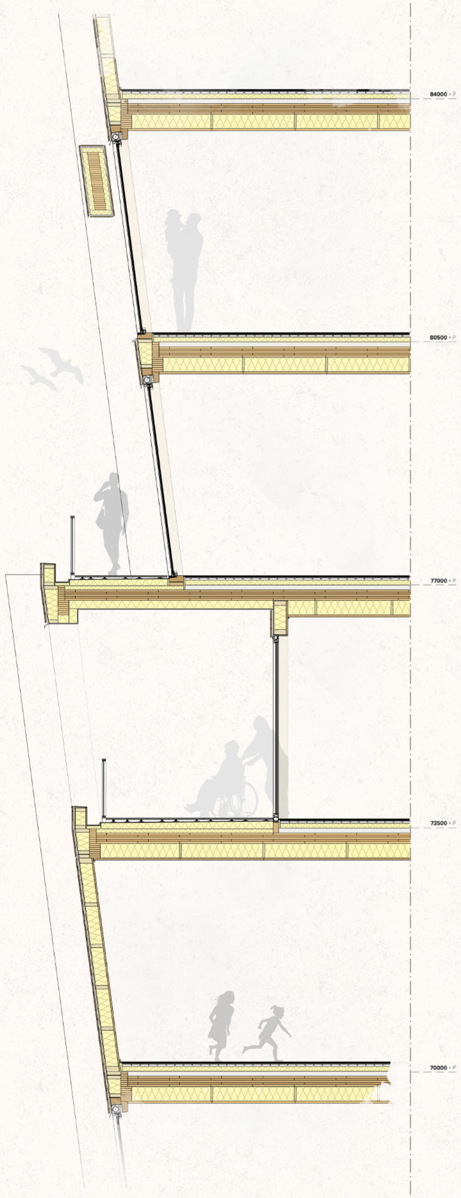
FRAGMENT
TOWER

Strand Woven Bamboo

The exoskeleton is finished with Moso Xtreme strand woven bamboo strips. This is the toughest kind of engineered bamboo and is very suitable for use outside. Over its lifespan it greys to give it a patina. In the harsh conditions of a skyscraper, it should be replaced every 30 to 35 years. This is not difficult and does not necessitate any damaging maneuvers. However, it adds ongoing CO_2 compensation throughout the building's lifespan.

Moso Xtreme facade cladding

Retrieved from: https://awood.nl/gevelparket/moso-bamboo-x-treme-gevelparket/



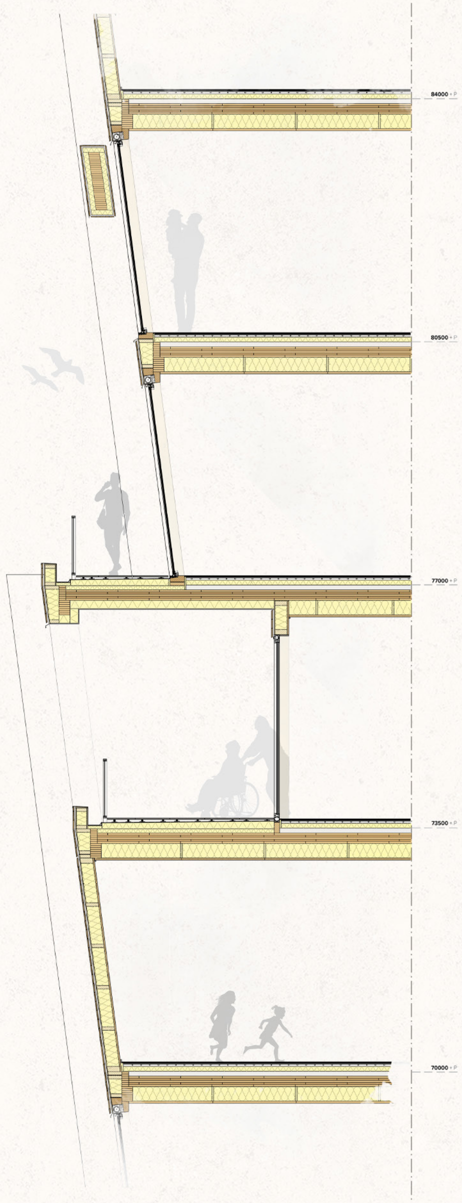
FRAGMENT
TOWER

Bamboo Exoskeleton
The exoskeleton of the building is largely composed of plybamboo LBL, which is the most efficient type of engineered bamboo for normal loads, because it retains its original fiber direction. The bracing is composed of glubam, which is engineered to widthstand load in multiple directions. This is due to the bracing being used at more severe angles and experiencing transverse loads in addition to typical loads.

Expanded Cork
Expanded cork is used to insulate the bamboo skeleton. This is not only one of the most environmentally friendly and thermally insulating insulation materials available, but it also has good moisture-blocking characteristics and naturally repels biological growth and pests.

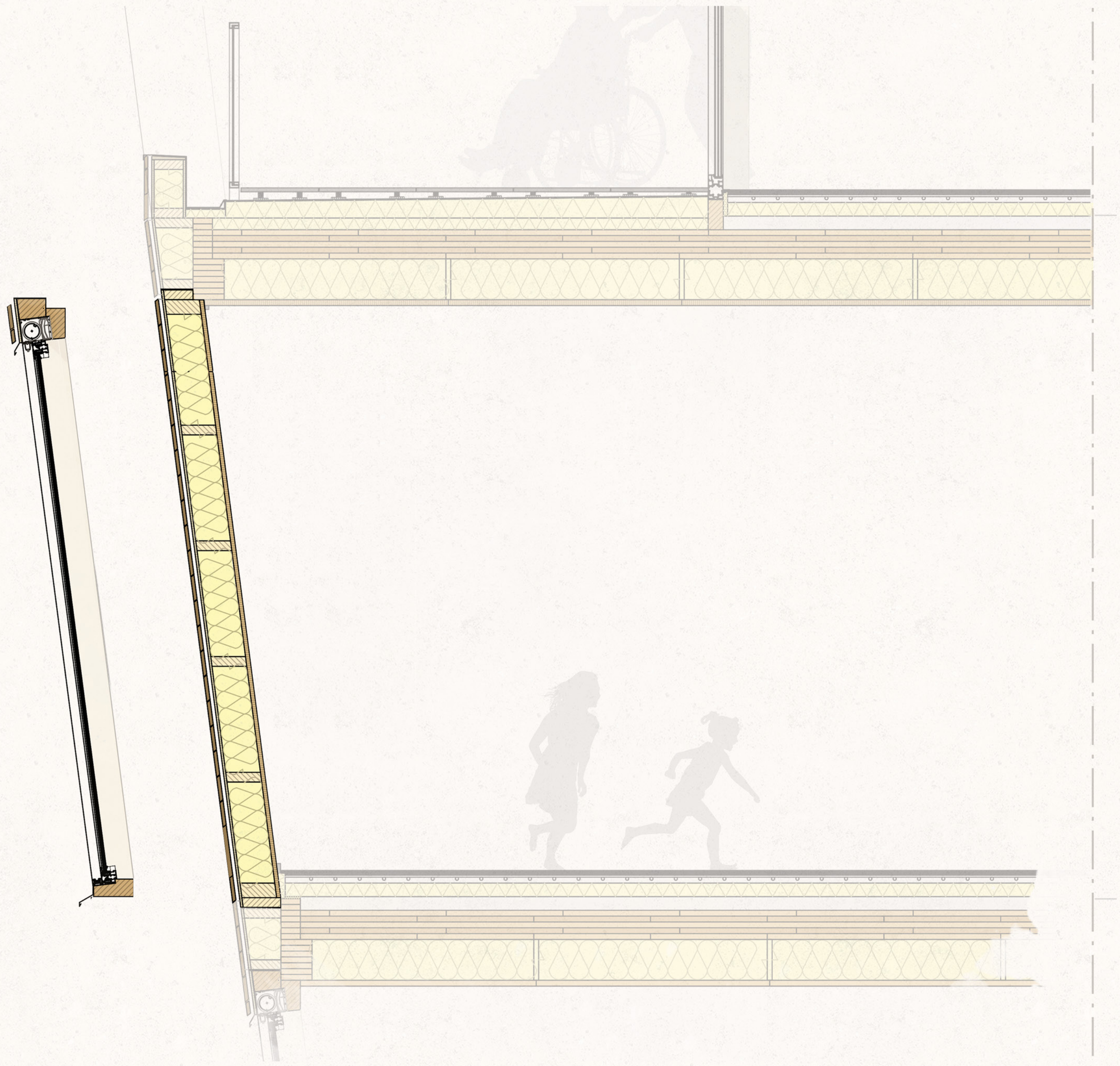
Contrast
The strand woven bamboo of the exoskeleton differs in color and strip height from the strand woven bamboo of the closed facade. This creates a strong contrast between the two, visually separating megastructure from infill. Because of this visual separation, when the infill is modified, the architectural image of the structure does not change dramatically, preserving its aesthetic quality while being exceedingly adaptable.

Wind
Large sections of the tower are located at a high elevation and, as a result, can be subjected to significant wind speeds. As a result, inwards oriented balconies were adopted because, when coupled with the exoskeleton beams, they offer a more enclosed outside space. This makes the balconies significantly more pleasant while retaining the open look and feel.



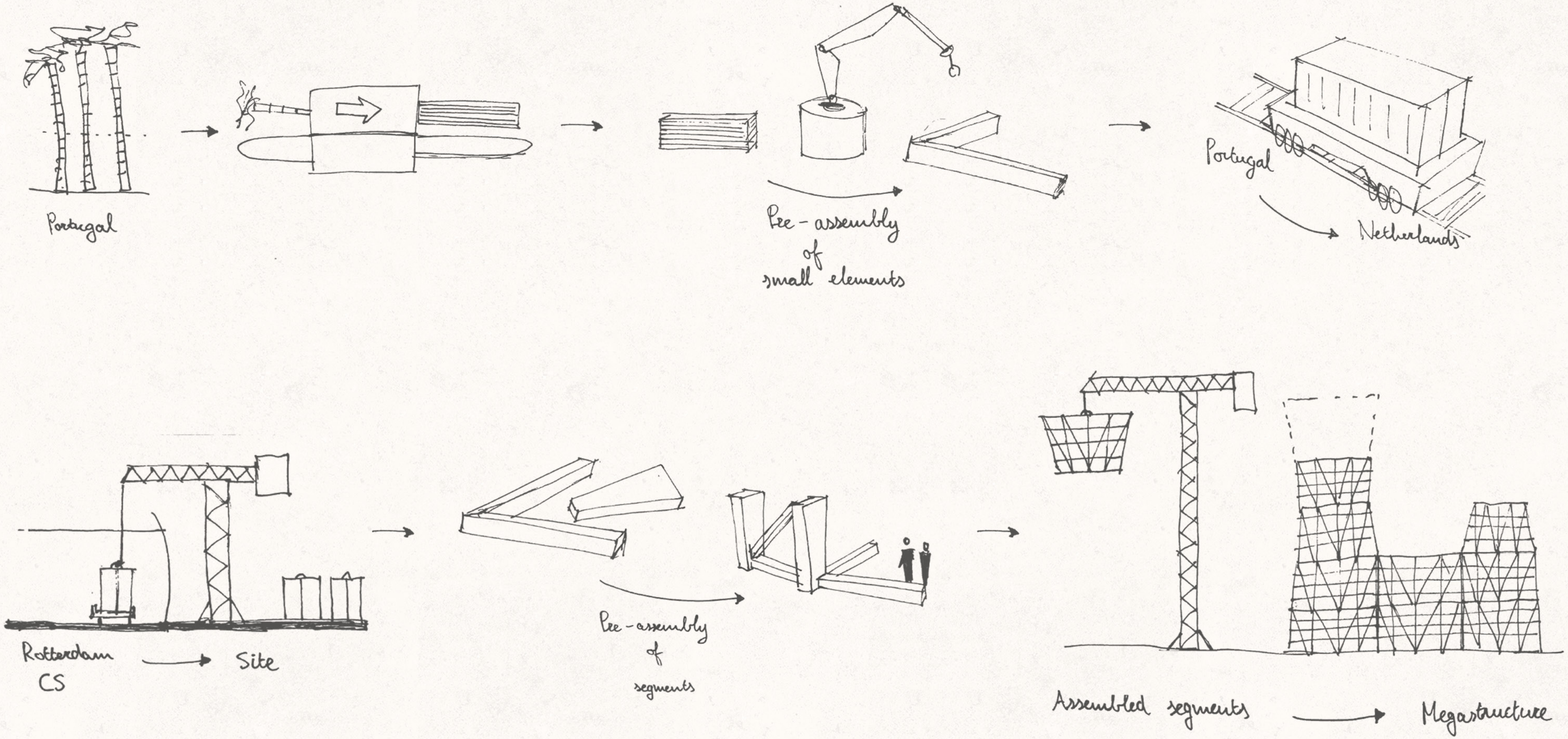
FRAGMENT
TOWER

Modular buildup
The facade is split up into modular segments, that are made in such a way that they can be directly swapped out with one another, without requiring modification to other connections. This not only facilitates easy adaptability in the future, but it also allows these complete building elements to be prefabricated and quickly assembled on site, massively increasing construction speed and thus reducing cost.



CONSTRUCTION

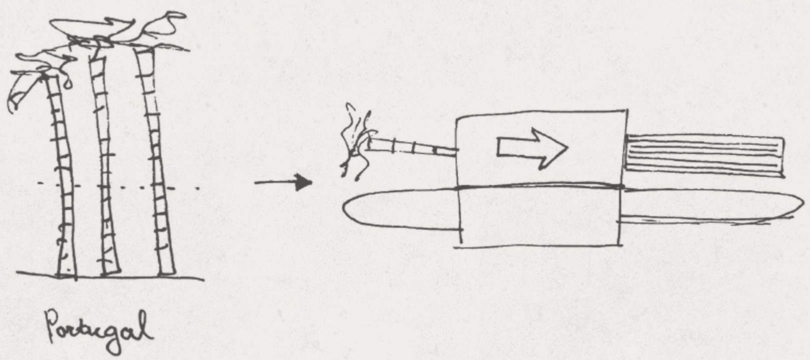
PROCESS



CONSTRUCTION
PROCESS

Growing & Harvesting
The Moso bamboo is grown in Portugal and harvested for use in construction. It is first brought into a dry location and left for a number of days to reduce the moisture content, before transport to the building element factory.

Conversion
In the factory, the dried bamboo is converted into building elements. These can be all sorts of engineered bamboo and many factories produce multiple if not all kinds.

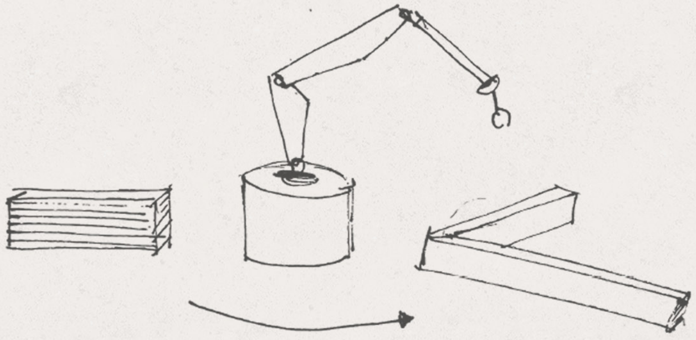


Moso Bamboo Stalks
Foto retrieved from: https://sc04.alicdn.com/kf/U7dfd74165-ca04422844d9ce47d1c7e3ez.jpg_50x50.jpg

LBL beam
Foto retrieved from: https://www.okorder.com/p/bamboo-wood-engineered-lumber-eco-building-material-interior-or-exterior-post-beam-member_1127161.html

CONSTRUCTION
PROCESS

Pre-assembly
After the building elements are produced, they can be pre-assembled into smaller building units, such as the wall modules used. This can be done partially by hand, but through digital manufacturing techniques, it can be more quickly be done by robot.



Laminated bamboo prefabrication
Foto retrieved from: https://mcgrawimages.buildingmedia.com/CE/CE_images/2016/May-Lamboo-3.jpg

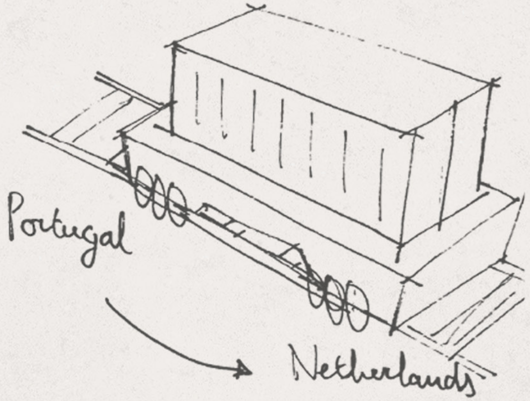
CONSTRUCTION
PROCESS

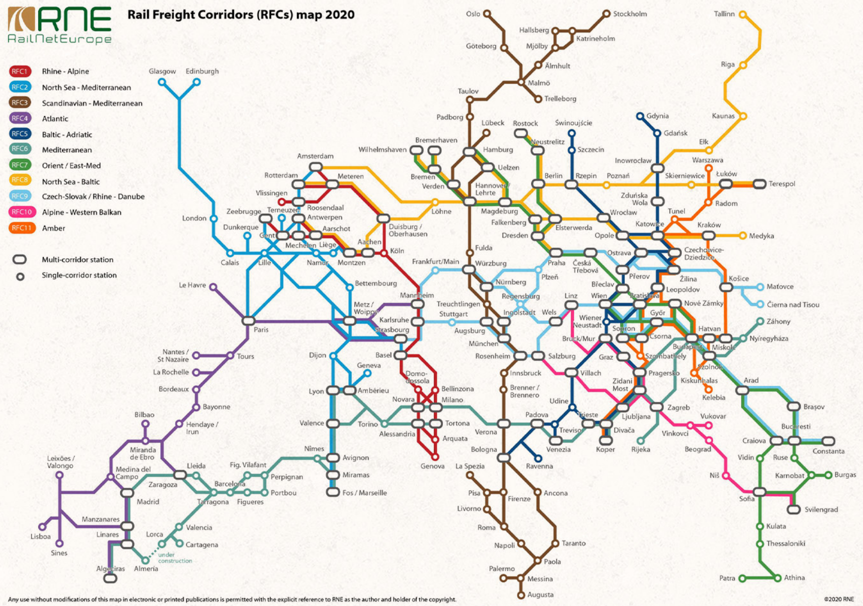
Train transport
The building elements can be easily transported from Portugal to Rotterdam via the RFC network. Transport routes RFC4 and RFC2 can be used. (Prorail, n.d.)

5x CO2 saving
By transporting the materials by train instead of truck, approximately 5 times less CO_2 is exhausted (Prorail, n.d.). This further increases the sustainability of the building.

Larger elements
Train wagons can carry significantly bigger items than trucks. As such, more pre-fabrication can be done in Portugal, saving time and cost.

ECT Area Rotterdam
Foto retrieved from: https://www.ect.nl/sites/www.ect.nl/files/styles/header/public/rail_t8a1345.jpg?itok=wee8xiXF





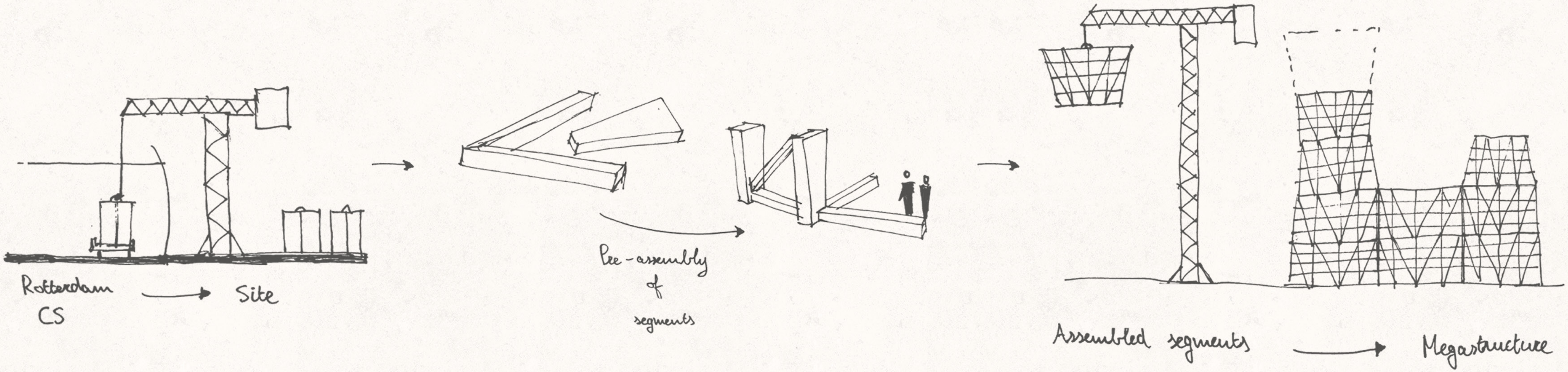
RNE Rail Freight Corridors Map 2020
Foto retrieved from: https://rne.eu-/wp-content/up-loads/2021-04-23_RNE_RFC_-Map-scaled.jpg

CONSTRUCTION
PROCESS

Segment assembly
Once at the site, the building elements can be offloaded directly of the train due to its positioning right next to Rotterdam Central Station.
Now the structural segments of the building can be assembled on the ground and a large amount of pre-assembly can already be done here. The megastructure elements can be connected, and the floors and facade can be added. Only the finishing is done later.

Building construction
Once a segment is finished, it can be placed on top of the existing segments and connected. Once placed, part of the construction workers can start connecting the plumbing and installing the finishing, while the other part continues buiding the other segments.

Wood Building Element Pre-Assembly
Foto retrieved from: https://passivegreen.files.wordpress.com/2013/06/7020522733_7c05a3c8a9.jpg

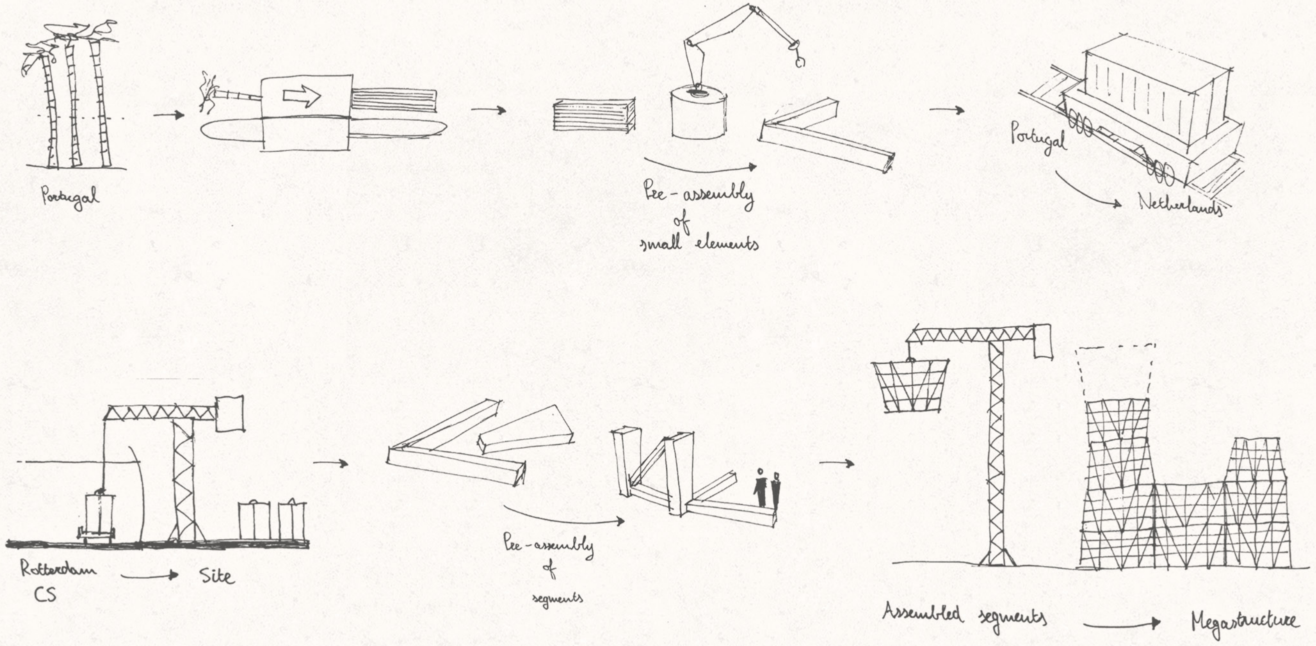


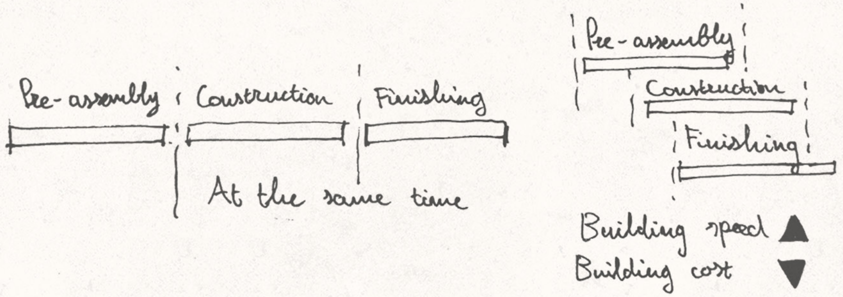
CONSTRUCTION
PROCESS

Time & cost saving

The construction progress as described is much more efficient than that of a traditional building. Much can be pre-assembled in factories and on-site and usage of heavy machinery like cranes is severely shortened. This can save a large amount of costs. Additionally, the large amount of prefabrication allows reduced construction time on-site, which can reduce nuisance, especially in such an urban, crowded area.

As such, it must be noted that although wood-like materials and bamboo are more expensive than concrete or steel, they can make up for a large amount of this cost by a more streamlined construction progress.





ENGINEERED BAMBOO

ECO-COST

ECO-Cost Neutral Construction

In construction, it is inevitable to use materials with poor ECO-cost performance, such as glass, aluminium, and insulation. However, through the use of Engineered Bamboo and/or many softwood products, this can be compensated, resulting in an ECO-cost Neutral building.

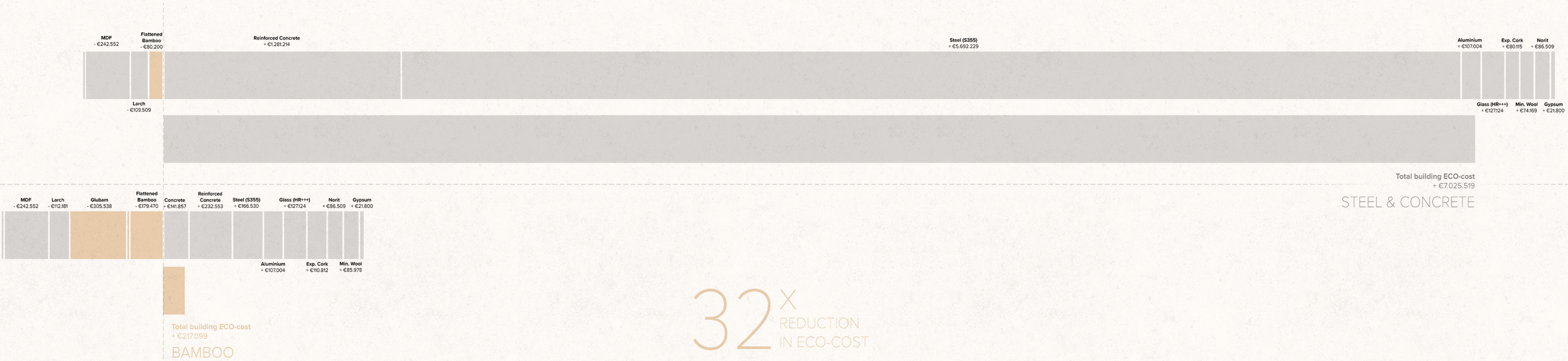
Using ECO-cost data from IDEMAT 2020, mechanical conversion values from the thematic research and volume data from own 3D models, the total volume of materials used was calculated. This allowed for a calculated estimate of total building ECO-costs. The same calculation was conducted for the building in its designed state and for the same building if it were constructed using a more traditional steel & concrete construction.

Steel performs poorly

The biggest gain in ECO-cost performances comes from eliminating steel as the main load-bearing material. Although much less volume of steel is required compared to bamboo, its high ECO-costs make it an exceptionally poor performer with regards to sustainability.

Bamboo & wood compensate

The bamboo used compensates for much of the lesser performing materials, because of the good ECO-cost performance, but also because of the relatively high volume. The wood from separator wall structures plays an important part as well.



32X REDUCTION IN ECO-COST

4. CONCLUSION

OBJECTIVES

General:
To research the potential and limitations of using European Moso bamboo (Phyllostachys Edulis) based building elements in large scale construction.

Thematic research objective:
To research the feasibility of using Moso bamboo building elements in different typologies and to formulate a practical design strategy for optimal application of engineered Moso bamboo building elements.

Design objective:
To design a high density housing project that uses engineered Moso bamboo building elements, applying and testing the afore mentioned design strategy. Additionally, quantifying what effects the use of Moso bamboo building elements has on the sustainability of the project

CONCLUSION

How does the application of Europe-produced Moso Bamboo building elements affect the design and sustainability of a large scale housing block in the Netherlands?

The most notable way using engineered moso bamboo is the vastly superior ECO-cost performance when compared to similar steel and concrete structures. Furthermore, bamboo is infinitely renewable, whilst also absorbing and storing CO2 in the process. This makes it a greatly more sustainable alternative to steel and concrete.

Engineered wood can offer similar advantages, especially in less mechanically challenging conditions, but the excellent strength-to-weight and strength-to-volume ratio of engineered moso bamboo, combined with its unparalleled renewability makes it a more favourable choice for application in highrise construction. The principles of design are similar to those of constructing with wood, thereby offering the same advantages, like more design freedom because of digital manufacturing, faster construction speed and better adaptability because of prefabrication and far more predictable fire-behaviour. The constraints commonly associated with wood like large floor-heights and/or small grid sizing are less of a hindrance with engineered bamboo.

The conclusion can be drawn that the application of engineered Moso bamboo as a structural material, especially in mechanically challenging conditions such as highrise construction, is viable and offers significant advantages over both steel, concrete and wood. The existing knowledge base on how to construct with engineered wood directly apply to engineered bamboo. Additionally, this research has added to this knowledge base with research into ECO-cost and renewability, and has given more handhold for designers by providing a design tool that assits and quantifies design decisions with regards to material.

Before application on a large scale, however, a number of topics warrant additional research.

DISCUSSION

Although the application of Moso-bamboo building elements appears viable, there are still a number of notable issues and developments, into which more research would be of value.

Types of resin used
An issue decreasing the sustainability of engineered bamboo is the resin used for the production. Currently many of the resins used are formaldehyde based, whose production requires petroleum and causes harmful waste products. The application of cellulose-based resins appear to be a promising alternative (Ferdosian et. al. 2016). As this is non-toxic and can be made from bamboo pulp, this would also increase overall product yield. Further research into the application of cellulose-based resins in engineered bamboo products would therefore be useful.

Hybrid materials
Growing development of extremely high-performance building elements that combine a natural material like wood with a synthetic material such as glass-fiber. These materials show great mechanical potential with performance that is on par or even better than that of S355 steel. Although the renewability and ECO-cost performance is negatively affected by the synthetic material used, these elements may prove a more sustainable alternative in situations where currently only steel suffices. Research into bamboo/synthetic hybrid materials is currently very limited and still very much in a theoretical stage. This topic warrants further research, especially for application in highrise.

Land use and economic and ecologic consequences of large scale bamboo farming
It could be argued that, based on the potential for use in construction, the large-scale growth of Moso bamboo in Europe should be stimulated. High nitrogen and carbon sequestration make bamboo forests particularly interesting with regards to current European climate goals and the consistently high annual yield makes managing a bamboo forest an interesting proposition for farmers. This would have implications on land-use and economy. Further research into the implications of large scale Moso bamboo growth in Europe could boost such developments.

QUESTIONS?