GODS BANEN ZERO

LCA IN THE EARLY DESIGN STAGE OF A MIXED-USE TIMBER BUILDING

Group: MA4 - ARK19
MSc04 ARK E2019
Aalborg University
June 2019

Andrea Ferrerio · Elena Rado · Matteo Tagnocchetti

TITLE SHEET

Aalborg University
Department: Architecture,
Design and Media technology
MSc04-ARK E2019

Group: MA4 - ARK19

Project title:
GODSBANEN ZERO: LCA in the early design stage of a mixed-use timber building

Project period: 01.02.19 - 23.05.19

Main supervisor: Michael Lauring
Technical supervisor: Tine Steen Larsen
External partners: Rob Marsh, Ryan Hughes

Master Thesis

Number of pages: 146

....

Andrea Ferrerio

....

Elena Rado

....

Matteo Tagnocchetti

"Il risultato è questo: che più Leonia espelle roba più ne accumula; le squame del suo passato si saldano in una corazza che non si può togliere; rinnovandosi ogni giorno la città conserva tutta se stessa nella sola forma definitiva: quella delle spazzature d'ieri che s'ammucchiano sulle spazzature dell'altroieri e di tutti i suoi giorni e anni e lustri."

"This is the result: the more Leonia expels goods, the more it accumulates them; the scales of its past are soldered into a cuirass that cannot be removed.
As the city is renewed each day, it preserves all of itself in its only definitive form: yesterday's sweepings piled up on the sweepings of the day before yesterday and of all its days and years and decades."

Italo Calvino, Le Città Invisibili (Torino 1972)

ABSTRACT

This report is the product of the Master Thesis for the M.Sc. in Technology - Architecture at Aalborg University.

The aim of this work is to investigate a relevant field of sustainable architecture: the application of Life Cycle Assessment (LCA) in the early design process, in order to obtain a building that has a close-to-Zero impact on the environment during his whole life. As a consequence, the thesis will deal with timber structure potential in a LCA functional and aesthetic perspective.

This topic is applied to a mixed-use building complex both with housing and public functions, located in Godsbanen, a district in Aarhus, Denmark.
The choice of the building typology is motivated by the fact that the demand for multi-dwelling houses in the Danish construction sector is high (statbank.dk, 2018) and therefore it is a typology that has need of LCA tools.

The result is based on an initial analysis about the site and the user groups, on the LCA and timber structures. The analysis is followed by the process phase in which the above-mentioned topics are investigated and applied to the project. In the last part the results of the process, the outputs and the presentation materials of the architectural project are shown.

The expected outputs are:
- A method to integrate LCA in the early design stage.
- General knowledge regarding effective architectural strategies that reduce the environmental impact of a building during his whole lifespan.
- General knowledge regarding the architectural potential and limitations of using a timber structure in comparison with a standard concrete structure, with a particular focus on LCA parameters.
- A finished architectural project that synthesize the LCA and timber knowledge gained.

INDEX

METHODOLOGY

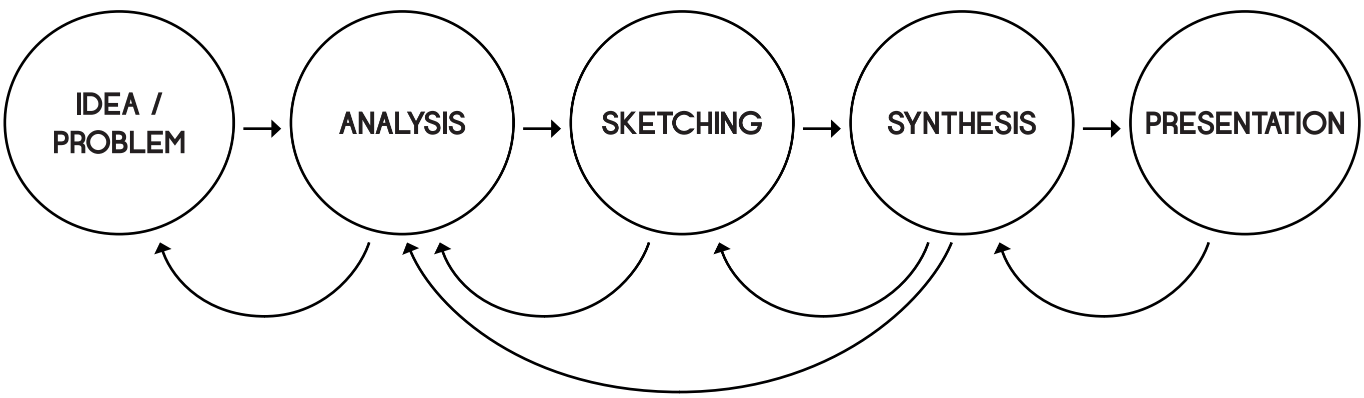
The overall method used during the process for this project has been the Integrated design process by Mary-Ann Knudstrup. The method facilitates design through an iterative drawing process on different knowledge, as to design while considering different aspects of architectural design such as function, structure, form and sustainability. These aspects are continuously considered for the research and for the design of the building.

The method consists of five phases: 1) Problem or Idea phase 2) Analysis 3) Sketching 4) Synthesis 5) Presentation, and the work between all these different phases happens iteratively.

1. Phase one is the initial phase that lays the groundwork for the rest of the project, based on finding an idea or a problem to be worked on and solved. For this project, it consists of two main questions raised in the group due to the interest in the sustainability field and in particular in the Life Cycle Assessment (LCA) topic: how can LCA considerations be integrated in the early design stages? How can the sustainability potential of timber be unfolded through the study of LCA?

2. Phase two is the analysis phase where different aspects that could have relevance to the project are investigated, and the information is distilled down and brought further into the project. Some of the aspects that have been analysed are the site characteristics, micro-climate, materials, timber structures and LCA theory and software. The tools used in this phase are sources such as literature, reference case studies and maps. Furthermore, due to the specific features of the project site, the local users (the municipality and local organizations) have been involved through informal communications to gather some initial information about the area character and future use.

3. Phase three is the sketching phase where different ways of sketching are utilized from hand sketches, mock-ups, workshops to 3D models and parametric modelling. The sketching phase aims to convert the information gained in the analysis phase into design that makes a base for the project that can be facilitated through the further process.
Even though the integrated design process, applied to a sustainable architecture project, would require the integration of many more aspects, such as indoor comfort and energetic evaluation during this phase, this thesis aims to focus prevalently on LCA iterations. Therefore, these other features will be considered in this phase but without the use of specific tools and calculations.
An LCA parametric tool provided by the external collaborators at C.F. Møller have been used in an iterative way during this phase.
The method used has been to test simple volumetric cases by changing different parameters such as number of storeys, width-length ratio and structural span in order to obtain results of trends in the LCA



ill. 1: The integrated design process

performance.
These data have then been turned into general knowledge and contributed to define the design strategies. This indirect way of proceeding has been done to avoid the imprecisions of the tool when applied to complex shapes while still looking to achieve relevant answers.

4. Phase four is the synthesis phase, that weaves the earlier phases together to create a holistic design by drawing together the knowledge of the analysis and sketching phase. During this stage a synthesis of general and Iteration-based strategies that benefit the LCA have been done to finalize the design. An alternative LCA tool has been used to document the project performance and to compare the results with the early design stage tool.

5. Phase five is used to communicate the project and it is the presentation of the final building design through visualizations, diagrams, drawings and 3D illustrations. All the final results and outputs got during the process regarding the LCA studies are shown in a form that is easily readable by both experts and professionals that are not familiar with the topic of LCA in architecture.
Another focus in this phase has been to present the choice of using a non-common solution, such as the exposed cross laminated timber (CLT) structure, in a way to effectively communicate the aesthetic and sustainability potential of timber together with the related issues of building high rise in wood.

As expected from the IDP, the design process was not linear: as the project evolved a step back to the analysis phase has been necessary, for example by researching further information on timber properties during the detailing and interior design phase.

The method serves as a structure for the project where it is possible to cycle back and forth through the phases of an iterative process. The process is used as a tool to get the group working through one overall model while implementing different tools through the project to create a holistic design. This is done by finding the key parameters and by looking at different aspects that can influence the design. Other factors should be included, to drive the project forward with a broad perspective. This process helps to create arguments to support the choices both of the main aspects that have primarily been looked at and the finalized decisions made throughout the project.
(Hansen & Knudstrup, 2005)

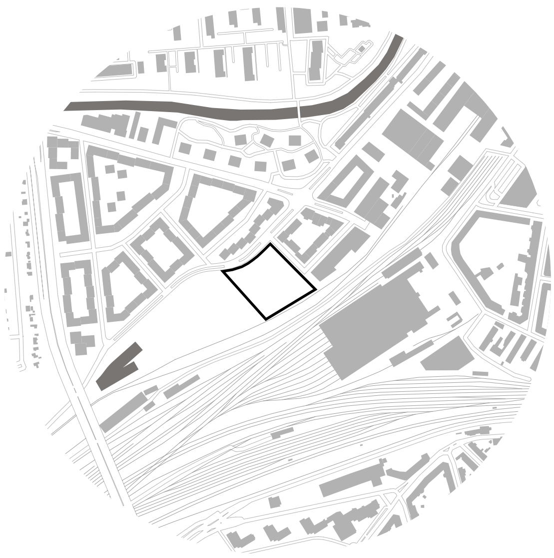
ANALYSIS

SITE ANALYSIS: LOCATION

The project site is located in Godsbanen, also called Aarhus K, a district in the south-western part of the city of Aarhus, Denmark, that is currently seeing a quick development.
The area is defined on the south-east by the old railway reparation terminal and on the west by the Ringgade, the high traffic road that surrounds the city of Aarhus.
On the north-west the limit is set by the Aarhus Å (river) while the Godsbanen building in Skovgaardsgade closes the area on the north-east.
The area is rich of history and is located in a critical position for the development of the city of Aarhus: it is a low-density area that stands between the city center and the Ringgade.
It is also in close proximity to a large number of cultural institutions such as the City Museum, the ARoS and the Music House.
The project site is set in the middle of this under development area. Next to it there will be residential buildings, a college and a production school and, on the other side, a big open space that will be used as event area. The total area of the plot is 10.000 m^2.

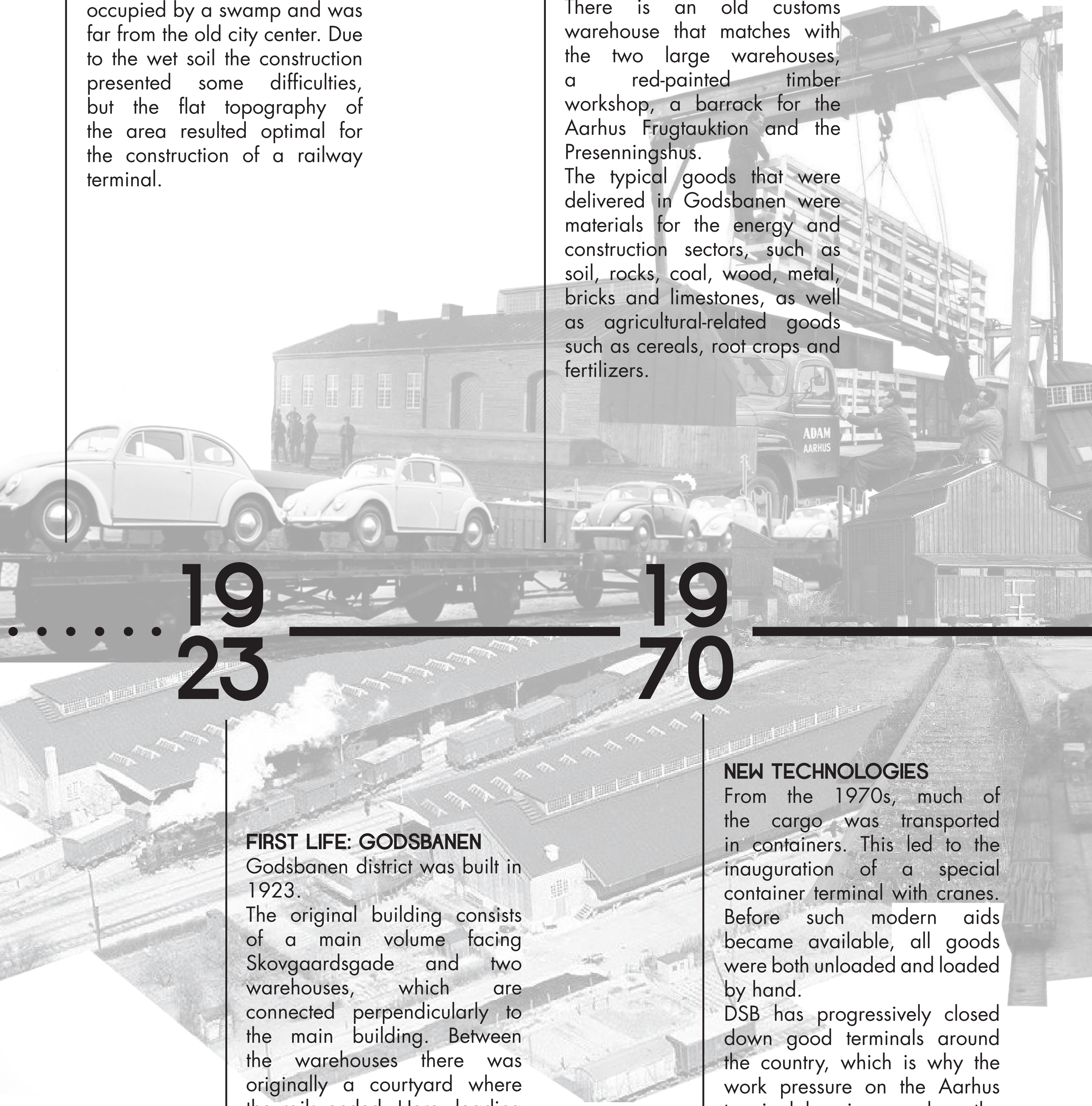
ill. 2: Aarhus in Denmark

ill. 3: Godsbanen in Aarhus



ill. 4: Project site in Godsbanen

HISTORY



1923

FIRST PLANS
Before the edification of the district the area was mainly occupied by a swamp and was far from the old city center. Due to the wet soil the construction presented some difficulties, but the flat topography of the area resulted optimal for the construction of a railway terminal.

FIRST LIFE: GODSBANEN
Godsbanen district was built in 1923.
The original building consists of a main volume facing Skovgaardsgade and two warehouses, which are connected perpendicularly to the main building. Between the warehouses there was originally a courtyard where the rails ended. Here, loading and unloading of the incoming and outgoing train goods took place.

1970

EXPANSION
New storage and manufacturing buildings are built.
There is an old customs warehouse that matches with the two large warehouses, a red-painted timber workshop, a barrack for the Aarhus Frugtauktion and the Presenningshus.
The typical goods that were delivered in Godsbanen were materials for the energy and construction sectors, such as soil, rocks, coal, wood, metal, bricks and limestones, as well as agricultural-related goods such as cereals, root crops and fertilizers.

NEW TECHNOLOGIES
From the 1970s, much of the cargo was transported in containers. This led to the inauguration of a special container terminal with cranes. Before such modern aids became available, all goods were both unloaded and loaded by hand.
DSB has progressively closed down good terminals around the country, which is why the work pressure on the Aarhus terminal has increased as the technical development has made it possible to handle larger quantities of goods.

ill. 5: History of Godsbanen

2000

TERMINAL CLOSING

Godsbanen closes in 2000 due to the loss of its utility.
As result of this first life, the whole area was mostly occupied by rails and storage buildings, which explains the current long shape of the district.
The Godsbanen in Aarhus was, at the time of its closure, the last of its kind in the country, and it is thus also the largest preserved Godsbanen in Denmark.

NEW PLANS

A public discussion on the use of the area started. From both the authorities and the local activists the idea to create a cultural and production center emerged. Many of the actors in today's cultural life in Aarhus already participated at that time, and the focus was on a center for performing arts, visual arts and literature.
In 2008 the municipality, with the economic support of Realdania, bought the area from DSB.

2009

SECOND LIFE: INSTITUT

Several new concepts for citizen involvement were developed and some spontaneous initiatives started. The most important one is the Institut of (X), a culture, business and education platform founded in 2009.
The outdoor spaces and park areas became public and everyone could use and co-develop them.
The mission of the Institut is the creation of the best possible neighbourhood for all while facilitating and enhancing cultural activities, combining artistic creativity with business, public debate and public education.

2010

THIRD LIFE: AARHUS K

From 2010 the municipality started the process of renovation of the Godsbanen buildings and the development of the whole district called Aarhus K. After an architectural competition, the historical buildings were renovated and a new iconic volume was built between the two long buildings in 2012. New functions have been created such as conference rooms, exhibition spaces, a theatre, a restaurant, offices as well as ceramic, wood and handicraft workshops.

2019

VISION

Between 2014 and 2017 a general plan was developed by the municipality, defining the vision for the area. During these phases a constant communication between the authorities, the citizens and the Institut for (X) allowed to come to the compromise to maintain 40% of the old non-historical buildings where the Institut operates.
The vision of the production center is to create a place where the production of art is at the top of the agenda. It must be a place where all actors within the field of performing arts, visual arts and literature get the best possible conditions for creating and developing their ideas.

(Christensen, 2009 ; Institut for (X), 2019 ; Godsbanen, 2019)

LOCAL VISION

From the history analysis it emerged that the area of Godsbanen was used for handling goods and as maintenance station of the DSB trains for most of its life.
In the recent years it is going through a process of transformation to a temporary functions area hosting urban gardens, small businesses, recycling facilities and various events, even if the industrial character of the area is still visible thanks to the old Godsbanen buildings as well as remains of railway tracks.
According to the municipality plans, the area is facing a process of profound transformation to become an integral part of the city creating a new neighbourhood with housing, public functions and business.
The aim is to develop an integrated project that includes all these purposes into a coherent building and that can provide the site of a functional and fluent connection between the cultural/educational area on the north-eastern part and the southern event area.
The district must be unique and provide Aarhus with different types of cultural and creative activities, accessible for both the inhabitants of Godsbanen and the tourists who come to visit it, but still respecting the area's raw and urban atmosphere.
To do so, it is important that the buildings and the materials relate to the

VISION

ill. 6: Street art Aarhus

ill. 7: Cafè in Berlin

ill. 10: Bar in Shoreditch, London

CONVERSION OF INDUSTRIAL AREA

ill. 8: High Line, New york

ill. 9: High Line, New york

CULTURE CREATIVITY EDUCATION

area's culture-historical nature, the landscape with industrial buildings, the Ringgade bridge and the trains (Teknik og Miljø, Aarhus Kommune, 2018).
The housing should be planned for young students or families that want to experience the vibrant and lively atmosphere of the area that is constantly changing and evolving.
In order to create opportunities for gathering between people and to strengthen the community life for the residents it must be provided with public spaces on the ground floor.
Meeting occasions can also be created by displacing the buildings' volumes as create different inclusive urban spaces and distinguish between them more easily.
The global network should be reinforced by creating passages through the volumes as to create the possibility to walk through them connecting the entire area.
The units should be created as flexible as possible in terms of structure and composition, as to make possible to disassemble it in the future or to change the internal settlement when needed.
(Aarhus Kommune Lokalplan nr. 1046 - 1062 - 1087, 2018)

SUSTAINABILITY

ill. 11: Camden Market, London

ill. 13: Former Neue Heimat, Berlin

ill. 12: Boxpark in Shoreditch, London

ill. 14: Clärchens Ballhaus, Berlin

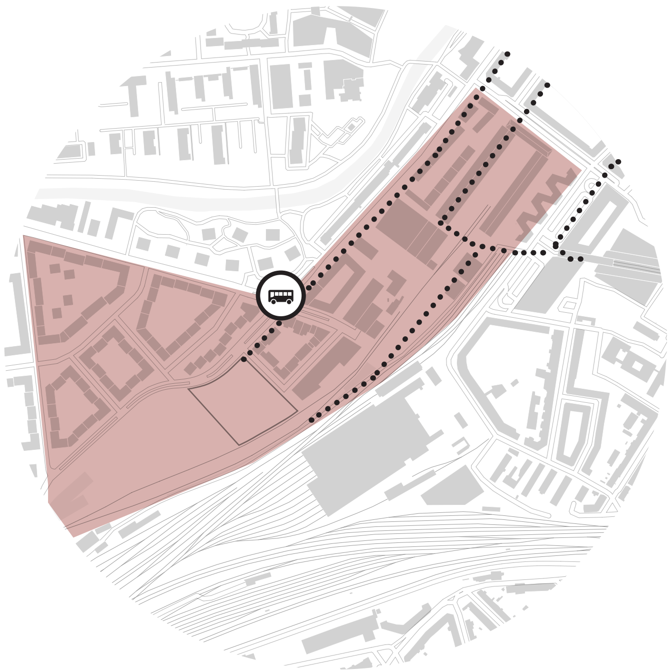
INFRASTRUCTURE

ill. 15: Aarhus districts and infrastructure - 1.20.000

DISTRICT

The map shows the 4 principal districts of Aarhus and how they are connected to the site.
Public transports reaching the area serve only the city center (stopping at the train station), Aabyhøj and the Northern districts, connected by bus line 12 (Midttrafik, 2019). Therefore, from the other districts surrounding Aarhus it is possible to reach the area only by private transport or by longer bus routes.
The city has an efficient cycling infrastructure system and the area is within walking distance from the city center and from Frederiksbjerg district.

- Bikes / Pedestrians (dotted line)
- Cars (solid line)
- Bus (dashed line)

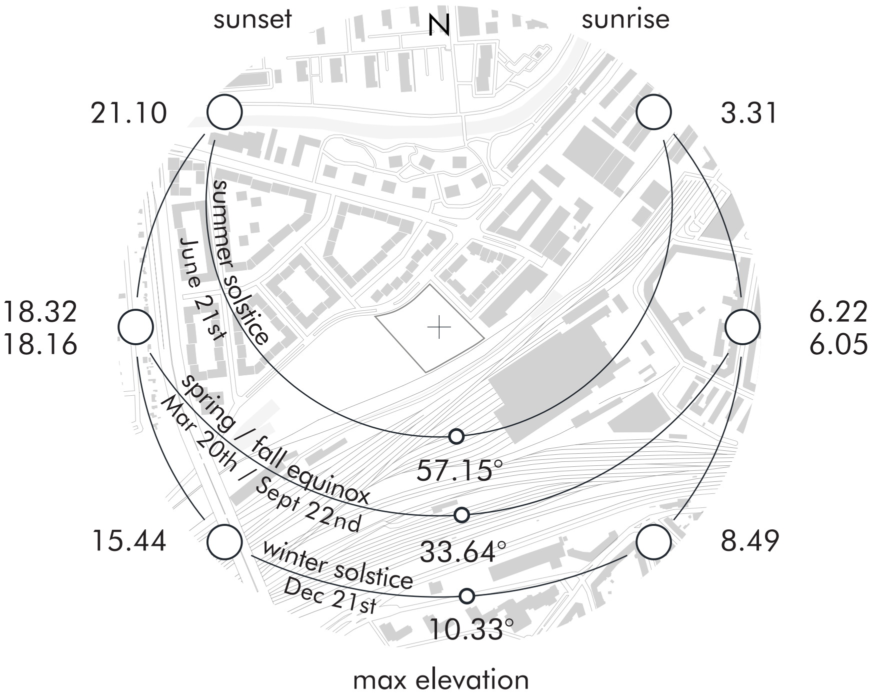


ill. 16: Godsbanen accesses - 1:10.000

SITE

The area is still quite physically detached from the South-eastern part of the city, since it is delimited by rails. The only easy access from the city center is on the North-eastern part through a commercial building or through a residential area.

MICROCLIMATE



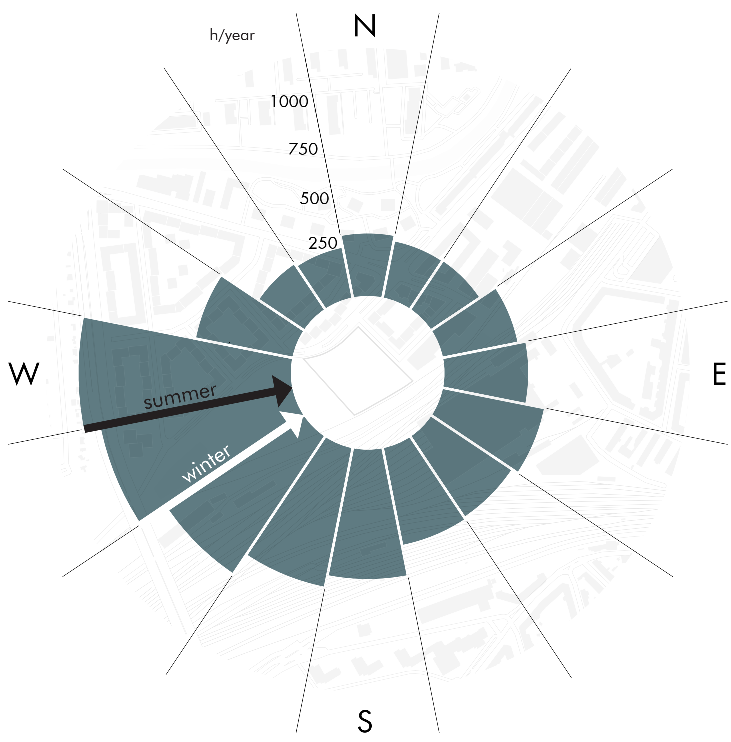
ill. 17: Sun path diagram (SunEarthTools, 2019)

SUN

The project site has a high exposition to the sunlight since there are no buildings right on the South. The site will be shaded only by the buildings on the North and only during the first and last hours of light in the summer.
Through the sun path study, it is possible to know the position of the sun relative to the site, the times of sunset and sunrise and the maximum elevation (at midday) for the solstice and equinox days. These informations are necessary for a good integrated design of the building shape and of the disposition of both the inside and outside spaces. (SunEarthTools, 2019)

WIND

The wind rose allows to see how the site is exposed to the wind showing the quantity of windy hours from every direction and the main winds in summer and winter. This is important especially for the design of the outside spaces where good wind conditions are essential for their usability. It is therefore suggested to have these spaces shielded especially from the winter winds (whose main direction in Aarhus is South-West, with an average speed of 4,9 m/s and a maximum of 19,4 m/s).
At the same time, it is necessary also to guarantee good ventilation conditions inside the building, possibly taking advantage of the natural cross ventilation, and this should be obtained especially during summer (here the wind has its main direction from West, with an average speed of 3,3 m/s and a maximum of 17,3 m/s).(Danish Meteorological Institute, 2018 ; Meteoblue, 2018).



ill. 18: Wind rose and main summer and winter winds in Aarhus (Danish Meteorological Institute, 2018 ; Meteoblue, 2018)

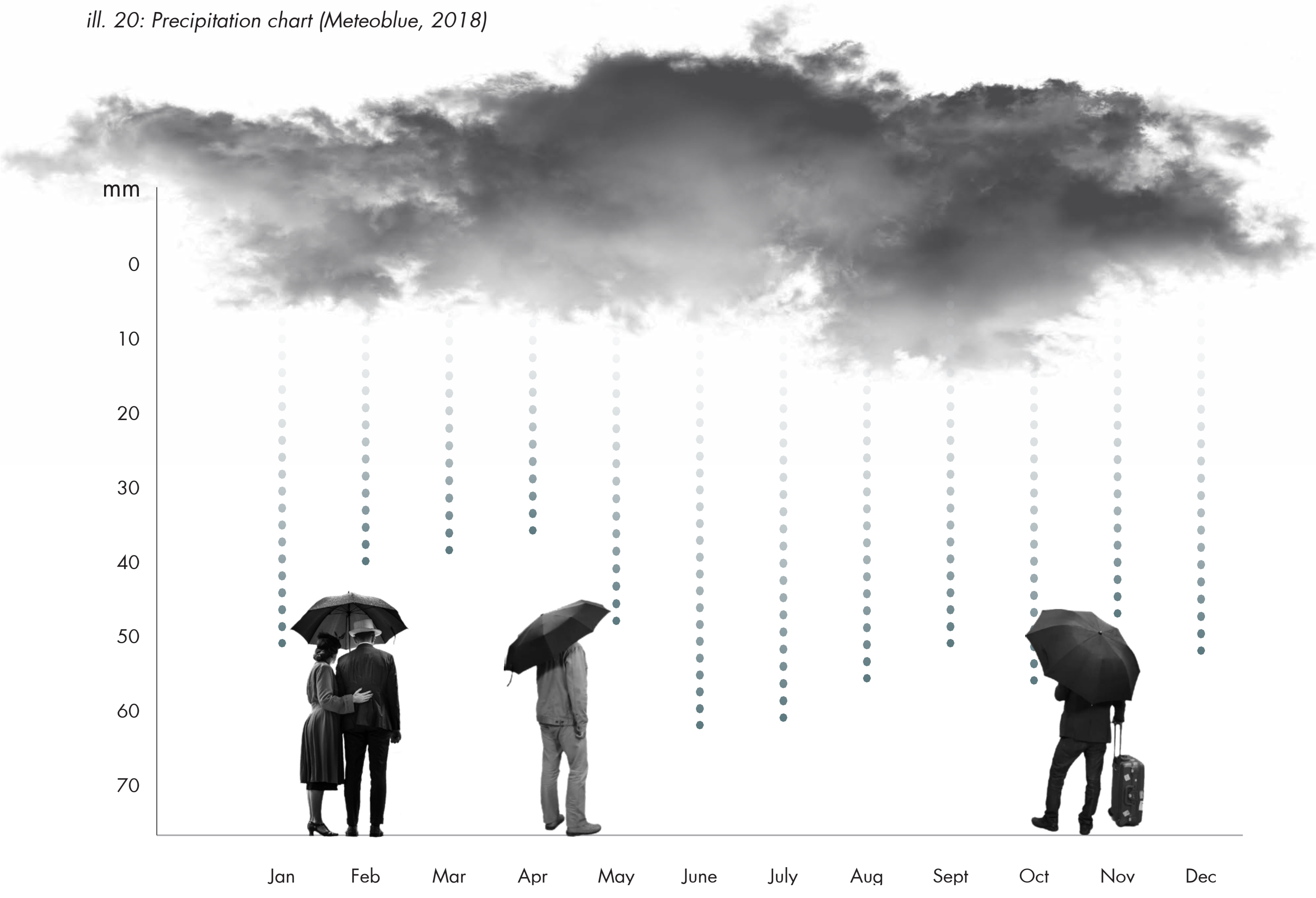
ill. 19: Water elements map

WATER

The map shows the water sources around Godsbanen area: the first and most important is the river Aarhus Å, not too far from the project site; then, some more water fonts, very close to the area, are planned as part of the vision for the future landscape.
In addition, looking at the history of the area, it emerged that the terrain has a swampy character. This issue was therefore already faced in the 1920's by filling 1.000.000 m³ of soil into the meadow, in order to make the area usable and to be able to build the freight rail (Danish Center for Urban History, 2009).
Also the rain is potential water on the ground and in the city of Aarhus it is quite frequent, especially during summer when it can reach 80mm.
(Meteoblue, 2018)

PRECIPITATION

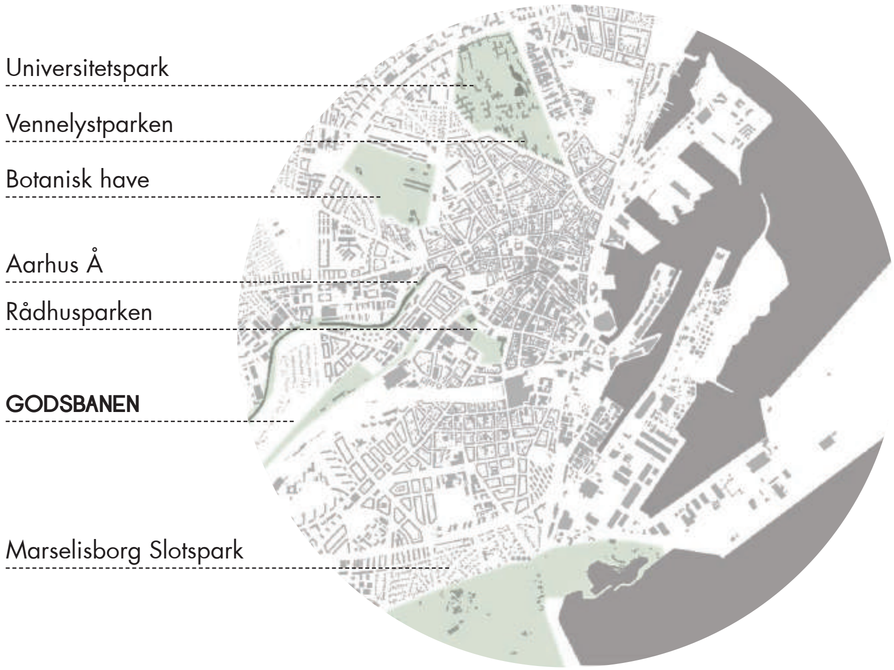
ill. 20: Precipitation chart (Meteoblue, 2018)



BIODIVERSITY

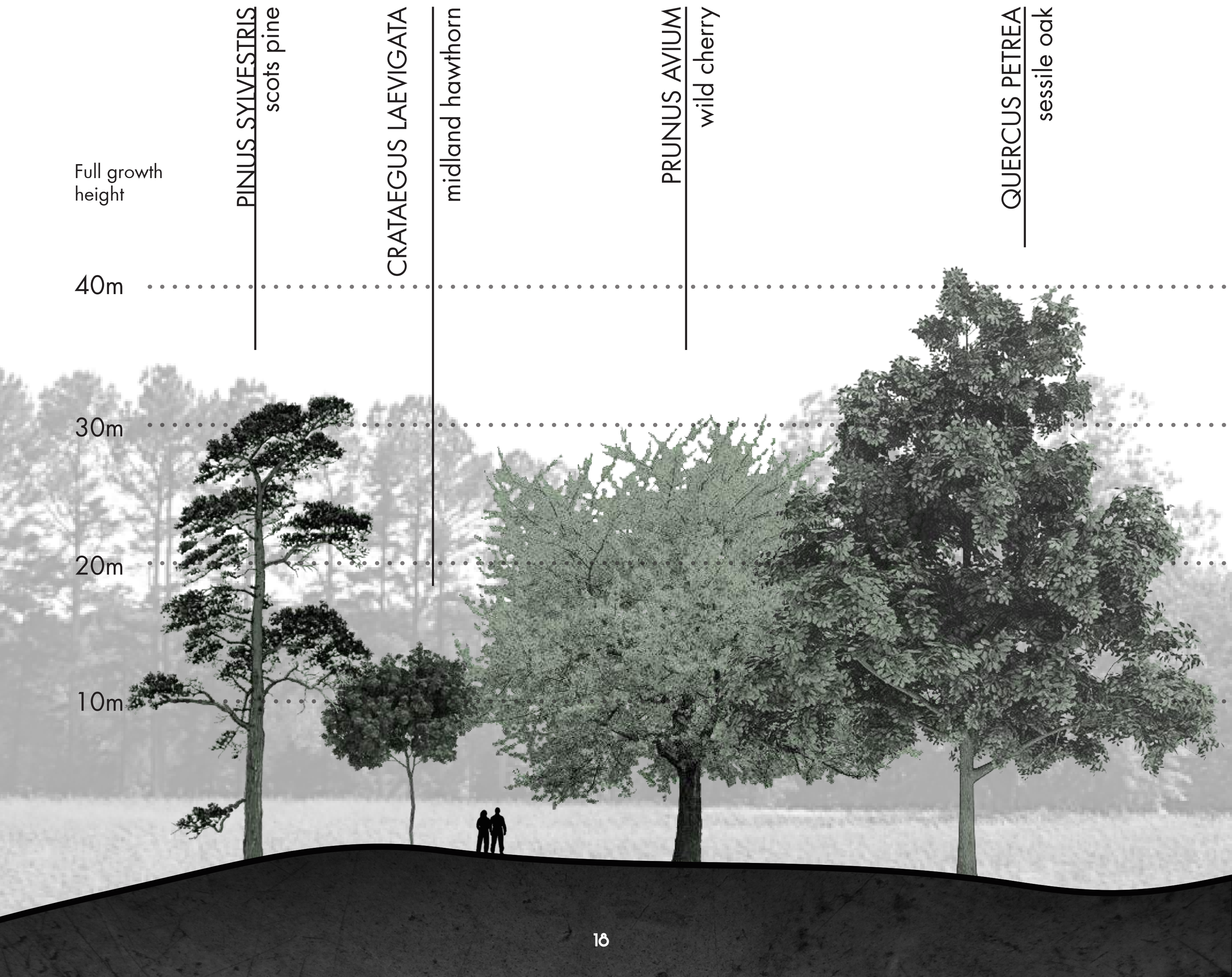
MORE TREES = LESS CO_2

The use of green elements is beneficial to reduce the GHG emissions of a city. Trees remove carbon dioxide from the atmosphere through the photosynthesis and store the carbon in their leaves, branches, stems, bark and roots. Furthermore, the greenery helps to reduce the temperatures and the heat isle effect.
The green area of Godsbanen is expected to contribute to the parks system of Aarhus, that counts three other big parks very close to the city center (ill. 21).



ill. 21: Parks in Aarhus

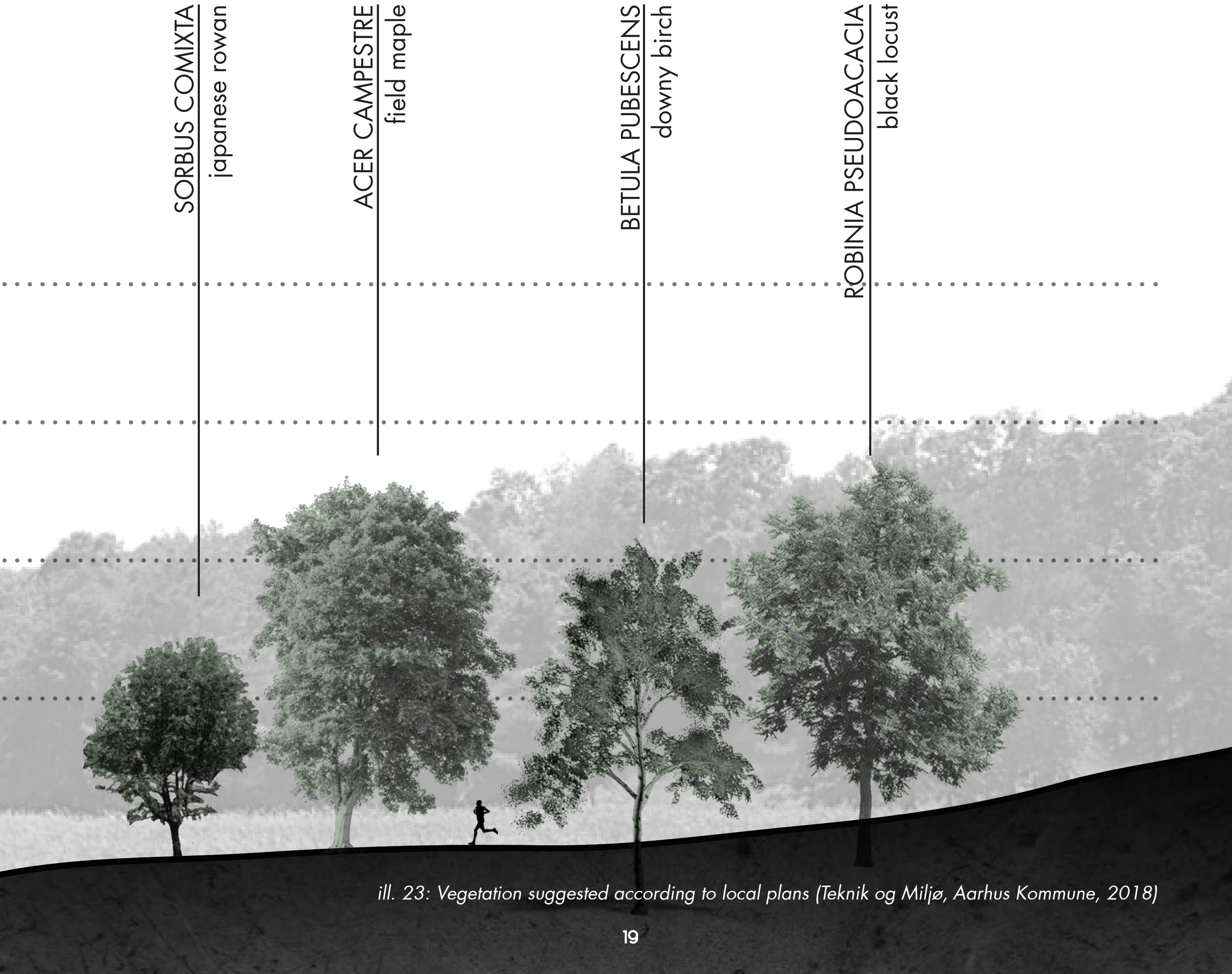
VEGETATION SPECIES



GREENERY IN AARHUS K

Around Godsbanen there are different green areas. One of the most relevant follows the river making a long green stripe that runs through the city. Other green areas are located between the buildings and they can have a public or, for instance in the courtyards, a more private character. More green elements are planned for the landscape design of Godsbanen, where there will be also a huge green event park.

ill. 22: Greenery in Aarhus K



ill. 23: Vegetation suggested according to local plans (Teknik og Miljø, Aarhus Kommune, 2018)

SITE ANALYSIS CONCLUSIONS

The site analysis brought to the following conclusions:

Godsbanen has an industrial and handicraft past that is still defining the character of the area, furthermore the local plans aim to evolve it in a cultural production district. Therefore, both private and public activities are planned to take place.

From the infrastructure analysis it emerged that there are some problems of access to the area due to the presence of the obstacle of the railways on the South and to a limited public transportation connection. This issue is even more critical taking into consideration that the area will be an important public event area.

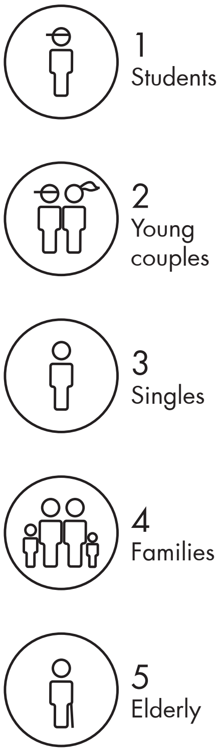
The microclimate analysis has shown that good environmental conditions are available to implement passive sustainability strategies: the area is open and free towards South, therefore solar gain and natural ventilation can be exploited.

Through the use of greenery, as specified in the local plan, the area would be integrated in the overall park system of Aarhus and it would have positive results in terms of CO^2 reduction.

SOCIAL ANALYSIS: LOCAL USERS

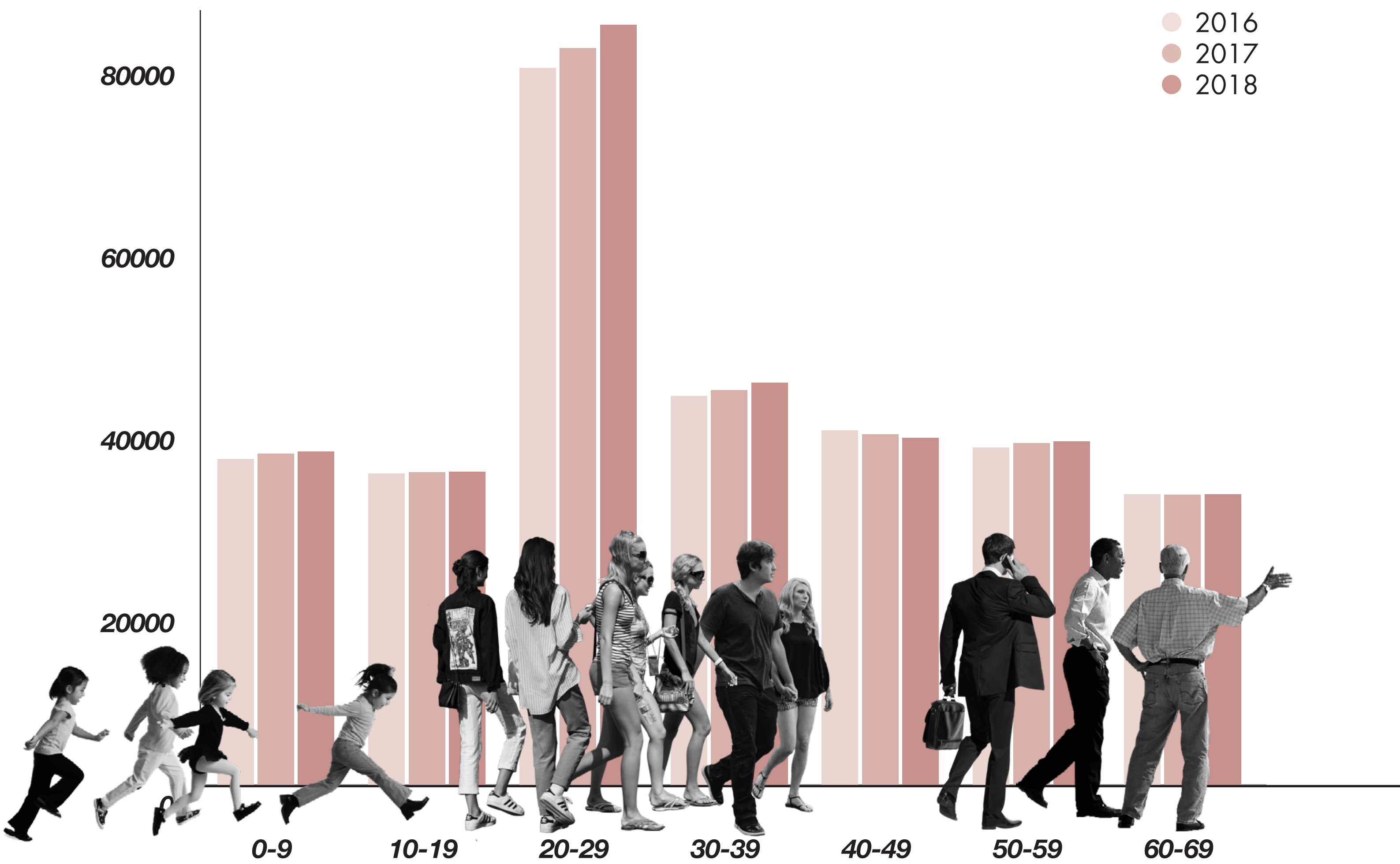
PERMANENT USERS

The new buildings in the district are mostly residential with some commercial/public functions on the ground floor.
Some of the project are currently under construction and will be ended in 2020.
The user groups addressed by those residential developments are wide: students, young singles, young couples and families. The only group that is not widely covered is elderly people.
The dwellings are also meant for low-middle income people (Nybygget ApS, 2019).



ill. 24: Residents distribution in the district

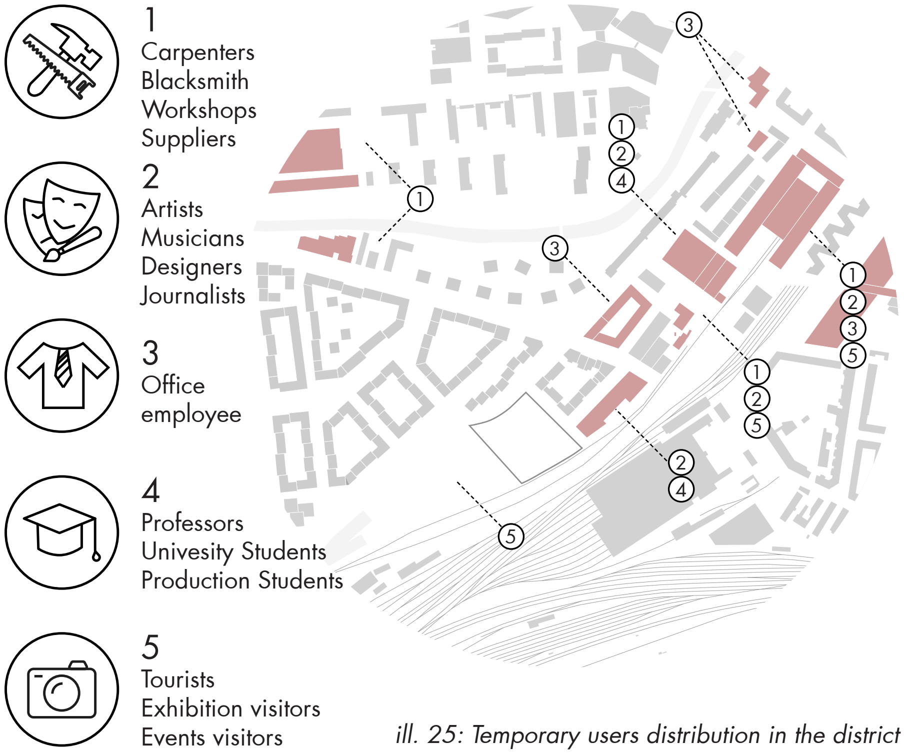
POPULATION IN AARHUS BY AGE GROUP AND SURVEY YEAR



TEMPORARY USERS

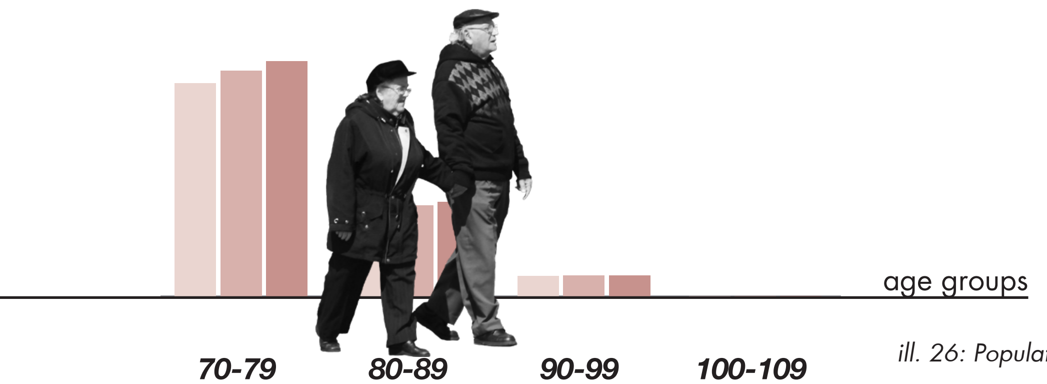
The area's users are dedicated to culture and production:

- Carpenters, blacksmiths and other craftsmen work and organize workshops in the Institut for (X) and in the Godsbanen building. Building material suppliers are located North-West from the area.
- The Godsbanen building is used by people that work in the news field (newspaper writing and printing center) and in the future the new architecture school and the prodiktionsskole will bring more culture-oriented people in the area.
- New offices such as the Lidl headquarters will find room in the volumes in the middle of the area, making it alive in the working time.
- Tourists visit the area in the high season due to his popularity in the city. Tours of the area are organized by the Institut for (X).



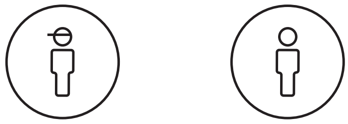
ill. 25: Temporary users distribution in the district

The overall population of Aarhus is 261570 with a density of 2874 people/km^2 (Danmarks Statistik, 2018).
Less than a fifth of the population live outside the municipality boundaries and almost all live in an urban area (Økonomi- og Indenrigsministeriet, 2018). The population of Aarhus is both younger and better-educated than the national average which can be attributed to the high concentration of educational institutions: more than 40% of the population have an academic title. The most present age group, facing a growth trend, is 20- to 29- year-olds and the average age is 37,5: this makes Aarhus the youngest city in the country (Danmarks Statistik, 2019).
This trend is due to the attraction of young people for universities, cultural and social events.



ill. 26: Population distribution by age and year in Aarhus (Danmarks Statistik, 2018)

USER GROUPS



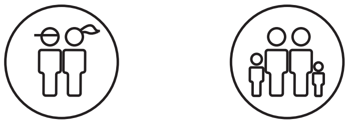
SINGLE YOUNG USERS

The annual population growth in the last 15 years in Aarhus is 0.83% which represents the largest rate in Denmark (OECD, 2016).
The percentage of people over 65 years old is the lowest in Denmark according to OECD and the category 20-29 years old is the largest in Aarhus.
For these reasons it is important to provide new dwellings to young people.
This category includes single, students and young workers, all with different needs and daily schedules, therefore it is essential to ensure a high level of flexibility in the units.

NEEDS

It would be reasonable to consider 25 m^2 for a single student unit considering the average of 23.8 m^2 in Aarhus. The number of square meters can increase until 40 m^2 for a single worker who might want to have more privacy by separating private and common spaces.
Young people general demands consist mainly in common spaces to interact, do sport or any other kinds of free time activity, therefore it is necessary to consider these needs in the project.

ill. 27: User groups



YOUNG COUPLES AND FAMILIES

The National Statistic shows clearly that both couples and families are increasing in number in the last few years. The number of families in Aarhus has increased by 1,9% from 2016 and 2017, and the number of couples has increased by 2,5% (Danmarks Statistik, 2019).

NEEDS

Families and couples necessarily have different needs according to the number and the age of people living in the apartment.
A dwelling for couple can vary from 40 to 70 m^2, meanwhile a family needs much more square meters to ensure the privacy for all the inhabitants. Between 4 and 6 rooms apartments would be suitable for families that have between one and three children.

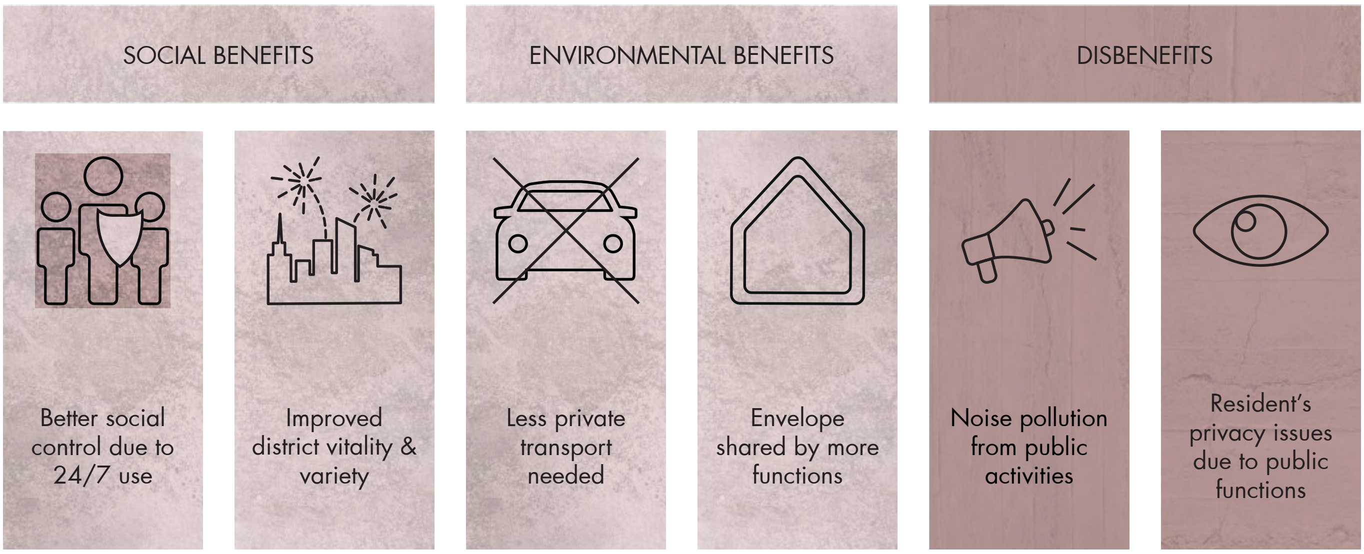
Families and couples probably wish to have common indoor and outdoor areas, even if they don't have the same need of interaction as the single users do. Children need to be provided with outdoor spaces for playing and doing sports.

MIXED-USE

DEFINITION

Mixed use in architecture is the practice of integrating different kinds of functions in the same building or area. The idea behind this solution is to concentrate public and private spaces in small distances from each other in order to provide qualitative and quantitative benefits for LCA and sustainability in general.

Many types of functions can be mixed (dwellings, hotels, offices, shops, restaurants, public facilities, etc.) but to different extents, since some combinations could result in counterproductive solutions, especially due to privacy or functional concerns (Stevenson, 2016).



ill. 28: Benefits and disbenefits of mixed use typologies.

ADVANTAGES AND DISADVANTAGES

The choice of the mixed-use path consequently brings up several advantages and disadvantages. As far as the social benefits are concerned, it is obvious that mixing public, working and living spaces contributes to create a strong communal atmosphere. The presence of facilities generates a self-sufficient "village-like" area that may improve the quality of life, as opposed to vast zones devoted to a single purpose.
The potential of this solution is the chance to create social and stimulating spaces, such as parks and restaurants, which are strongly connected with the private sphere. Furthermore, a sort of "social control" is generated from this kind of spaces, since the 24/7 use makes them continuously occupied.
The possibility to condense the functions in short distances results in a decrease of mobility needs with advantages both in term of GHG emissions and time usage; for instance, the possibility to have the working place and the leisure facilities in the same building or in the same neighbourhood drastically reduces the time that the user "wastes" moving and commuting, with positive results in increasing the free time and consequently decreasing stress.
Environmental benefits in energy consumption terms may be possible considering both the transportation savings and the potential of sharing the consumptions between the different uses (especially when condensed in the same envelope).
On the other hand, issues concerning privacy could come up (acoustic and visual discomfort), especially in case of mixing of dwellings and public facilities. In this case, considerations about people flows and layout should be done, for instance by promoting floor separation (public ground floor, private upper floors) and providing separate accesses.
A similar problem is the risk of mixing functions that can clash among themselves for spatial or usage reasons; acoustic and visual problems should be avoided during the layout design: for instance, a function that requires a certain acoustic comfort (conference room, relaxation spaces...) should not be mixed or placed close to a function that operates with a different noise level (leisure buildings, auditoriums...) (Stevenson, 2016).

SOCIAL ANALYSIS CONCLUSIONS

The local people analysis defines that both permanent and temporary users should be considered in the project. Demographic data and the local plan help with the definition of the permanent user while the study of the temporary users brought to the conclusions that artisans and other local professions should be integrated.

The social analysis has given useful data about the population in Aarhus. From these informations it is possible to see that the site is in a very young city and the demand of dwellings for the young population leads to the decision of the final user group for the project: students, young single users, young couples and families.
The different needs of these groups, both in terms of functions and of square meters, will guide the definition of the spaces.

It is clear that mixed use has important advantages in terms of LCA and sustainability for a complex building. The combination of dwellings and public functions brings to both social and environmental benefits increasing the quality of the project and having positive impact on the overall LCA.

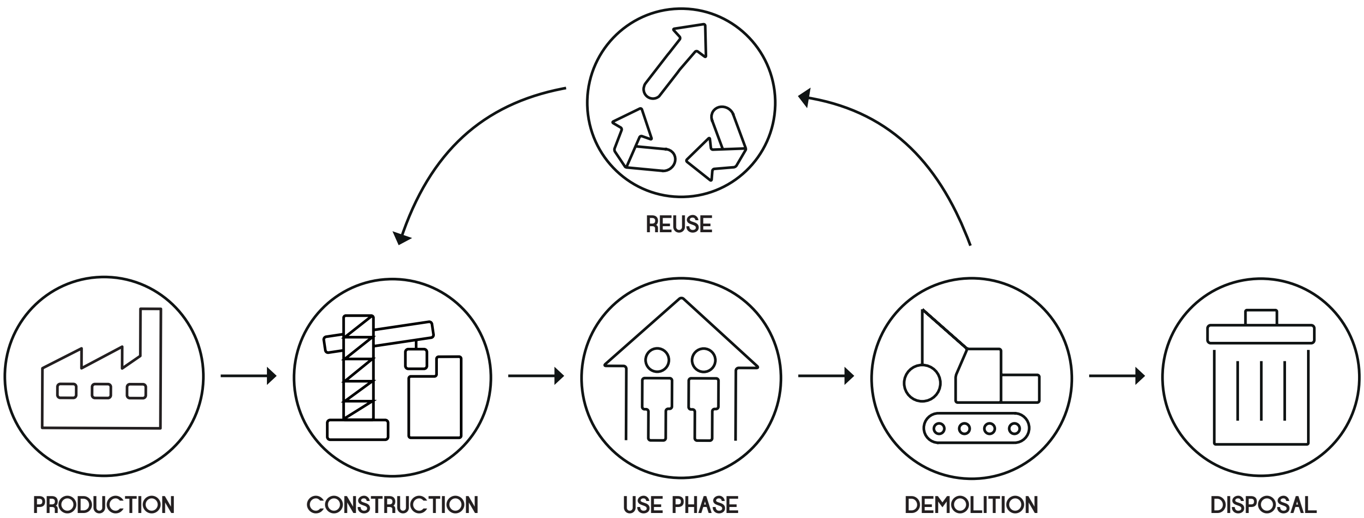
TECHNICAL ANALYSIS: LCA THEORY AND METHODOLOGIES

LCA THEORY

LCA is a method defined by the international standards ISO 14040 and 14044 (International Organization for Standardization, 2016) to analyse environmental aspects and impacts of product systems from the extraction of raw materials to the End-of-life of the date product.
The considered environmental impact include use of resources, human health and ecological consequences.
This method is, for this reason, limited to establish the quantity of the environmental impact, excluding the economic and social factors.
The simplified life cycle of a product is represented by the graph (ill. 29).

STRUCTURE OF LCA

The structure used by ISO consists of 3 phases: Goal and scope definition, Inventory analysis, Impact assessment. All these phases are always dealing with the Interpretation, as an iterative approach is often necessary due to possible changes during the analysis.
The goal needs to be clear and it consists in the objective of the study, the reason why the LCA study is conducted, a definition of the target groups and its eventual public accessibility.
The Inventory analysis it's defined by the ISO standard 14040:2006 as "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its entire life cycle" (International Organization for Standardization, 2016).
This analysis is followed by the second phase of life cycle assessment, called "Impact Assessment", necessary to calculate the potential environmental impacts related to an examined product system. (Hollberg, 2016)



ill. 29: LCA simplified diagram

WHY IS LCA NECESSARY IN THE BUILDING SECTOR?

The energy demand of buildings during their life cycle can be split in two types: the operational and the embodied energy.
The focus in the last years has always been to reduce the operational energy in the use phase, and this has caused an increase of the ratio between operational and embodied energy.
Considering that more and more nearly zero-energy buildings are going to be built, and these are defined as buildings that produce almost the same amount of energy that they consume during a year, the embodied energy is bound to increase until covering almost the total energy demand of buildings.
This examination brings out the need of moving this focus to the energy in the production, construction and end life phase, as to minimize it.
(Hollberg, 2016)

WHERE AND WHEN TO APPLY IT?

The application of LCA in the building sector appears to be a quite hard subject, considering the complexity of the building components, the very long-life span, the current and continuous flexibility in the change of use. The architectural design process makes also the application of LCA even more difficult, as it consists on many stages that, often, don't follow a timing.
It is important to underline that the first stages of the design process are the ones that affect most the energy demand of the project, as the choices taken during these phases are crucial in terms of sustainability. Another crucial parameter that affects the energy demand of the building is the life span of it.
According to some researches considering the typical normalization of results in an annual basis is not enough to address the objective of LCA. Analysing typical construction solutions with different life spans (between 50 and 120 years) it is demonstrated that their energetic impact decreases as their life increases, mainly due to the division of the energy over a bigger amount of time. (Marsh, 2016)

HOW TO APPLY IT?

LCA is not a broadly diffuse method used in the design process as it is considered complex and it takes time to be understood and applied.
Parametrizing this method, the expectation is to achieve a simplified and optimized system that makes LCA easily accessible to the designer from the early stages of the design process.
LCA software programs started to be developed in the last 10 years and they have different characteristics according to their generation. The first ones are based on spreadsheet and require more experience than the second-generation ones, that are based on 3D CAD models.
These programs are: LIxcel, Rb-tool, PLCA-tool, CAALA and LCAbyg. (Hollberg, 2017)

POTENTIAL EFFECTS INDICATORS

During their life cycle, buildings generate emissions in the air, water or soil causing environmental issues as global warming or summer smog and these damages can be measured using indicator substances (Green Building Council Denmark, 2014). These indicators refer to a building, therefore the units are considered divided by the area and the time (/m^2/year). The benchmark values are taken from the German DGNB's reference values for construction being them more updated and strict than the Danish version (German Sustainable Building Council, 2018, table 4, p.67).

GREEN HOUSE EFFECT / GLOBAL WARMING POTENTIAL

in kg CO_2-Eq/m^2/year (max: 5,17 kg CO_2-Eq/m^2/year)

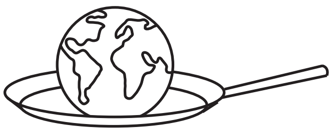
The green house effect or global warming potential is measured in CO_2-Equivalent that express the impact on global worming of a green house gas relative to the same quantity of CO_2. This value normally refers to a 100 years period, as greenhouse gases (GHG) stay in the atmosphere for varying amounts of time. This allows to sum the contributes of different GHG.

1kg CH_4 = 25kg CO_2

1kg N_2O = 298kg CO_2

1kg HFC-23 = 14.800kg CO_2

ill. 30: GWP of materials



ill. 31: Global warming

OZONE DEPLETION POTENTIAL

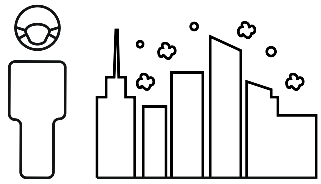
in µg R11-Eq/m^2/year (max: 292 µg R11-Eq/m^2/year)

The Ozone Depletion Potential of a substance indicates the potential of destruction of the ozone layer in comparison to the chlorofluorocarbon (CFC-11).
The ozone layer helps to protect the earth from the sun's UVA and UVB radiation that could potentially cause overheating, but it is threatened by halocarbon compounds that are harming it.

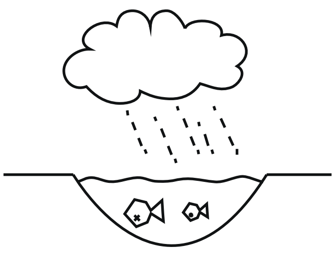
PHOTOCHEMICAL OZONE (SMOG)

in g C_2H_4-Eq/m^2/year (max: 2,31 g C_2H_4-Eq/m^2/year)

"The Photochemical Ozone Creation Potential designates the equivalent of harmful trace gases by reference to their mass"
(DGNB, 2014).



ill. 32: Ozone concentrations



ill. 33: Acid rain effect

ACIDIFICATION

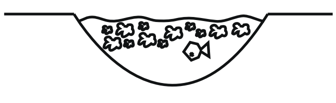
in g SO_2-Eq/m^2/year (max: 20,4 g SO_2-Eq/m^2/year)

The acid potential quantifies the effect of acidifying emissions such as sulphur and nitrogen. This compounds react with water in the air causing "acid rain" that contaminate the soil and damages animals, plants and buildings as well.

NUTRIENT STRESS

in g PO_4^{3-}-Eq/m^2/year (max: 2,6 g PO_4^{3-}-Eq/m^2/year)

The nutrient stress or eutrophication potential indicates phosphorus and nitrogen compounds' pollution caused by the manufacture of building products and the extraction of combustion emissions. It causes an increase of nutrient content in bodies of water and soils and this can lead for instance to the acceleration of algae's growth and to fish dying.



ill. 34: Water contamination

LCA TOOLS FOR ARCHITECTURE

Nowadays different tools for LCA calculations are available. LCA tools are generally meant to be used for documentation, but the recent application of this method to the building industry raised the need for tools that can be used already from the early design stage.

Lixcel

Developed in the early 2000s, it consists of three spreadsheets (results, entry format and life span of building materials).
These excel-based spreadsheets were generally calculating the embodied energy and the embodied global warming of one kg or m^2 of material according to variable parameters as the life span of materials or the depth.
The system was too complex and time- consuming, therefore it was abandoned after few years.

PLCA-tool

This tool runs with Grasshopper, which is directly connected to the 3D Rhino model.
The main difference with the other tools is that it combines embodied and operational energy in one calculation.
The results are clearly visible in Rhino thanks to different colours that represent different energy use in each part of the building.

CAALA

It combines the calculation of operational and embodied energy as Rb-tool, expect for that is a plug-in for SketchUp.
This tool has a simplified monthly quasi-steady approach.

Rb-tool

This tool is a plug-in for Autodesk Revit that calculates the embodied energy and embodied global warming potential of building elements. It also determines the possible reuse and recycling of the building element. The production energy value is taken from Ökobau. dat (2014) and it is further connected to the energy of the use phase.
It is considered as one of the easiest tool thanks to the connection with Revit that makes it comprehensible for students and the immediate graphical result that provides result in real-time.

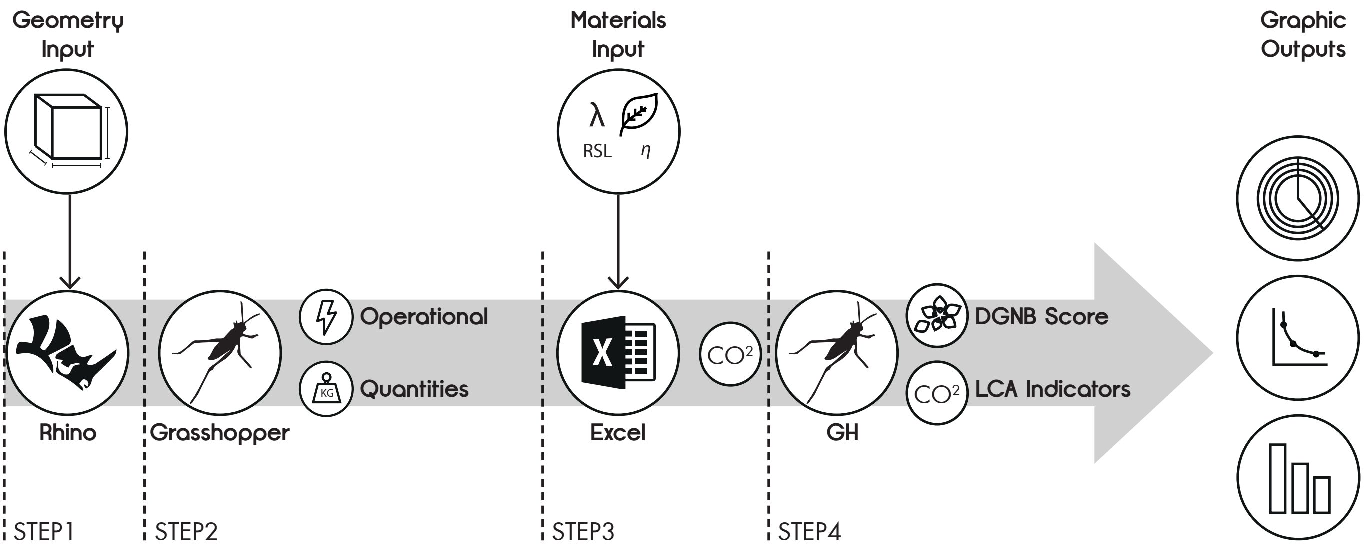
LCAbyg

LCAbyg is a Danish digital tool developed by the National Building Research Institute, Aalborg University and the Danish Transport, Construction and housing Authority, that can be used to calculate the building overall environmental profile and resource consumption.
The inputs are the informations about the building parts and the building energy consumption and the tool automatically calculates the LCA and collects the results in a report.
This tool can be used in the early design stages but, since it is not linked to a parametric model, the geometry must be inserted manually.

LCA TOOL DESCRIPTION

PARAMETRIC TOOL

The tool that will be used in the project has been provided by C.F. Møller architects, where it is currently under development by the sustainability department.
The tool is parametric and based on grasshopper and works as shown in the picture below (ill. 35).
The LCA indicators are calculated by multiplying the material quantities by the unit values, that are defined in an external excel file, and then brought back in grasshopper to generate user friendly outputs.
The results are then used to calculate the LCA performance according to the DGNB-DK standard
The tool is meant for internal use and therefore simple input and output definitions have been designed.



ill. 35: Parametric work flow

PARAMETRIC WORKFLOW

STEP1
The geometry is defined by using Rhino/Grasshopper: the only inputs needed are two solids, one for the building and one for the roof (if not flat).

STEP2
The grasshopper definition automatically defines the needed building components in a simplified way:
- External walls and roof are automatically defined from the model input.
- The floors are defined by the definition through a storey height parameter. The original volume is automatically divided in storeys. The height parameter is editable
- Windows are defined by % of glazed surface on the overall outer walls. This parameter is editable.
- Internal bearing walls are defined by dividing the internal space by a grid. The amount of structural element can then be reduced by adjusting a % parameter. Both the grid and the % are editable parameters.
- The basement is automatically generated by using the ground floor surface. The structure of the basement can be defined in a similar way as done with the internal walls.
The total area of each component and an approximated operational energy are defined and exported to an excel file.

STEP3
The inputs are automatically inserted in a specific excel file where the building components are already sorted. Here is possible to define the materials (and therefore the thickness) of each component. A linked LCA database allow a fast calculation of all the indicators needed.
The results are then exported back to grasshopper to turn them in user friendly interfaces.

STEP4
The overall LCA indicators and the GWP of each building component are used in the grasshopper definition to calculate the DGNB weighted score.
These data are then used to generate easily readable data.

ADVANTAGES AND LIMITS OF THE TOOL

Being the tool still under development, one of the thesis purposes has been to give feedback on its potential and limits in the early design stage:

ADVANTAGES

- Being the geometry input based on a model instead of on manually inserted quantities, the tool is optimal for early design stages when the uncertainties are high and the geometries change quickly.
- The automatically generated building components allow to focus on limited design parameters without ignoring the others.
- Being the tool based on grasshopper it is very easy to edit the definition when different or more detailed input are needed. This result in a very high flexibility and adaptability of the tool which is usually not available in tools not based on grasshopper.
- The tool gives easily readable outputs and automatically compare them with benchmarks from DGNB. Furthermore, it automatically calculates the DGNB weighted score allowing an easy comparison between the different iterations.

LIMITS

- The tool doesn't allow to simulate complex shapes due to the way the grasshopper definition generates the building components. This limits the possible iterations and doesn't allow nonrectangular shapes to be investigated unless local adjustments to the definition are done (which make the process slower and not iterative). The simplification of a complex shape in rectangular one does not work either since the definition does not recognize the intersecting surfaces as internal walls.
- The need to export data in excel "break" the otherwise linear grasshopper workflow. This result in the impossibility to have an LCA result immediately after changing the input geometry. A tool that works completely in grasshopper would allow even faster feedback, improving the early design stage.
- Even though the tool relies on a wide material database few options of components thickness are available, limiting the possibility of precision when moving from early to late design stages
- The approximations of the structure turned out to be hard to predict being them based on a simplified calculation.

CONCLUSIONS

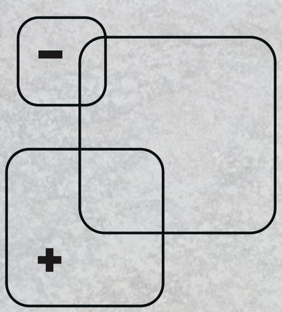
The improvement of the geometry input limitations combined with the switch to a completely parametric workflow would allow the tool to be used in both early and late design stages.

Due to the limitations listed above, the tool will be used in the early design stage on abstract simple volumes to investigate the LCA response when changing specific geometric and structural parameters.
Since the tools is meant only for the early design stages it will not be used for the final documentation. The investigations will aim to investigate the trend in the DGNB score when changing a parameter rather than the score amount itself.
In fact, the aim of the design process is to understand which strategies generally improve the LCA of a building and not so much to understand the extent of it, being the available tools not precise enough to give secure numeric outputs.

SUSTAINABILITY STRATEGIES

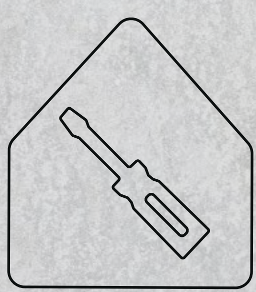
Since not all the phases of the design process can be developed in a thorough way, an overview of design strategies that generates benefits in a sustainability perspective and have a direct or indirect positive effect on the LCA has been done.
These strategies cover both design, user and management actions and are proved to generate a reduction of GHG emission or material use/ waste, possibilities of circular economy or extension of the life span. (GXN team, TU Delft & City of Amsterdam, 2018).

LESS CO_2 | LESS MATERIAL USE / WASTE | CIRCULAR ECONOMY | EXTENSION OF LIFE SPAN



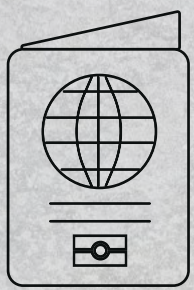
FLEXIBLE INTERIORS

Flexible and adaptable spaces have the potential for different uses, longer lifetime and less resource waste.



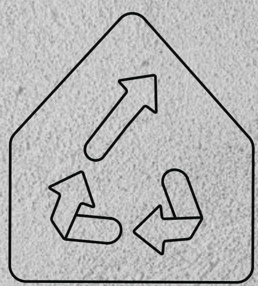
DESIGN FOR DISASSEMBLY

Flexible and dry joints between elements allow for easy assembly and disassembly.



MATERIAL PASSPORT

Contains information such as defined content and intended period of material use, disassembly, restoration and reuse, and quality assurance and approvals.

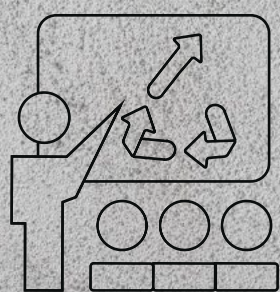


SHARING/REUSE CENTER

A place to engage in sharing and reuse of materials and goods that would otherwise be discarded.

UPCYCLING WORKSHOPS

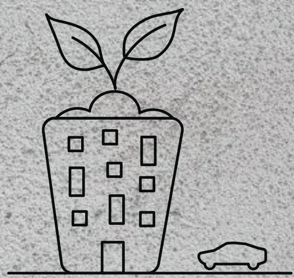
Public workshops allow communities to create their own contributions to the circular public space.



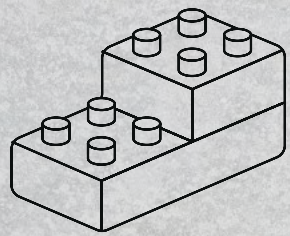
ill. 36: LCA and sustainability strategies

URBAN FARMING

Community involvement and socialising while growing herbs and vegetables in a green and stimulating landscape.



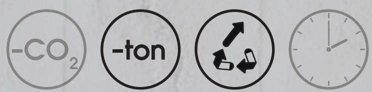
PREFABRICATION & MODULARITY

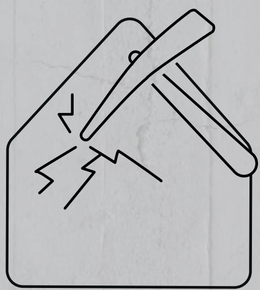


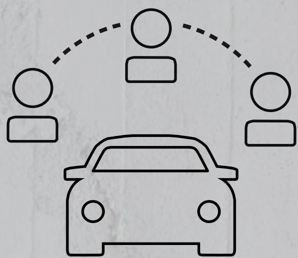
Prefabricated modular elements that are designed for disassembly allow building flexibility and greater material reuse.

URBAN MINING

Future building materials can be found directly in the urban fabric, as more buildings are designed for disassembly the potential grows.





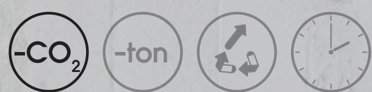


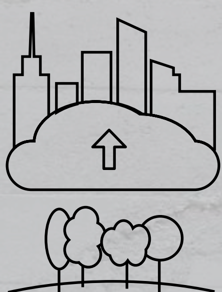
CAR SHARING FACILITIES

To decrease dependence on cars, share resources, alleviate congestion, and ultimately reduce harmful emissions.

SUSTAINABLE DRAINAGE SYSTEM

Constructed landscapes to slow and filter storm water runoff decreases the return of pollutants into the environment.





RAISED INFRASTRUCTURE

Raising whole or parts of infrastructure and buildings ensure integration of local ecosystems through green and blue corridors.

CASE STUDIES LCA

AMSTERDAM, 2014

CIRCL PAVILION

This pavilion has a structure designed for disassembly. Wooden window frames have been cut into floor boards, tiled floors are made from reused concrete. Insulation is made from old jeans of employees of the bank. All the materials have been recorded in a material passport.
It also uses direct current instead of alternating current to minimise the loss of energy during the conversion. Social sustainable strategies are also implemented, as employees wearing uniforms produced from recycle plastic. (GXN Team, 2018)

ill. 37: Circl Pavilion

AMSTERDAM, 2017

BUIKSLOTERHAM

Converting from an industrial site into a sustainable district, it's an urban development based on circular principles.
Houses are going to be built with sustainable materials as ceramic bricks and wooden floors with a concrete topping and using passive strategies to reduce the energy consumption, as natural ventilation and photovoltaic cell for the energy production. (GXN Team, 2018)

ill. 38: Buiksloterham

AMSTERDAM, 2017

PARK 20|20

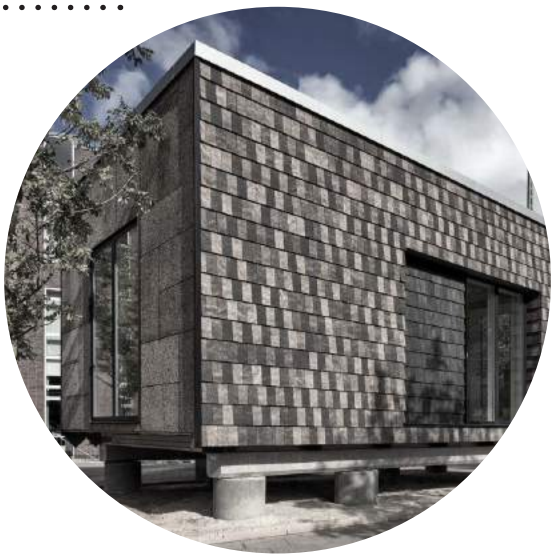
It is a masterplan project that includes environmental and social sustainability principles as the materials' reuse and the optimization of working environment.
The focus is to create a healthy and productive working environment to increase the productivity of employees.
The key strategy is to provide flexible working spaces in terms of life span and composition.
The buildings are connected to the grey water purification system and the roofs are provided with photovoltaic cells for the energy needs.
(GXN Team, 2018)

ill. 39: Park 20|20

COPENHAGEN, 2018

THE CIRCLE HOUSE

It is a demonstration project made by 3XN to show the principles of sustainable circular solutions.
This Demonstrator has been designed to disassembly as the 90 % of all materials must be reused at a high value. It is made of burnt reclaimed wood, cork panels with visible joints, upcycled plastic shingles. The project is going to be built in the "Lisbjerg Bakke" in Aarhus using three typologies: two and three storey terraced houses and five-storey towers. The superstructure is going to be the same for the three of them and made of 6 concrete elements. (GXN Team, 2018)



ill. 40: The Circle House

LONDON, 2018

BLOOMBERG'S NEW EUROPEAN HEADQUARTERS

Situated in the City of London it consists on a mixed-use building that hosts cafés, restaurants, public art and offices.
It includes a water-saving vacuum drainage system and an on-site Combined Heat and Power generation centre as to lower environmental and cost impacts. (OneclickLCA, 2018)

ill. 41: Bloomberg's headquarters

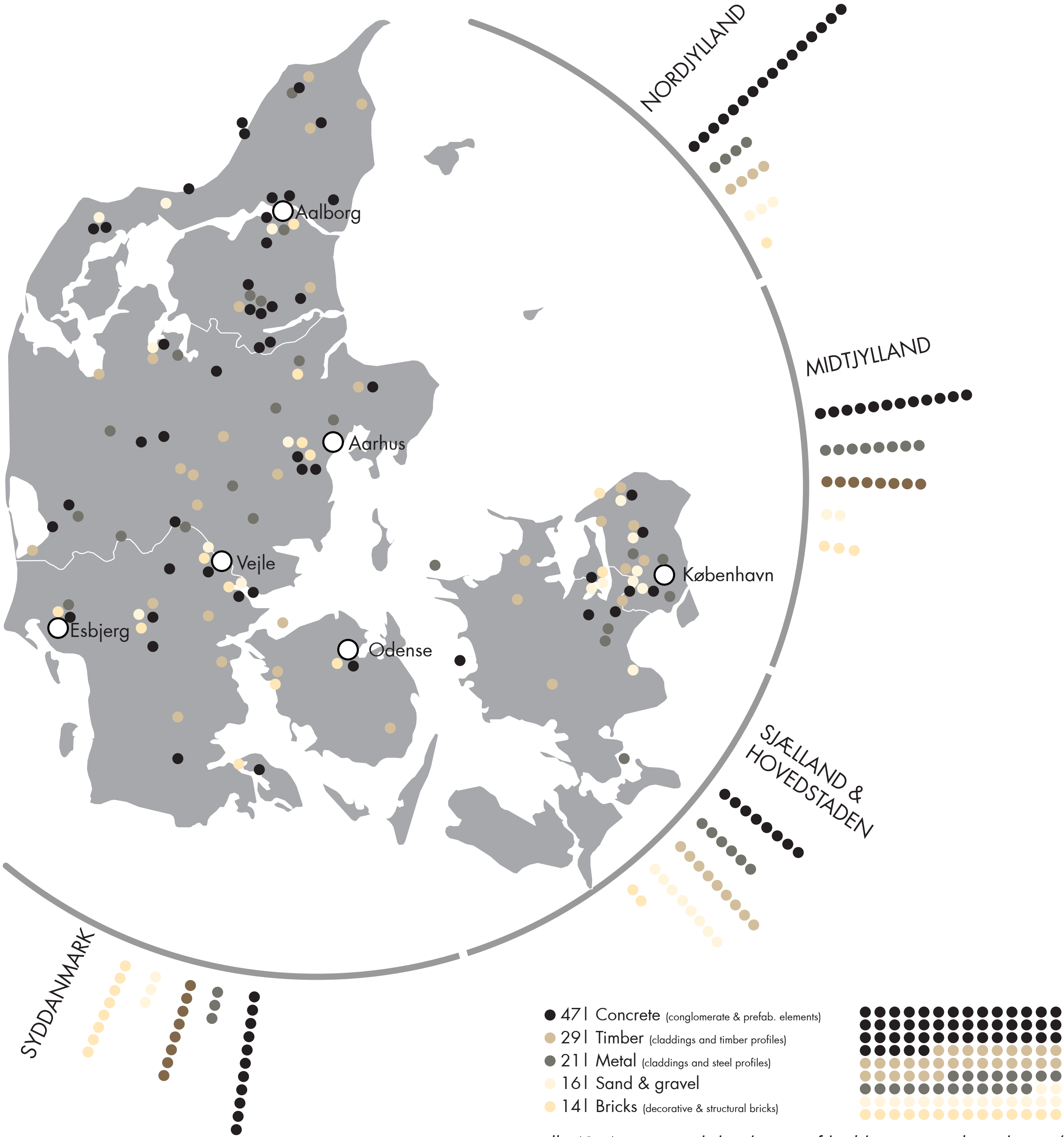
AMSTERDAM, 2015

DE CEUVEL

It is a sustainable park and office park that is going to be used as example of circular economy approach and of cleaning of polluted soil.
Some soil-cleaning plants are creating a unique landscape with the wooden walkway.
It hosts public workspaces for creative purposes, creating an alternative space in the service of the citizens. (GXN Team, 2018)

ill. 42: The Ceuvel

BUILDING MATERIALS



ill. 43: Amount and distribution of building material producers/ suppliers in Denmark (Nordiske Medier A/S, 2019).

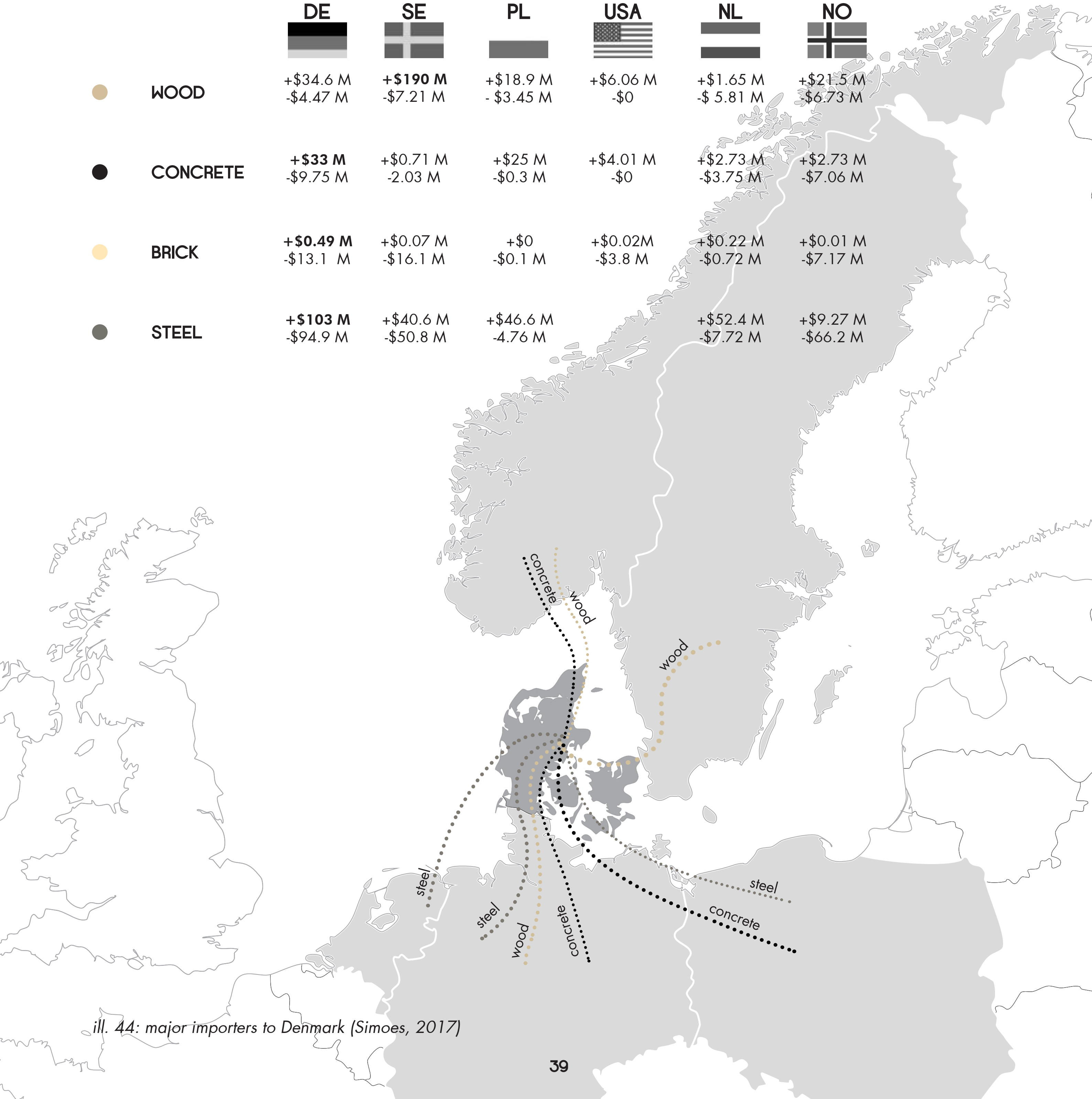
BUILDING MATERIALS IN DENMARK

Denmark building sector is dominated by concrete producers that affect the way new buildings are designed.
Prefabricated concrete elements are widely used in the new buildings in Aarhus together with bricks cladding.
Concrete producers and suppliers (both conglomerate and prefabricated building elements) represent the 37% of the total building materials main suppliers surveyed, with a higher concentration in the Jutland peninsula.
A good amount of wood producers is also available, but they are mainly for flooring/cladding materials and only a few are dedicated to the production of timber structural profiles. Metal elements are the third more relevant products, equally divided between structural profiles and claddings (Nordiske Medier A/S, 2019).

BUILDINGS MATERIALS OUTSIDE DENMARK

According to the statistics (Simoes, 2017) the major exporter of wood to Denmark is Sweden, which covers the 50% of the total Danish wood import. The rest of construction materials is mostly imported from Germany, the country that generally deals most with Denmark. It is the first for concrete and steel Danish imports.
Poland is also an important partner, as it is the fourth wood provider, the second for concrete and the fourth for steel.
The import/export studies reveal that most of the brick is local as Denmark exports it for a value of $ 46.3 M, and only a few percentage is imported from Germany, Netherlands and USA ($ 811 K in total). On the other hand, clay used for bricks is mostly imported from Germany ($ 5.05 M).

	DE	SE	PL	USA	NL	NO
WOOD	+$34.6 M -$4.47 M	**+$190 M** -$7.21 M	+$18.9 M - $3.45 M	+$6.06 M -$0	+$1.65 M -$ 5.81 M	+$21.5 M -$6.73 M
CONCRETE	**+$33 M** -$9.75 M	+$0.71 M -2.03 M	+$25 M -$0.3 M	+$4.01 M -$0	+$2.73 M -$3.75 M	+$2.73 M -$7.06 M
BRICK	**+$0.49 M** -$13.1 M	+$0.07 M -$16.1 M	+$0 -$0.1 M	+$0.02M -$3.8 M	+$0.22 M -$0.72 M	+$0.01 M -$7.17 M
STEEL	**+$103 M** -$94.9 M	+$40.6 M -$50.8 M	+$46.6 M -4.76 M		+$52.4 M -$7.72 M	+$9.27 M -$66.2 M

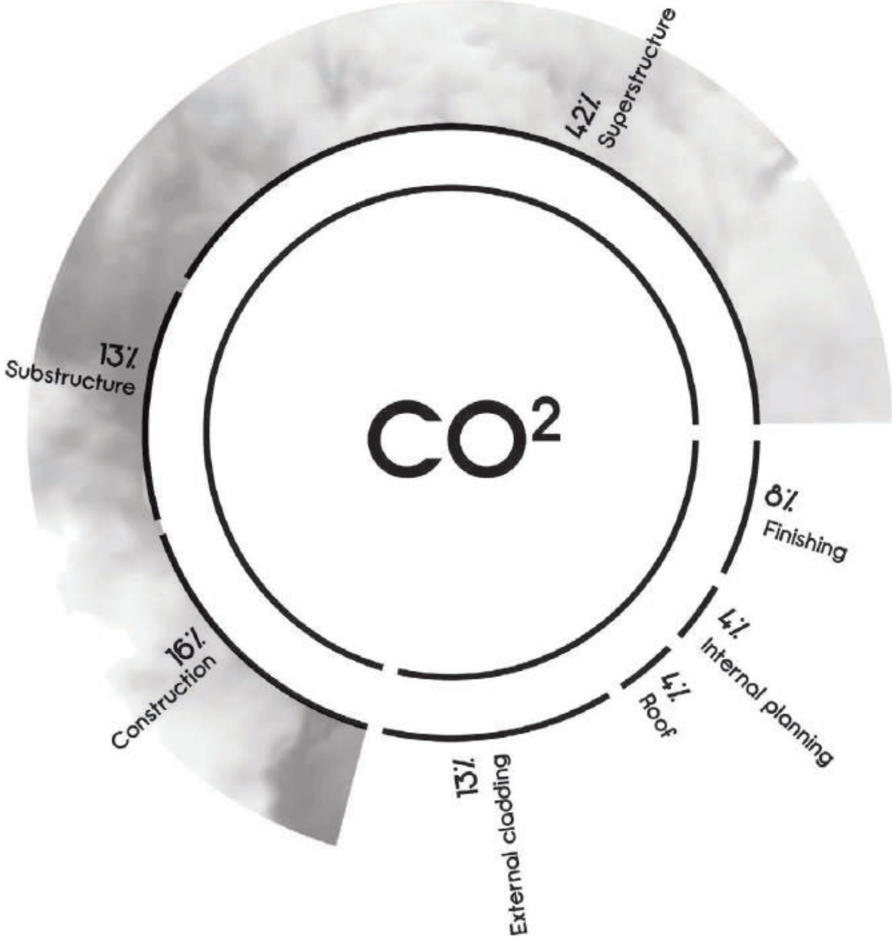


ill. 44: major importers to Denmark (Simoes, 2017)

LCA AND STRUCTURE

WHY IS THE STRUCTURE WORTH A RESEARCH?

The structural part of the building affects strongly the environmental impact of the project: 71% of the embodied energy of a non-residential building is related to the structure and construction, with a 55% concentration in the superstructure and substructure (Kaethner & Burridge, 2012).
Therefore, in an embodied energy reduction perspective, knowledge-based design of the structural system is worth to be made.



ill. 45: Embodied energy distribution in non-residential buildings

TIMBER VS CONCRETE

The construction industry in Denmark uses mostly prefabricated concrete structure due to the relevant presence of concrete suppliers in the country: most of the projects that are currently under construction in Aarhus, both in Aarhus Ø and in Godsbanen, use a reinforced concrete structure.

This trend has been kept during the last years even though researches that compares the environmental impact of concrete and timber structures show better results for the latter: timber structures are found to cause a climate change impact that is 34-84 % lower than the reinforced concrete structures.

Therefore, constructing timber structures can result in avoided GHG emissions, indicated by a negative climate change impact. Compared to the reinforced concrete structures, this equal savings greater than 100 % (Skullestad et al., 2016).
This environmental paradox is caused by several reasons:

- The strong presence of prefabricated concrete industry in the Danish construction sector.
- The low experience of building timber structures in the Danish context.
- The strict legislation that affects high rise buildings.

Among these reasons the legislations, in the specific the fire regulation, are the bigger obstacles to the research and application of timber structures.

THE LIMITS OF THE FIRE LEGISLATION

Beside the standard provisions such as the requirement for a safe escape route and the accessibility for firemen vehicles, the Danish building regulation set some specific fire safety principles regarding the structure:

- The materials, building parts, structures and installations used must be fire-resistant in relation to their location and use.
- Structures need to have enough load bearing capacity in case of fire.

The fire regulation becomes even more strict for specific categories of buildings such as for facilities with sleeping spaces (dwellings, hotels, …) and with more than two storeys above ground: this situation is defined as the maximum fire risk category (Trafik-, Bygge- og Boligstyrelsen, 2018)

This extreme classification brought architects either to avoid timber structures in high rise building or to cover the structural part with materials, such as plaster, that eventually generate a bad impact on the LCA.

From a comparison of the actual building regulations in the EU emerged that:

"Despite of the existence in the European Union of the Construction Products Regulation and the development of Eurocodes, there is a broad variety of criteria and requirements for buildings in the various European countries because fire safety in buildings is governed by national legislation. These national legislations are based on historical experience and quite often on prejudice about the use of bio-based building products in the absence of scientific knowledge on the fire safety of these products" (Mikkola, 2017).

Recently the fire regulation has been contested by architects in the UK due to the excessive strictness on CLT structures: "Engineered timber products such as cross-laminated timber must be exempt from the UK government's ban on combustible cladding materials, as they are essential in the global battle against climate change" (Frearson, 2018).

ill. 46:
Max height of timber bearing structure according to national fire safety legislation (Mikkola, 2017)

AESTHETIC QUALITIES OF TIMBER

To fully exploit the architectural potential of timber case studies have been researched.
The choice of exposing wood, as structure or as cladding, open up to several aesthetic possibilities.
Externally wood is used mainly as cladding to define the character of a building; exposing the structure would result in maintenance problems and therefore it is not very common.
Internally the structure can be exposed completely or partially and helps to create a warm atmosphere and other perceptive benefits.

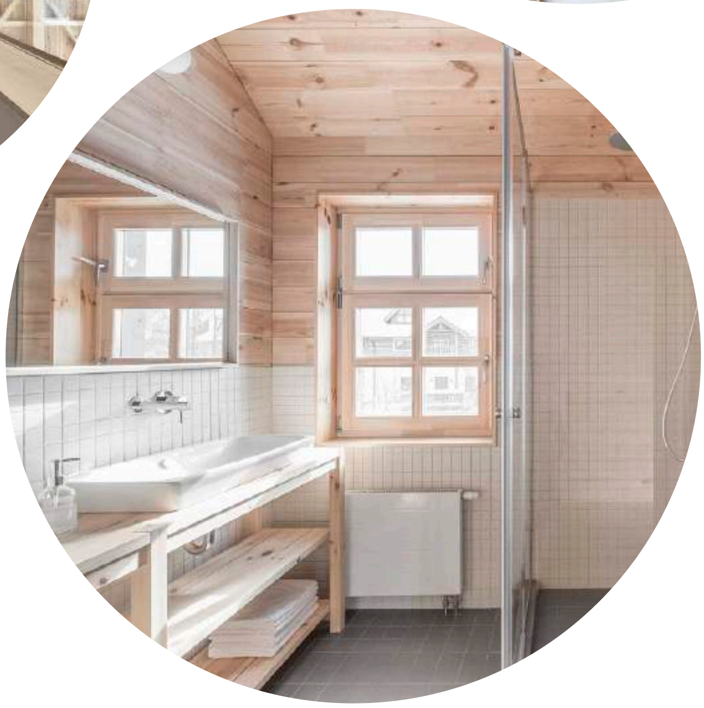
EXTERNAL QUALITIES

The use of wood on the external surfaces helps to transmit a warm and natural character. The aesthetic is also affected by the patina given by the capacity of wood to respond to the atmospheric and meteorological conditions.
Combinations of different textures and colours can result in interesting and modern aesthetics.

ill. 47, 48, 49: Dwellings in Västerås, Haraldsplass Hospital (C.F. Møller), Lisbjerg Bakke (Vandkunsten) *ill. 50, 51: Wooden house in Amsterdam(MAATworks), House H (Hirvilammi Arch.).*

INTERNAL QUALITIES

In indoor spaces exposing wood can produce benefits for perception and comfort.
The tendency of people to prefer wooden pieces of furniture or surfaces in their home when there is the possibility may be motivated by the improved health and well-being caused by natural materials (Bakker et al., 2017).
Furthermore, the colours and texture of wood transmit the sensation of 'warmth', 'comfort' and 'relaxation' in people (Rice et al., 2006).



... AND DANGERS

Apart from the fire concerns, exposing wood can result in a bad solution if the maintenance problems are neglected. For instance water resistant claddings or other are not avoidable on surfaces close to water and humidity sources such as sinks and showers.

ill. 52, 53: Freiland-Hof home (EGGER), Tarusa house (PROJECT905),

STRUCTURAL CASE STUDIES

ill. 54, 55: UBC Brock Commons

UBC BROCK COMMONS

It consists on a student residence building of 17 stories in wood over a concrete floor. It was a demonstration project to show that working with wood reduces timelines for construction and can generate mid-rise/ high-rise buildings. Lateral and vertical stability is achieved thanks to the combination of concrete cores and prefabricated steel elements that cooperates with the timber frame.
The construction based on glulam columns and CLT panels has been prefabricated off-site and assembled in site.
Both the materials and the construction methodology are sustainable, as the energy used during the fabrication and the installation lowers carbon footprint (Archdaily, 2016).

MURRAY GROVE

It is the first tall building entirely constructed by pre-fabricated solid timber, from the bearing walls to the elevator core. It consists on a nine-storey tower built with structural panels disposed in different locations on each floor and a timber core that ensure the stability of the structure. The material use is optimized thanks to the placement of bigger units on the first floors and smaller on the upper floors.
It has also been planned to be flexible, as internal walls can be removed without influencing the stability of units above and below.
The walls consist on spruce strips glued together crosswise and in three layers (Architectmagazine, 2009).

ill. 56, 57: Murray Grove

ill. 58, 59: Esmarchstrasse

ESMARCHSTRASSE

It is a high-quality timber building located in Berlin.
The architects obtained the permit to build over the 13 meters high for Berlin's timber construction rules, reaching the seven-storey structure.
For the first time the glued laminated timber has been exposed.
The reinforced concrete stairway has been set apart from the building as to achieve the fire protection requirements and to allow an individual apartment layout required by the clients.
The bearing structure is concentrated on the facade plane as to let the apartments' layout free and allow flexibility in the internal composition (Wooddays, 2008).

TECHNICAL ANALYSIS CONCLUSIONS

Life Cycle Assessment integration in the design phase is a topic under development nowadays in the sustainable architecture field.
This thesis will therefore focus on this topic by using one of the parametric tools already available and provided by C.F. Møller, since they are more effective and they give the possibility to make more and faster design iterations. These tools give the possibility to evaluate all the indicators, but the main focus will be on the Global Worming Potential (GWP) since it is the most important one (it accounts for the 40% of the DGNB LCA evaluation). The different iteration results will be compared and 5,2 kg CO_2-Eq/m^2/year will be used as evaluation benchmark. (German Sustainable Building Council, 2018). The reference life span period is set to 100 years. Furthermore, the DGNB weighted score will be used during the process and the final documentation with the goal to achieve 100% score.

Different LCA strategies for architecture will be implemented in the project with the priority for prefabrication, modularity, interiors flexibility and design for disassembly.

Through the study of construction materials, it was possible to have an overview on which materials are used the most in the Danish building industry and on where they come from. Part of the materials are produced locally but the majority is imported from abroad (Sweden is, for example, the main wood provider). Concrete, even if it is not the most sustainable material, turned out to be the most used construction material in Denmark.

The focus of the thesis investigation on structural iterations is justified by the fact that 71% of embodied energy is related to structure and construction; different timber structures are tested over concrete and steel ones due to their better performance regarding the LCA.

Therefore, the project will challenge the current Danish fire regulation in order to come up with a proposal that better perform environmentally. Different typologies of timber structure with or without cladding material will be tested in order to achieve those benefits.

PROCESS

PROJECT PROGRAM

VISION

The aim is to create a building that expresses the Life Cycle Assessment and timber construction potentials and reflects the urban character of the area. The LCA investigations will be translated on a study of a possible reduction of the material use and the recycle of it at the end of the building's life. This will be done with a disassembly timber structure that will be exposed as much as possible considering to question the Danish fire regulation, so that its appearance will clearly reflect its sustainable nature. The project should also be physically and functionally connected to the area, already characterized by mixed-use buildings hosting public functions, retails and housing, and it should recall its recent history through the placement of recycle facilities, workshops and temporary activities.

DESCRIPTION

The project site is 10.000 m^2 and the functions that will be hosted are both public and private.
A FAR of 200% is set since it relates to the urban density of the nearby sites and it is proved to be optimal in a sustainability perspective (Lauring et al., 2010).

PRIVATE SPACES

The private part will include the dwellings for students, young single, couples, families and the relative shared facilities; it will occupy about 60% of the total m^2 of the building (12.000 m^2) and the typologies included will be:

- 1 room apartments for singles or couples
- 3 rooms apartments for families with 1 child
- 4 rooms apartments for families with 2 children and students groups

Approximate total number of dwellings: 150.

The layout of the apartment will be flexible and responsive in order to be adapted to different needs. The size and percentages of the different typologies are set according to the current residential situation in Aarhus and will be adjusted in order to make room for slightly more 3-4 rooms apartment due to the better energy performances of those (Danmarks Statistik, 2018).

Some private shared functions will be designed for the occupants. Among these the private parking is excluded, since it would go against the LCA goal, but it will be replaced with a car sharing service.
Bike parking are calculated according to these regulations as well (Teknik og Miljø, Aarhus Kommune, 2018).
Spaces shared by the occupants will consist in:

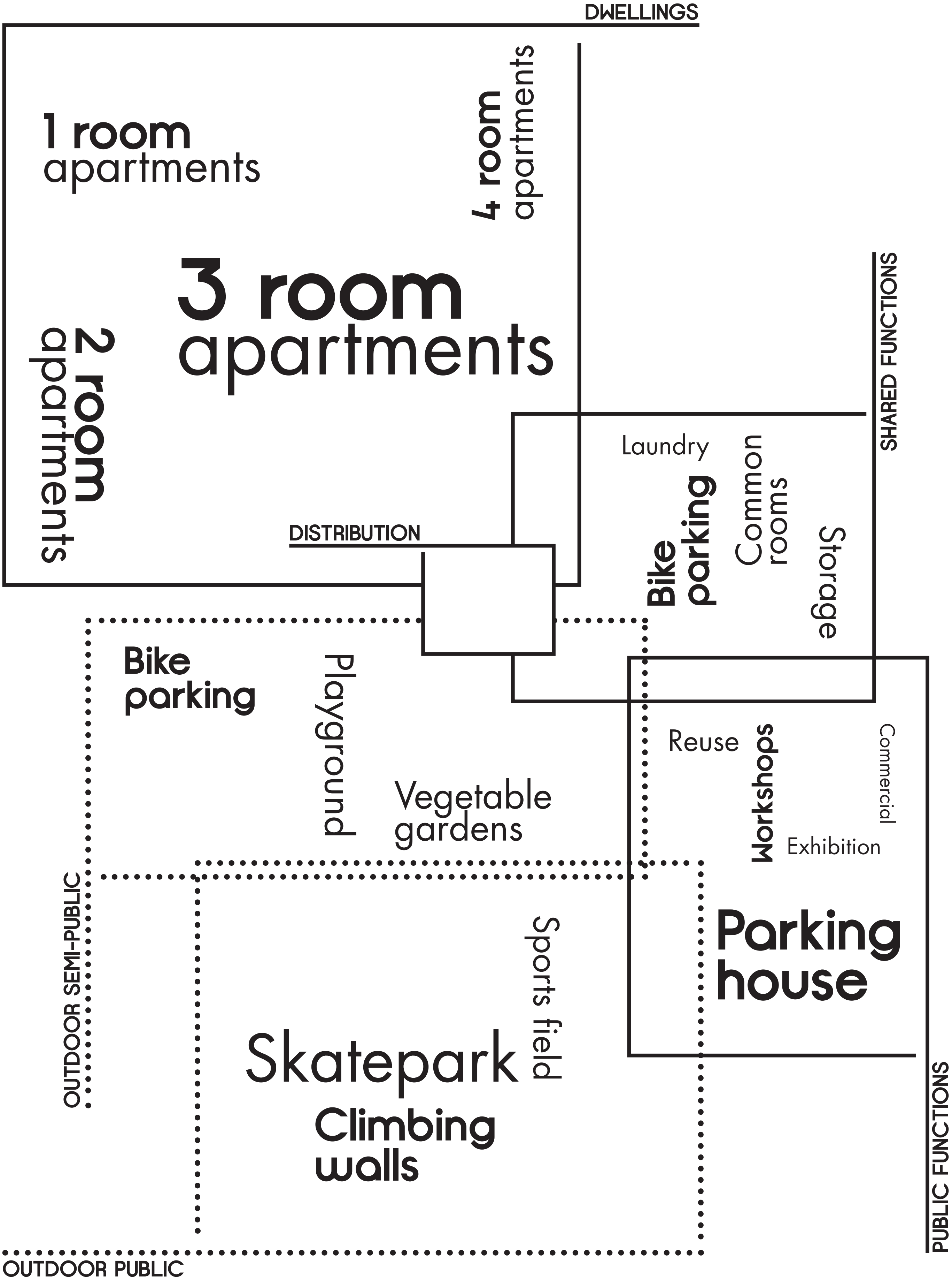
- storages
- recycling refuse
- laundry rooms
- car sharing parking spaces (about 50 parking lots)
- private bike parking (about 580 parking lots)
- shared rooms

PUBLIC SPACES

Public spaces are open both to the occupants and to the public and will occupy up to 40% of the total m^2 of the building (8.000 m^2). These public functions aim to both contribute to reduce the life cycle impact of the building and to respond to the actual needs of the local users, both permanent and temporary.
The municipality planned the construction of a parking house in the Northern part of the site due to the future presence of a big event area in the district that will attract many visitors. The pollution of the soil and the flooding issues does not allow to place functions below the ground floor and therefore the parking can be placed only above ground (Teknik og Miljø, Aarhus Kommune. 2017).
Since a detailed local plan for the parking is not available an assumption of the total parking places needed has been done according to the site plot; even though private transportation would be against the thesis LCA topic, parking spaces are needed due to the public events and therefore the project will include an integrated public parking but with less places than the estimated ones.

Public/business functions that will be included are:

- cultural workshops
- production workshops
- reuse station
- exhibition spaces
- vegetable gardens
- commercial spaces: retails, café, restaurants, thrift shops, ...
- public parking (about 160 parking lots)



ill. 60: Functions diagram

DESIGN CRITERIA

From the analysis results and from the first sketching phase, the main design criteria for functional, technical, aesthetic and sustainable aspects have been defined. All the criteria have been divided between the different phases of the design process, starting from overall planivolumetric considerations until more detailed parts of the project.

Functional	Technical	Aesthetic	Sustainable	**PLANIVOLUMETRIC**
		●	○	FAR 200%
●		●	○	Volumes high raised towards North / low raised towards South to ensure sunlight and to relate to the context
●		●		Keep a connection between the built area and the event park
		●		Maximum 3 blocks
●				Volumes towards the street and the railway as noise barrier
		●		Dissolving volumes towards event park
●	●	●		Building depth 12 m
		●		Human scale open spaces
●		●		Raised open spaces
●		●		Visual comfort: good light conditions and views
	●		○	Achieve the maximum goal of DGNB for LCA

Functional	Technical	Aesthetic	Sustainable	**FUNCTIONS LAYOUT**
	●	●	○	Mixed use in section
●				Public and common functions mostly on the ground floor
●				Public and shared functions concentrated towards the street, the park and the railway
●				Parking on the street side
	●		○	Thermal comfort: single side and cross ventilation
●				Acoustic comfort: public and private functions division

STRUCTURE

- Wood as main building material
- Modularity and prefabrication
- Design for disassembling
- Exposed structure to define the character of the building
- Optimized structure according to LCA

INTERNAL LAYOUT

- Flexible layout
- Use aesthetic and sensorial properties of wood to define the interior spaces
- Visual comfort: 20% glazed windows
- Acoustic comfort: internal spaces division
- Thermal comfort: passive solar gain

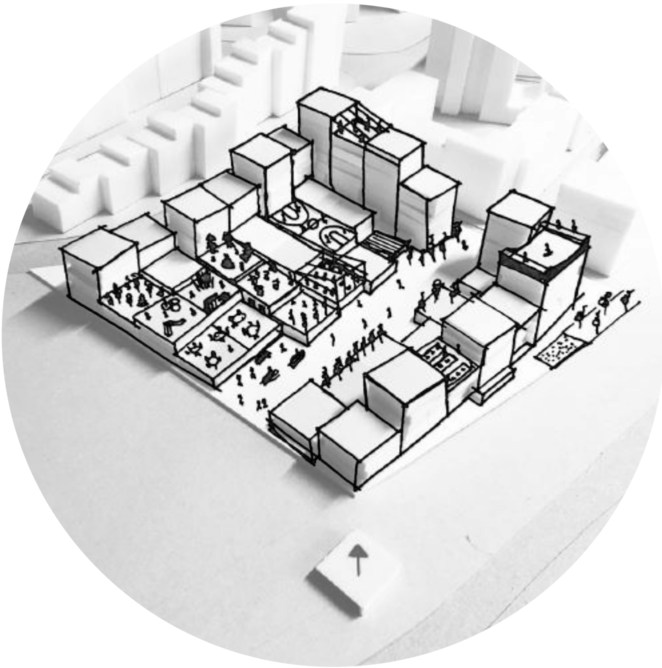
EXTERIOR

- Shadings on the facade
- Active strategies: solar cells integration
- Landscape connected with the park
- Water collection strategies

FIRST VOLUMETRIC ATTEMPTS

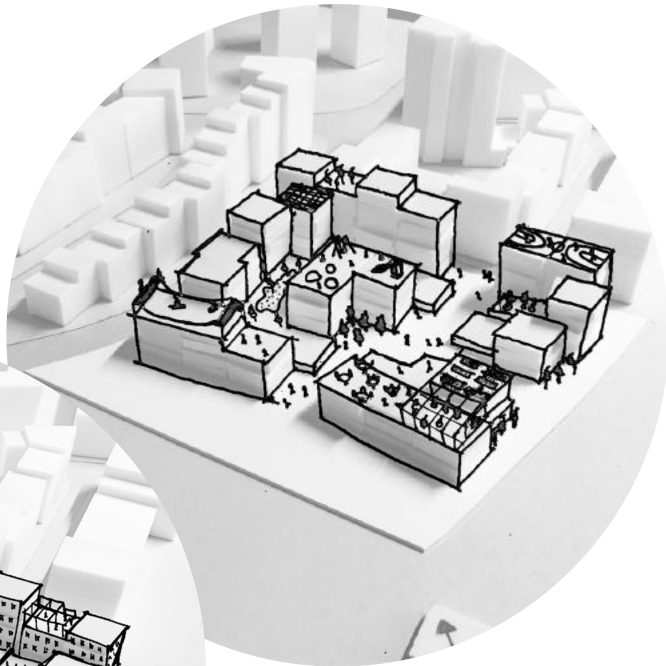
"A strong connection with the park could help to divide the complex and give the opportunity for good public areas, but would generate an out-of-proportion internal open space."

ill. 61: Volume test 1



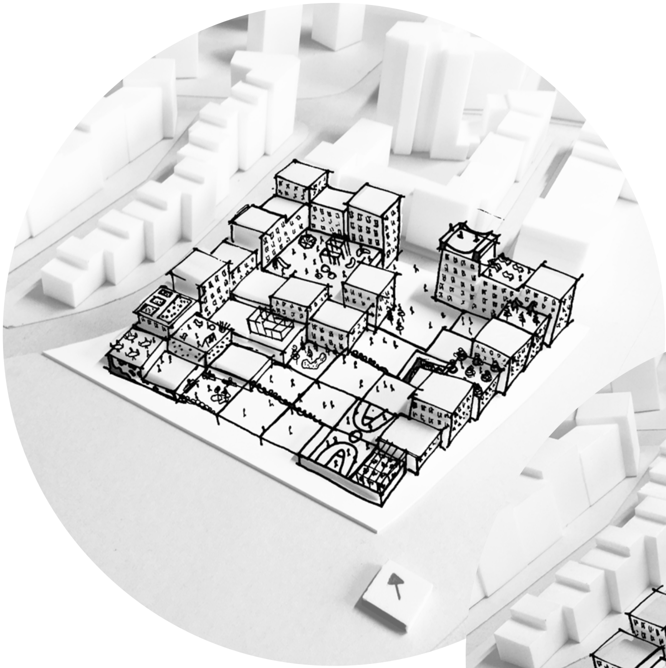
"A triple access would make the site more open and public but could cause problems in term of privacy since the room for semi-public outdoor spaces is limited."

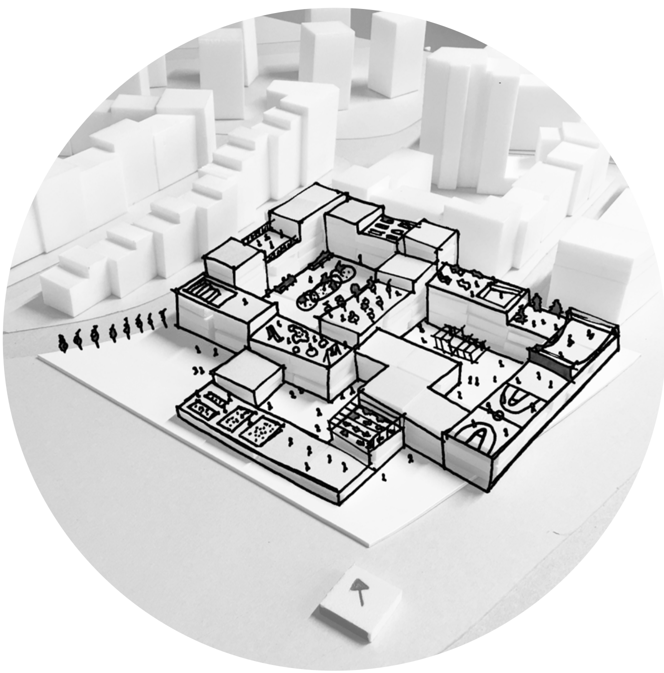
ill. 62, 63: Volume test 2-3



"The use of high volumes in the internal part of the site results in a more divided open space that allows the creation of different outdoor spaces, public and semi-public. This is also supported by the possibility to use the roof of the lower public buildings and create a vertical gap."

ill. 64, 65: Volume test 4-5





"The courtyards layout would generate more compact volumes and open spaces that have a more human scale. On the other hand, the connection between the park and Godsbanen would be lost..."

ill. 66: Volume test 6

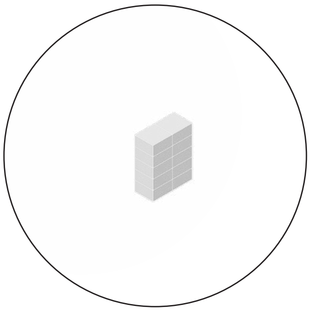
LCA ITERATIONS - HEIGHT AND WIDTH

In order to achieve a better awareness of the LCA behaviour in relation with the building shape an analysis on simple volumes has been done.
The relevant ones for the project have been included in the report, while the others are collected in the Appendix 1.
The very first test has been done by simply increasing the total volume.
The other parameters that have been tested are the number of storeys and the width of the building: the investigated values come from the context design criteria (width between 8 and 24m, height of maximum 12 storeys). In order to have comparable results a fixed total volume is set (5400m^3).

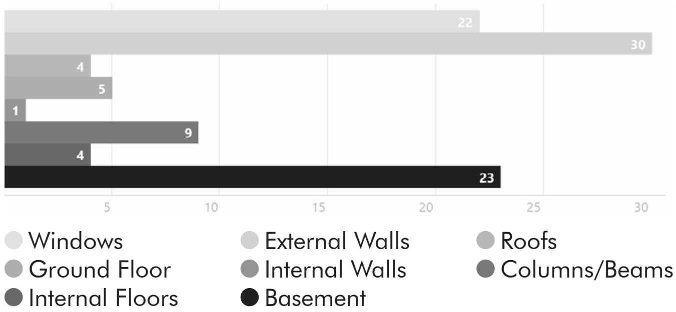
The structure is approximately defined by the Grasshopper definition and is generated according to a fixed percentage on the total volume; the same is assumed for the glazed area that is set as 20% of the external wall surface.
The material assumed are the same for all the iterations and are as follow:
- structure (bearing walls and slabs) in CLT
- external walls in CLT, mineral wool insulation and standard cladding
- roof in CLT, mineral wool insulation and standard cladding
- internal non-bearing partitions in wood panels
- foundations in concrete
- triple glazed windows with wooden frame

TOTAL VOLUME

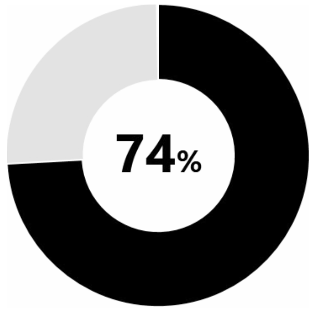
1000 m³



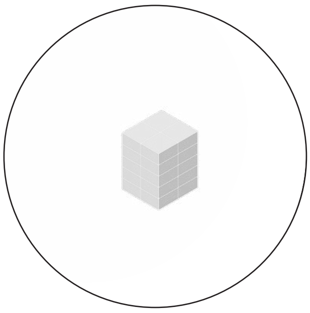
CO_2 GLOBAL WARMING POTENTIAL (%)



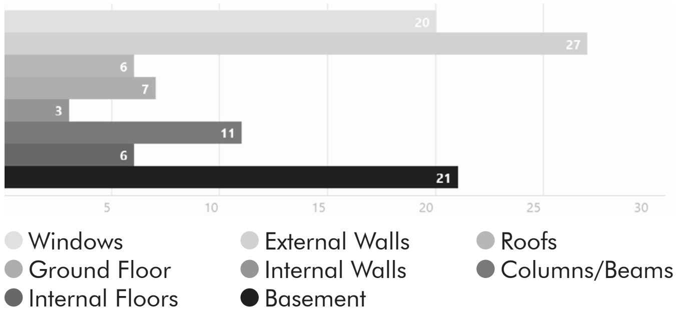
DGNB LCA SCORE



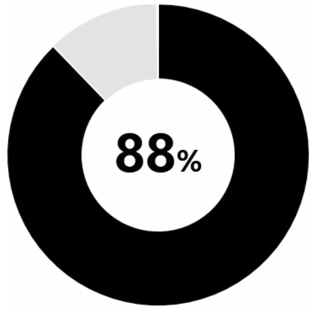
2000 m³



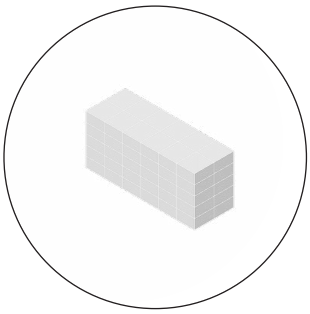
CO_2 GLOBAL WARMING POTENTIAL (%)



DGNB LCA SCORE

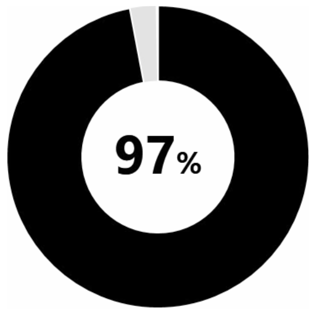


6000 m³

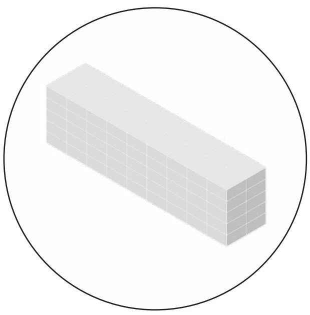


CO_2 GLOBAL WARMING POTENTIAL (%)

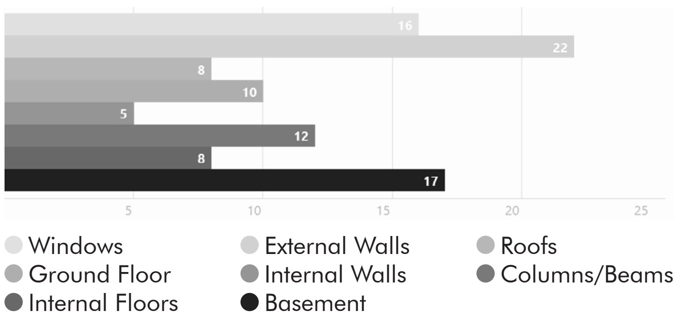
DGNB LCA SCORE



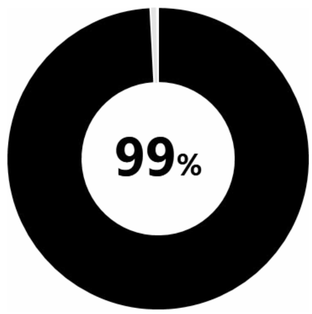
10.000 m³



CO_2 GLOBAL WARMING POTENTIAL (%)



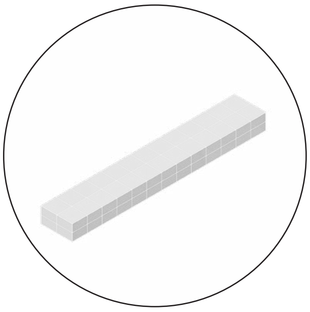
DGNB LCA SCORE



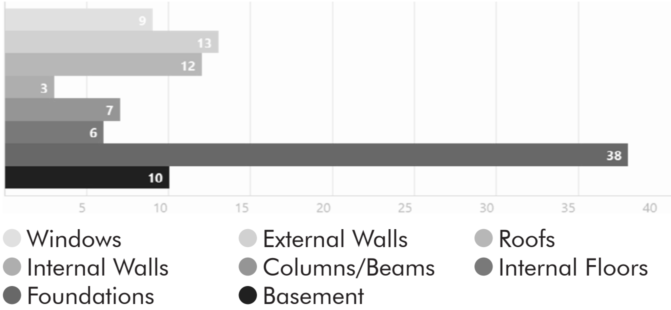
ill. 67: Total volume tests

NUMBER OF STOREYS

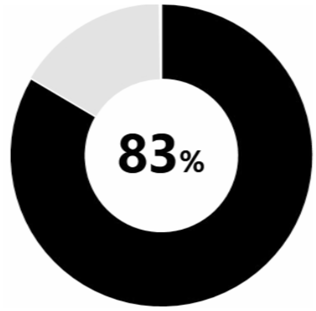
2 STOREYS



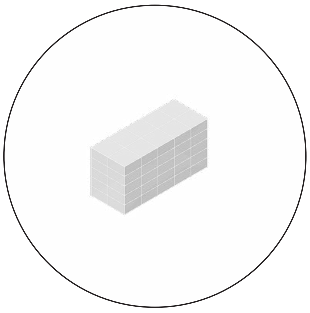
CO_2 GLOBAL WARMING POTENTIAL (%)



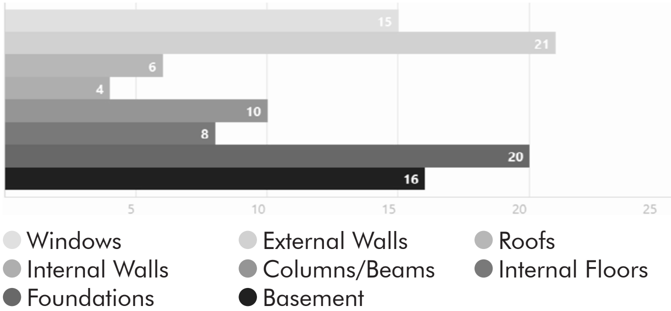
DGNB LCA SCORE



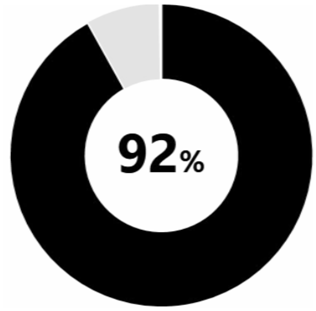
5 STOREYS



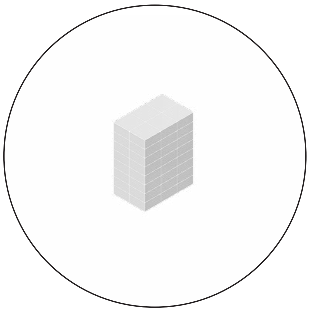
CO_2 GLOBAL WARMING POTENTIAL (%)



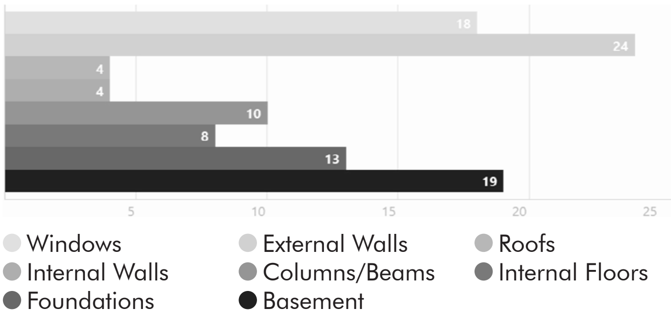
DGNB LCA SCORE



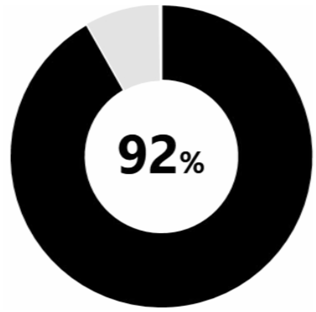
8 STOREYS



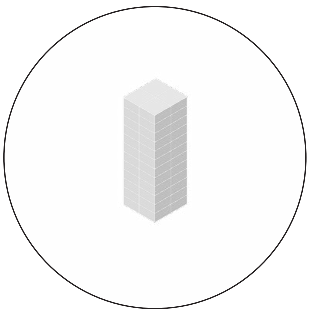
CO_2 GLOBAL WARMING POTENTIAL (%)



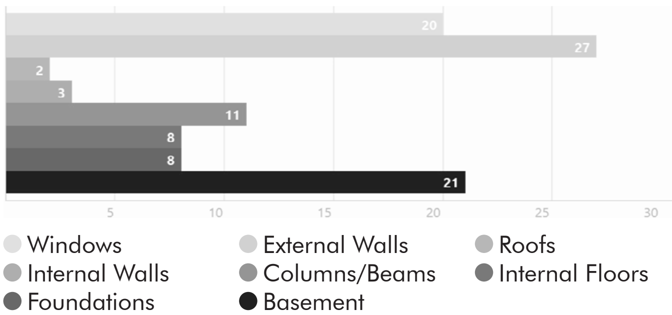
DGNB LCA SCORE



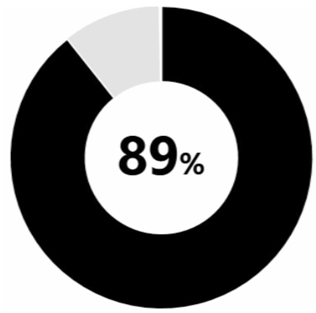
12 STOREYS



CO_2 GLOBAL WARMING POTENTIAL (%)



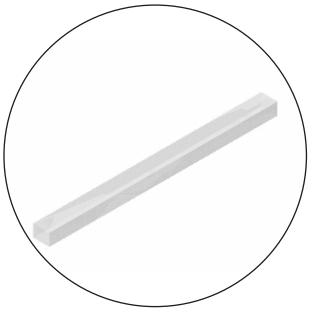
DGNB LCA SCORE



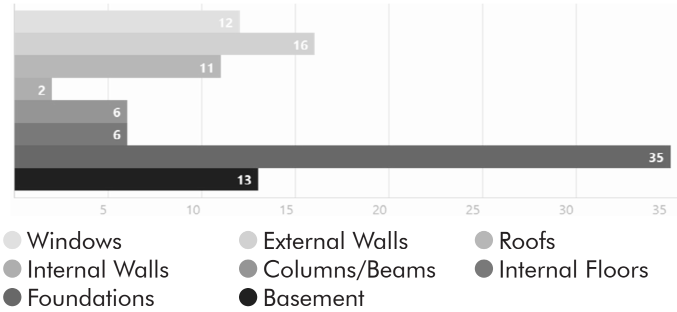
ill. 68: Number of storeys tests

LENGHT-WIDTH RATIO

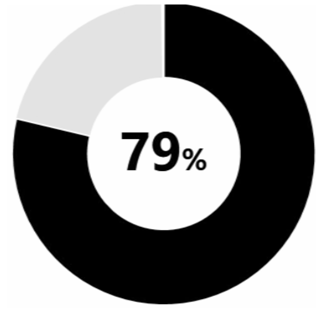
8m (1:14)



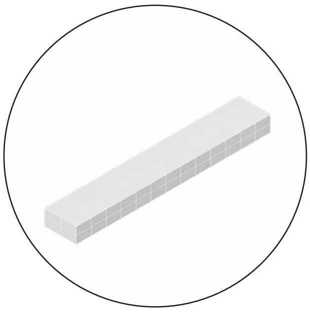
CO_2 GLOBAL WARMING POTENTIAL (%)



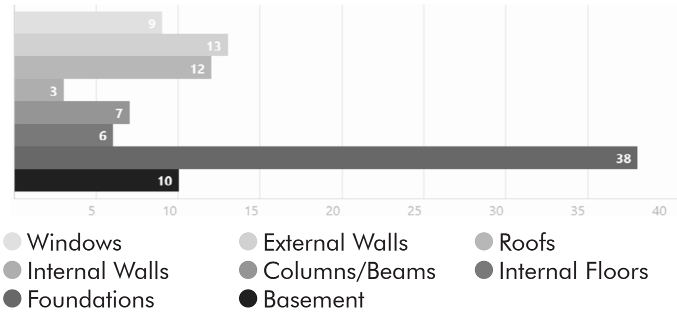
DGNB LCA SCORE



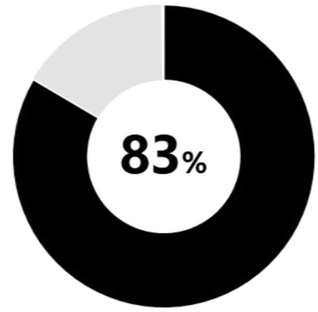
12m (1:6)



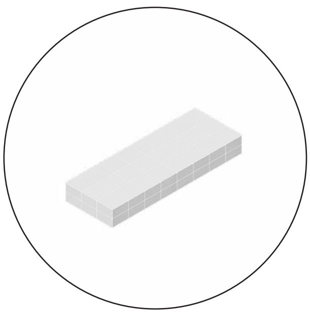
CO_2 GLOBAL WARMING POTENTIAL (%)



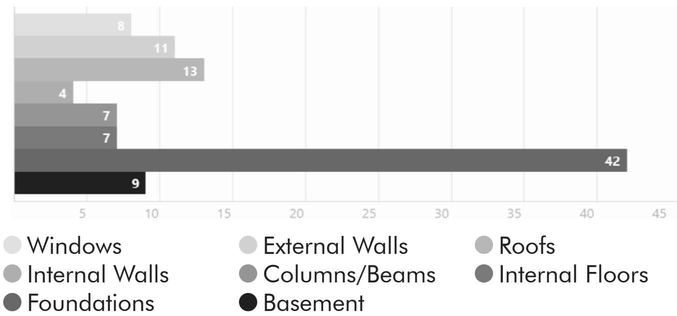
DGNB LCA SCORE



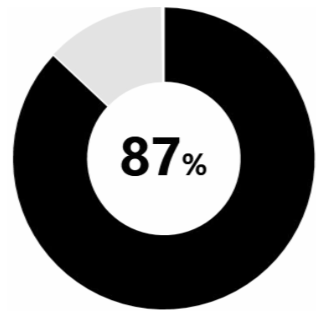
18m (1:3)



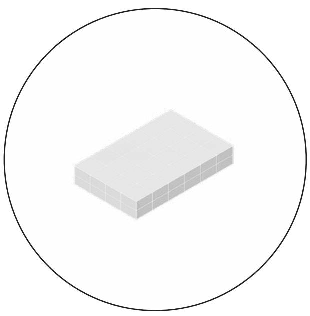
CO_2 GLOBAL WARMING POTENTIAL (%)



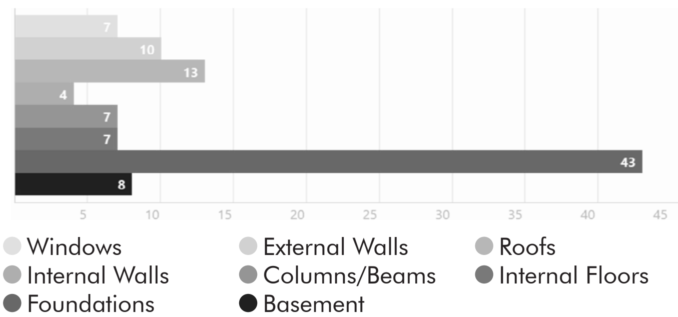
DGNB LCA SCORE



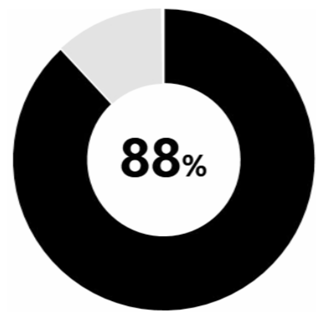
24m (1:1.5)



CO_2 GLOBAL WARMING POTENTIAL (%)



DGNB LCA SCORE



ill. 69: Lenght-width ratio tests

RESULTS & CONCLUSIONS

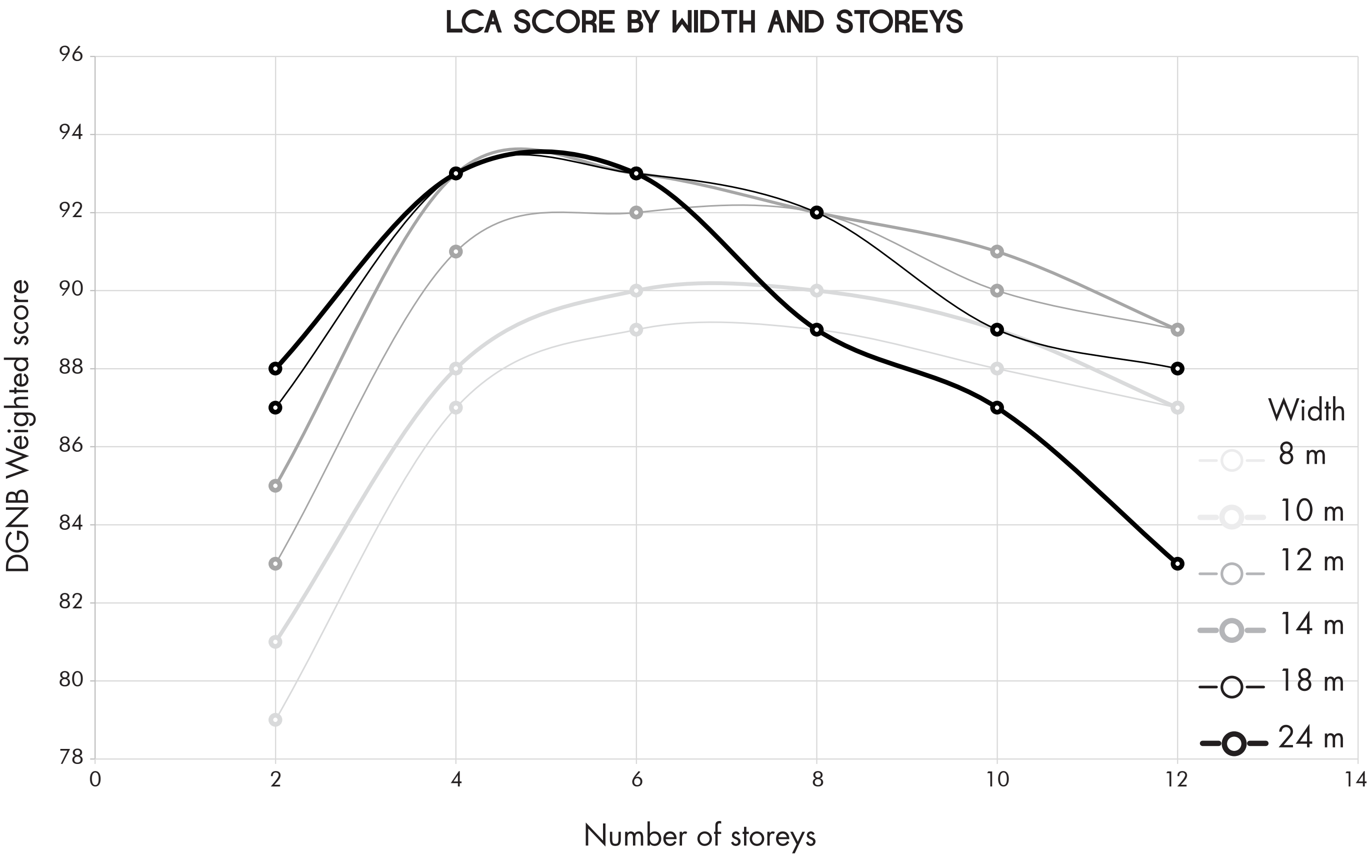
The general volumetric study shows how the DGNB way of calculation of the LCA indicators, based on a building area, generates better results for higher volumes. Even though the increase of volume logically results in more material used, the division of the pure LCA indicators with the increased m^2 generates lower figures since the floor surface increment is higher than the material quantity one.
As shown in ill. 71, the LCA Score growth rate has a logarithmic-like trend: with small starting volumes the m^3 increase generates a high growth while with higher starting volumes (in the test around 7000 m^3) the score growth decreases until it becomes almost steady.
The other test results show a different behaviour for the two parameters evaluated:

- The height does not have a linear response. The LCA score increases by raising the number of storeys until it reaches a peak that varies according to the width between 4 and 8 storeys (ill. 70). After the peak the score starts to decrease. The speed of the decrease is higher the wider the volume is.
This behaviour is due to the different amount of foundation and roof surface in relation to the external wall surface: especially the foundations have a higher impact on LCA, since they are in concrete.
The increase of the height with a fixed volume causes a lower ground surface and therefore a reduction of foundation material needed. This amount even out with the external walls material at the peak points after which the foundation reduction benefit is lower than the external surface increase.
The different decrease curve of the different width tests is also due to this relation between foundation and external wall surface.

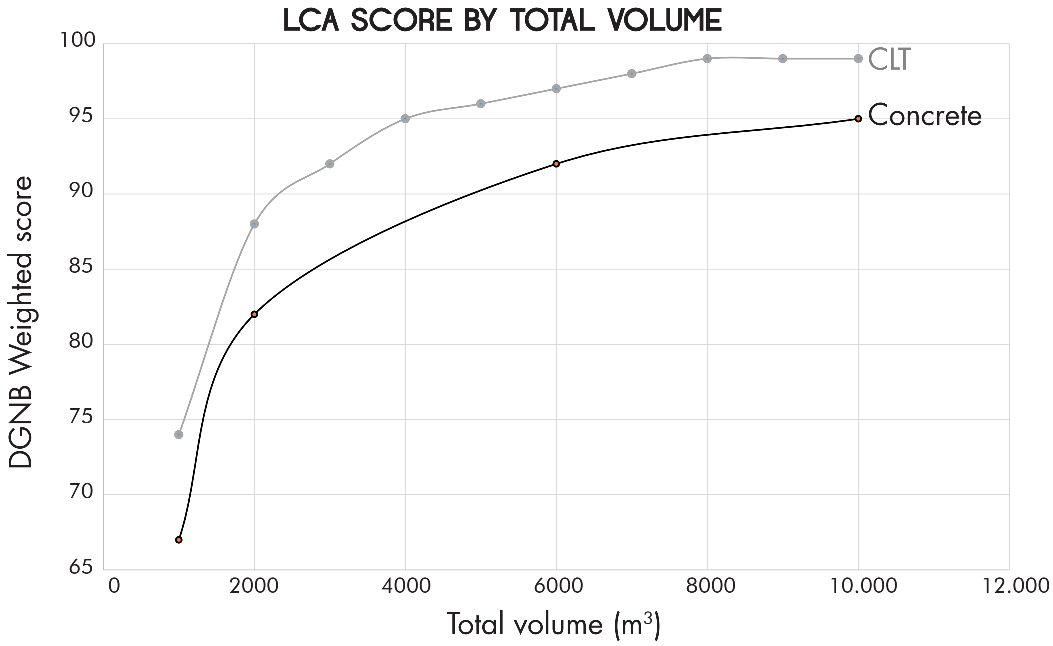
- The width variations have a linear response. The more the proportion between length and width of the volume gets close to 1:1, the better the LCA score is. This is due to the reduction of the external wall surface which results in less material used.
The results show that the design criteria previously set to relate with the context and to achieve a good daylight can be integrated with the LCA optimization: height between 4 and 8 storeys and a width between 12m and 18m is fulfilling both technical and aesthetic requirements.

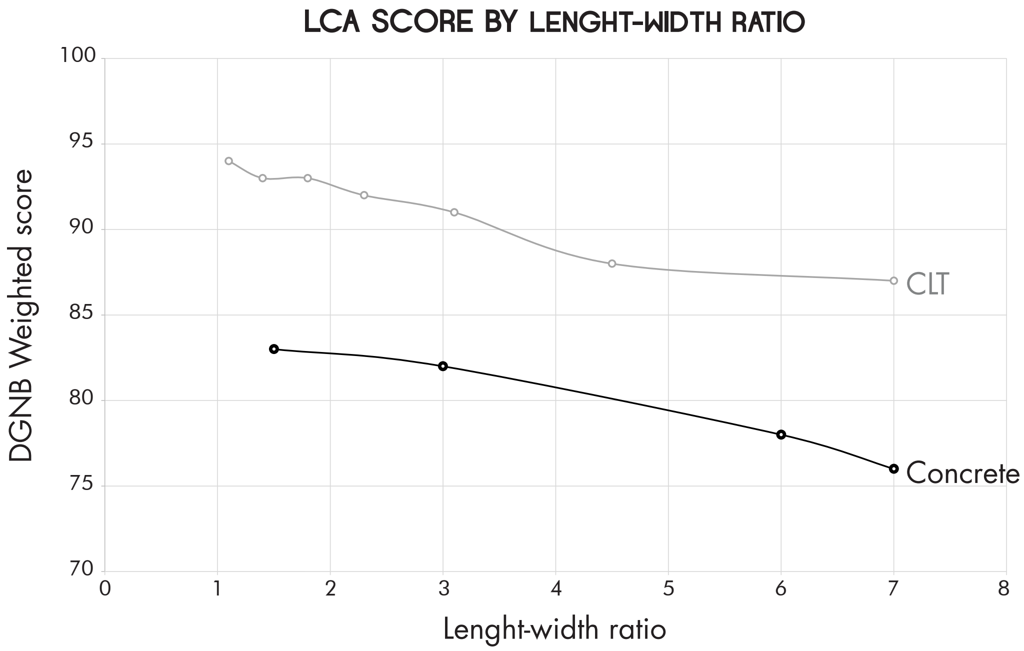
The comparison with the same iterations made by using a concrete structure shows the same trends with lower overall scores due to the higher environmental impact of the material.

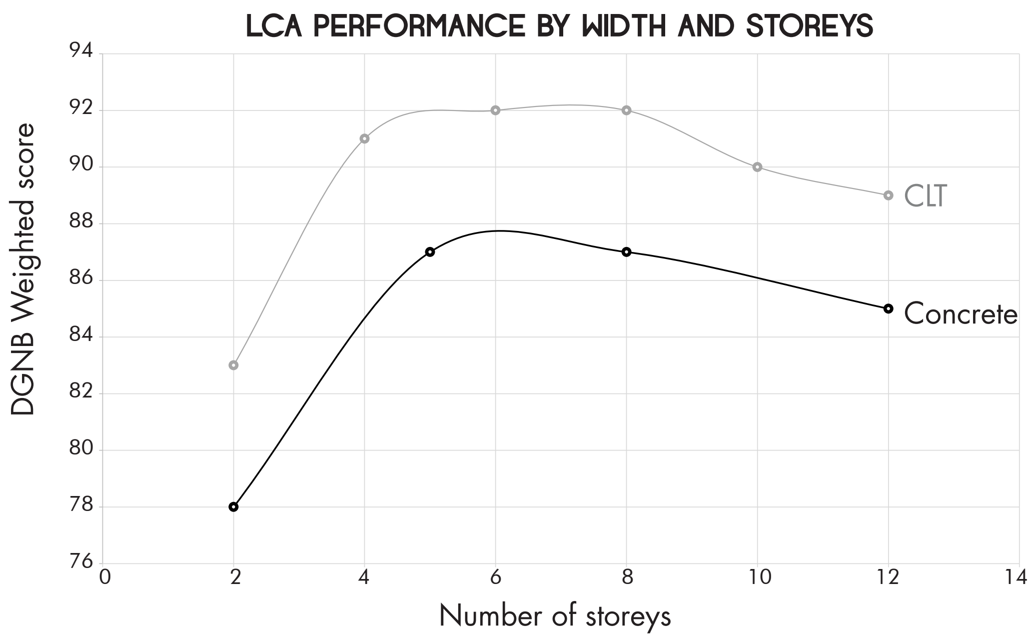
Detailed iterations made with concrete structure can be found in Appendix 2.



ill. 70: Graph showing the iterations results







ill. 71, 72, 73: Graphs showing the iterations results in comparison with concrete

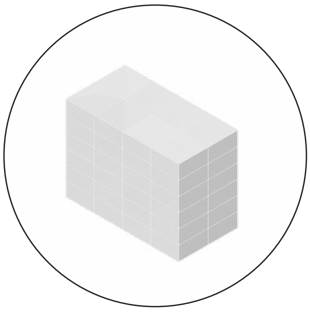
LCA ITERATIONS - FRAGMENTATION

The local vision states that the volumes in this area should create defined outdoor spaces through gaps in the facades; the municipality wish is to create playful outdoor public areas to reflect the character of the district and to provide more qualitative spaces. (Aarhus Kommune Lokalplan nr. 1046 - 1062 - 1087, 2018)
For this reason, a test has been done to evaluate the consequences on the LCA of creating a gap between two volumes, both in horizontal and vertical.
The horizontal gap is measured in % of gap on the width while the vertical one is defined as the difference between the number of storeys of the two volumes.
In order to have comparable results a fixed total volume is set (5400m^3).

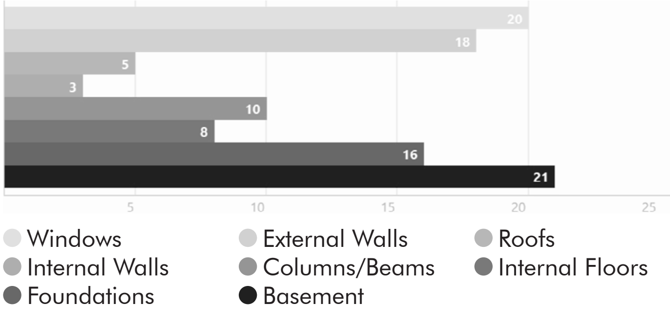
The structure is approximately defined by the Grasshopper definition and is generated according to a fixed percentage on the total volume; the same is assumed for the glazed area that is set as 20% of the external wall surface.
The material assumed are the same for all the iterations and are as follow:
- structure (bearing walls and slabs) in CLT
- external walls in CLT, mineral wool insulation and standard cladding
- roof in CLT, mineral wool insulation and standard cladding
- internal non-bearing partitions in wood panels
- foundations in concrete
- triple glazed windows with wooden frame

VERTICAL GAP

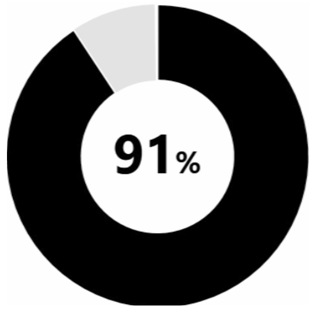
0 STOREYS



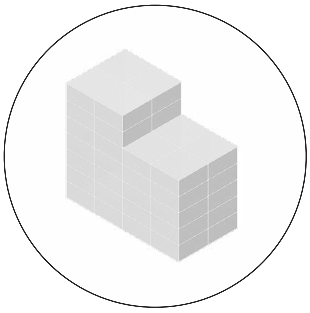
CO_2 GLOBAL WARMING POTENTIAL (%)



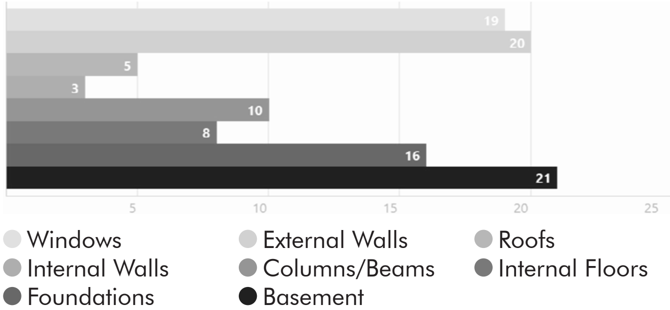
DGNB LCA SCORE



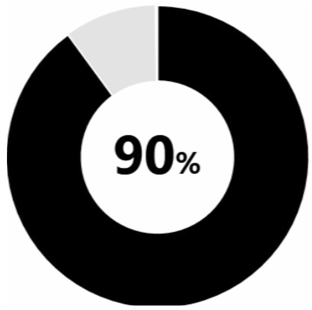
2 STOREYS



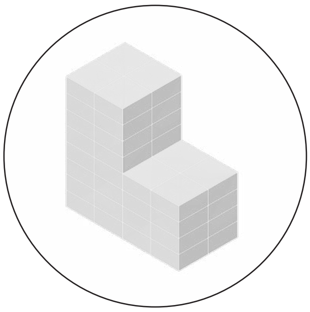
CO_2 GLOBAL WARMING POTENTIAL (%)



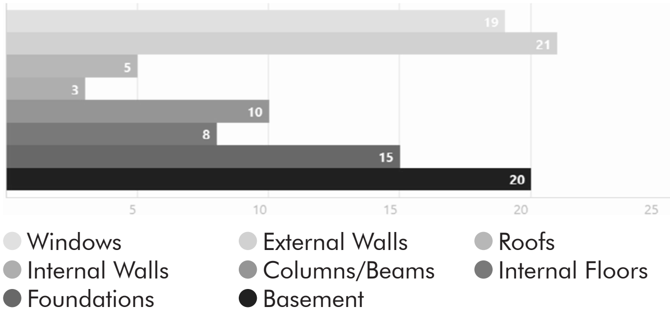
DGNB LCA SCORE



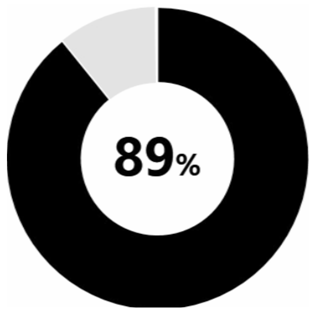
4 STOREYS



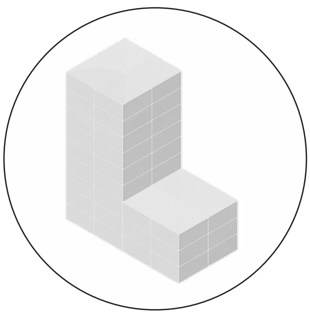
CO_2 GLOBAL WARMING POTENTIAL (%)



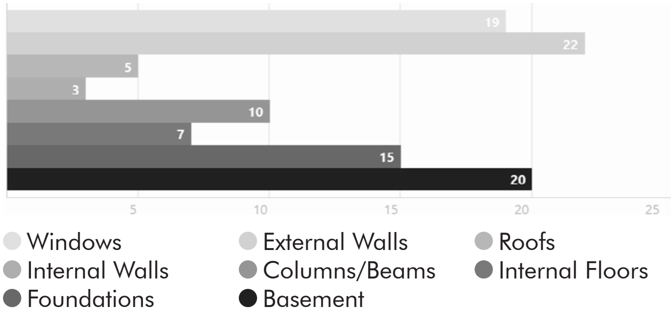
DGNB LCA SCORE



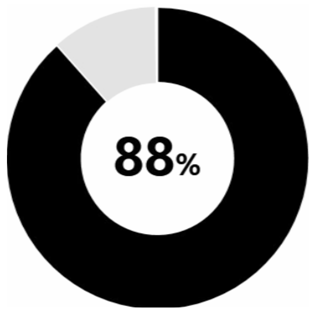
6 STOREYS



CO_2 GLOBAL WARMING POTENTIAL (%)



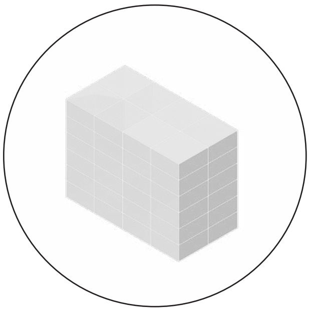
DGNB LCA SCORE



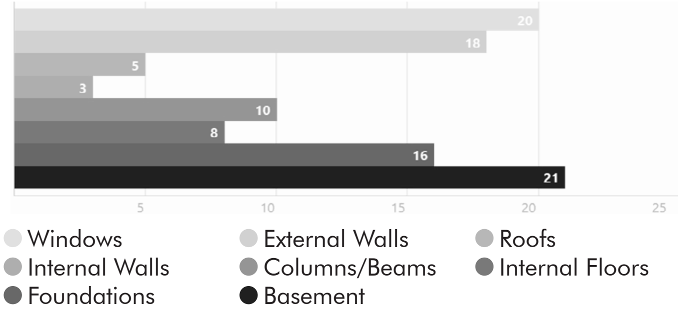
ill. 74: Vertical gap tests

HORIZONTAL GAP

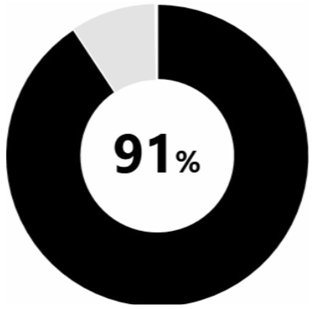
0%



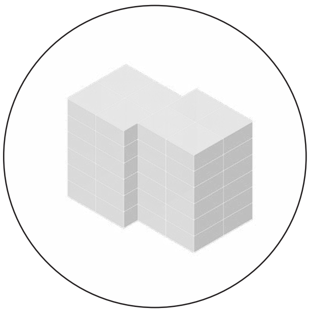
CO_2 GLOBAL WARMING POTENTIAL (%)



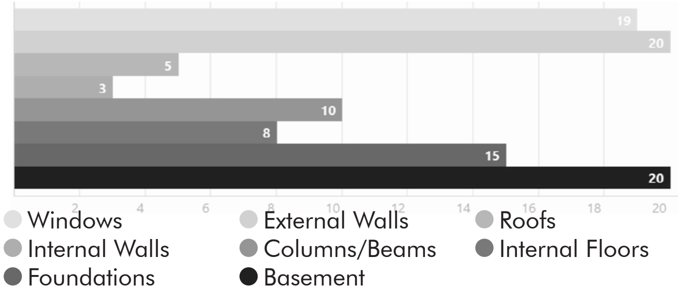
DGNB LCA SCORE



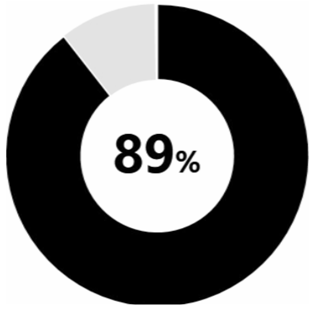
25%



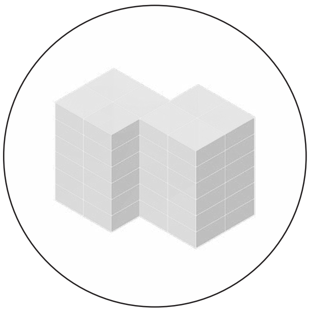
CO_2 GLOBAL WARMING POTENTIAL (%)



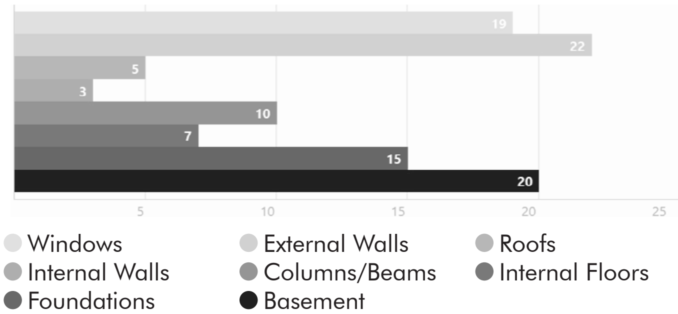
DGNB LCA SCORE



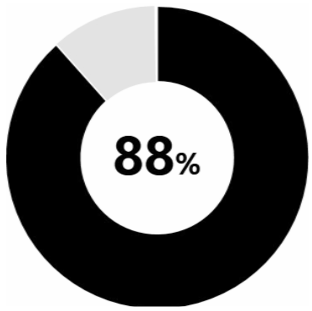
50%



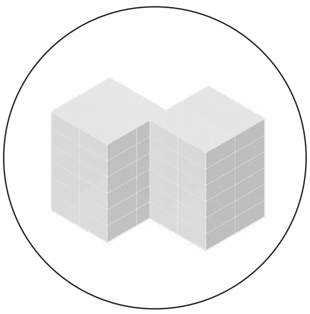
CO_2 GLOBAL WARMING POTENTIAL (%)



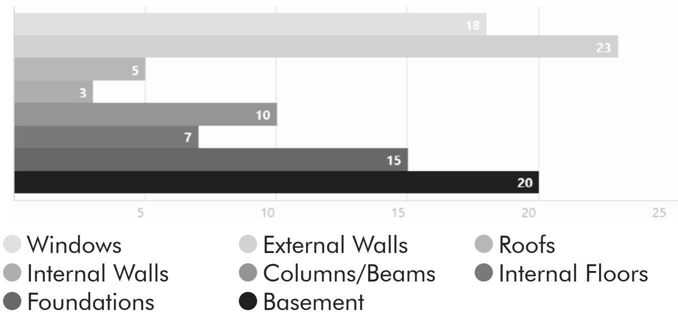
DGNB LCA SCORE



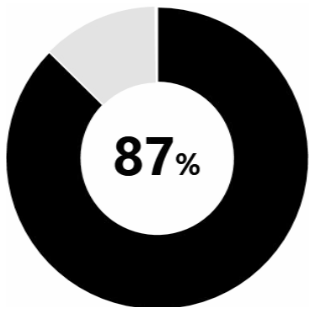
75%



CO_2 GLOBAL WARMING POTENTIAL (%)



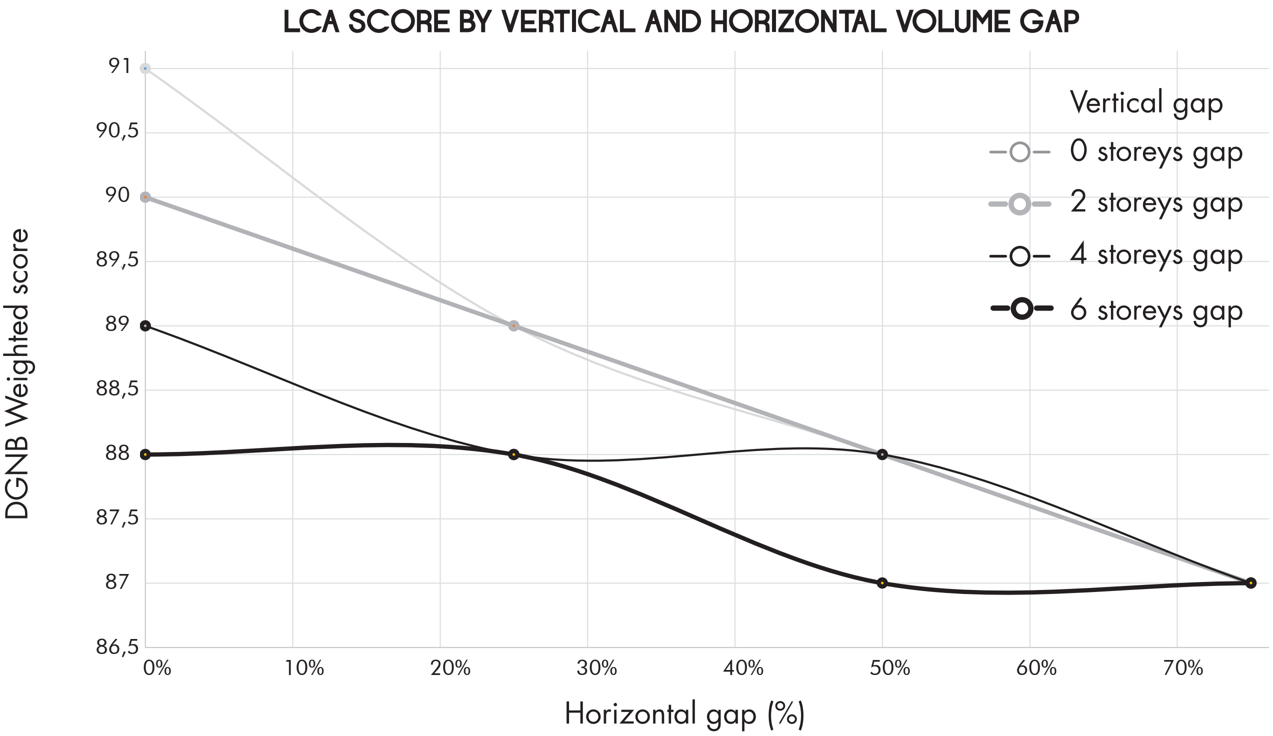
DGNB LCA SCORE

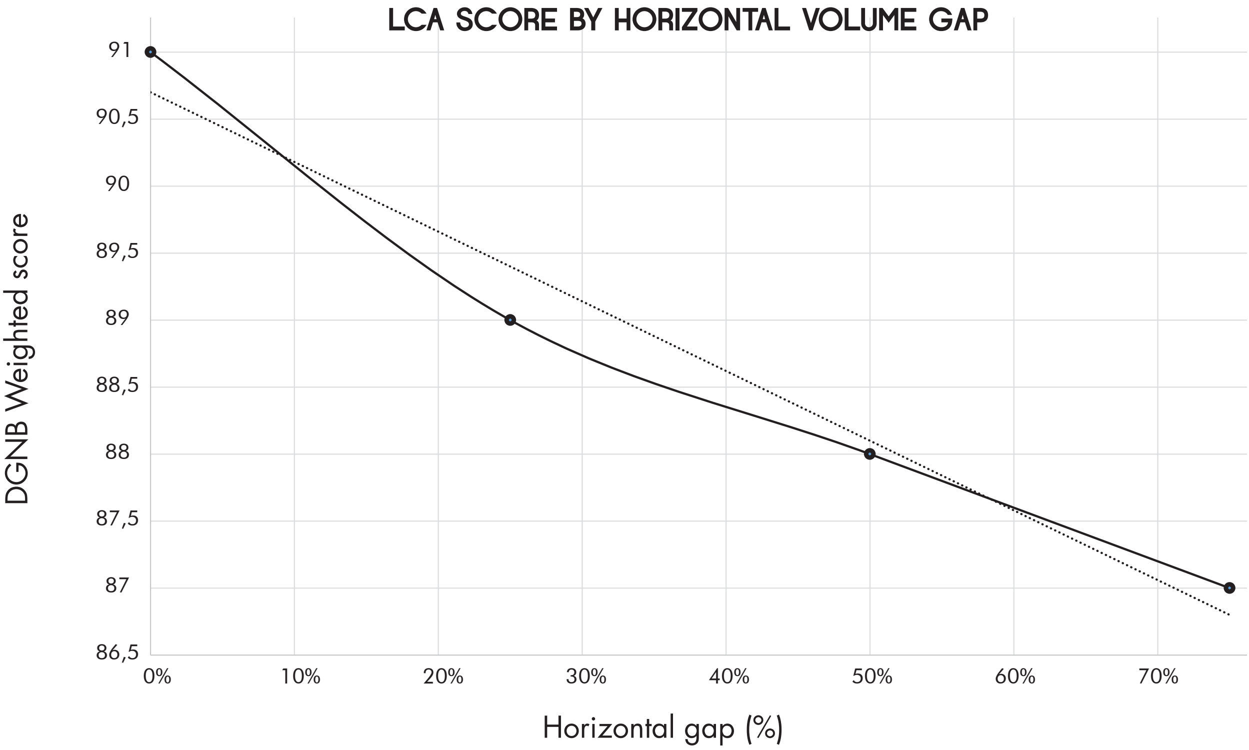


ill. 75: Horizontal gap tests

RESULTS & CONCLUSIONS

The results showed a similar behaviour for the two parameters evaluated:
In both cases the LCA score gets worse the bigger the gap is due to the increase of the external wall surface.
The score decrease trend is linear and the two parameters don't affect each other.
The comparison between the most optimal situation (no gaps) and the worst one in both the cases (maximum gap in vertical and maximum gap in horizontal) shows that the handicap of implementing gaps stands between 4 percentage point of difference in the overall score.
The investigation shows the need to compromise between LCA and the design quality. If needed, a worse LCA score, even though it would be constrained within a low extent of % points, will be obtained in order to achieve a better result in term of outdoor spaces and context integration.

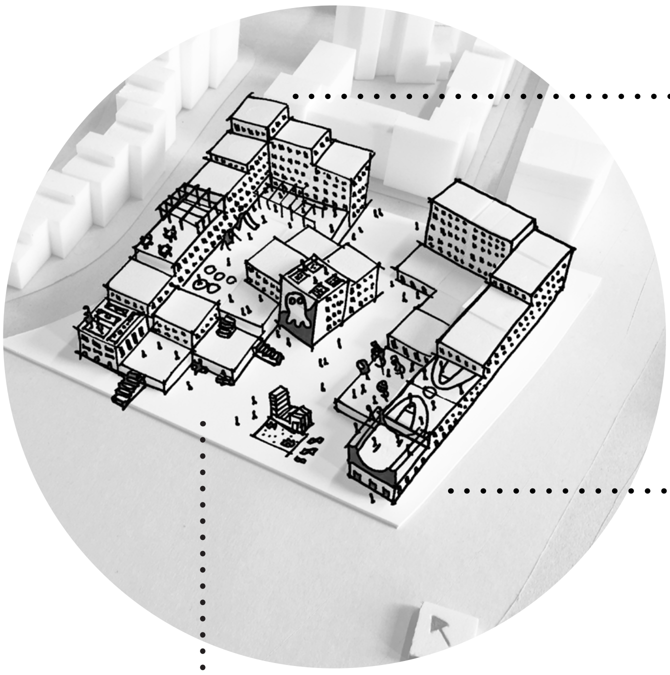




ill. 76, 77: Graphs showing the results from the fragmentation iterations

APPLICATION AND CONCLUSIONS

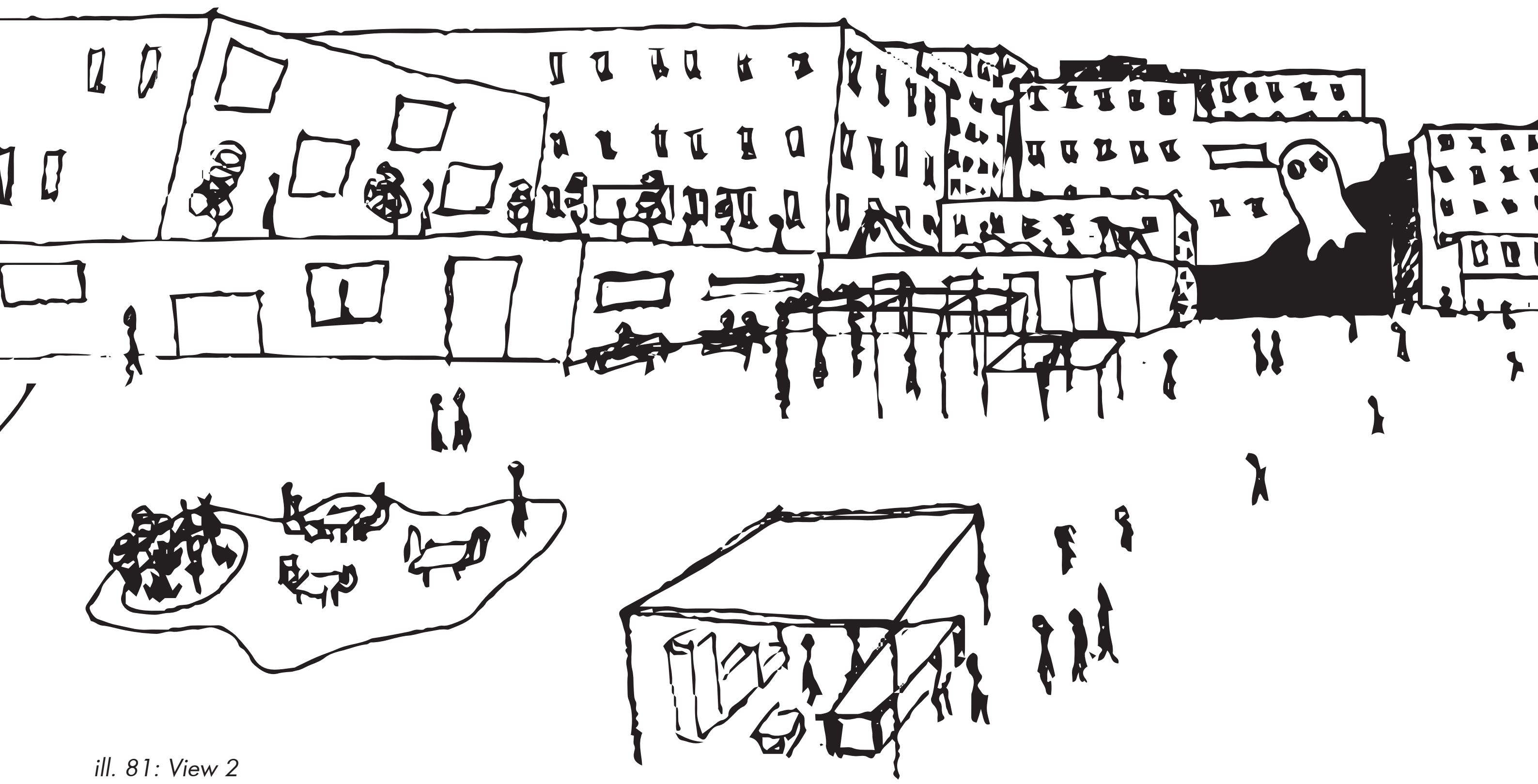
HEIGHT UP TO 8 STOREYS
The reduction of ground floor area in favour of the height reduces the surface of foundation needed.



MODULARITY
The modularity permits the reuse of the material and it makes the transportation and production easier.

ill. 78: Volume test

FLAT ROOF
Compact roof shapes generate benefit in terms of material quantity.



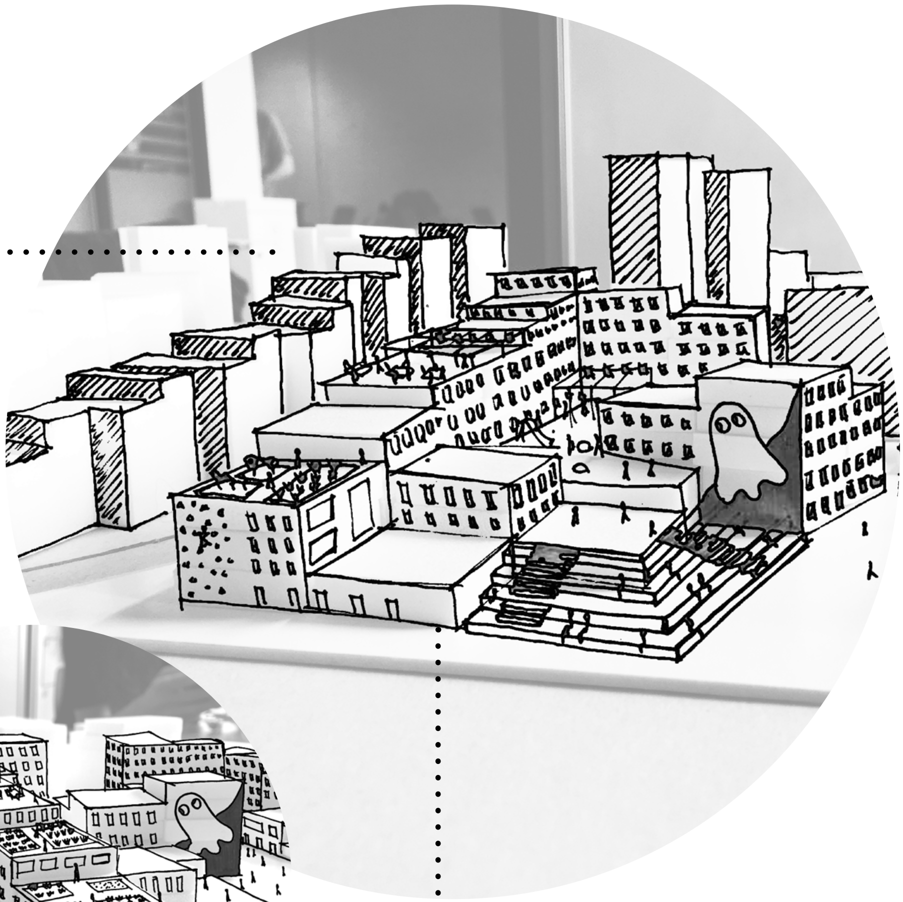
ill. 81: View 2

REGULAR FRAGMENTATION

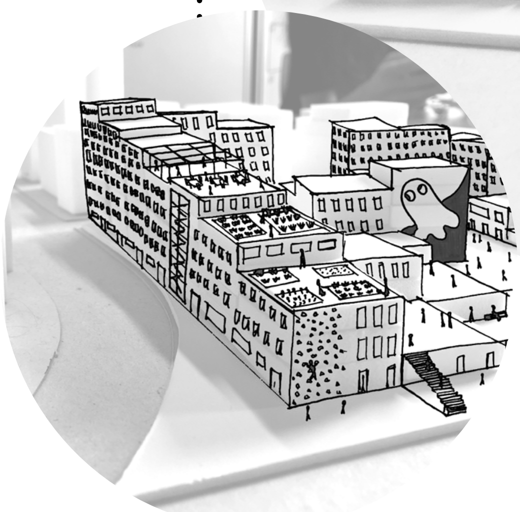
A more regular fragmentation of the volumes avoids the excess of external wall surfaces.

POSSIBILITY OF FRAGMENTATION

Even though the compact shape is the best in terms of LCA, the disadvantages of small displacements are negligible.



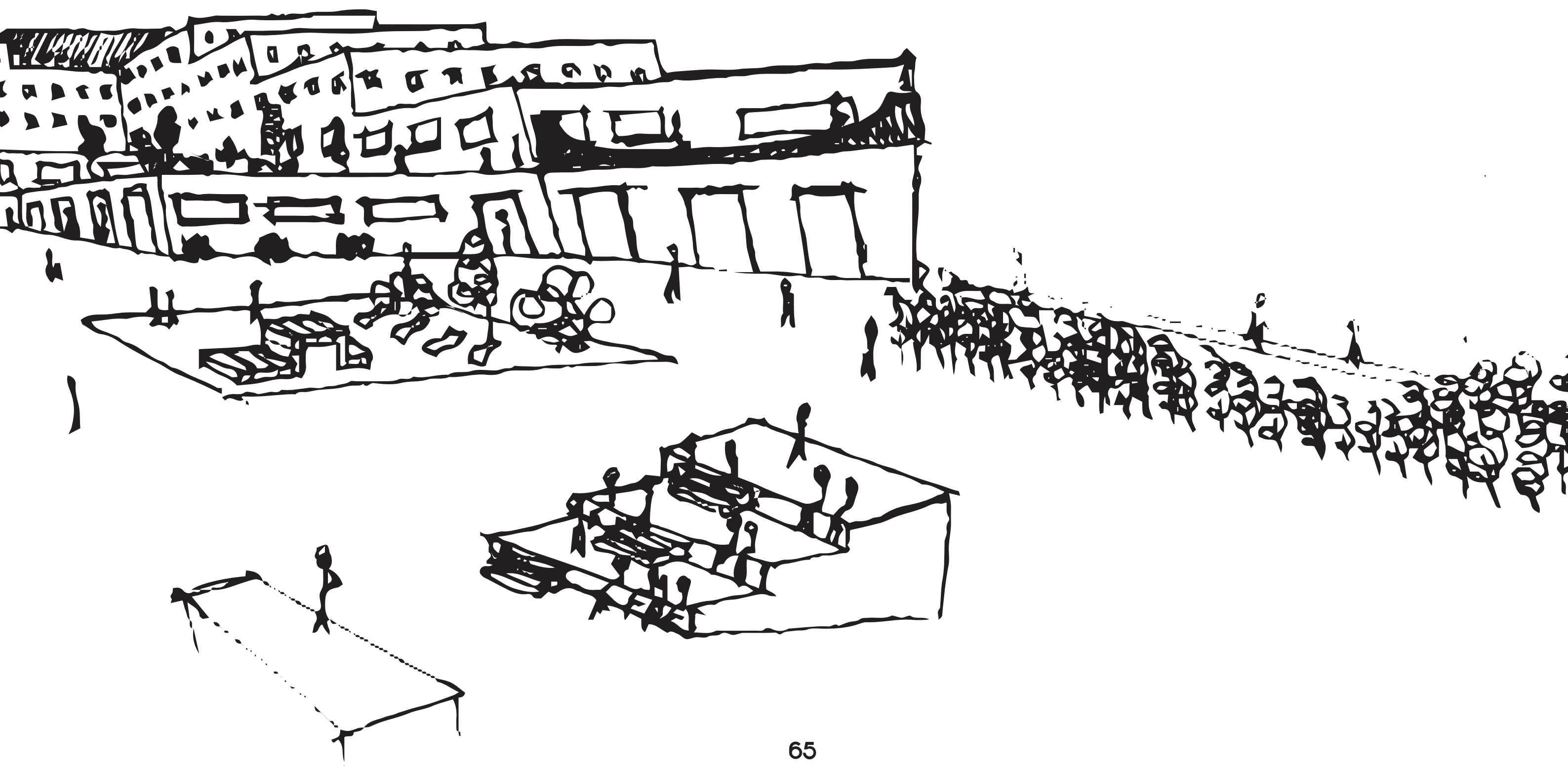
ill. 79: View 1



ill. 80: View 2

REGULAR DEPTH

The volumes depth is a compromise between the LCA investigation and the indoor comfort needs.



DISTRIBUTION AND LAYOUT

DISTRIBUTION SCHEME

After the definition of the overall volumetric and functional layout the design focus moved to the internal distribution and flows.
Many tests have been carried out to implement different apartments' layouts with different types of distribution. The option of having a corridor to connect the dwellings have been discarded after the first attempt as it wasn't optimal for daylight and privacy into the apartments. The distribution has been moved either at the center of the plan or closer to the facade towards the road, generating different types of fire escape routes. The option that has been chosen (option 7) is compromising between a more direct escape route and a good overall connection between courtyard, street and apartments.

OPTION 1

ill. 82: Horizontal distribution, vertical distribution and fire escape n.1

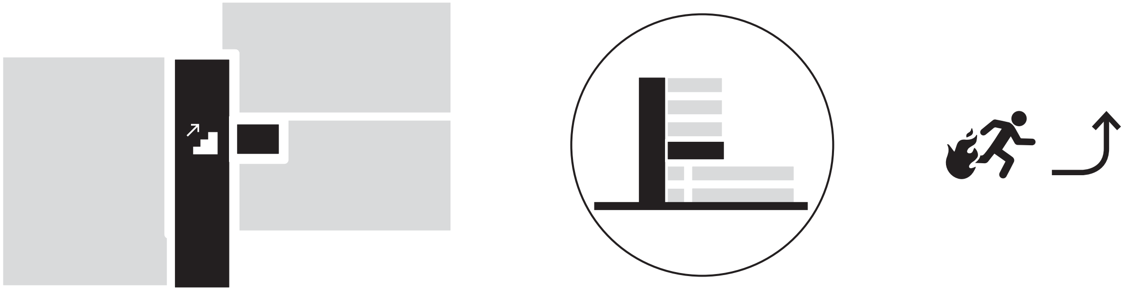
OPTION 2

ill. 83: Horizontal distribution, vertical distribution and fire escape n.2

OPTION 3

ill. 84: Horizontal distribution, vertical distribution and fire escape n.3

OPTION 4



ill. 85: Horizontal distribution, vertical distribution and fire escape n.4

OPTION 5

ill. 86: Horizontal distribution, vertical distribution and fire escape n.5

OPTION 6

ill. 87: Horizontal distribution, vertical distribution and fire escape n.6

OPTION 7

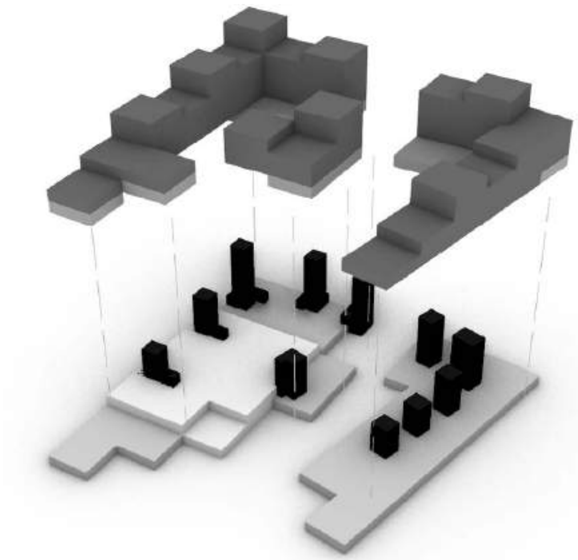
ill. 88: Horizontal distribution, vertical distribution and fire escape n.7

FUNCTION LAYOUT

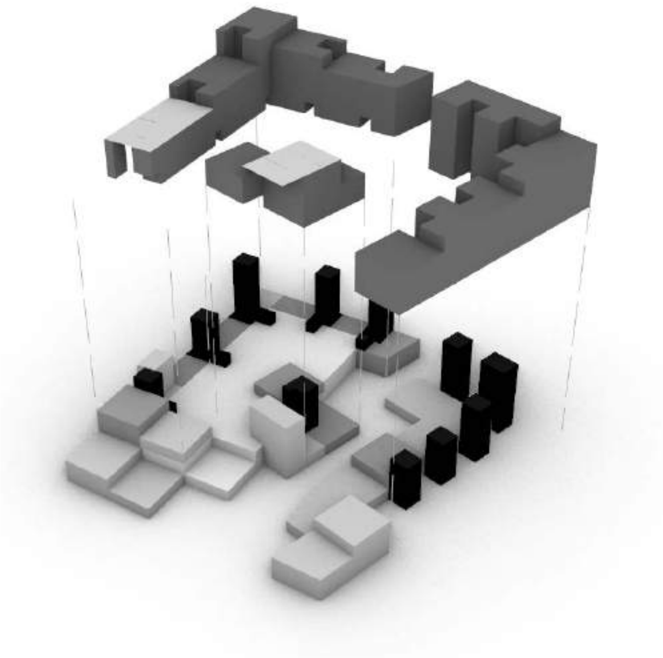
- Distribution
- Apartments
- Common spaces
- Public
- Parking

ITERATION 1

The first attempt consisted on concentrating the public functions downstairs and all the apartments in the upper floors. The configuration was still rigid and limited by the cube modules. For this reason, the parking was positioned towards the facade facing the main road.



ill. 89: Functions iteration n.1



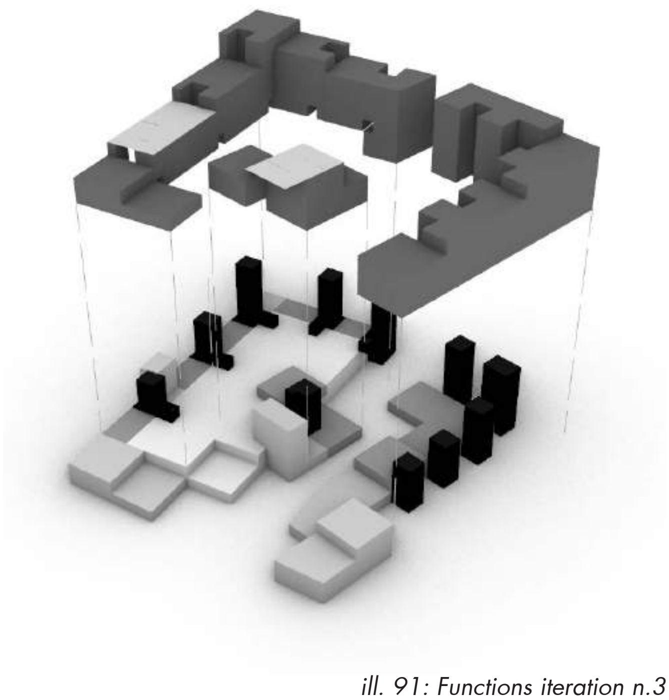
ill. 90: Functions iteration n.2

ITERATION 2

In the second iterations the parking has been moved in the inner part of the building on the ground and first floor, and it is covered by public and shared functions in order to hide it from the facade and improve the quality of the space in front of it.

ITERATION 3

The public spaces have then been reduced and concentrated mainly towards the park. This resulted in a more private area in the northern end of the site where dwellings and common functions are located.

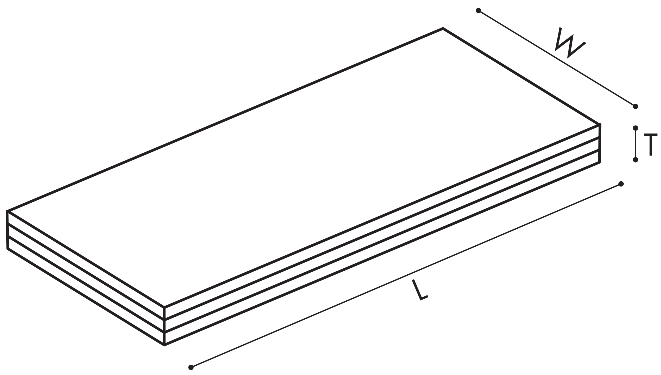


ill. 91: Functions iteration n.3

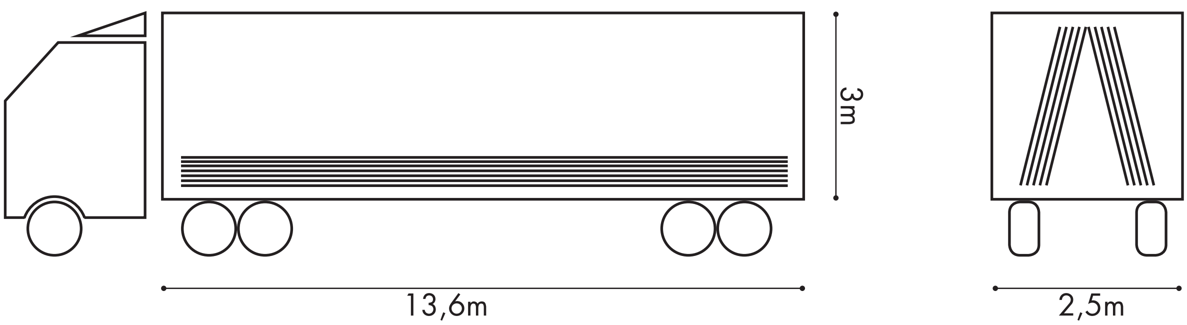
STRUCTURAL GRID

In order to design a modular system a structural grid has been chosen. The spans evaluated have been deducted from CLT elements listed in brochures providers from Finland, Sweden and Austria.
To make the disassembly and transportation easier the dimensions of a truck and the spatial logistic has been involved in these considerations.

	Thickness	Length	Width
FI	3-8 Layers	8m 16m	2,45m 2,95m
SE		8m 30m	1,20m 4,80m
AT		12m 20m	2,40m 3,00m



ill. 92: CLT sizes

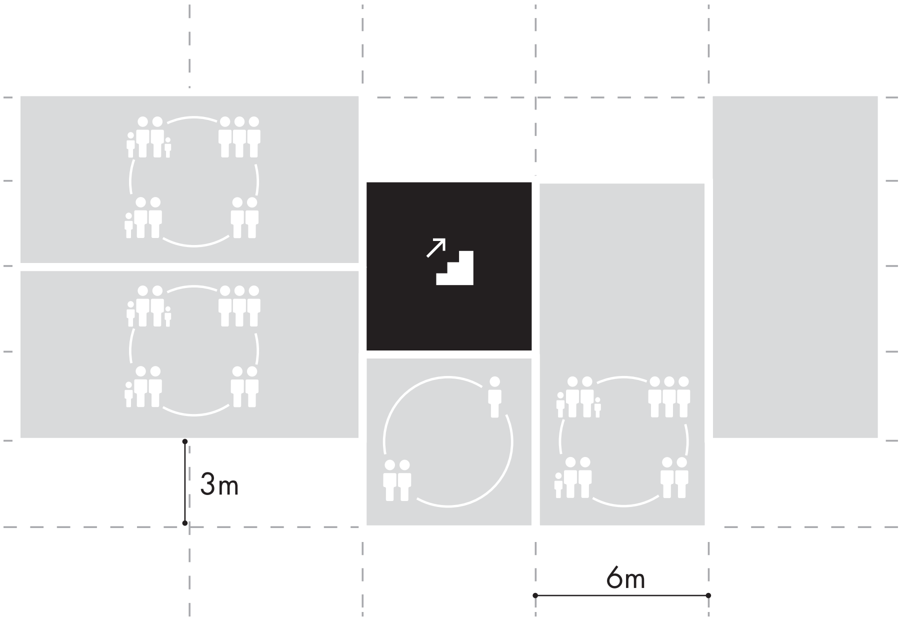


Max 2,95x13,6m
Max 25t (50m^3)

Max 3x13,6m
Max 24t (45m^3)

ill. 93: Truck dimensions

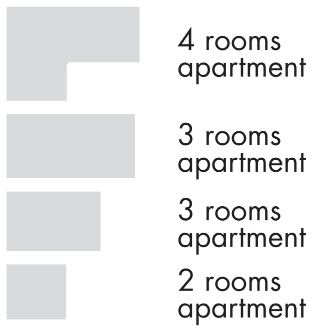
APARTMENTS MODULARITY

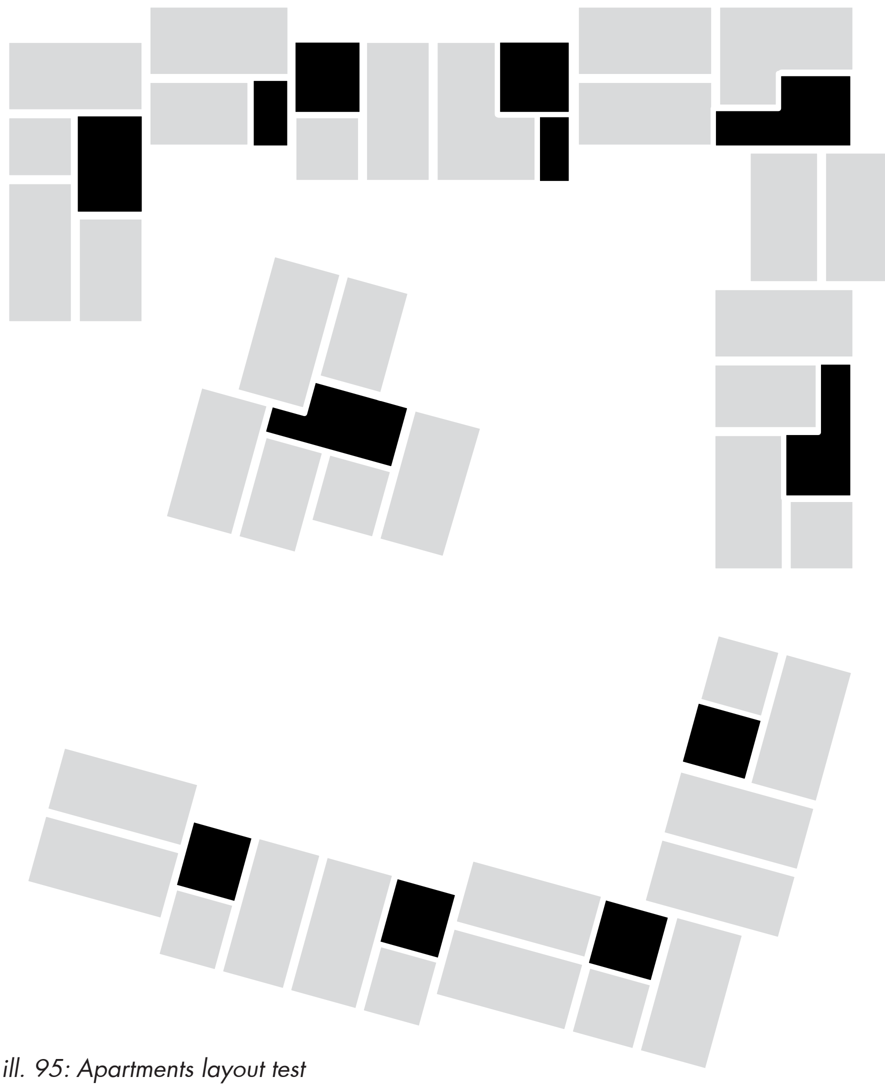


ill. 94: Structural span test

STRUCTURAL SPAN

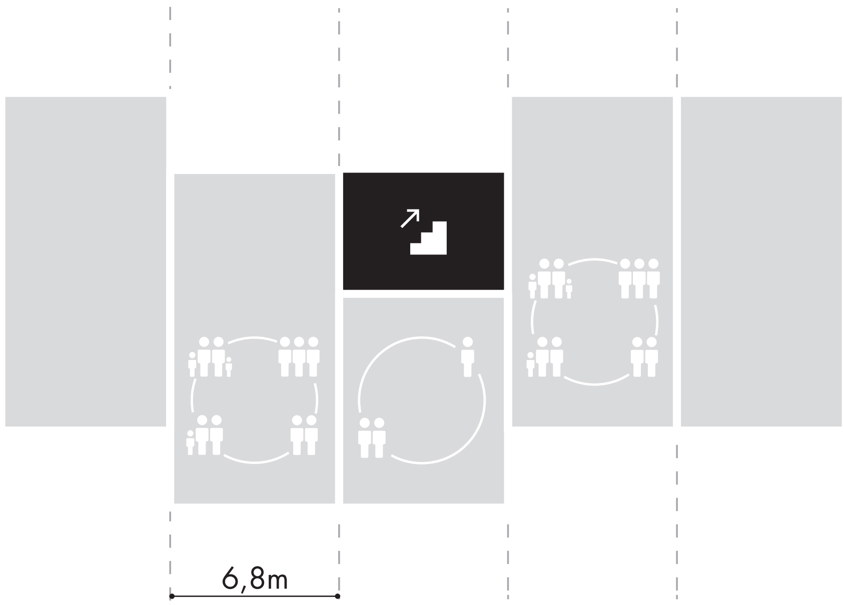
A structural span of 6 meters is optimal to create a system of modular structural panels since it would match with the floor height. Therefore, a single module of 3x12m would cover all the structure needed and allow flexibility and reuse.
On the other hand, the 3m grid results in issue for the internal layout since it doesn't allow to have both living and bedroom in a 6m span. This can be solved by rotating some of the apartments in horizontal that allows to use a 12m span but does not give possibility for a double facing North-South.





The application of the apartments layout to the masterplan generates 4 different modular typologies but results in some exceptions in the corners, in the middle volumes and where the connection with the courtyard is needed.

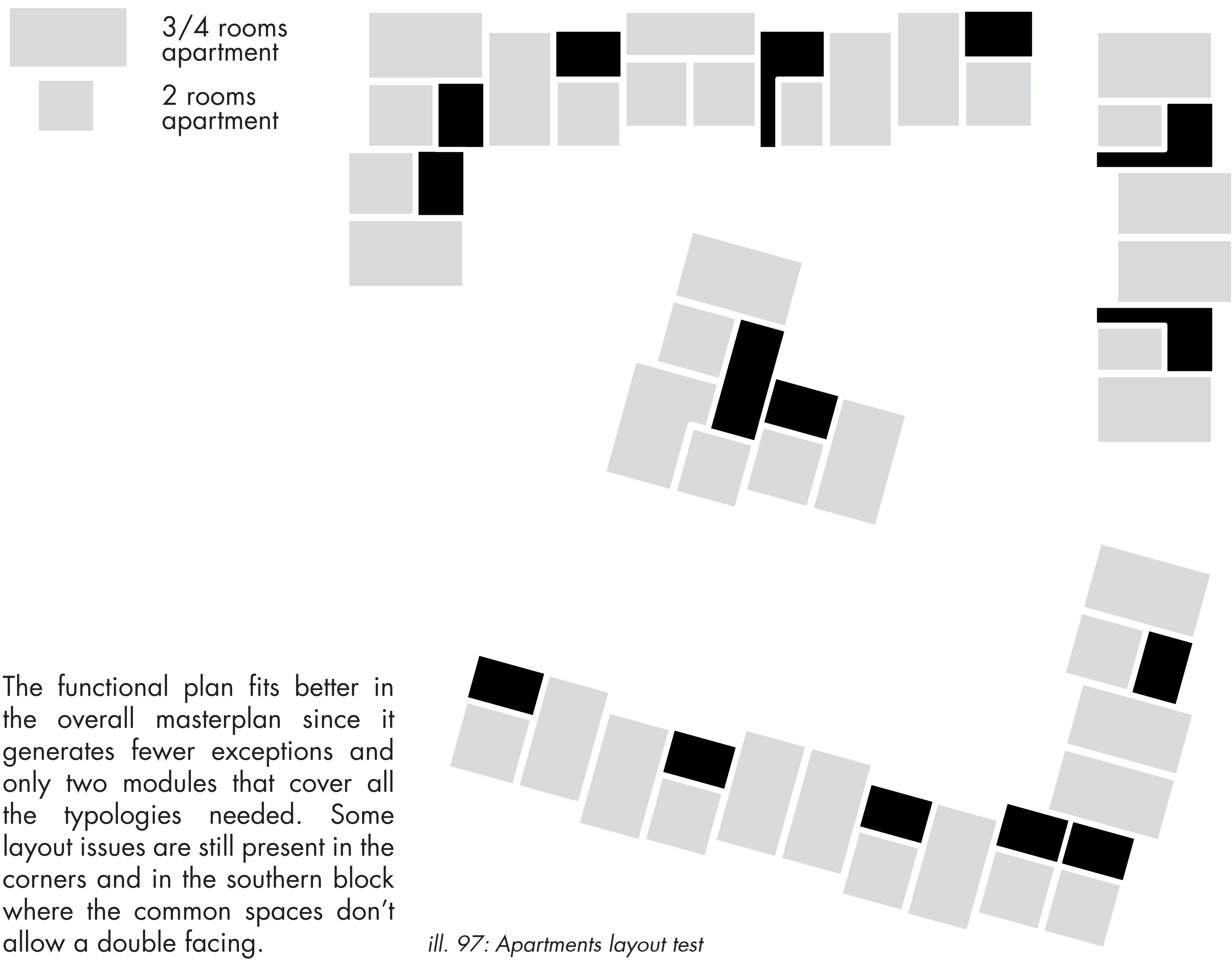
ill. 95: Apartments layout test



ill. 96: Structural span test

FUNCTIONAL SPAN

A span of 6,8m gives the possibility to have double facing and good internal layout.
The increased span in horizontal generates structural modules that are not as regular as the one based on a structural grid but still leave room for flexibility.



The functional plan fits better in the overall masterplan since it generates fewer exceptions and only two modules that cover all the typologies needed. Some layout issues are still present in the corners and in the southern block where the common spaces don't allow a double facing.

ill. 97: Apartments layout test

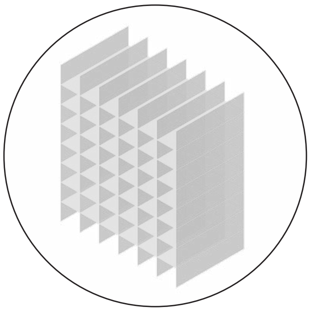
LCA ITERATIONS - STRUCTURE

The following phase consisted in the study of how a CLT timber structure respond in term of LCA in the early design stages by working with simple volumes.
The parameters that have been evaluated are the structural span and height.
The dimensions of the timber structural elements for each iteration have been obtained through Calculatis, an online calculator freely provided by the Finnish CLT supplier Stora Enso (Stora Enso, 2019).
The online calculator uses ULS calculations to verify the CLT element and takes into account the ULS fire verification: since the only option given was to apply plaster cladding this input has been set and it has been assumed that an alternative solution with a similar fire resistance will be used in the final design.
The foundations have been kept fixed in the span tests while for the height iterations a simple proportion with the loads amount has been assumed.
(Appendix 3)

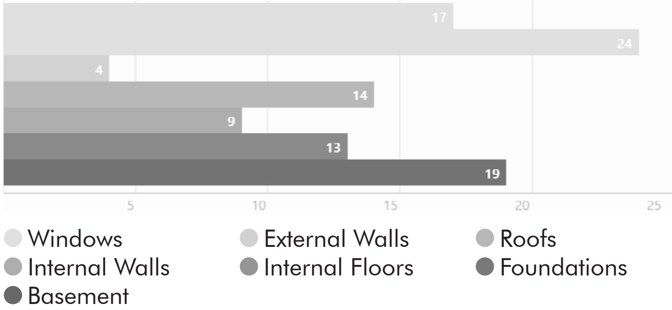
In order to have comparable results a fixed total volume is set.
The structure is defined manually in the Grasshopper definition.
The material assumed are the same for all the iterations and are as follow:
- structure (bearing walls and slabs) in CLT
- external walls in CLT, mineral wool insulation and standard cladding
- roof in CLT, mineral wool insulation and standard cladding
- internal non-bearing partitions in wood panels
- foundations in concrete
- triple glazed windows with wooden frame

STRUCTURAL SPAN

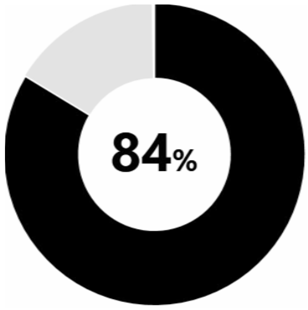
3,4m



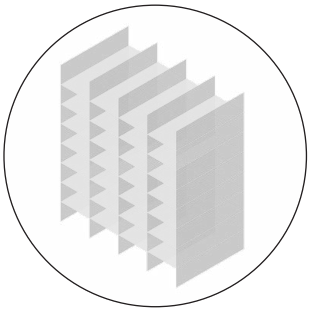
CO_2 GLOBAL WARMING POTENTIAL (%)



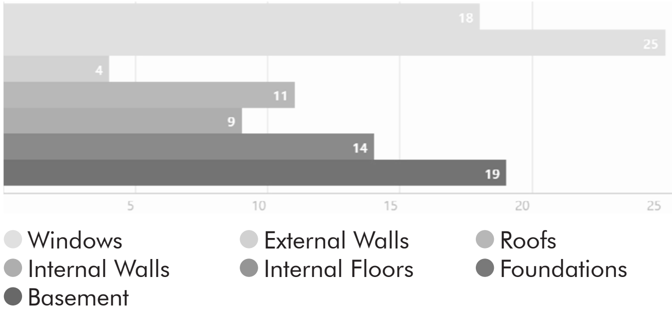
DGNB LCA SCORE



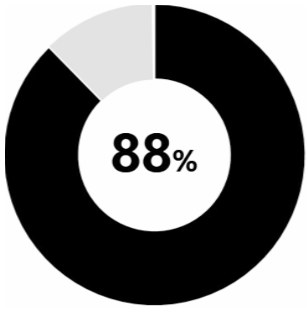
5,1m



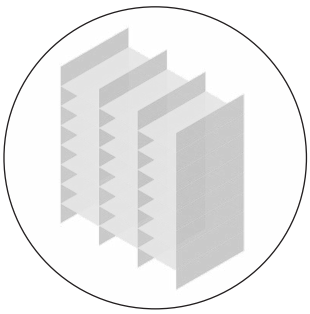
CO_2 GLOBAL WARMING POTENTIAL (%)



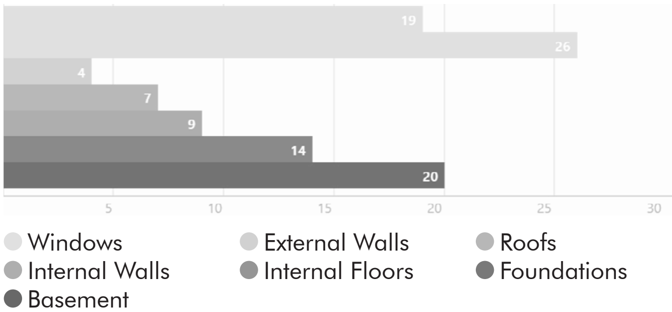
DGNB LCA SCORE



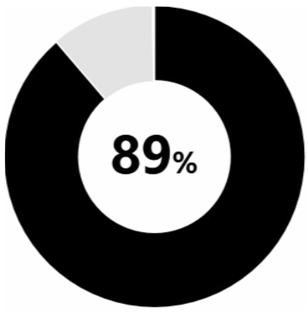
6,8m



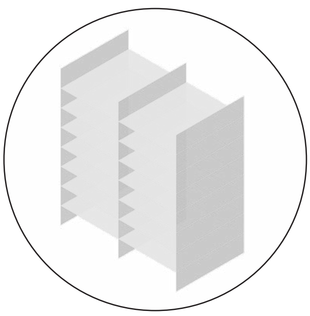
CO_2 GLOBAL WARMING POTENTIAL (%)



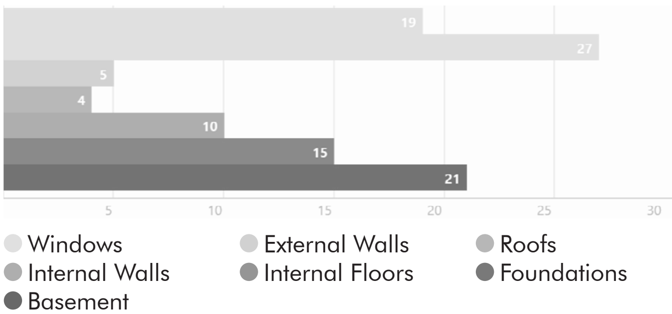
DGNB LCA SCORE



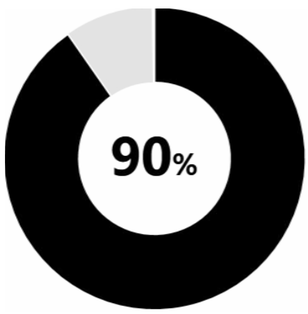
10,2m



CO_2 GLOBAL WARMING POTENTIAL (%)



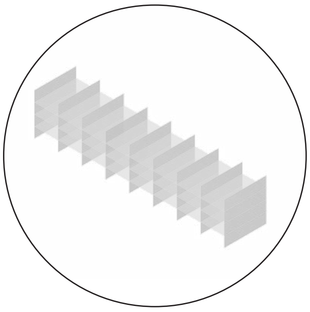
DGNB LCA SCORE



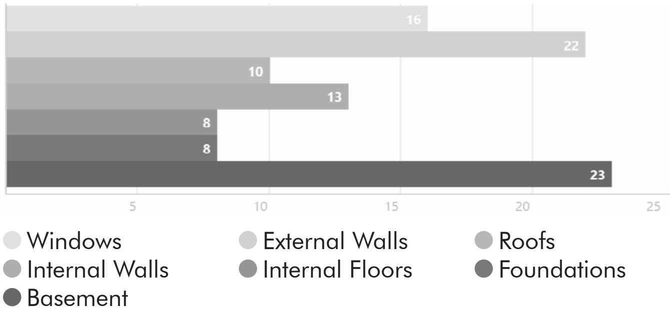
ill. 98: Structural span tests

STRUCTURAL HEIGHT

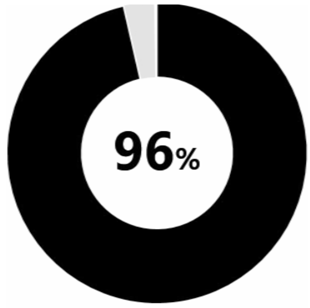
4 STOREYS



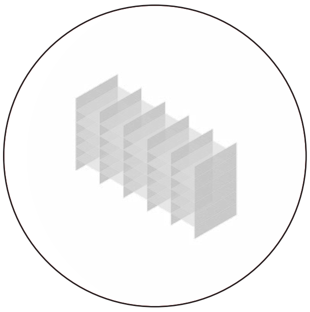
CO_2 GLOBAL WARMING POTENTIAL (%)



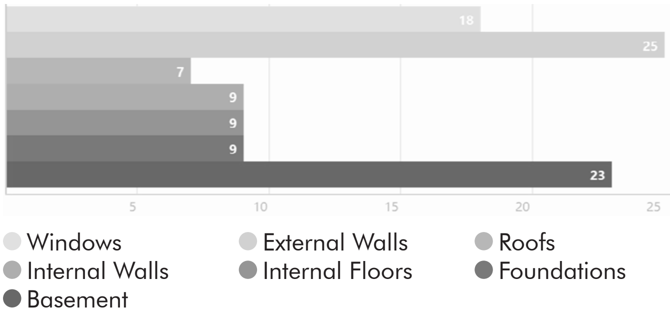
DGNB LCA SCORE



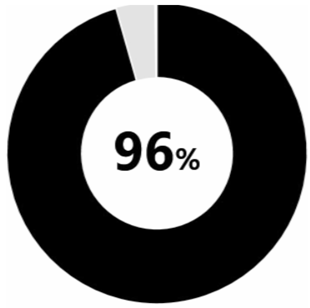
6 STOREYS



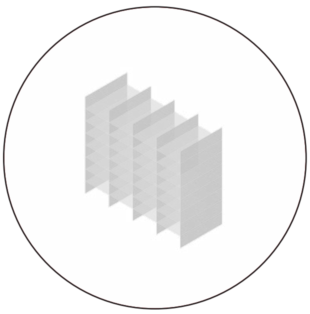
CO_2 GLOBAL WARMING POTENTIAL (%)



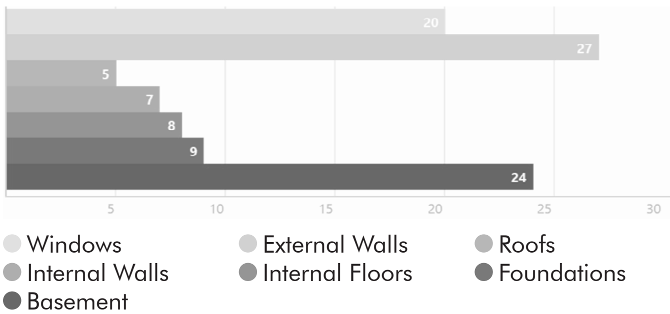
DGNB LCA SCORE



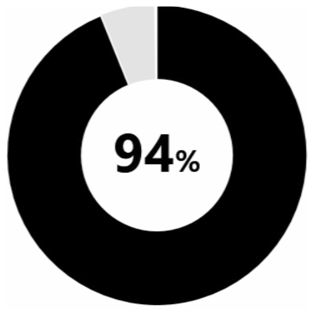
8 STOREYS



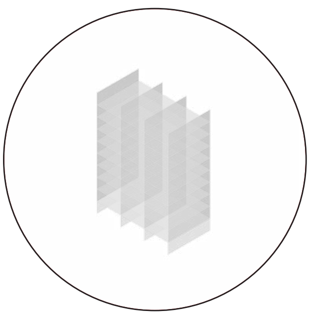
CO_2 GLOBAL WARMING POTENTIAL (%)



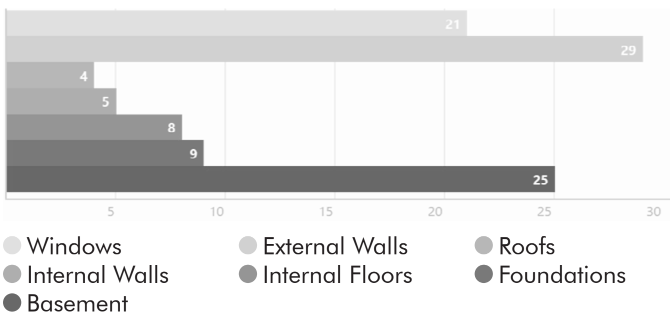
DGNB LCA SCORE



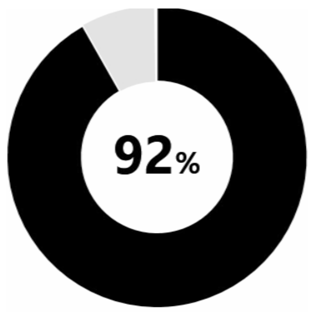
10 STOREYS



CO_2 GLOBAL WARMING POTENTIAL (%)



DGNB LCA SCORE

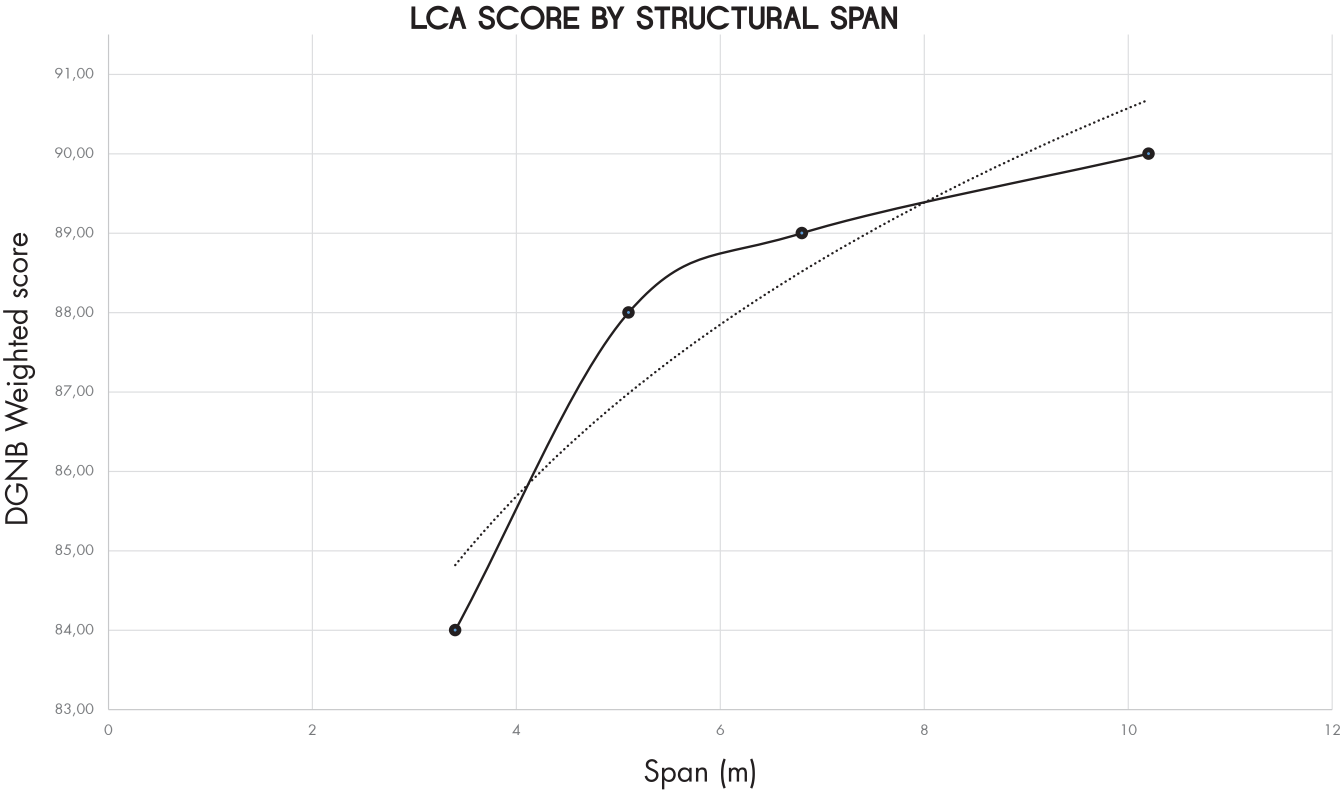


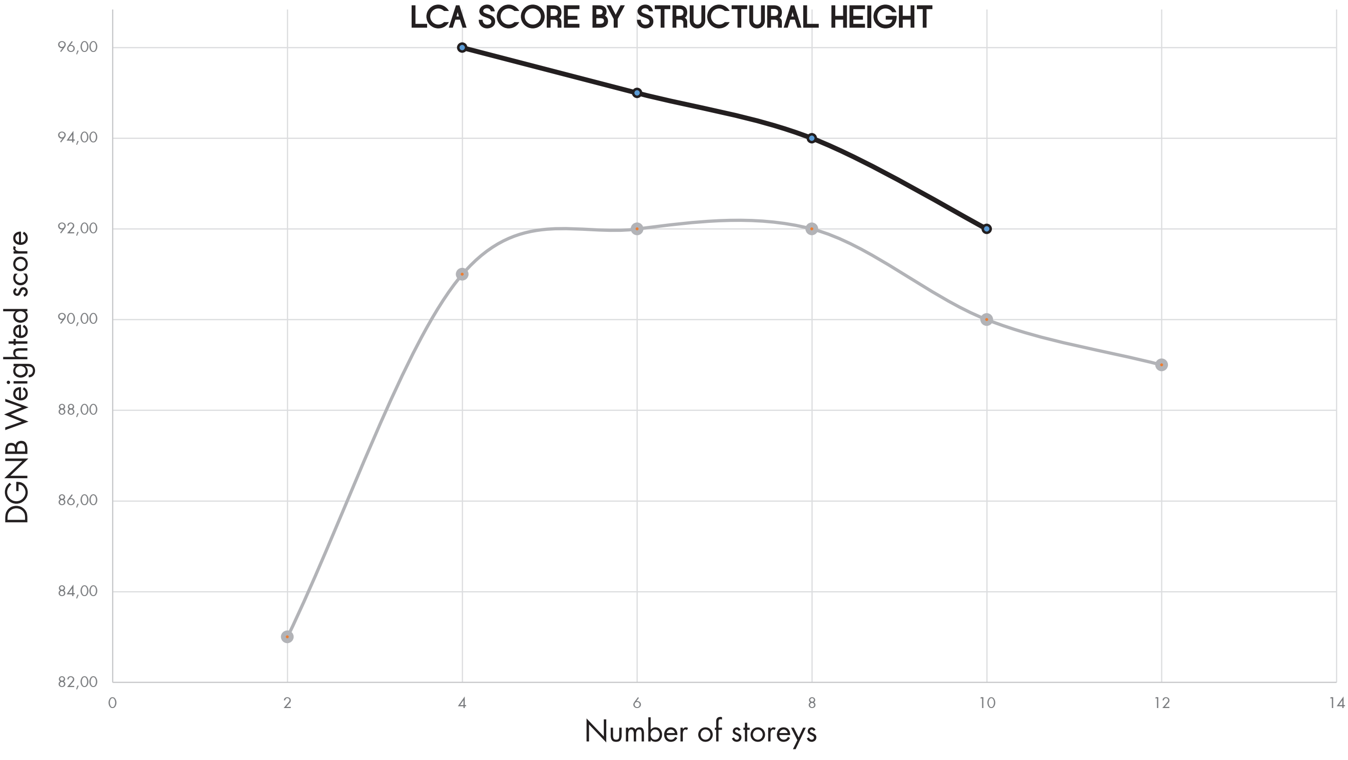
ill. 99: Structural height tests

RESULTS & CONCLUSIONS

The variations in the structural span show an improvement of the LCA score directly proportional to the increase of the distance.
This is due to the reduced amount of bearing walls needed which affects the results more than the opposite increase of width of the CLT elements.

The structural height iterations show a trend similar to the general height iterations previously done (Ill.00). The higher results are motivated by the manually inserted structure that is smaller than the one assumed in the first tests.
The LCA score decreases when increasing the number of storeys mainly due to the increase of external walls surface. The internal structure surface is almost the same in all the cases and the different width doesn't affect the results in a relevant way. The foundations impact is slightly reduced in the higher cases due to the smaller area of the plateau.





ill. 100, 101: Graphs showing the structural iterations results

INTERIORS

The last stage of the process consisted in the detailed design of the interiors of the apartments, with a focus on the surfaces' material.
Even though the main goal is to expose wood as much as possible, plaster claddings are present on specific surfaces both for functional and aesthetic reasons.
First, plaster has been applied on surfaces that are directly exposed to the risk of fire and this occurs in particular in the kitchen areas.
Another functional use of plaster is as protection for surfaces exposed to humidity, water and splashes, for instance in the bathrooms and, again, in the kitchens. Surfaces covered by plaster are also easier to be cleaned, so this material can be placed according to this consideration as well.
Plaster, in addition, can have advantages in term of visual comfort: light-coloured plaster is able to reflect lighter than wood, making the room brighter.
Wood remains the main material in the environments and the combination and contrast with a different one makes it even more emphasized.
Different compositions of the materials have been tested according first to the previously mentioned functional considerations and then to aesthetic qualities.
After some research on how to address the fire safety of the apartments, a solution that does not involve plaster have been adopted: the over-dimensioning of the structure, combined with the use of a phosphate-based fire retarder. An over-sizing of about 8cm of the CLT elements should be enough to allow a load-bearing capacity of 120 minutes standard-fire, required by the legislation.
The amount of extra thickness has been calculated by multiplying the charring rate of treated CLT elements by the time required (0,62 mm/min*120min) (Johansen and Werenberg, 2019).
Unfortunately, the behaviour of this solution in term of LCA is not easy to predict due to the uncertainties connected with the fire-retardant production: this made impossible to compare this solution with a standard one with plasterboard.

ill. 102: Interior materials composition 1

ill. 103: Interior materials composition 2

P R O J E C T

CONCEPT

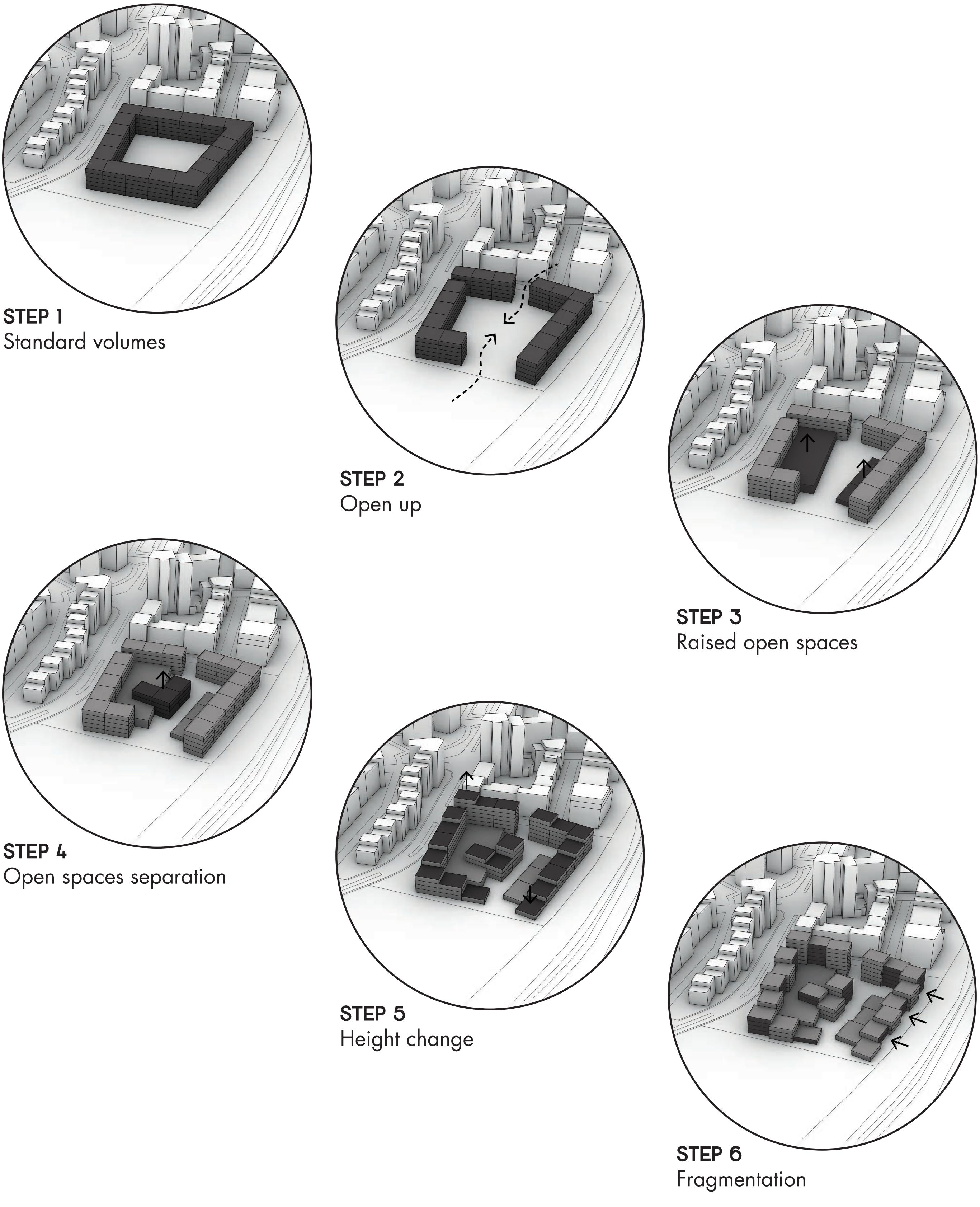
Godsbanen Zero: a new center of interaction for the area, a close-to-Zero environmental impact building, a starting point for the era of wood in the construction sector.

A pile of wooden boxes that frame a mixture of public and private that co-live in a balanced and Zero-impact way. Wood is both a canvas on which these activities come to life and a friendly companion that is involved in the everyday life of the people.

ill. 104: Concept illustration

SHAPE

The design criteria and the process phase brought to the definition of the final shape of the building resulted from the following main considerations:



ill. 105: Shape diagram

MASTERPLAN

The building complex is located between the new buildings of Godsbanen and the event park. The different blocks are split and a semi-public courtyard takes place in the middle, directly accessible from the park and from the city and closed towards the main road and the rails. The pedestrian access from Godsbanen is connected more to the new path made on the old rails and less to the inner courtyard, in order to keep a more private character but still remaining open. The other side, instead, is very open and connected with the park and with a border that slowly blurs. The buildings keep the alignment with the urban surrounding and follow the characteristic fragmentation of volumes. Most of the roofs are practicable just for maintenance, while some are accessible even by the public with open air functions and seats.

PROJECT NUMBERS

Plot Size:	10.000 m^2	
Gross area:	19.345 m^2	
FAR:	194%	
Parking:	4.112 m^2	21%
Public:	2.096 m^2	11%
Private:	13.137 m^2	68%
- Dwellings:	11.775 m^2	
- Common:	1.362 m^2	
Number of units:		140
- 1 room		55
- 3/4 room		85
Total potential residents:		450
Car parking lots:		150
Covered bike parking lots:		370

ill. 106: Masterplan - 1:500

THIRD FLOOR PLAN

The complex hosts 140 apartments in total, all provided with bedrooms, kitchen, living room, bathroom and private balcony facing south. The apartments follow a modular scheme and are independent one to another, including in the project the LCA strategies of prefabrication, modularity and design for disassembly. The internal partitions are flexible as well with the possibility to be easily moved, removed or added. The upper floors are mainly occupied by dwellings, but in some cases the public functions reach even the last floors resulting in a more mixed-use building.

ill. 107: Third floor plan - 1:500

SECOND FLOOR PLAN

The elevated courtyard is accessible both from the outside through public stairs and elevators or, by the occupants, directly from the building. Playful stairs connect the different levels of the landscape and are integrated with sitting spaces. Even if the courtyard is accessible by the public it keeps a semi-private character being separated from the event park by the height difference and by the buildings themselves. In this courtyard there are open common spaces, children playgrounds and vegetable gardens where the users can grow and even sell their own products, including in the project the LCA strategy about urban farming.

ill. 108: Second floor plan - 1:500

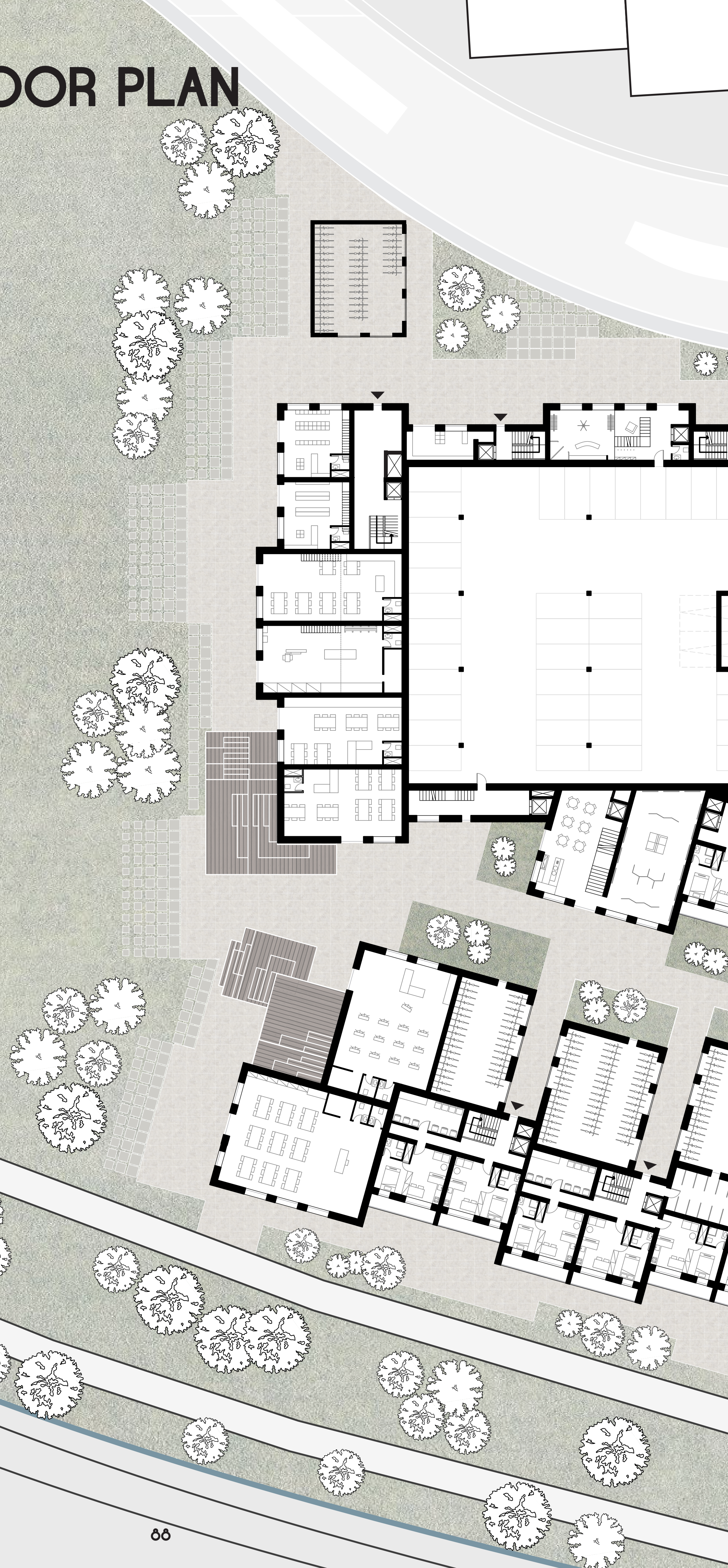
FIRST FLOOR PLAN

While on the first floor of the lower block there are apartments, in the upper ones there are shared and public facilities. Shared spaces such as laundry rooms and storages are directly accessible from the private stairs. All the spaces at the second floor are next to the two storeys parking that has room for 150 cars and can be used both by the users and the public. Car sharing is also included as a LCA strategy. The lower block has access to a second elevated courtyard with playgrounds, gardens and spaces for children.

ill. 109: First floor plan - 1:500

GROUND FLOOR PLAN

On the ground floor, the main accesses to the apartments, to the public activities and to the parking are distributed. Most of the public activities are gathered on the ground floor. Towards the main street there are mostly retails, thrift shops and cafés, reflecting the typology of activities present in the new buildings on the other side. In some cases, they occupy more than one storey. The functions facing the park, instead, include a reuse station, a small grocery, and workshops with activities such as carpentry, ceramics and graphics. These functions give to the project the LCA quality of sharing, reusing and upcycling. Other spaces such as exhibition areas and conference rooms are included as well. Bike parking, both private and public, and common spaces for the occupants are distributed along the different sides of the complex and below the elevated courtyards. The landscape is the result of the integration of the different heights of the courtyard and materials compositions. Wooden stairs connect the different levels alternating with decks and seats and stone pavements define the paths combining with green spaces and blurring towards the park.

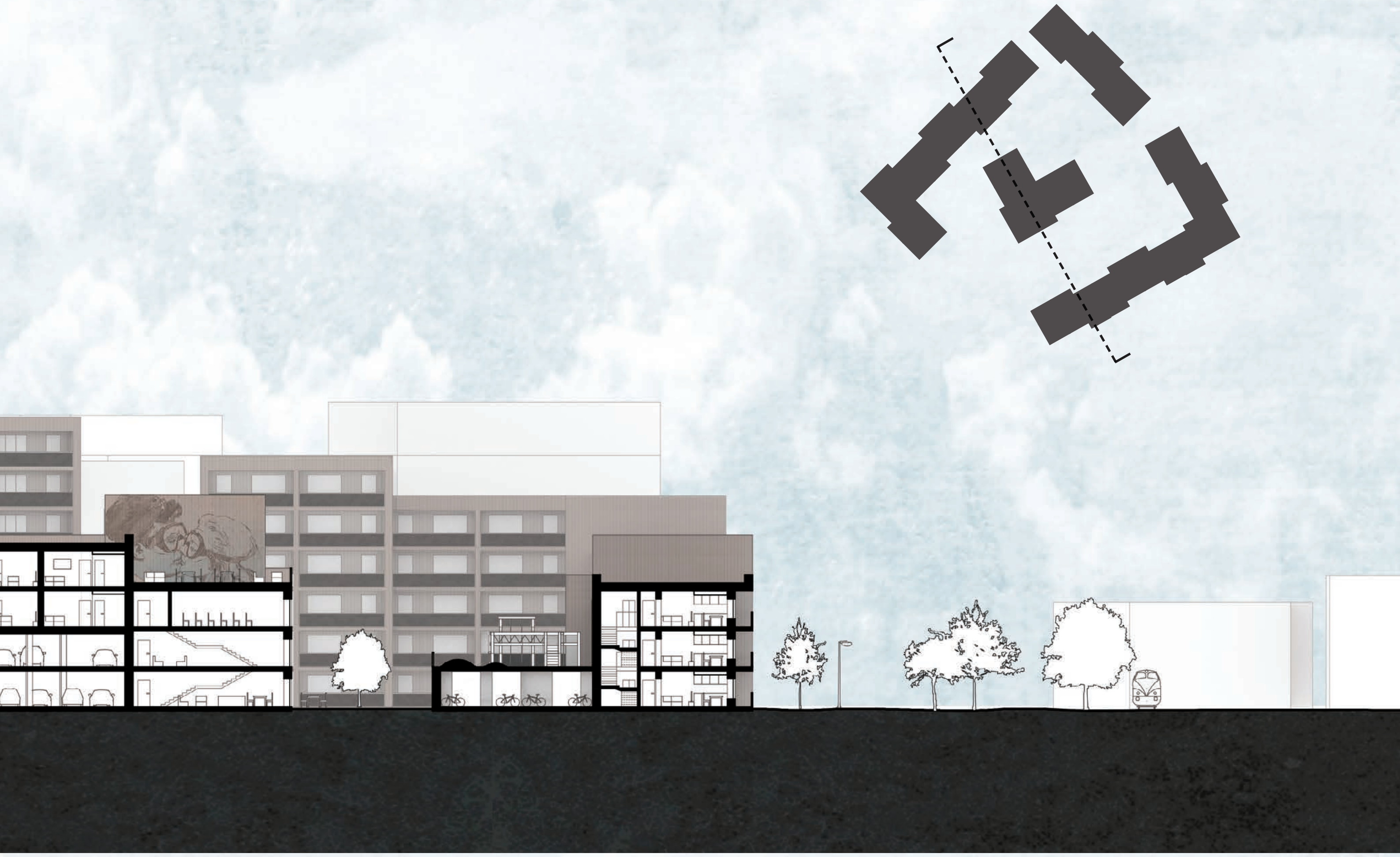


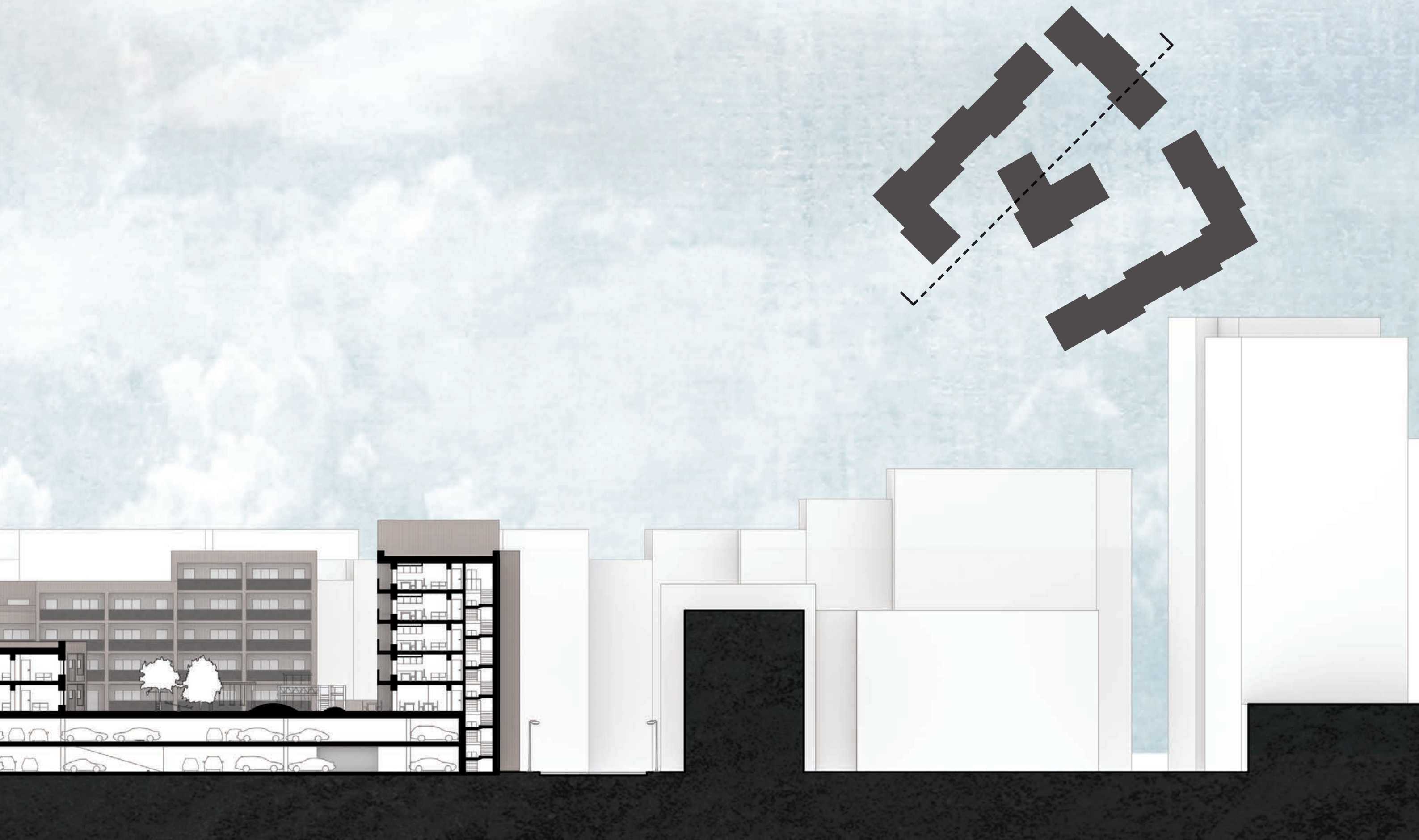
ill. 110: Ground floor plan - 1:500

CROSS SECTIONS

The heights follow the surrounding buildings with their characteristic steps shape and decrease towards the park. In section, the mix of different uses between dwellings, shared and public functions, the parking and the elevated courtyard are visible.

ill. 111, 112: Cross sections - 1:500

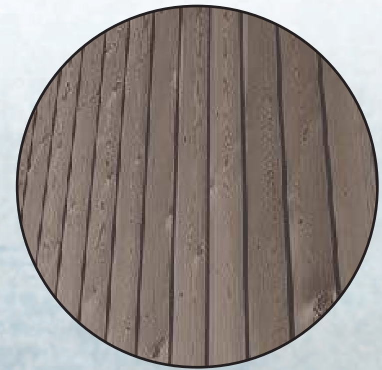




NORTH-WEST ELEVATION

STREET ART
Street art is used on big blind facades, following the characteristics and the vision of the area.

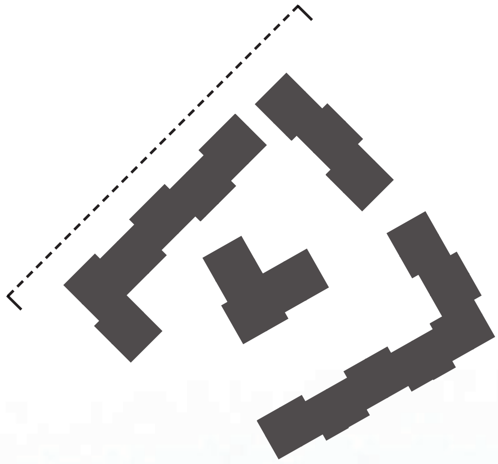
ill. 113: Street art



ROUGH AND PROCESSED LARCH
The external cladding is in larch wood. It is kept slightly rough except for the surfaces in proximity of the apartments where it is lighter and smoother.

ill. 114: Larch wood

ill. 116: North-West Elevation - 1:250



STRING COURSE

String courses prevent precipitation water to run along the whole wood facade.

ill. 115: String course

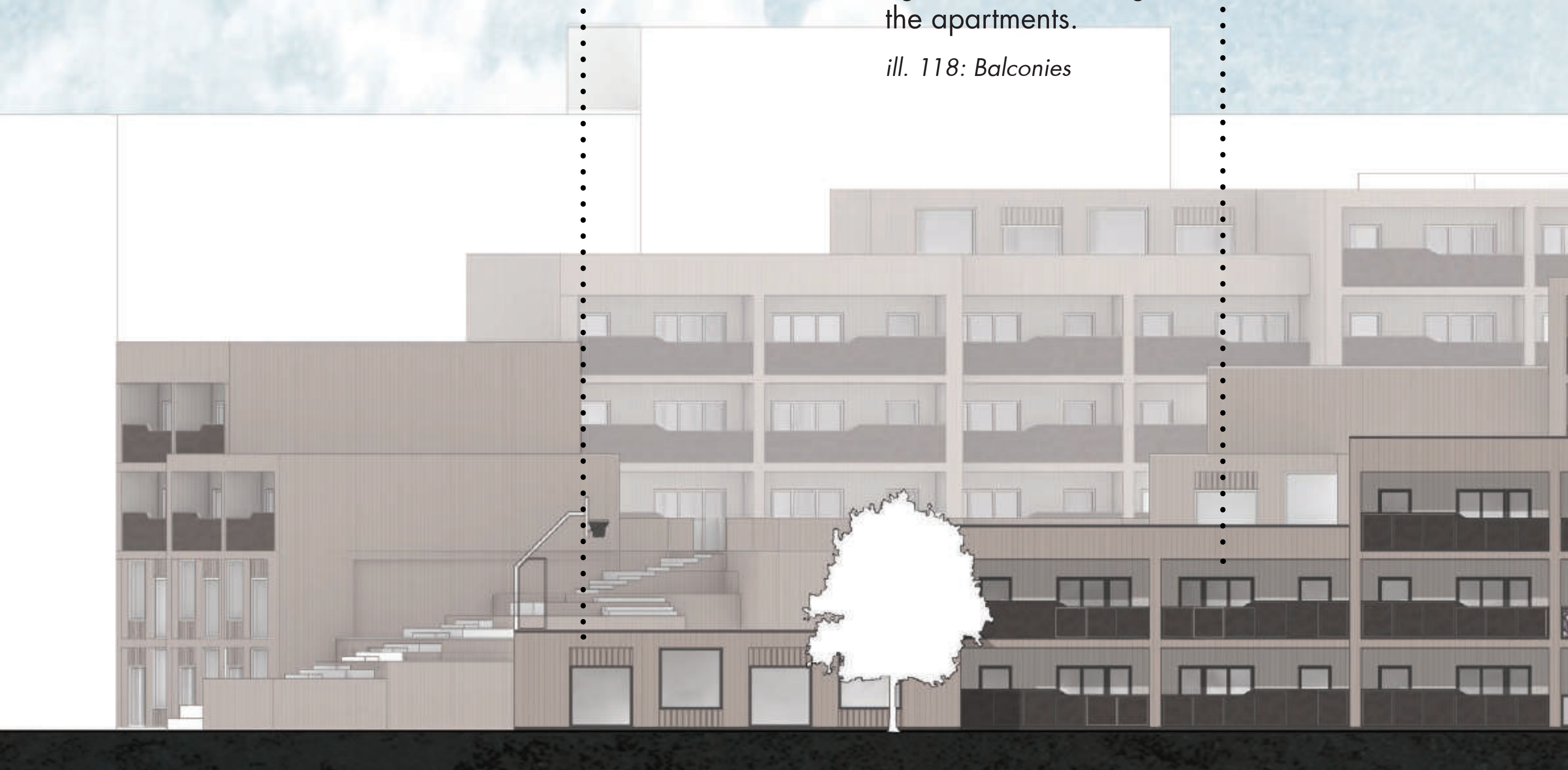
SOUTH-EAST ELEVATION

DIFFERENT PATTERNS
Different patterns are used for the wood boards composition to make the facade look more playful.

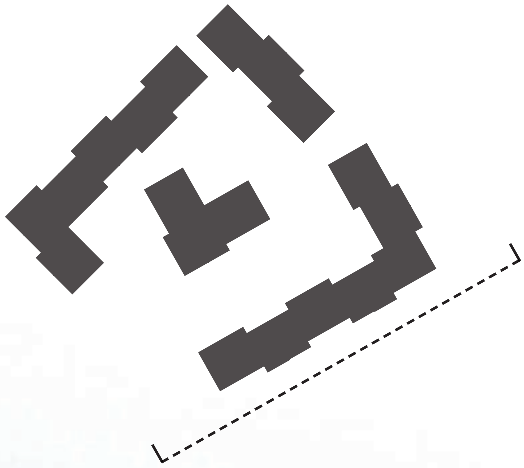
ill. 117: Different patterns

BALCONIES
Balconies are designed as recesses in the facade. Larch wood here is kept smoother to be more pleasant to the touch and lighter to let more light in the apartments.

ill. 118: Balconies



ill. 120: South-East Elevation - 1:250



ARTISTIC PANELS

Photovoltaic panels are placed on the railings and they give the possibility to be personalized by the user with a particular printed film.

ill. 119: Artistic solar panels


Parkering

ill. 121: View from the main street

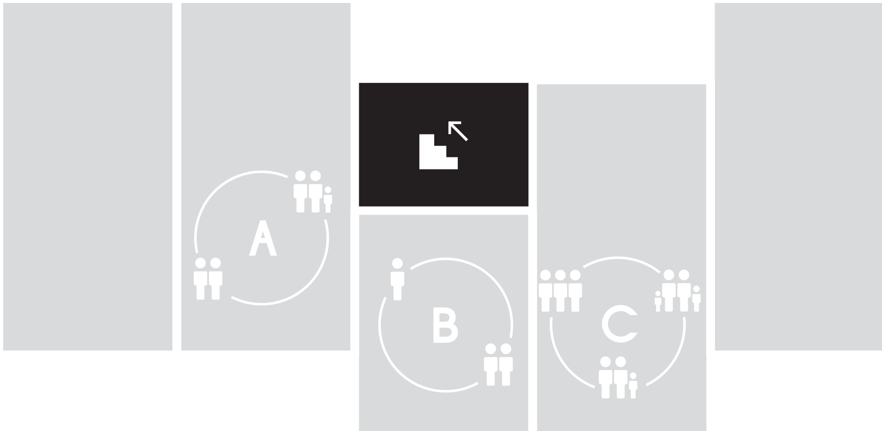
APARTMENTS TYPOLOGIES

All the apartments are based on a standard module and are therefore flexible. All the typologies have a balcony on the south facade that gives room to some outdoor activities while shading the exposed windows.

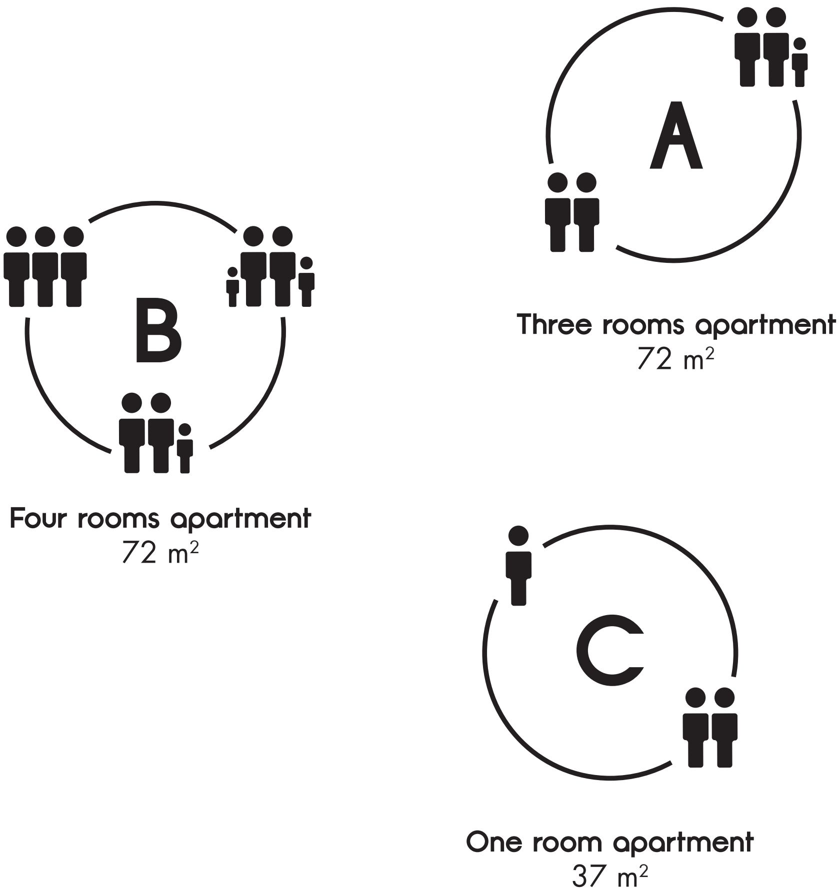
- Typology A is a three rooms apartment for couples with one child. The layout occupies a module and consists in two bedrooms, one facing south-east/west and one facing north-west/east, and a big open space living room/kitchen.
This typology can be easily turned into the typology C by adding a partition wall to define an additional bedroom (for an extra child of for a change of residents).

- Typology B is a four-rooms apartment for students and families with one or more children. The layout occupies a module and consists in three bedrooms, one facing south-east/west and two facing north-west/east, and a living room/ kitchen.
This typology can be easily turned into the typology A by removing a partition wall (and therefore a room) to increase the living room area (in case a resident moves out or due to a resident's change).

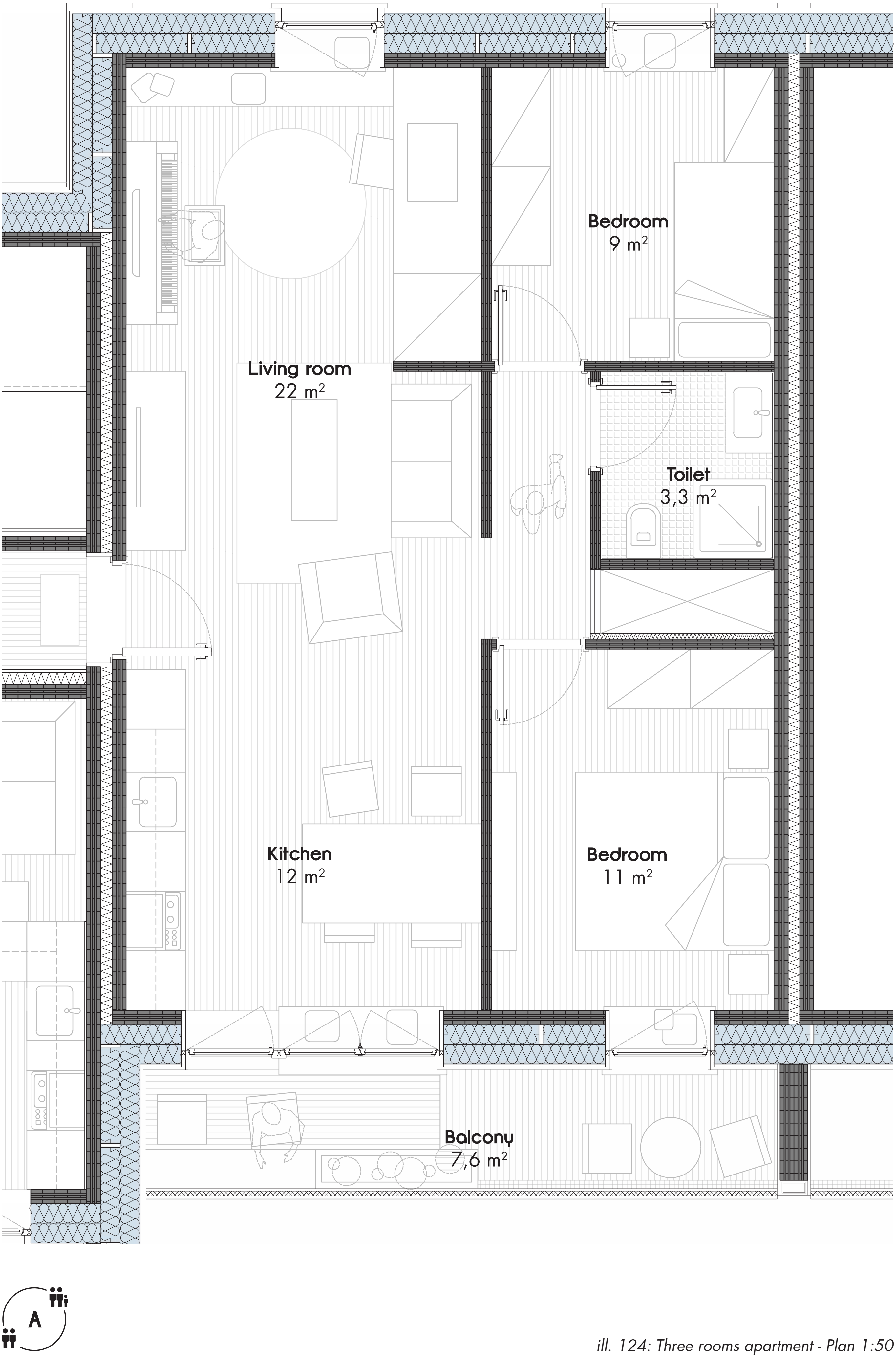
- Typology C is a one room apartment for singles and couples with no children. It consists in an open plan layout with a small living room, a kitchen and a bedroom divided only by furniture. This typology is combined in the same module with the staircases.



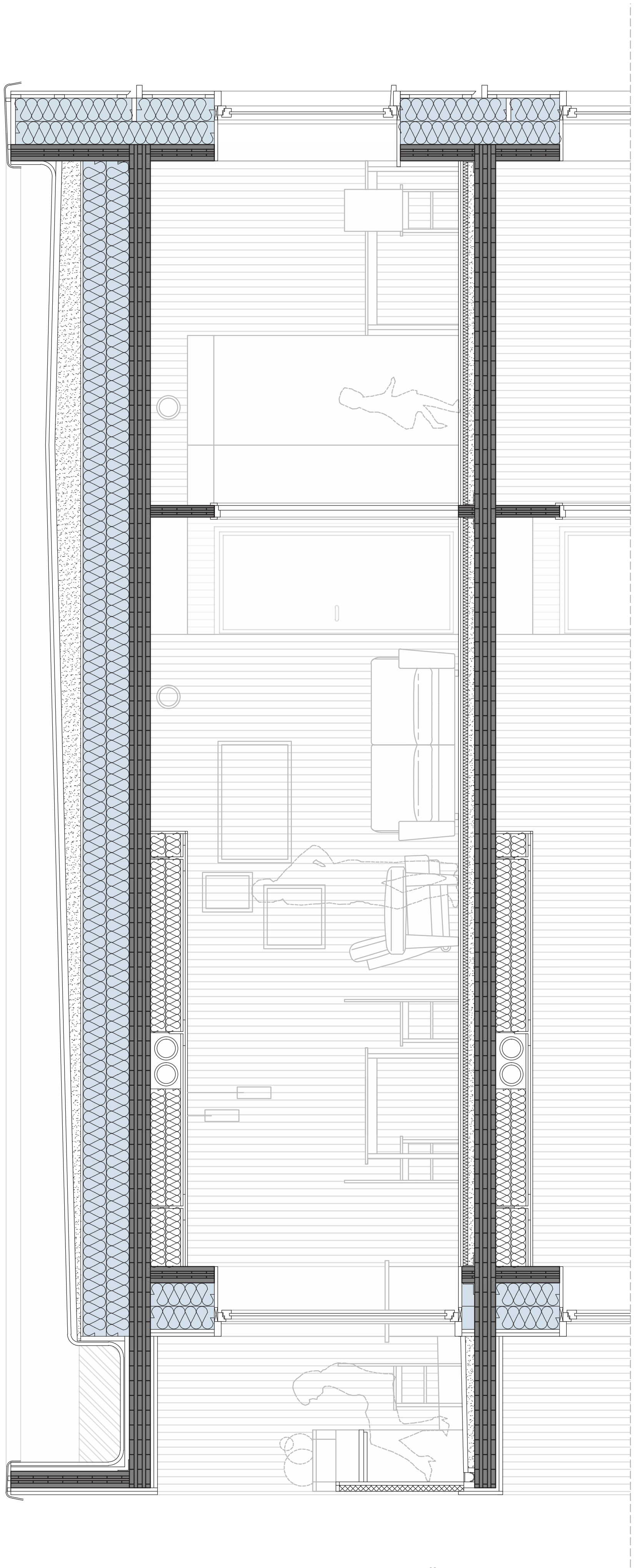
ill. 122: Apartments composition



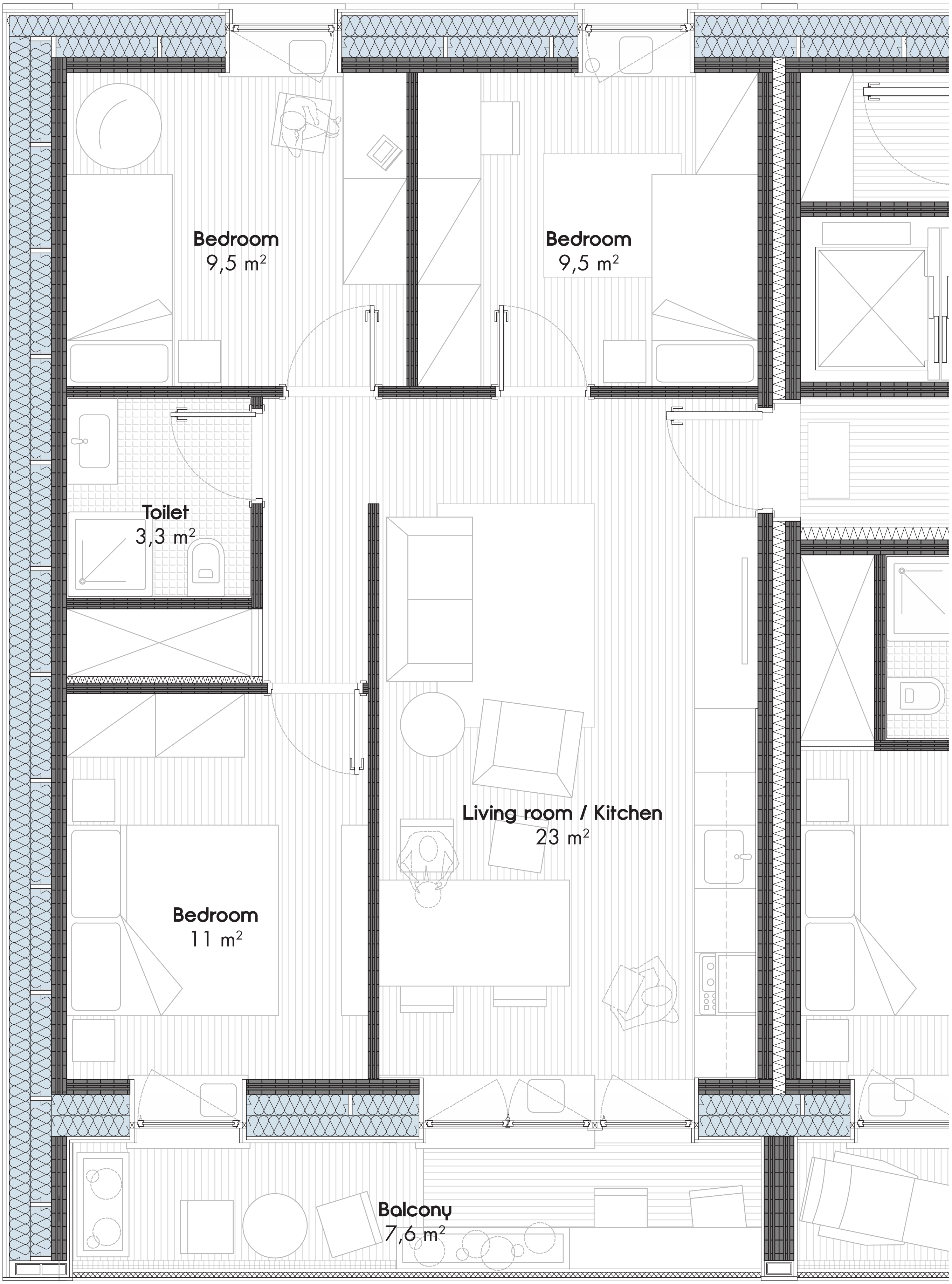
ill. 123: Apartments typologies



ill. 124: Three rooms apartment - Plan 1:50

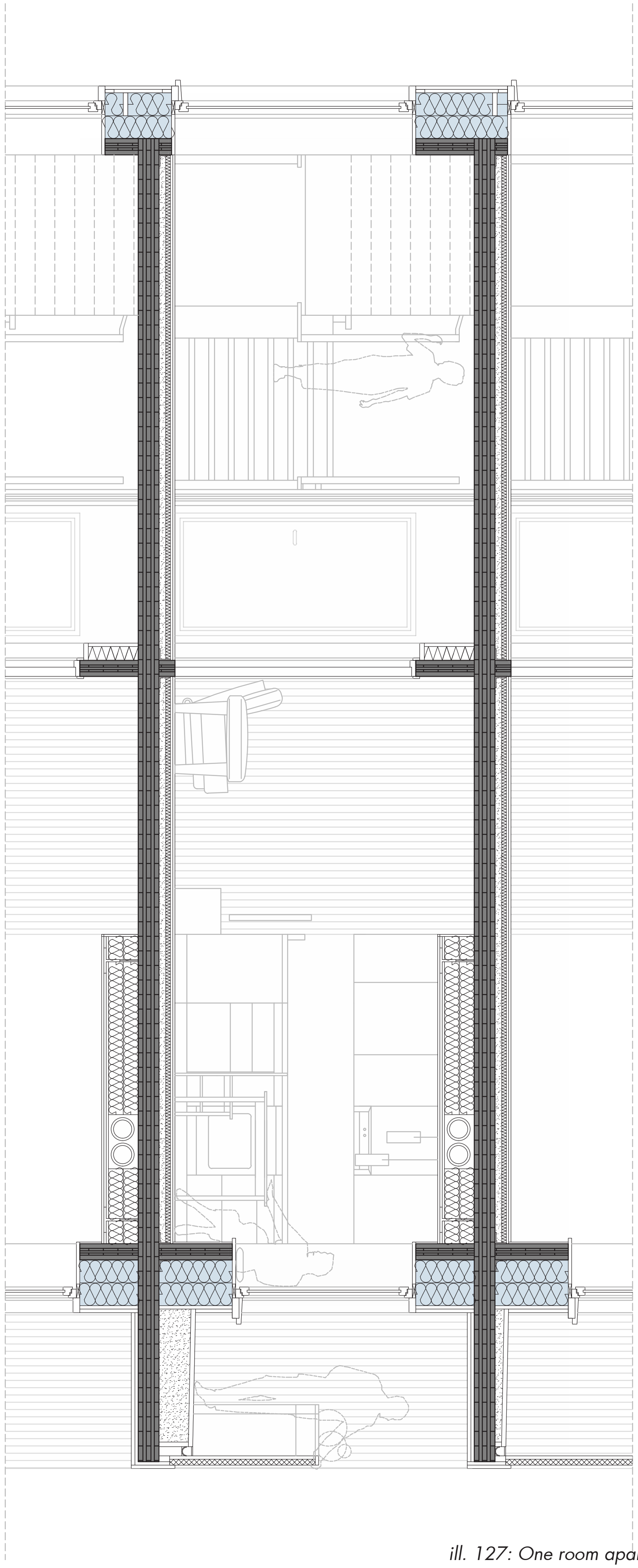


ill. 125: Four rooms apartment - Section 1:50

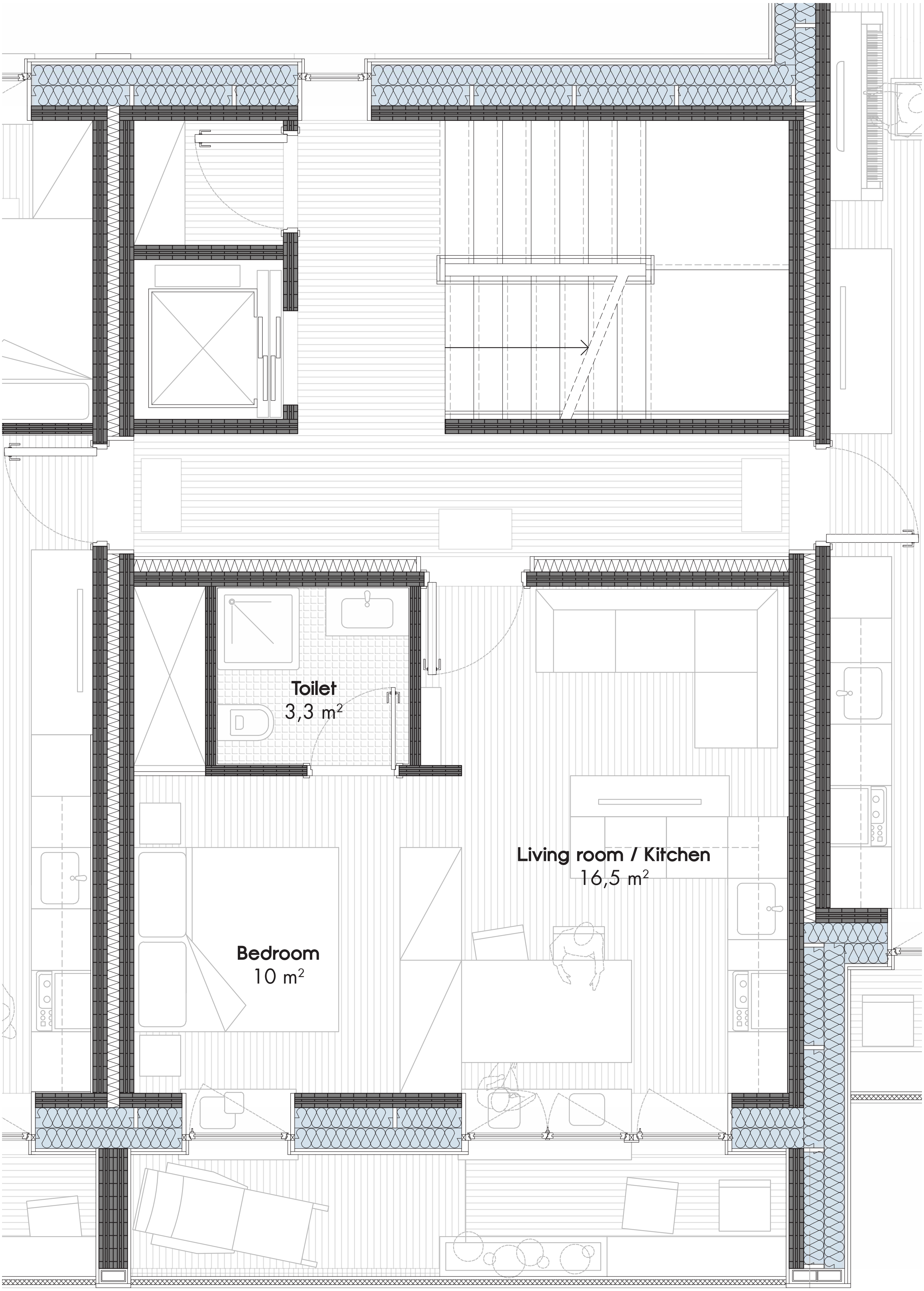


B

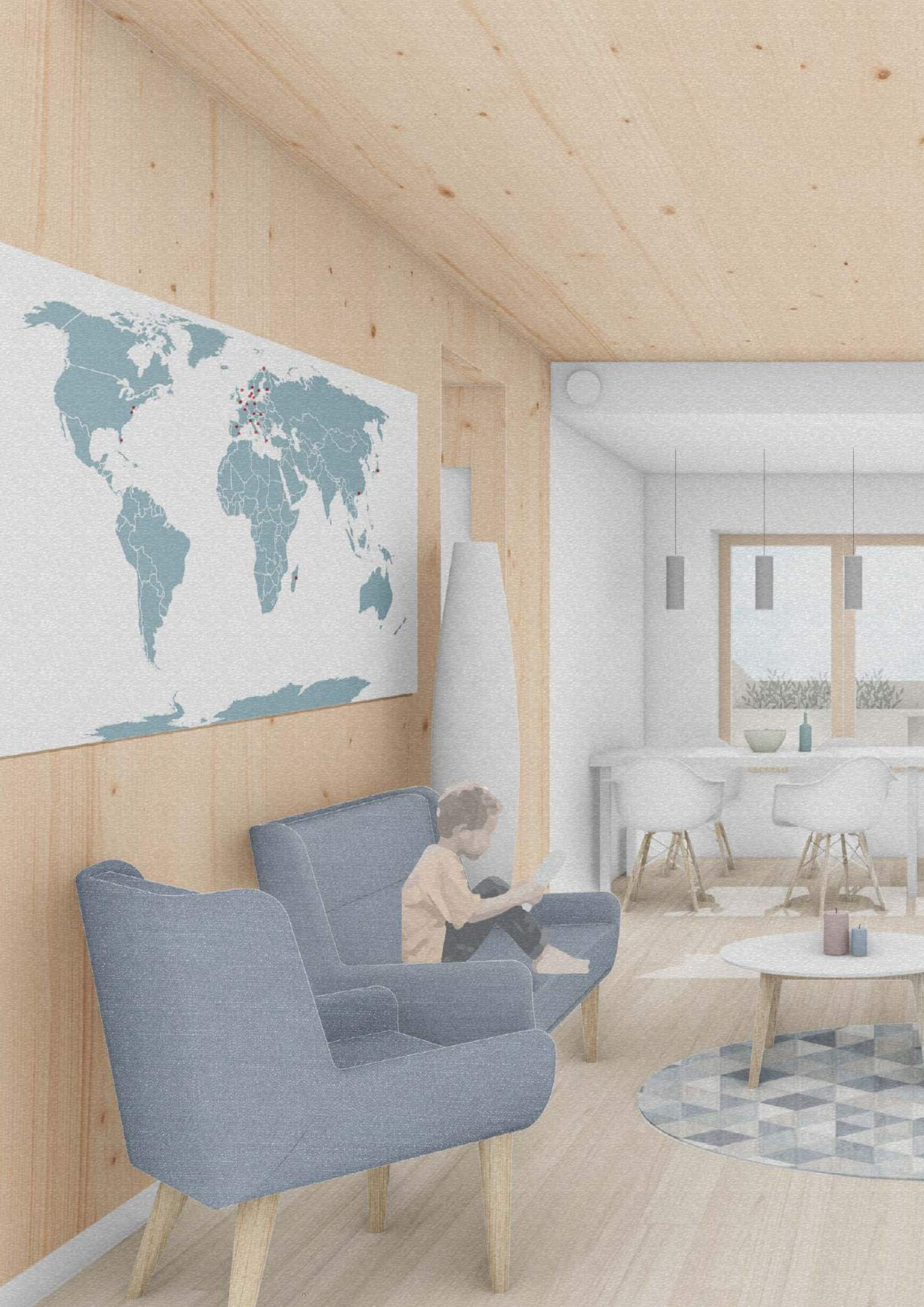
ill. 126: Four rooms apartment - Plan 1:50



ill. 127: One room apartment - Section 1:50



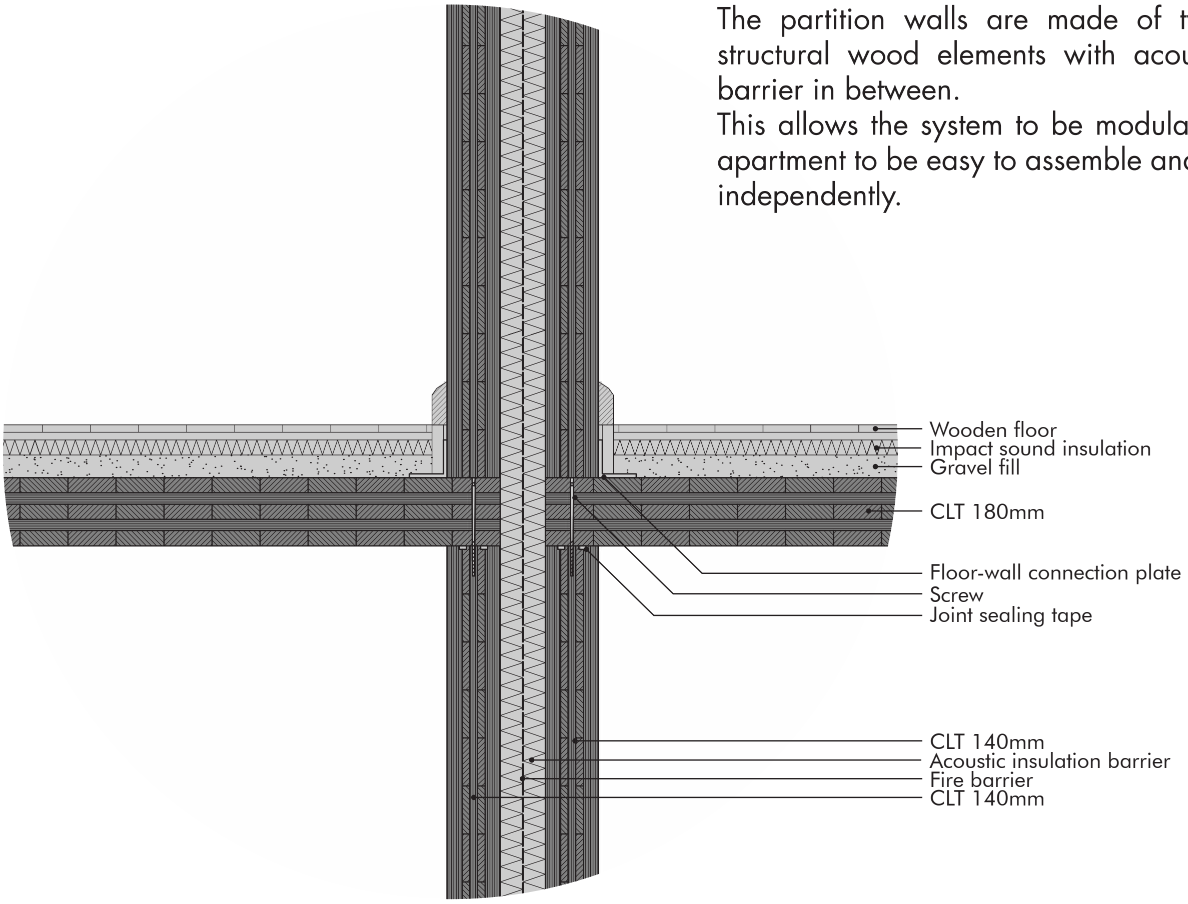
ill. 128: One room apartment - Plan 1:50



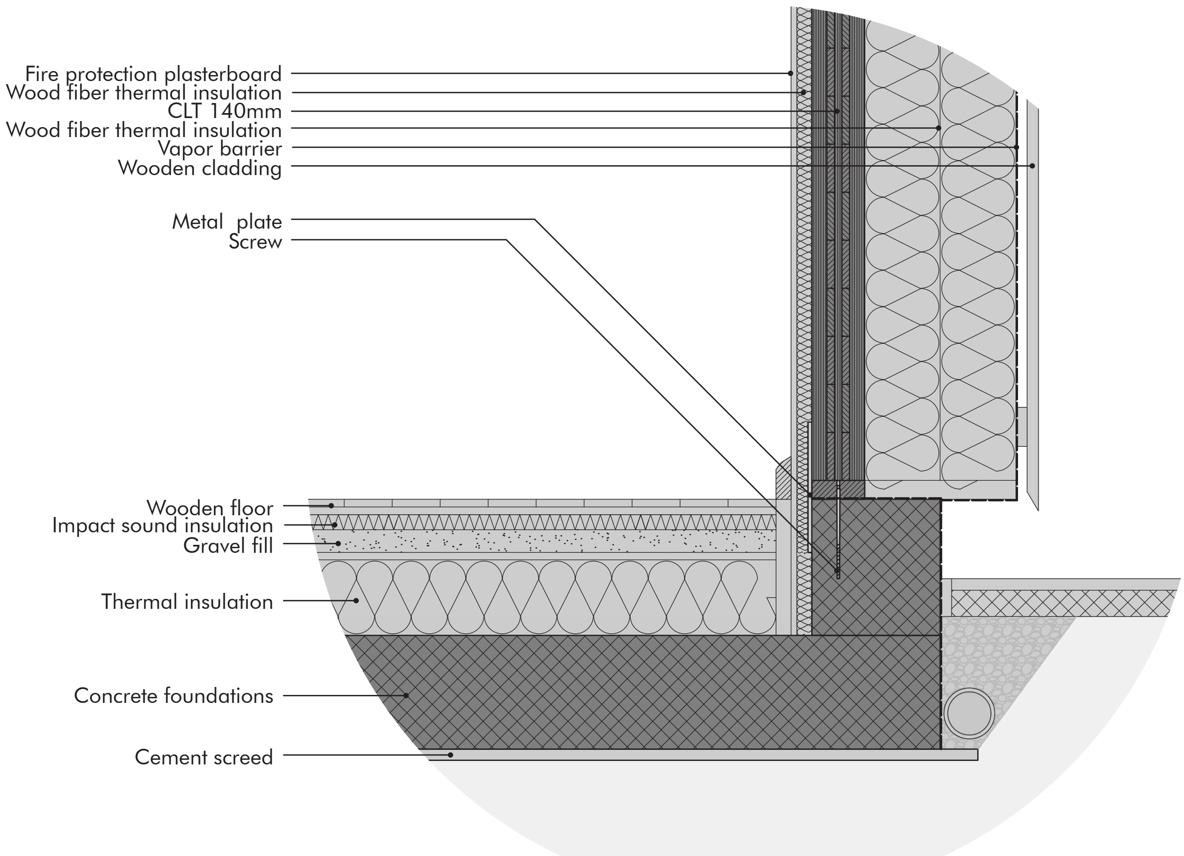
ill. 129: Interior view of the apartment

CONSTRUCTION DETAILS

The partition walls are made of two detached structural wood elements with acoustic and fire barrier in between.
This allows the system to be modular letting each apartment to be easy to assemble and disassemble independently.



ill. 130: Apartments partition walls detail 1:20



ill. 131: Ground connection detail 1:20

BENEFITS OF WOOD

Designing with timber brings up a series of advantages and disadvantages, if compared with traditional steel or concrete solutions.

SUSTAINABILITY

The CLT structure requires way less CO_2 to be processed and produced than all the other structural materials. The CO_2 storage capacity and the fact that it relies on a renewable source such as forests, makes timber, by far, the most sustainable of materials. The negative emission coming from the CO_2 storage capacity can potentially result in CO_2 neutral or even negative building.

FAST CONSTRUCTION & DISASSEMBLY

The dry joints and the prefabrication allow short construction times. The easy dry joints, made mostly with screws, make the whole construction process easier to manage and allow the disassembly and reuse. Furthermore, this type of building generally results in less noise produced on the building site.

AESTHETIC QUALITIES

The use of exposed wood structure in the interiors results in a warmer perception of the indoor spaces by activating senses such as tactility and olfaction.

RISK OF FIRE

As visible in the fire regulations, timber is widely perceived as more at fire risk than steel and concrete. However, when timber burns, the outer layers char and end up insulating the centre of the structural element against heat and fire. Different protection solutions are available nowadays (plasterboards, fire retardants...) and are helping to change the common disbelief around timber.

THERMAL PERFORMANCE

The light timber envelope can typically achieve a good thermal performance with a thinner construction. The low thermal mass allows the rooms to heat up and cool more quickly than concrete or masonry solutions.

CONDENSATION

Condensation normally occurs on the surfaces and on the inner layer of the envelope. Timber needs to be protected through vapour barrier or it will rot.

ill. 132: Construction of a CLT building

FIRE SAFETY STRATEGIES

The fire safety is one of the main issues when dealing with high rise timber building. As mentioned in the analysis phase the Danish fire regulation is generally very strict and set limits for the development of CLT solutions. Other countries regulation, such as the Austrian and German ones, show more flexibility in these terms.
On the other hand, researches that challenge this limits are ongoing and some of them already proved that solutions with exposed CLT can work for multi-storeys residential buildings (Johansen and Werenberg, 2019).
Furthermore, architects are arguing that CLT should not be considered in the same category as highly combustible thin cladding material since it has better properties, being slow-burning, self-charring, self-extinguishing and structurally predictable (Frearson, 2018).
Even though the actual trend seems to predict a possible solution to efficiently build high rise timber buildings in respect with fire safety, there is not yet proof that this can be accomplished for buildings higher than 5 storeys.

An over-sizing of about 8cm of the CLT elements, combined with application of phosphate-based retardant, should be enough to allow a load-bearing capacity of 120 minutes standard-fire, required by the legislation.
The amount of extra thickness has been calculated by multiplying the charring rate of treated CLT elements by the time required (0,62 mm/min*120min) (Johansen and Werenberg, 2019).

The behaviour in term of LCA of the solution adopted is not easy to predict due to the uncertainties connected with the fire retarder production: this made impossible to compare this solution with a standard one with plasterboard. The strategies chosen for the project are approximated and not verified by the current rules but aim to investigate and display an alternative to plaster claddings in order to exploit the benefits of exposed timber: this is done with the hope that the future developments will prove this solution feasible.

PLASTERBOARDS IN CRITICAL POINTS

The spots with higher risk of fire, such as the kitchen, are protected with plaster sidings on the adjacent surfaces.

MODULARITY AND FIRE BARRIERS

Each apartment tower is structurally independent and a fire barrier is located in between the two CLT walls.

OVERSIZED AND TREATED CLT

The exposed structure is oversized to increase the charring time and is treated with a fire retardant.

SMOKE DETECTION SYSTEMS

Standard smoke detectors are provided and connected with the closest firemen station.

EASY ACCESS FOR VEHICLES

The staircases and the apartments are close to spaces accessible from vehicles in order to allow fast interventions.

PLASTERBOARDS AND SPRINKLERS

The lower floors where common and public functions are located will have a standard fire protection with sprinklers and plaster. This is because this spaces are crucial for the fire safety being escape routes.

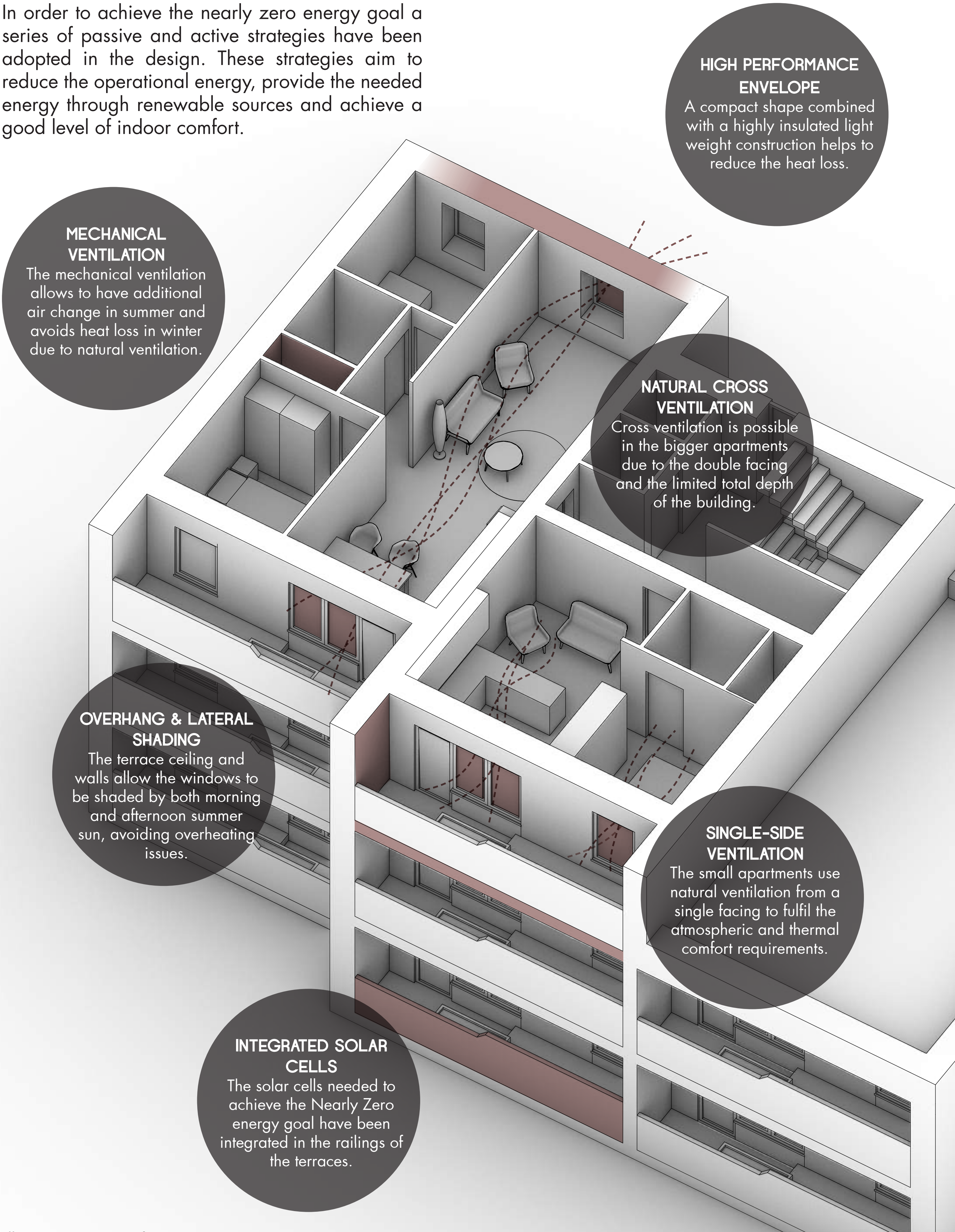
STRAIGHT AND DIRECT ESCAPE ROUTES

The distribution spaces are reduced to the minimum so that a quick and linear escape route is easy to recognize for the residents.

ill. 133: Fire safety strategies

INDOOR COMFORT STRATEGIES

In order to achieve the nearly zero energy goal a series of passive and active strategies have been adopted in the design. These strategies aim to reduce the operational energy, provide the needed energy through renewable sources and achieve a good level of indoor comfort.



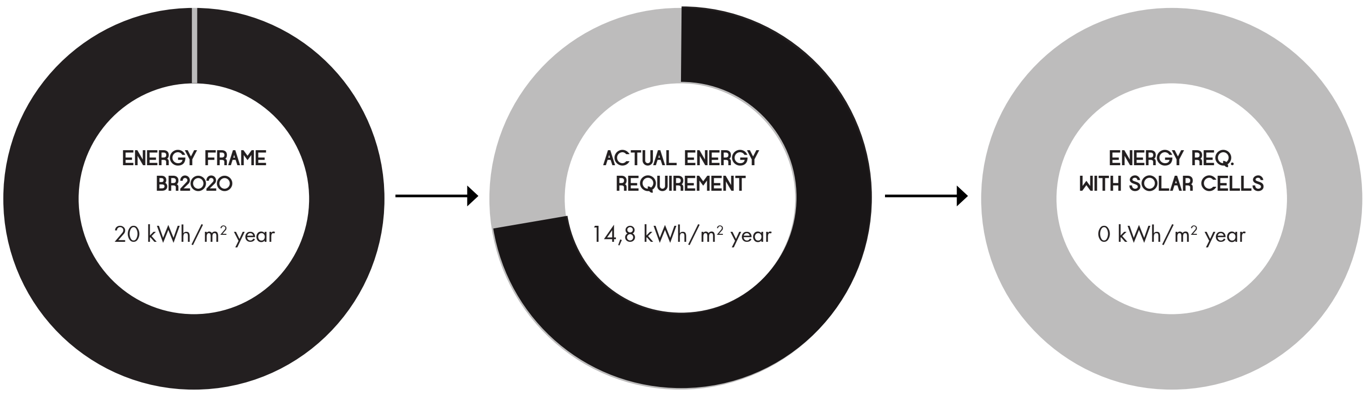
ill. 134: Indoor comfort strategies

ACTIVE STRATEGIES

ENERGY REQUIREMENT

Design criteria and passive strategies have been adopted in order to obtain a good indoor comfort and to reduce the energy consumption, and active strategies are needed to cover the remaining operational energy of the building.
Solar cells have been chosen, in particular mono-crystalline, since they have a high efficiency and require less space than other typologies.

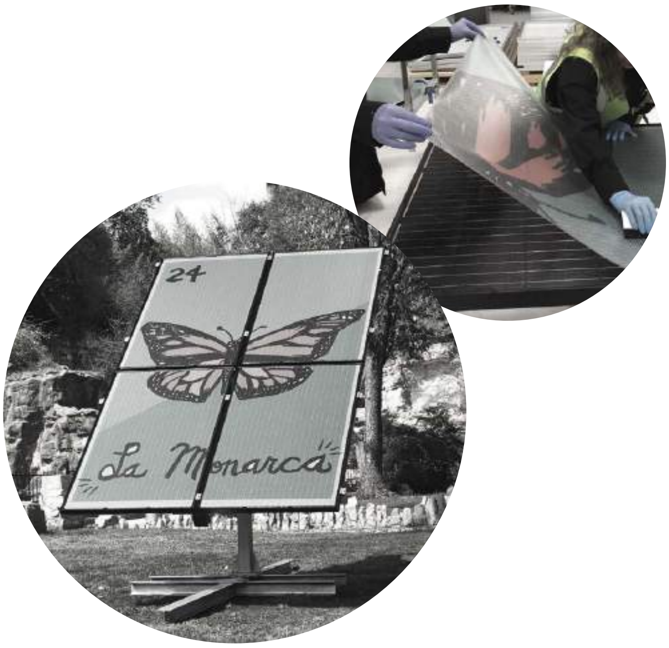
One of the design criteria is about the integration of photovoltaic panels in the design of the building. A solution is the application of the solar cells on the railings of the balconies, since they all have a good exposition to the sun, they are easily accessible and maintainable and cover a good amount of area.
In order to understand if the total area of the railings is enough, first a calculation of the operational energy of the building has been done using Be18. The result obtained from the software is, as visible in the Appendix 4 , 14,8 kWh/m^2 year, below the Energy Frame BR2020 relative to residential buildings, that is 20 kWh/m^2 year.
By calculating the total area of the railings and applying the efficiency of the solar cells, the result shows that the energy requirement of the building is covered by the amount of photovoltaic panels applied to the design, reaching the Nearly Zero Energy Building standard (Appendix 4).



ill. 135: Energy results from Be18

AESTHETIC OF SOLAR CELLS

The solar cells are integrated in the design of the building, but they can still result too heavy in the overall aesthetic of the building, due to their big amount and to the dark colour that hardly matches with the wood. Looking at the character of the area, a solution can be the integration of street art with the solar cells. This is possible thanks to a particular technology consisting in a thin film that can be printed with any pattern or drawing and that can be then applied right on the surface of the panel. This film is made so that the efficiency of the solar cells does not decrease, giving the opportunity to the user to personalize his balcony railing. This can be done, for instance, in one of the workshops present in the complex. The first example of this technique was realized in 2017 in Texas at the Land Art Generator Initiative and it was called "La Monarca".
(Land Art Generator, 2017)



ill. 136, 137: Personalization of solar cells

LIFE CYCLE ASSESSMENT

-1.06 $KgCO_2eq./m^2/y$

PRODUCT/MANUFACTURE STAGE

This stage includes the energy needed for the production, transport and processing of the building materials. The GWP is negative due to the sustainability of timber given by the renewable source and the carbon storage.

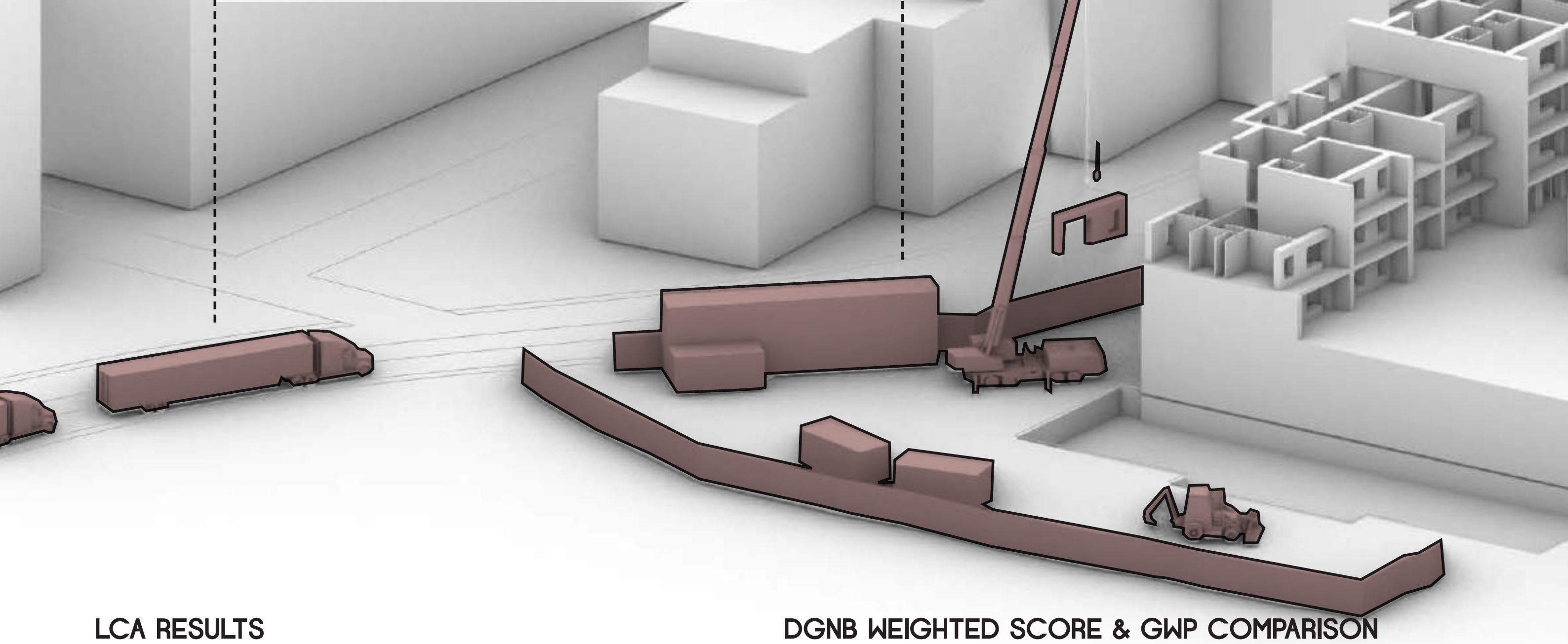
A1 | Raw material extract/process/supply ●
A2 | Transport ●
A3 | Manufacture ●

N.A. $KgCO_2eq./m^2/y$

CONSTRUCTION PROCESS STAGE

The second stage consists in the energy needed to transport the material from the production to the building site and all the consumptions related to the building site itself. The current LCA databases do not cover this stage.

A4 | Transport to the site ○
A5 | Assembly/Install in the building ○



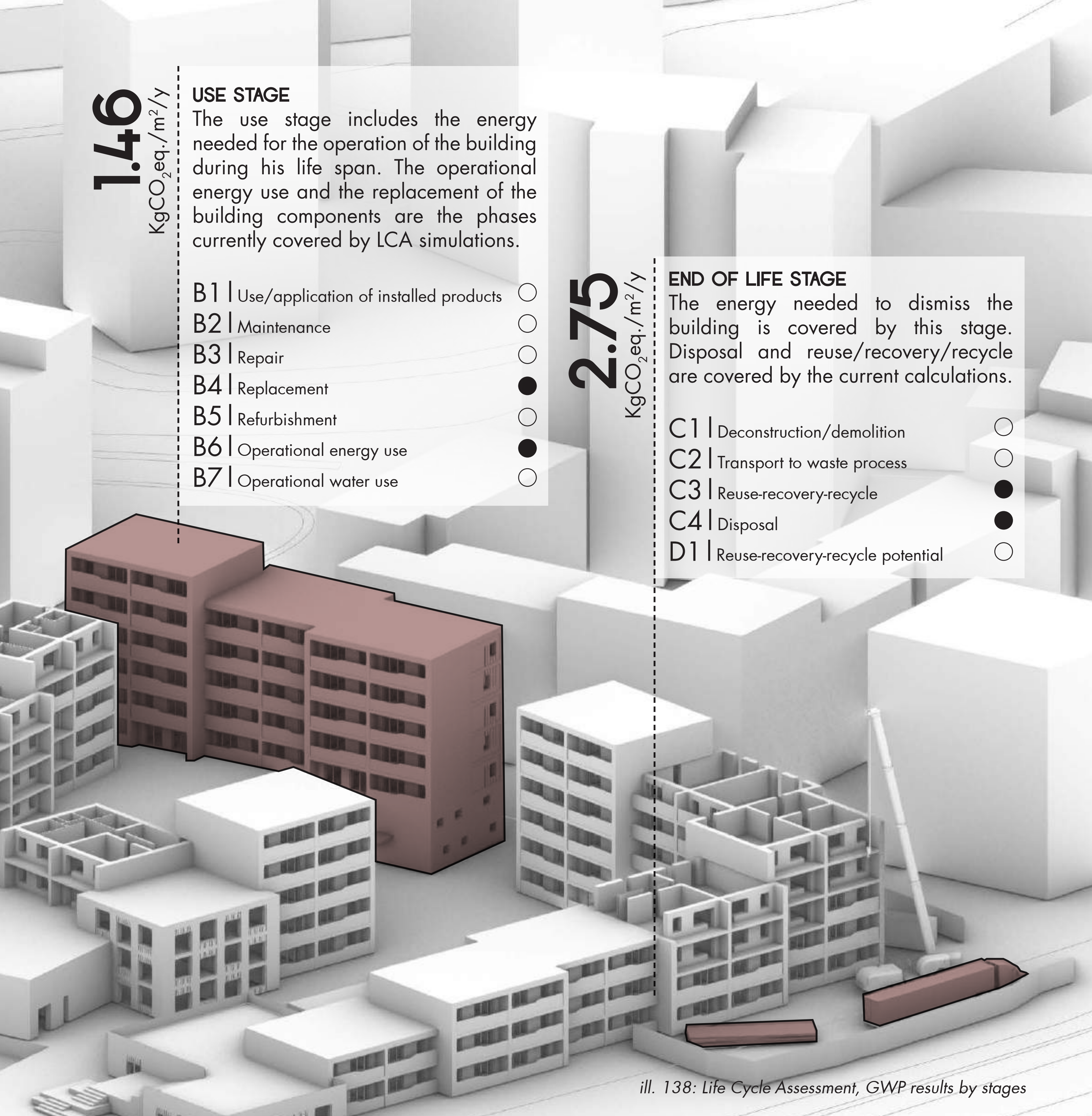
LCA RESULTS

The Life cycle assessment of the project has done using LCAByg 3.2 (Appendix 5).
The results show a low environmental impact of the building thanks to the use of timber and to the design strategies adopted. This is proved by the maximum DGNB weighted score obtained and by the comparison with the same building simulated using a concrete structure which results in halved emissions..
The DGNB score obtained fulfils the original goal of the project and shows the potential to achieve a nearly-zero environmental impact of an architectural project through an integrated design process.

DGNB WEIGHTED SCORE & GWP COMPARISON

3,17
$KgCO_2eq./m^2/y$

6,03
$KgCO_2eq./m^2/y$



1.46 $KgCO_2eq./m^2/y$

USE STAGE

The use stage includes the energy needed for the operation of the building during his life span. The operational energy use and the replacement of the building components are the phases currently covered by LCA simulations.

B1	Use/application of installed products	○
B2	Maintenance	○
B3	Repair	○
B4	Replacement	●
B5	Refurbishment	○
B6	Operational energy use	●
B7	Operational water use	○

2.75 $KgCO_2eq./m^2/y$

END OF LIFE STAGE

The energy needed to dismiss the building is covered by this stage. Disposal and reuse/recovery/recycle are covered by the current calculations.

C1	Deconstruction/demolition	○
C2	Transport to waste process	○
C3	Reuse-recovery-recycle	●
C4	Disposal	●
D1	Reuse-recovery-recycle potential	○

ill. 138: Life Cycle Assessment, GWP results by stages

CO_2 GLOBAL WARMING POTENTIAL (%)

The breakdown of the LCA by building elements shows that, after CLT, the foundations are the main contributor of CO_2 eq. being in concrete. After the structure, the high amount of completions, such as insulation and claddings, is the factor that defines the result the most.

Foundations	22%
Super-structure	25%
Completions	23%
Windows	15%
Installations	15%

TIMBER BEATS CONCRETE

Iterations made both with concrete and timber structure show LCA results that are definitely in favour of timber. Choosing timber over concrete is the more effective way to drastically improve the environmental score of a project.

COMPACTNESS MEANS BETTER LCA ...

A perfect cube would be optimal in term of LCA since the volume and the amount of material used both for foundations and external walls are reduced. Generally speaking, a standard building depth of about 12m and a height between 4 and 6 storeys give the best LCA performance.

... BUT BE AWARE OF EXTREME COMPACTNESS

Even though the mere numbers speak in favour of compactness, small change in the volumes such as facade fragmentation or height differences can be worth the price if it results in a better architectural expression. The LCA disadvantages are very limited if the fragmentations are made wisely. Playful geometries generate more interesting spaces than compact shapes, that eventually make a project more successful.

WINDOWS ARE WORSE THAN ENVELOPE

LCA-wise, placing a window is way worse than leaving an opaque envelope. This does not mean that windows should be limited to the minimum, but the environmental cost should be considered along with daylight and thermal comfort considerations when designing a facade.

DURING THE DESIGN, STRUCTURE IS NOT SO IMPORTANT FOR LCA

Even though structural elements account for about 70% of the LCA of a project, results has shown that it is not so important during the early design phase. The same type of structure applied to different geometries turns out to not be influential on the LCA since the amount of material tends to be the same in every situation. Therefore, if we exclude the choice of the type of structural elements, changes to the structure in the early design stages do not bring any considerable result LCA-wise.

ill. 139: View from the park

CONCLUSION

CONCLUSION

The thesis work has shown that, with the due limitations given by the tools still under development, it is already possible to integrate LCA in the early stages of an architectural project.
Even though the method used in the Godsbanen Zero project is not completely iterative, being based on quick calculations on abstract volumes which have then been translated into general architectural criteria, the use of parametric tools will allow to apply the same workflow to actual project shape.
The way the tool has been used during the process phase is easily adaptable to future developments of parametric tools.

The LCA results obtained show a better LCA behaviour for compact volumes than for articulated ones, due to the relevance of the external wall surface in the overall balance.
On the other hand, small fragmentations of the external envelope result in a slightly worse LCA score that can be worth the price if they generate more interesting architectural language than simple compact volumes.
The iterations done on the relation volume-structure turned out to be not so relevant on the LCA results. The structure could affect the LCA more when studied in terms of material optimization rather than in the volumetric iteration stages.

The experimental use of cross laminated timber structure for a high-rise building brought to some sub-conclusions:
- The aesthetic and sustainability benefits of timber are more than proved by both the analysis references and by the project results.
- The fire safety regulation currently present in Denmark doesn't allow the full exploitation of the potential of timber but some solutions that does not involve covering the wood surface are already under research.

The final project meets the expectations of achieving a close-to-Zero environmental impact while maintaining a good architectural language and a good integration with the context of Godsbanen.
The compromise between rules-of-thumb (modularity, flexibility, ...) and strategies deducted from LCA iterations (timber structure, compactness, optimal height, ...) resulted in a good way to develop an architectural design in a limited time while maintaining a good LCA score.

REFLECTIONS

LCA RESULTS

The strategies deducted through the LCA iterations turned out to be on the same line of the standard heat loss strategies: more compact shapes are preferable over solutions that increase the amount of exposed surfaces.
In both cases this is due to the amount of external walls total area that gives the best LCA score when minimized.

Another relevant result has been the low importance of the structure in the very early design stage: when working with simple volumes the structure does not affect that much the final score if compared with the influence of the external envelope.
This result is affected by the fact that the LCA phases covered are still few and basically concentrated in the production phase.
As a consequence, the trend in LCA result is mainly affected by the quantity of material alone since factors such as the maintenance or the transportation are not involved.

The limit given by using a simple number to translate a complex assessment with several variables generates more reflections.
The lack of possibility to input project information such as location and specific function defines a limited range of outputs.
For instance, local availability of materials or the consequences of different use types are not thoroughly included in the math.
This is because it is not always possible to have a database that fits the context in which the project is located, as not every country has its own one.
The development of national material databases could result in a more contextualized assessment.
There is also a lack of data regarding the construction phase such as the components assembly method or the construction time and other unexpected events that usually result in more emissions.
A complete collection of data from finished cases is needed to develop an accurate comparison method that considers the most relevant variables (seasonal logistic, construction delays...).

The calculation phase of the LCA should include more complete and exhaustive inputs and as a consequence the calculation method should become more flexible.
Some certifications such as the DGNB try to fill the gap by including some qualitative parameters aside the quantitative one represented by the LCA weighted score.
Some of these parameters are: potential to achieve climate neutrality, use of reused components or structural elements, building that generates energy for the other users...
The achievement of these parameters' goals results into a bonus score that is implemented into the final DGNB score.
It can be problematic though to integrate and compare them from an early design stage due to their no-quantitative nature.
In conclusion it is still not possible to have a precise and complete idea of the total environmental impact of the building due to the lack of some data and the complexity of the life cycle of the building itself.
LCA in architecture is still an under-developing field that is constantly providing new and updated methods that try to combine quantitative and qualitative parameters in the design.
For the architect that approaches the topic of LCA from the early design stages it is important to be aware that the results are affected by the limits and potentials mentioned above.

LCA & EARLY DESIGN STAGE

The integration of LCA in the design process is starting to be a discussion topic in the construction field and hopefully this thesis will contribute to this process.
The method used in this thesis could be expanded and applied to even more detailed investigations when the LCA tools and databases will allow it.
The hope that is shared by the group is that LCA will be integrated in the architectural design in the same way as the energetic calculations already are.
In a thorough design process, information about the consequences of using certain design strategies instead of others should be available and inform the design since the very beginning.

Using the whole life cycle as parameter brought to a different way to interpret the design itself: the process includes not only the traditional choice of geometry and use of the building but also decisions that affect the birth and death/reuse of the building components. Time is therefore a further factor that has not been addressed in most of the projects done until recently.
This broaden even further what an architect should have under control during the design phase.

Following this logic, the building should be designed as a product that is part of a circular economy and should therefore already consider the before-use and after-use stages.
For the after-use some design solutions are already available and have been used in built projects, such as the reuse of upcycled elements or the design for disassembly. Less architectural solutions have been developed to address the before-use phases such as design strategies that reduce the energy needed on the building site or during the production phase.

In this scenario a conflict between LCA requirements and design freedom arises: when should the one prevail on the other? How can we effectively integrate the LCA strategies without sacrificing the aesthetic and what is the admissible environmental price to pay in exchange of a purely aesthetic benefit?
The answers to these questions could come from two sides:
- On one hand the regulation could set a limit of CO^2 per building that architects and engineers should respect; the DGNB LCA reference is the one that has been used for this project and is already a base to which compare the design decisions consequences. However, DGNB parameters are not enough strict.
- On the other hand, architects could use their sensibility to define when pursuing an LCA benefit is affecting the functional or aesthetic qualities of the design in such a bad way that the project itself would result unsuccessful.

In conclusion, a big challenge on how to re-interpret the design could come from introducing LCA as an early design stage parameter. The difficulties that will come in understanding how to use the data in an effective way are not predictable yet but, on the other hand, the potential benefits that a more informed design will have, especially in the reduction of the environmental impact of an architectural project, are sure.

LCA TOOLS POTENTIAL AND LIMITS

The use of two different LCA calculation tools allowed an indirect comparison between their effectiveness and potential role in the design stage:

- LCAByg is a software meant for the documentation of a finished design; the geometry must be defined manually by inserting the material amounts and it is therefore not possible to use it quickly in the early design phases. The input options are more precise and consider more building components than the parametric tool but requires way more time to be completed.
- The parametric tool provided by C.F. Møller is based on Rhino and Grasshopper and therefore iterations can be done in a very short time since the material amounts are automatically calculated from a 3D model. This tool has been designed to be used during the early design stages and it is not sufficiently complete to be used in later phases due to the extent of the approximations.

Parametric tools are naturally more effective in the early design stage due to the short time needed to change the geometry and to the automatic approximations that do not require all the building components definition.

A big advantage of a parametric tool is the high flexibility that allow the tool to be personalized and edited according to the desired result.

For instance, even though the original grasshopper definition was built to define a random structure starting from a given volume, a simple modification to some components allowed to test a more defined structural system while maintaining the parametric model.

This is usually not possible in most of the software that rely on a strict user interface.

Furthermore, this flexibility is the reason why, even though defects are present in the parametric tool used, this kind of software should be preferred over more static ones in the early design stages. These tools are faster and easier to develop than standard ones and can be easily adapted to the large variety of architectural tasks that occur in the construction sector.

This flexibility could also allow the tool to be used in later design stages: a clearer way to define the building components could be used to broaden the investigation field and even work with the material optimization.

A common "weakness" that affects both the tools is the incompleteness of the LCA databases currently available: only 6/7 LCA stages out of 17 are covered due to the difficulty to collect reliable data in the transport, construction and maintenance phases.

In LCAbyg some imprecisions have also been found in the outputs, therefore the calculations for the final score of the building both in concrete and in wood have been carried out by hand.

During the hand calculation phase, it was noticed that the benchmarks' values in the DK DGNB are not strict enough to highlight the differences between concrete and wood.

These differences are visible only from the indicators values but, once weighted according to the regulations, they give the same results.

For this reason, the German DGNB calculation has been used instead of the Danish one.

A stricter regulation with lower benchmarks would be needed especially when materials that have low emissions as wood are implemented in the calculation.

For instance, in a comparison between two different wooden structure buildings it wouldn't be possible to notice the differences between them as any calculation with a wooden structure would result in the maximum score.

TIMBER POTENTIAL AND LIMITS

The use of timber in high-rise residential buildings in Denmark is still a field widely unexplored: taking as example Godsbanen only, most of the new buildings are built in prefabricated concrete.
This is due to several reasons such as the wider concrete know-how in the country and the limits imposed by the fire safety regulation to timber structures.
If we consider this "status quo", the thesis aims to be provocative and proposes a sustainable alternative that is probably not doable in this very moment but is very likely to be possible in the near future.

The project shows some of the potentials that could be unfolded by removing the actual limits:
- Choosing timber over concrete already results in a better environmental choice, being timber obtained from a renewable source.
- The prefabrication of the building components would give the same benefits as it already does with the prefabricated concrete. In addition, the lower energy needed for the production/manufacturing combined with the dry joints would result in shorter building times and therefore in less energy used.
- The way cross laminated timber is assembled allows a faster dismantling making a project more resilient than a concrete one. This affects positively the end life stage as well, being both the reuse and the demolition less energy consuming.
- The possibility to expose the CLT structure in the interiors opens up for new architectural languages: the CLT skeleton could be used in the same expressive way as raw exposed concrete, masonry and steel has already been in the past. Furthermore, avoiding using the plaster, which is not sustainable, would tear down the last doubts around the sustainability of timber structure since they should not rely anymore on a concrete-based material for the fire protection.
The use of exposed CLT would have the potential to be honest, by showing the way the building stands, while transmitting a warm atmosphere, being more suitable for residential situations in contrast with the cold concrete texture and colour.
The solution proposed in the project is only one of the possible languages that could come from the combination of exposed timber with plaster or other types of cladding.

On the other hand, using exposed timber naturally brings to deal with the strictness of the fire legislation. As mentioned in the presentation phase, this thesis relies on the future developments of the fire safety sector, field in which alternative and potentially more sustainable solutions to plaster are emerging.
These legislative limits combined with the common disbelief that wood is less safe than steel or concrete in a fire situation are the last barriers before the potentials above mentioned can be completely expressed.

In conclusion, two points were critical during the development of the project and should be investigated to have a more complete perspective on how to build with timber:
- During the definition of the facade design, the decision between a wood or plaster cladding was difficult due to the indecision on which of those is to be considered more sustainable in an LCA perspective. Even though wood is way less energy consuming than plaster during the production/ manufacture stage, no data are available to compare the maintenance energetic costs of the two materials: the complications that come from using wood in a high-rise building, such as the need to be changed after some years and the difficulty to be reached and maintained at bigger heights, could result in a worse LCA if compared with the lower maintenance needed for a plaster facade.
The final choice of wood was motivated by the architectural language wished but the need of a more informed design in this stage is something that the group is aware of.
- During the design of the interiors of the apartments, the fire safety issue brought to a conflict between the strategies to use. The wish to expose the CLT to investigate the aesthetic potential brought to the use of an alternative solution: the combination of an oversized structure with the use of a fire retardant, that, according to the legislation requirements, is supposed to work.
This solution raises a sustainability doubt: are the extra timber and the fire retardant better than using a standard plasterboard in term of LCA?
To answer this question a specific comparison of these two solutions using an LCA tool should be done.

APPENDIX

APPENDIX 1 - LCA TIMBER ITERATIONS

During the process phase further iterations with timber have been done to have a more complete picture of the LCA behaviour.
The parameters tested that have not be included in the main body of the report are: the number of volumes, the building typologies, the roof typologies and the percentage of glazed surface.

PERCENTAGE OF GLAZED SURFACE

The amount of glazed surface on the façade is usually a compromise between daylight, passive solar gain/ shading and aesthetics considerations.
The iterations done by changing the % of glazed surface aim to give a further parameter to compromise with.
The results show that increasing the total glazed surface generates a lower LCA score, meaning that the construction of windows requires more energy compared to the construction of external walls.

NUMBER OF VOLUMES

The division of the total volume in two or more buildings has been tested.
Due to the increase of the external walls and foundation surface, splitting the volume results in a lower LCA score.

BUILDING TYPOLOGY

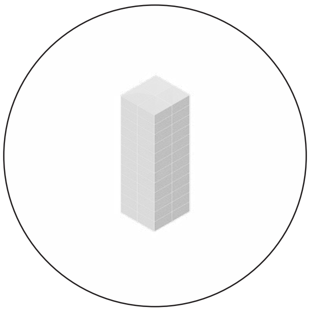
The most common housing typologies of the area have been studied to understand which have the biggest potential in terms of LCA: the courtyard, the high rise and the linear blocks.
The value of the total volume has been kept for all the iterations to make them comparable, meanwhile the depth and the height are different according to the typology.
The best shape according to the LCA analysis is the courtyard housing as it is more compact and it has less exposed surfaces. What contributes mostly to the CO_2 Global Warming Potential are the foundations, followed by the windows and the external walls, while in the high-rise typology the external walls are the most impactful in terms of GWP. The windows have a big impact in the courtyard typology as more openings are needed to provide good light conditions, while in the linear buildings the foundations are the most impactful, followed by the external walls and the windows.

ROOF TYPOLOGIES

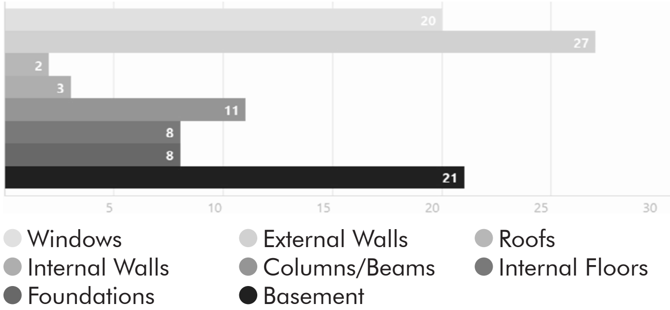
Different types of roof have been studied to understand which have a better result on the LCA of a building.
The flat roof is the most efficient one in terms of LCA (90% in the DGNB LCA Score), as it has less exposed surface. The building elements that affects the result most are the foundations and the external walls while the roof accounts for a far lower extent in comparison.
At the second place according to the DGNB LCA Weighted Score there is the simple hip roof, with a percentage of 88%. In this case the roof has an impact of 12% in the total GWP, while the flat roof consists only on a 7%.
The typical front gable roof is also efficient in terms of LCA, with its 88% in the DGNB LCA score, while the other two shed roof typologies give a worse LCA value, mostly caused by a greater external wall surface.

NUMBER OF VOLUMES

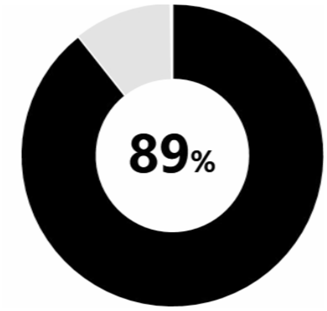
1 VOLUME



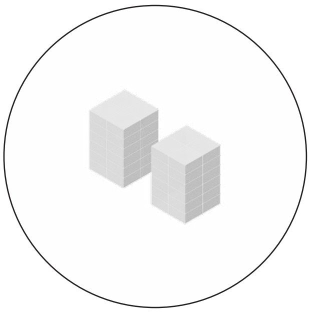
CO_2 GLOBAL WARMING POTENTIAL (%)



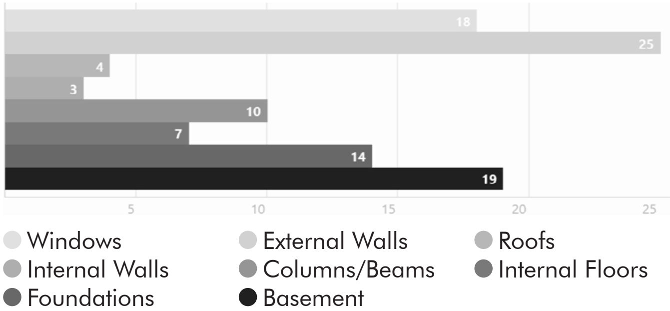
DGNB LCA SCORE



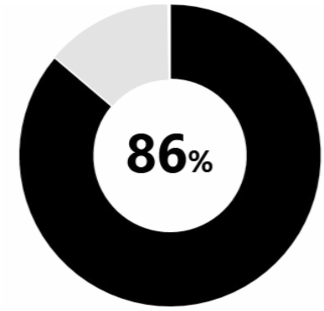
2 VOLUMES



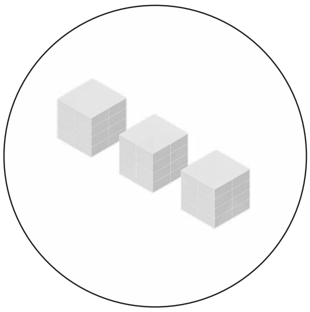
CO_2 GLOBAL WARMING POTENTIAL (%)



DGNB LCA SCORE

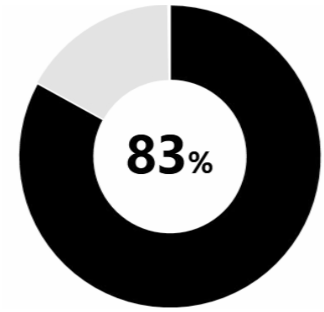


3 VOLUMES

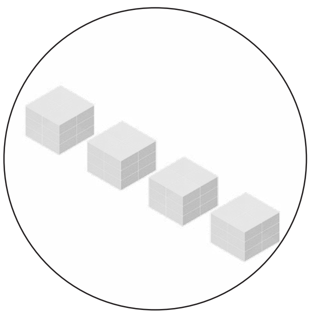


CO_2 GLOBAL WARMING POTENTIAL (%)

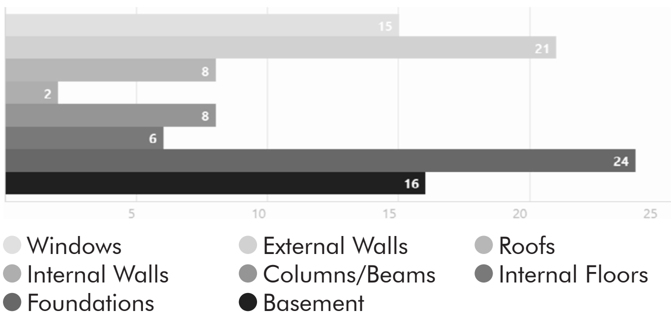
DGNB LCA SCORE



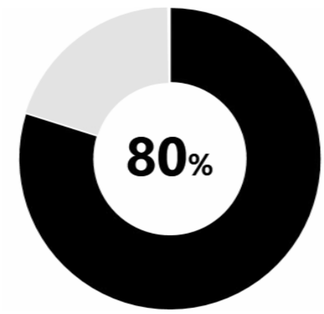
4 VOLUMES



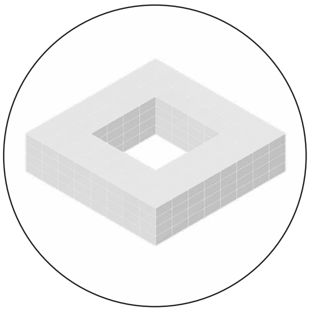
CO_2 GLOBAL WARMING POTENTIAL (%)



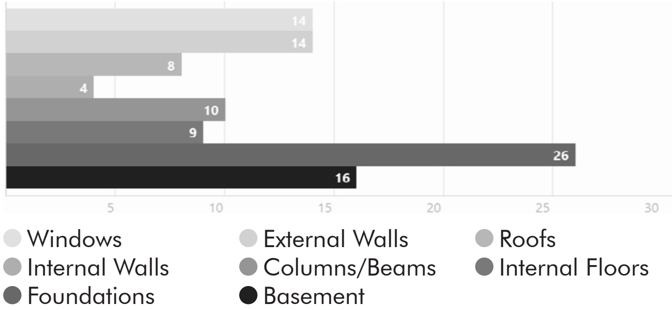
DGNB LCA SCORE



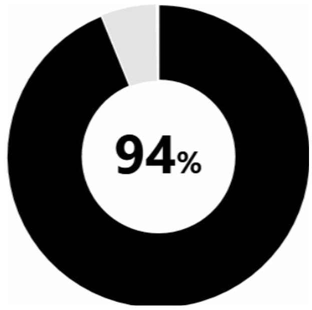
COURTYARD



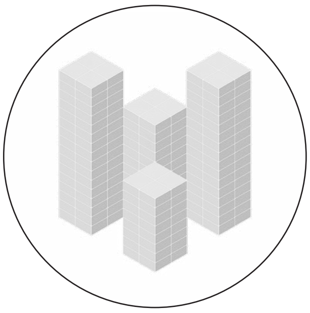
CO_2 GLOBAL WARMING POTENTIAL (%)



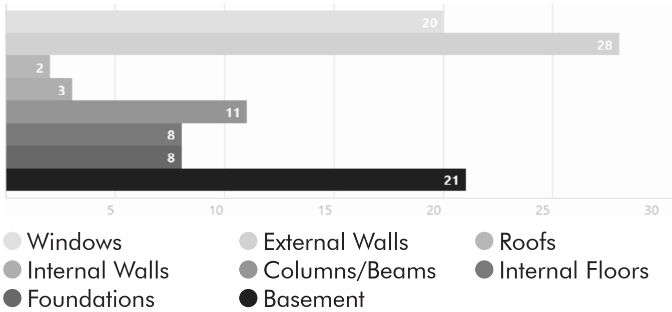
DGNB LCA SCORE



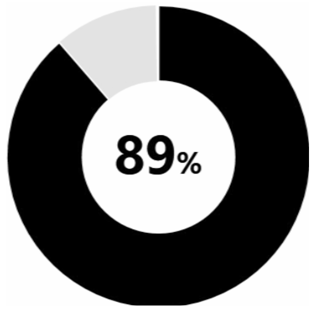
HIGH RISE



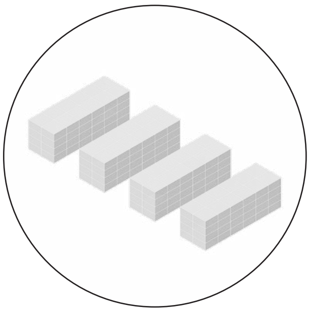
CO_2 GLOBAL WARMING POTENTIAL (%)



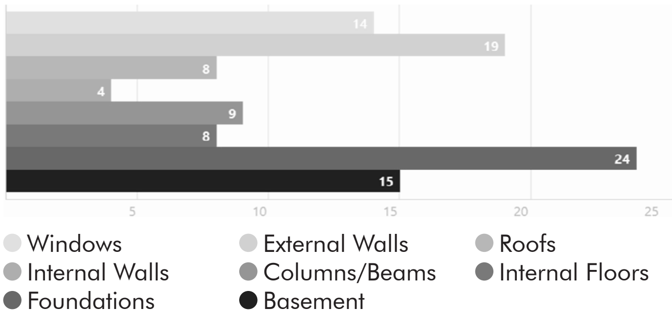
DGNB LCA SCORE



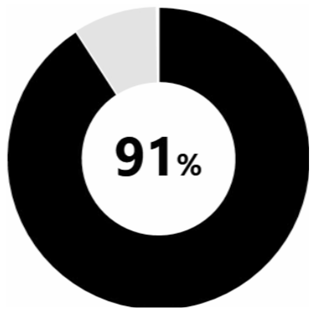
LINEAR BLOCKS



CO_2 GLOBAL WARMING POTENTIAL (%)

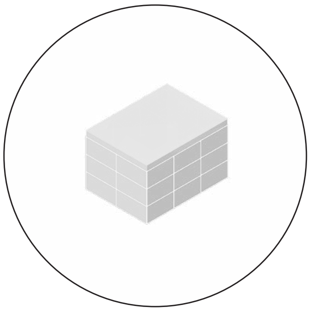


DGNB LCA SCORE

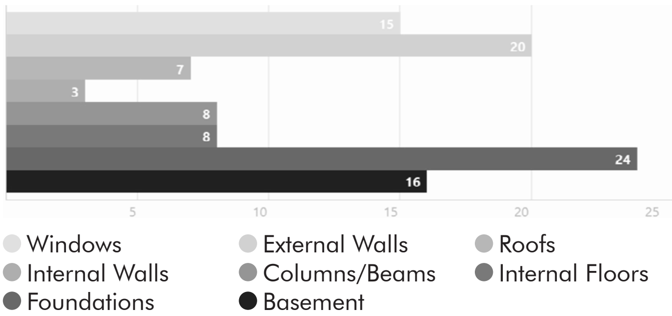


ROOF TYPOLOGIES

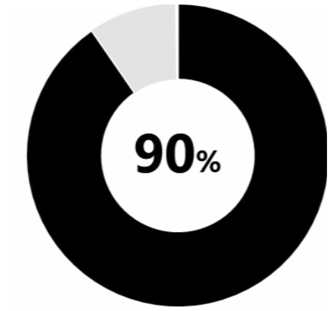
FLAT



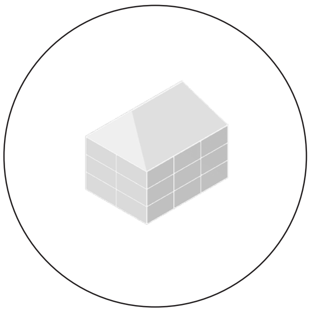
CO_2 GLOBAL WARMING POTENTIAL (%)



DGNB LCA SCORE

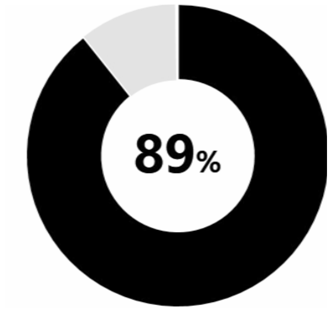


SIMPLE HIP

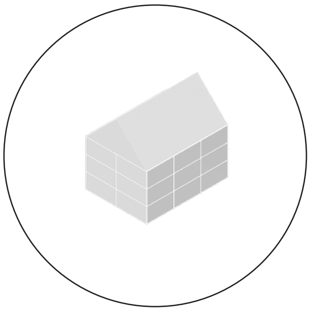


CO_2 GLOBAL WARMING POTENTIAL (%)

DGNB LCA SCORE

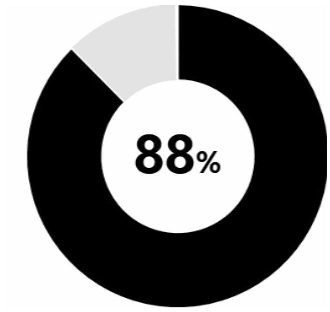


FRONT GABLE

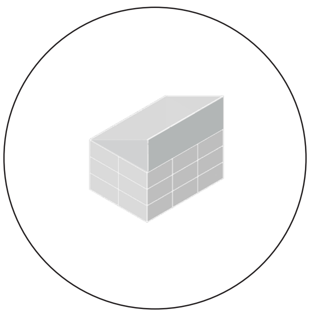


CO_2 GLOBAL WARMING POTENTIAL (%)

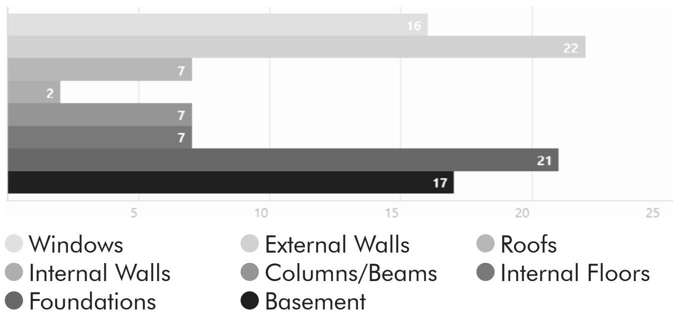
DGNB LCA SCORE



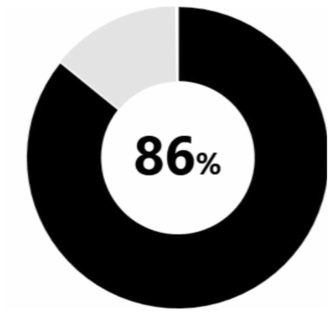
SHED



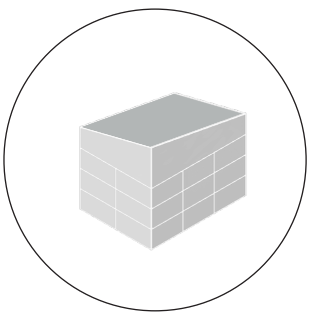
CO_2 GLOBAL WARMING POTENTIAL (%)



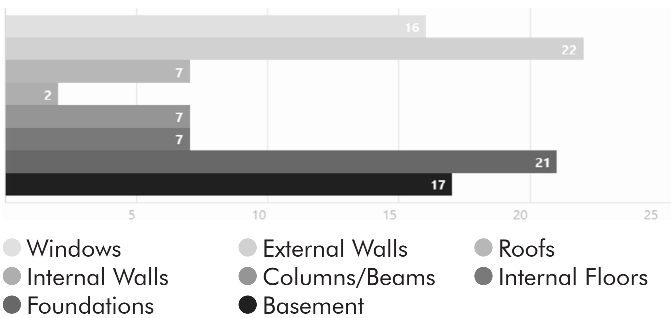
DGNB LCA SCORE



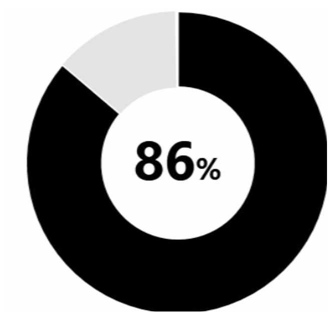
SHED 2



CO_2 GLOBAL WARMING POTENTIAL (%)

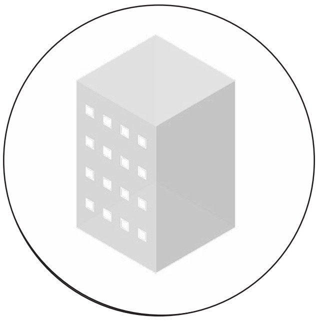


DGNB LCA SCORE

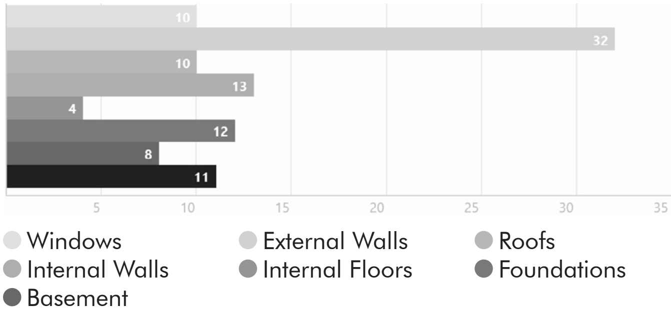


PERCENTAGE OF GLAZED SURFACE

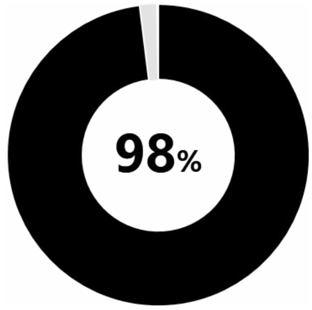
10%



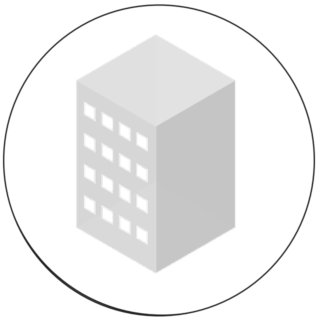
CO_2 GLOBAL WARMING POTENTIAL (%)



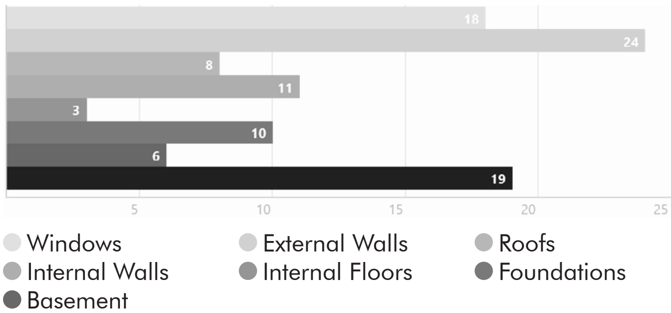
DGNB LCA SCORE



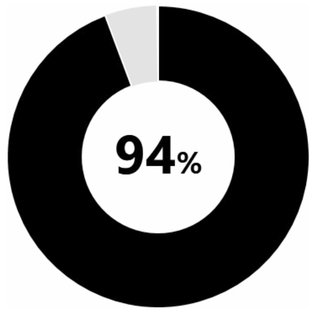
20%



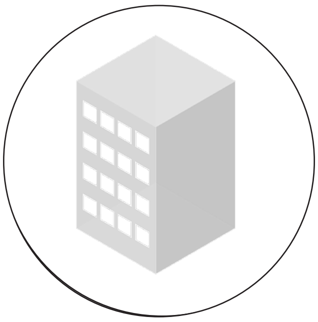
CO_2 GLOBAL WARMING POTENTIAL (%)



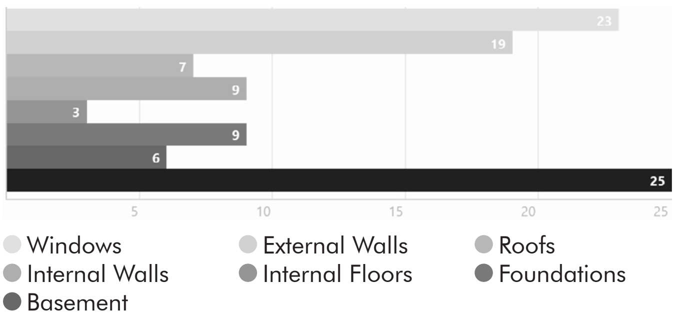
DGNB LCA SCORE



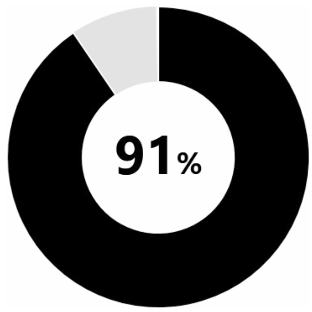
30%



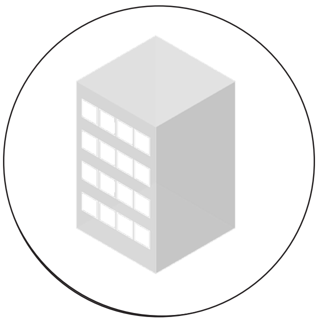
CO_2 GLOBAL WARMING POTENTIAL (%)



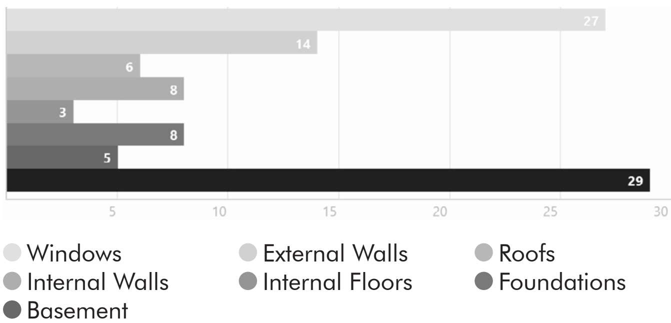
DGNB LCA SCORE



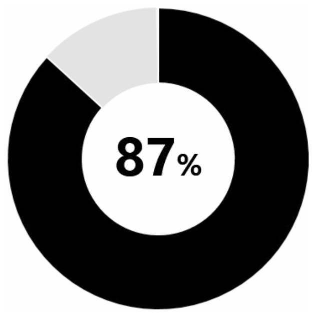
40%



CO_2 GLOBAL WARMING POTENTIAL (%)



DGNB LCA SCORE

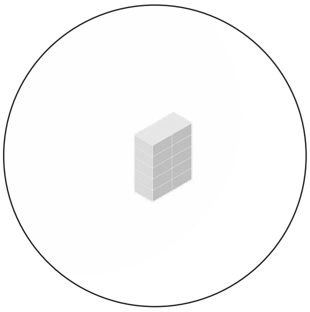


APPENDIX 2 - CONCRETE ITERATIONS

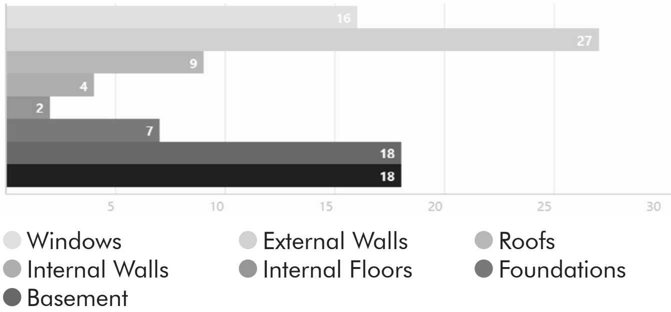
To give an actual proof of the better LCA behaviour of timber structures the same iterations have been repeated by using a concrete structure. This is to have a comparison.
The parameters repeated have been the total volume, the height and the width-length ratio of the volume.
The results are synthesised in the main report and in the following pages the detailed results are presented.

TOTAL VOLUME (CONCRETE)

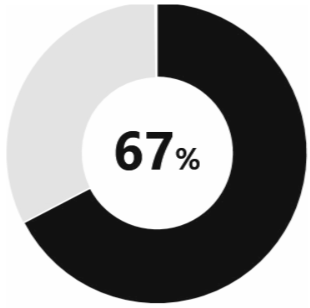
1000 m³



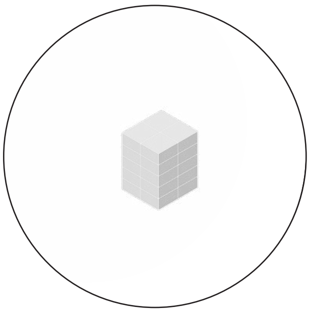
CO$_2$ GLOBAL WARMING POTENTIAL (%)



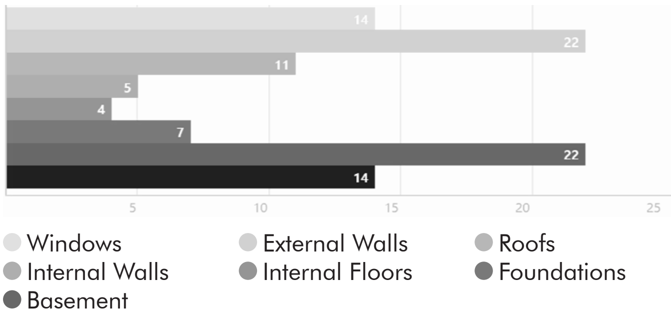
DGNB LCA SCORE



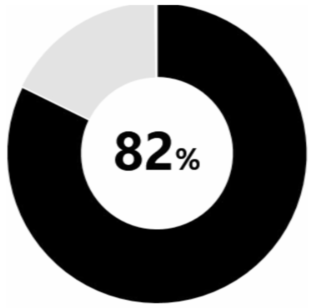
2000 m³



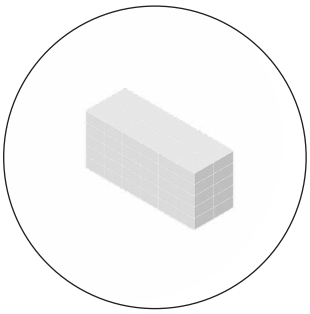
CO$_2$ GLOBAL WARMING POTENTIAL (%)



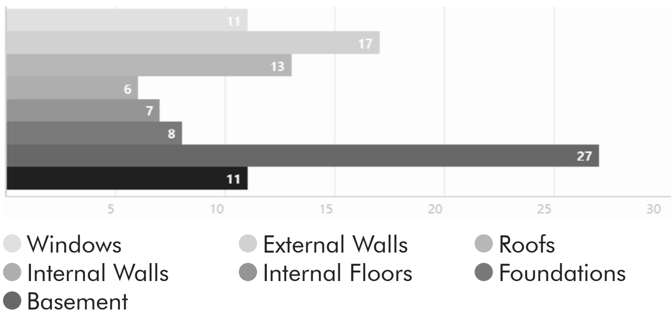
DGNB LCA SCORE



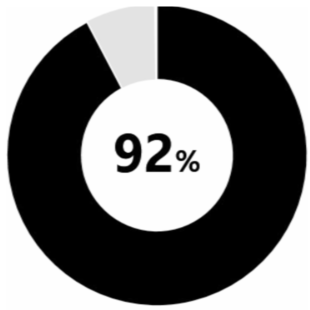
6000 m³



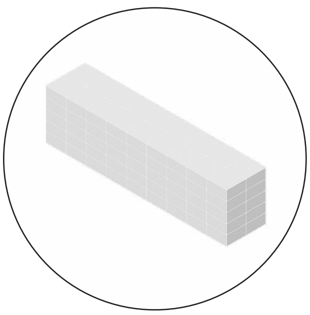
CO$_2$ GLOBAL WARMING POTENTIAL (%)



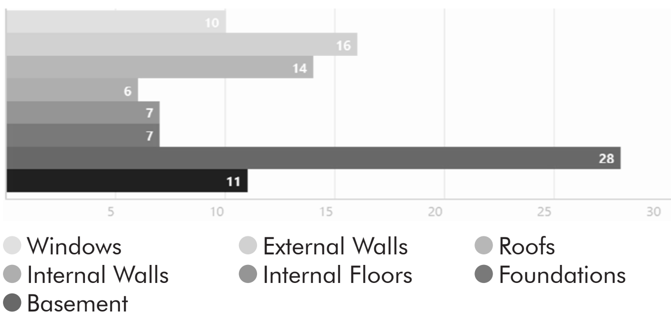
DGNB LCA SCORE



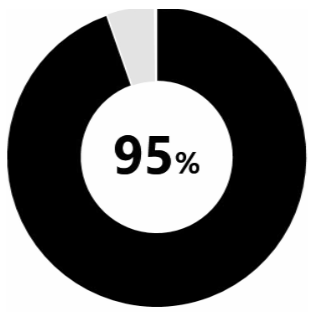
10.000 m³



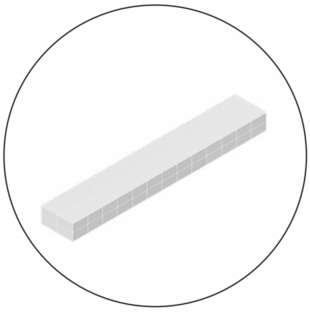
CO$_2$ GLOBAL WARMING POTENTIAL (%)



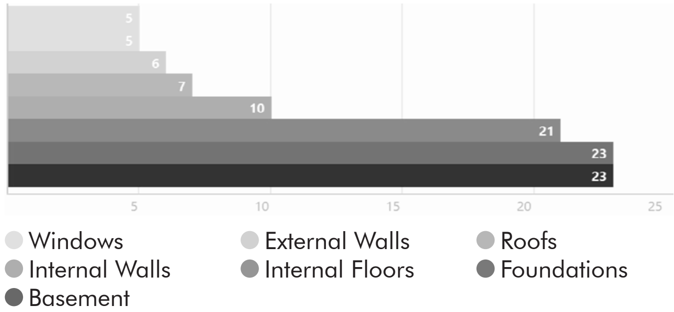
DGNB LCA SCORE



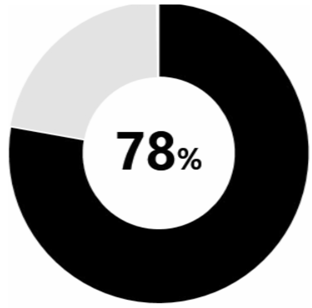
2 STOREYS



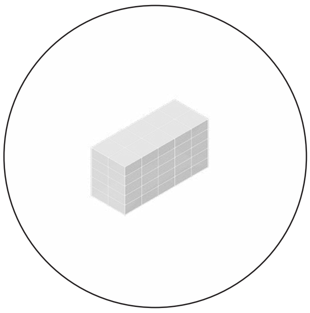
CO_2 GLOBAL WARMING POTENTIAL (%)



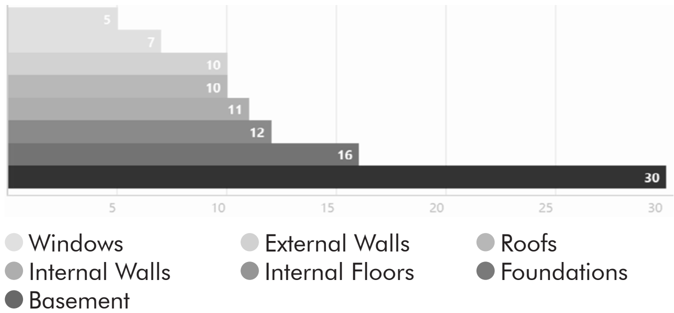
DGNB LCA SCORE



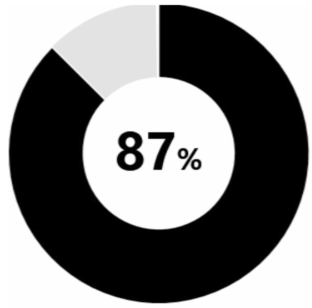
5 STOREYS



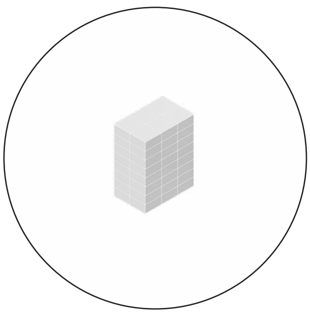
CO_2 GLOBAL WARMING POTENTIAL (%)



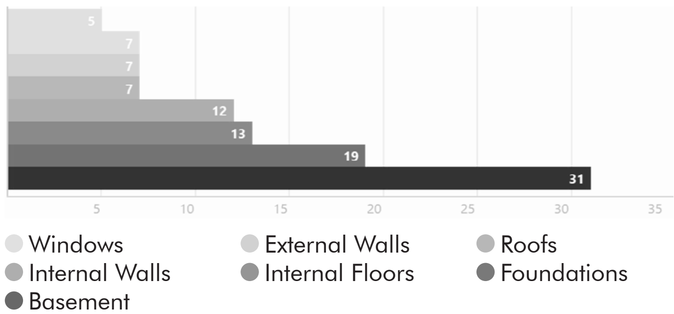
DGNB LCA SCORE



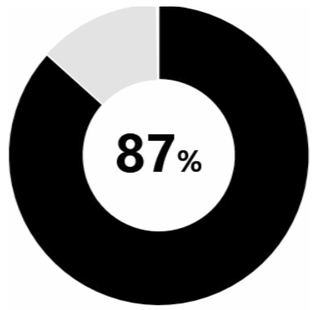
8 STOREYS



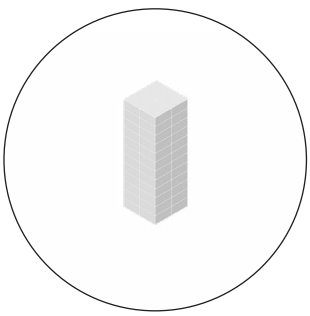
CO_2 GLOBAL WARMING POTENTIAL (%)



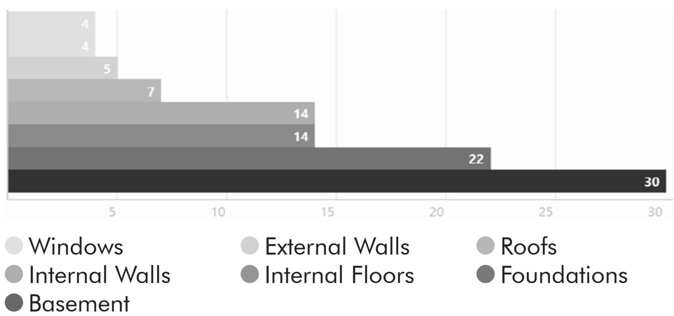
DGNB LCA SCORE



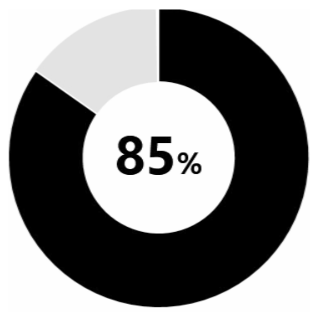
12 STOREYS



CO_2 GLOBAL WARMING POTENTIAL (%)

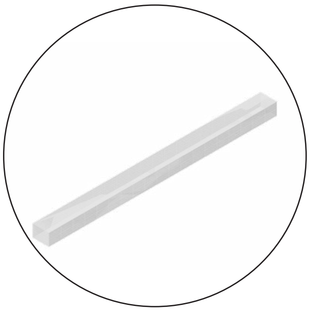


DGNB LCA SCORE

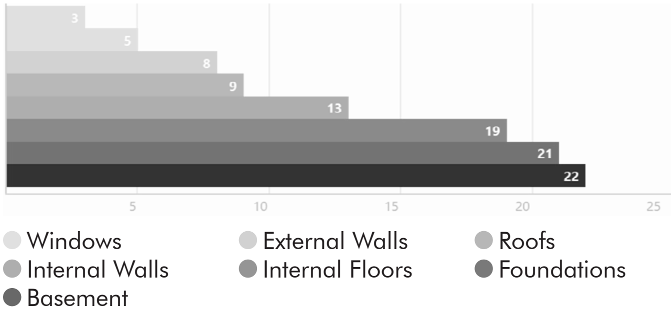


LENGHT-WIDTH RATIO (CONCRETE)

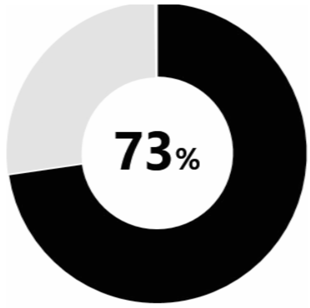
8m (1:14)



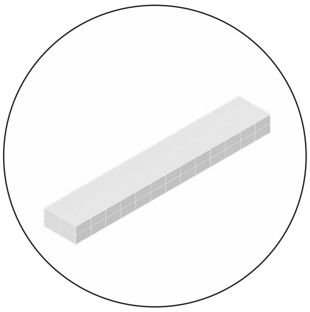
CO_2 GLOBAL WARMING POTENTIAL (%)



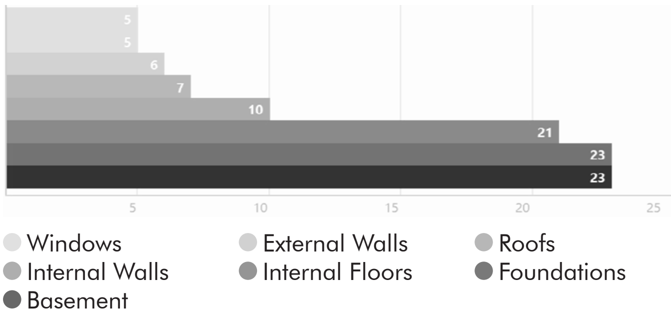
DGNB LCA SCORE



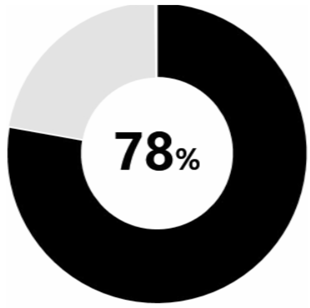
12m (1:6)



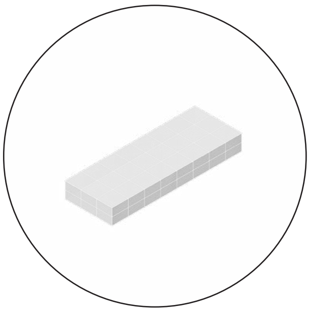
CO_2 GLOBAL WARMING POTENTIAL (%)



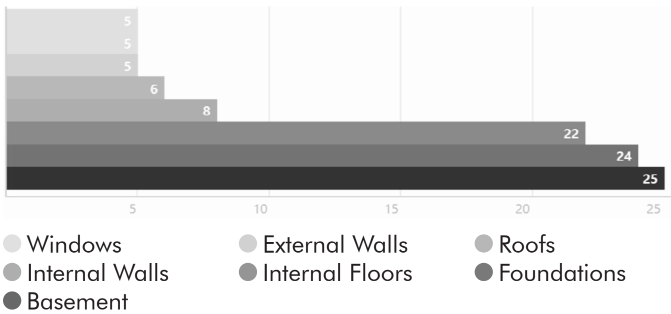
DGNB LCA SCORE



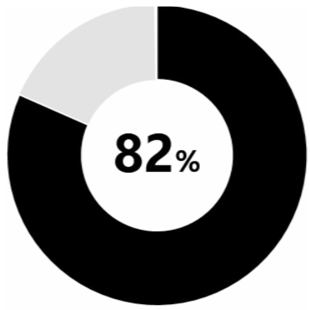
18m (1:3)



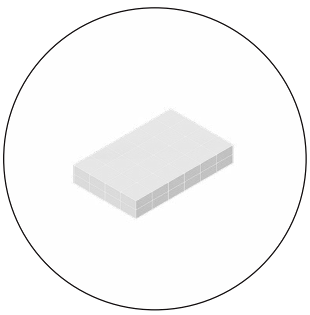
CO_2 GLOBAL WARMING POTENTIAL (%)



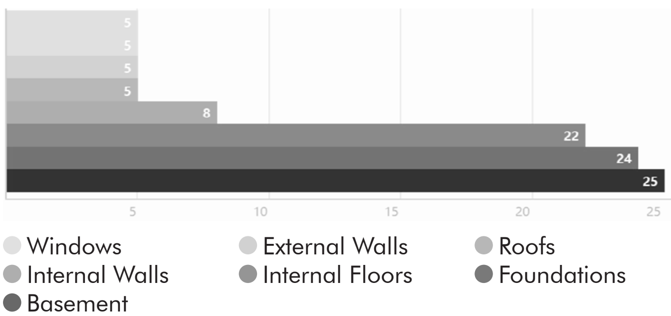
DGNB LCA SCORE



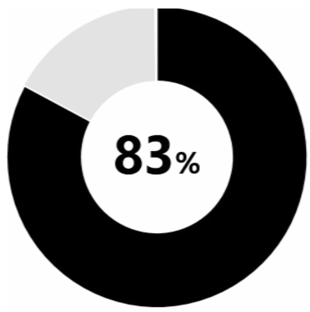
24m (1:1.5)



CO_2 GLOBAL WARMING POTENTIAL (%)

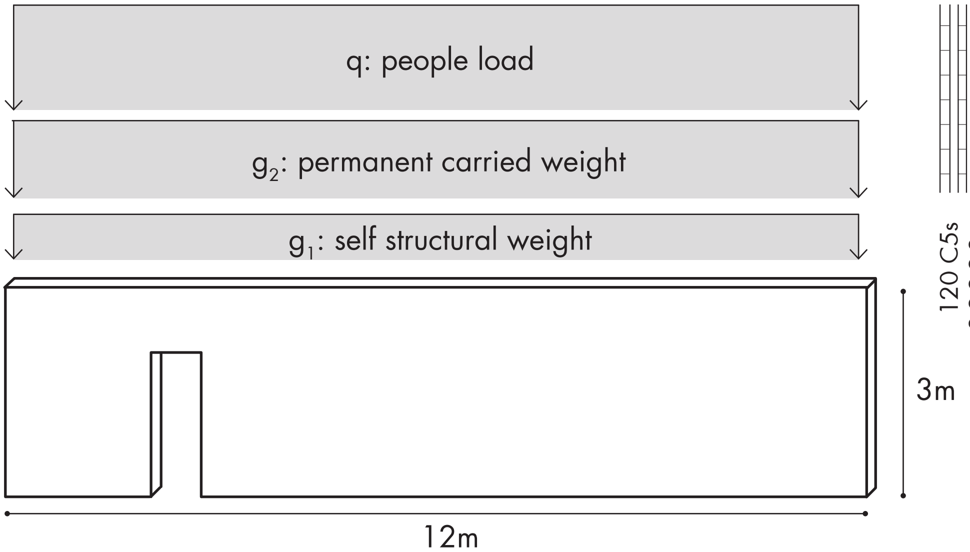


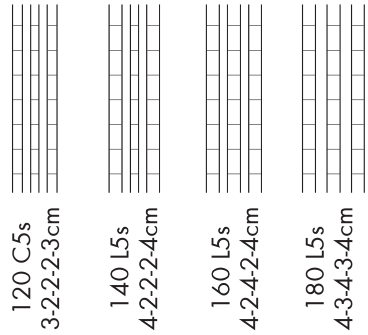
DGNB LCA SCORE



APPENDIX 3 - CLT CALCULATIONS

The dimensions of the timber structural elements for each iteration have been obtained through Calculatis, an online calculator freely provided by the Finnish CLT supplier Stora Enso (Stora Enso, 2019).
The online calculator uses ULS calculations to verify the CLT element and takes into account the ULS fire verification.
The loads have been applied as shown in the tables below and a quick calculation has been done to define the amount per storey.
The foundation have been dimensioned in a simplified way: the depth of the foundation plateau has been increased with the same proportion of the increase of the loads in each case, starting from a 30cm thickness.



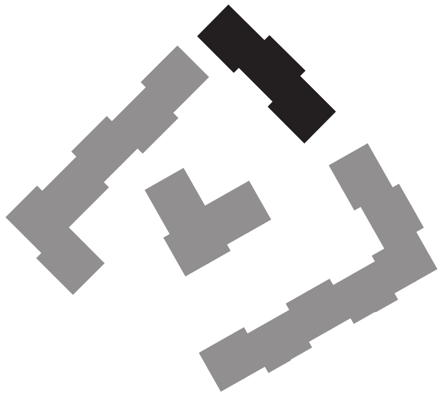


Span	Loads (KN/m) g_1	g_2	q	CLT dim.	ULS/SLS	ULS fire
3,4m	1,8	25,2	47,6	120mm C5s	0,51/0,05	0,42
5,1m	1,8	37,8	71,4	120mm C5s	0,75/0,63	0,07
6,8m	2,1	58,5	95,2	140mm L5s	0,73/0,61	0,10
8,5m	2,1 2,4	73,5 84	119	140mm L5s 160mm L5s	0,91/0,12 0,87/0,11	0,75 0,41
10,2m	2,7	113,4	142,8	180mm L5s	0,82/0,13	0,41

Height	Loads (KN/m) g_1	g_2	q	CLT dim.	ULS/SLS	ULS fire
4 st.	1,8	18	40,8	120mm C5s	0,46/0,05	0,40
6 st.	1,8	30	68	120mm C5s	0,72/0,07	0,60
8 st.	2,1	58,8	95,2	140mm L5s	0,71/0,01	0,64
10 st.	2,4	86,4	122,4	160mm L5s	0,87/0,51	0,13

APPENDIX 4 - OPERATIONAL ENERGY

ENERGY REQUIREMENT



To verify whether the nearly zero energy goal was achieved Be18 has been used to calculate the operational energy and the amount of PVs needed. The results have also been used to complete the Life Cycle Assessment, being the operational energy included in the stage B of the LCA but not directly calculated by LCAByg.
In this appendix the detailed calculation made on one of the building blocks (visible in the illustration), considering only the private functions, is presented:

ENERGY FRAME BUILDINGS 2020 (kWh/m² year)			
Total energy frame		20 kWh/m² year	
Total energy requirement		13,2 kWh/m² year	
CONTRIBUTION TO ENERGY REQUIREMENT		**NET REQUIREMENT**	
Heat	14,6	Room heating	0,0
Electricity	0,4	DHW	13,6
Excessive in rooms	0,0	Cooling	0,0
SELECTED EL. REQUIREMENTS		**HEAT LOSS FROM INSTALLATIONS**	
Lighting	0	Room heating	0,9
Heating of rooms	0,0	DHW	0,5
Heating of DHW	0,0		
Heat pump	0,0	**OUTPUT FROM SPECIAL SOURCES**	
Ventilators	0,4	Solar heat	0,0
Pumps	0,0	Heat pump	0,0
Cooling	0,0	Solar cells	0,0
TOTAL	31,1	Wind mills	0,0

In addition, the energy consumption of the public functions has been assumed as 25 kWh/m² year, the maximum allowed by the building regulation. Therefore, the overall operational energy has been calculated as:

Private functions area x Private functions operational energy =
13.137 m² x 13,2 kWh/m² year = 173.408,4 kWh/ year

Public functions area x Public functions operational energy =
2.096 m² x 25 kWh/m² year = 52.400 kWh/ year

Tot. operational energy =
(173.408,4 + 52.400) / (13.137 + 2.096) = 225.808,4 / 15.233 = 14,8 kWh/m² year

SOLAR CELLS

Once that the operational energy was obtained, it was possible to calculate, still on Be18, how much area the solar cells should cover in order to supply that amount of energy. Considering the same building block and referring only to the private functions, main focus of the project, the results showed that the total area of the railings is enough for the solar cells needed, with also a small surplus.

Energy requirement for private functions	13,2 kWh/m^2 year
Solar cells area applied to railings (for reference block)	212 m^2
Energy requirement with solar cells	- 0,9 kWh/m^2 year

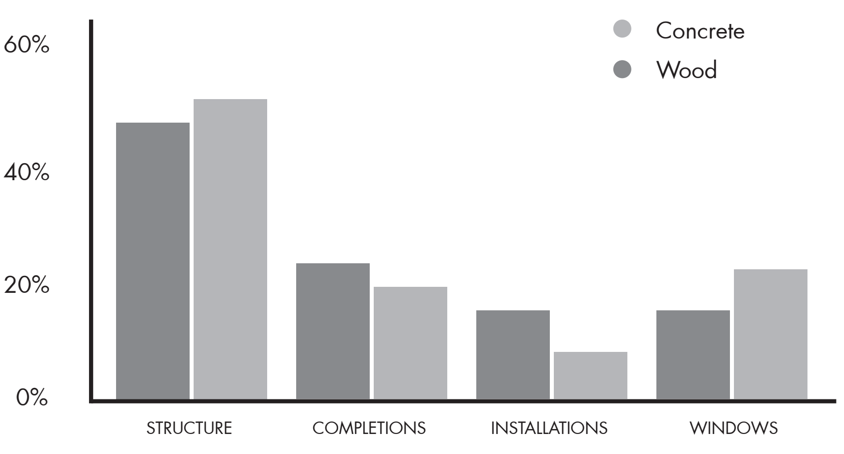
Taking into consideration also the public functions, the total energy requirement of 14,8 kWh/m^2 year is slightly higher than the energy the solar cells designed can provide (0,7 kWh/m^2 year missing). However, the value is very low and, potentially, extra solar cells still have the possibility to be applied in the project in places such as the roofs and other parts of the facades.

APPENDIX 5 - LIFE CYCLE ASSESSMENT

LCA CALCULATION

A final calculation of the Life cycle assessment of the building has been bone by using the software LCAByg. The software's way to proceed is to define the LCA indicators and the DGNB weighted score by multiplying the inputs (detailed quantities and materials) by an internal database.
In this appendix the detailed calculation is presented. In order to simplify the calculation of the LCA of the project, only one of the building blocks has been considered (the same used for the energy requirement calculations).
The first stage to calculate LCA consisted on inserting the heated floor area and the total gross area in square meters, also specifying the building type (in this case Residential multi-storey).
Afterwards the materials have been added by category following a tree structure from the foundation to the roof construction, including structural walls, partitions, windows, stairs, solar panels, heating system and other electrical/mechanical utilities.
Each category corresponds to a building part, that in turn is divided into different materials, measured in cubic meters, each one with its own properties (product stage, life span, mass factor, Global Warming Potential etc..). The products are taken from the external source Ökobau.dat 2016 that it is an online database with life cycle assessment datasets on building materials.
After all the materials have been placed, the operational energy consumption for heat and electricity in KWh/ m2 is required; the data entered come from the Be18 calculation.
In order to explore the properties of different materials, the same part of the building has been tested both with a wooden structure (the actual one) and a concrete structure. In the second iteration the completions have been changed to concrete or other materials as well, to enhance the properties of wood in general.
The calculation outputs consist on the total value of each indicator and on the values of each part of the building for each benchmark.
The results have been gathered in 4 groups as following: structure, completions, installations and windows, with a GWP, ODP, POCP, AP and EP value for each one of them.

	GWP kg CO_2-Eq/m^2/year	ODP Kg R11-Eq/m^2/year	POCP Kg C_2H_4-Eq/m^2/year	AP Kg SO_2-Eq/m^2/year	EP Kg PO_4^{3-}-Eq/m^2/year
Wood	3,17	$6,32 \times 10^{-8}$	$2,36 \times 10^{-3}$	$1,10 \times 10^{-2}$	$1,70 \times 10^{-3}$
Concrete	6,03	2×10^{-8}	$2,46 \times 10^{-3}$	$1,92 \times 10^{-2}$	$2,51 \times 10^{-3}$



The first table shows the result of each benchmark for both the wood and the concrete building. It can be deducted that the concrete has generally bigger values apart from the Ozone Deplementation Potential.

The graph compares the concrete and the wood building in terms of Global Warming Impact, dividing them into parts.
The percentage derives from the impact of each building part in relation to the total GWP.

DGNB DK Calculation

	GWP_{cref} 9,4	ODP_{cref} $5,3*10^{-7}$	$POCP_{cref}$ 0,0042	AP_{cref} 0,037	EP_{cref} 0,0047
Wood	33,7%→100%	12%→100%	56%→100%	30%→100%	36%→100%
Concrete	64%→100%	4% →100%	58%→100%	52%→100%	54%→100%

German DGNB Calculation

	GWP_{cref} 9,4	ODP_{cref} $5,3*10^{-7}$	$POCP_{cref}$ 0,0042	AP_{cref} 0,037	EP_{cref} 0,0047
Wood	33,7%→100%	12%→100%	56%→100%	30%→100%	36%→100%
Concrete	64%→88%	4% →100%	58%→100%	52%→100%	54%→100%

-The benchmarks' values have been weighted according to the DGNB DK (Green Building Council Denmark, 2014, Table 2, p.11, table 5, p.12) and then according to the German DGNB (German Sustainable Suilding Council, 2018, Table 1, p.26). In both cases the evaluation has been carried out using the point allocation for indicators of the German DGNB (Table 4, p.29) as it is less permissive than the Danish one (as shown in the tables above).

-The total DGNB Score for each building has been calculated with the following formula from DGNB DK (Green Building Council Denmark, Table 4, p.12):

$$CLP = (SP_{GWP}*GGWP + SP_{ODP}*G_{ODP} + SP_{POCP}*G_{POCP} + SP_{AP}*G_{AP} + SP_{EP}*G_{EP})$$

CLP (Wood) = (100%*0,40+100*0,15+100*0,15+100*0,15+100*0,15)= 100%

CLP (Concrete) = (100%*0,40+100*0,15+100*0,15+100*0,15+100*0,15)= 100%

-The result looks the same even if the benchmarks' values of the concrete building are much higher.
As this regulation is not strict enough to show readable results, the German DGNB has been used instead (German Sustainable Building Council, 2018, Table 4, p.29):

CLP (Wood) = (100%*0,40+100*0,15+100*0,15+100*0,15+100*0,15)= 100%

CLP (Concrete) = (88%*0,40+100*0,15+100*0,15+100*0,15+100*0,15)= 95,2%

-Both of them are weighted according to the Danish weighting keys, to make them comparable (Green Building Council Denmark, table 4, p12).

-In conclusion, the building in concrete has a lower DGNB score, as the material generates a bigger environmental impact.

REFERENCES

BIBLIOGRAPHY

Archdaily (2016). *Woodlofts Buiksloterham / ANA architecten*, ArchDaily, 14 Mar [Online]. Available at URL: <https://www.archdaily.com/783615/woodlofts-buiksloterham/> ISSN 0719-8884 [Accessed 6 Feb 2019].

Bakker, R., Ramage, M., Foster, R. (2017). *Natural building materials* [Online].Available at URL: https://futureofconstruction.org/solution/natural-building-materials/?fbclid=IwAR0JyjnCbG-zJXpvw7FYt7betvpL5YggL00vufVTPLgvLx1lPG9mzWeAvil [Accessed: 5 April 2019].

Chen, D. (n.d.). *Mass Timber for sustainability, case studies in contemporary wood architecture*. Carnegie Mellon University

Christensen, S.B. (2009). *Århus Godsbanegård - historie og kulturarvsanbefalinger: Rapport til Århus Kommune*. Aarhus.

Collin, A. (2018). *"Pixel Facade" System Combines a Love for Nature With Next-Generation Workspaces*, Archdaily, 7 May [Online]. Available at URL: https://www.archdaily.com/893745/pixel-facade-system-combines-a-love-for-nature-with-next-generation-workspaces

Danish Meteorological Institut (2019). *Vejrarkiv* [Online]. Available at: https://www.dmi.dk/vejrarkiv/ [Accessed: 25 February 2019].

Danmarks Statistik (2018). *BOL101: Dwellings by region, type of resident, use, tenure, ownership and year of construction (2010-2018)* [Online]. Available at: http://www.statbank.dk/statbank5a/default.asp?w=1920 [Accessed: 27 February 2019].

Danmarks Statistik (2019). *BOL201: Residents by County, use, tenure, ownership, year of construction, age and sex*. [Online]. Available at: http://www.statbank.dk/statbank5a/default.asp?w=1920 [Accessed: 18 February 2019].

Danmarks Statistik (2019). *FOLK1A: Population at the first day of the quarter by region, sex, age and marital status.* [Online]. Available at: http://www.statbank.dk/statbank5a/default.asp?w=1920 [Accessed: 18 February 2019].

Frearson, A. (2018). *Architects urge government to consider environmental cost of timber building restrictions*, Dezeen, 3 December [Online]. Available at URL: https://www.dezeen.com/2018/12/03/clt-exempt-combustible-cladding-ban-uk-government/?fbclid=IwAR36c_h1hnmYi9hRXdMSapFbFVUMFIYl0LMCr6ctHUP-feVlG9NyhxPI0jc [Accessed 18 February 2019].

German Sustainable Building Council (2018). *DGNB system – New buildings criteria set, Env1.1 / Building Life Cycle Assessment* [Online]. Available at: https://www.dgnb-system.de/en/system/version2018/criteria/building-life-cycle-assessment/index.php [Accessed: 18 February 2019].

Godsbanen (2019). *Godsbanens Historie* [Online]. Available at: http://godsbanen.dk/om-godsbanen/godsbanens-historie/ [Accessed: 18 February 2019].

Green Building Council Denmark (2014). *DGNB criterion env 1.1-Life Cycle Impact Assesment. Green Building Council Denmark* [Online].Available at: http://www.dk-gbc.dk/publikationer/dgnb-manual-for-etageejendomme-og-raekkehuse-2016/?fbclid=IwAR37Hnvj1F9cybqOOaBnk0eBvnQW6feBEZnuBlvgj_kUW58FvuOpYdkaS90 [Accessed: 18 February 2019].

GXN Team, TU Delft & City of Amsterdam (2018). *Upcycle Amstel Stad – Tools*, pp. 46-57 [Online]. Available at URL: https://gxn.3xn.com/project/up-cycle-amstel [Accessed: 18 February 2019].

GXN Team (2018). *Circle House Demonstrator* [Online]. Available at URL: https://gxn.3xn.com/project/circle-house-demonstrator [Accessed: 18 February 2019].

Hansen, HTR. & Knudstrup, M-A. (2005). *The Integrated Design Process (IDP): a more holistic approach to sustainable architecture*, in S Murakami & T Yashiro (eds), Action for sustainability: The 2005 World Sustainable Building Conference. Tokyo National Conference Board, pp. 894-901, Tokyo, Japan.

Hollberg, A. (2016). *Parametric Life Cycle Assesment: Introducing a time-efficient method for environmental design optimization*, Researchgate, (pp.1-23) [Online]. Available at URL: https://www.researchgate.net/publication/316460202_Parametric_Life_Cycle_Assessment_Introducing_a_time-efficient_method_for_environmental_building_design_optimization [Accessed 2 February 2019].

Hollberg,A. Habert,G., Schwan,P., Hildebrand,L., (2017). *Potential and limitations of environmental design with LCA tolls, University of Ljubljana*. Researchgate (pp. 1-6) [Online] Available at URL: https://www.researchgate.net/publication/323946127_Potential_and_limitations_of_environmental_design_with_LCA_tools [Accessed: 18 February 2019].

Institut for (X) (2019). *Homepage* [Online]. Available at: https://institutforx.dk [Accessed: 18 February 2019].

Kaethner, S., Burridge, J. (2012). *Embodied CO2 of structural frames*. The Structural Engineer, Volume 90 (5) [Online]. Available at URL: https://www.istructe.org/journal/volumes/volume-90/issues/issue-5/articles/embodied-co2-of-structural-frames [Accessed: 20 February 2019].

Lauring, M., Silva, V., Jensen, O.B. & Heiselberg, P. (2010), *The Density of Sustainable Settlements*. in TS Larsen & S Pedersen (eds), Towards 2020 - Sustainable Cities and Buildings: 3rd Nordic Passive House Conference 7-8 October 2010. Aalborg Universitetsforlag, Aalborg, Aalborg, Denmark.

Mairs, J. (2016) J*ean Paul Viguier selected ahead of Sou Fujimoto for timber-framed tower complex in Bordeaux, Dezeen*, 21 March [Online]. Available at URL: https://www.dezeen.com/2016/03/21/jean-paul-viguier-hyperion-wooden-tower-st-john-belcier-bordeaux-france-cross-laminated-timber/ [Accessed 6 Feb 2019].

Marsh, R. (2016). *Building lifespan: effect on the environmental impact of building components in a Danish perspective*. Researchgate library [Online]. Available at DOI: 10.1080/17452007.2016.1205471 [Accessed: 18 February 2019].

Meteoblu (2018). *Climate Aarhus* [Online]. Available at: https://www.meteoblue.com/en/weather/forecast/modelclimate/aarhus_denmark_2624652 [Accessed: 13 February 2019].

Midttrafik (2019). *Koreplaner* [Online]. Available at: https://www.midttrafik.dk/koreplaner/ [Accessed: 14 February 2019].

Mikkola, E. (2017). *Comparison of national fire safety requirements within COST Action FP1404*, International Wood Products Journal, Volume 8 (2, pp. 71-73) [Online]. Available at DOI: 10.1080/20426445.2016.1247130 [Accessed: 18 February 2019].

Nordiske Medier A/S (2019). *Building Supply - Byggematerialer* [Online]. Available at: https://www.building-supply.dk/company/search/1144/byggematerialer [Accessed: 20 February 2019].

Nybygget ApS (2019). *Find byggeri* [Online]. Available at: https://www.nybygget.dk/find-byggeri/ [Accessed: 18 February 2019].

OECD (2019). *Well-being in Danish cities*, OECD Library [Online]. Available at DOI: 10.1787/9789264265240-en [Accessed: 18 February 2019].

Økonomi- og Indenrigsministeriet (2018). *ØIMs Kommunale Nøgletal* [Online]. Available at: http://www.noegletal.dk/ [Accessed: 18 February 2019]

Rice, J., Kozak, R., Meitner, M.J. (2006). *Appearance wood products and psychological well-being* [Online]. Available at URL: https://wfs.swst.org/index.php/wfs/article/view/180/180 [Accessed : 5 April 2019].

Simoes, A. (2017). *The Observatory of Economic Complexity - Denmark* [Online] Available at: https://atlas.media.mit.edu/en/profile/country/dnk/ [Accessed: 20 February 2019].

Skullestad, J. L., Bohne, R. A., Lohne, J. (2016). *High-Rise Timber Buildings as a Climate Change Mitigation Measure - A Comparative LCA of Structural System Alternatives*, Energy Procedia, Volume 96 (pp. 112-123) [Online]. Available at DOI: 10.1016/j.egypro.2016.09.112 [Accessed: 20 February 2019].

Stevenson, F., Baborska-Narozny, M., & Chatterton, P. (2016). *Resilience, redundancy and low-carbon living: coproducing individual and community learning*. Taylor & Francis Library [Online]. Available at DOI: 10.1080/09613218.2016.1207371 [Accessed: 25 February 2019].

SunEarthTools (2019). *Solar tools – Sun position* [Online]. Available at: https://www.sunearthtools.com/dp/tools/pos_sun.php?lang=en [Accessed: 12 February 2019].

Teknik og Miljø, Aarhus Kommune (2017). *Godsbanenarealerne Aarhus K – Kvalitetsprogram* [Online]. Available at: https://aarhus.dk/media/9140/20170830-kvalitetsprogram.pdf [Accessed: 15 February 2019].

Teknik og Miljø, Aarhus Kommune (2017) *Godsbanen Arealerne Aarhus K*. [Online], Available at URL: https://godsbanearealerne.dk/media/7341/udviklingsplan-for-godsbanearealerne-2017-reduceret.pdf [Accessed: 27 February 2019].

Teknik og Miljø, Aarhus Kommune (2018). *Forslag til Lokalplan nr. 1087 Kollegie og ungdomsboliger på Godsbaneareal*, Aarhus Kommunes Localplaner library [online], Available at URL: http://lokalplanerweb.aarhuskommune.dk/Lokalplaner.aspx?omraade=midtby [Accessed: 18 February 2019].

Teknik og Miljø, Aarhus Kommune (2018). *Retningslinjer for anlæg af parkeringsarealer i aarhus kommune* [Online]. Available at: https://aarhus.dk/media/11207/retningslinjer-for-anlaeg-af-parkeringsareal-i-aak-2018.pdf [Accessed: 27 February 2019] .

Trafik-, Bygge- og Boligstyrelsen (2018). *Bygningsreglementet* [Online]. Available at URL: http://bygningsreglementet.dk [Accessed: 18 February 2019].

ICONOGRAPHY

ill. 1-5: Own illustrations

ill. 6: Kontrastar. (2013) *Graffitist i frit fald* [Online]. Available at: https://kontrastart.com/2013/04/10/streetart-i-aarhus/ (Accessed: 5 February 2019)

ill. 7: Cicoberlin. (n.d.) *Berlin Hipster* [Online]. Available at: https://passenger-x.de/rezepte/hipster-style-fruehstueck-berlin-schillerkiez-roamers/ (Accessed: 5 February 2019)

ill. 8: Flickr. (n.d.) *High Line* [Online]. Available at: http://verein.fractalyn.com/chelsea-high-line-new-york/ (Accessed: 5 February 2019)

ill. 9: High Line. (2017) *High Line* [Online]. Available at: https://nypost.com/2017/03/20/several-art-exhibitions-to-take-residence-on-high-line/ (Accessed: 5 February 2019)

ill. 10: Barriobars. (2017, August 28). *Come wind on down to Barrio for a bank holiday finale fiesta!* [Instagram status update]. Retrived from: https://www.instagram.com/p/BYVk9CjH-Y3/?utm_source=ig_embed

ill. 11: Bibikow, W. (2018) *Camden Market* [Online]. Available at: https://www.tripsavvy.com/the-best-street-markets-in-london-4165253 (Accessed: 5 February 2019)

ill. 12: Hoxton and Shoreditch. (n.d.) *Hoxton and Shoreditch* [Online]. Available at: https://www.visitlondon.com/things-to-do/london-areas/hoxton-and-shoreditch (Accessed: 5 February 2019)

ill. 13: Wei, C. (2016) *Former Neue Heimat building* [Online]. Available at: https://www.shermanstravel.com/advice/going-underground-a-guide-to-berlins-artsy-alternative-neighborhoods/ (Accessed: 5 February 2019)

ill. 14: Strimpel, Z. (2014) *Clärchens Ballhaus* [Online]. Available at: https://www.cntraveller.com/article/linienstrasse-guide-berlin (Accessed: 5 February 2019)

ill. 15-36: Own illustrations

ill. 37:Tijhuis, P. (2018) *The Circl Pavilion* [Online]. Available at: https://www.dezeen.com/2018/03/25/doepelstrijkers-applies-circular-economy-principles-at-flexible-and-sustainable-circl-pavilion/ (Accessed: 12 February 2019)

ill. 38: Studioninedots, DELVA Landscape Architecture/Urbanism, Vero Visuals. (2013-2021) *Cityplot Buiksloterham* [Online]. Available at: https://studioninedots.nl/project/cityplot-buiksloterham/ (Accessed: 12 February 2019)

ill. 39: Park 2020_9. (2017) *Park 2020_9* [Online]. Available at: http://www.mcdonoughpartners.com/projects/park-2020-master-plan/park2020_9/ (Accessed: 12 February 2019)

ill. 40: The Circle House (n.d.) *The Circle House* [Online]. Available at: https://www.building-supply.dk/article/view/629055/oplev_fremtidens_losninger_i_nyt_demohus?ref=rss (Accessed: 12 February 2019)

ill. 41: Young, N., Hargreaves, A. (2017) *Bloomberg's European HQ* [Online]. Available at: https://www.archdaily.com/882263/bloombergs-european-hq-foster-plus-partners (Accessed: 12 February 2019)

ill. 42: Van Wijk, M. (2017) *De Ceuvels husbåde* [Online]. Available at: https://arkitekten.dk/2017/11/i-amsterdams-forurenede-baghave/ (Accessed: 12 February 2019)

ill. 43-46: Own illustrations

ill. 47: Joergen True (2018) *Haraldsplass Hospital* [Online]. Available at: https://www.archdaily.com/907881/haraldsplass-hospital-cf-moller-architects (Accessed: 5 April 2019)

ill. 48: Nikolaj Jakobsen (2019) *Dwellings in Västerås* [Online]. Available at: https://www.archdaily.com/912415/cf-moller-architects-completes-swedens-tallest-timber-building (Accessed: 5 April 2019)

ill. 49: Own picture

ill. 50: Marcel van der Burg (2010) *Wooden house in Amsterdam* [Online]. Available at: https://www.archdaily.com/798255/wooden-house-maatworks (Accessed: 5 April 2019)

ill. 51: Jussi Tiainen (2016) *House H* [Online]. https://www.archdaily.com/792963/house-h-a-house-hirvilammi-architects (Accessed: 5 April 2019)

ill. 52: EGGER (2016) *Freiland-Hof home* [Online]. https://www.archdaily.com/catalog/us/products/12933/egger-products-in-freiland-hof-egger (Accessed: 5 April 2019)

ill. 53: Polina Poludkina (2018) *Tarusa house* [Online]. https://www.archdaily.com/912787/tarusa-house-architectural-bureau-project905 (Accessed: 5 April 2019)

ill. 54: Brudder (2017) *Brock Commons* [Online]. Available at: https://www.atlasobscura.com/places/brock-commons (Accessed: 13 February 2019)

ill. 55: Acton Ostry Architects & University of British Columbia. (n.d.) *Brock commons* [Online]. Available at: http://www.skyscrapercenter.com/building/brock-commons-tallwood-house/22424 (Accessed: 13 February 2019)

ill. 56: Waugh Thistleton Architects. (2009) *Murray Grove* [Online]. Available at: http://waughthistleton.com/murray-grove/ (Accessed: 13 February 2019)

Ill. 57: Waugh Thistleton Architects. (2009) *Murray Grove Floor Section at Exterior Wall* [Online]. Available at: https://www.architectmagazine.com/project-gallery/murray-grove (Accessed: 13 February 2019)

Ill. 58: Standardizer. (2017) *E3 in Berlin, Kaden + Lager* [Online]. Available at https://blog.allplan.com/en/flying-high-with-wood (Accessed: 13 February 2019)

ill. 59: Bois Consult Natterer SA. (2012) *Construction detail* [Online]. Available at: http://www.promolegno.com/fileadmin/proholz/media/zuschnitt/berliner-baugruppen.pdf (Accessed: 13 February 2019)

ill. 60-112: Own illustrations

ill. 113: Blu (2014) *Graffiti by Blu in Aarhus* [Online]. Available at: http://streetartarhus.blogspot.com/2014/12/danish-famous-murals.html (Accessed: 14 May 2019)

ill. 114: Equestrian Fencing & Timber (n.d.) *Siberian Larch* [Online]. Available at: https://www.equestrianfencing.com/?product=siberian-larch-shadowgap (Accessed: 14 May 2019)

ill. 115: Own picture

ill. 116: Own illustration

ill. 117: Cuggia, R., (2016) *Cité de la Grande Triperie* [Online]. Available at: https://architectura.be/fr/actualite/13586/cite-de-la-grande-triperie-les-etudiants-de-lumons-sont-choyes-a229 (Accessed: 14 May 2019)

ill. 118: Nikolaj Jakobsen (2019) *Dwellings in Västerås* [Online]. Available at: https://www.archdaily.com/912415/cf-moller-architects-completes-swedens-tallest-timber-building (Accessed: 14 May 2019)

ill. 119: Land Art Generator (2017) *La Monarca* [Online]. Available at: http://landartgenerator.org/solar-murals.html (Accessed: 12 May 2019)

ill. 120-131: Own illustrations

ill. 132: Structurlam (n.d.) *Structurlam* [Online]. Available at: https://www.structurlam.com/construction/products/d/cross-laminated-timber-clt/ (Accessed: 15 May 2019)

ill. 133-135: Own illustrations

ill. 136-137: Land Art Generator (2017) *La Monarca* [Online]. Available at: http://landartgenerator.org/solar-murals.html (Accessed: 12 May 2019)

ill. 138-139: Own illustrations

Appendix: Own illustrations

This work would not have been possible without the help and support of our families to which our first thanks go.
Thanks to Michael and Tine that assisted us during this journey and to Rob and Ryan for the exciting collaboration and learning opportunity.
In the end, "tusind tak" to Denmark, for the hospitality and the valuable contribution that has given to our personal and professional maturation that today marks an important milestone for us.