Master's thesis

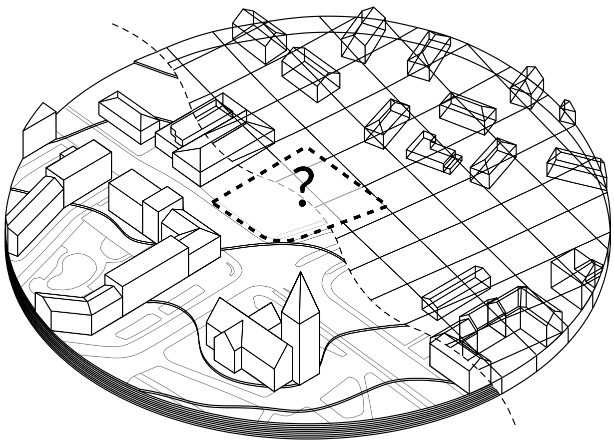
NTNU
Norwegian University of Science and Technology
Faculty of Architecture and Design
Department of Architecture and Technology

Marta Anna Szabelewska

Bridging digital and analog tools in bioclimatic design

Development of an experimental setting for bioclimatic design processes

Master's thesis in Sustainable Architecture
Supervisor: Luca Finocchiaro
Co-supervisor: Anshuman Abhisek Mishra
June 2024



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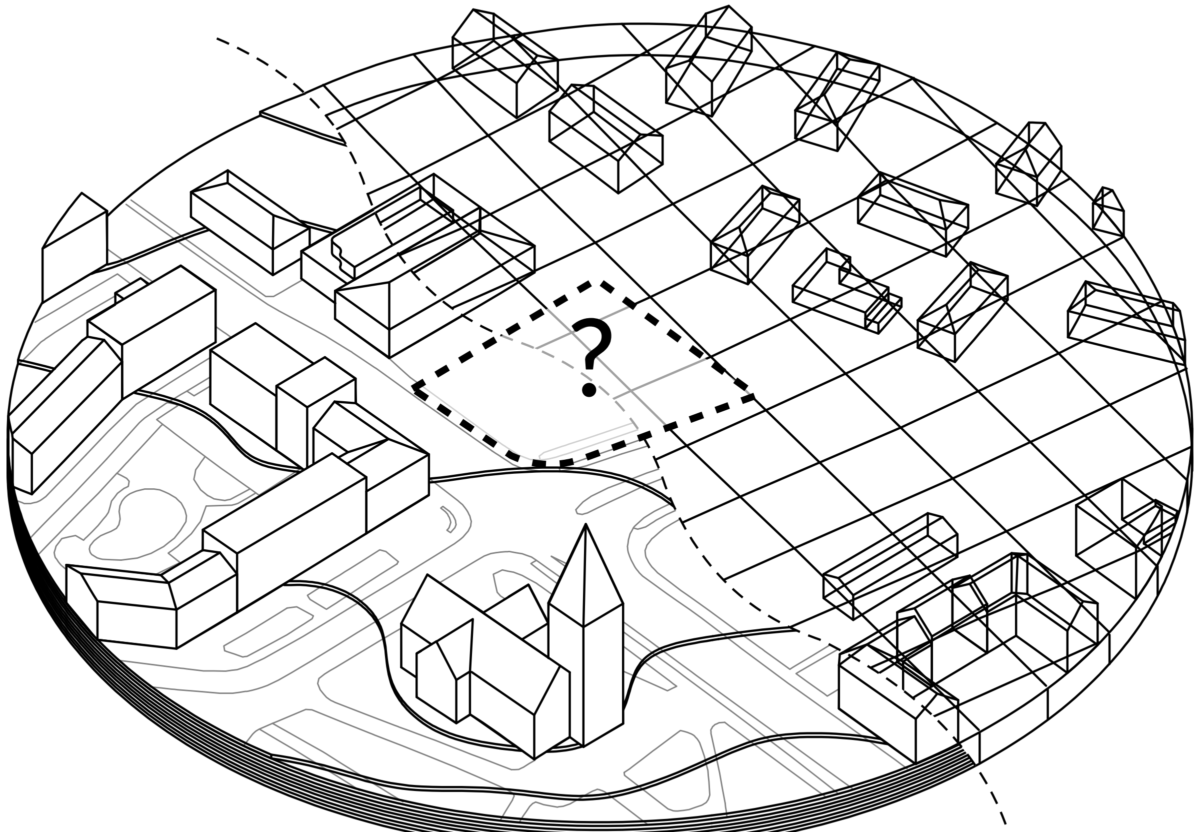

Bridging digital and analog tools in bioclimatic design.
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Marta Anna Szabelewska

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Abstract

Digital simulation tools are commonly used in bioclimatic design to analyze the environmental performance of buildings. However, several studies suggest that involving analog tools in the process might better facilitate holistic approaches to architectural projects. The question is therefore how to balance the use of analog and digital tools.

Within the thesis, an experimental bioclimatic design process involving both analog and digital tools for environmental design is proposed and then followed, while reflecting upon how particular tools support the complexity of architectural design.

The main method adopted in the thesis is research through design, as a concrete design case is used to create space for broader reflections. A residential and commercial building is designed, with the focus on both environmental performance and fitting into the urban context. The thesis moreover implements Kolb's cycle of experiential learning to ensure space for conceptualization and reflection on developed activities.

keywords: digital, analog, tool, design process, bioclimatic design, experiential learning

Sammendrag

Digitale simuleringsverktøy brukes ofte i bioklimatisk design for å analysere miljøprestasjonen av bygninger. Derimot, noe forskninger foreslår at analoge verktøy kan bedre støtte holistisk design. Derfor, målet er å svare hvordan man kan balansere bruken av digitale og analoge verktøy.

I masteroppgaven, en eksperimentell bioklimatisk designprosess med digitale og analoge verktøy ble foreslo og fulgt, mens reflekterer om hvordan begge typer av verktøy kan støtte arkitektonisk design.

Hoved metoden i oppgaven er forskning gjennom design. En bolig og kommersiell bygning ble designet, med fokus på både miljøprestasjon og harmoni med urban kontekst. I masteroppgaven erfaringslæring teori brukes for å organisere forskningen.

Acknowledgments

I would like to thank my supervisors Luca Finocchiaro and Anshuman Abhisek Mishra for all the help they provided, bringing meaningful insights both on the theoretical and the architectural side. I want to also express my gratitude to Mariya Stefanova Stoyanova Bond for introducing me to the experiential learning theory and for the moral support. Finally, I want to thank my friends and family for the patience they showed during all the ups and downs of my work on the thesis.

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1.Introduction

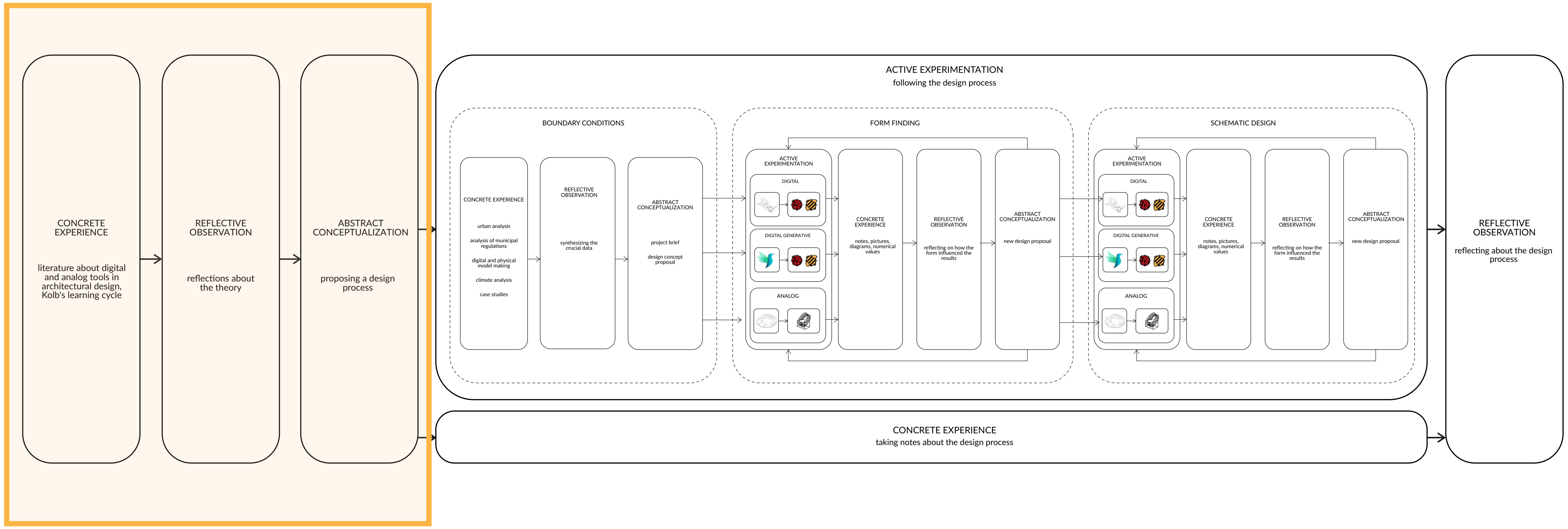


fig. 1. The introduction stage in context of the whole thesis process

1.1. Background

1.1.1. Digital vs analog

Both digital and analog tools are commonly used by architects during design development. Creating a concept is rarely a linear process: quite often, it involves moving back and forth when new ideas are developed or new problems are discovered. It is also not uncommon to switch through different design tools: from hand sketching and physical modeling to various types of software, including Computer Aided Design (CAD), Building Information Modeling (BIM) or parametric techniques [5, 14].

One of the main characteristics of digital tools is that they provide plenty of information. This can either be an advantage or a setback, depending on the phase of the project and the level of expertise of the user. For example, students who are not yet familiar with specifics of architectural design, can find the amount of data accessible in software overwhelming [5]. On the other hand, the potential to provide very detailed information makes software tools advantageous for translating an initial concept into a more realistic design. Digital tools bring also the possibility of creating forms that would be very challenging, or even impossible, to design by hand. However, simply being able to use certain program functionality might push the architect into choosing a specific design solution. It can be said that '*software tools are not innocent anymore* [14]', as the technical possibilities and level of expertise in certain software might influence the design significantly [14].

Analog tools are sometimes viewed as allowing one to notice things that were not clear in the digital medium, despite less precision and providing no numerical answers [14]. Physical models are also easy to understand for people without expertise in the architectural field [5]. Their presence in real-life space allows for gathering around, seeing them from different angles and even touching them, which makes them a good communication tool due to engaging intuitive ways of perception. Physical modeling shows also some evidence of supporting a better understanding of design problems and new ideas, which has been tested during a study at School of Planning and Design Excellence, Hindustan Institute of Technology and Science, Chennai, India. The students of 'Climate and Built Environment' course were asked to take part in an exercise, during which they had to create a physical model of a building adapted to a particular climate, based on theoretical background that had been provided during a lecture. It has been concluded, that using physical modeling supported the process of synthesizing the topic that had been discussed in class, lead to a deeper comprehension, and even supported creativity. [4] However, it can also be stated that while the analog techniques are effective for creating ideas, they are not so efficient for presenting them [10]. What is more, hand-made sketches and models usually cannot easily be scaled or modified, making it more difficult to move into further design stages.

Since both the digital and analog tools seem to have some significant values, it is sometimes suggested that combining them might have a positive impact on the design processes:

> [...] the answer to the pseudo-dilemma of analog or digital is both. Designers simply use a plethora of analog and digital tools in many different, innovative ways. As Jerry Laiserin points out, "no single tool provides the best solution for representing any design idea. In fact, exploring design ideas through multiple tools helps insulate designers from the subtle influences (and/or limitations) provided (and/or imposed) by the affordances of any single medium or tool."
>
> Thus, we should not be looking for conflict between analog and digital media; instead the right words to describe the current and evolving landscape are co-existence, complementing and evolution of tools. The goal should be a fine-tuned tool or a set of tools that will truly assist the architect during conceptual design and will be so transparent that the architect focuses on the design and not on the tool.
>
> (Parthenios, 2008)

Since the analog and digital tools seem to complement each other, it can be concluded that architects should be supported in acknowledging the available options and choosing a set that will most effectively support their practice. Investigating the limitations and possibilities brought by different tools might foster this process.

1.1.2. Bioclimatic design

While the built environment sector is responsible for 37% of global greenhouse gasses emissions [18], the climatic impact of architecture cannot be overlooked. By implementing strategies that reduce the energy use of designed buildings, architects might mitigate the negative environmental impact of the industry.

The bioclimatic design approach postulates designing buildings adapted to the local climate, aiming to provide comfort to the users by utilizing natural conditions [13]. Therefore, the need for energy to heat, cool down, or ventilate the building should be reduced. This kind of techniques traditionally used to be present in vernacular architecture, being based on experience, but the emergence of modern building typologies and materials calls for a more structured approach [12].

Due to the precision and computational possibilities, digital tools have the potential to be effectively used for estimating the environmental performance of buildings. At the same time, analog tools might support handling qualitative parameters related to space and proportion, as well as help build an understanding of bioclimatic design principles [4]. Therefore, the goal of bridging digital and analog tools remains very accurate in the context of bioclimatic design.

1.2. Goal and desired outcomes

The aim of the thesis is to develop an experimental bioclimatic design process involving the use of both analog and digital tools, and reflect upon it.

Hopefully, the results can be found useful by architects working with bioclimatic design, and support them in choosing a set of tools suitable for their tasks. It is also assumed that the results might be beneficial for those working in architectural education or studying a related field, as the proposed methods can be utilized by both professionals and students.

The main question that is aimed to be answered is: *'How to balance the use of digital and analog tools to support a holistic bioclimatic design process?'*

The thesis is planned to have a double outcome: an architectural design proposal and a reflection on the used tools and their impact on the design process.

1.3. Methodology

The main method used in the thesis was research through design. The first step was to propose a design process incorporating both analog and digital methods. Then, the process was followed, resulting in a proposal for a new mixed-use building. While following the process, notes on the used tools were made. The final reflection was facilitated by establishing a set of assessment criteria for the tools: resources needed, accuracy of results, and impact on design decisions.

To structure the research, experiential learning theory has been adopted. According to it, learning can be defined as '*the process whereby knowledge is created through the transformation of experience*' [9]. Therefore, knowledge is a result of grasping and transforming experience - where grasping refers to taking in information, and transforming means interpreting and acting on that information. Experiences become the basis for observations and reflections, and these reflections are synthesized into abstract concepts. Those can be used to create new implications for actions and be actively tested, helping to create new experiences. This process can be described by the experiential learning cycle (or Kolb's learning cycle), consisting of two modes of grasping experience: Concrete Experience and Abstract Conceptualization, and two modes of transforming experience: Reflective Observation and Active Experimentation [9].

In the planned research, experience played a crucial role, as all the design proposals were actively tested regarding their environmental performance. Therefore, the experiential learning cycle has been recognized as accurate in describing the process.

Particular elements of the cycle have been used with the following meaning:

- Active experimentation – actively testing concepts, ideas, and assumptions
- Concrete experience – encountering any objective element: theory, results of an experiment
- Reflective observation – the process of analyzing the experience, thinking about it, forming observations and reflections
- Abstract conceptualization – making conclusions and transforming the experience into abstract concepts

In order to illustrate the duality of conducted work and expected thesis outcomes (the reflections upon used tools as the first outcome, and the project proposal as the second one), a double-loop system has been proposed.

The first loop (the 'outer loop') has been used to describe the structure of the thesis. Here, learning is focused

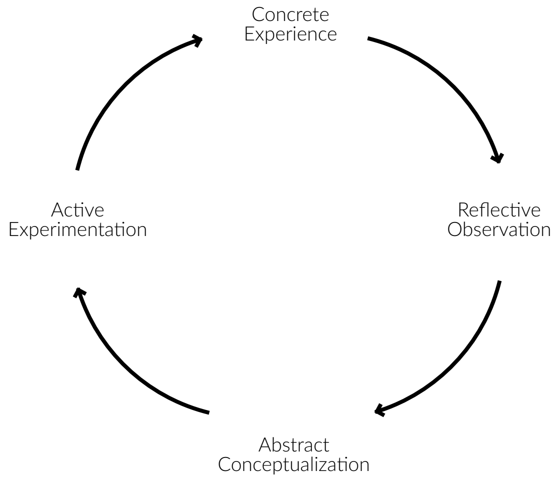


fig. 2. The experiential learning cycle

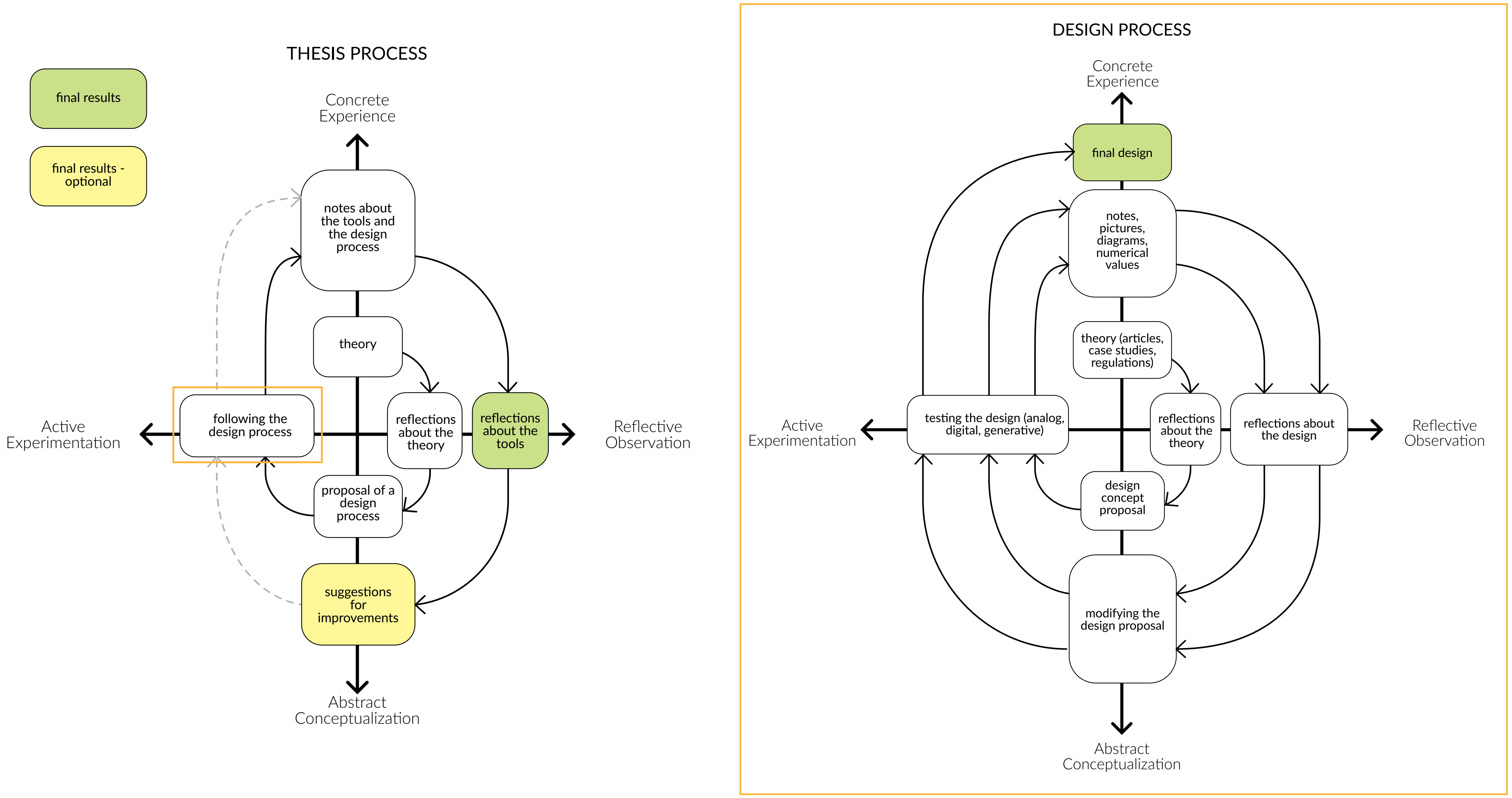


fig. 3. Double loop diagram based on the experiential learning cycle

on getting new insights into the organization of the design process and how different tools can support it.

The second loop (the ‘inner loop’) represents the process of architectural design itself and is contained in the active experimentation stage of the outer loop. Learning refers here to discovering how particular design solutions perform environmentally, functionally, and aesthetically. It serves as a basis for making design decisions.

This means, that the outer loop has only been performed once during the work on the thesis, as only one design proposal has been developed, and one set of reflections has been formed at the end. On the contrary, there have been many iterations within the inner loop. The design process followed a pattern of proposing a design solution (or a set of solutions), testing it, and either choosing one of the initial options or proposing a new one, repetitively on different project development stages, until a final design solution has been achieved.

The double loop system has later been translated into a linear scheme (fig. 4), to provide a better understanding of expected stages.

However, it should be noted that the experiential learning cycle is an idealized representation of the learning mechanism, and in reality, the process is sensitive to the learning situation and topic. It can be entered at different stages, and happen in many small cycles or even partial cycles. Particular elements of the cycle might be skipped or iterated a few times before entering another stage, for example, thinking and reflecting can be performed over some time before switching to acting and experiencing [9].Therefore, the loops and the linear representation of the process proposed in the thesis should also be understood as idealized depictions of the processes happening during the research, rather than exact stages that were consciously followed. Hence the report structure also aligns with the proposed cycles only to a certain extent.

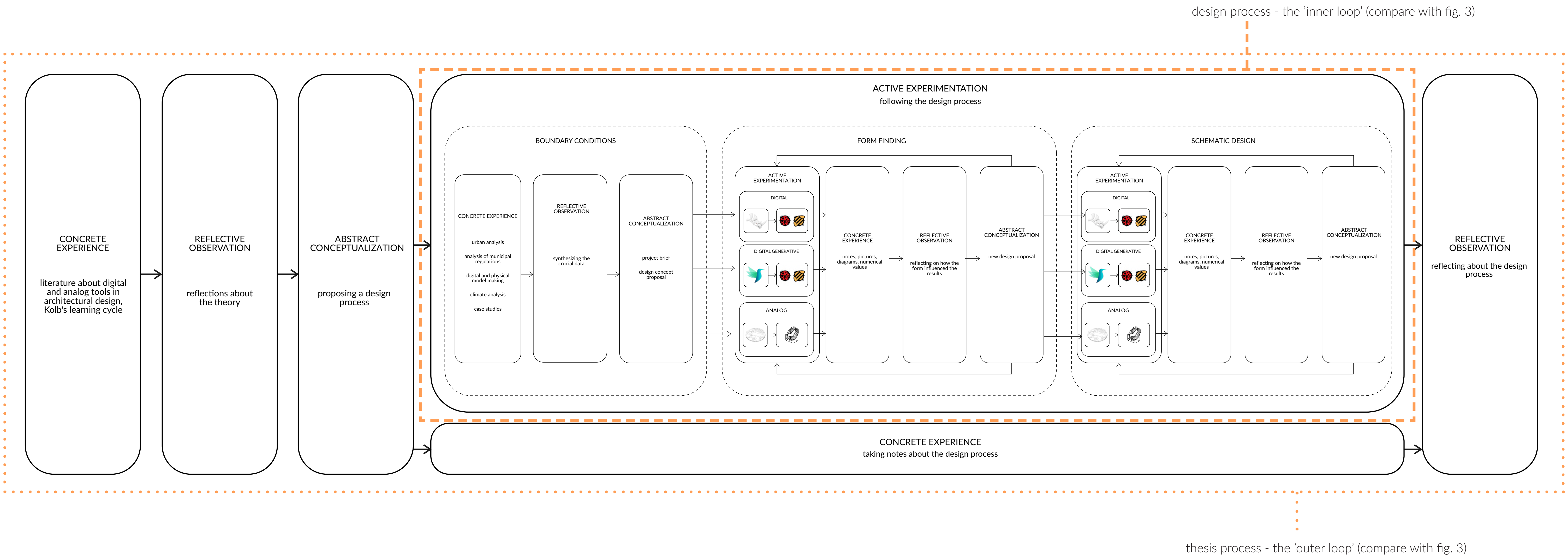


fig. 4. The two loops of the thesis and design processes transformed into a linear flowchart

1.4. Tools and softwares

Since the aim of the thesis was to reflect on the tools that might support bioclimatic design, the following set was the main focus:

Analog:

- Manual heliodon (Orchard Heliodon, Betanit)
- Automated heliodon (Orange Heliodon, Betanit, with GraOS operating system)

Digital:

- Rhinoceros 3D, version 7 - a 3D modeling tool
- Grasshopper - visual programming environment integrated with Rhinoceros 3D
- Honeybee and Ladybug (version 1.5 was used until experiment 4, later version 1.8) - extensions of Grasshopper allowing for climatic simulations
- Colibri - extension for Grasshopper allowing for creating iterative algorithms
- Design Explorer - open source tool for analyzing results from parametric design, available at https://tt-acm.github.io/DesignExplorer/

Additionally, Climate Consultant 6.0 has been used for analyzing weather data, but has not been considered a design tool, since the software does not allow to test any design solutions. What is more, Simscale - simulation software allowing for performing Computational Fluid Dynamics (CFD) simulations - was used for part of the inital analysis, but has not played any important role in the later stages of the project.

Besides that, other types of software were used for preparing architectural models and drawings:

- Archicad 26, Graphisoft
- Lumion 2024
- Affinity Designer
- Adobe Photoshop 2021
- Adobe Indesign 2024

However, they were not considered environmental design tools and therefore are not analyzed in the further parts of the thesis.

It should also be noted, that the terms *digital* and *analog* are used in this report in a manner typical for architectural environment, which can also be observed in the analyzed literature [5, 10, 14]. Analog should therefore be understood as equivalent of manual or physical, referring to models existing in real-life space and simulation tools based on such models. Digital refers to drawings and models created within software, and simulations performed fully within one.

What is more, for the sake of this work, a distinction between digital and generative methods has been introduced. A generative tool is understood here as one that allows for creating multiple solutions thanks to an iterative algorithm. It was assumed worth distinguishing due to a different workflow and different possibilities and limitations, compared to a 'traditional' modeling in CAD software.

Another important clarification that has to be made is about the skills needed to run the studies. Since in some cases, level of difficulty is described while reflecting on the tools, it should be mentioned that the author had around five years of experience in Rhinoceros and Grasshopper, and around two years of experience in Ladybug and Honeybee while working on the thesis. Colibri and Design Explorer were relatively new tools, however the idea behind their purpose was known beforehand. Finally, the heliodon was a completely new tool.

Since in some of the parts of the thesis time consumed by particular simulations is mentioned, it should be noted that they have been run with the following setup: 64-bit Microsoft Windows 10, 16 GB RAM, Intel(R) Core(TM) i5-9400F.

fig. 5. Manual heliodon.
source: https://www.betanit.com/heliodon/, accessed 27.05.2024

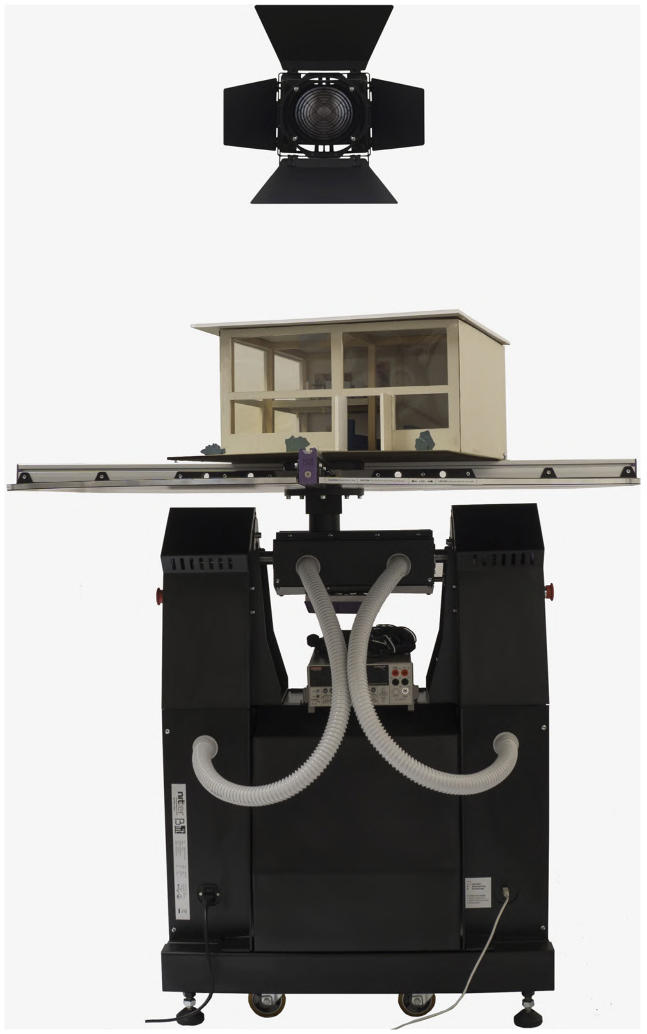


fig. 6. Automated heliodon.
source: https://www.betanit.com/heliodon/, accessed 27.05.2024

fig. 7. Software tools analyzed in the thesis

2. Boundary conditions

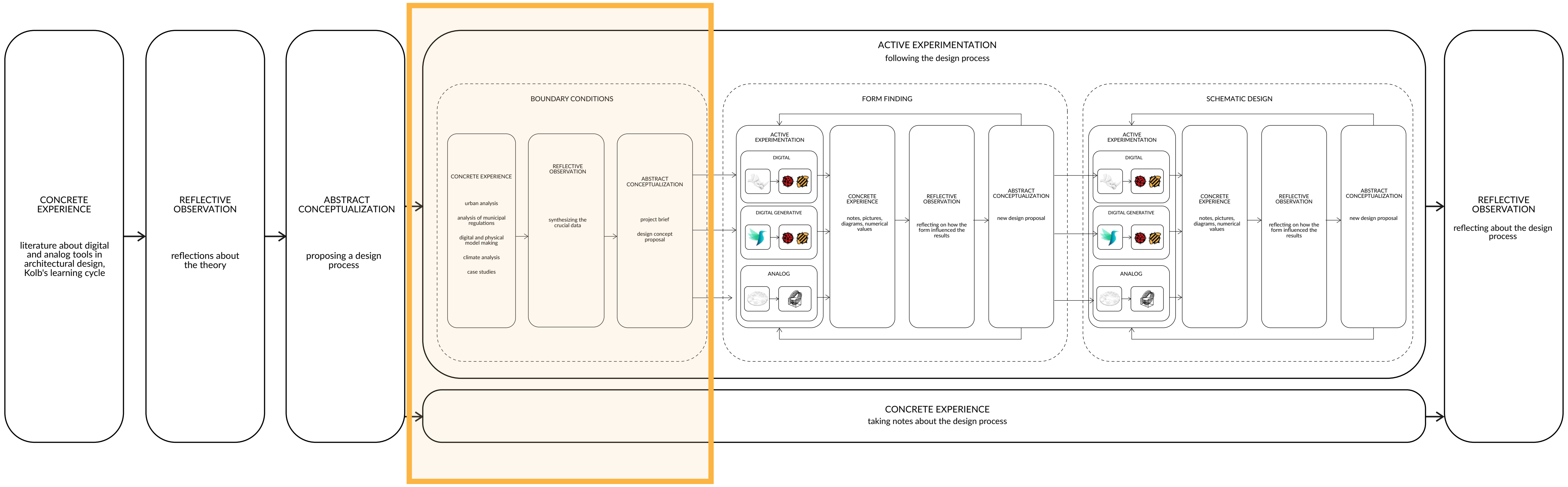


fig. 8. The boundary conditions stage in context of the whole thesis process

2.1. Introduction

The goal of the boundary conditions stage was to provide context for the project: urban, environmental, and ideological. Understanding those conditions would provide a basis for making conscious design choices in the later stages of the work, allowing to create a functional proposal well fitted into the neighborhood. As a result of the analysis, a design brief and project goals were defined.

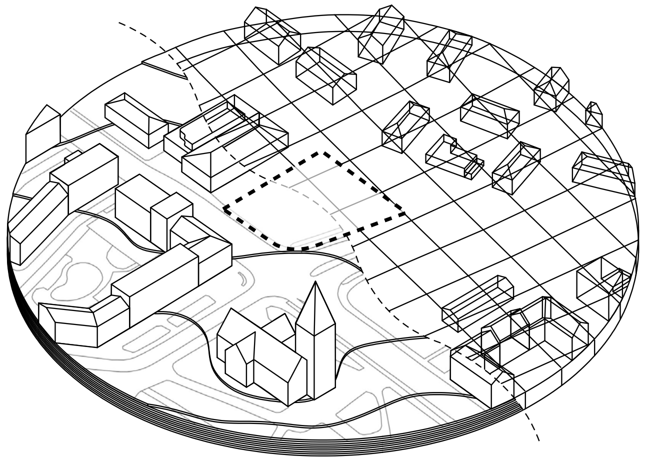


fig. 9. Graphical representation of the boundary condition stage

2.2. Site analysis

2.1.1. Site location

fig. 10. Location of the plot in the scale of the country

fig. 11. Location of the plot in the scale of the city

fig. 12. Location of the plot in the scale of the neighborhood

2.2.1. Urban analysis

The building plot is located at Innherredsveien 71, in Trondheim, Norway.

From the south, west, and north, the site is surrounded by streets, neighboring with only one building: the Rosendal Kafe and Teater, located by the easter border of the plot. The Rosendal Kafe has a terrace facing directly the analyzed plot.

A significant number of the surrounding areas have high cultural significance according to Trondheim municipality classification. The site itself is not protected yet, but has been proposed to join the cultural consideration zone. The neighboring Rosendal Kafe is considered to have high antiquarian value. [17]

The Innherredsveien street is one of the main communicatin routes in the area, spanning from Bakke Bridge to Rotvoll. Such exposure might provide a vibrant city atmosphere to the site, but also exposes it to traffic noise. A refurbishment of Innherredsveien has been planned, with the goal of transforming it into a modern main street, with the emphasis on the comfort of pedestrians and cyclists, and accessibility of public transport.

There is plenty of green areas around the analyzed plot: Lademoen park, green courtyards of the residential buildings on the north, and private gardens of the houses on the south. Despite the hill on the south, the plot itself does not have much height differences.

Currently, there is a petrol station located on the site, but it is planned to be demolished. Therefore, it is not included in any of the further design stages.

fig. 14. Urban analysis - functions

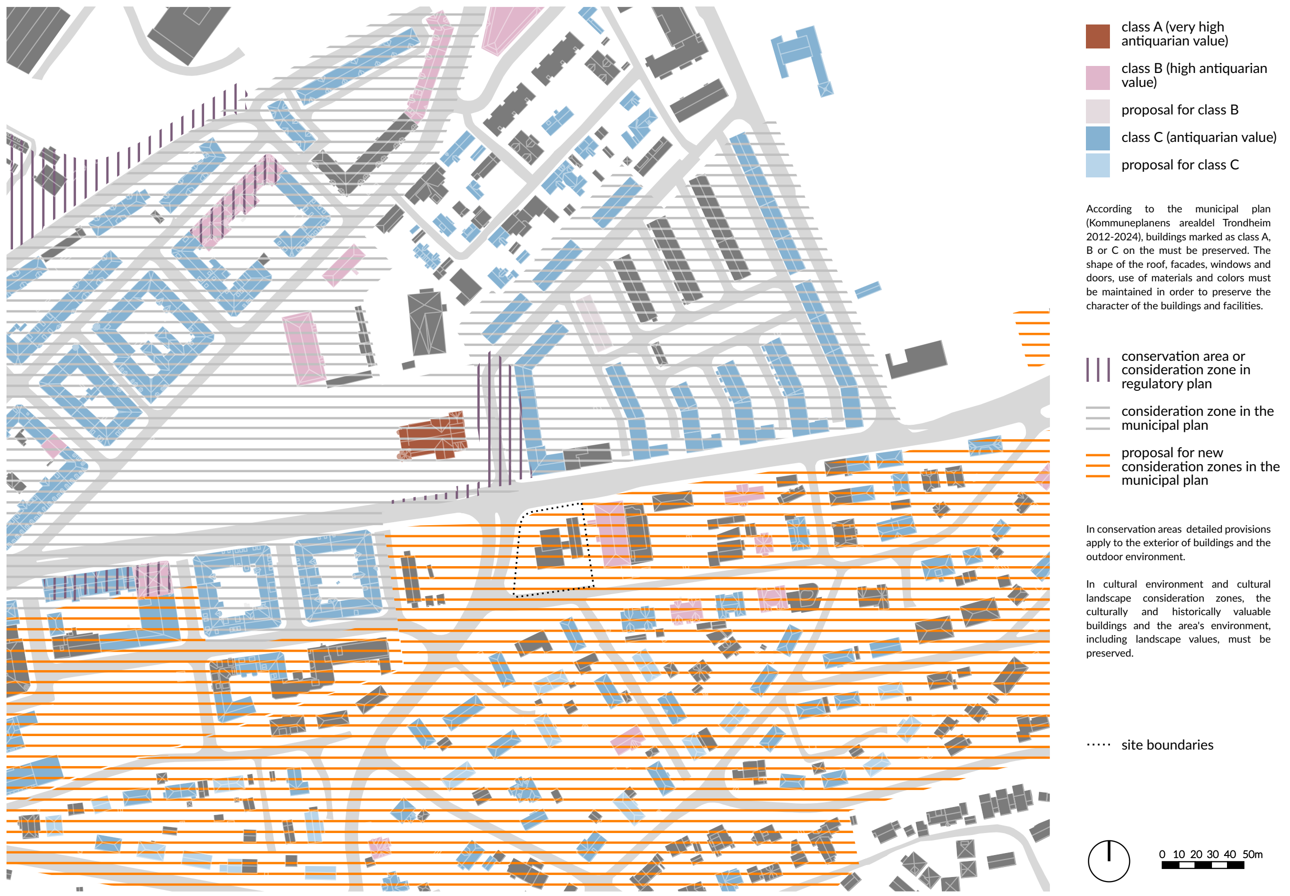


fig. 13. Urban analysis - cultural importance

fig. 15. Urban analysis - transport

fig. 16. Urban analysis - greenery

fig. 17. Urban analysis - noise

fig. 18. The site within urban context, aerial view.
source: Google (2024), available at https://www.google.com/maps accessed 30.05.2024

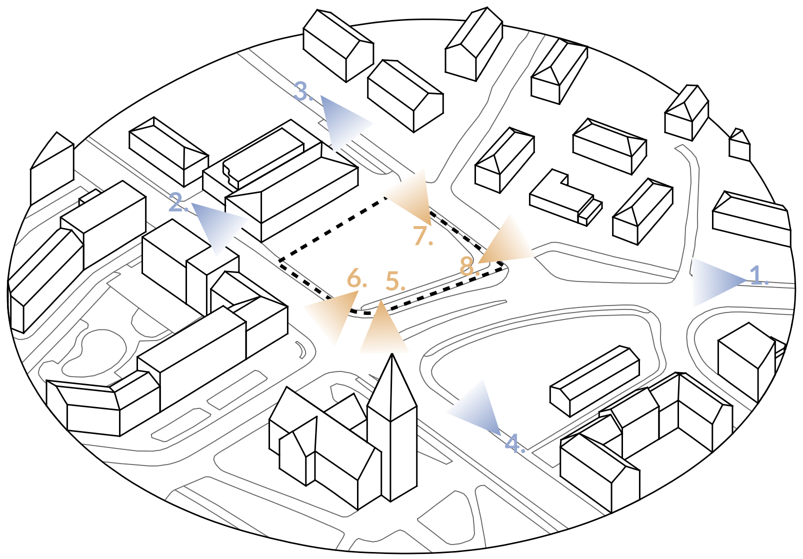
2.2.2. Views


1.


2.


3.


4.




5.


6.


7.


8.

fig. 19. Views from the site and from the surrounding areas

2.2.3. Local typologies

fig. 20. Building typologies around the plot

Lying between the areas of Lademoen and Rosendal, the plot is surrounded by a variety of building typologies.

From the north, a functionalist housing development of Voldsminde is located. The buildings have very simple, minimalistic forms, with square windows and balconies. There are spacious green areas between the residential blocks.

From the south, there is a district of old wooden houses, some of which date back to XIX w. The styles vary from very simple to heavily ornamented, and facades are painted in a variety of colors.

From the west, Jugendstil tenement houses can be found. They are characterized by enclosed courtyards, slanted roofs and chamfered corners.

On the other side of the road crossing, Lademoen church is located.

2.2.4. History of the site

fig. 21. Analysis of the history of the site.
historical maps obtained from https://kart.1881.no/trondheim/7068-trondheim/innherredsveien-71, accessed 04.03.2024

2.3. Site models

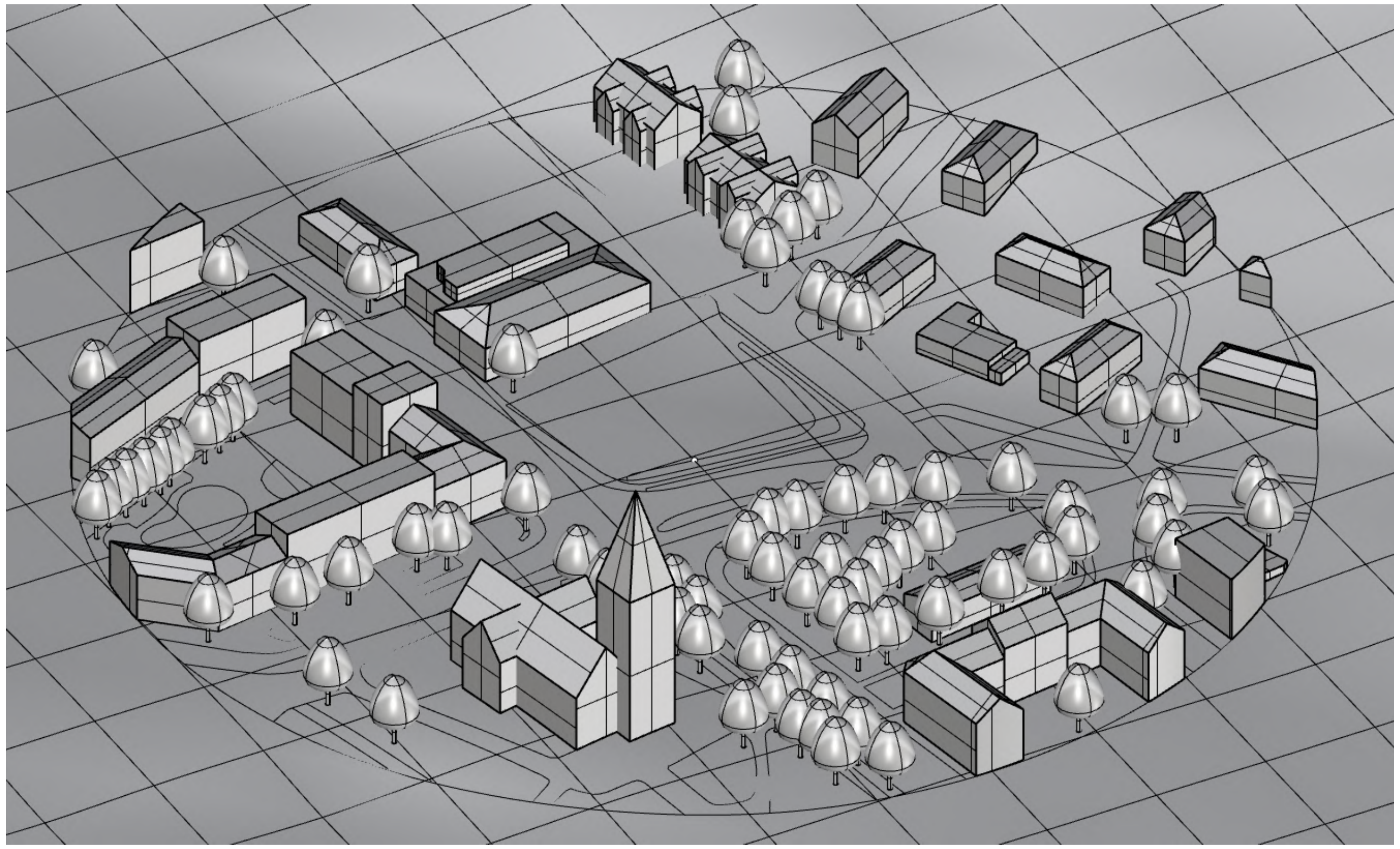


fig. 22. Digital site model

fig. 23. Analog site model

Creating site models was the first stage in which both digital and analog techniques were used.

The digital model was created first, based on a city model published by Felles datakatalog [7]. Since the original model was available in .3ds format, and the software used for analysis was Rhino (requiring .3dm format), it had to be converted. After the conversion, the geometry type was *mesh*, with many inaccuracies, which made it necessary to remodel the buildings in the area used for analysis, since Boundary Representation (BREP) was a geometry type needed for Ladybug and Honeybee simulation. It was a relatively simple, but time-consuming process. The streets and pavements outlines were obtained from the municipality map [17], downloaded in PDF format, and imported into Rhino. Since it was a vector drawing, it was automatically read as *curve* geometry and required no extra processing.

In order to make the comparison between digital and analog simulations coherent, the same area has been chosen for analysis in both environments. The limiting factor was the size of the manual heliodon, which allows for using a model with a maximum radius of 120cm. The scale chosen for the physical model was 1:200, which meant a circle with diamater of 240m in 1:1 scale.

To make the future analysis more realistic, not only surrounding buildings but also natural terrain has been considered. In the case of the digital model, the topography was included in the file published by Felles datakatalog, requiring only changing the geometry type from *mesh* to BREP. Since there are a lot of terrain differences in Trondheim, for example, there is a hill present on the south of the site, it was decided to include a wider range of terrain than of surrounding buildings, up to 1km in each direction. In the case of the analog model, within the range of 240m, the terrain was modeled as layers with a height difference of 0.8m between them (resulting from using 4mm plywood). To include also the influence of the hills, their outline has been projected into a cylinder with a diameter of 240m and modeled as a surface wrapped around the plywood model.

It was initially assumed that obtaining the data about the surroundings and preparing a clean digital model would be the biggest challenge. After completing this stage, it was expected to be easy to create a physical model through digital fabrication. However, it required much more time and effort than expected. Since laser cutting was chosen as a fabrication method, the geometry had to be transformed into flat outlines, cut out, and manually assembled. It posed new problems, such as optimizing material usage or technical difficulties with the laser cutter. In this case, access to the machines was provided by the university, as well as some of the materials, which made it possible to successfully complete the task.

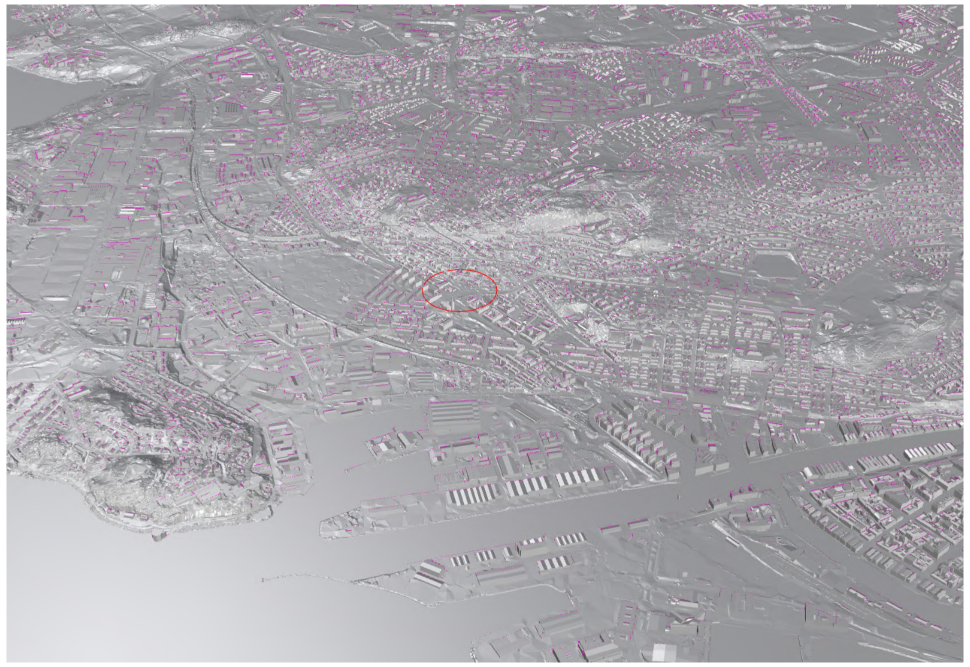


fig. 24. The original digital model of the city, obtained from Felles datakatalog

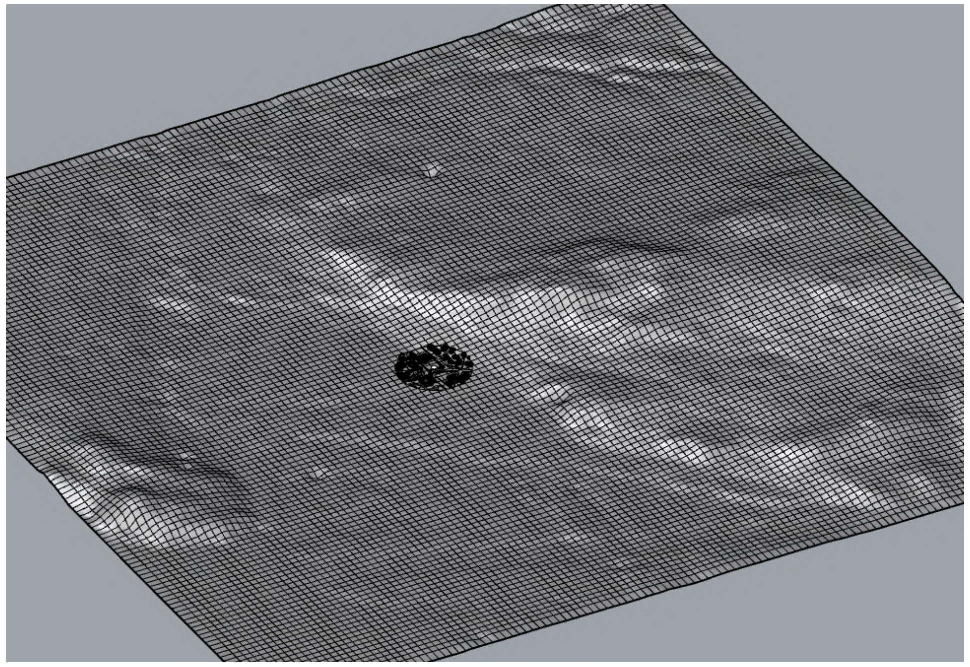


fig. 25. The model of the terrain and buildings chosen for the analysis, transformed into BREP geometry

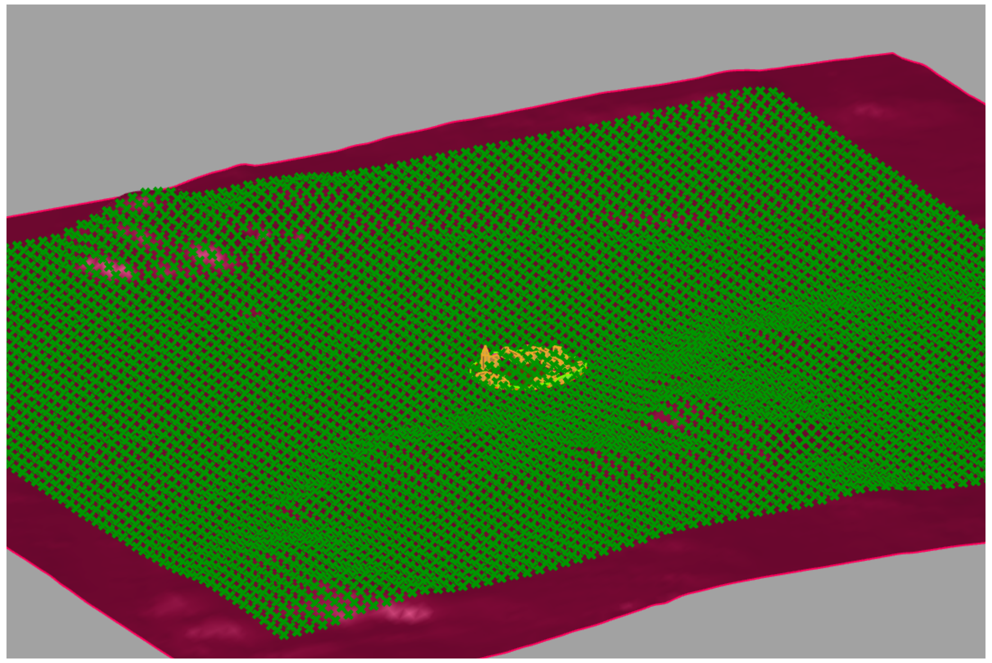


fig. 26. Points projected on the terrain surface

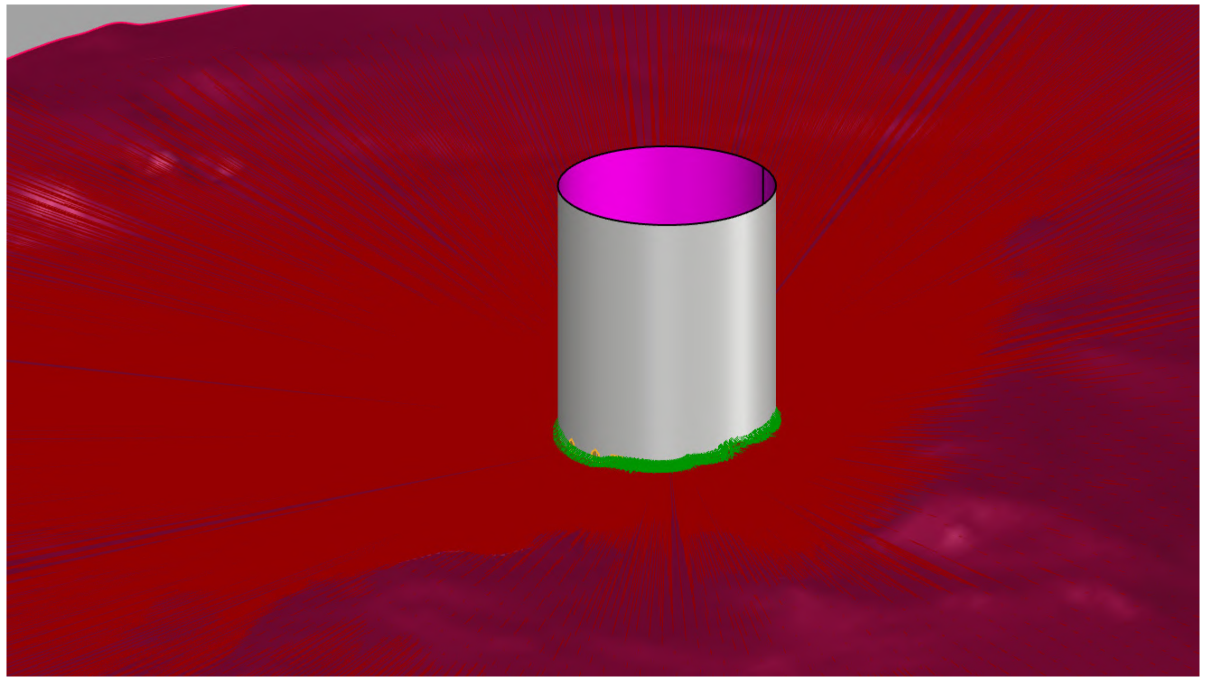


fig. 27. Points from the terrain projected to a point in the middle of the analyzed site, creating lines cutting through a cylinder with the diameter of 240m

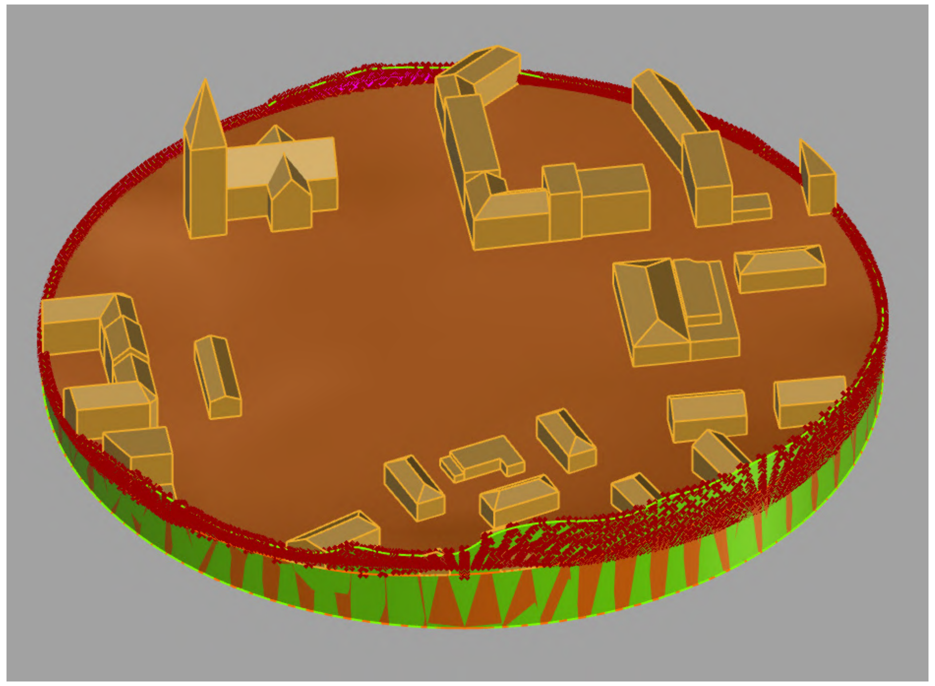


fig. 28. A simplified outline of the surrounding terrain has been obtained and used to represent the topography in the analog model

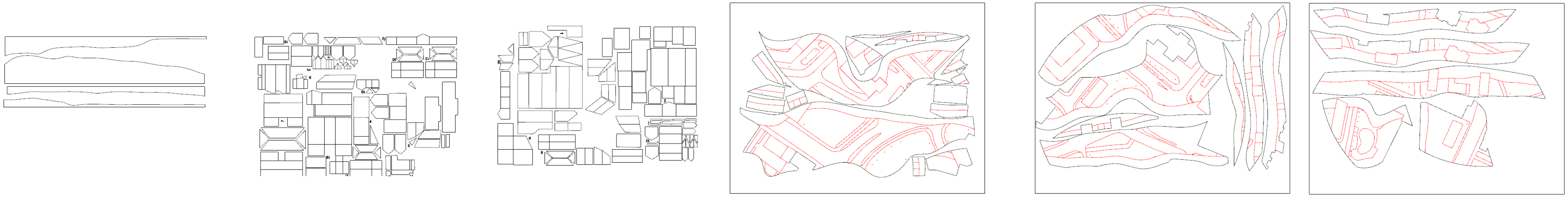


fig. 29. Outlines of the terrain layers and buildings prepared for fabrication at laser cutter

2.4. Climate analysis

2.4.1. Climate in Trondheim

Trondheim is located in the northern hemisphere, in the subarctic climate zone (Dfc), according to the Köppen-Geiger classification. The weather data used for analysis has been taken from the Trondheim Voll weather station, located at 64.4106° north and 10.4538° east. The software used for analysis was Climate Consultant and Grasshopper (Ladybug).

The temperature in Trondheim falls below the comfort range throughout most of the year. The minimal recorded temperature was -14°C in January, and the maximal recorded temperature was 27°C in August. On average, January and February are the coldest months with a mean temperature of -1°C, and July and August are the hottest months with a mean temperature of 15°C. The annual mean temperature is 6°C.

For most of the year the sky is clouded, with an average cloud cover of 60%. The cloud cover is lowest in May with an average of 42%, and highest in October with an average of 78%.

The sun's altitude stays relatively low throughout the year, with significant differences between the seasons. The highest altitude during the summer season is 49.89°, on the solstice at 12.00. On the winter solstice, which is the shortest day of the year, the sun reaches only an altitude of 3.32° at 12.00.

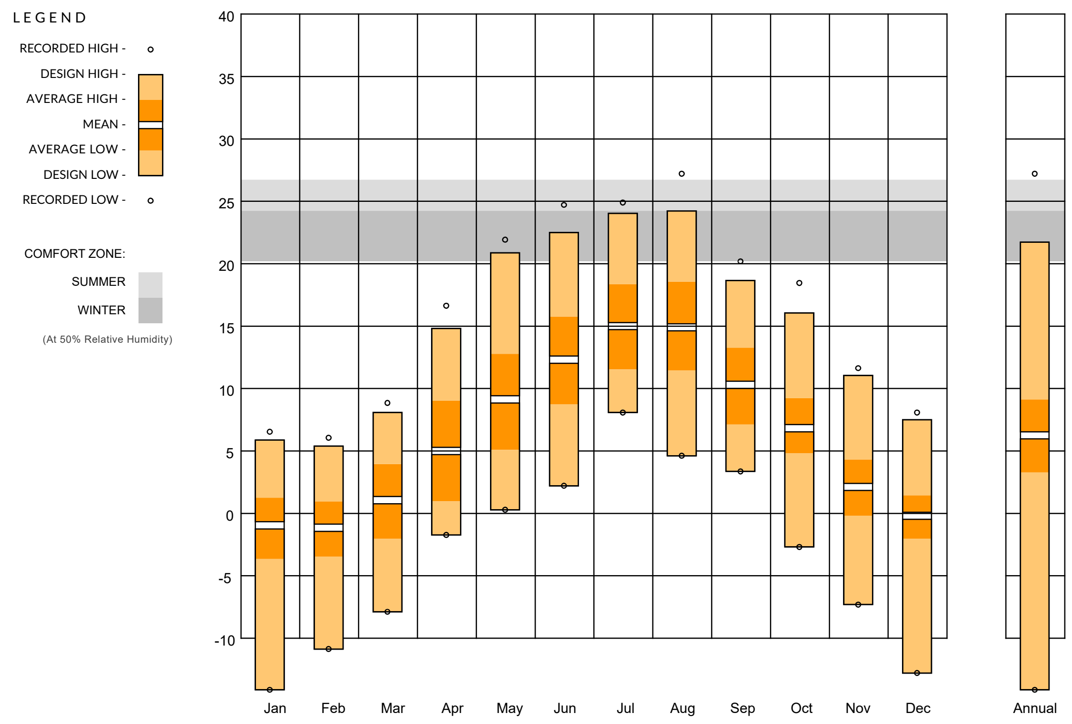


fig. 30. Temperature ranges in Trondheim. Weather data analyzed with Climate Consultant 6.0

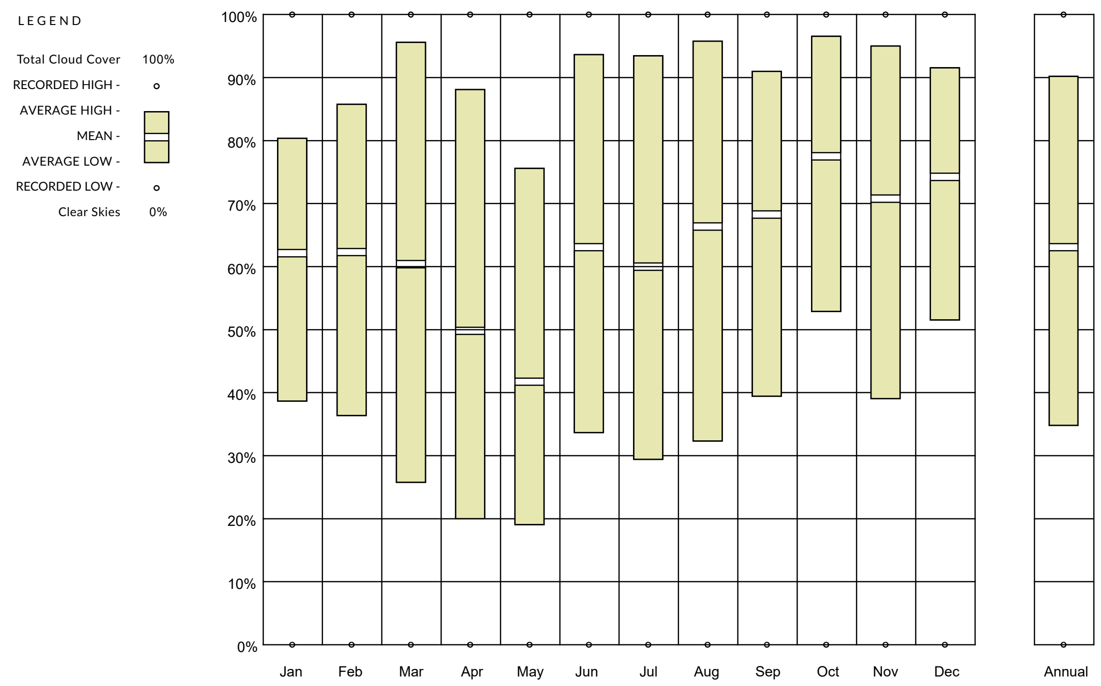


fig. 31. Cloud cover in Trondheim. Weather data analyzed with Climate Consultant 6.0

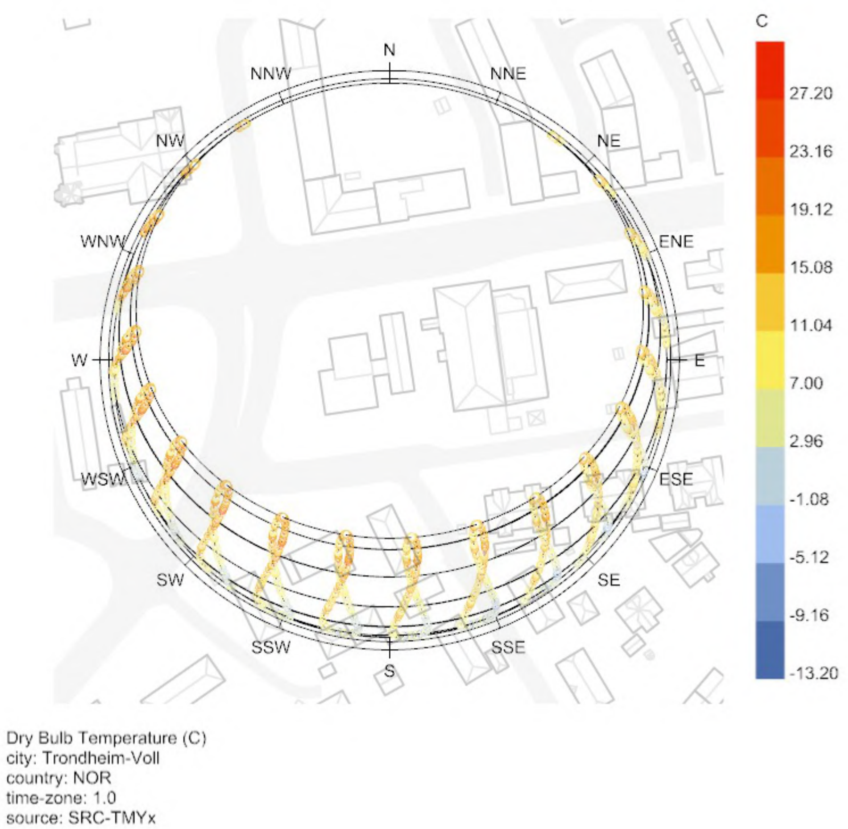


fig. 32. Sun path in context of the analyzed site. Weather data analyzed with Ladybug

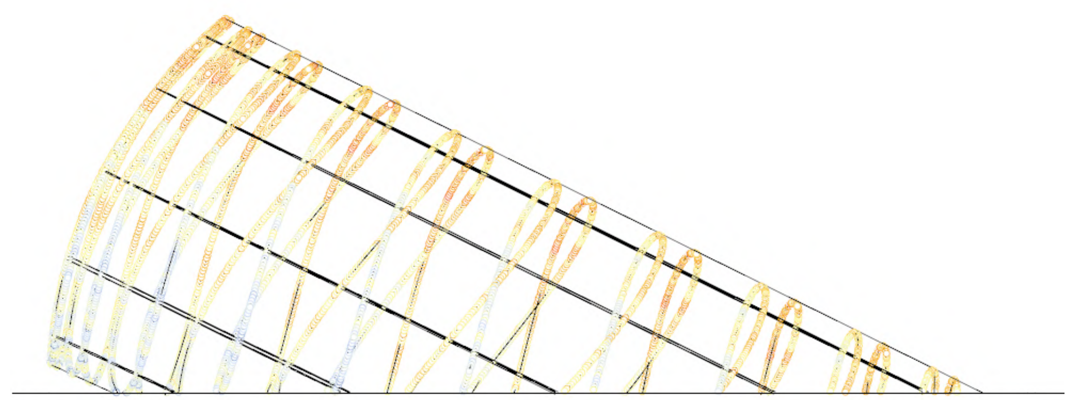


fig. 33. Sun path in Trondheim, side view. Weather data analyzed with Ladybug

A psychrometric chart has been used to find suggested strategies for providing thermal comfort in the climate of Trondheim. Without any strategies applied, the temperature is at a comfortable level only for 2.1% of the year (185 h). The most effective passive strategies that might support thermal comfort are related to heat gains: internal heat gain and passive solar heat gain. However, according to the chart, implementing a heating system would still be necessary to provide full thermal comfort through the year.

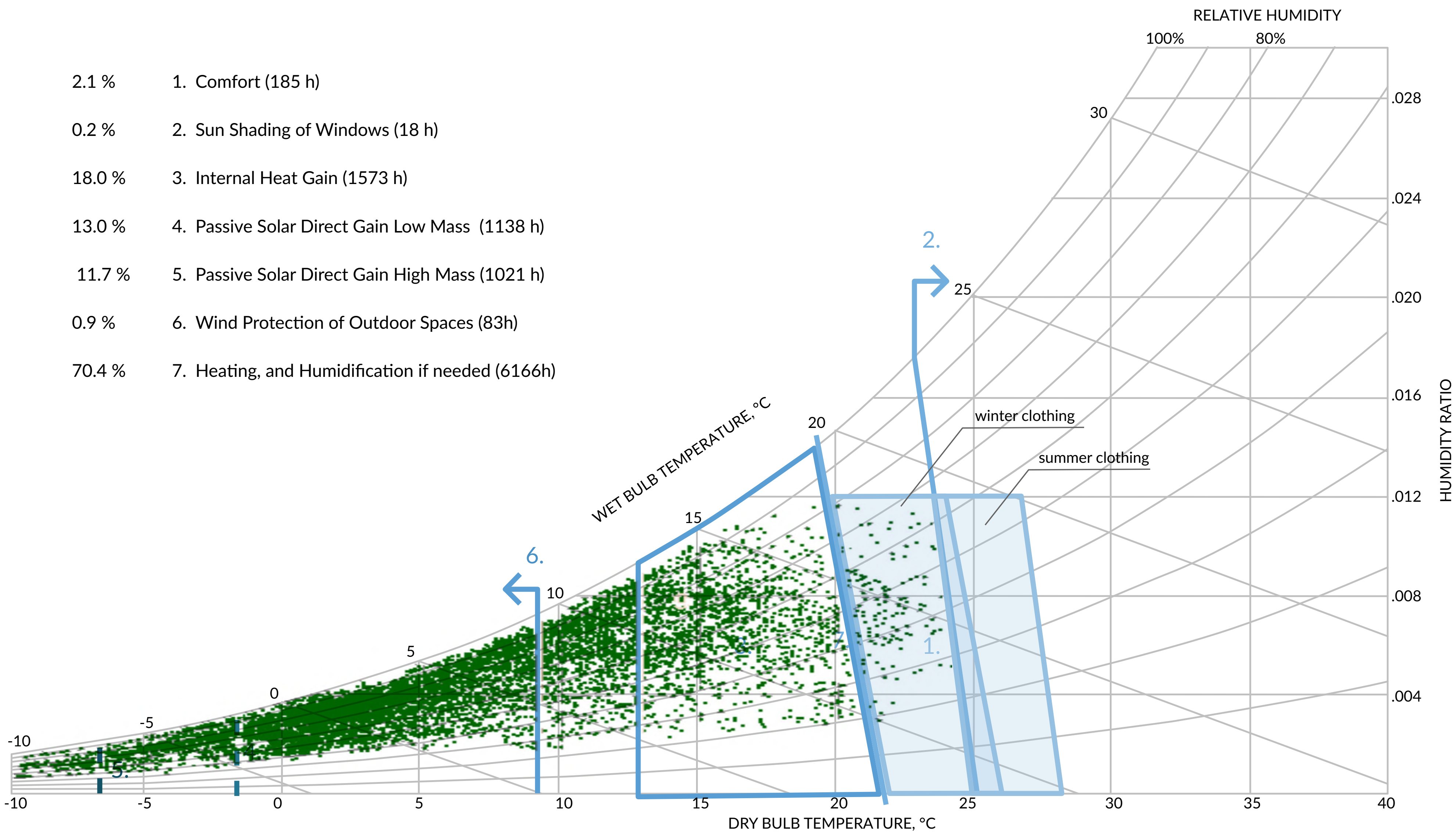


fig. 34. Psychrometric chart. Data provided by Climate Consultant 6.0

fig. X.

2.4.2. Site wind analysis

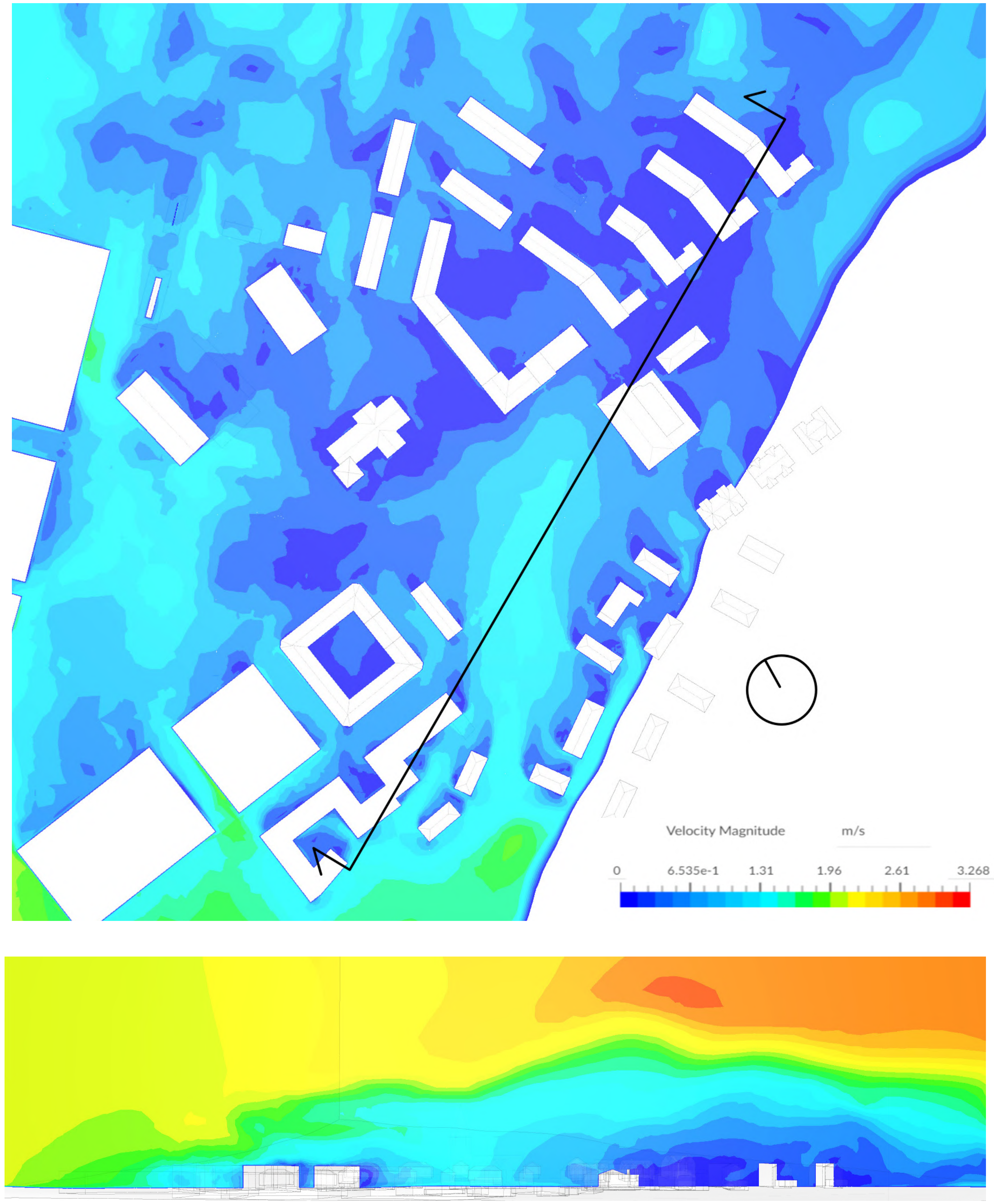


fig. 35. Analysis of wind conditions on the site. Data obtained from Simscale.

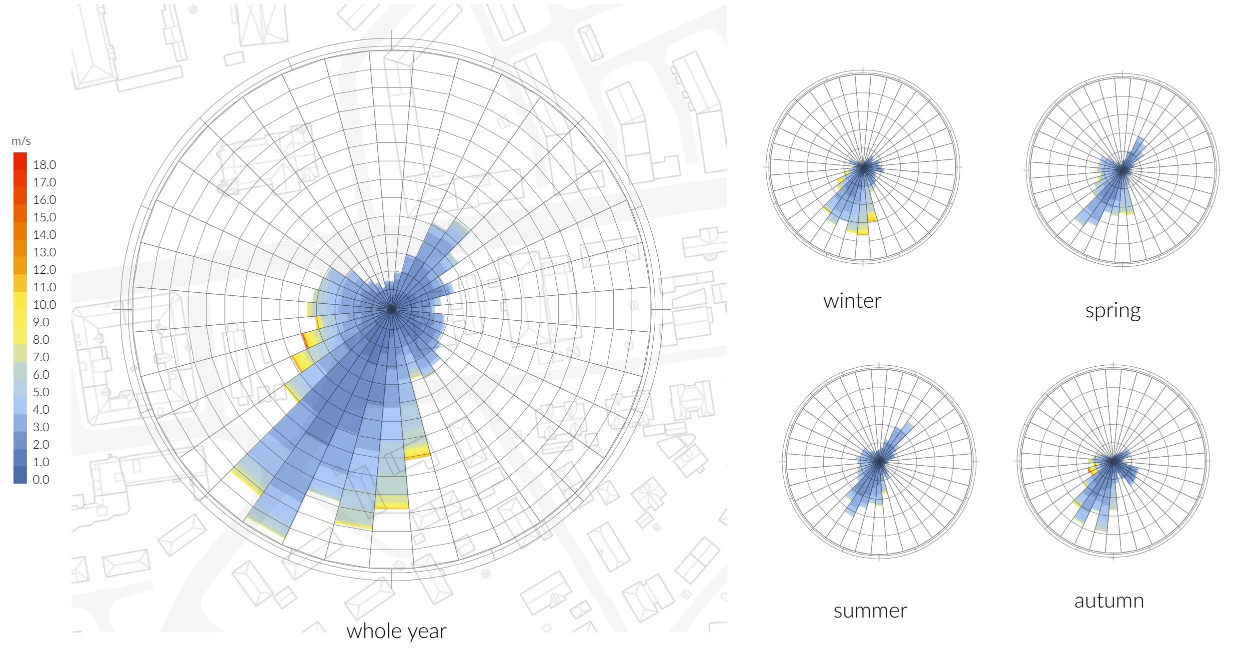


fig. 36. Typical wind speeds and directions in Trondheim. Data analyzed with Ladybug

The prevailing wind direction in Trondheim is SW, with a speed of 2m/s. During spring and summer, winds from NE are also quite common, with a speed of 5m/s. During winter, wind from the south tends to appear, with a speed reaching up to 10 m/s. The highest noted wind speed in Trondheim has been 18m/s, noted in autumn. However, it is very uncommon, and has only been recorded for 1 hour per year.

A study of the influence of the prevailing wind (2 m/s, SW) has been done to assess whether there is a risk of excessive wind speeds. It has been concluded, that even though there is some chance of winds speeding up in the Fv865 street, the prevailing wind should not cause much discomfort. However, some sheltering co-uld be provided for the outdoor spaces on the plot, to protect them from the stronegr winds occuring occas-sionally.

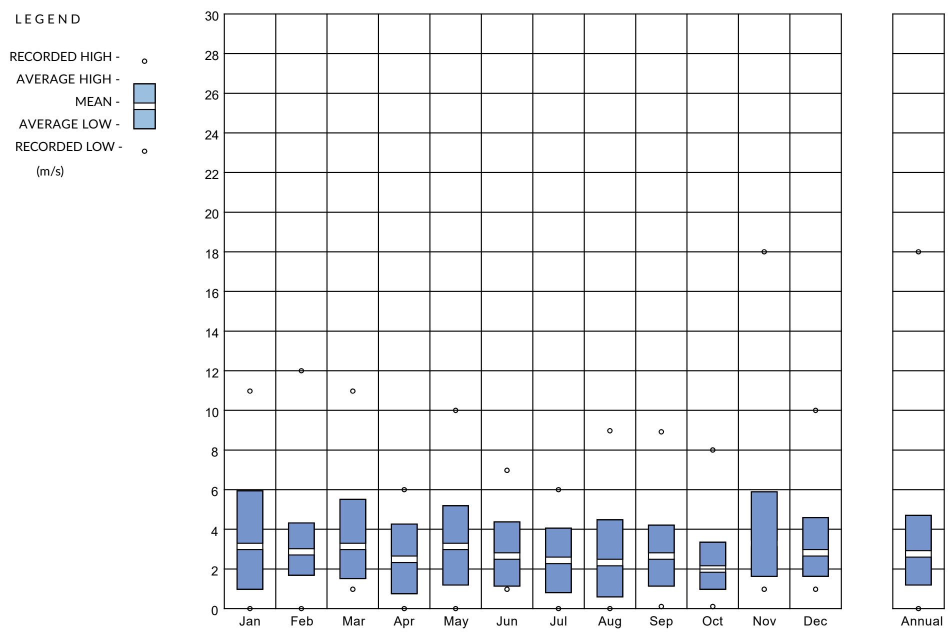


fig. 37. Typical wind speeds in Trondheim. Data analyzed with Climate Consultant 6.0

2.4.3. Experiment 1. Solar conditions on the site.

Setup and goals:

Experiment type: digital

Used tools:

- Rhinoceros 3D
- Ladybug + Honeybee

The goal of the experiment was to assess the solar conditions of the site. Therefore, the research question was:

How much direct sun hours and incident radiation does the site obtain, without any building proposed?

There were three dates chosen for the analysis:

- Summer sosltcie
- Equinox
- Winter solstice

Additionally, the annual average value has been gathered.

Two types of data have been collected: direct sun hours and incident radiation.

Results:

Analysis of direct sun hours and incident solar radiation has proven that the site has excellent solar exposure, with very little shade from the surrounding buildings or greenery.

However, due to the presence of the hill in the south, there is no direct solar radiation on the site during winter solstice. As the sun does not rise above the altitude of 3.32 degrees, it remains hidden behind the terrain through the whole day.

Notes on the process:

Since the model used for the analysis was prepared beforehand, running the study was very fast. The script prepared in Grasshopper was simple enough not to pose an extra challenge and the limited amount of results obtained at this stage was easy to extract.

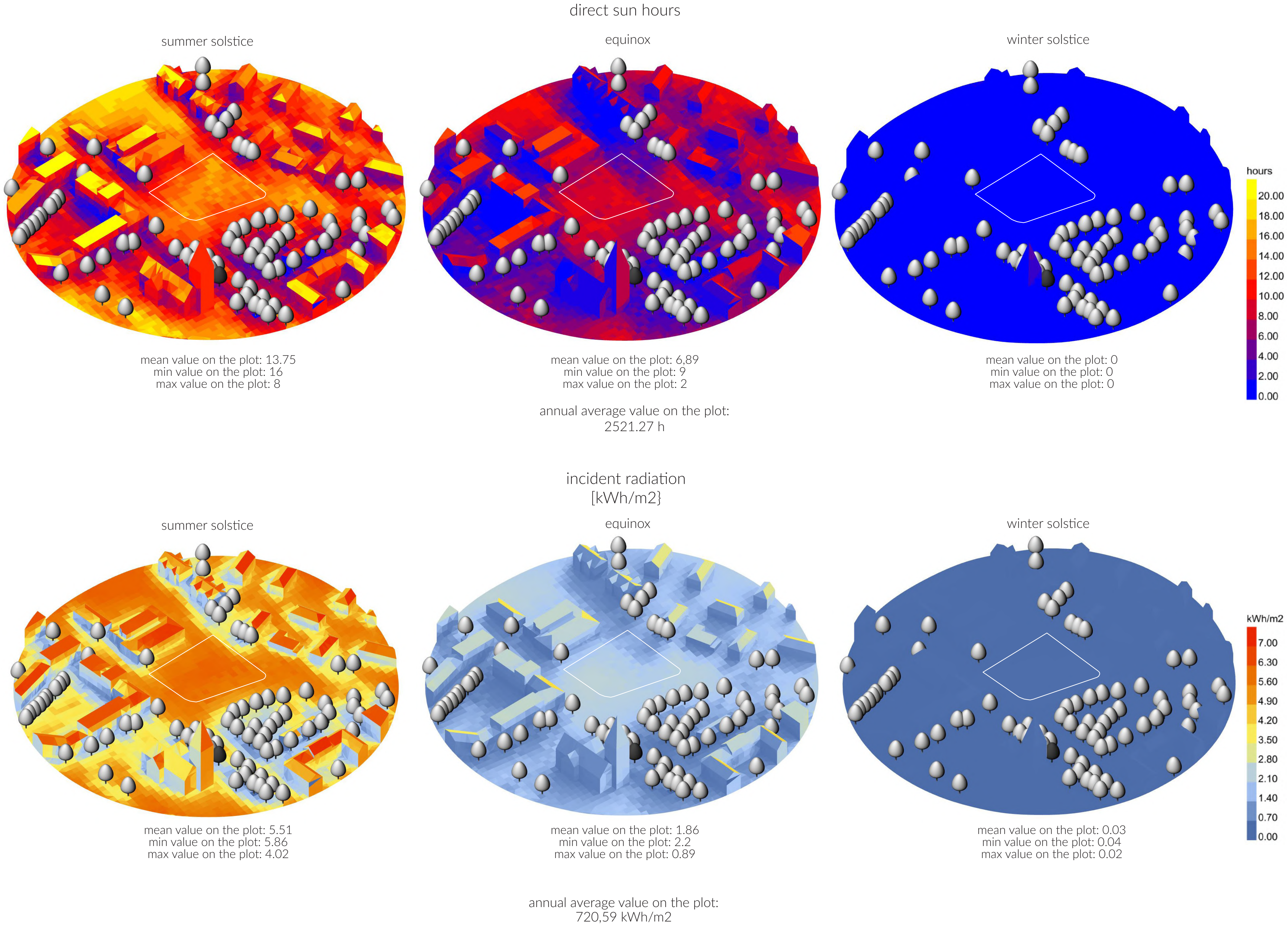


fig. 38 Digital analysis of the solar conditions on the site

2.4.4. Experiment 2. Solar conditions on the site.


June, 12.00


May / July, 12.00


April / August, 12.00


March / September, 12.00


February / October, 12.00


January / November, 12.00


December, 12.00

fig. 39. Analog analysis of the solar conditions on the site

Setup and goals:

Experiment type: analog

Used tools:
- manual heliodon
- physical site model (plywood, cardboard), scale 1:200

The goal of the study was the same as in experiment 1: to asses solar conditions of the site, before any design proposal is made. However, the heliodon does not allow for collecting data over a period of time, only during particular points in time. What is more, the precision is limited to month and hour, without the possibility of choosing a particular day. Therefore, analysis has been done for 12.00 each month, to get a comparison of conditions during the highest sun altitude through the year.

The research question was therefore:

How much sunlight does the site obtain when the sun is at the highest altitude for each month?

Results:

For most of the tested points in time, there were no shadows casted on the analyzed plot. The site seemed very well exposed to solar radiation, with very little influence from surrounding objects. The study provided some input about the months that were omitted in experiment 1, such as October and February, showing that during that time some shadows from the trees on the south could reach the plot. However, this influence seemed to be minimal. The lack of direct solar radiation in December, even at the highest sun altitude, has been confirmed.

Notes on the process:

Operating the heliodon was very intuitive and took about 15 minutes to learn, despite no previous experience with the tool. Also, the results were very easy to understand. However, less precise data was provided, and it seemed that there was a bigger risk of errors compared to the digital study. Since the brightness might vary between the pictures depending on the camera settings, this can bring some inaccuracies when comparing the results. What is more, since the heliodon lamp is so close to the table, the place in the middle appears as much brighter than the rest of the model, and not all the shadows are parallel to each other. That suggests that in order to obtain the best results, the model should be placed close to the middle of the table.

Another factor that suggested a lot of space for errors and inaccuracies was a technical problem that was encountered, as the measuring plate for setting the latitude was not calibrated well. This required extra caution before running the study.

Not much extra value compared to the digital study has been provided at this stage.

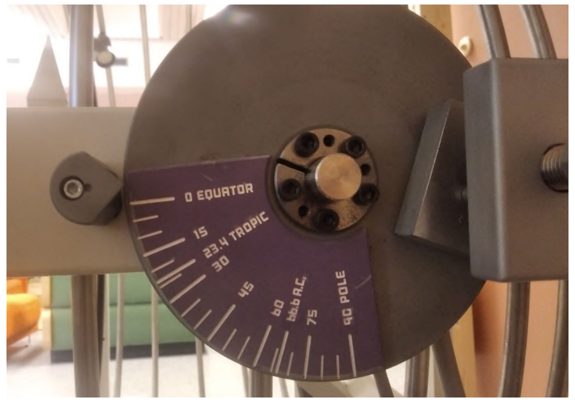
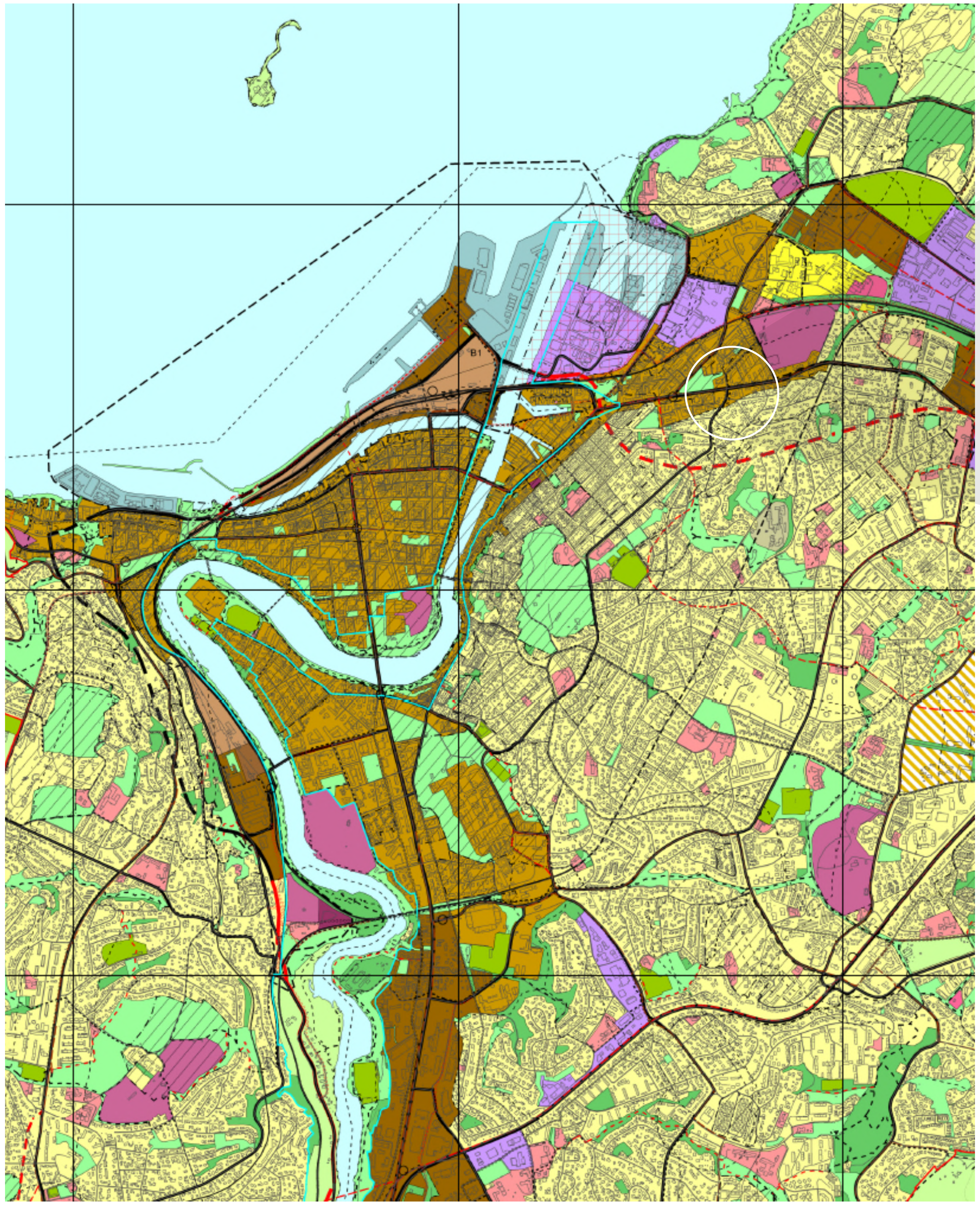


fig. 40. Problems with the heliodon calibration - equator line should be horizontal

2.5. Municipal regulations



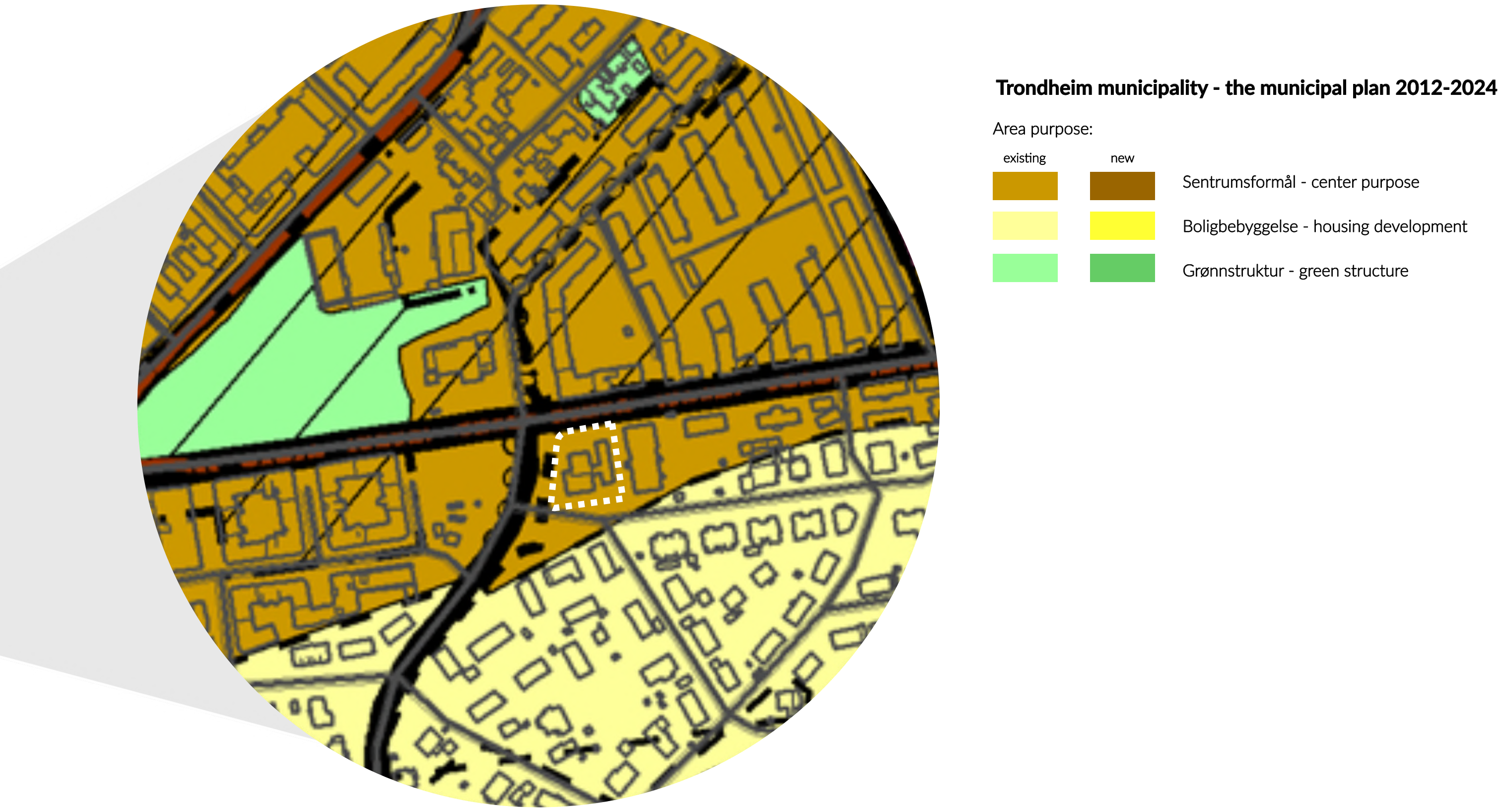


fig. 41. Analysis of the local regulations in Trondheim

According to the municipal local regulation plan (Kommuneplanens arealdel 2012-2024 [16]), the site is located in an area classified as *sentrumsformål*, which can be translated as having a center purpose. What is more, it is located in *indre sone* – an inner zone – in the classification regarding parking spaces.

A summary of regulations resulting from the plot belonging to those categories has been made, and used in the further parts of the process as a basis of assessing proposed solutions and making design decisions. The rules have been listed below:

- Minimal number of dwellings on the plot: 10 dwellings / 1000m²
- Minimum 0,5 car parking places must be provided per 70m² usable area or per housing unit. 5% must be for people with reduced mobility (4,5x6m).
- Minimum 2 bike parking places must be provided per 70m² usable area or per housing unit
- Minimum 30m² of outdoor space must be provided per 100m² of usable area or per housing unit.

At least half of the outdoor space must be at the ground level and shared. Outdoor space means suitable outdoor recreation areas for the residents, either shared or private. Drivable footpaths, carriageways, parking spaces for cars and bicycles, and areas for waste facilities do not count as outdoor spaces.

- Maximal level of noise for outdoor spaces: 55 dBA
- Sun/shading analysis must be done for outdoor spaces for:

  - Equinox, 15.00

  - Summer solstice, 18.00
- Distance between blocks of flats at the opposite sides of the plot must be min. 1,5 the buildings' average cornice height.

2.6. Case studies - cohousing

The prevailing function of the building planned on the site was residential, however, it was assumed that the design should go beyond a conventional housing development. An inspiration for providing extra value to the planned building has been found in the idea of cohousing, understood as a 'form of community living that contains a mix of private and communal spaces with substantial self-managed common facilities and activities aimed at everyday living'. [3]

It has been shown in multiple studies, that cohousing might bring benefits for the wellbeing of residents. By creating lively social networks and supporting a sense of community, it might enhance emotional, physical, and economic security [3].

The idea of cohousing has been present in Scandinavian countries for years. In Denmark and Sweden, it grew rapidly especially in the 1970s and 1980s [2,11]. In 1977, an association called Bo i Gemenskap (Living in community) was established by a group of Swedish architects, researchers, and journalists. They propagated the idea of creating cohousing units of 20-50 apartments, with common areas such as a kitchen, dining room, living room, or workshop, allowing residents to take part in common activities and providing easier and more enjoyable living conditions. One of the crucial ideas was giving up 10% of space from individual apartments in order to introduce shared spaces, providing all the residents more space than they otherwise would have access to, despite having less of private areas. [2]

Echoes of this approach can be found also in modern movements. A current example that has been found particularly inspiring is the Gaining by sharing model. According to the authors, 'Gaining by Sharing centers around the concept that every inhabitant has their own private dwelling, slightly smaller than normal units, fully equipped and organized around generous and inspiring shared spaces. Shared spaces are well integrated – becoming part of everyday life. The spatial concept is designed to create a shared environment that supports the community of the residents- to facilitate both informal meetings and planned social acitivities [8].' The goal is to create a sustainable community and enhance the environmental, social, economic and architectural qualities of residential projects. It must however be noted, that the model requires the participation of the future residents, which was not realistic in the case of this thesis. Nevertheless, other principles of Gaining by Sharing have been an inspiration for the project program and goals.

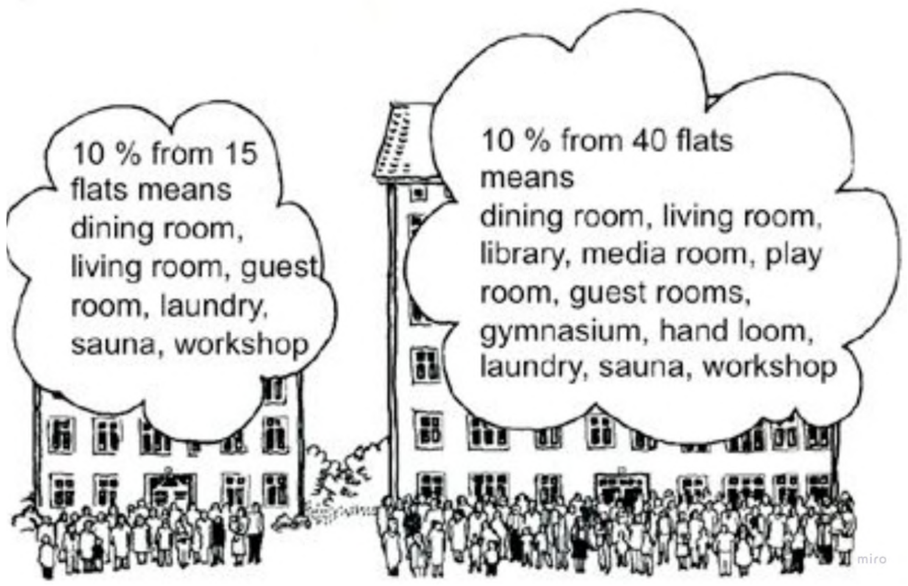


fig. 42. The principles of shared spaces in cohousing, according to the Bo i Gemenskap group [2]

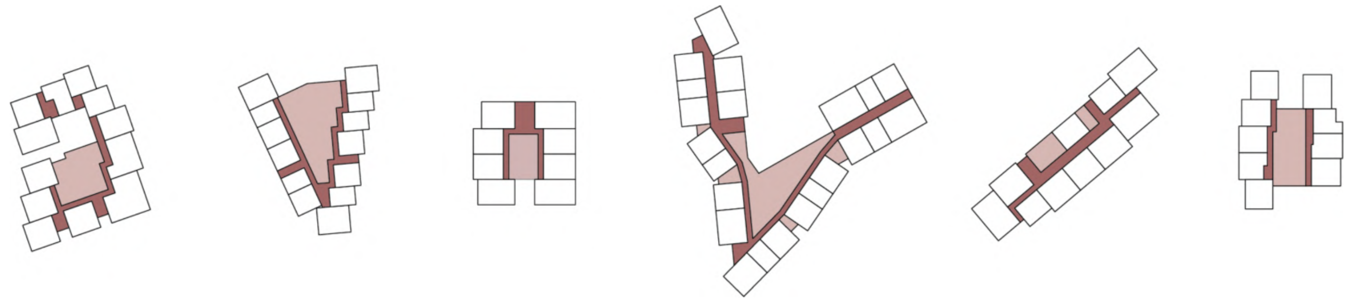


fig. 43. Examples of the relation betwen private and shared spaces, according to Gaining by Sharing [8]

fig. 44. Main hall in Vindmøllebakken, housing project designed with the principles of Gaining by Sharing [8]

fig. 45. Dining room in Vindmøllebakken, housing project designed with the principles of Gaining by Sharing [8]

2.7. Project brief

The project brief resulted from all the previous analysis, with the aim of finding a solution connecting the urban constraints and possibilities, climate adaptiation, and the ideas of cohousing.

Project location: Innherredsveien 71, Trondheim, Norway

Plot area: 2010.6 m²

Function: mixed-use – residential with commercial spaces

Users: residents of mixed ages and at different life stages (students, singles, couples, families, seniors, ...)

Program:

- Residential units – at least 20 apartments (~70m²/apartment), from 1 to 3 bedrooms
- Shared spaces for the residents (~10% of total residential area): common kitchen and dining area, living room/leisure space, space to work and study, art room, workout area, laundry, workshop, greenhouse
- Public outdoor space well connected to the city life (area according to Kommune Arealdel, min. 30m² per dwelling)
- Commercial spaces
- Bike parking (2 places per apartment)
- Car parking (0.5 place per apartment)

The proposed building is meant to utilize the plot area in a way that fulfills the requirement of minimal number of apartment units, potentially aiming for a higher number. However, the outdoor spaces are also meant to be prioritized as providing extra value for the residents. A great potential for a green, social area is identified on the plot.

What is more, the goal of the design is to provide comfortable living conditions for the residents, increasing their well-being by allowing for socialization in common areas, and also extending the space that they can treat as home beyond the door of their apartments.

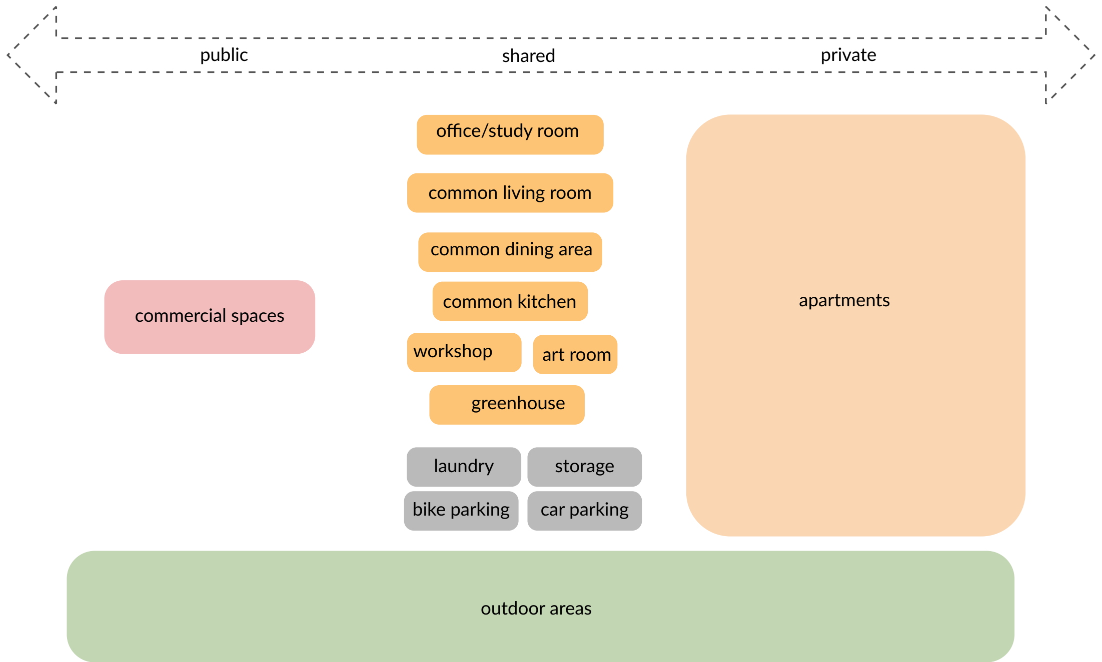


fig. 46. Graphical representation of the building program

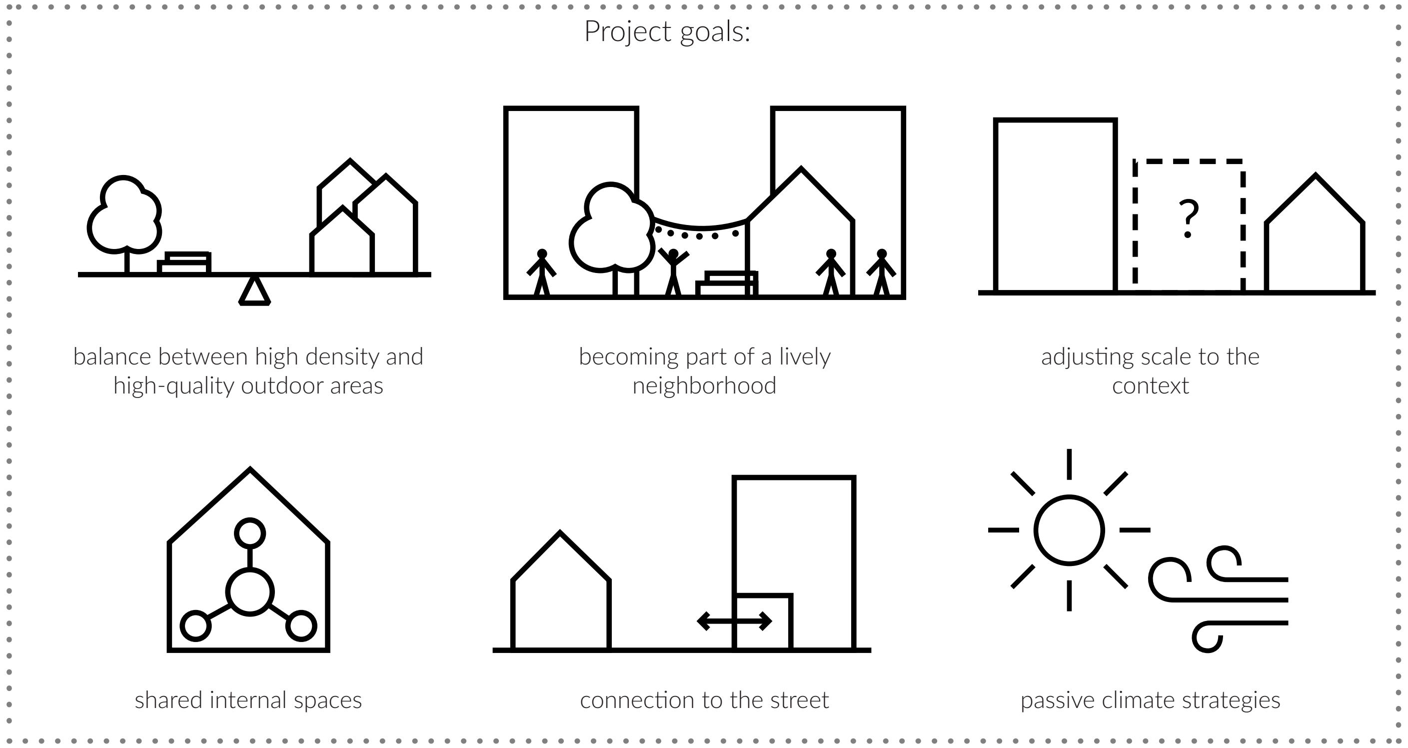


fig. 47. Main project goals

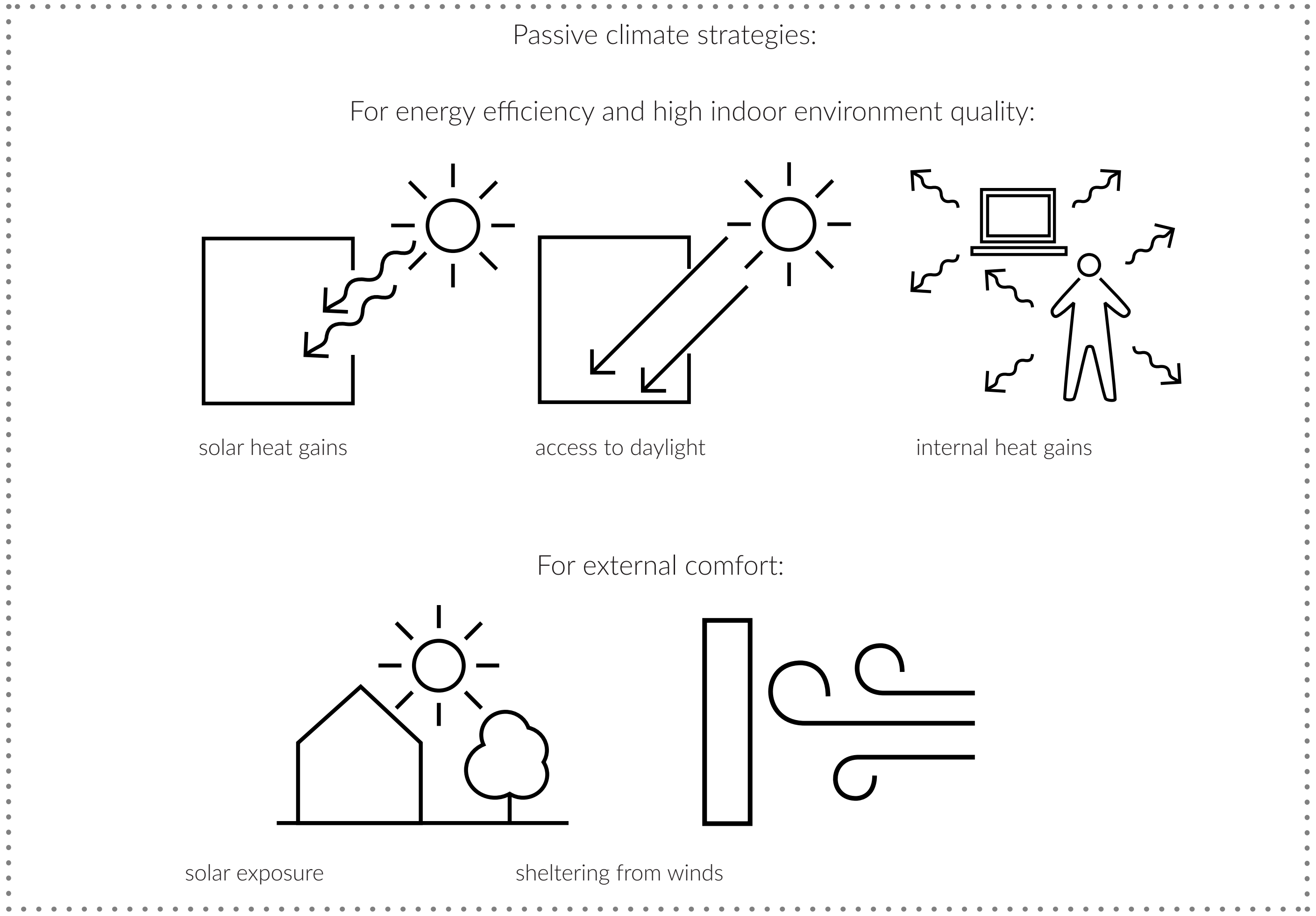


fig. 48. Passive climate strategies planned to be used in the project

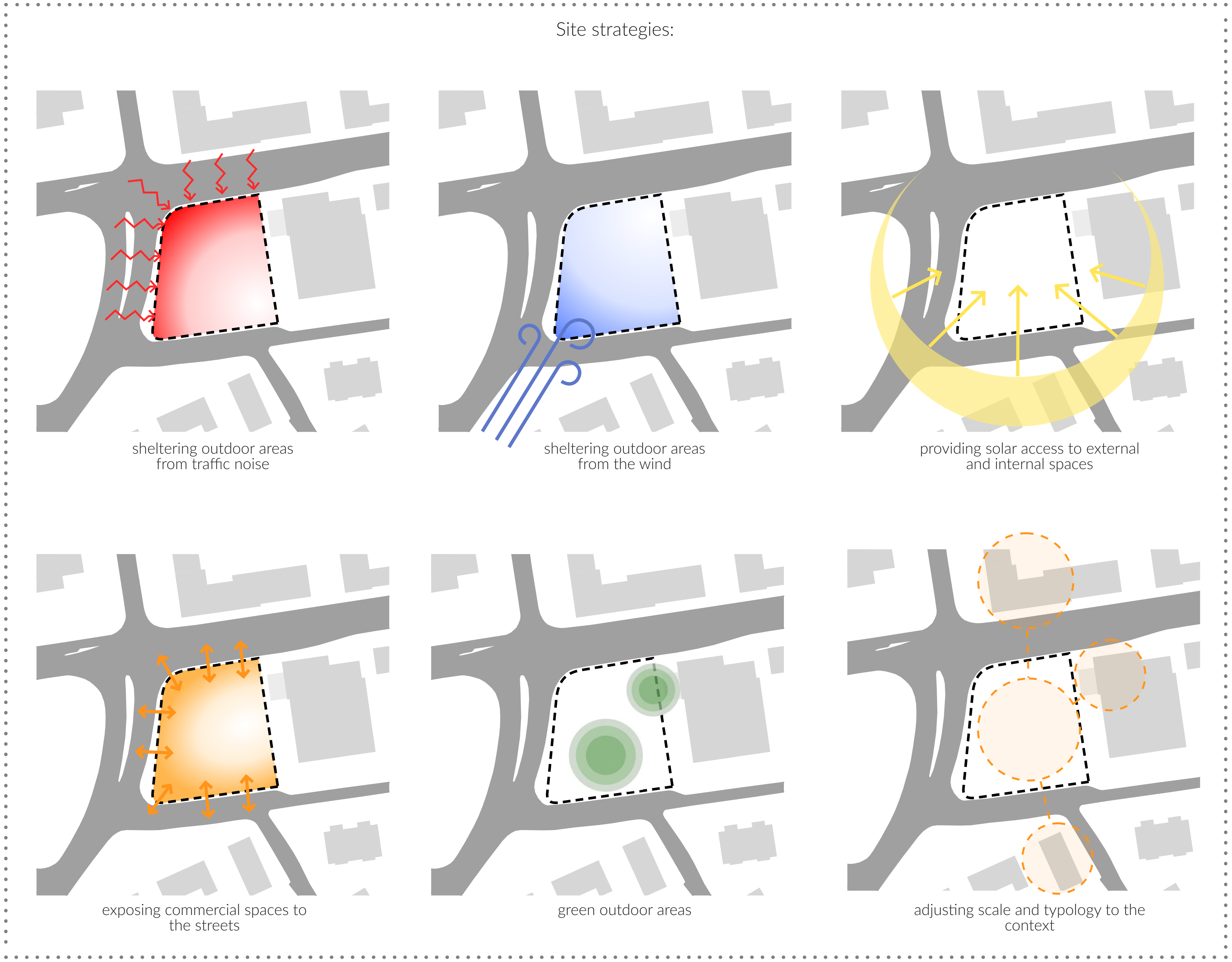


fig. 49. Site strategies to be used in the project

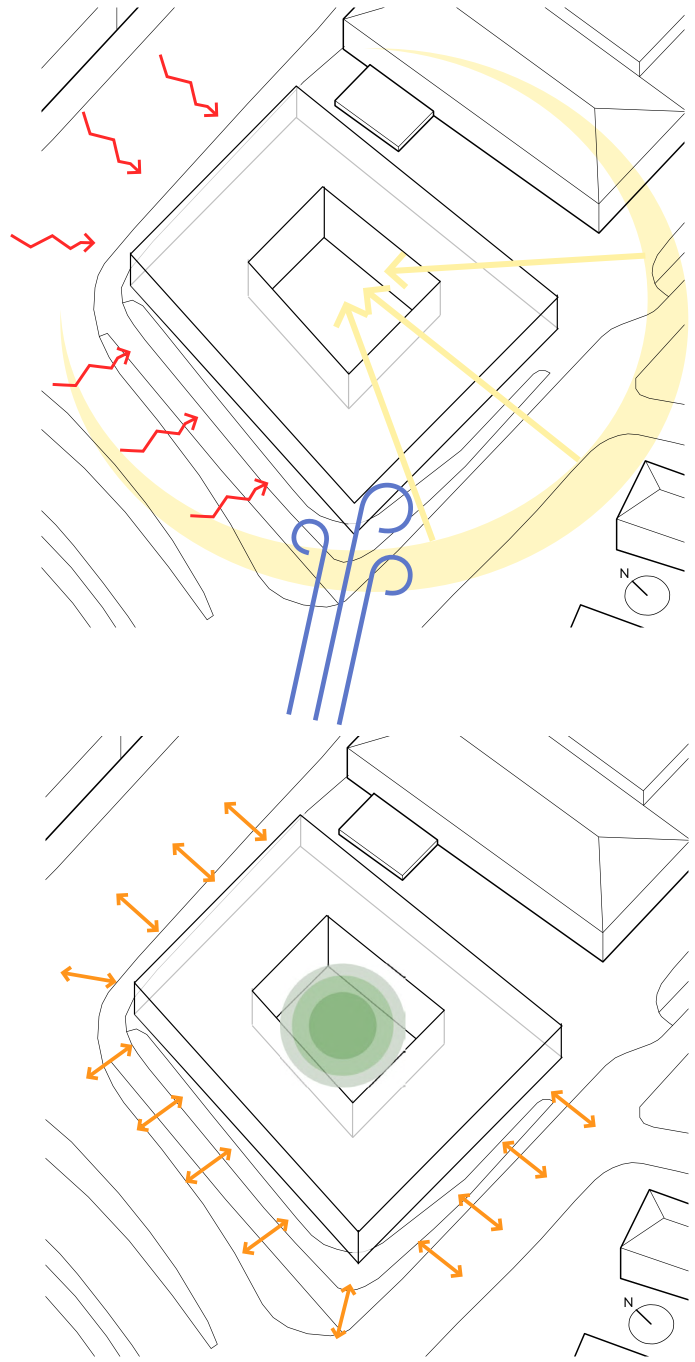


fig. 50. An initial idea of a form that could fulfill the site strategies

3.Form-finding

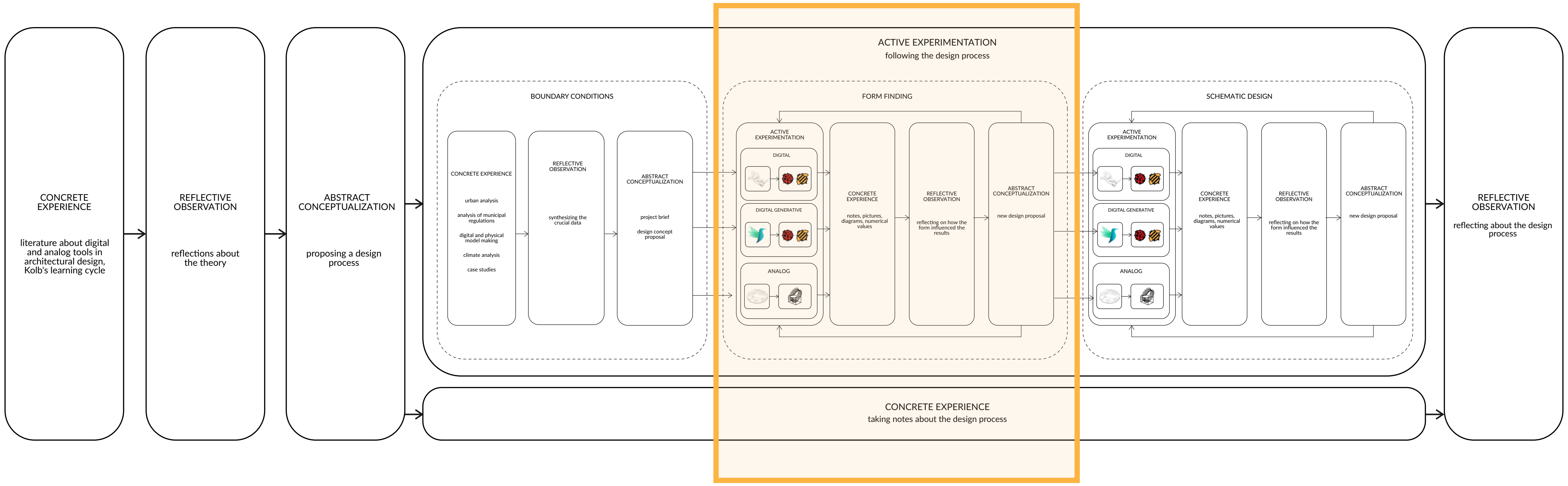


fig. 51. The form-finding stage in context of the whole thesis process

3.1. Introduction

The goal of the form-finding stage was to propose an initial massing of the building. The main focus was centered around external conditions: solar access and the relationship between the building and the urban surroundings.

During this stage, three experiments were carried out: two analog and one digital.

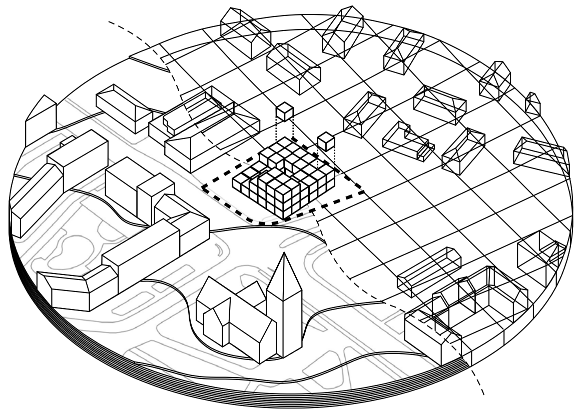


fig. 52. Graphical representation of the form-finding stage

3.2. Experiment 3. External solar access. Intuitive study.

3.2.1. Setup and goals

Experiment type: analog

Used tools:
- manual heliodon
- physical site model (plywood, cardboard), scale 1:200
- wooden blocks (3x3x1.5cm)

According to the area development plan, the minimal number of residential units on the plot is 20. Since one of the goals of the project was to find a balance between urban density and providing public outdoor spaces, 3 different densities have been tested: 20 apartments (low density), 40 apartments (middle density), and 60 apartments (high density).

Considering that an average apartment size is 70 m² (according to municipal regulations), this was the size of a testing unit for one apartment. Each of those units was represented by a pair of 6x6x3m² cuboids, in order to obtain more design flexibility. Those units were scaled to 1:200, resulting in a set of wooden blocks with the dimensions 3x3x1.5cm.

The goal of experiment 1 was to answer the following questions:

1. What building form contributes to providing solar access in the outdoor area on the plot?
2. What building form contributes to providing solar access to the Rosendal Kafe terrace?

Question 1. was the main focus, however, since the new building should not have a negative influence on the existing surroundings, the terrace of the Rosendal Kafe was included in the tests as a neighboring outdoor public area.

Since this was an intuitive study, different forms and ideas were created and tested while carrying out the experiment. Only variants that helped form some conclusions are presented in the report. Tested forms were based on the initial plot strategies. The results were documented as photographs of the building forms during mentioned points in time (at certain positions of the heliodon lamp).

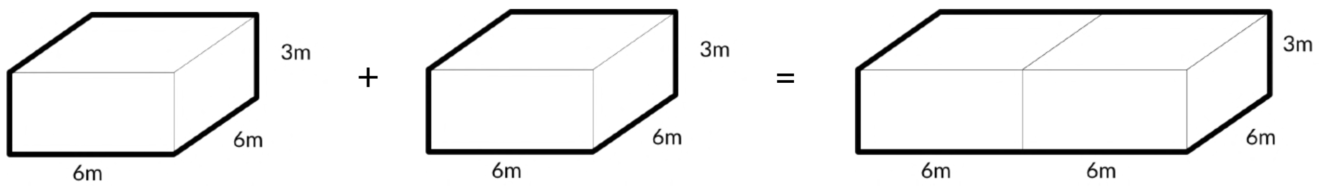


fig. 53. Test units for apartments.

There were four points in time chosen for tests. Two of them were mentioned in the area development plan as moments in which solar conditions for outdoor spaces must be tested:

- Summer solstice at 18.00
- Equinox at 15.00

Another two were proposed in order to test the solar conditions when the sun is at its highest altitude during particular seasons:

- Summer solstice at 12.00
- Equinox at 12.00

The winter solstice has been omitted in the study due to no direct sun access during this time (see experiments 1 and 2).

3.2.2. Results

The forms that were tested first, had the massing spread along the plot borders from north and west, to create an outdoor area sheltered from the street noise. Leaving the plot open from the south allowed to obtain very good solar conditions at the plot during summer solstice and equinox at 12.00 (see fig. 55).

Placing up to five stories from the south lead to almost unchanged conditions on the plot during the summer solstice at 12.00. However, during the equinox at 12.00, even two stories placed from the south partially limited solar access, and with the height of 3 stories, the shadow of the building reached the middle of the plot.

During summer solstice at 18.00 and equinox at 15.00, placing any parts of the building on the west side of the plot limited the solar access. However, by lowering the height in the south-west direction, and in the direction from the outside to the inside of the plot, the solar conditions could be significantly improved.

To provide sunlight to the Rosendal Kafe terrace, it was necessary to leave a space between the new building and the terrace. During summer solstice and equinox at 12.00, it was enough to keep a distance of approximately 6m (one wooden block length) even when the building height reached 4 stories. However, during the summer solstice at 18.00 and equinox at 15.00, even 1 story places in close proximity to the terrace from the west limited solar access.

3.2.3. Notes about the process

This study helped to confirm some intuitive assumptions regarding the building form and its influence on outdoor spaces – for example, that lowering the building to the south helps provide more direct sunlight in the internal courtyard. What is more, those initial assumptions could be translated into more concrete forms and give a better understanding of the scale and proportion that can be used for further project development. Both modeling and testing were intuitive and allowed for fast and easy assessment of solar conditions, without any extra skills.

However, it was difficult to obtain more precise data, either about the solar conditions or the building and site properties (for example, to assess whether the outdoor area fulfills the minimum area requirement). Furthermore, it was not possible to easily go back to previously tested solutions, besides modeling them again or looking at the pictures taken.

It also turned out, that with the heliodon set to the right latitude for Trondheim, it was not possible to easily reach the middle of the table. Therefore, instead of continuously testing different forms at a particular sun position, it had to be rotated to a vertical position whenever the building form was changed. Even though it did not influence the results, it made quick optimization more difficult.

What is more, the calibration problem encountered during the initial site analysis was still present, resulting in extra caution needed to set the latitude correctly.

One of the positive aspects of conducting the analog study was that the presence of the model in the studio sparked some conversations and comments from other students, from simple questions about the project, to suggestions regarding tested forms, bringing extra input to the process which was planned as an individual work.

fig. 54. Heliodon set to the latitude of Trondheim, limiting the access to the table

fig. 55. Examples of forms tested in experiment 3.

3.3. Experiment 4. External solar access. Comparison of typologies.

3.3.1. Setup and goals

Experiment type: analog

Used tools:
- manual heliodon
- physical site model (plywood, cardboard), scale 1:200
- wooden blocks (3x3x1.5cm)

In experiment 4, the same set of tools as in experiment 3 was used. Again, each apartment unit was represented by a pair of 6x6x3m cuboids (3x3x1.5cm in 1:200 scale).

Experiment 4 followed a more defined structure compared to experiment 3. Firstly, 3 typologies commonly used for residential architecture were identified: a tower, a house with pavilions (called a pavilion typology in the further part of the thesis), and a building with a courtyard (called a courtyard typology in the further part of the thesis). Then, each typology was tested for 3 densities (20, 40, and 60 apartments).

The results were documented as photographs of the building forms during mentioned points in time (at certain positions of the heliodon lamp).

The goal of experiment 4 was to answer the following questions:

1. Which building typology contributes best to providing solar access in the outdoor area on the plot?
2. Which building typology contributes best to providing solar access to the Rosendal Kafe terrace?

There were four points in time chosen for tests. Two of them were mentioned in the area development plan as moments in which solar conditions for outdoor spaces must be tested:

- Summer solstice at 18.00
- Equinox at 15.00

Another two were proposed in order to test the solar conditions when the sun is at its highest altitude during particular seasons:

- Summer solstice at 12.00
- Equinox at 12.00

The winter solstice has been omitted in the study due to no direct sunlight access during this time (see experiments 1 and 2).

3.3.2. Results

Courtyard typology seemed to limit the accessible outdoor area the most compared to the other typologies, with massing placed along all borders of the plot. What is more, this building shape provided sunlight access to the outdoor part of the plot during all tested points in time only when the lowest density was applied. With the middle density, solar conditions seemed accepatble at 12.00 for summer solstice and equinoxes, but in the afternoon hours the courtyard was fully shadowed. With the high density, solar access was provided to the courtyard only during one of the tested moments: at 12.00 during the summer equinox.

Pavilion typology allowed to obtain more outdoor area. Again, the lowest density allowed for the most solar access. However, for the middle and high density, it seemed that the outdoor parts of the plot still received sunlight for most of the time, with the only problematic point being 18.00 during summer solstice.

The tower left the most free space on the plot. Also, the effect that the building had on the solar conditions on the plot did not depend on tested density. However, the higher the density, the more of surrounding the area the building would overshadow, including the Rosendal Kafe and the residential buildings on the opposite side of Innherredsveien.

With the courtyard typology, the Rosendal Kafe obtained good access to sunlight at 12.00, both for the equinox and summer solstice. However, during afternoon hours, the terrace was fully overshadowed regardless of tested day and density.

Pavilion typology also provided good solar exposure to the terrace at 12.00 for the summer solstice. However, with middle and high density, the terraced became overshadowed at 12.00 during the equinox. During the afternoon hours, it was almost fully in the shadow for both tested days, receiving some sunlight only with low and middle density during the equinox.

Tower was the only typology that provided solar access to the terrace at 18.00 during summer solstice, due to the fact the building was moved to the center of the plot instead of being placed directly next to the terrace. However, it fully overshadowed the terrace at 15.00 during the equinox, regardless of tested density. The solar conditions remained relatively good at 12.00 during both tested days for all tested densities.

3.3.3. Notes about the process

While the previous experiment helped to develop some intuition regarding the built form and sunlight, running a more structured study made it much easier to organize the work and make clear conclusions. It helped to make the proposed forms less abstract, and more easily translatable into buildings. However, while working with wooden blocks rather than more precise models, it was still tempting to overly simplify the form, and for example keep right angles instead of adapting to urban constraints.

Similarly to experiment 3, the tests in experiment 4 were fast and intuitive, but the amount of gathered data was very limited. What is more, since the set of tools was the same as in experiment 3, all the technical difficulties also remained the same.

fig. 56. Results of experiment 4

3.4. Experiment 5. External solar conditions. Comparison of typologies.

3.4.1. Setup and goals

Experiment type: digital

Used tools:
- Rhinoceros 3D
- Ladybug + Honeybee

Despite different set of tools used, experiment 5 was structured similarily to experiment 4, with apartments being represented by pairs of 6x6x3m cuboids. Again, the same 3 building typologies were tested for 3 urban densities (20, 40, and 60 apartments). However, access to numerical data allowed for analysis of wider range of parameters, and therefore, a larger set of research questions was proposed:

1. Which building typology contributes best to providing solar access in the outdoor area on the plot?

2. Which building typology contributes best to providing solar access to the roof of the designed building?

3. Which building typology contributes best to providing solar access to the facades of the designed building?

4. Which building typology contributes best to providing solar access to the Rosendal Kafe terrace?

The collected data was mean incident radiation (kWh/m²) measured for building facades and roof, and mean direct sun hours, measured the outdoor area on the plot, for the terrace if the Rosendal Kafe, and for the building's facades and roof. What is more, total plot area, built up area and accessible outdoor area were measured, as well as the building volume, external surfaces area and area-to-volume ratio.

Using a digital tool allowed also for collecting data over a period of time, rather than at a certain point in time. Therefore, in experiment 5, the data was collected for two whole days:

- Summer solstice
- Equinox

The winter solstice has been omitted in the study due to the fact, that the plot has no direct sun access during this time (experiments 1 and 2).

3.4.2. Results

Outdoor area

Measuring the accessible outdoor area and comparing it with the municipal requirements helped assess whether all proposed solutions aligned with local regulations. It turned out that one proposal, the building with courtyard typology and high density (60 apartments), would not be acceptable. The required outdoor area for this number of residential units is 1800 m² (60 x 30m²), half of which should be at the ground level and commonly accessible (900m²), while the outdoor area proposed in this solution was only 714,61m². The proposals for courtyard typology with medium and low density would be accepted, even though the outdoor area would be the same, since the requirement for an outdoor area for those densities is 300m² and 600m². For all the other typologies and densities the results were also acceptable.

Incident radiation

The tower received the highest mean incident radiation per square meter of the facades, regardless of the tested density. This was probably caused by the fact, that none of the building parts overshadowed each other. When it comes to incident radiation on the roofs, pavilion typology with high density had the best results.

Direct sun hours

The tower provided the highest value for mean direct sun hours on the plot, which confirmed the initial conclusions from experiment 2. It also received the most sunlight on the facades from all tested options, which aligns with the results obtained for incident radiation. When it comes to solar access to the roofs, the pavilion typology with high density achieved the best results.

Surprisingly, the highest result for the Rosendal Kafe terrace was achieved by courtyard typology with low density, even though during particular points in time this solution did not provide much access to sunlight.

Area-to-volume ratio

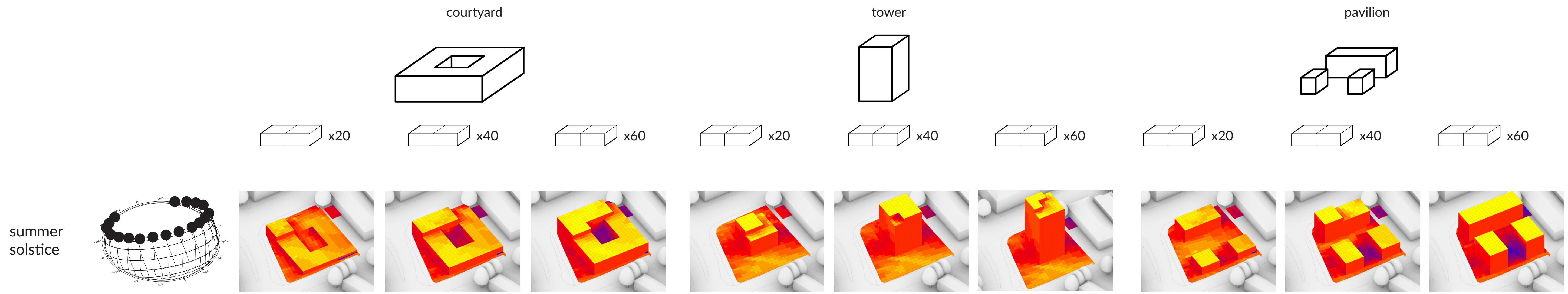
The smaller the area-to-volume ratio, the more compact the building form, and potentially lower energy losses. The best results were achieved by the tower typology, and for high density regardless of typology.

3.4.3. Notes about the process

The main advantage of running the digital study was obtaining more data, which might support making conscious design decisions. It was also much easier to organize the design options and switch between them, as they could be kept on separate layers in the software.

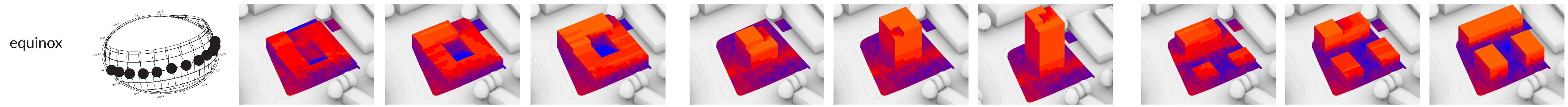
However, preparing the models for simulations was less intuitive than in the analog study, despite proficiency in Rhino. Since the tools can be very accurate, the dilemma of being very precise and slower, or faster and less accurate occurred. In the analog study, it was a rough estimation by default. Finally, it was concluded that precision was necessary to make the script work properly, as some operations were automated (for example connecting all the cuboids into one solid in order to measure external surface). It was also noted that while following certain building densities in analog experiments was easy, as long as the proper amount of wooden block was used, this also became less intuitive in the digital setting. Since blocks could be placed inside one another and therefore become hidden, it required more focus to make sure that the model was built correctly.

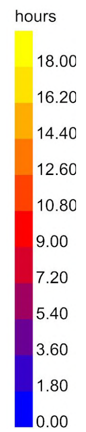
What is more, preparing the script for the simulations, and deciding which data should be collected was another challenge that did not exist in the analog study. A large amount of different data is difficult to compare and decisions about what should be prioritized are needed. Furthermore, preparing a clean script for the simulations, that can be easily understood by others or used again in further stage of the work, was also time-consuming. Another challenge was manually switching through all the design options and saving the results, which could have been automated if iterative method was used (for example Colibri).



Summer solstice, mean value [hours]:

	courtyard x20	courtyard x40	courtyard x60	tower x20	tower x40	tower x60	pavilion x20	pavilion x40	pavilion x60
plot:	8,98	7,40	6,82	10,45	10,02	10,03	9,34	7,82	7,19
terrace:	7,67	5,13	4,13	8,00	5,87	5,20	6,60	4,87	3,00
facades:	6,00	6,42	6,38	8,00	8,82	9,20	7,03	7,25	7,08
roof:	13,99	14,95	16,23	15,26	19,00	16,73	16,03	16,64	19,22



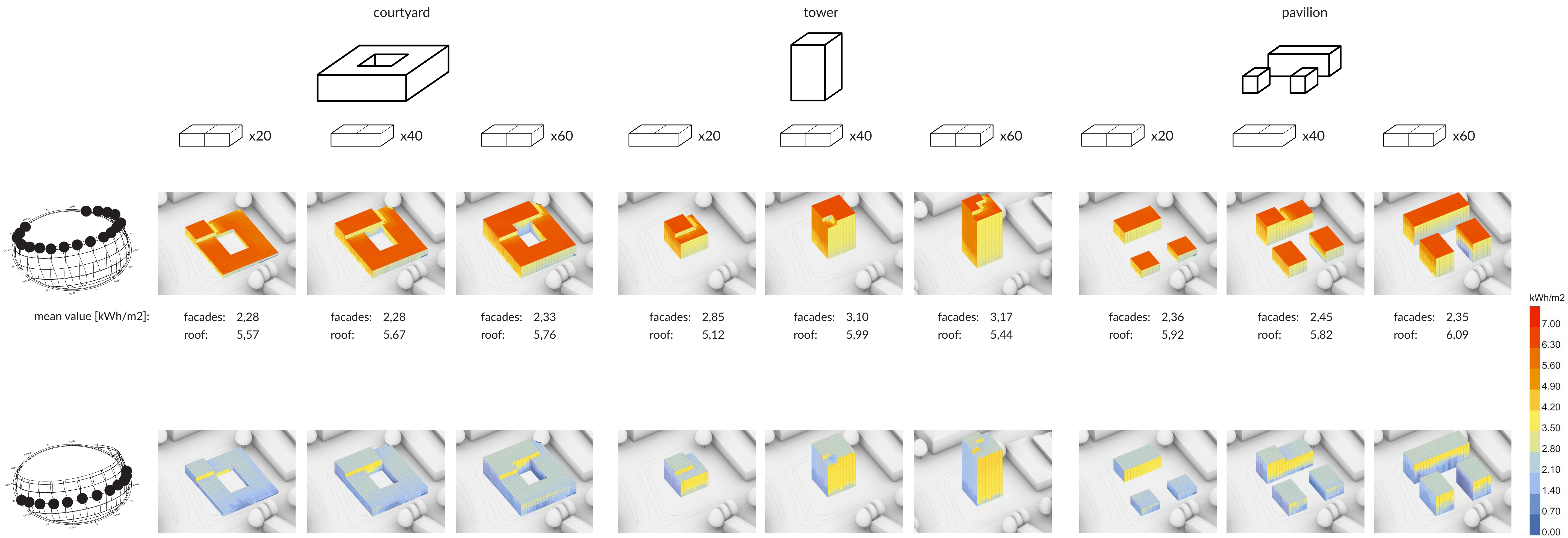


Equinox, mean value [hours]:

	courtyard x20	courtyard x40	courtyard x60	tower x20	tower x40	tower x60	pavilion x20	pavilion x40	pavilion x60
plot:	3,65	3,06	2,85	4,50	4,46	4,49	4,09	3,00	2,80
terrace:	4,67	2,67	2,00	3,53	3,27	3,27	4,87	4,00	1,67
facades:	2,87	3,27	3,31	5,02	5,48	5,56	3,63	4,03	3,76
roof:	7,81	9,27	10,38	10,26	11,74	10,68	9,90	10,21	12,00

	courtyard x20	courtyard x40	courtyard x60	tower x20	tower x40	tower x60	pavilion x20	pavilion x40	pavilion x60
plot area [m2]:	2010,61	2010,61	2010,61	2010,61	2010,61	2010,61	2010,61	2010,61	2010,61
outdoor area [m2]:	714,61	714,61	714,61	1686,61	1686,61	1686,61	1434,61	1218,61	1146,61
built-up area [m2]:	1296,00	1296,00	1296,00	324,00	324,00	324,00	576,00	792,00	864,00
volume [m2]:	4320,00	8640,00	12960,00	4320,00	8640,00	12960,00	4320,00	8640,00	12960,00
area [m2]:	3384,00	4104,00	4824,00	1656,00	2592,00	3600,00	2376,00	3816,00	4968,00
a/v:	0,78	0,48	0,37	0,38	0,30	0,28	0,55	0,44	0,38

fig. 57. Results of experiment 5. Direct sun hours.



mean value [kWh/m2]:	courtyard x20	courtyard x40	courtyard x60	tower x20	tower x40	tower x60	pavilion x20	pavilion x40	pavilion x60
summer solstice – facades:	2,28	2,28	2,33	2,85	3,10	3,17	2,36	2,45	2,35
summer solstice – roof:	5,57	5,67	5,76	5,12	5,99	5,44	5,92	5,82	6,09
equinox – facades:	0,88	1,08	1,08	1,67	1,81	1,87	1,35	1,39	1,25
equinox – roof:	1,96	2,14	2,26	2,10	2,35	2,24	2,17	2,27	2,37

	courtyard x20	courtyard x40	courtyard x60	tower x20	tower x40	tower x60	pavilion x20	pavilion x40	pavilion x60
plot area [m2]:	2010,61	2010,61	2010,61	2010,61	2010,61	2010,61	2010,61	2010,61	2010,61
outdoor area [m2]:	714,61	714,61	714,61	1686,61	1686,61	1686,61	1434,61	1218,61	1146,61
built-up area [m2]:	1296,00	1296,00	1296,00	324,00	324,00	324,00	576,00	792,00	864,00
volume [m2]:	4320,00	8640,00	12960,00	4320,00	8640,00	12960,00	4320,00	8640,00	12960,00
area [m2]:	3384,00	4104,00	4824,00	1656,00	2592,00	3600,00	2376,00	3816,00	4968,00
a/v:	0,78	0,48	0,37	0,38	0,30	0,28	0,55	0,44	0,38

fig. 58. Results of experiment 5. Incident radiation.

3.5. Final typology

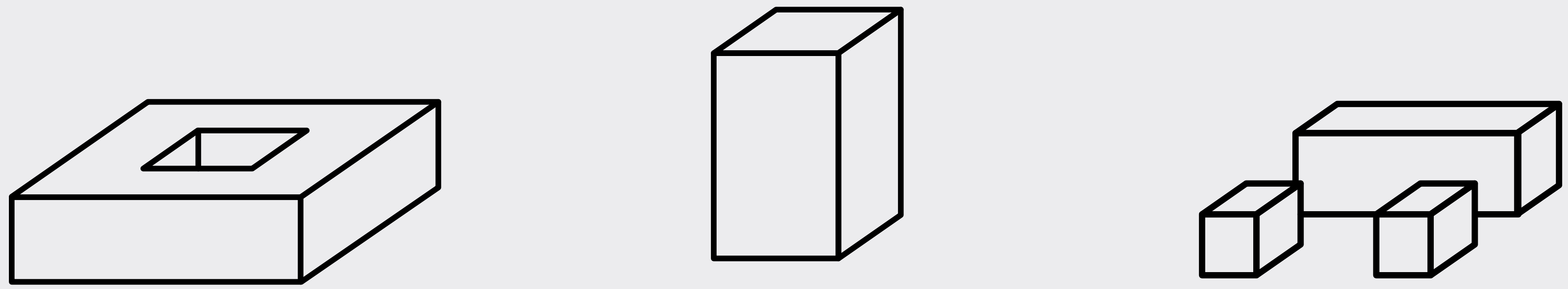
In order to choose the final typology to be further developed, many factors were considered. While from the solar studies it could be concluded that the tower should be built at the plot, it did not necessarily fulfill other goals of the project (see fig. 59).

The courtyard typology seemed to fit best into the urban context, while also providing sheltering from noise and from wind for the outdoor areas.

The pavilion also had some advantages which were worth considering, and it was concluded that such qualities as semi-open courtyard could be included in the final design. However, the courtyard typology would remain the main inspiration.

The next step was to develop strategies to better adapt the chosen typology to local conditions, based on experiments 3-5. Some of the ideas included diversifying the height or providing breaks in the building to obtain better sunlight access in the outdoor areas. For example, keeping the plot open from the south, or minimizing the height of the building on the south could help achieve a sunny courtyard. Creating a break in a building mass close to the café terrace could prevent overshadowing it.

It was concluded that implementing a set of climate adaptive strategies into a typology that fits well into the urban context, gives a chance to develop a design proposal that answers to the variety of different needs. The strategies were tested and developed in the further phase: schematic design.



The form matches local typologies and has the potential for high density. It provides good exposure for commercial spaces, since the facades are adjacent to the streets. One of the biggest strengths of the enclosed courtyard is sheltering the outdoor spaces from noise and wind. However, providing good solar exposure might be challenging, and it also poses the risk of isolating from urban life and making the courtyard a private area rather than a public space.

This typology provides a lot of open outdoor space, that can be easily accessed from the street. Both the building and the plot receive a high level of solar radiation. However, the outdoor area is completely exposed to traffic noise, which currently reaches values above the acceptable level of 55 dBA. What is more, if any commercial spaces were designed on the groundfloor, they would have quite a limited area and would not be placed in the direct proximity of the street. Another disadvantage is that the form does not match the local urban context, as there are no examples of this typology in the neighborhood. Therefore, even though the form has many assets, it might not be the answer to the needs of this particular site.

The form matches with local typologies, referring to the wooden houses on the south of the plot. Its potential lies also in creating a partially enclosed outdoor area, which could be sheltered from traffic noise and wind while still providing good solar exposure. What is more, the courtyard could remain in open for public access and create a connection with urban life. However, in order to fit into the wooden house style, the density would have to be kept at a low level. What is more, it can be questioned whether a building located on the corner of two important streets should not have a more urban character.

fig. 59. Summary of qualities of different typologies

4. Schematic design

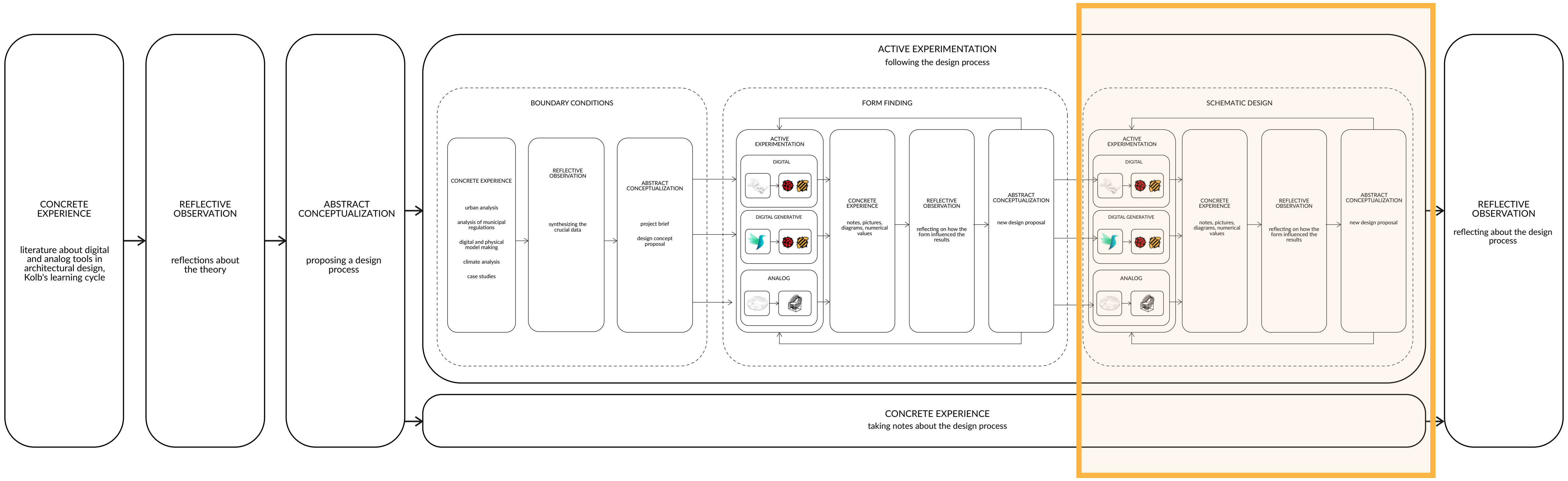


fig. 60. The schematic design stage in context of the whole thesis process

4.1. Introduction

The goal of schematic design phase was to develop the initial building massing into a more realistic and detailed design proposal. During this stage, not only external conditions were analyzed, but also internal qualities, including daylight and energy, as well as functionality of the interior and outdoor spaces.

In the schematic design phase, five experiments were carried out: four digital and one analog.

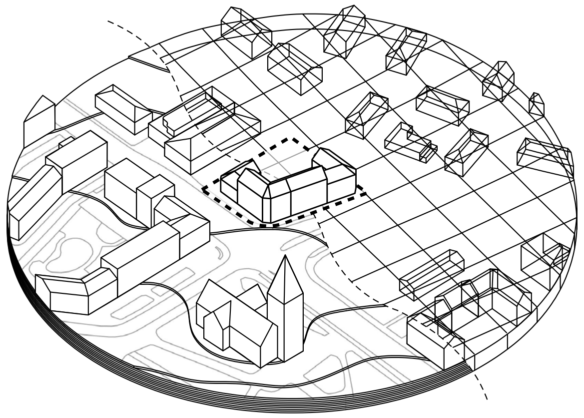


fig. 61. Graphical representation of the schematic design stage

4.2. Experiment 6. Form optimization.

4.2.1. Setup and goals

Experiment type: digital - generative

Used tools:

- Rhinoceros 3D
- Ladybug + Honeybee
- Colibri + Design Explorer

Since during the form-finding stage it was concluded that courtyard typology has the potential to be further developed into a form well-adjusted to local conditions, experiment 6 was focused on adapting the form to provide solar access in the outdoor areas, while still fulfilling other site strategies.

The building model was more detailed compared to previous studies. The roof was sloped at the angle of 40 degrees, similarly to tenement houses by Innherredsveien 67 and 69. The corners were chamfered to also resemble the style of XIX-century housing. The western part of the designed building was slightly rotated to align with the street Fv865.

The following steps were followed in order to run an optimization of the building form:

1. A building with a courtyard was formed, enclosing the site from all sides
2. An opening was cut from the south for better solar access, while still sheltering from the noise and the wind from the west and north
3. The building was divided into 6 parts
4. The height of each part was diversified separately. The range was between two and four floors (with a sloped roof present at every variant). It has been decided that the height below one floor or over four floors would not fit well into the chosen typology aesthetics and urban conditions.

The goal was to answer the following question:

1. Which combination of stories numbers provides acceptable level of solar access to the courtyard, while fitting well into the urban context?
2. Which combination of stories numbers provides acceptable level of solar access to the terrace of Rosendal Kafe, while fitting well into the urban context?

Collected data consisted of direct sun hours collected for the plot and for the terrace. Measurements were done during an annual period, and during two points in time:

- Summer solstice at 18.00
- Equinox at 15.00

12.00 was no longer tested, as not much diversification was expected during that time. The courtyard became mostly open to the south, which was expected to provide enough solar access at noon.

Information about the building area was also collected in order to assess the number of residential units.

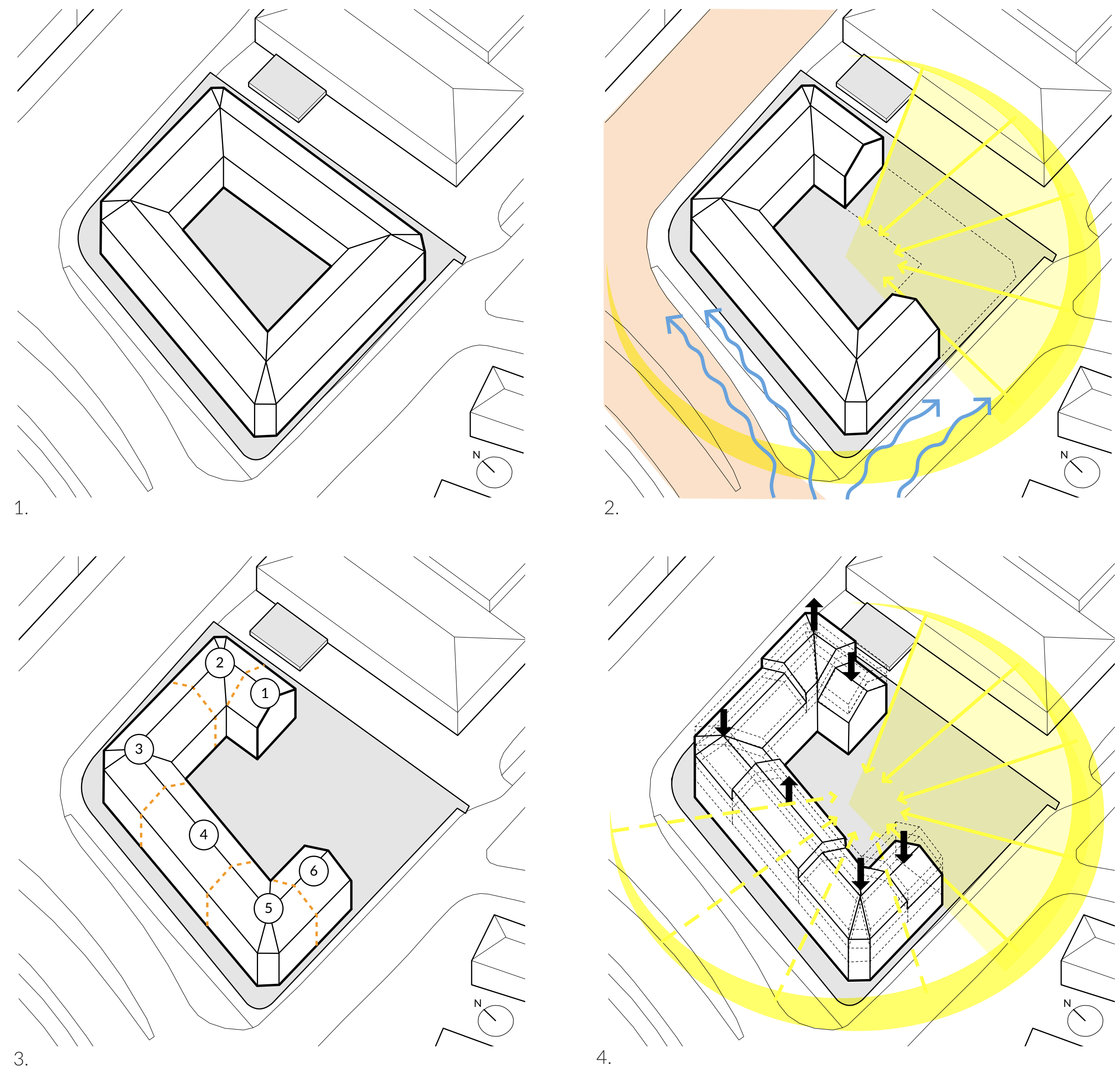


fig. 62. Steps of experiment 6

However, the ground floor area was excluded in the calculation, as it has been decided that only commercial spaces should be placed there. The area below the sloped roof has also been excluded to simplify the calculation, and because the function of those spaces has not been decided yet during this stage.

In total, 729 solutions were obtained. Calculating each solution took around 15 seconds, resulting in a total simulation time of around 3 hours.

Besides numerical values, graphical representations of each option and results were collected.

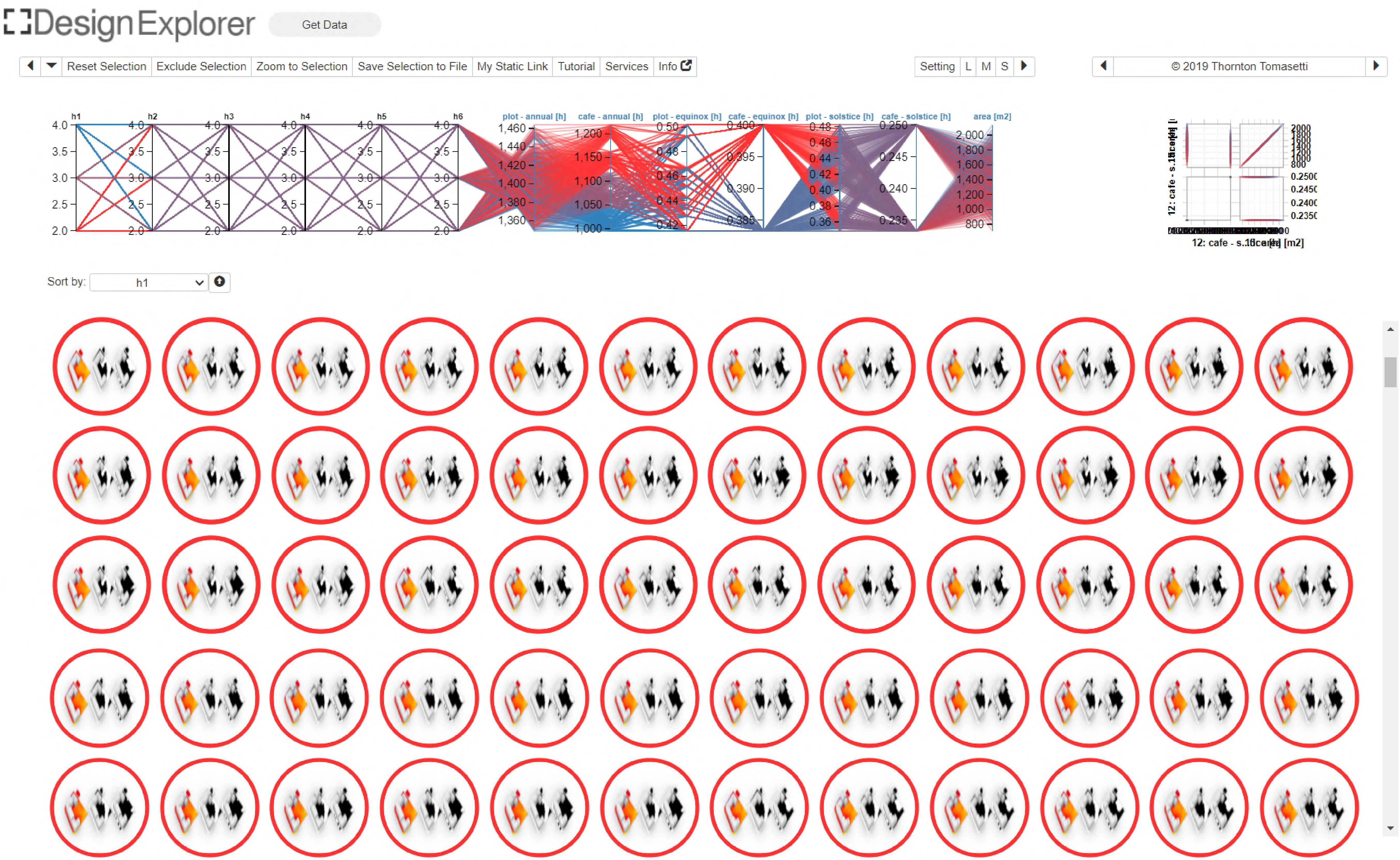


fig. 63. The possible solutions for experimet 6 visualized in Design Explorer

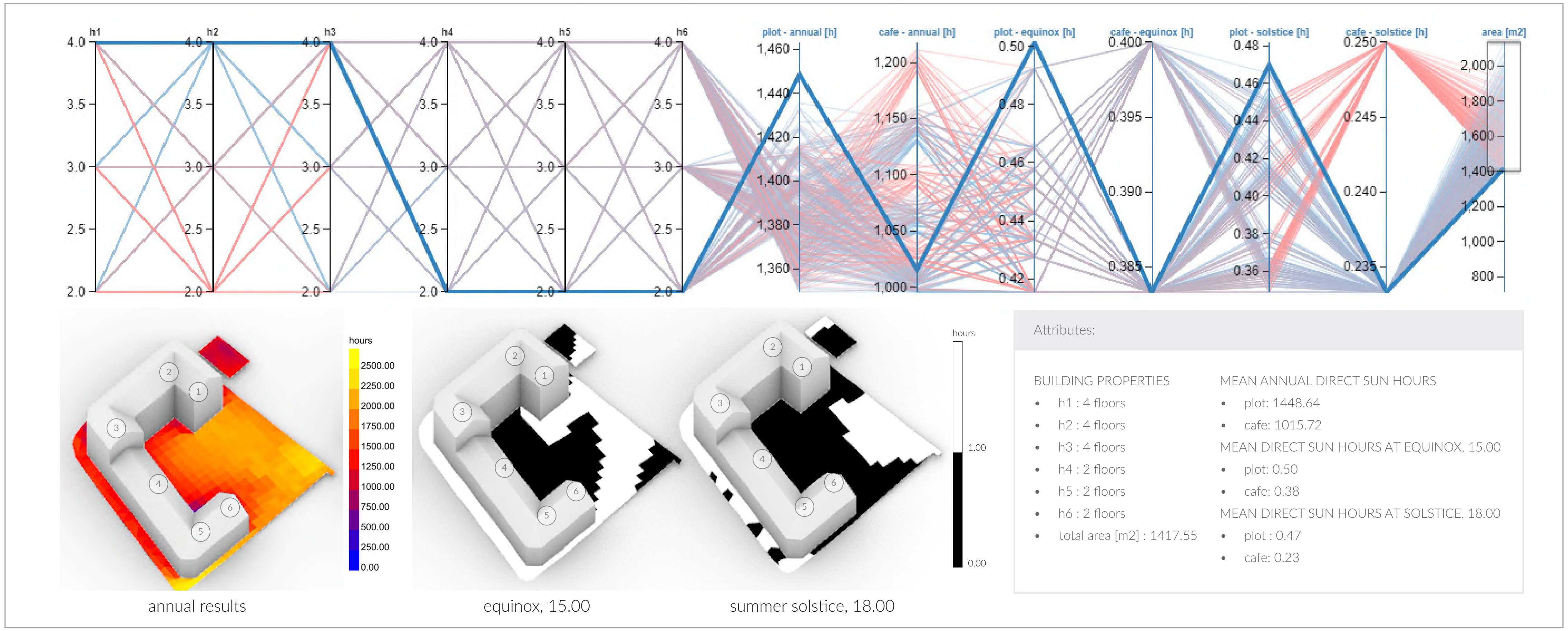


fig. 64. Solution with best solar exposure of the plot, with variants below 1400m² of floor area excluded

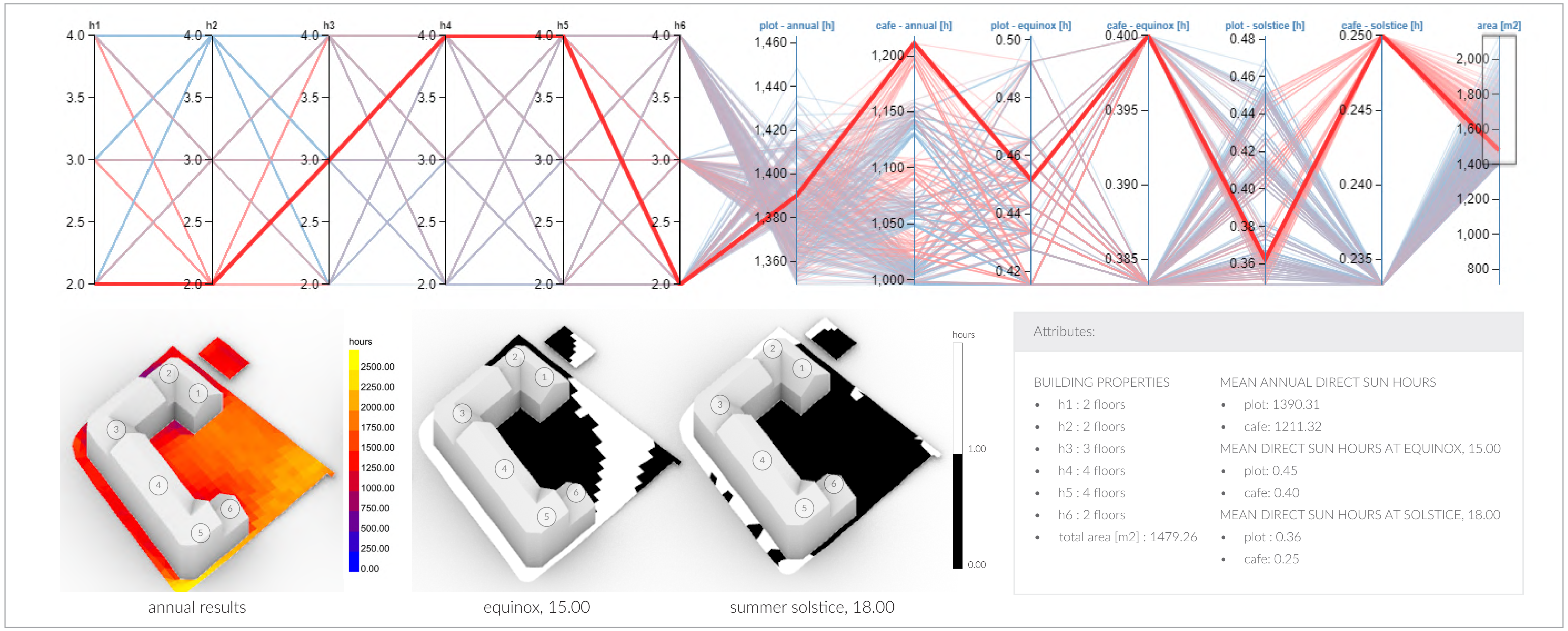


fig. 65. Solution with best solar exposure of the cafe, with variants below 1400m² of floor area excluded

4.2.2. Results

The first stage of optimization was to eliminate the results that did not fulfill the requirement of the minimal number of residential units. As the minimal number of units was 20, and the typical apartment size was 70m², no variant below 1400m² was further considered. Secondly, it was tested which variant provided the most direct sun hours for the plot (fig. 64). It turned out that the same variant provided the best results annually, for the summer solstice and for the equinox. However, the area of residential units was close to the minimum (1417,55m²). The form had a height of 2 stories from the south and a height of 4 stories from the north.

The variant that provided the best results for the café had a form gradually sloping down towards the north--east corner of the plot. While beneficial for the neighboring area, it did not provide good values for the plot (fig. 65).

The variant presented in figure 64 could have been chosen due to providing the best solar conditions for the plot. However, it has been decided that other factors also have to be taken into consideration. First of all, it was concluded that a conscious choice should be made regarding the height of building segments 1 and 2, to fit into the context of the neighboring Rosendal Kafe. Since the Rosendal Kafe has a high antiquarian value, it should be well exposed in the urban landscape, and placing a building twice as high in close proximity could be contrary to that assumption. Adjusting the scale to the neighbor could allow for blending into the existing context. What is more, the terrace of the Rosendal Kafe could serve as an extension of the public spaces planned in the courtyard, becoming part of one functional system. Therefore, it could be treated with a priority comparable to the newly designed spaces. As a result, it was concluded that only design variants with the height of segments 1 and 2 reduced to 2 stories should be further analyzed.

After implementing this change, it became clear that the terrace of the café would be well exposed to sunlight, but providing good solar exposure to the cour-

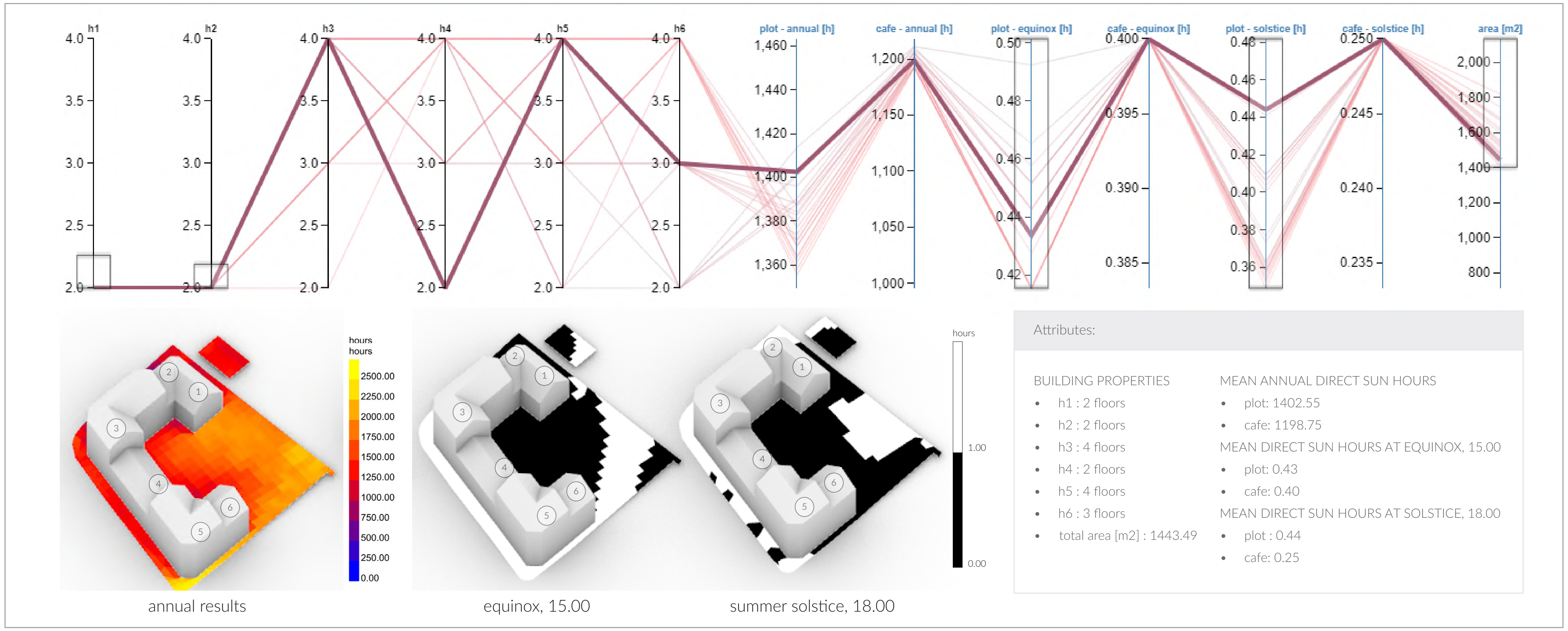


fig. 66. Solution with best solar exposure of the plot during summer solstice, with variants below 1400m² of floor area excluded, and height of segments 1 and 2 limited to 2 floors

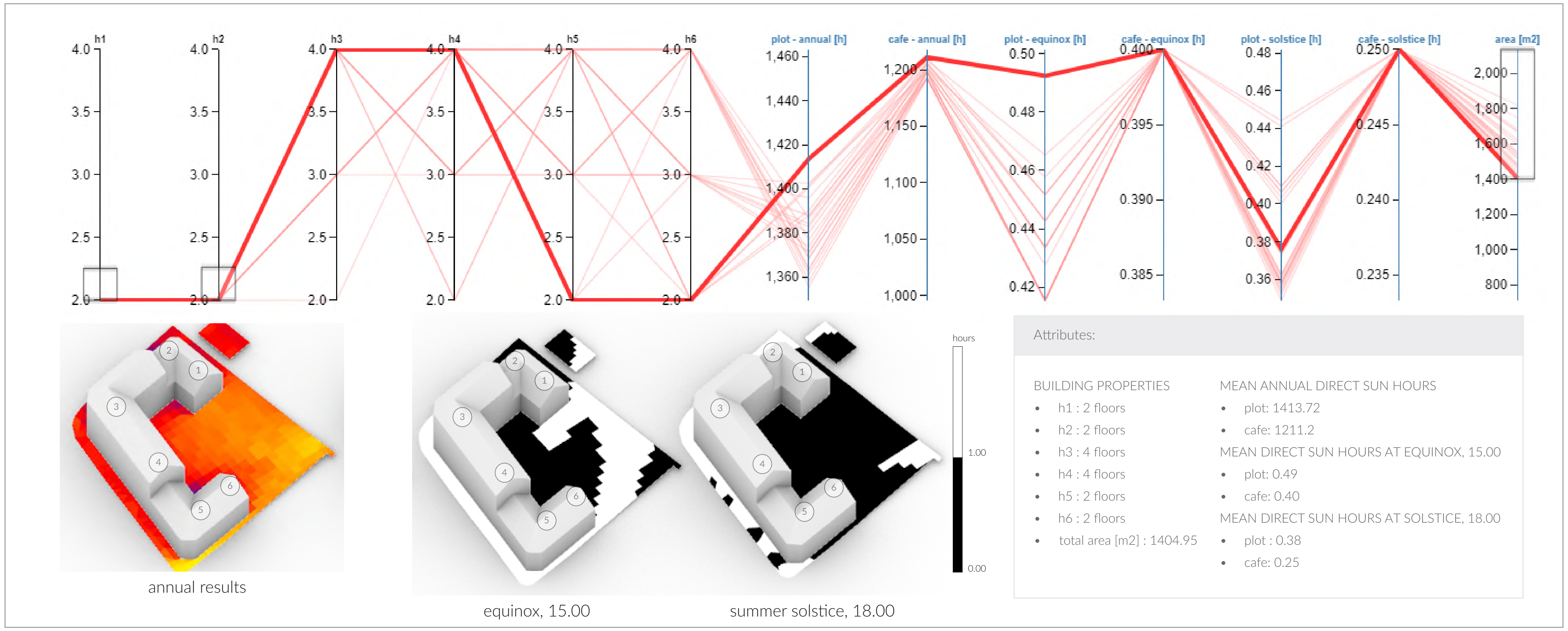


fig. 67. Solution with best solar exposure of the plot during equinox, with variants below 1400 m²of floor area excluded, and height of segments 1 and 2 limited to 2 floors

tyard might be a challenge.

The results with the best solar exposure for the plot during the summer solstice were now different from those with the best results during the equinox, since the variants working well for both had been eliminated (fig. 66 and 67). The variant that provided the highest solar exposure during the equinox provided also the highest value annually, therefore seemed more favorable (fig. 67).

Before deciding on the final solution, one more change has been introduced. Since in the variant presented in the figure 67 the area of residential units was close to the minimum, it has been decided to increase it by changing the height of segments 3 and 4 from 2 to 3 stories (fig. 68). As a result, the area was increased from 1404,95 m² 1612,37m², which meant an improvement of 15%. The solar exposure of the café terrace remained high, while it decreased for the courtyard. However, the reduction of solar access has not been very significant compared to the gain of the area: the mean annual value dropped by 2%, mean value for the solstice by 5%, and mean value for the equinox by 8%. It could also be noted, that the difference in the mean annual direct sun hours between this variant, and the variant presented initially as having the most beneficial results for the plot (fig. 64) is only 5%. It has therefore been concluded that the variant presented in figure 68 offers a good compromise between functional, aesthetical and environmental needs, and should be chosen as a final solution.

4.2.3. Notes about the process

The generative process did not differ much from regular digital analysis when it comes to the difficulty of preparing the model and the script for the simulation. It was already noted during experiment 5 that automated iterating through a set of design solutions should improve the work quality. Both types of experiments required certain proficiency in Rhino and Grasshopper software, while Design Explorer turned out to be a very intuitive tool. Therefore, the biggest difference between a regular digital study and a generative one

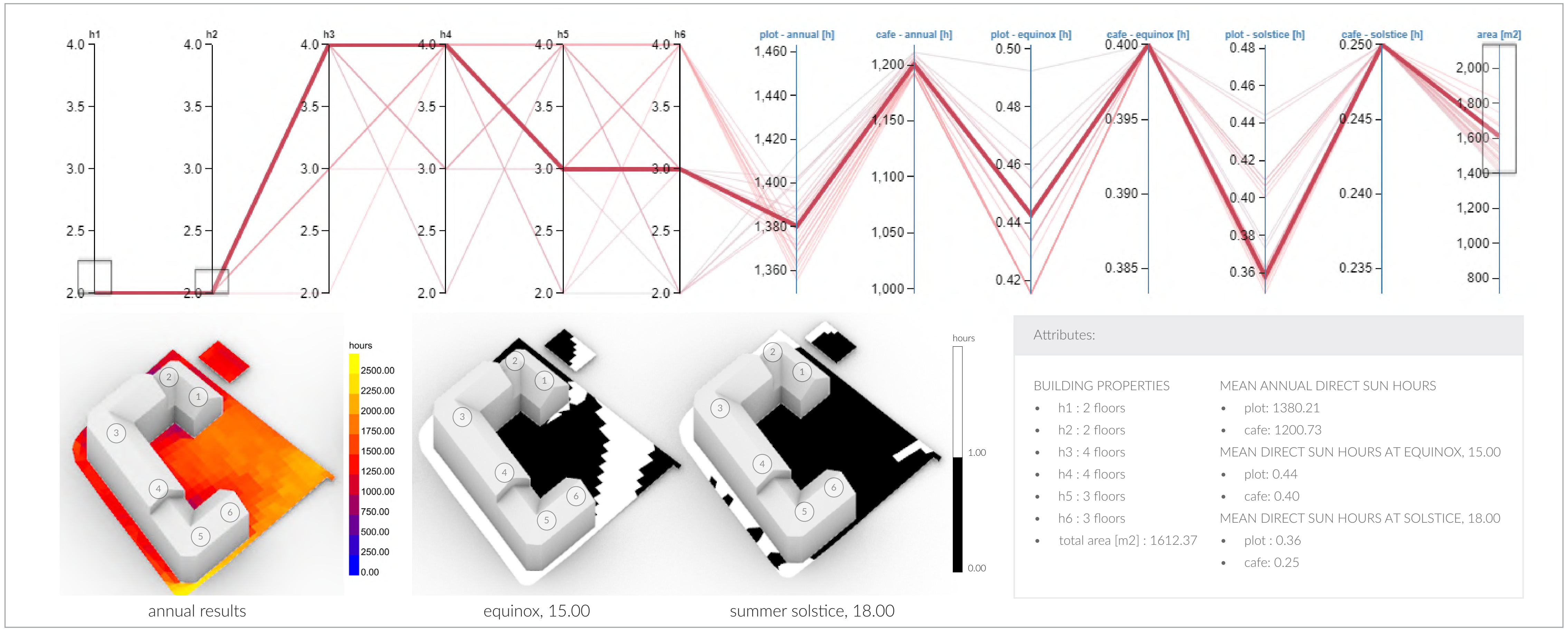


fig. 68. Final form

was the amount of data that could be obtained, and the easiness of analysis.

However, using the generative method was also connected with a higher risk of failure. Since each part of the software has its bugs and flaws, combining them resulted in more potential errors. While iterating through the solutions with Colibri, several problems were encountered, such as results not being saved, or being saved with the wrong graphical setting, resulting in the need to repeat the simulations. Therefore, while automating the process might save a lot of time, more effort must be made at the beginning to make sure that the whole process will go as planned.

Using Design Explorer helped to organize the results, compare them, and easily eliminate those that were not relevant. Also, the tool might help notice connections between different parameters and build a better understanding of the problem.

The biggest limitation was the calculation time, as using too many inputs might result in unacceptable simulation time.

4.3. Experiment 7. Prelimiarny apartments dimensions.

4.3.1. Setup and goals

Experiment type: digital - generative

Used tools:
- Rhinoceros 3D
- Ladybug + Honeybee
- Colibri + Design Explorer

The goal of experiment 7 was to propose a set of apartment templates that could be further incorporated into floorplans. The focus was on 1-bedroom and 2-bedroom apartments since they have been recognized as the most common types based on several case studies. Each template has been described by width, depth, and window-to-wall ratio (WWR).

WWR is a parameter obtained by dividing the glazing area by the wall area. It was assumed that the higher WWR, the more daylight would be provided to the interior, increasing visual comfort, however, the energy losses might also be higher. While energy was not measured during this study, it was assumed that WWR should be kept at a possibly low level.

At the same time, it was concluded that a shallow and wide apartment should provide better access to daylight than a narrow and deep one. However, the latter option should make it possible to fit more units into a building.

Therefore, it was concluded that width, depth, and WWR should be balanced together, and the following question has been proposed:

Which combinations of apartment width, depth, and WWR provide sufficient daylight level to a residential unit?

To simplify the study and allow for flexibility in the further design stages, apartments were modeled as cuboids without any internal divisions. Each of the tested apartments had an internal height of 2.8m. What is more, no external context has been included, since the templates were meant to be used at any part of the building.

To assess whether sufficient access to daylight is achieved, mean DF has been measured for each variant. According to TEK 17 [6], the mean DF for a room used for permanent residence cannot be smaller than 2%. Since the DF value does not depend on the orientation, all the variants were facing the same direction.

Additionally, the floor area of each variant has been measured.

Tested WWR varied from 0.1 to 0.9, with the step of 0.1, and the apartment dimensions varied from 4m to 12m for the width (with the step of 1m) and from 4m to 9m for the depth (with the step of 1m). This resulted in 486 variants in total. Calculating each solution took from 15 to 20 seconds, resulting in a total simulation time of around 2.5h. Besides numerical values, graphical representations of each result were collected.

4.3.2. Results

Due to the nature of the study, the result did not consist of one best solution, but rather a set of variants to choose from. In the following paragraphs, two examples of working with the obtained data are proposed, based on technical requirements and design intuition.

The first step of analyzing obtained data was to choose options with mean DF>=2%. To find out which solutions were suitable for 1-bedroom apartments, the set of results was limited to apartments with floor areas between 30 and 40 m². Subsequently, both maximum depth and width were limited to 7m. Finally, the WWR ratio has been limited to below or equal to 0.5. As a result, 17 solutions were obtained, all of which fulfilled the minimum DF requirement, and seemed to have proportions consistent with a good design practice.

A similar process has been followed for 2-bedroom apartments, with area limited to 40-50m², width to 10m and depth to 8m.

4.3.3. Notes on the process

Using the generative method allowed to obtain number of solutions that would not be possible to be tested manually. The challenge was again working with a large amount of data and choosing which results should be prioritized, as the decision regarding the final solution was still the responsibility of the user, not the software. However, it can be concluded, that this kind of study can help build intuition regarding the relation between different design parameters (in this case WWR, apartment dimensions, and mean DF).

The calculation time was not a significant obstacle, since after choosing the input ranges based on good design practice, the amount of iterations was still within reasonable limits. However, it should be noted that setting up the study again required a lot of attention, to make sure that all the iterations will be saved correctly.

One of the biggest limitations of the study was the fact that the window shapes were generated automatically by the software based on the given WWR, so the influence of differentiating their shape and placement was overlooked. Because of that, it was concluded that the results should be treated rather as guidelines than final solutions.

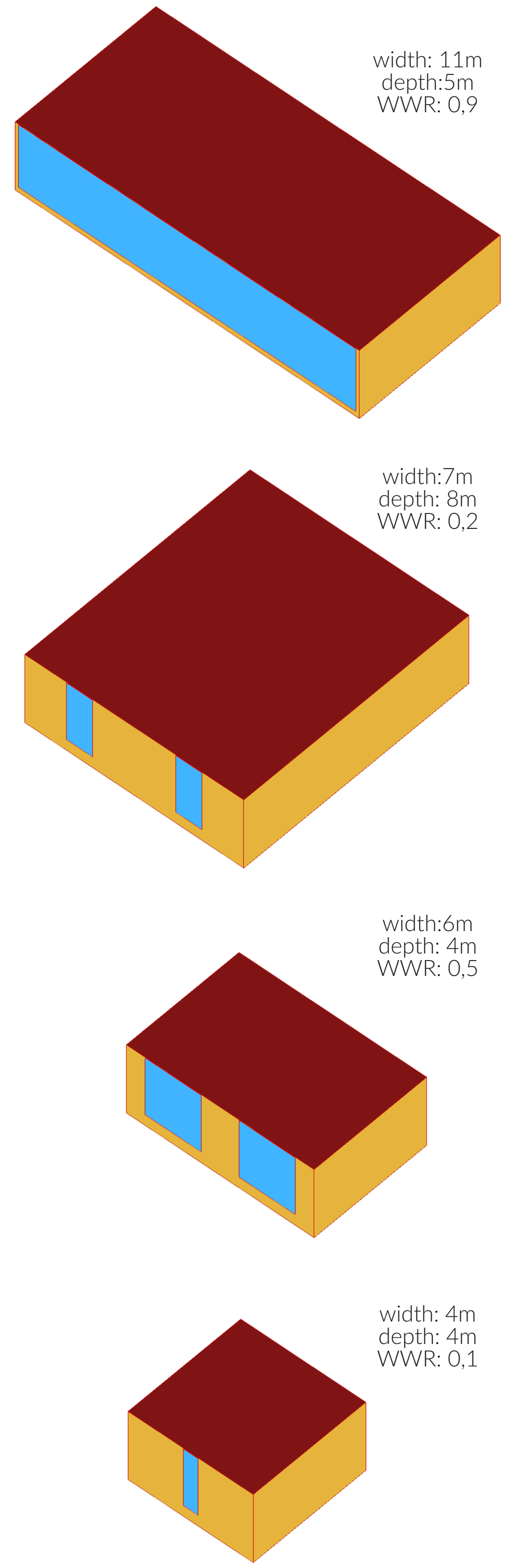


fig. 69. Examples of apartment generated by the algorithm. The placement of windows is automatic, based on WWR.

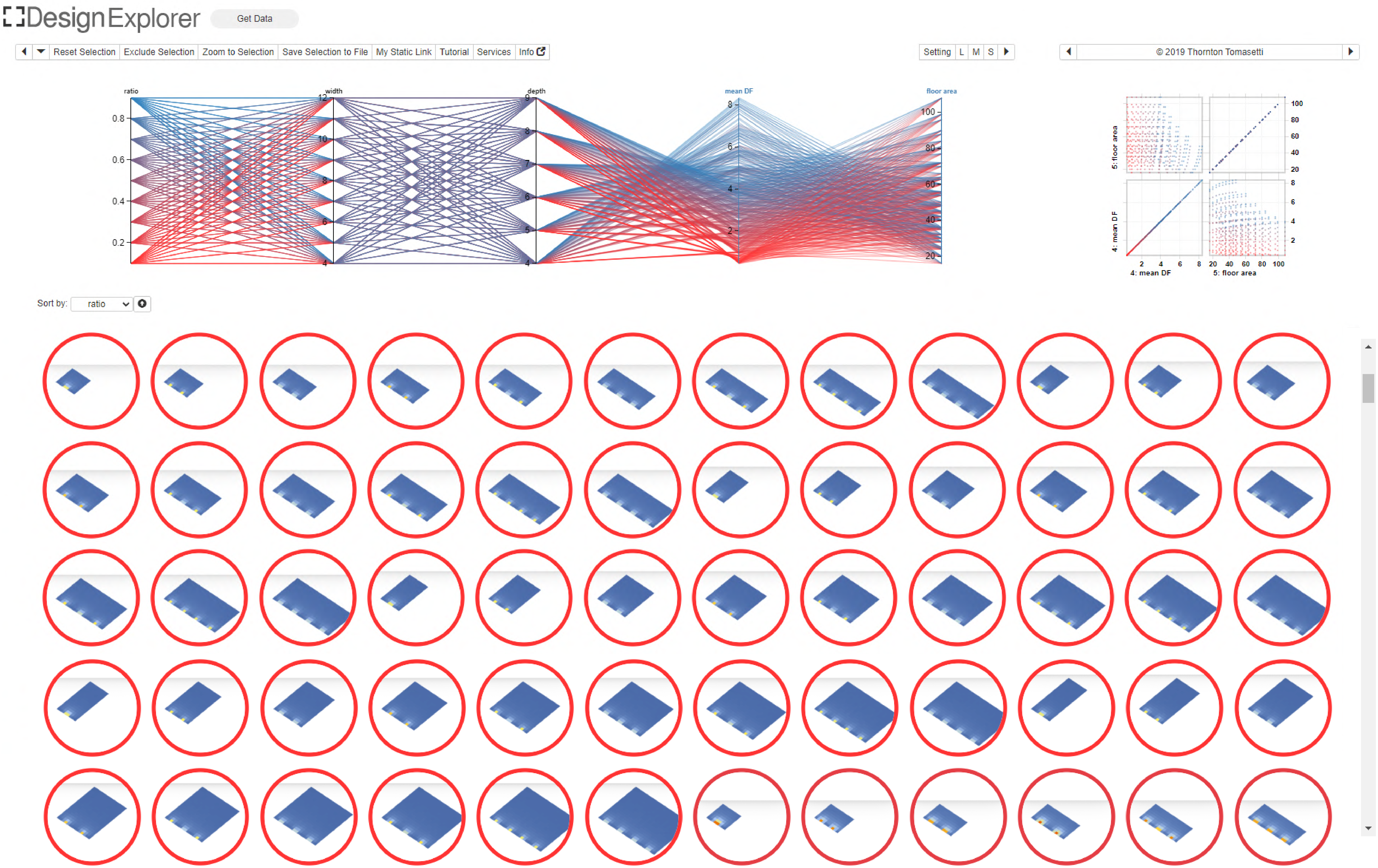


fig. 70. Some of the solutions analyzed with Design Explorer in experiment 7

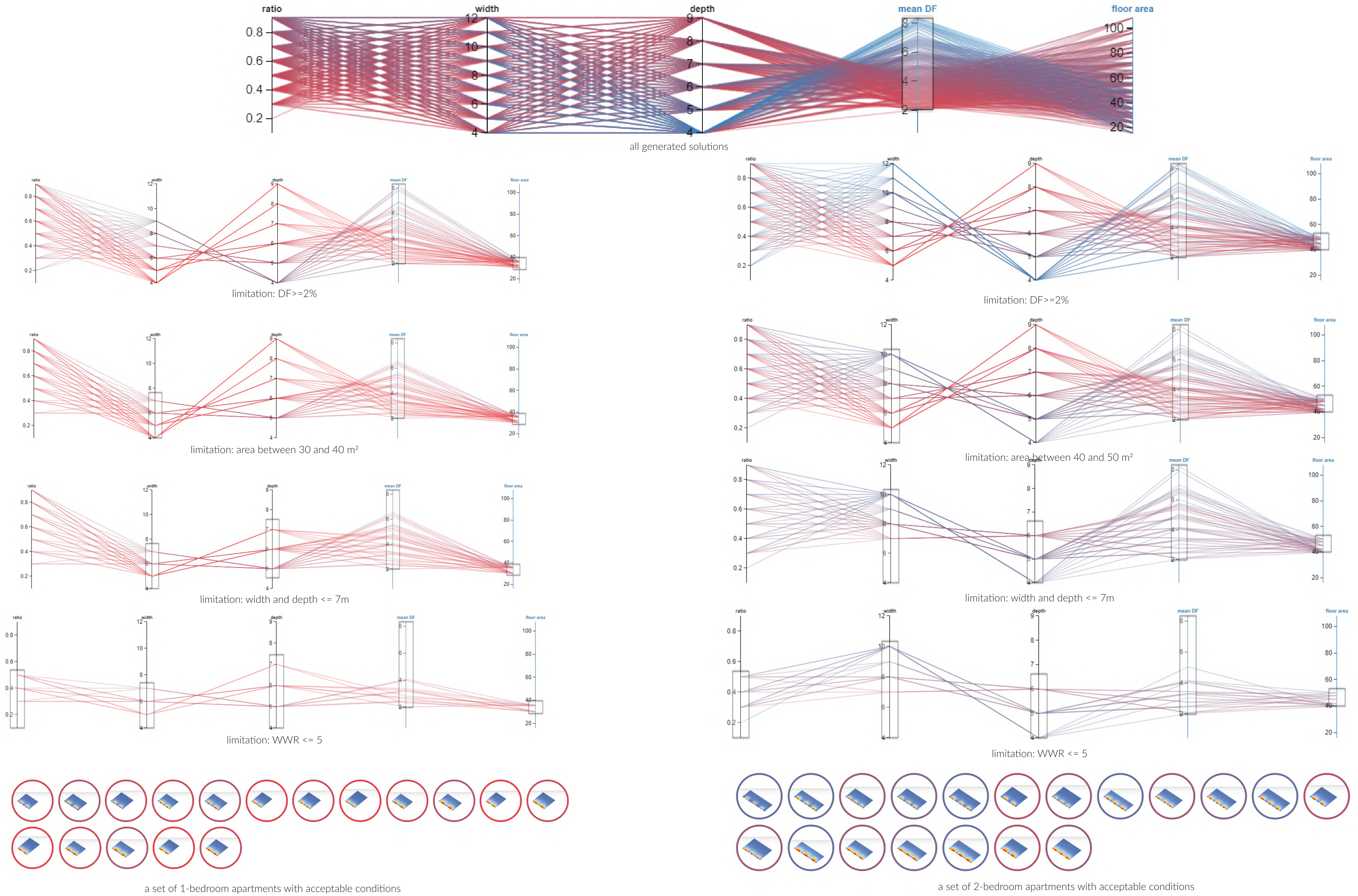


fig. 71 An example of choosing possible design solutions by modifying the range of acceptable parameters within Design Explorer

4.4. Experiment 8. Energy & daylight.

4.4.1. Setup and goals

Experiment type: digital

Used tools:
- Rhinoceros 3D
- Ladybug + Honeybee

When carrying out experiment 8, the main design idea and floorplan proposals were already developed. It has been decided that shared spaces and corridors will be gathered around the courtyard, while apartments will face the street.

After adapting the results of experiment 7 to interior plans, the dimensions of 1-bedroom apartments were set to 5.5x6.5m, while 2-bedroom apartments to 9.5x5.5m. Furthermore, 3 proposals for glazing schemes have been created, following either 0.3, 0.4, or 0.5 WWR, each of which has been suggested to be sufficient for such apartment areas in the previous study. However, since the windows' shapes and placement differed from the ones tested in experiment 7, it seemed reasonable to repeat the daylight study for more defined design proposals. What is more, this time the urban context has also been included, as well as building orientation. Besides DF, Daylight Autonomy (DA) has also been tested. Daylight Autonomy is a parameter calculated by the percentage of hours during which a particular point receives illuminance above a certain level (in this case, more than 300 lux).

There were also small windows placed between the corridor and the apartments, which were meant to provide daylight in the parts of the apartments most distanced from the facades.

Furthermore, different design options for the corridor and shared areas were proposed. This variation was focused on optimizing energy performance. In options A and B, the same floor layout has been used, and only the energy use schemes were different. In option C, the corridor was widened and became fully glazed, with the intention of increasing the greenhouse effect and potentially reducing heating loads.

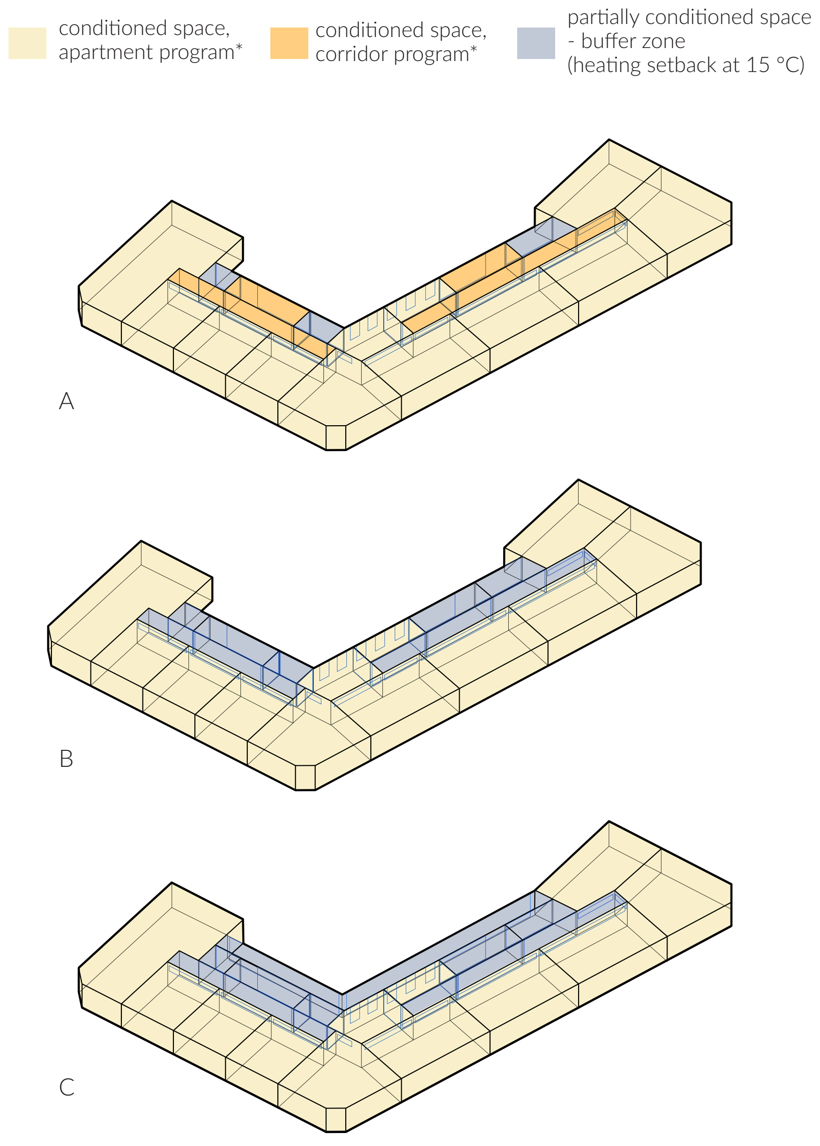


fig. 72. Three proposals of a conditioning scheme on a typical floor

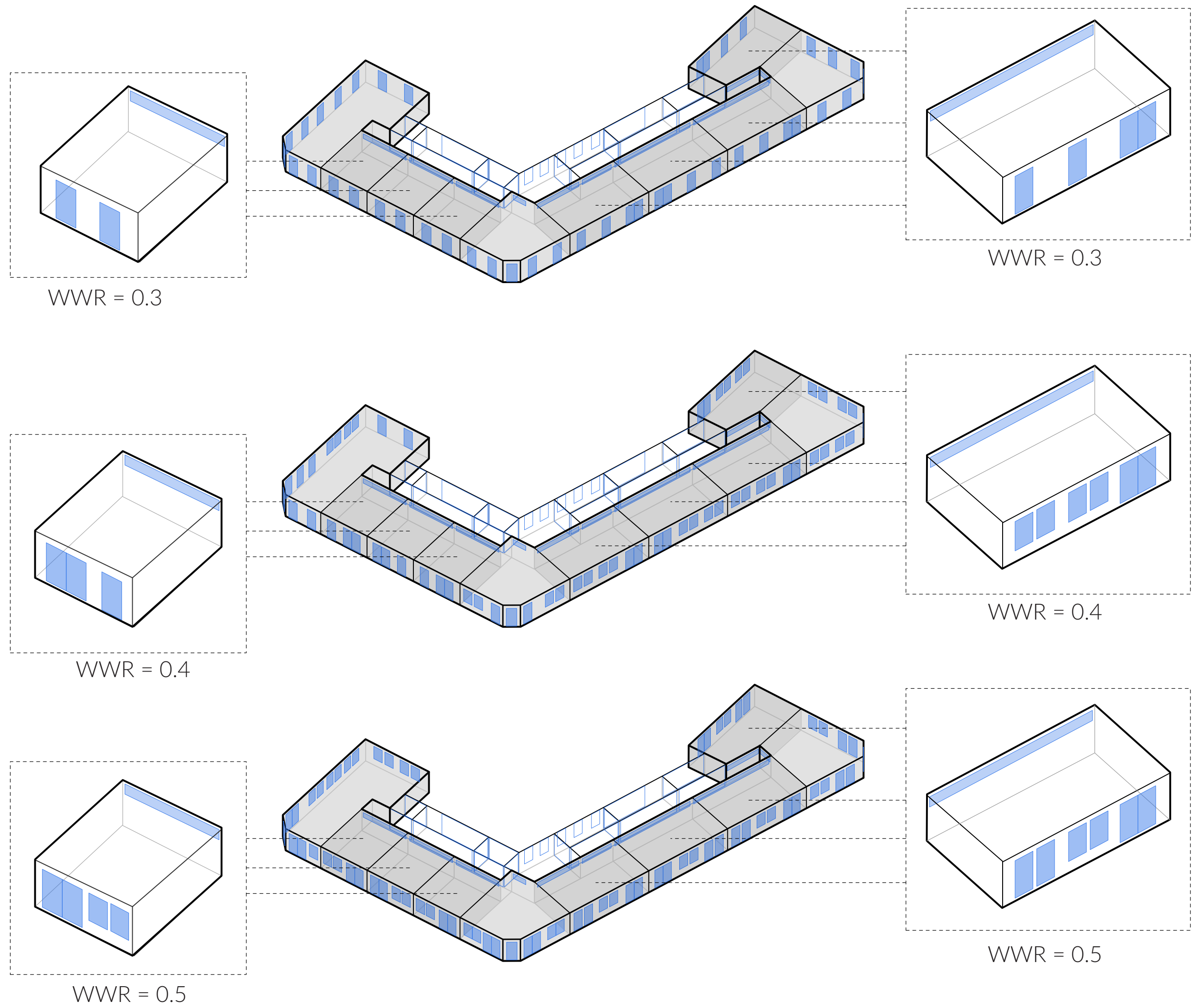


fig. 73. Three proposals of a facade design, based on WWR in typical apartments

Since the tested floor did not have any surfaces adjacent to the exterior besides the walls, only the external walls and windows have been defined in order to fulfill TEK 17 energy requirements (U value for walls ≤ 0.18 W/(m 2 K)), U values for windows ≤ 0.80W/(m 2 K)).

The following question was meant to be answered:

Which combination of glazing designs and corridor variants performs best regarding daylight access and annual energy loads?

Experiment 8 was planned to be an automated study, with Colibri being used to iterate between the 9 design options (combinations between 3 glazing schemes and 3 corridor schemes), however, due to technical difficulties, the study was finally run manually.

Only one floor was chosen for the study, recognized as the most typical one, and the results were extrapolated for the rest of the building.

4.4.2. Results

Despite the initial assumption that even WWR = 0.3 should provide sufficient DF level, the mean DF for the 1-bedroom apartments facing north was below 2%. Both WWR = 0.4 and WWR =0.5 provided acceptable DF for all the apartments. The lowest main DA was noted in apartments facing north with WWR = 0.3 (DA = 13.74%), and was improved to 18.66% by increasing WWR to 0.4 and to 23.64% by increasing WWR to 0.5.

*Program is related here to a set of settings in Honeybee, describing the schedules and energy loads for a particular type of space

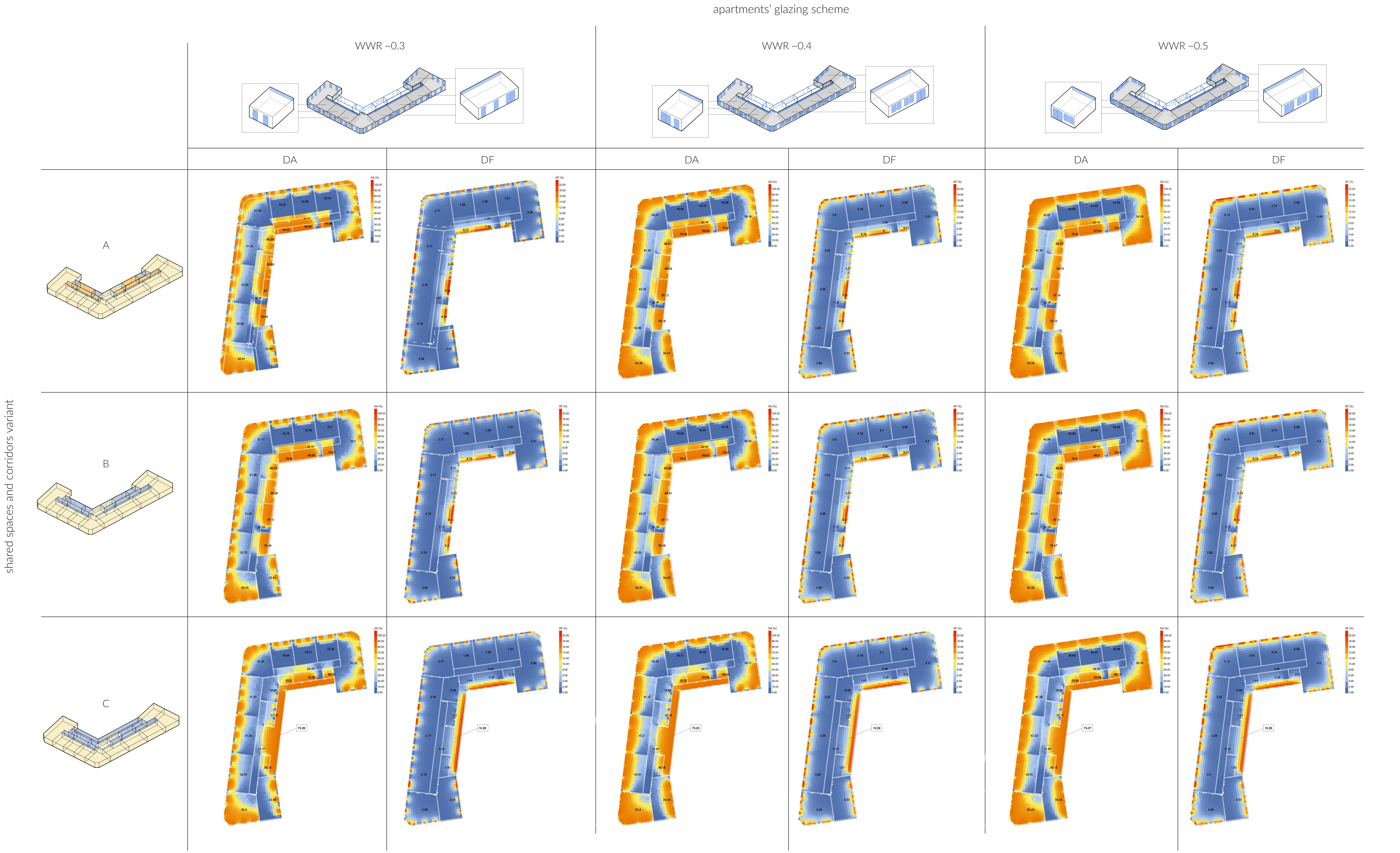
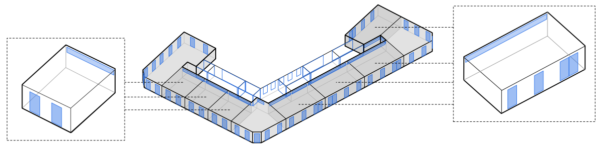


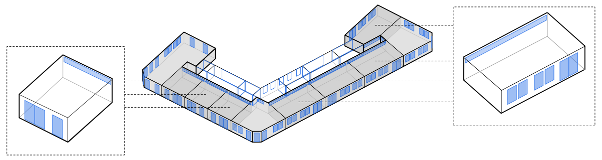
fig. 74. Results of the experiment 8. Daylight Factor and Daylight Autonomy.

apartments' glazing scheme

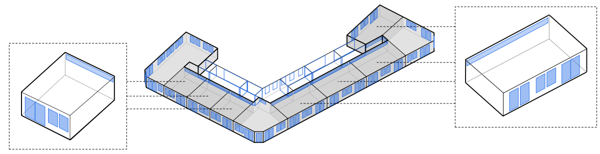
WWR ~0.3



WWR ~0.4

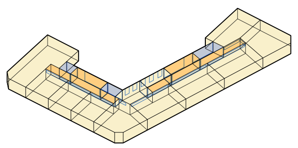


WWR ~0.5

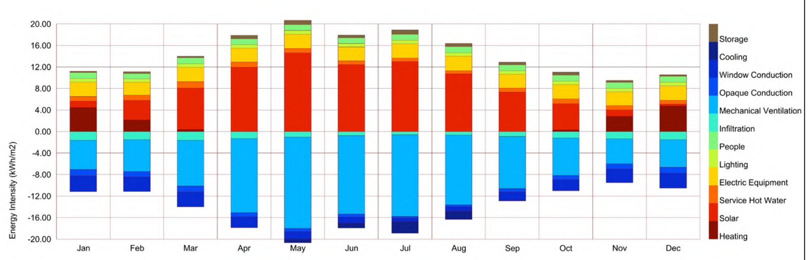


shared spaces and corridors variant

A



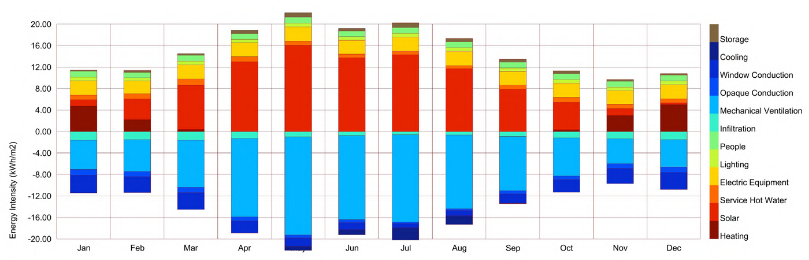
energy balance (WWR ~0.3)



annual energy load [kWh/m2]

cooling	heating	lighting	equipment	hot water	total
5,35	14,94	7,85	31,27	31,89	91,29

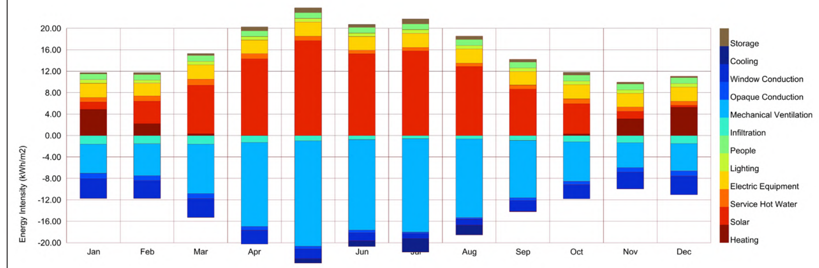
energy balance (WWR ~0.4)



annual energy load [kWh/m2]

cooling	heating	lighting	equipment	hot water	total
5,73	15,66	7,85	31,27	31,89	92,39

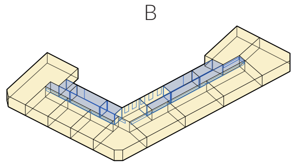
energy balance (WWR ~0.5)



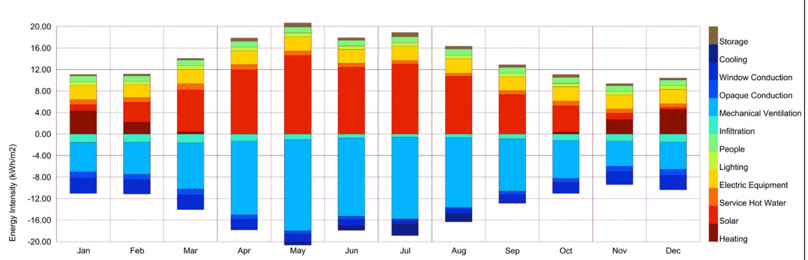
annual energy load [kWh/m2]

cooling	heating	lighting	equipment	hot water	total
6,32	16,16	7,85	31,27	31,89	93,48

B



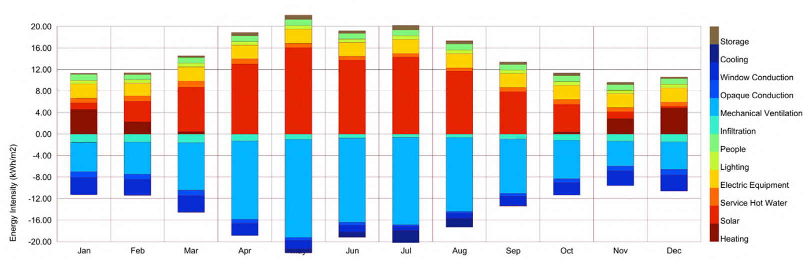
energy balance (WWR ~0.3)



annual energy load [kWh/m2]

cooling	heating	lighting	equipment	hot water	total
5,28	14,64	7,85	31,27	31,89	90,92

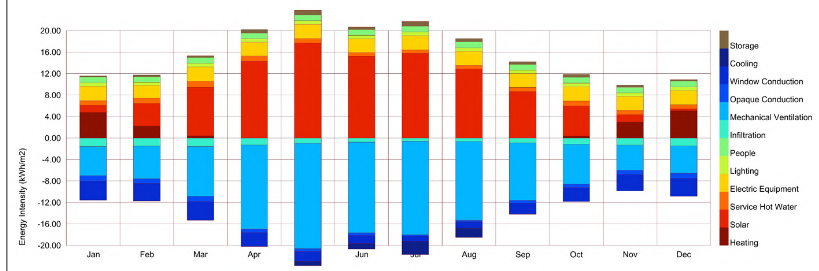
energy balance (WWR ~0.4)



annual energy load [kWh/m2]

cooling	heating	lighting	equipment	hot water	total
5,65	15,35	7,85	31,27	31,89	92,00

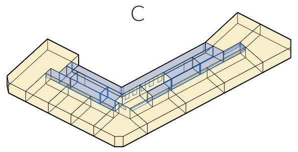
energy balance (WWR ~0.5)



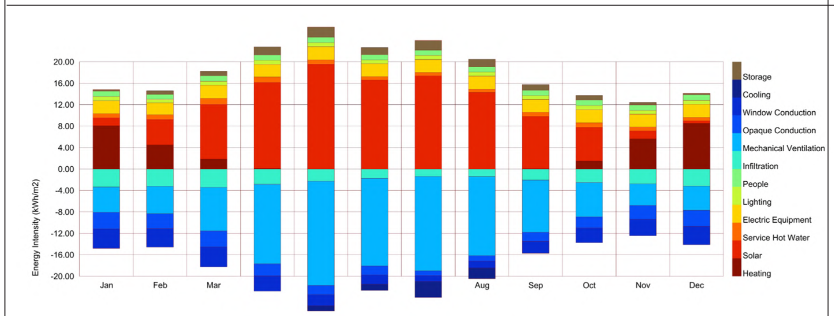
annual energy load [kWh/m2]

cooling	heating	lighting	equipment	hot water	total
6,23	15,83	7,85	31,27	31,89	93,06

C



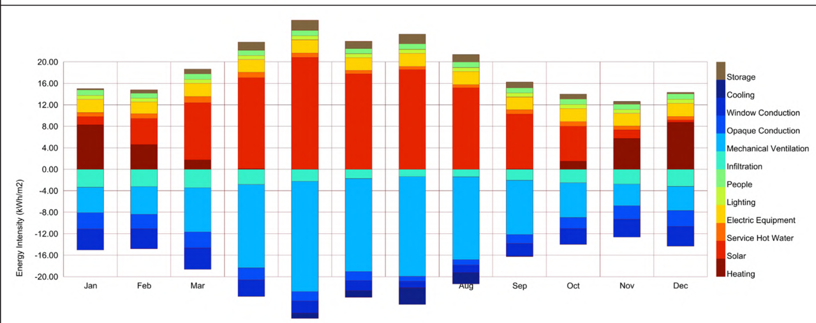
energy balance (WWR ~0.3)



annual energy load [kWh/m2]

cooling	heating	lighting	equipment	hot water	total
7,22	30,30	8,85	28,79	29,36	104,52

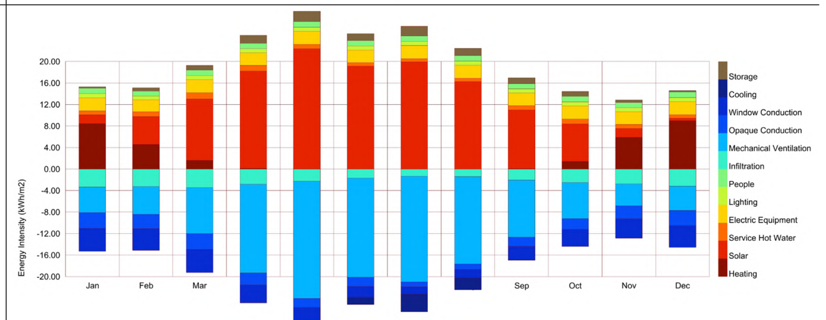
energy balance (WWR ~0.4)



annual energy load [kWh/m2]

cooling	heating	lighting	equipment	hot water	total
7,59	30,83	8,85	28,79	29,36	105,42

energy balance (WWR ~0.5)



annual energy load [kWh/m2]

cooling	heating	lighting	equipment	hot water	total
8,11	31,13	8,85	28,79	29,36	106,23

fig. 75. Results of the experiment 8. Energy loads

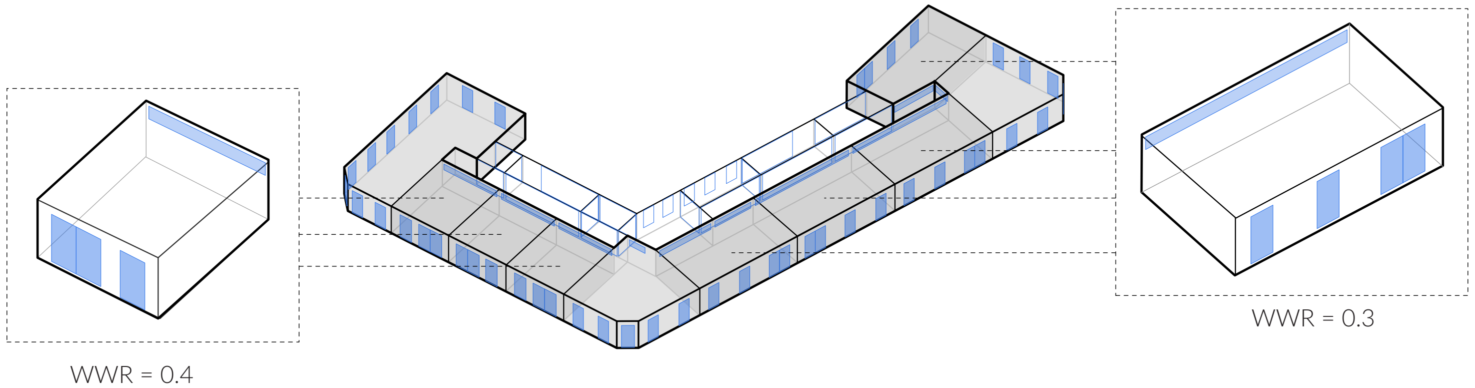


fig. 76. Final windows' scheme

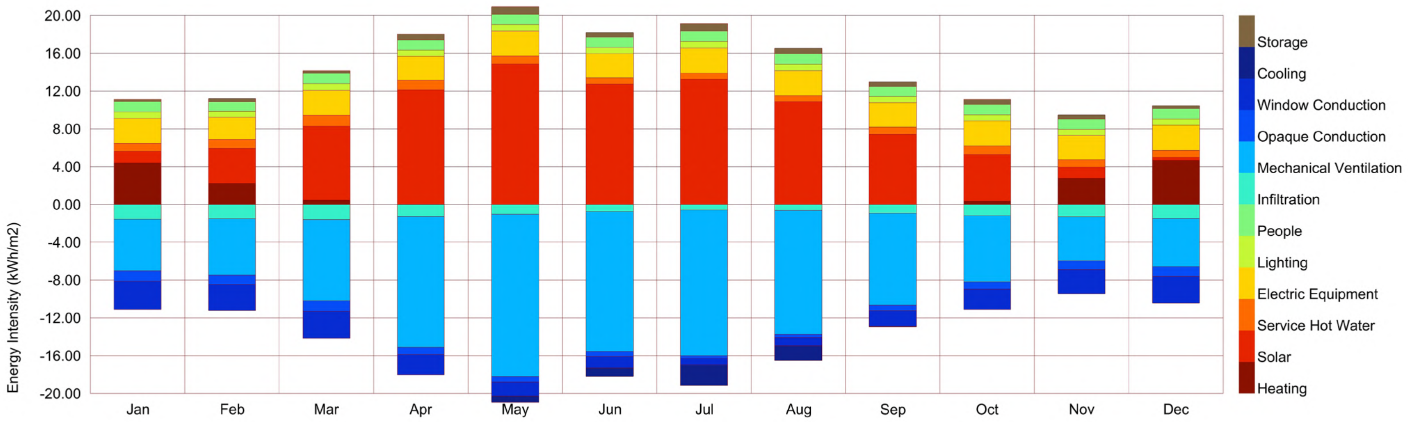


fig. 77. Energy balance for the solution with the final windows' scheme

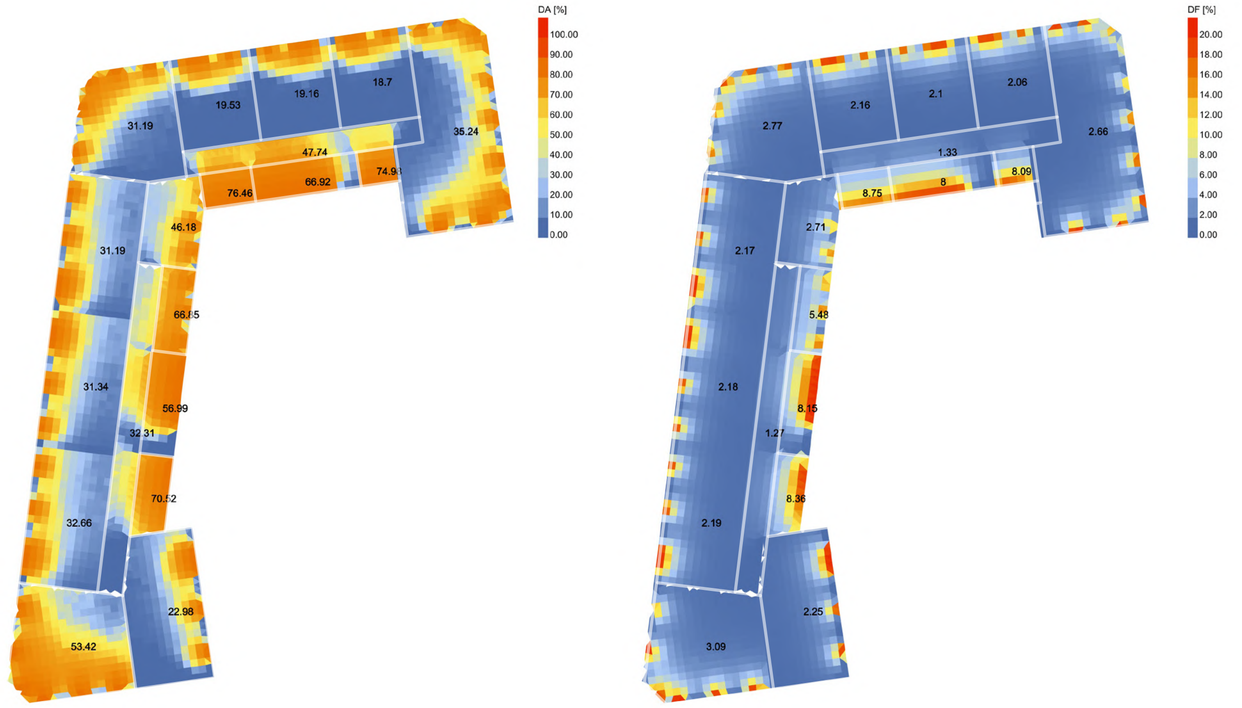


fig. 78. Daylight analysis of the solution with the final windows' scheme

Contrary to the initial assumption, the windows between the apartments and the corridor had very little effect. No influence was visible on the graphical representation of daylight distribution. What is more, changing the variants of corridor design did not influence the daylight conditions for the apartments. However, when it comes to the shared spaces, widening the corridor in variant 3 resulted in insufficient daylight access.

The lowest annual energy load was achieved by the combination of WWR = 0.3 for the apartments' windows and variant B for the corridor. As expected, with increasing the WWR, energy consumption increased as well. The difference between corridor variants A and B was below 0.5 kWh/m², with slightly better results for the variant B. The biggest difference was made by switching from variant B to variant C, and the idea of using the greenhouse effect to improve the energy performance was in this case disproven. The wider corrdior provided also more shading in the internal spaces.

As a result, it was concluded that in the final glazing design should be a mix of WWR = 0.3 and WWR = 0.4. WWR should be increased to 0.4 only in the 1-bedroom apartments facing north, to provide the minimal mean DF level. For the corridor scheme, variant B should be used as the most energy efficient, and providing sufficient daylight level to the shared spaces.

4.4.3. Notes on the process

Even though Colibri was meant to be used to iterate through the solutions, finally it was easier to save all the results manually. While operating Colibri, a lot of troubles were encountered regarding saving visual graphical results – daylight diagrams and energy balance charts. Specifically, exporting text tags with mean DF and DA values on daylight charts was very challenging. Therefore, it was concluded that with only 9 results to analyze, it would be more efficient to gather the results manually. What is more, with such number of results, it was easy enough to decide which ones are the best and to see connections between different parameters even without the use of Design Explorer. It can be concluded that even though it would be more efficient to gather the data with Colibri, in the case of a study consisting of just a few samples it is not necessarily more beneficial to use the iterative method.

4.5. Experiment 9. Influence of internal windows.

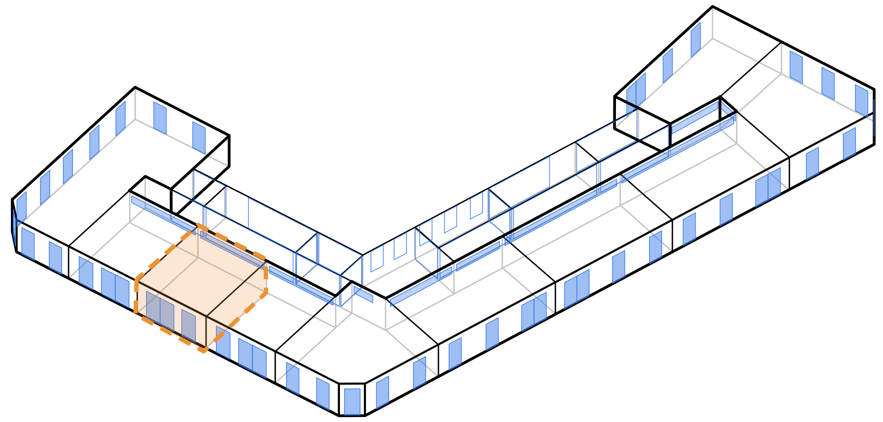


fig. 79. Room analyzed in experiment 9.

4.5.1. Setup and goals

Experiment type: digital

Used tools:
- Rhinoceros 3D
- Ladybug + Honeybee

The idea for conducting experiment 9 was based on the fact, that the windows between apartments and the corridor seemed not to affect the daylight conditions in apartments, according to the experiment 8. However, intuitively it was assumed that such a design solution should provide more daylight to the interior.

Therefore, a separate study was proposed, in order to confirm or disprove this assumption.

One of the 1-bedroom apartments facing north was chosen as a case study, and three different patterns of internal windows were proposed. What is more, a variant with no internal window was tested.

The study was carried out with the same external context that was used in experiment 8. The main research question was:

Can the presence of internal windows improve daylight conditions within the designed living room?

4.5.2. Results:

The differences between particular solutions were extremely small, especially in the DF analysis. The difference between the solution with no internal window and a small internal window was 0.01 for DF and 0.16 for DA. There was no difference between options B and C (a small window and a wide window) when it comes to DF, and a difference of 0.19 for DA. Lowering the sill height from 1.8m to 1.4 helped to improve the results a bit, but the difference was still low (0.03 for DF and 4.24 for DA).

It can be concluded, that placing a window 1.8m over the floor level brings almost no improvement compared to no internal window, and the width of such a window has no significance. In order to achieve better daylight conditions, the internal window would have to be placed lower on the wall, however, this would lead to lowering the comfort of residents by interfering with their privacy.

4.5.3. Notes on the process:

Experiment was an extension of experiment 8, as the same Rhino model and Grasshopper algorithm were used. The only difference was changing the internal window options. Therefore, it was very quick to run, and since the amount of results was also very limited, it was easy and fast to analyze.

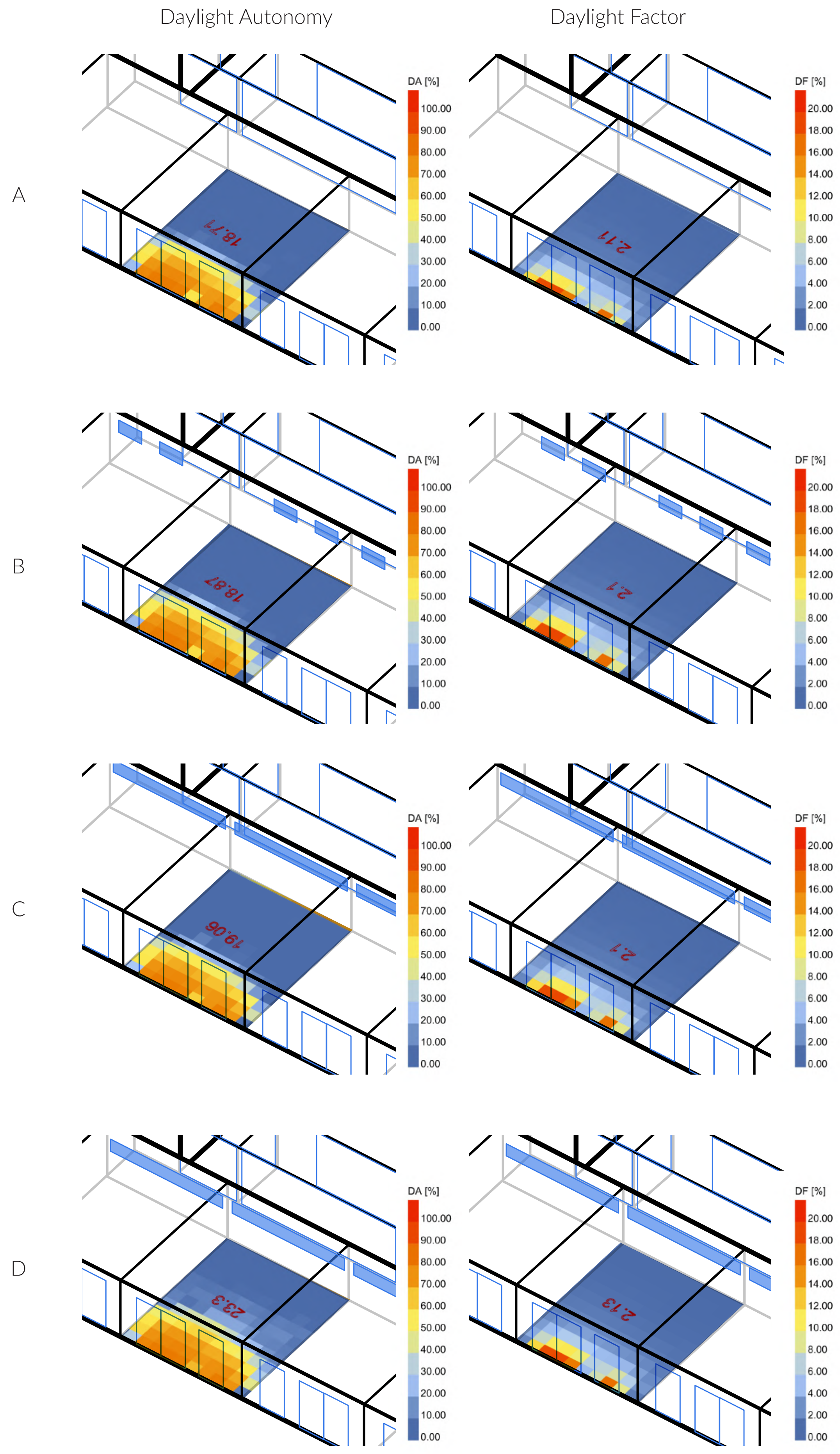


fig. 80. Results of daylight analysis in experiment 9., with mean value of DA od DF marked in the room

4.6. Experiment 10. Influence of internal windows.

4.6.1. Setup and goals

Experiment type: analog

Used tools:
- Automated heliodon
- Cardboard model, scale 1:20

The experiment 10 was a further continuation of the internal daylight comfort study. Since the internal windows had no significant effect on the numerical results (DA and DF), but were still expected to influence how the space is perceived by providing some ambient light, it was decided to conduct an analog study focused on visual perception. To achieve that, a model of an apartment was constructed, with an adjacent part of the corridor. The same apartment as in experiment 9 was chosen.

Since this study was focused on the visual perception of the interior, internal divisions of the apartment were also included. Only the view from the living room, toward the wall adjacent to the corridor, was analyzed. Two variants of the internal window were tested, as well as a wall with no internal window (see fig. 84 and 85). The window with lower sill height (1.4m) was omitted, as it was concluded that it would not be considered in the design due to the privacy of the residents.

Since the results were saved as photos, only data from particular points in time could be gathered, in contrary to the digital studies of DA and DF. Eight points in time were chosen for the analysis:
- Summer solstice at 9.00
- Summer solstice at 12.00
- Summer solstice at 15.00
- Summer solstice at 18.00
- Equinox at 9.00
- Equinox at 12.00
- Equinox at 15.00
- Equinox at 18.00

The main research question remained the same as in experiment 9:

Can the presence of internal windows improve daylight conditions within the designed living room?

4.6.2. Results:

In contrast to the digital study, the analog experiment showed a clear difference between the variant with no internal windows, and the variants in which internal windows were present. The change was limited mostly to the brightness of the walls and ceiling around the window opening. However, it was also perceived that the whole room became slightly brighter in options B and C compared to option A, with dispersed light reaching even parts of the floor. Despite that, it seemed that the amount of daylight provided by the internal opening would not be sufficient for work or any other activity requiring good lighting conditions. Nevertheless, it was concluded that internal windows should be included in the final design, and variant C was chosen as having a more significant effect. It was also assumed, that the exact design of the opening could be slightly modified, to keep the structural consistency of the building (for example, a beam should be placed over the window, as the opening has been made in a structural wall).

4.6.3. Notes on the process:

Using the automated heliodon was not as intuitive as using the manual one. It was still considered an analog study, since an analog model was used, and the type of gathered data was the same. However, it was operated through software, where all the points in time have been set up. Because in this type of heliodon, the movable element was the table with the attached model, and the lamp was stationary, it seemed far less intuitive to understand the relation between the sun's position and particular points in time. The accuracy of the results seemed higher compared to the manual heliodon, since the lamp was brighter and placed further from the model. However, using this solution brought also more technical issues, as the model had to be built sturdy enough not to fall apart during the rotation of the table. It means that making a quick changes in the model (like in experiments 3 and 4, when wooden blocks were used) would be more difficult.

Also, some problems with the camera used were encountered, making it difficult to achieve the same exposure time in all the pictures. Therefore, some post-processing was necessary, to make the results legible, leaving a lot of space for potential errors.

It can be therefore concluded, that the tool provides results that are more accurate compared to the manual heliodon (by providing a greater distance between the lamp and the model, and by allowing to choose a particular day for the analysis, not only month). However, it requires a preparation of a more durable model, and might not be as effective in building intuition regarding the movements of the sun as the manual heliodon.

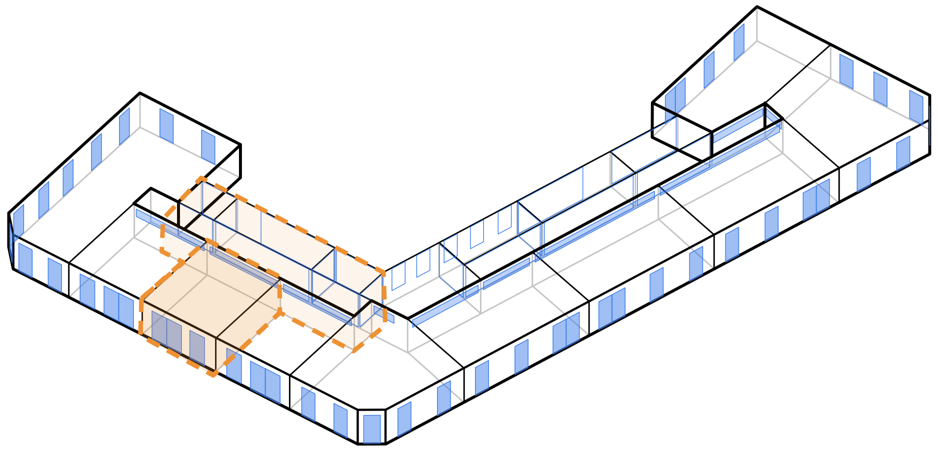


fig. 81. Scope of the model prepared for experiment 10

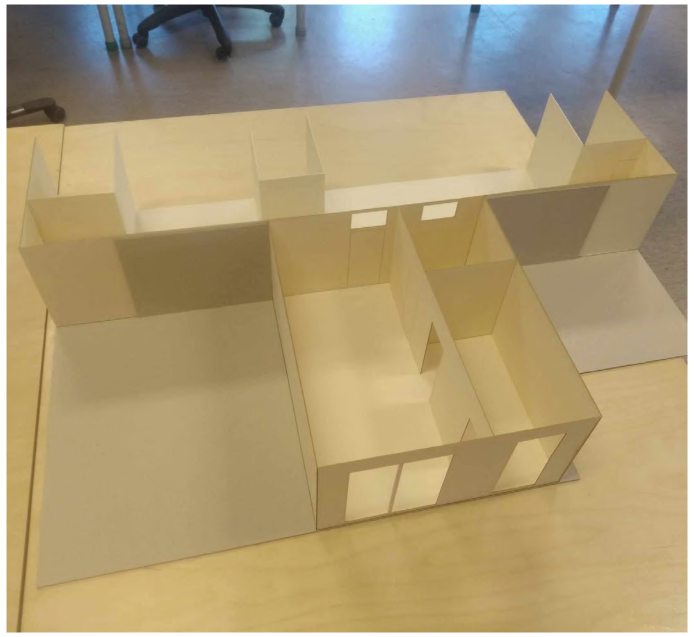


fig. 82. Model prepared for experiment 10

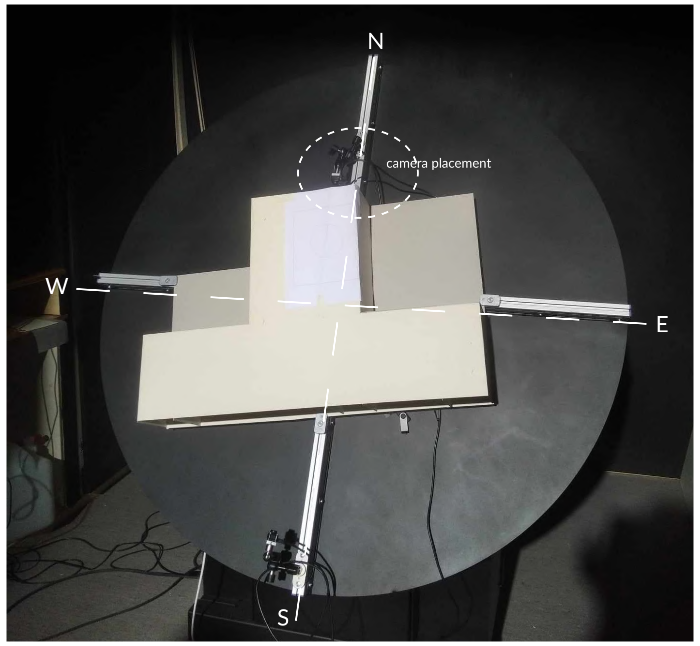


fig. 83. Model attached to the automated heliodon table, calibration in progress

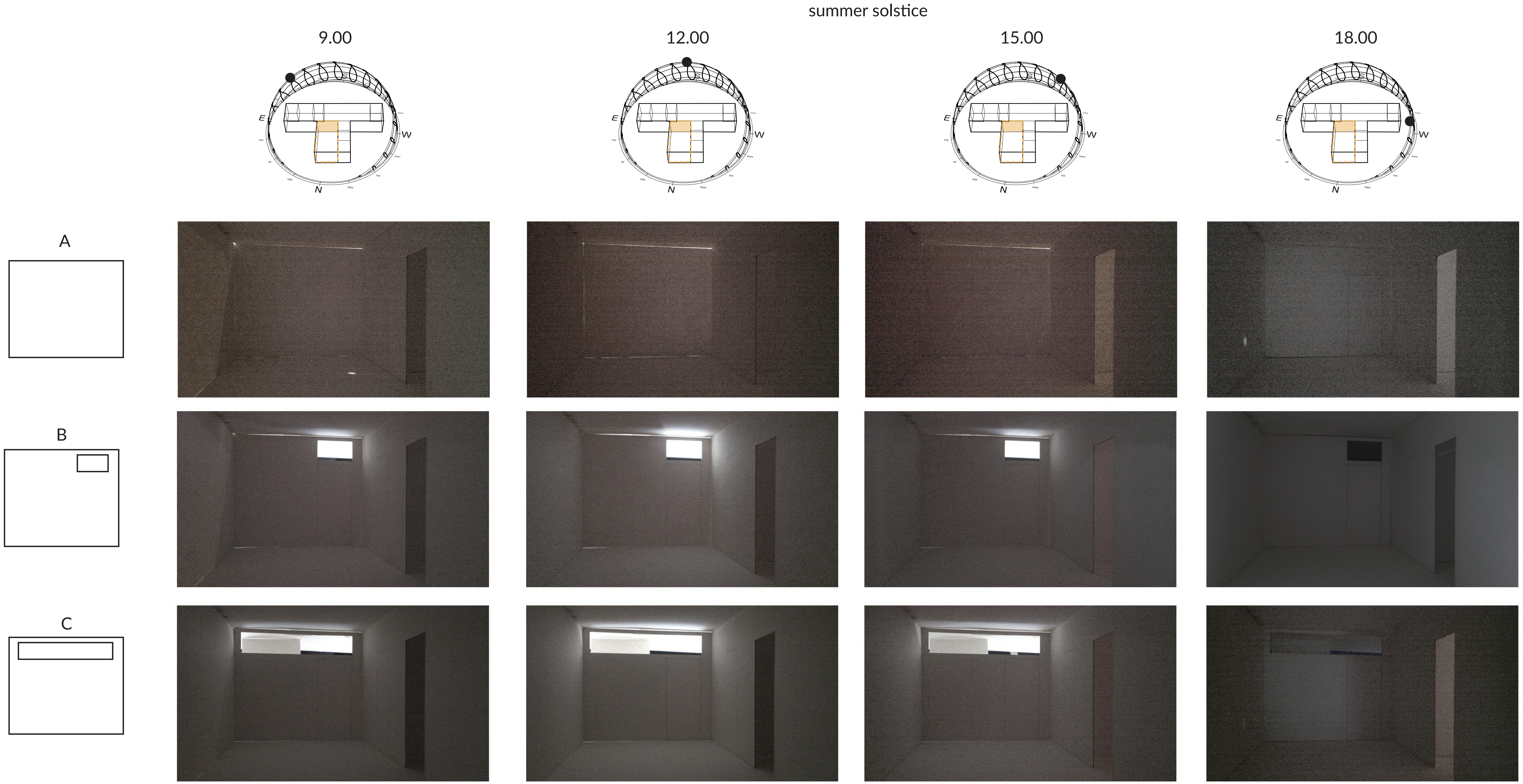


fig. 84. Results of experiment 10, summer solstice

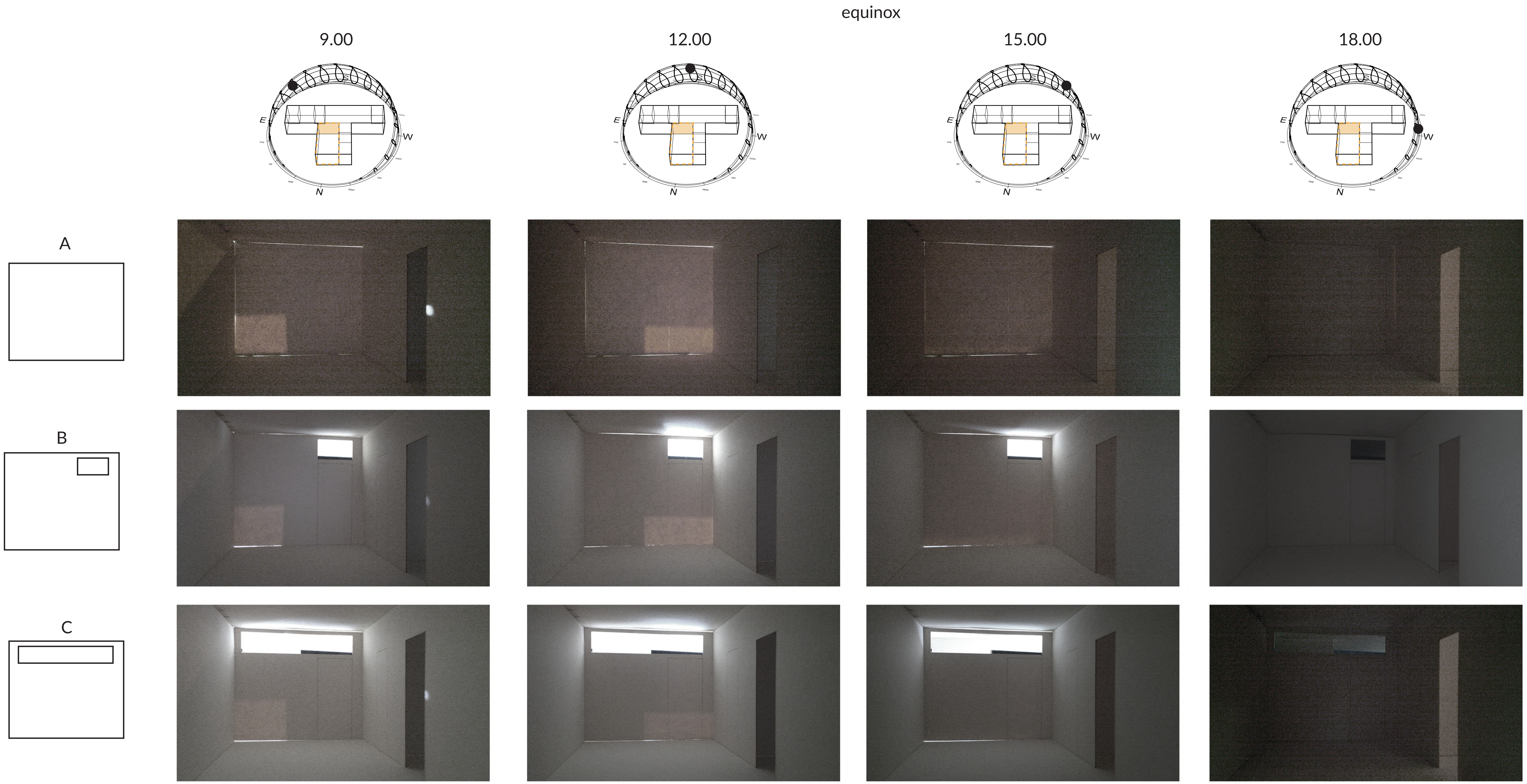


fig. 85. Results of experiment 10, equinox

4.7. Final design

The final design concept is based on the idea of connecting the residents to each other, and to the urban life. Since the idea of cohousing has been recognized as having a postive impact on physical and mental wellbeing, some shared spaces have been proposed within the building, allowing the people living there to engage in common activities. While some of the residential units offer a minimal living area, the shared rooms provide more space than would otherwise be accessible.

All of the shared spaces, both activity rooms and buffer zones, are facing a semi-open courtyard. The ground floor of the building is fully utilized for commercial activities, and the courtyard is meant to be an extension of those. Serving as a common ground between different cafés and restaurants, and between the city and the building itself, is meant to be a space full of life.

The typology of a house centered around a courtyard was a primary inspiration for the form, and the properties of neighboring tenement houses were used as guidelines regarding the height and proportions. On the other hand, it was intended to make use of the advantages of the pavilion typology, making the courtyard partially open. As a result, the outdoor space is sheltered from strong wind or noise, but still open to solar radiation.

It has also been concluded, that cooperation with the neighboring Rosendal Kafe and Teater could be achieved, with the goal of extending the courtyard and creating a green and social area spreading between both buildings. This idea is present in the final design, as the site proposal is extended beyond the plot boundaries.

The designed building has a usable area of 3332.27m², which is much more than estimated in the experiment 6 (1612.37m²). One of the reasons is that the form tested in the generative study was only 9 m wide, and this dimension has reached up to 11,6m in the final proposal. What is more, in the initial analysis the spaces below the sloped roof were not included in the total area, while they have been utilized in the final design. Moreover, a basement and a workshop have been added to the building, also increasing the usable area.

The conditioned shared spaces, excluding the workshop, occupy an area equivalent to 9.5% of the total apartments' area, which is very close to the goal of 10%. If the workshop, despite being placed in a separate building, is also included, this ratio rises to 16%.

However, the workshop might also be considered a partially commercial space, rented out to people from the neighborhood, besides being utilized by the residents.

The partially conditioned buffer zones occupy 10% of the total usable area, and are meant not only to provide better energy efficiency but also bring extra activities for the residents, allowing for indoor gardening and informal meeting with the neighbors.

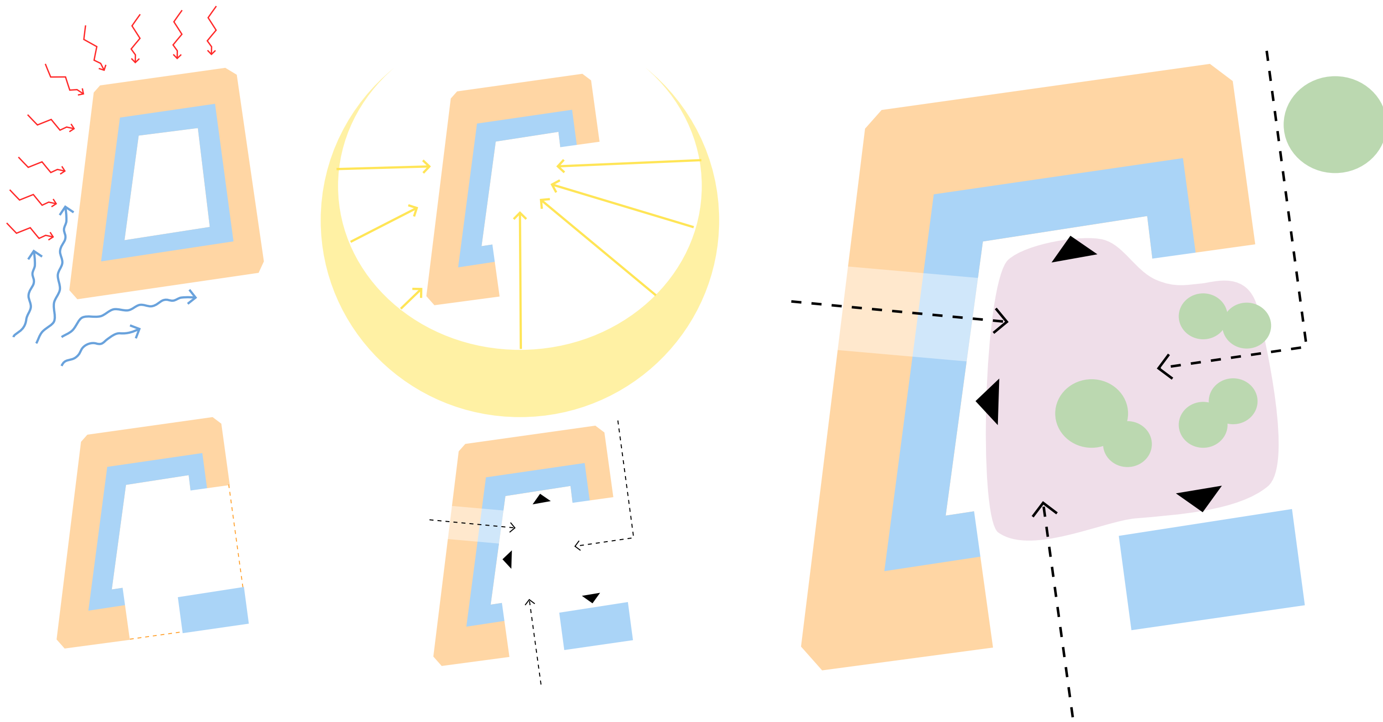


fig. 86. Concept development

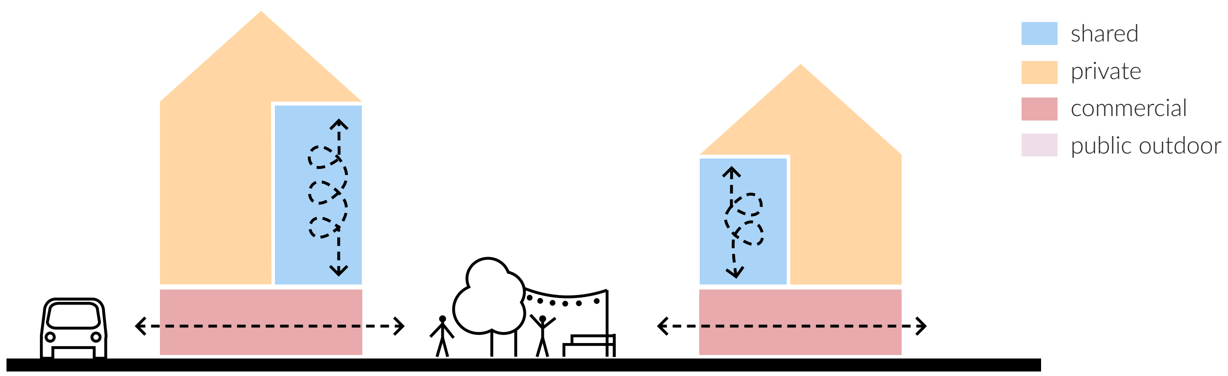


fig. 87. Conceptual section of the building

	apartments	shared rooms	greenhouses	corridors	commercial spaces	storage and technical spaces	TOTAL
usable area (m²)	1339.89	216.35	43.31	302.71	603.31	826.64	3332.27
level of conditioning	conditioned spaces	conditioned spaces	buffer zones (partially conditioned)	buffer zones (partially conditioned)	conditioned spaces	conditioned spaces	-

fig. 88. Areas in the final building according to function

4.7.1. Functional distribution

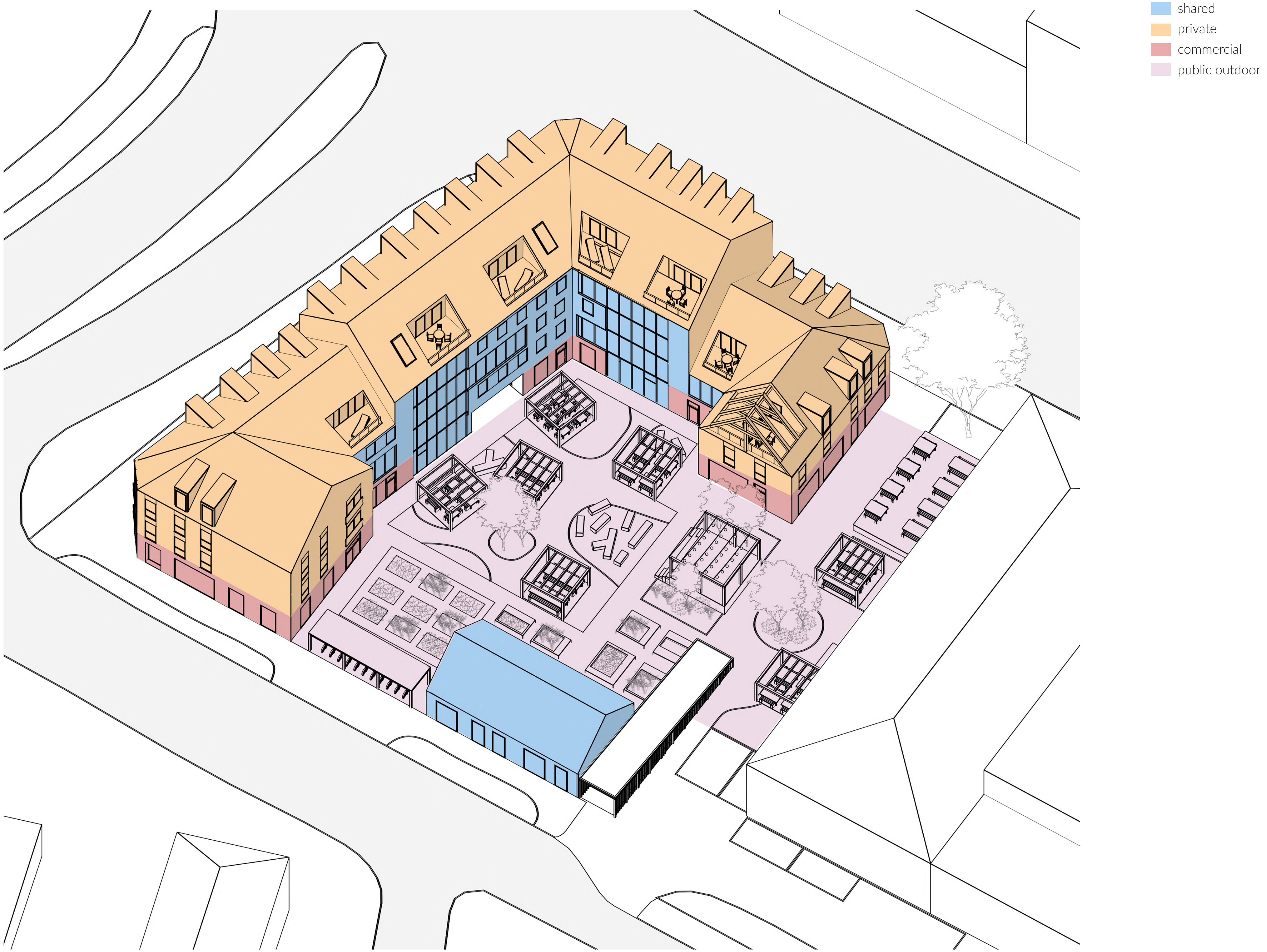
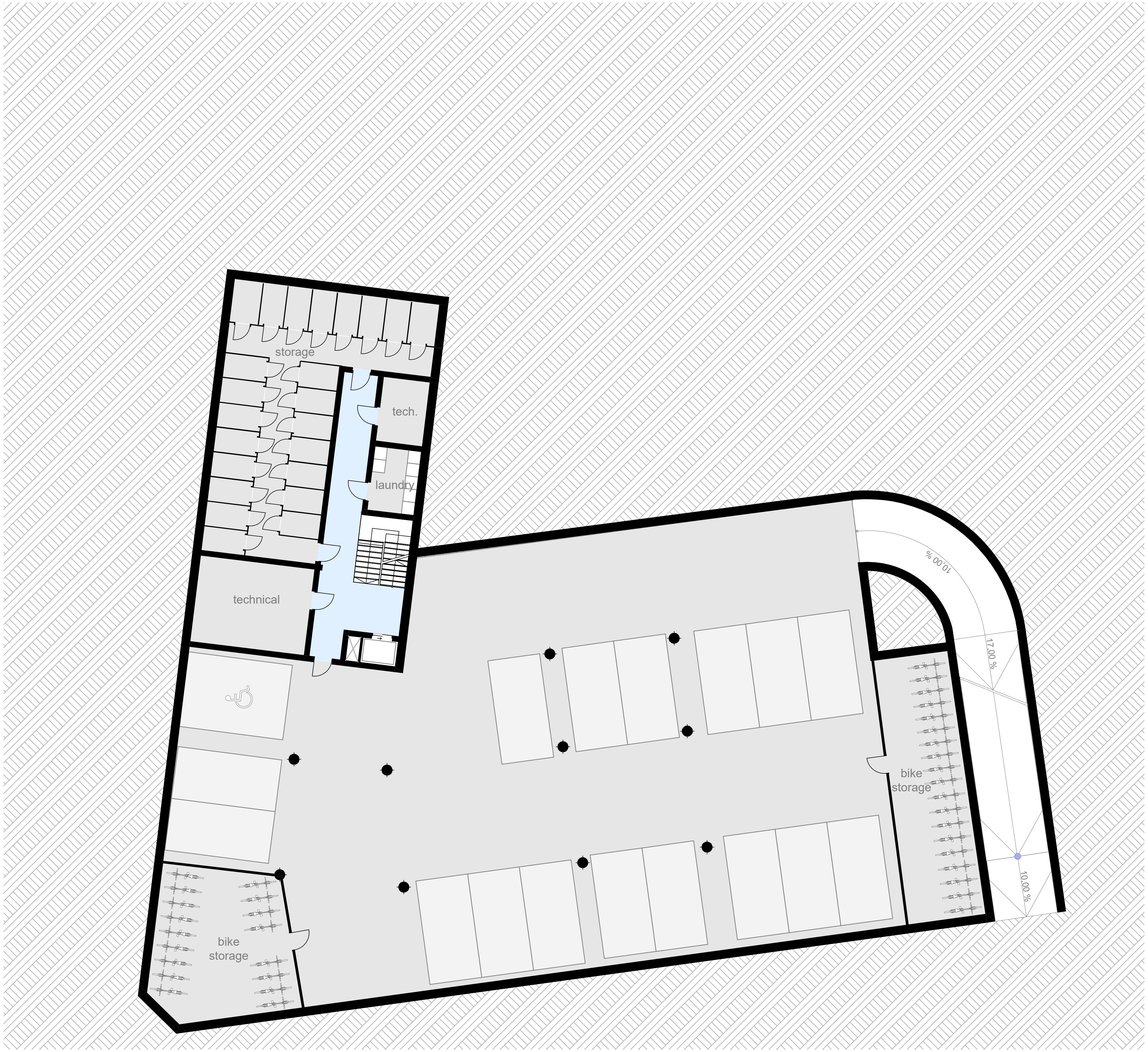


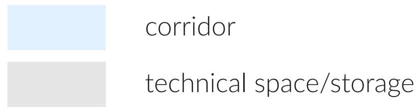
fig. 89. Axonometric representation of the project

4.7.2. Site plan | 1:500

fig. 90. Site plan

4.7.3. Basement plan | 1:200





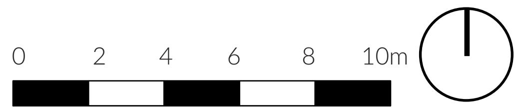


fig. 91 Basement plan

4.7.4. Groundfloor plan | 1:200

fig. 92. Groundfloor plan

4.7.5. First floor plan | 1:200

fig. 93. First floor plan

4.7.6. Second floor plan | 1:200

fig. 94. Second floor plan

4.7.7. Third floor plan | 1:200

fig. 95. Third floor plan

4.7.8. Fourth floor plan | 1:200

fig. 96. Fourth floor plan

4.7.9. Section | 1:100

The corridors, staircases, and greenhouses are designed to function as a buffer zone for the rest of shared areas and for the apartments. During winter, the solar radiation is captured through the large glazings, and the heat can be transferred to other parts of the building. Since the building's structure over the ground level is made of CLT (due to low expected emboddied emissions), the floors in the staircases are finished with stone, to provide higher thermal mass and better heat storage capacity. During summer, there is a possibility of natural ventilation across the building.

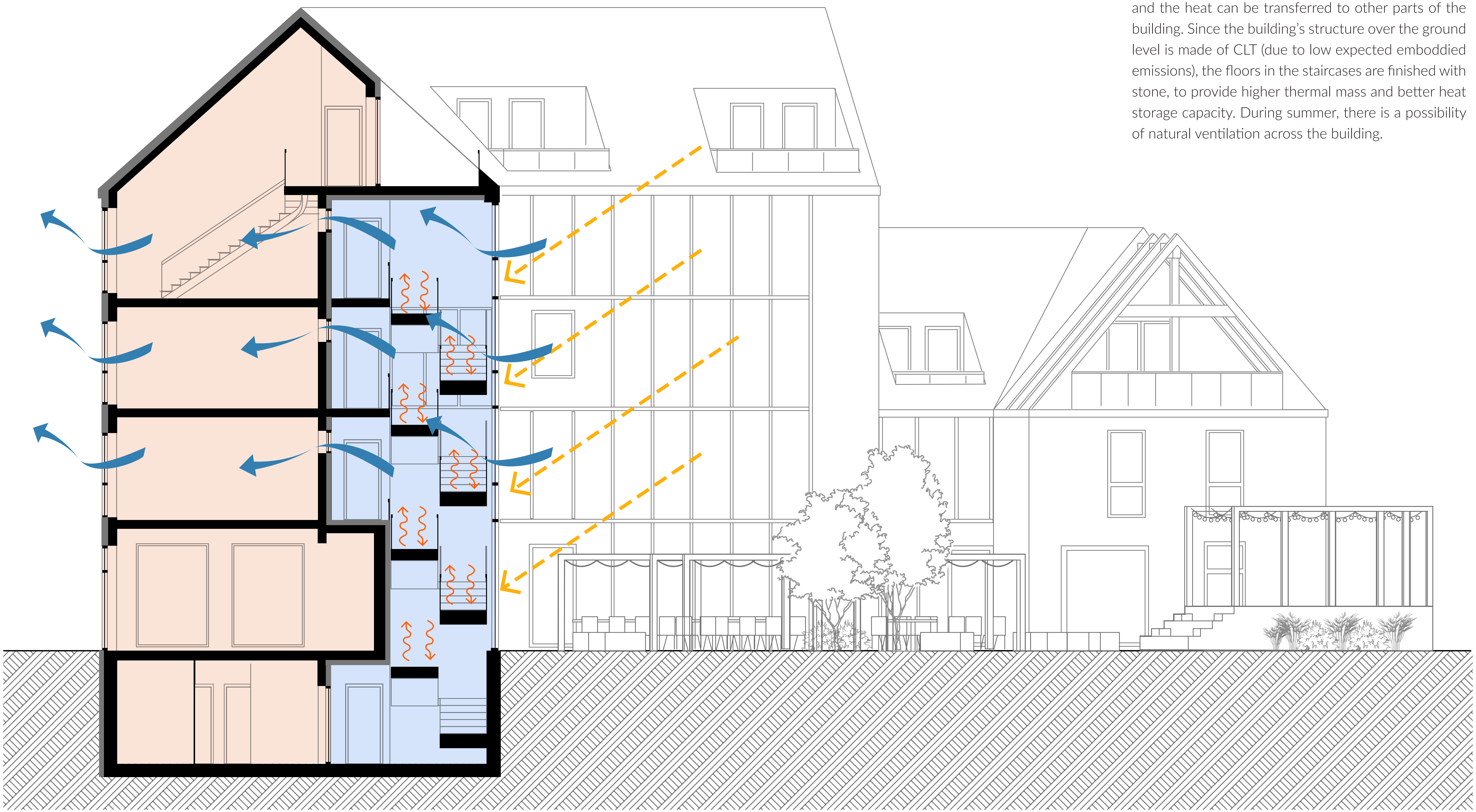


fig. 97. Expected environmental performance of the buffer zone

4.7.10. North facade with context | 1:250

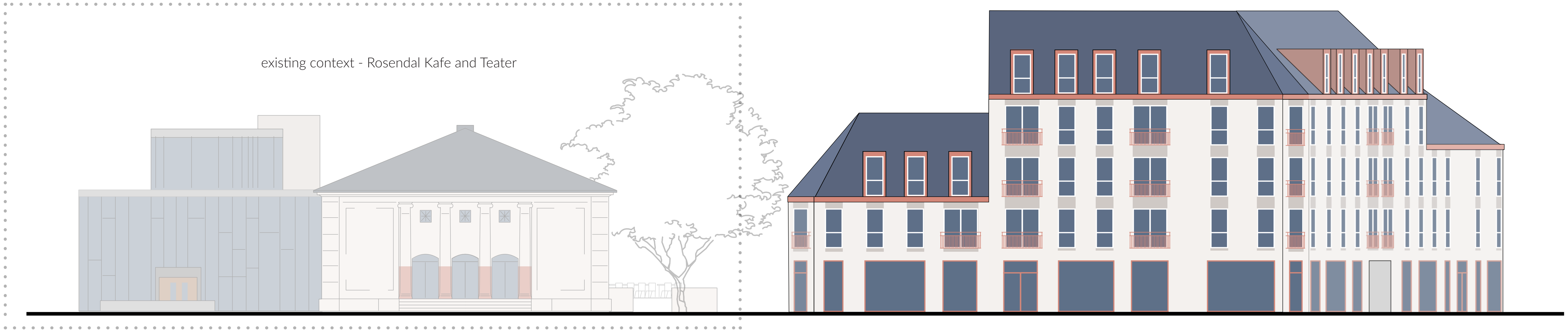


fig. 98. North facade

4.7.11. West facade | 1:250

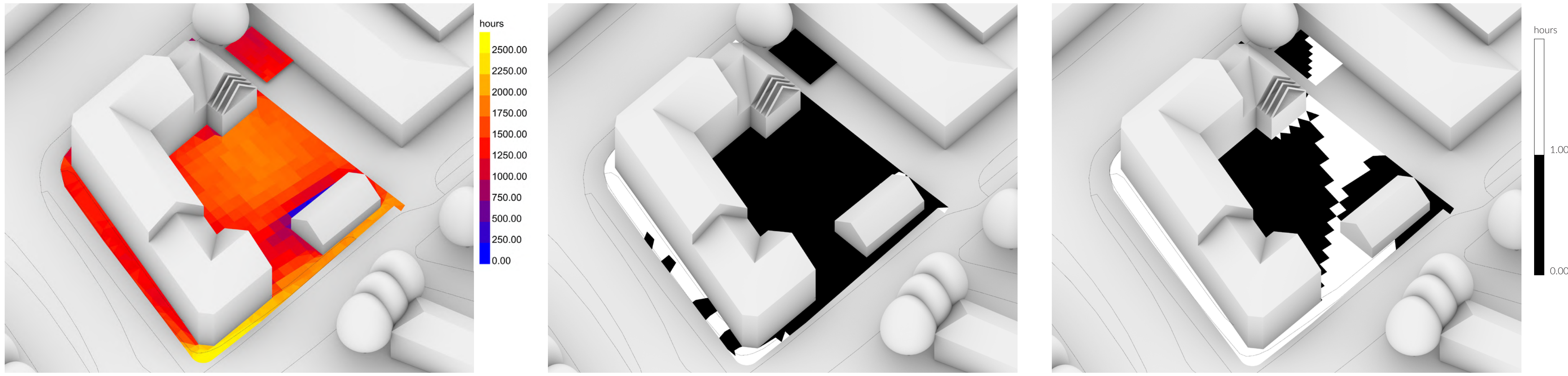
fig. 99. West facade

4.7.12. Daylight site analysis

annual mean direct sun hours:

summer solstice at 18.00, mean direct sun hours:

equinox at 15.00, mean direct sun hours:



Annual mean direct sun hours:
- plot: 1381.13
- terrace of the cafe: 1101.8

Summer solstice at 18.00:
- plot: 0.31
- terrace of the cafe: 0

Equinox at 15.00:
- plot: 0.46
- terrace of the cafe: 0.47

fig. 100. Solar conditions on the site

fig. 101. View from the courtyard, at euqinox at 15.00

The results of the final solar analysis of the site differ slightly from the effect of experiment 6, in which the form of the building was chosen and analyzed regarding solar conditions. This is because while the concept was being developed, the proportions of the building were modified in the attempt of creating functional plans. First of all, a small building has been added in the south-east corner of the plot. Second of all, the southern part of the main buiding has been reduced even further, compared to the form analyzed previously. What is more, the main part of the building became around 3m wider.

As a result, the conditions during summer solstice became worse compared to the final results of experiment 6, both for the plot and for the terrace of the cafe. However, both places receive more direct sunlight during equinox. And finally, the mean annual amount of direct sun hours on the plot remained almost unchanged (1380.21 increased to 1381.13). The mean annual value for the cafe terrace decreased by 100 hours, but hopefully the presence of new social outdoor spaces can compensate for that.

4.7.13. Visualizations

fig. 102. View from the courtyard, summer solstice at 12.00

fig. 103. View from the Innherredsveien street

fig. 104. View from the square in front of Lademoen Church

fig. 105. View from one of the houses by Gamle Kongevei street

5. Summary

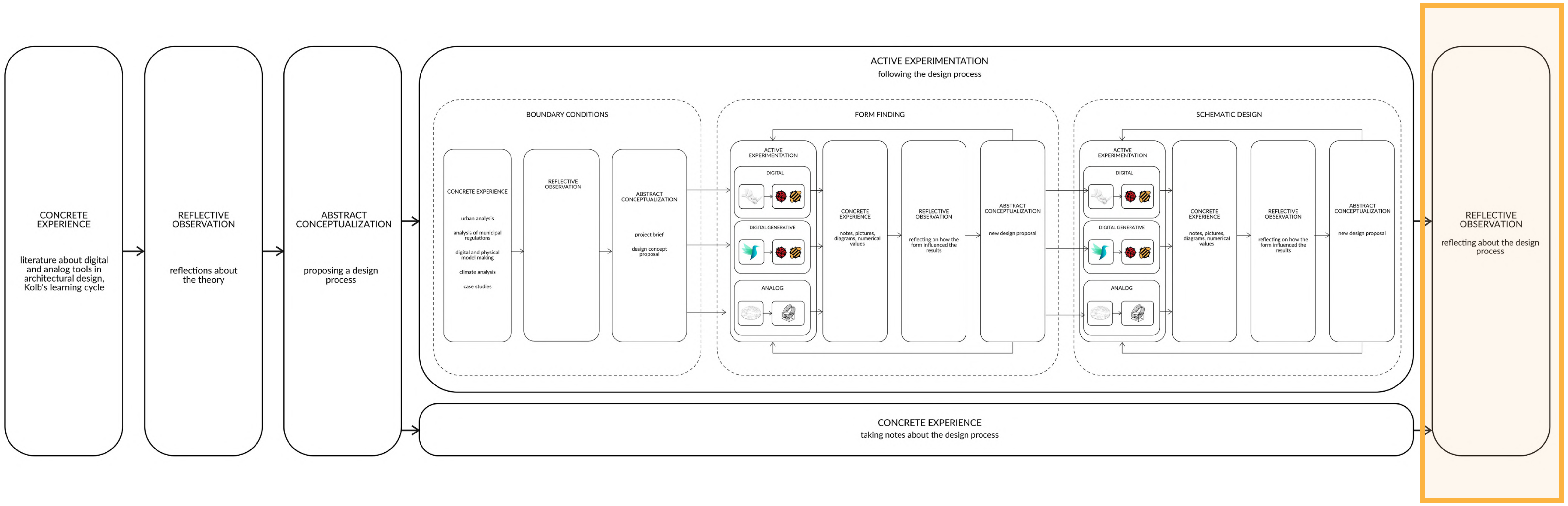


fig. 106. The final reflection stage in context of the whole thesis process

5.1. Conclusions and discussion

One of the main challenges faced during the work on the thesis was the uncertainty regarding the extent to which the design process should be planned. It was assumed that following a clear structure would make it easier to form reflections and ensure that a set of different tools was included. However, even though the general stages of architectural design are universal and can easily be predicted (such as site analysis, concept proposal etc.), it is a creative process, which often involves decisions based on intuition.

It was challenging for the author to decide whether to follow a structured plan of analysis and support every decision with evidence, or make some choices in a more intuitive way. Perhaps, following a typical design process and forming reflections afterward would be less demanding. Conducting such a study could also be more effective if the subject and object were separated, while in this case, the author was responsible for planning the process, following it, and reflecting on it.

What is more, despite the effort to follow the initial structure, not all the tools were used exactly as planned, and some steps were added or skipped based on current needs. For example, no generative study was conducted in the form-finding phase, due to time limitations and not finding a good justification for using this tool.

Another challenge arose from using the experiential learning theory as a base for describing the anticipated steps. Since the stages of learning happen subconsciously, and not always in the same order, using this scheme as a basis of a work plan brought some confusion, especially at the early stages. However, the theory helped define the goal and structure of the thesis, as it was used to distinguish between reflections on the tools and on the design itself.

Despite the faced difficulties, the double outcome of the thesis has been achieved.

As anticipated, the main difference between the digital and analog tools was the type of results they provided. Using analog tools resulted in obtaining no numerical data, which made it more difficult to analyze and compare different solutions in the context of environmental performance. One of the biggest setbacks with this kind of study was also the time needed for the preparation stage. Perhaps, in case of this thesis, the site model was unnecessarily precise and could have been constructed with less time-consuming methods. However, it can be argued, that preparing a model of terrain in an analog form would in most cases require more work than a digital one, as the digital model is usually used a basis of the analog version. Therefore, it could be beneficial in situations, in which the same model can be utilized by a larger number of people or for a longer period of time, to make up for the resources spent on the preparations.

What is more, conducting the analog studies did not require much expertise, and should be possible to be performed by individuals without much experience. It can therefore be found useful in educational settings or during design workshops involving people from outside the industry (for example, while developing cohousing projects involving future residents).

The digital tools provided very accurate results and allowed for easier analysis of the data, however, posed also a bigger risk of failure due to software errors or lack of skills. What is more, the amount of data provided was in some cases overwhelming, making the author realize that obtaining any information should always be preceded by a clear intention. It should also be noted that how effective a particular design tool is, might depend on personal preferences and set of skills (for example, not knowing the software well will make it a very limiting tool, while proficiency allows for more freedom). Therefore, to obtain more objective data, further research would be needed, with more participants following the same process. The author might have a tendency to work with digital tools rather than with analog ones, which might have influenced some choices.

The generative method should be considered a part of the digital workflow but has been distinguished as a separate tool for the sake of the thesis. It has been observed that the possibility of testing hundreds of solutions might be extremely useful when a general idea of the project has already been created, and some criteria for assessing the results have been set. However, when the architect is in the very early stage of the design, this method might not be found helpful, as a clear intention is required to create the algorithm.

An interesting reflection can be made upon the experiments which were very similar to each other in either tool or intention. For example, the only difference between experiments 3 and 4 was the degree to which the study was planned. Since experiment 3 was fully intuitive, it was observed that hardly any surprising result was obtained, as most of the proposed forms followed rules based on previous experience and knowledge. Also, describing the results was quite challenging due to the lack of structure. On the other hand, the more organized study brought some surprising elements, as the forms were first designed, and then tested, leading to some discoveries. However, this approach seemed to slightly limit creative freedom.

On the other hand, experiments 9 and 10 differed in the tool used, but the intention was very similar – testing the influence of internal windows. While experiment 9 did not show much evidence of importance of this design solution, it became very clear in experiment 10, as different kind of data was provided. It could be an argument towards the synergy of digital and analog, since each of them gave different results, allowing for a more conscious design decision. However, it can also be noted, that some of the tools should be possible to be replaced with others, and digital glare analysis could be done instead of the automated heliodon study.

In order to give a structure to the final comparison of the tools used, firstly a questionnaire regarding the impact of each experiment on design decisions has been filled out (fig. 107). Then, a summary of qualities of particular tools have been done, distinguishing such elements as needed resources, accuracy of the results, and the influence on design decisions (fig. 108).

Unfortunately, due to time limitations, only daylight and energy analysis have been conducted during the work on the thesis. The final form and reflections on the tools could be different if, for example, wind analysis was also included as one of the design drivers.

Another interesting approach for future studies would be mixing digital design with analog simulation tools and the opposite (for example, 3D printing a form generated in Grasshopper and testing it in heliodon). Even though some element of digital fabrication was included in the thesis, it was limited to preparing the site model.

To sum up, this report will hopefully provide some useful insights for architects and researchers working with bioclimatic design, despite some setbacks and limitations. It is aimed to inspire both students and professionals to reflect upon their own work process, and encourage them to make more conscious decisions about the tools they are using, in order to increase the efficiency and agility of their practice.

	BOUNDARY CONDITIONS		FORM FINDING			SCHEMATIC DESIGN				
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
Type of the study (A - Analog, D - Digital, G - Generative)	D	A	A	A	D	G	G	D	D	A
1. Experiment:										
- Unplanned free experimentation (in order to discover unexpected things)			●							
- Planned experiments (testing of conditions)	●	●								
- Planned experiments (testing of solutions)				●	●	●	●	●	●	●
2. Discovery:										
- Something surprising/unexpected	●			●	●					
- Something opposite to expected			●	●	●			●		
- Got confirmation on speculation / theory	●	●	●	●	●	●	●		●	●
- 'Saw the bigger picture'			●	●	●	●	●	●	●	
- Didn't discover anything										
3. Reflections:										
- Critical reflection on own design			●	●	●	●		●	●	●
- Reflections on discoveries	●	●	●	●	●	●	●	●	●	
- Reflections on possible solutions	●	●	●	●	●	●				
- Reflections on initial objectives			●	●	●					
4. Design choices:										
- Due to a discovery			●		●		●	●		
- Due to an experiment				●	●	●	●	●		●
- Due to a reflection (compromise)			●		●	●				
- Confirmation of initial design choices			●				●			●
5. Module influenced the design development			●	●	●	●	●	●		●

A - analog, D - digital, G - generative

fig. 107. The influence of the used tools on the design decisions.

The questionaire presented in the table has been adapted from a conference paper 'Bridging Analog and Digital Realms: Fostering Sustainable Design Innovation Through Integrated Teaching Techniques' [15], with changes allowing to fit better into the thesis process.

	ANALOG	DIGITAL	DIGITAL - GENERATIVE
RESOURCES NEEDED (PREPARATION STAGE)	software: none / Rhinoceros 3D, Grasshopper The need for using software depended on the type of the model and on the fabrication method. In case of preparing the site model for experiments 3 and 4, using CAD software was necessary. For simpler models that were prepared fully manually (wooden blocks), no software was needed. machines/hardware: laser cutter, circular saw, PC The laser cutter and PC were necessary for models produced with digital fabrication (site model, apartment for experiment 10). Using circular saw was a great help in preparing the blocks of solid wood. materials: cardboard, plywood, wooden blocks time & risk of failure: Needed time varied significantly depending on the type of the study. Especially preparing a site model was a very time consuming process, since a digital model had to be made first, then prepared for fabrication and finally manually assembled. However, making a simple model, like the apartment for daylight study, took a few hours rather than days. Risk of failure was relatively low, however, especially during the digital fabrication process there were some errors and material waste. Using the automated heliodon required time to attach the model and place cameras. More time should be spent on adjusting the camera's setting (exposure time) to make the results reliable.	software: Rhinoceros 3D, Grasshopper, Ladybug, Honeybee The models for analysis were either prepared in Rhinoceros or programmed fully in Grasshopper. machines/hardware: PC materials: none time & risk of failure: Depending on the complexity of the model and type of conducted study, time varied significantly. Additionally to preparing the geometry, setting up the script was a quite time consuming process, partially because decisions regarding the type of collected data needed to be made. Despite some proficiency in the software, it was relatively easy to make mistakes, and even small inaccuracies would result in the script not working. Unfortunately, there are also bugs present in the software, which sometimes slowed down the work.	software: Rhinoceros 3D, Grasshopper, Ladybug, Honeybee, Colibri The models for analysis were either modeled in Rhinoceros or programmed fully in Grasshopper. machines/hardware: PC materials: none time & risk of failure: The same type of setup as for a regular digital study was needed, with an additional part of creating the iterative algorithm, resulting in a longer preparation time. Again, careful decisions needed to be done regarding the type of collected data, and additionally, regarding the number of iterations. Also, the issue of how to ensure proper data collection was in some cases problematic, to the point of giving up on using Colibri in experiment 8.
RESOURCES NEEDED (EXECUTION STAGE)	software: none / GraOS There was no need for a use of software when using the manual heliodon. For the automated one, software provided by the producer was used. machines/hardware: manual heliodon, automated heliodon, PC PC was only needed to operate the automated heliodon. time & risk of failure: Very low risk of failure. However, with camera not adjusted correctly, results were difficult to compare due to differences in brightness. Also, using the automated heliodon might pose some risk of destroying the model.	software: Rhinoceros 3D, Grasshopper, Ladybug, Honeybee, Excel machines/hardware: PC time & risk of failure: Exporting results was a quite monotonous and time--consuming process. If the script was prepared correctly, risk of failure while running the simulations was low.	software: Rhinoceros 3D, Grasshopper, Ladybug, Honeybee, Colibri, Design Explorer machines/hardware: PC time & risk of failure: Obtaining results was very efficient if the setup had been prepared correctly. However, with too many iterations planned, there was the risk of program malfunctioning.
ACCURACY OF THE RESULTS	No numerical data was obtained. There was a possibility of taking approximate measurements, for example of areas that are overshadowed, but it was considered not very effective and finally has not been conducted. However, thanks to interacting with a physical model in a 3D environment, it was slightly easier to notice the interrelations between the designed building and its surroundings. What is more, understanding the results was very intuitive.	Both numerical and graphical data were obtained. Therefore, the results were much more accurate compared to the ones from analog tools. However, analyzing the results within Grasshopper was not very easy, and using Excel was necessary at some points.	Both numerical and graphical data were obtained. Therefore, the results were much more accurate compared to the ones from analog tools. Using Design Explorer improved the comfort of working with data significantly, allowing for analyzing hundreds of results.
IMPACT ON THE DESIGN DECISIONS	The impact on the design decisions was mostly based on intuivie assessment of the results, as not much data was provided. In case of the need to confirm particular requirements (for example the minimal level of DF), analog tools were not very helpful. However, they turned out to be quite effective when qualities other than numerical values needed to be assessed. Also, due to the constant presence of the model in the studio, it was easier to imagine new solutions.	This kind of tool seemed to be flexible enough to be used at any design stage. Since numerical data was provided, it allowed to make decisions according to objective requirements. What is more, testing new design options did not require use of any extra materials, sometimes making it easier and faster to test new solutions compared to the analog studies.	The biggest strength of this type of tool was the amount of data provided, and the possibilty of comparing them easily. It was difficult to use the generative method at the very beginning of the process, but it was extremely useful when the general concept was decided, and details had to be adjusted. Working with many results brought also some insight into the need for compromises in the design process, as sometimes maximising one parameter lead to a poor performance of the design in other aspects.

fig. 108. Summary of notes and reflections about the tools

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