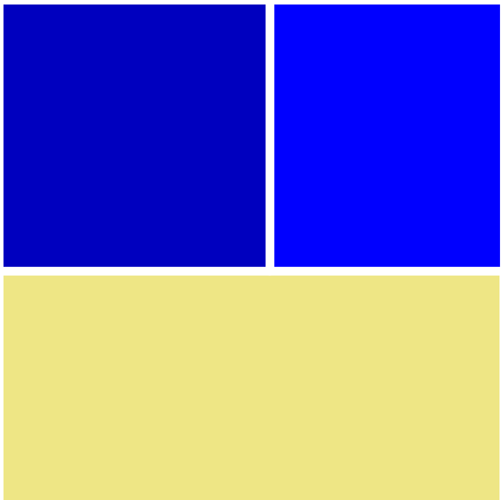

TEMPERATURE ZONING IN HIGH-PERFORMANCE RESIDENTIAL ARCHITECTURE

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TITLE PAGE

Title: Temperature Zoning in High-Performance Residential Architecture

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SANTA KRIEVA

"Thirty spokes are joined together in a wheel, but it is the centre hole that allows the wheel to function.

We mould clay into a pot, but it is the emptiness inside that makes the vessel useful.

We cut out the door and windows from the walls to form an apartment, but it is the emptiness inside that makes it livable.

We work with the substantial, but the emptiness is what we use."

DAO

ABSTRACT

A high-performance building with high insulation and mechanical ventilation can reduce its energy use significantly. However, recent research has revealed that the actual energy use of these buildings is not as accurate as the calculated amount.

The lack of thermal comfort in low-energy buildings is one of the main factors that contribute to the performance gap between the building's occupants and the energy efficiency of the building. It is crucial as people spend 90% of their time indoors. Most people would prefer to have warm bathrooms and cold bedrooms, but they are satisfied with the comfort of the living room.

This thesis strives to research and design air with a focus on user needs and integrates thermal thinking architecture into the early project stages.

READING GUIDE

The thesis report begins with an introduction to the thesis topic and the author's motivation, an introduction to the project context and related theory. The thesis defines the delimitations and narrative of the project. The second part of this thesis project is a project-based research chapter based on the method of IMRAD. After, a research-based project proposal follows. Lastly, conclusions and reflections on the research questions and work are stated. Finally, the research simulation detailed results supplement the thesis report.

The thesis layout is designed to be read and printed but can also be viewed digitally. ''PageWie – Two page – Show cover page separately'' settings should be applied when viewed digitally.

All illustrations, tables and charts are original, if not stated otherwise and referenced.

CONTENT

PROJECT AND RESEARCH INTRODUCTION

INTRUDUCTION

People spend considerable time at home, and the indoor climate they experience affects the buildings' energy consumption and their well-being and health. After many years of the one-sided focus on the energy performance of buildings, it is becoming clear that more emphasis should be placed on the quality of buildings' indoor environment (Hellwig, 2019).

High-performance residential buildings with high insulation envelopes and heat-recovered mechanical ventilation significantly reduce energy use. However, recent research implies a performance gap between the calculated energy use and the actual measured energy use in energy-efficient houses(Hellwig et al., 2020). The homogenized and fixed indoor temperature in current low-energy buildings does not satisfy occupants. Multi-family dwelling occupants prefer warmer bathrooms and colder bedrooms T < 16°C but are highly satisfied with the living room's thermal comfort (Georges et al., 2019). Recent research has shown that exposure to mildly cold or warm environments has significant health benefits, supporting dynamic and drifting temperatures for healthy indoor environments(Luo et al., 2022).

Therefore, thermal comfort-related behaviour is one of the reasons contributing to this performance gap. An individual's thermal comfort perception, preference and attention to human adaptation potential might be the right direction for a new thermal comfort thinking in architecture (Hellwig, 2019). The interrelation between people and the thermal environment significantly impacts the buildings' energy consumption and human well-being and health (Teli, 2019). Temperature zoning in high-performance residential building design will simultaneously achieve satisfaction regarding thermal comfort and lower energy performance (Berge et al., 2017).

This designed-based research study's case motivation and intention are to investigate how to design high-performance residential architecture in Denmark with two thermal zones and, even more, how can these thermal zones be flexible to facilitate unpredictable user configurations.

MOTIVATION

These thesis motivation and ambition is to develop thermal thinking and integrate it into the residential architecture design. It strives to design air and place users at the centre of the design.

HYPHOTESIS

Temperature zoning in high-performance residential building design can simultaneously achieve user satisfaction regarding thermal comfort and lower residential architecture energy performance.

RESEARCH QUESTIONS

- How to design residential architecture with two thermal zones to meet user demand for cold bedrooms?
- How to design flexible cold bedrooms to adapt to users' family configurations and accommodate new forms of co-living?

DESIGN CRITERIA

- User-centred architecture
- Two temperature zones
- Flexibility to adapt to user unpredictability
- High-performance and high-quality architecture
- Enhance social and environmental sustainability

Fig 1: Site aerial view (SDFE, 2008).

LOCATION

Bleggaardsgade 18 - 28, 7100, Vejle, Denmark, is the project location. These uninhabited properties in the heart of the city of Vejle have development potential and a need for residential architecture. The urban context surrounding the chosen location will contribute to the simulations and design proposals.

The Local Plan 1000 is active at the site location; the local plan contributes to securing a city centre that is at once dynamic, exciting, inspiring and which exudes quality.

Vejle Midtby has been developed over a long period from the Middle Ages up to the present day. Therefore, Vejle city centre has architectural and cultural-historical qualities, which often have a background in craftsmanship tradition, which we rarely find in recent construction.

In the Municipal Atlas, red tile and black slate roofs are demanded, and brick facades are recommended, as some of that helps to give Vejle its character, as the city is seen from above, partly from the hills and partly from the Vejle fjord bridge. One must be able to see and experience the houses' culture, historical and architectural qualities.

Building modern and contemporary architecture is possible and essential when it considers and interacts with the surroundings. Here we think of all the surrounding buildings, the neighbourhood, the district, the landscape, and nature (Vejle Kommune, 2020).

Fig 2: Photos of Bleggaardsgade.

SITE

BLEGGAARDSGADE

MATERIALITY AND DETAILS

Fig 3: Photos of Bleggaardsgade and close neighborhood.

PHENOMENOLOGICAL STUDIE

It is mid-May. After a bedtime routine, I walk to my room. I left the windows open this evening. The space is cold and very fresh. I walk quickly to change and hide under the crispy and heavy-down blanket. At first moments it is freezing, and it is the only thought in my mind; being in the moment disconnects me from everything that happened to me throughout the day. Slowly, my body heat makes me warm, and a moment later, under the blanket, I feel safe, calm, and protected. I fall asleep. Morning arrives. It is still cold as I leave the windows open. I quickly get up, wear my morning dress, and leave the room. I sit at the table with a cup of green tea, the sun is shining, and I think about my cold bedroom. I believe that a cold bedroom gives us pleasure and satisfaction by changing conditions from uncomfortable to comfortable. Undressing in the cold and fresh room, getting in the warm bed, and getting from the warm bed cold room to a sun-exposed morning coffee experience. Even more, I think it has something to do with childhood memories when we have been wrapped in blankets to sleep and covered with a heavy blanket. A cold bedroom provides conditions where we can recreate this experience and feel safe, calm, protected and carefree and enjoy our night's rest and recharge.

A week-long experiment was performed to understand the user's wish for a cold bedroom and its reasons A week-long experiment was performed to understand the user's wish for a cold bedroom and its reasons to enhance motivation and passion for working on the project. The text is meant to capture the ambience of cold bedroom perception. It can only serve as a momentary and somewhat subjective emotional perception.

"Atmosphere is something between the subject and the object; therefore, an aesthetic of atmosphere must also mediate between the aesthetics of reception and the aesthetics of the product or of production. Such an aesthetics no longer maintains that artistic activity is consummated in the creation of a work and that this product is then available for reception, whether from a hermeneutical or a critical standpoint. An aesthetics of atmospheres pertains to artistic activity that consists in the production of particular receptions, or to the types of reception by viewers or consumers that play a role in the production of the 'work' itself." (Böhme and Thibaud, 2016, p. 112)

MICROCLIMATE STUDIES

Microclimate environmental analysis is performed to be informed of outdoor thermal conditions. Sun exposure and seasonal wind analyses are made to translate them into outdoor thermal comfort charts that surround the architecture. The main intention is to be informed, reflect, and validate indoor thermal conditions and observe climate change throughout the year. The UTCI Universal Thermal Climate Index (ISB Commission 6, n.d.) predicts the heating season as indoor thermal conditions tend to adapt to climate conditions.

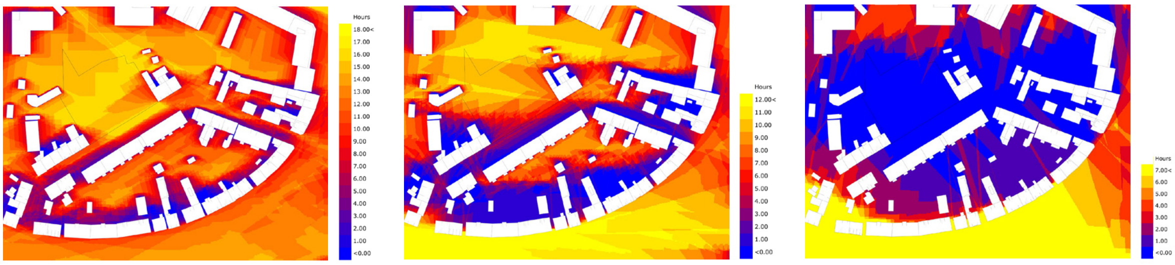


Fig 4: Sun hour analysis of the site

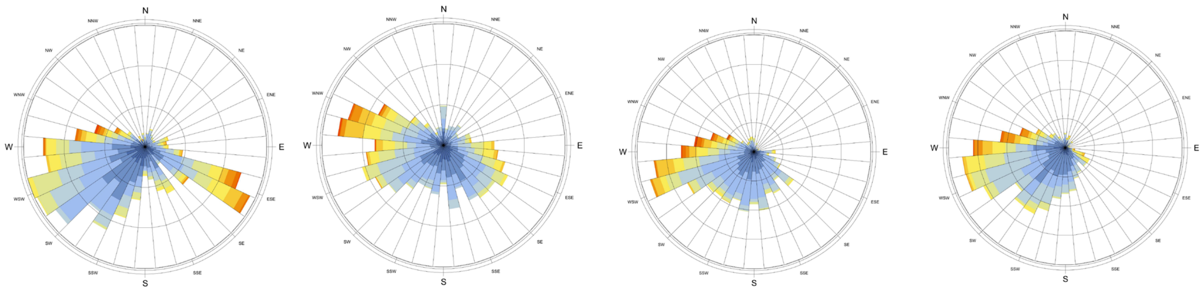


Fig 5: Seasonal wind roses - winter, spring, summer and autumn.

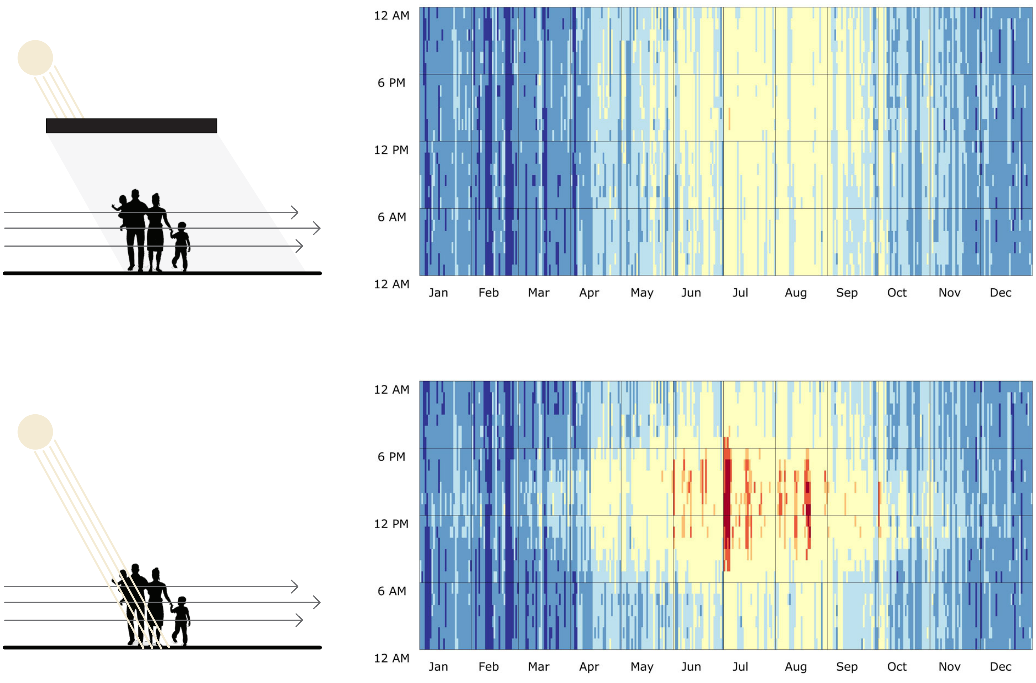


Fig 6: UTCI thermal comfort.

THERMAL COMFORT THEORY

The concept of user need satisfaction is important because, in the 21st century, most people spend about 90% of their time indoors. This means that the design of a space should be able to provide them with the necessary mental and physical well-being (Huthmacher, 2019).

Like all mammals, humans are complex thermal engines that are constantly exchanging energy with the environment. The concept of thermal comfort is a subjective evaluation that can be used to measure the satisfaction of the mind. Although the principles of thermal comfort are universal, the responsiveness of individuals to different types of environments can vary.

Various factors can affect the perception of thermal comfort by humans. These include the type of environment that they are exposed to, their physiological and psychological conditions, and their actions and responses (Zhao et al., 2021).

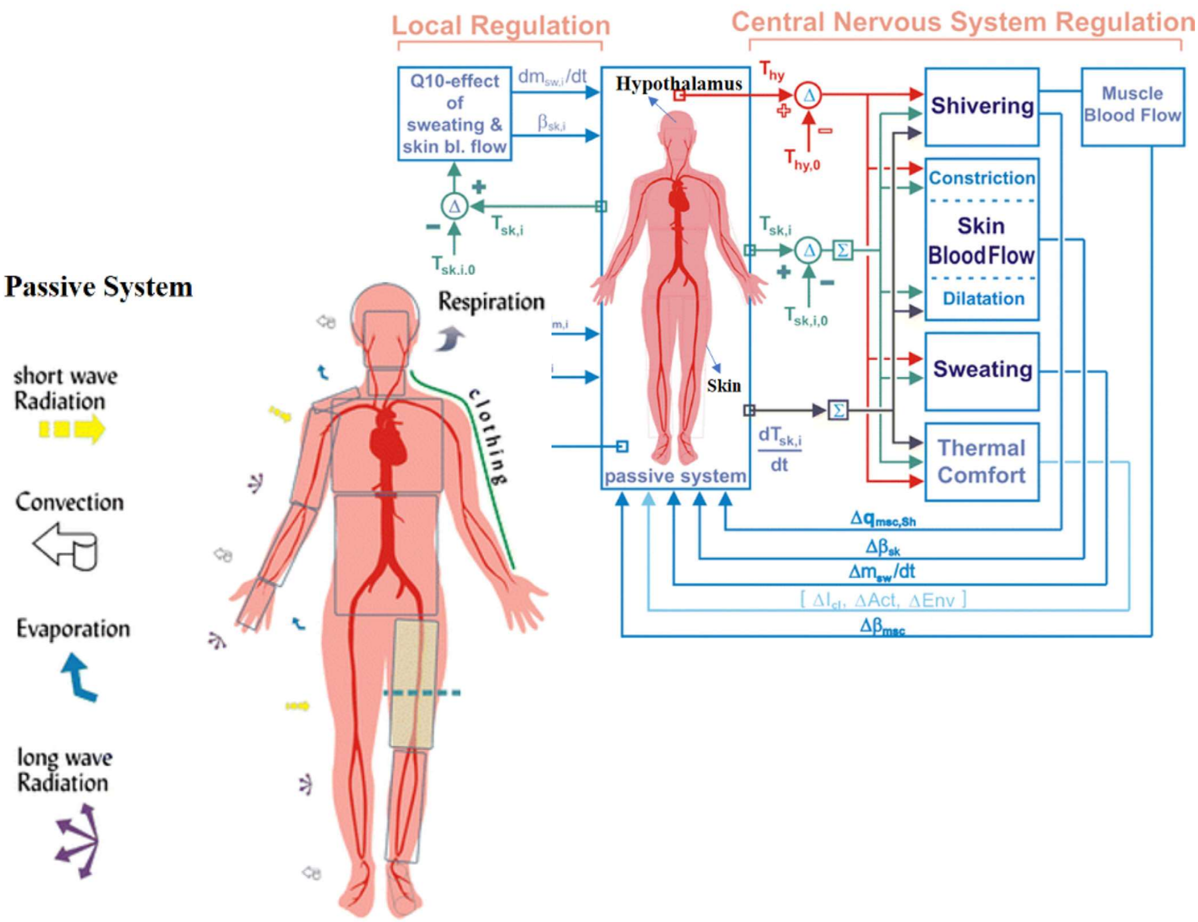


Fig 7: Passive and active system for human thermal comfort model (Zhao et al., 2021).

- The transfer of heat from one object to another is referred to as conduction. This is when the body directly contacts a warm or cold object.
- The concept of convection refers to the process of transferring heat from the body to the surrounding air. When the warm air rises from the body, it is replaced by cooler air.
- The transfer of heat from one object to another is referred to as radiation. This occurs when the two objects' temperatures are different.
- Humidity is heat by evaporation.

The concept of thermodynamics refers to the fact that energy can never be destroyed or created. Its only purpose is to be transferred to another form.

The degree to which people perceive heat is also influenced by their socio-psychological and physiological conditions (Stouhi, 2019). These include their mood and level of fatigue. Control over their thermal environment can also improve their health. Exposure to varying temperatures can also improve one's health. The positive effects of cold acclimation can be seen in various physiological and metabolic processes, such as the development of brown fat and the metabolism of skeletal muscle and energy expenditure (Luo et al., 2022). On the other hand, the effects of heat acclimation can be beneficial to various organs, such as heart rate and blood pressure(IWBI, 2015).

The concept of the mean radiant temperature refers to the relationship between the body's thermal properties and the surfaces of the room. The operative temperature is what people experience when they're inside a space. The dry-bulb temperature is the ambient air's temperature minus the moisture content. The relative humidity measures the moisture level in the air (Roudsari and Mackey, 2022).

A well-balanced combination of building systems adapted to a given area's climate conditions is referred to as thermal comfort. A well-designed building system should be considered not only as a functional facility but also as an environment conducive to its occupants' well-being. When it comes to people, the concept of functional and social living is fundamental. The concept of thermal comfort is part of a holistic approach to sustainability that's carried out through regulations and standards. Having the ability to customize the conditions of space is also essential for people. It allows users to make their own decisions regarding their own comfort (Huthmacher, 2019).

HIGH-PERFORMANCE ARCHITECTURE THEORY

Last century We gained unprecedented control over the thermal environment using energy-consuming equipment. The most common definitions and practices of high-performance architecture are passive house standard, zero energy build and Danish regulation definition of low energy housing. All of them have a common aim, and they do not contradict.

PASSIVE HOUSE

The concept of passive house is a building standard that is both energy-efficient and affordable at the same time. It can be applied to any type of construction. Although it's not a brand name, it's a proven construction method that can be used by anyone.

Compared to traditional buildings, passive houses can provide up to 90% energy savings when it comes to space heating and cooling.

The advantages of passive houses are their ability to use various types of heat sources, such as the sun and internal heat recovery, which can render traditional heating systems unnecessary during the cold winter season. They can also be equipped with passive cooling techniques, such as strategic shading.

The high level of comfort that passive houses provide is due to how their internal temperatures don't vary much from those of the air inside. Also, their building envelope and roof are made of highly insulated materials, which can keep the heat out.

One of the most important advantages of passive houses is their ability to provide continuous fresh air, which can prevent unpleasant air drafts. A high-efficient heat recovery unit can also be used to re-use the heat from the exhaust (Passive House Institute and Dr.Feist, 2015).

ZERO ENERGY BUILDING

A Zero Energy Building is designed to provide a low energy demand and is able to use fossil free energy sources. This type of building is also based on the combination of its energy savings and the supply of renewable energy from various sources.

Aside from reducing the energy consumption of a house, a Zero Energy Building also aims to produce renewable energy that can cover the house's energy usage. This is done through the building's design and construction. A building should offer the right environment for its users, such as having good daylight conditions, good ventilation, and comfortable indoor temperatures.

It is essential that the design of ZEBs is holistic, as it involves the entire building envelope and its energy efficiency. This means that the building should be designed with a low energy demand and be comfortable and energy-efficient. This can be reached through the use of various building materials and techniques, such as the use of low-energy windows and the building envelope's insulation.

The house is designed with high architectural quality, and it is also equipped with various features that can help reduce its energy consumption. These include the use of passive solar heat, natural ventilation, and good daylight conditions.

The energy consumption of a building can be covered by its various systems, such as the use of sup ply systems. These systems are designed to meet the specific requirements of the building (Anne Kirkegaard Bejder et al., 2014).

LOW-ENERGY BUILDING

To promote the development of extra energy-efficient construction, BR includes a definition of low-energy buildings 'building class 2020'. Use of the building class is initially voluntary, but from 2020 it is expected to form the basis for stricter energy regulations in the building regulations.

The area-dependent clause has been omitted in the requirement for the energy framework in building class 2020 as a result of the high level of insulation and the low heat loss from installations where the energy demand does not depend significantly on the size of the building.

In order to achieve a low energy demand of this order of magnitude, it is necessary to combine different strategies, e.g.:

- Reduction of thermal bridges
- Extra insulation thickness in walls and use of highly insulating glazing and components
- Optimum utilization of sunlight and daylight, including orientation of the building in relation to sun and shade conditions
- Energy-efficient ventilation
- Smoothing out temperature changes over the day by using materials indoors with a high heat capacity
- Use of renewable energy.

Low-energy buildings have the right to exemption from connection to district heating or natural gas supply and the right to use electric heating (Aggerholm and Gray, 2018).

DELIMITATIONS

These projects are location-based, and therefore all research results are location-based. The same research performed in a different context could provide different results. Still, I believe that it should generally inform of good thermal thinking practices in residential architecture.

This project's primary focus and narrative is user and user demand for certain thermal comfort. Project scope and order of priority is the indoor thermal environment, volume, and zones to complement it.

Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987, p. 15).

The project scope of sustainability is social sustainability and, precisely, indoor thermal comfort that, as suggested, directly influences environmental sustainability. This project does not aim to investigate economic sustainability, even though it is part of the holistic approach (DGNB, 2018).

Tectonics is the art of construction. The project scope of tectonics is in the choice of construction materials to enhance the environmental sustainability and technology of these construction materials. Due to typology and its fire and sound demands (Ministry of Transport, 2018) by regulations project does not aim to investigate poetic aspects of construction. But architecture seeks to add a modern brick tectonic approach to the location context (Al-Alwan and Mahmood, 2020; Vejle Kommune, 2020).

PROJECT BASED RESEARCH

INTRODUCTION

People spend considerable time at home, and the indoor climate they experience affects the buildings' energy consumption and their well-being and health. After many years of the one-sided focus on the energy performance of buildings, it is becoming clear that more emphasis should be placed on the quality of buildings' indoor environment (Hellwig, 2019).

High-performance residential buildings with high insulation envelopes and heat-recovered mechanical ventilation significantly reduce energy use. However, recent research implies a performance gap between the calculated energy use and the actual measured energy use in energy-efficient houses(Hellwig et al., 2020). The homogenized and fixed indoor temperature in current low-energy buildings does not satisfy occupants. Multi-family dwelling occupants prefer warmer bathrooms and colder bedrooms T < 16°C but are highly satisfied with the living room's thermal comfort (Georges et al., 2019). Recent research has shown that exposure to mildly cold or warm environments has significant health benefits, supporting dynamic and drifting temperatures for healthy indoor environments(Luo et al., 2022).

Therefore, thermal comfort-related behaviour is one of the reasons contributing to this performance gap. An individual's thermal comfort perception, preference and attention to human adaptation potential might be the right direction for a new thermal comfort thinking in architecture (Hellwig, 2019). The interrelation between people and the thermal environment significantly impacts the buildings' energy consumption and human well-being and health(Teli, 2019). Temperature zoning in high-performance residential building design will simultaneously achieve satisfaction regarding thermal comfort and lower energy performance (Berge et al., 2017).

This designed-based research study's case motivation and intention are to investigate how to design high-performance residential architecture in Denmark with two thermal zones and, even more, how can these thermal zones be flexible to facilitate unpredictable user configurations.

Research-based master thesis hypothesis:

Temperature zoning in high-performance residential building design can simultaneously achieve user satisfaction regarding thermal comfort and lower residential architecture energy performance.

Research questions:

1. How to design residential architecture with two thermal zones to meet user demand for cold bedrooms?

2. How to design flexible cold bedrooms to adapt to users' family configurations and accommodate new forms of co-living?

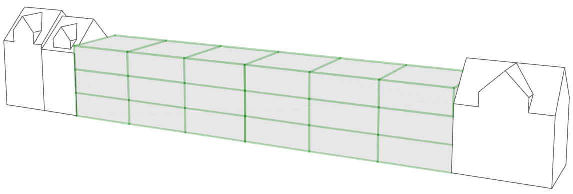
STUDY SITE

The project location is Bleggaardsgade 18 - 28, 7100, Vejle, Denmark. Vejle is a Danish city with a historical and cultural architectural identity. These uninhabited properties in the city's heart of Vejle have development opportunities and a need for residential architecture. The surrounding urban context will contribute to simulations and, therefore, to design-based research and research-based design proposal. Moreover, Vejle's old town local plan protects the study site; historical architectural values and identity will challenge the modern and integrated design approach and vice versa (Vejle Kommune, 2020).

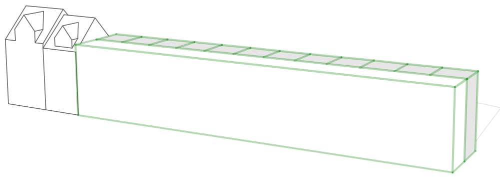
Fig 8: Study site aerial view (SDFE, 2008).

METHODS
TEST GEOMETRY

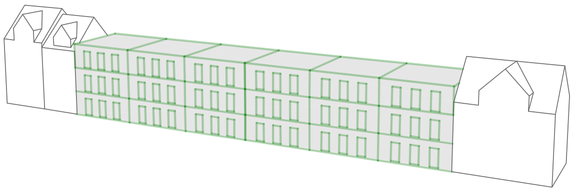
The study site and its active local plan are the starting point for finding project volumes that serve as test geometry set-up for this research. First, it intends to obtain maximum building volume; therefore, the building is established between the street facade alignment border and allowed maximum width. Then building volume of a maximum of two and a half floors is designed, and the roof floor is transferred into a mansard roof as it fulfils requirements and allows equal apartment configurations throughout the building. The volume fractionates into eighteen equivalent-size apartments, each with two bedrooms. All bedrooms are orientated to the North to have identical solar gains and context shading conditions throughout the year to analyse results and intended strategies better. According to the daylight requirements of windows, the minimum amount is integrated into the volume to meet high-performance residential architecture standards. Finally, the test geometry of nine apartments is used to continue research to reduce simulation time and have the most compact scenario possible – a middle apartment to analyse.



Maximum volume with equal-size units



Equal size bedrooms, all orientated to the North



15% window floor sqm ratio

Optimal test geometry with compactness conditions

Fig 9: Test geometry design process.

HIGH PERFORMANCE PARAMETERS

High-performance architecture in Denmark is a low-energy building defined by Danish regulations and standards(Aggerholm and Gray, 2018). This design-based research implements these standards, integrates them into the test geometry set-up, and uses it as the base point for this project to build on.

Low-energy housing defines by its energy performance and indoor thermal comfort to enhance environmental and social sustainability. To achieve this high performance in residential architecture government provides guidelines of recommended practise that consist of insulation level of components of the building, airtightness, reduction of thermal bridges, window parameters and energy-efficient ventilation strategy (Aggerholm and Gray, 2018). It is supplied with input data for calculations of the energy frame of the architecture and, therefore, integrated into the design process. The case strictly depends on mechanical ventilation as it is one of the chosen variables to investigate. Natural ventilation would not allow precise reflection on mechanical ventilation performance and impact in case intention, therefore, venting and night ventilation are not assigned to the base model.

		Input	Source
1	**HIGHLY INSULATED COMPONENTS**	ROOMS HEATED T > 15 °C	SBI 213
	Ground floor	U 0.1	SBI 213
	External wall	U 0.15	SBI 213
	Partitions with 5 °C lower	U 0.4	SBI 213
	Roof	0.1	SBI 213
2	**AIRTIGHTNESS**	0.5 l/s per m² Tested with 50 Pa	SBI 213
3	**REDUCTION OF THERMAL BRIDGES**	Do not contain thermal bridges to a significant extent due to the risk of condensation.	SBI 213
4	**WINDOWS**		SBI 213
	Daylight requirement	Floor window ratio > 15%	SBI 213
	Energy requirement	Floor window ratio < 22 %	SBI 213
	Light transmittance	> 0.75	SBI 213
	U-value	U 1.40	SBI 213
5	**VENTILATION**		DS 447
	Energy-efficient ventilation	MC HR	BR 18
	HR	> 80 %	BR 18
	Outside air supply	0.3 l/s m² 0.5 ACH	BR 18

Tbl 1: Danish low-energy housing recommendations.

		Source
Energy labeling (for heating, ventilation, cooling and domestic hot water per m² heated floor area)		SBI 213
Housing	30 +1000/A kWh/m2 year	SBI 213
Low-energy housing	20 kWh/m2 year	SBI 213
	Supplied with heat pump	SBI 213
Thermal comfort		DS/EN ISO 7730
Room temperature	T 27 C > MAX 100 H	SBI 213
	T 28 C > MAX 25 H	SBI 213
Indoor Air Quality		DS/EN 15251

Tbl 2: Danish low-energy housing energy and thermal comfort demands.

		Source
Optimum utilization of sunlight and daylight		SBI 213
Use of renewable energy.		SBI 213
Set point for space heating	20 °C	SBI 213
Setpoint for venting	T in > 23 °C	SBI 213
Set point for night ventilation	T in > 24 °C	SBI 213
Heat capacity		SBI 213
Extra easy Light walls, floors and ceilings, e.g. skeleton with plates or boards, completely without heavy parts	40 Wh/K m 2	SBI 213
Medium easy Some heavier parts, e.g. concrete deck with wooden floor or aerated concrete walls	80 Wh/K m 2	SBI 213
Medium heavy Several heavy parts, e.g. concrete deck with clinker and brick or clinker concrete walls	120 Wh/K m 2	SBI 213
Extra heavy Heavy walls, floors and ceilings in concrete, brick and clinker	160 Wh/K m 2	SBI 213
Heat contribution from people	1.5 W per m² heated floor area	SBI 213
Heat contribution from equipment	3.5 W per m² heated floor area	SBI 213
llumination level [lux]	200 lux	DS/EN 12464-1
Domestic hot water	250 liters per m² heated floor area	SBI 213
Domestic hot water	55 °C	SBI 213
Heat pump COP	> 3.6	BR18
Energy neutrality	1725 kWh/year per apartment	SBI 213

Tbl 3: Danish low-energy housing input parameter recommendations.

ZONE OCCUPANCY SCHEDULE

A zone occupancy schedule is established by assuming that two thermal zones and, therefore, rooms in between them are separated and closed. Bedrooms are planned to be occupied only for night sleep and do not serve any other function. One bedroom in text and diagrams identified as BR 1 is designed with one occupant, and a second bedroom, further in text and diagrams identified as BR 2, is planned with two occupants. The intention behind occupancy choice is to facilitate a diversity of family configurations and accommodate new forms of co-living. Livingroom occupant schedule is designed to serve three people families when one is expected to work from home, another to work part-time, and the last to work full-time.

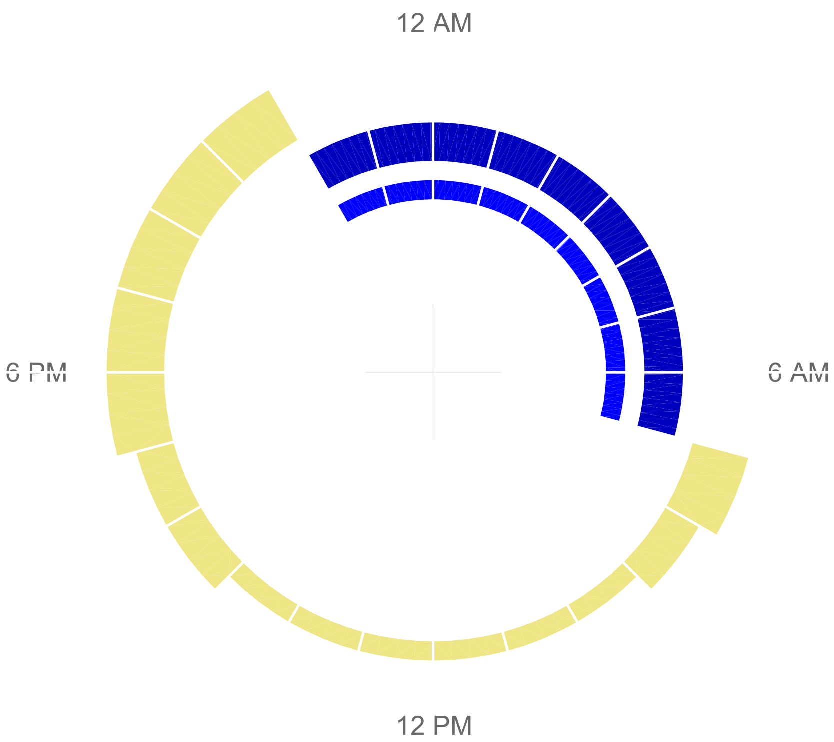


Fig 10: Zone occupancy schedule.

CHOSEN STRATEGIES

The state-of-the-art implies that user unsatisfaction with the indoor thermal environment leads to user behaviour that doesn't align with the intended building program and leads to an energy gap between the calculated and measured energy performance of residential architecture. Reported energy use in low-energy buildings from Denmark shows about 25 to 40% more energy use in practice than calculated (Hellwig et al., 2020). Recent research in Norway has demonstrated that many occupants would like colder bedrooms (i.e. < 16°C) in combination with a higher temperature in the living areas (Georges et al., 2019). Even more recent research has shown that exposure to mildly cold or warm environments has significant health benefits (Luo et al., 2022). Therefore, this research attempt to design a residential architecture case with two thermal zones. The state-of-the-art suggests that envelope and partition construction thermal resistance and conductivity combined with a centralized overflow ventilation system with heat recovery creates a homogeneous indoor environment (Berge et al., 2017). Therefore, the intention is to research these parameters through an iterative design approach.

Chosen design-based research strategies are:

1. Envelope construction thermal resistance and conductivity.
2. Bedroom partition construction thermal resistance and conductivity.
3. Ventilation with heat recovery.
    - Centralized mechanical ventilation with heat recovery and balanced airflow per system.
    - Decentralized mechanical ventilation with heat recovery and balanced airflow per room.

Chosen strategies integrated as variables in automated iterative modelling will serve as input for these case studies.

CHOSEN OUTPUTS

After establishing test geometry, discovering input parameters of high-performance residential architecture in Denmark, and choosing strategies to investigate how to satisfy user preferences, output parameters need to be established to analyse results. First, housing energy performance frame and indoor thermal comfort as output parameter improve self-validation and data control of the results. Fulfilment of these criteria validates all research output parameter data from simulation loops. The energy frame for the building is lower or equal to 20 kWh/m2 per year per heated floor area, and room temperature does not exceed 27 °C for more than 100h per year and 28 °C for more than 25h per year (Aggerholm and Gray, 2018). After, data is processed in a two-step evaluation. First, by percentage when bedroom temperature meets user demand T < 17 °C for room occupancy period 10 pm to 7 am. This method allows operative best iterations and variable selection to be evaluated by the second step. Second and last room seasonal median air temperatures are calculated for each room to visualize results to conclude and reflect on them. Even more hourly operative temperature plots are made to visualize and communicate zone air thermal performance. They are supplemented with energy balance diagrams to have an overview and support for decision making.

		Source
Energy labeling (for heating, ventilation, cooling and domestic hot water per m^2 heated floor area)		SBI 213
Housing	30 +1000/A kWh/m2 year	SBI 213
Low-energy housing	20 kWh/m2 year	SBI 213
	Supplied with heat pump	SBI 213
Thermal comfort		DS/EN ISO 7730
Room temperature	T 27 C > MAX 100 H	SBI 213
	T 28 C > MAX 25 H	SBI 213
Indoor Air Quality		DS/EN 15251

Tbl 4: Danish low-energy housing energy and thermal comfort demands.

PROCESS

After theoretical, decision making and design process research, empirical data is investigated. Test geometry and surrounding location context are created in Rhino. Next, these geometry and zone properties are translated and assigned to Grasshopper. Fixed and variable high-performance building parameters are set with the environmental modelling Ladybug Tools plug-in Honneybe. Honeybee supports detailed thermodynamics. Specifically, it creates, runs, and visualizes the results of energy models using EnergyPlus/OpenStudio. It accomplishes this by linking the Grasshopper/Rhino CAD environment to these engines. After self-validation of the model, it is assigned to the automated iterative modelling tool TTToolbox Colibri. Colibri helps iterate through all possible combinations of a series of inputs and compiles the resulting data into a CSV of input and output values per iteration. Furthermore, all results are visualized and communicated through Design Explorer. After the result analyses, one can adjust inputs or assign different strategies to perform the next loop of iterations (Roudsari and Mackey, 2022).

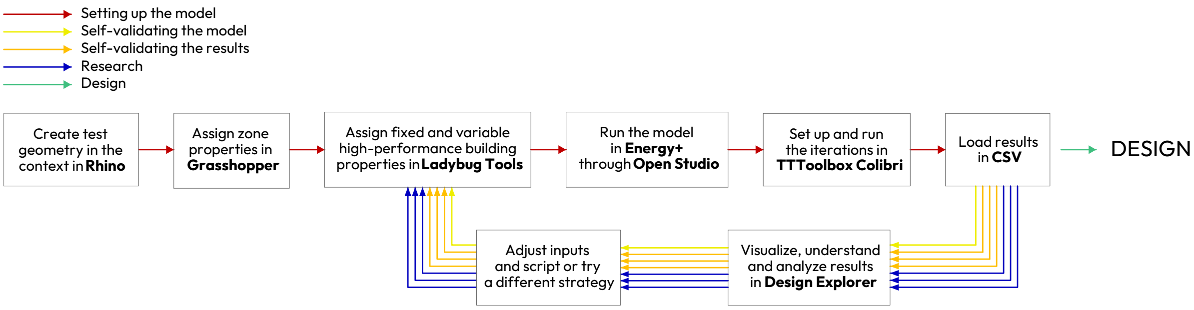


Fig 11: Research process diagram.

One can assign all variable parameters to the Colibri model to perform parametric modelling at once but ventilation strategy. Therefore, after self-validation of the model and self-validation of the results, final research loops are run to compare centralized MVHR with balanced airflow and decentralized MVHR with balanced airflow. Heating set points, occupancy schedule and shading system are fixed parameter but envelope and partition thermal resistance, fresh air amount inlet into the rooms and ventilation system heat recovery performance as variable parameters. Ventilation systems with balance airflow are chosen as one would assume that when trying to establish two temperature zones, one would avoid air mixing between rooms. This system provides air inlet and extraction for each room. A centralized MVHR system means that there is one ventilation unit per apartment, and the air of all rooms is mixed in a heat recovery system and, therefore, potentially heating and cooling rooms. While a decentralized MVHR system means a separate ventilation unit for each room, air does not mix.

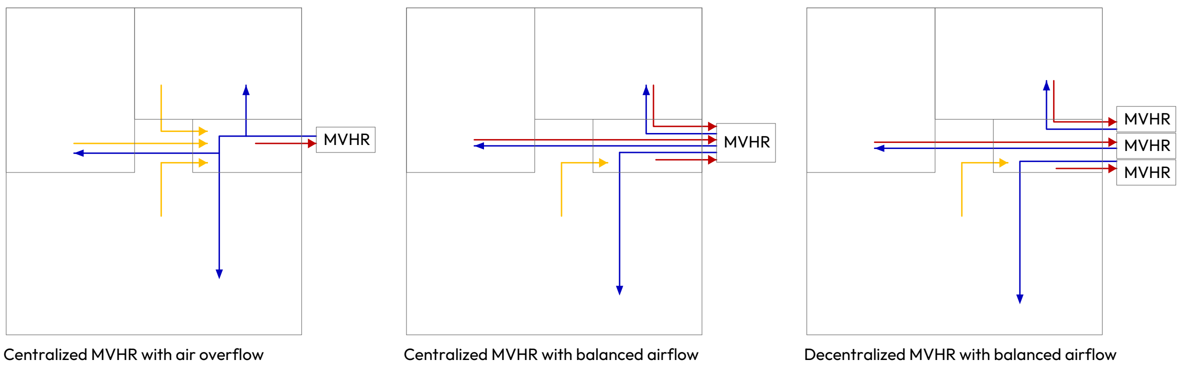


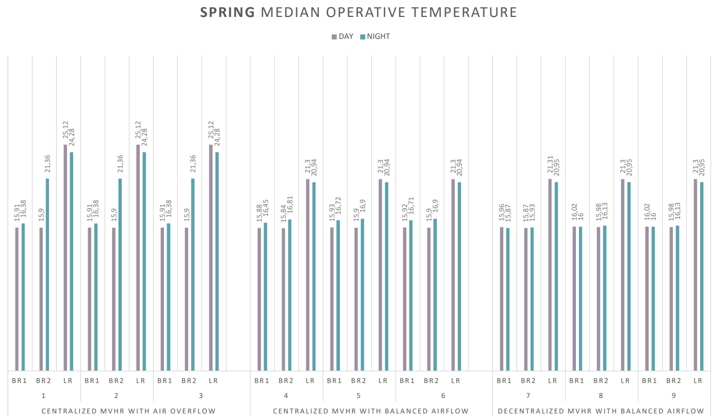
Fig 12: MVHR air supply and extraction principles.

RESULTS

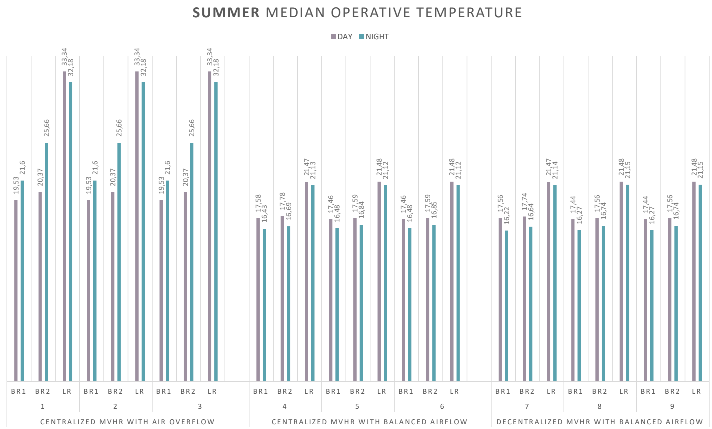
First, results are categorized after the percentage of user satisfaction, which means, as explained previously, how much percentage of occupancy time zone temperature is T < 17 °C. One can see that with centralized MVHR with balanced airflow and currently practised ACH in housing, regardless of the envelope and partition thermal resistance; the user satisfaction percentage is as low as 49% per one-occupant bedroom and only 4% per two-occupant bedroom. Even more hourly temperature plots present that in these scenarios, there is overheating in all rooms, and chosen strategy cannot provide regulation required thermal indoor comfort. As for the following scenarios, ACH has been improved to fulfil thermal comfort regulations; it shows a higher percentage of user satisfaction. Centralized MVHR with balanced airflow and increased fresh air inlet presents results very different between rooms, with up to 89 % of user satisfaction in the bedroom of one occupant and 60% in the two-occupant bedroom. Finally decentralized MVHR scenario presents that user satisfaction with thermal comfort for occupancy time when bedroom T < 17 °C increases up to 95% for one-occupant bedrooms and up to 89% for two-occupant bedrooms. While these scenario thermal comfort requirements are fulfilled by the apartment, it presents an increase in energy frame as seen at energy intensity balance; temperature conditions improve because heat recovery for bedrooms has decreased.
When looking at results translated in median operative temperatures per room and even more categorized per season and time of the day, one can observe that temperatures follow outdoor climate by increasing during summer and decreasing over winter.

NR IN GRAPH	INPUTS											OUTPUTS		
	MVHR	HEATING SET.PT. BR	HEATING SET.PT. LR	BR EXT U	INT U	ACH BR1	ACH BR2	ACH LR	HR BR1	HR BR2	HR LR	OT BR1 % < 17	OT BR2 % < 17	ENERGY FRAME kWh/sqm year
1	**Centralized MVHR . Balanced airflow**	16	21	0,15	0,9	0,5			95			49	4	7
2				0,15	0,4	0,5			95			49	4	7
3				0,15	0,15	0,5			95			49	4	7
4	**Centralized MVHR . Balanced airflow**	16	21	0,4	0,15	4,5			95			89	60	8
5				0,15	0,15	4,5			95			80	56	8
6				0,15	0,4	4,5			95			80	56	8
7	**Decentralized MVHR . Balanced airflow**	16	21	0,4	0,15	5		4,5	50		95	95	89	18
8				0,15	0,15	5		4,5	50		95	95	89	17
9				0,15	0,4	5		4,5	50		95	95	89	17

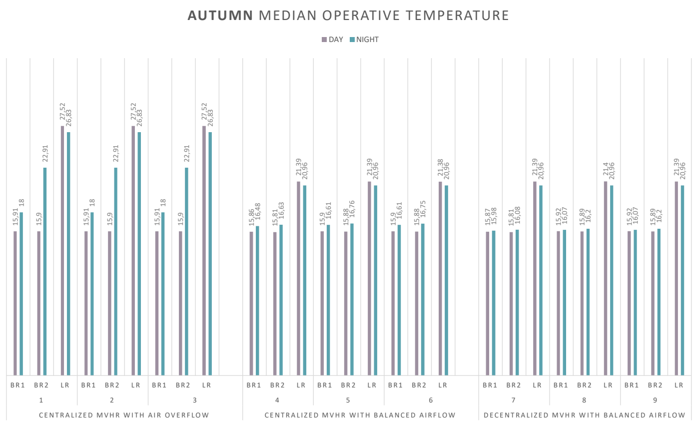
Tbl 5: Research result most optimal variable combinations.



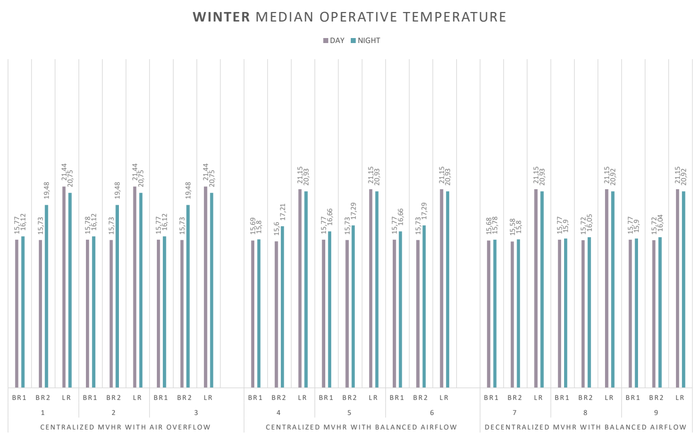
Cht 1: Spring operative temperature chart.



Cht 2: Summer operative temperature chart.



Cht 3: Autumn operative temperature chart.



Cht 4: Winter operative temperature chart.

2. CENTRALIZED MVHR

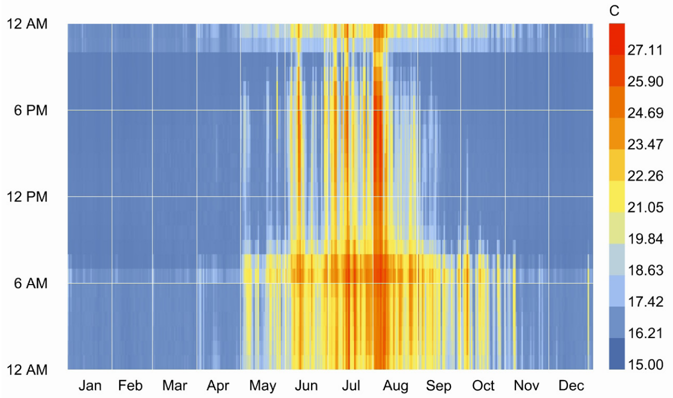


Fig 13: One-occupant bedroom operative temperature plot of annually hourly data.

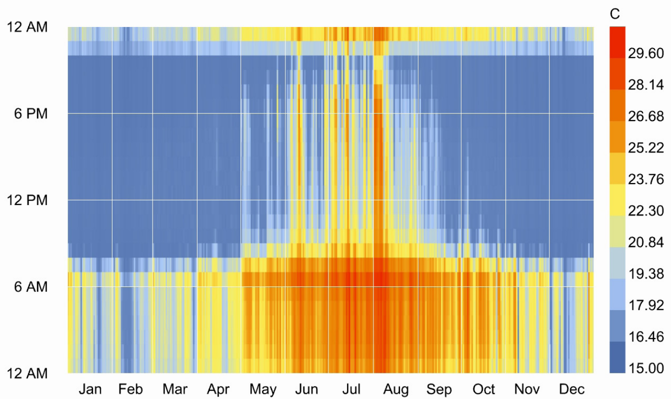


Fig 14: Two-occupant bedroom operative temperature plot of annually hourly data.

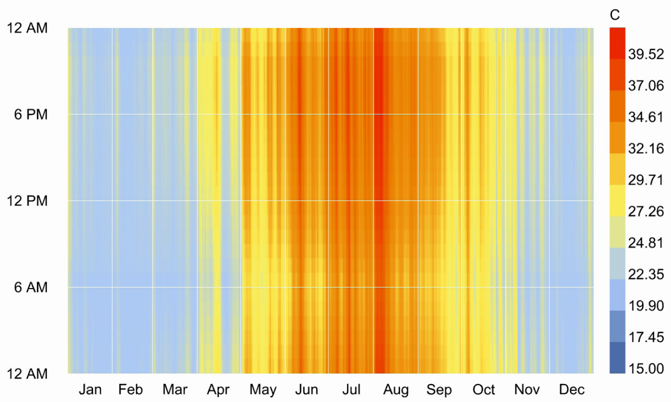


Fig 15: Living room operative temperature plot of annually hourly data.

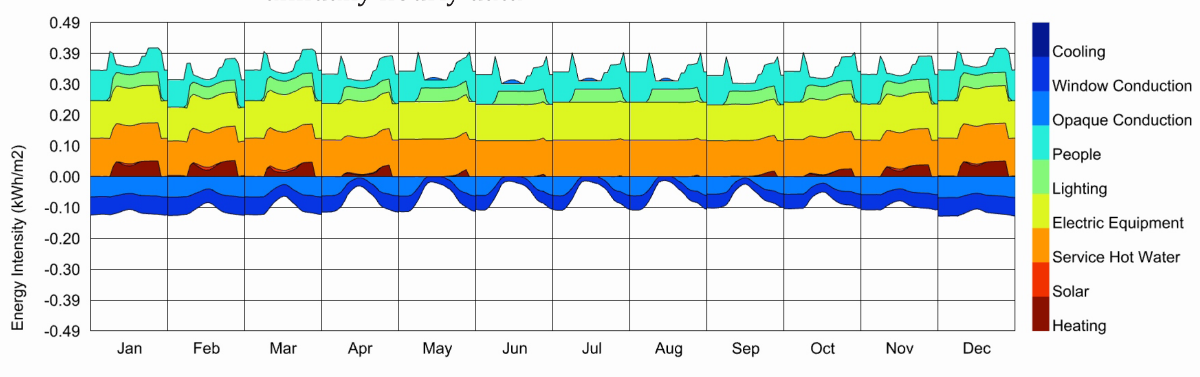


Fig 16: Thermal load balance.

6. CENTRALIZED MVHR

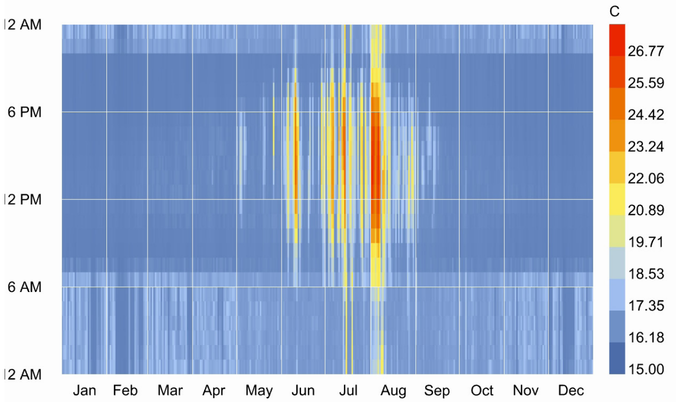


Fig 17: One-occupant bedroom operative temperature plot of annually hourly data.

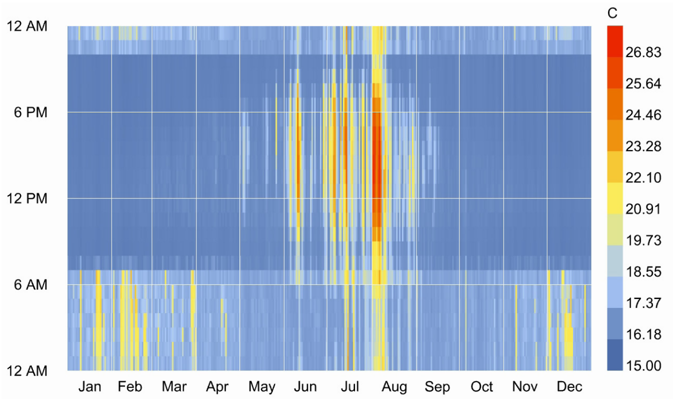


Fig 18: Two-occupant bedroom operative temperature plot of annually hourly data.

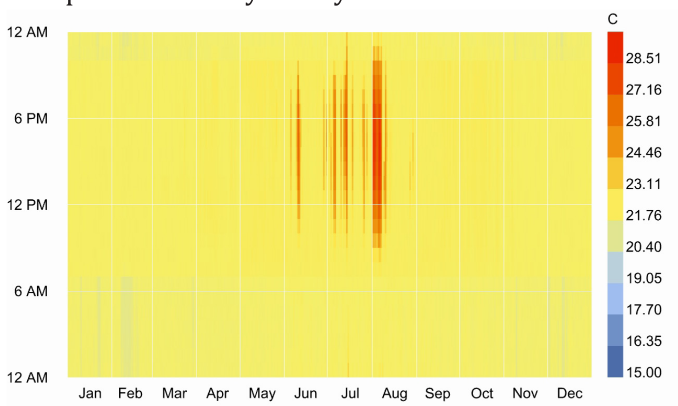


Fig 19: Living room operative temperature plot of annually hourly data.

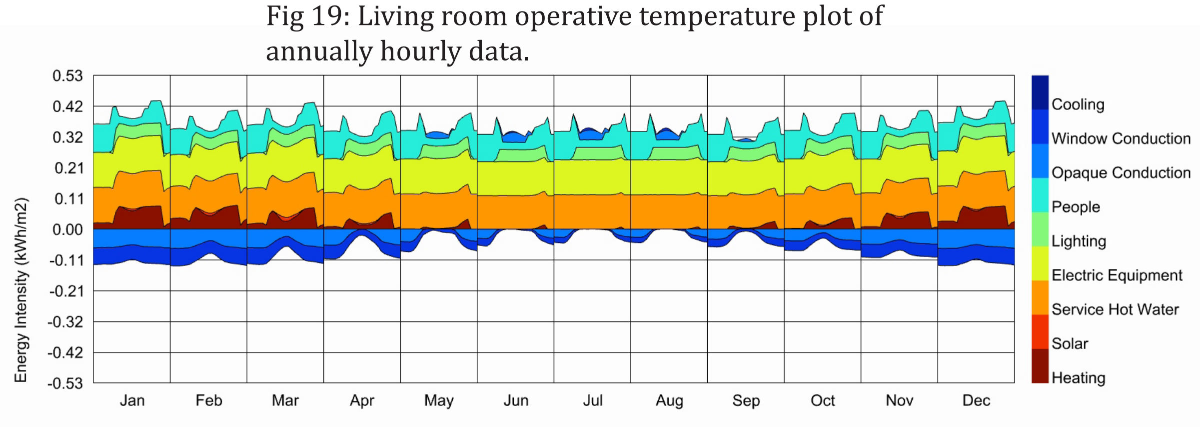


Fig 20: Thermal load balance.

9. DECENTRALIZED MVHR

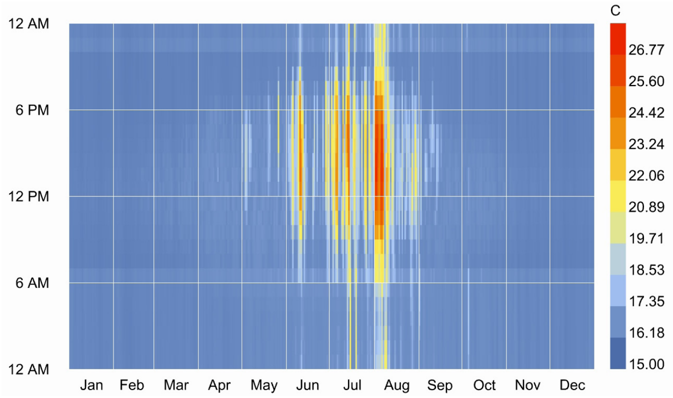


Fig 21: One-occupant bedroom operative temperature plot of annually hourly data.

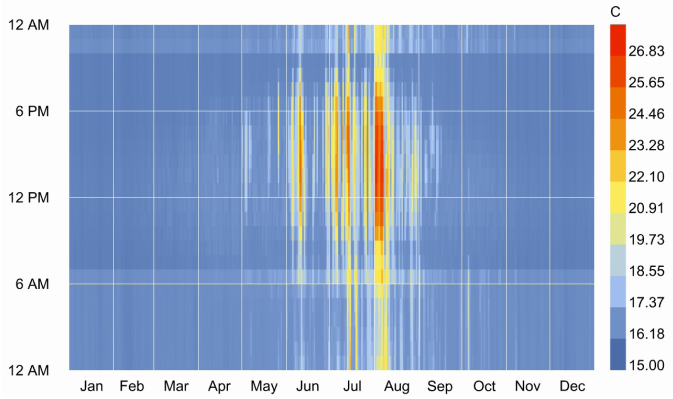


Fig 22: Two-occupant bedroom operative temperature plot of annually hourly data.

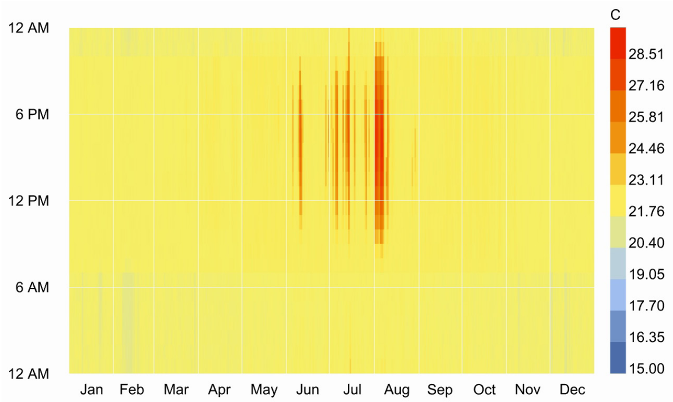


Fig 23: Living room operative temperature plot of annually hourly data.

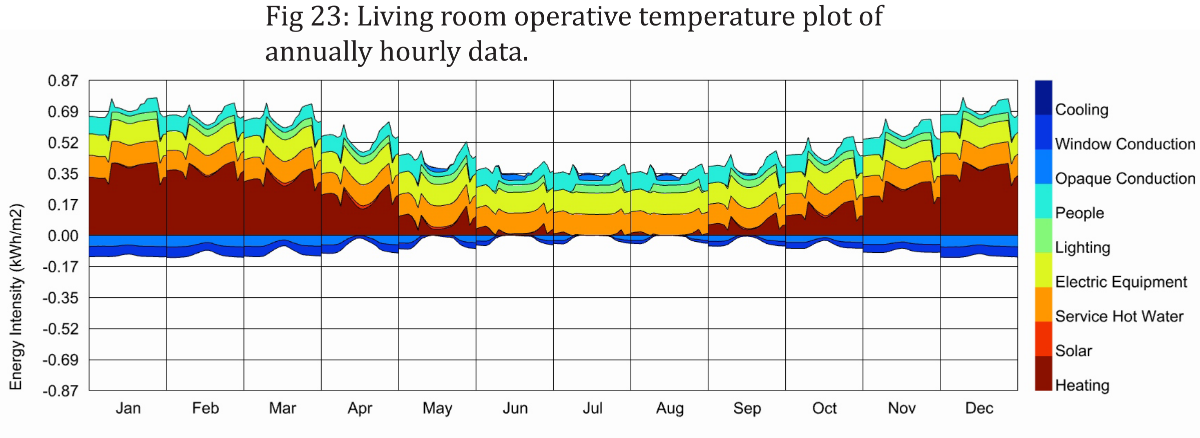


Fig 24: Thermal load balance.

DISCUSSION

This research asks how to design residential architecture with two thermal zones to meet user demand for cold bedrooms. For these purposes, parameters are forced to see what it would take to accomplish user demand only with construction thermal resistance and ventilation system. Therefore, one could question and should discuss this digital empirical try.

First, when not supported with any cooling strategies, the current situation with MVHR and low fresh air inlet does not fulfil thermal comfort regulations. Moreover, it does not provide user wished climate in bedrooms or rooms. Therefore, this solution requires the implementation of passive or active cooling.

Second, one of the research goals is to facilitate flexibility and accommodate a variety of user configurations and unpredictable user special needs. One should not vary the parameter of envelope thermal resistance as it has a crucial role in the energy frame if one chooses to use the bedroom for other functions and, therefore, prefers different thermal conditions in the zone.

Then, the increase of mechanically supplied fresh air inlets up to ACH 5 should be researched further to investigate the user perception of air movement and comfort. Even more, one could question the system unit size; more processed air in the system increases the unit size, decreasing the habitable housing area. Additionally, one could question ventilation unit building physics and limitations. It should be explored to ensure that temperature differences when mixing in the units do not cause condensation and, therefore, damage the system.

Finally, the solution's spacial requirements should be investigated further when considering decentralised ventilation. The most critical discussion here is whether the energy performance is acceptable, as the main goal is to enhance environmental and social sustainability. Even more, one should not overlook that without a heat pump as a heating source, this solution would not fulfil the energy frame requirements of low-energy housing in Denmark.

RESEARCH BASED DESIGN CRITERIA

After result compilation and discussion, research-based design criteria have been established.

- Heat pump as source for heating and hot domestic water.
- Floor heating with heating set points per room.
- Increase of thermal resistance of partitions.
- Shading system to lock out summer sun and gain winter solar heat.
- Additional shading system with set points
- Closed volumes without air mixing between zones.
- Cold bedrooms occupied only for sleeping and no other function
- Centralized MVHR with 1ACH
- Venting with set points
- Night cooling with set points

These criteria reflect back to SBI 213 recommended good practise and guidelines for low-energy housing supplemented with sensor operated set points (Aggerholm and Gray, 2018).

RESEARCH BASED PROJECT PRESENTATION

The residential architecture proposal presents the result of design-based research and interdisciplinary, integrated design. These high-performance housing design places user and user demands in the centre of focus and primarily designs air between constructions and openings. Architecture strives to enhance social and environmental sustainability simultaneously. This project presents me strive to implement thermal thinking in residential architecture. The project, located in Vejle city canter at Bleggaardsgade, offers a modernized high-quality brick architecture approach to complement surroundings with a classical architectural identity.

Architecture offers internal simplicity. It strives to facilitate various family configurations and to accommodate new forms of co-living. Two zones, when closed, offer thermal satisfaction for night sleep and, at the same time, provide flexibility in their use. Two potentially thermally different zones are complimented with a non-defined spacious living room filled with daylight.

Fig 25: Project proposal entrance visualisation.

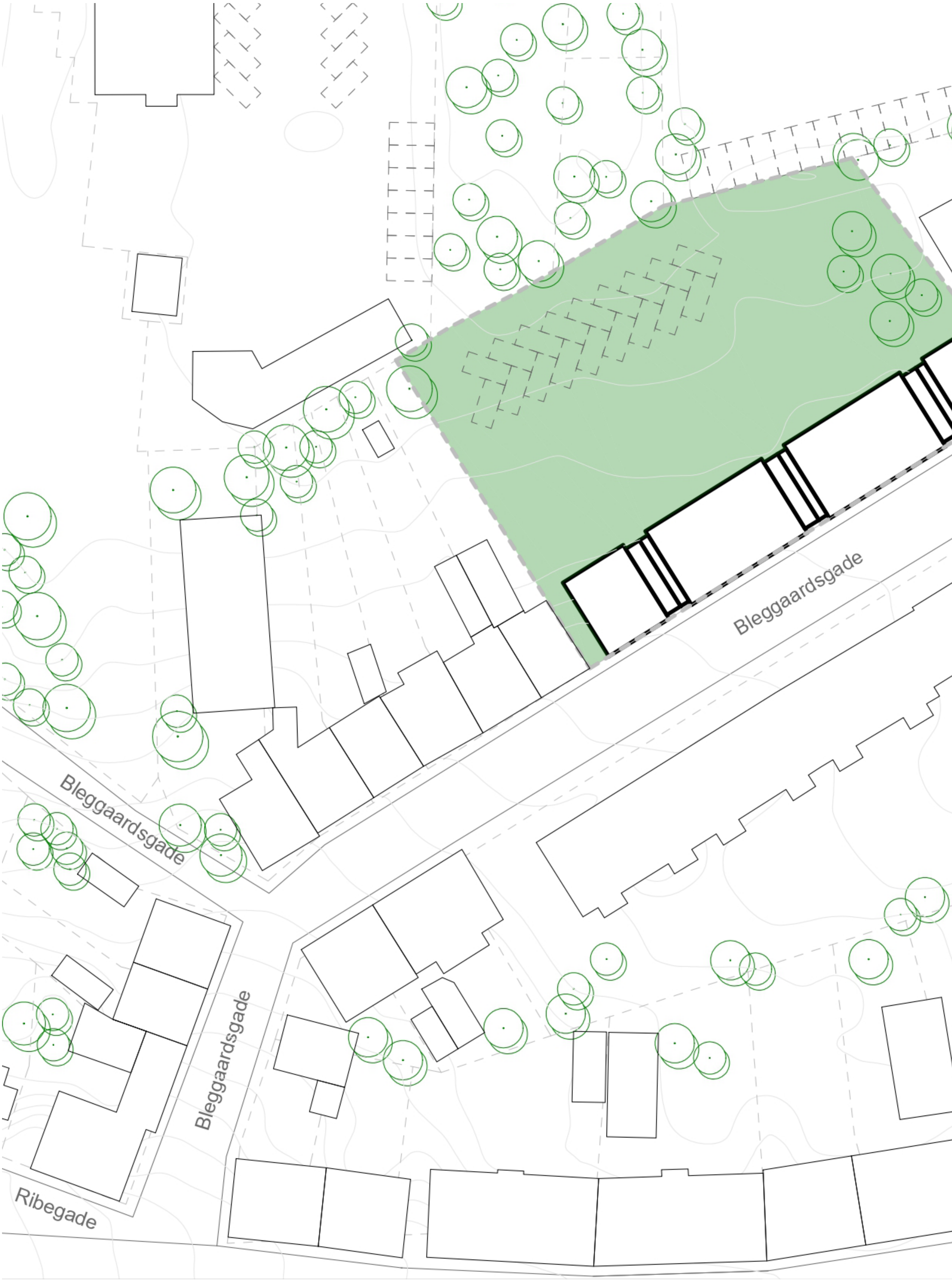
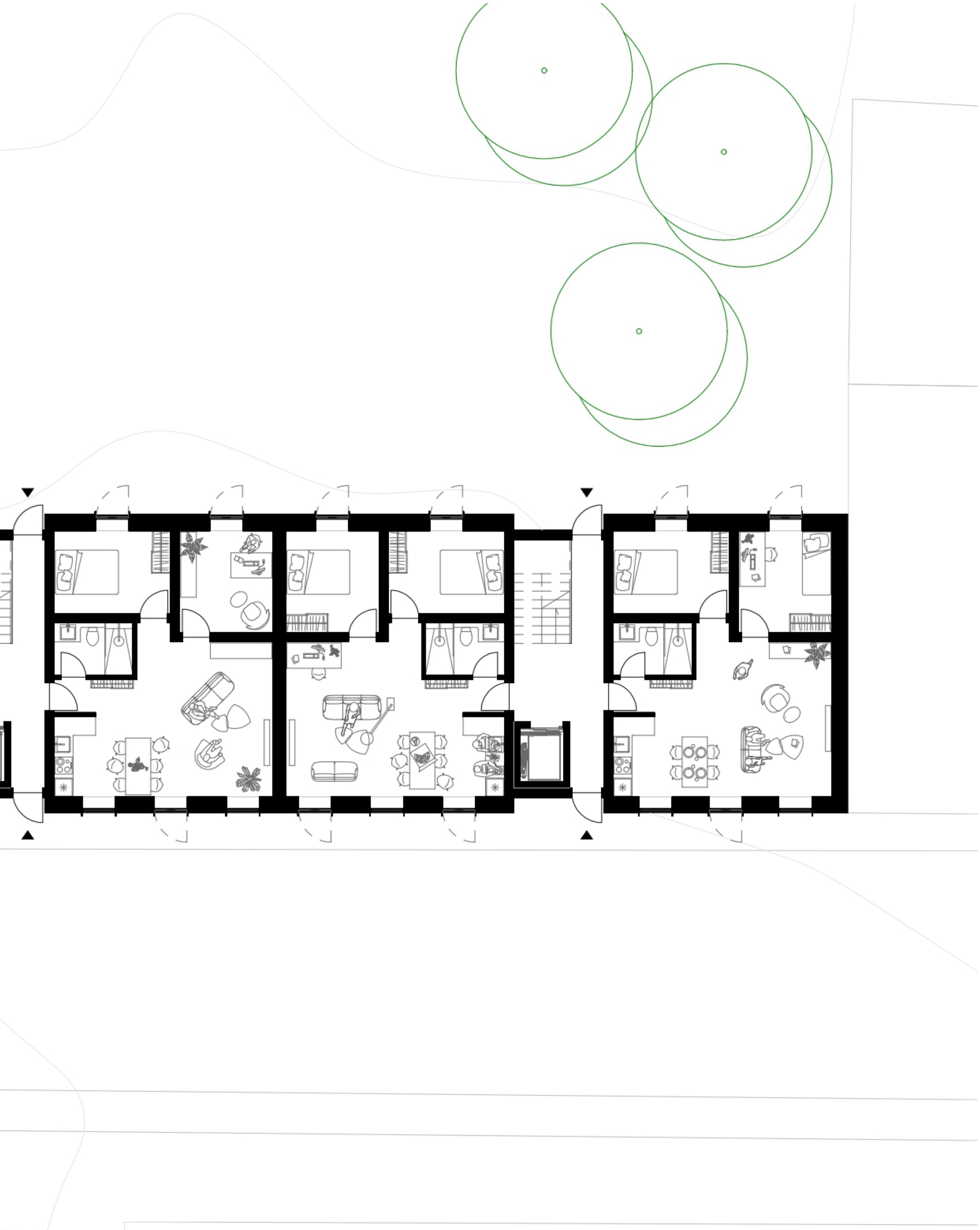


Fig 26: Site plan | Scale 1:500.


Aasen
Bleggaardsgade
KOLDINGVEJ
Kiddesvej

Fig 27: Living room proposal visualisation.

Fig 28: Ground floor plan | Scale 1:150.



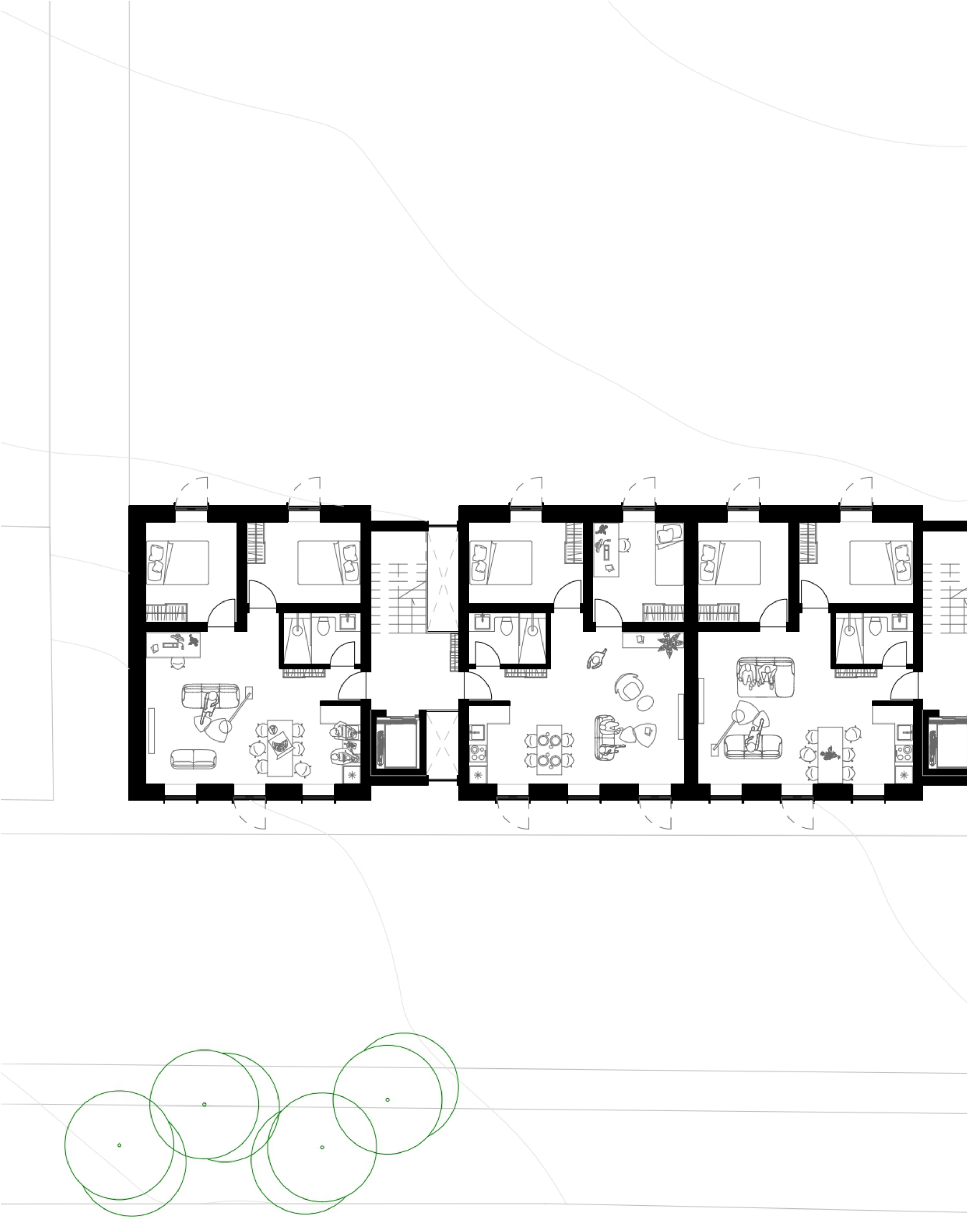


Fig 29: First floor plan | Scale 1:150.

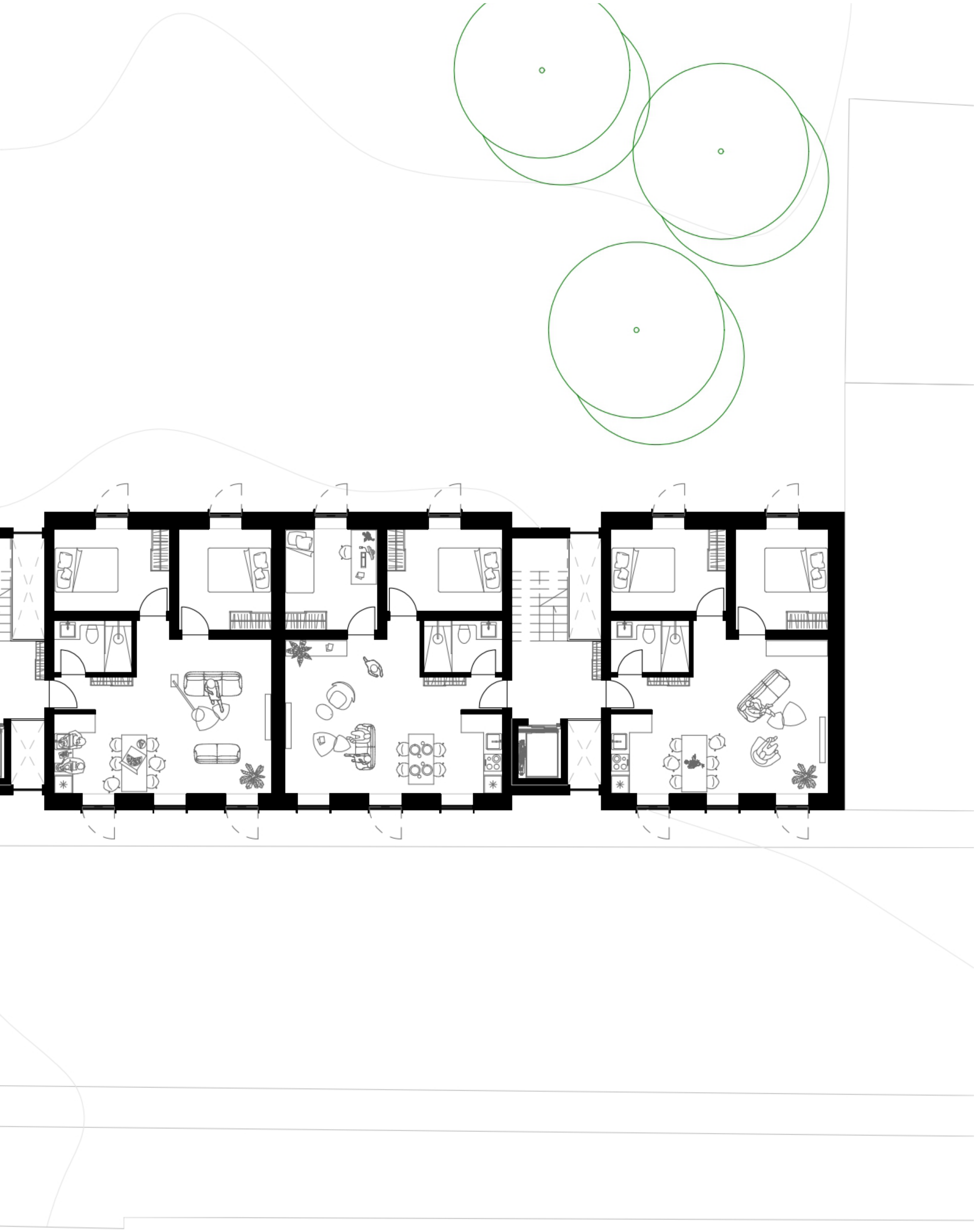


Fig 29: Mansard floor plan | Scale 1:150.

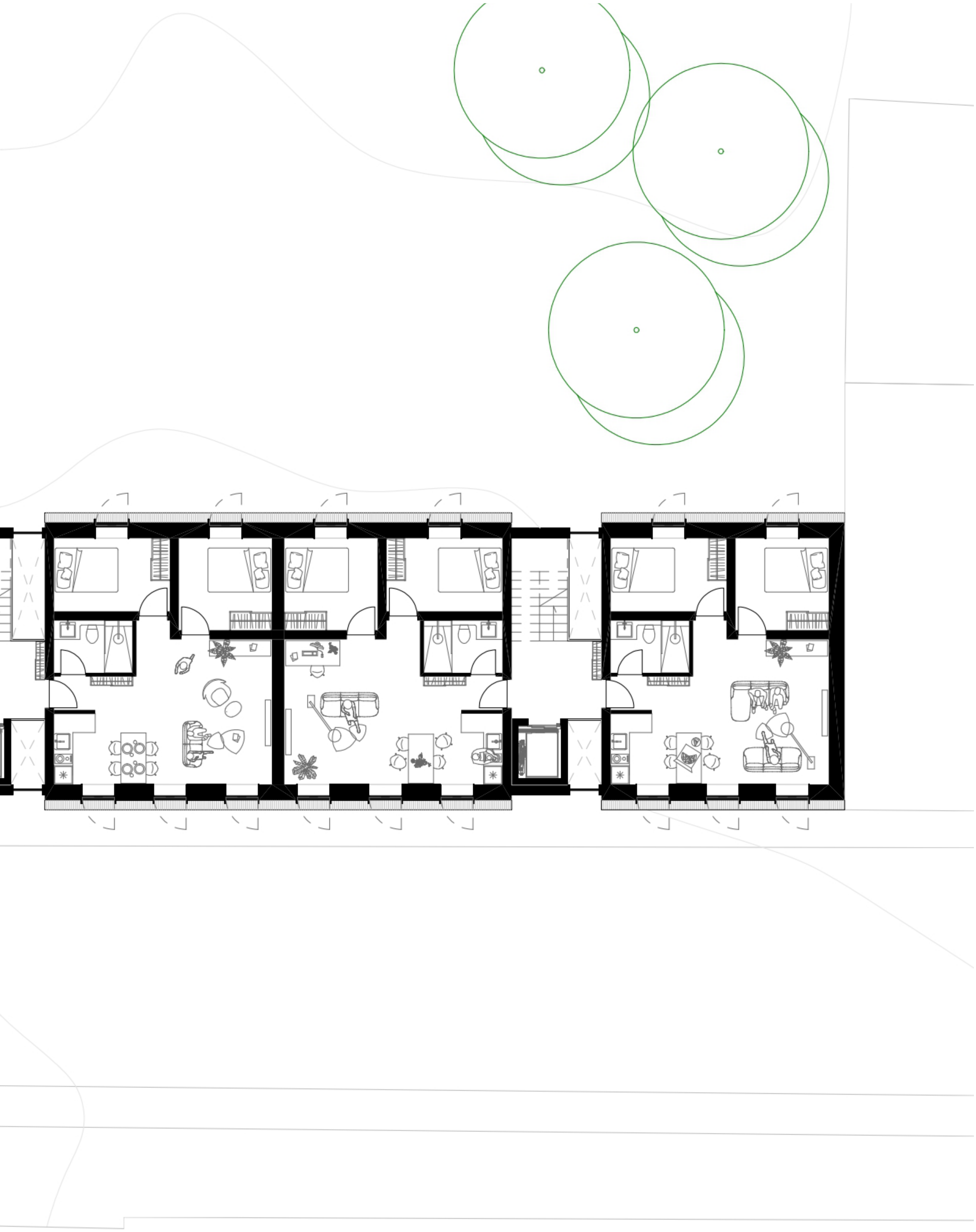


Fig 30: Project proposal visualisation.

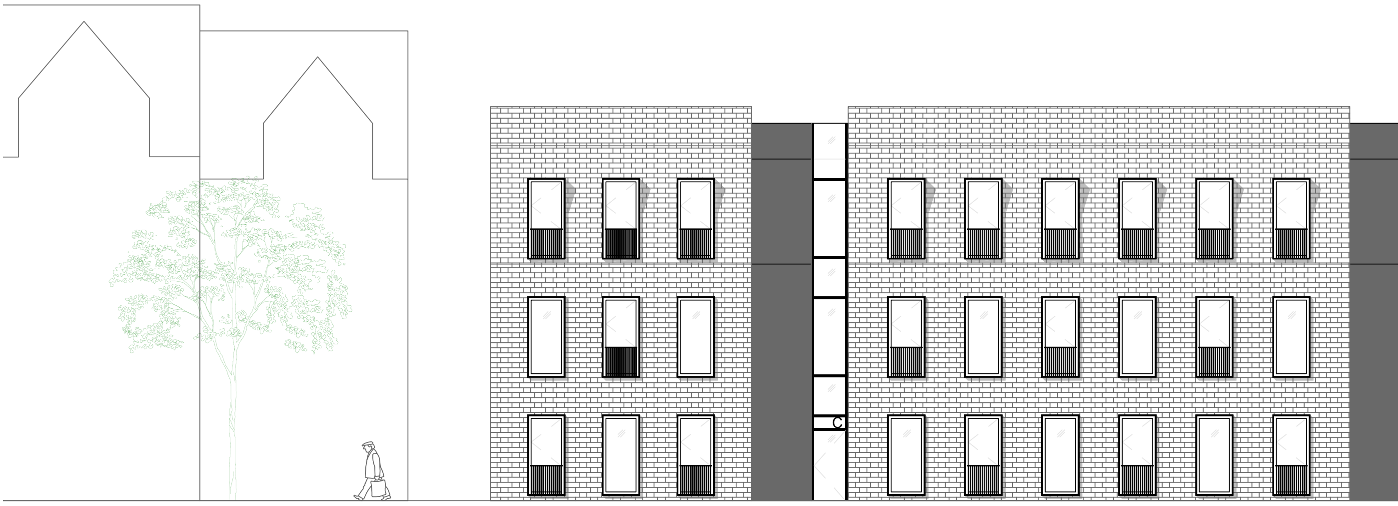


Fig 31: South facade | Scale 1:200.

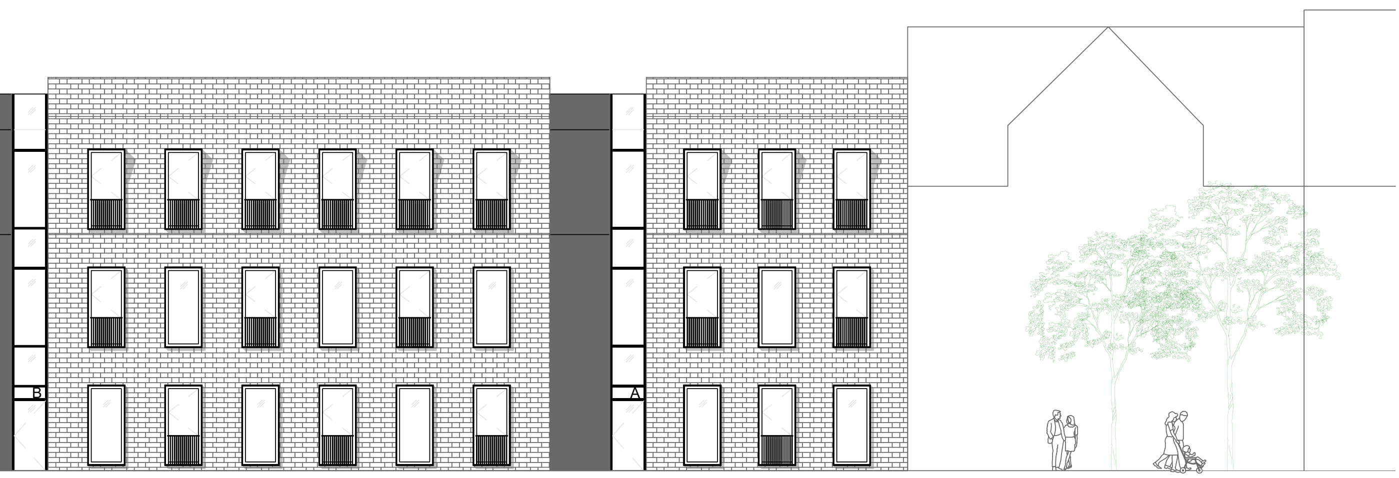
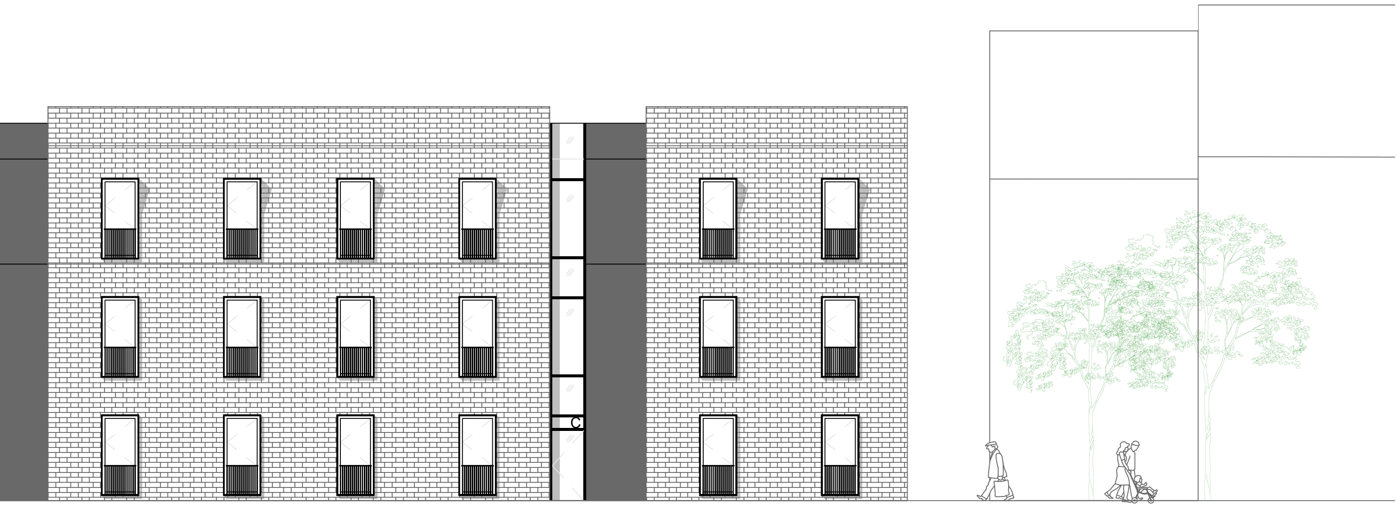

B
A

Fig 32: North facade | Scale 1:200.



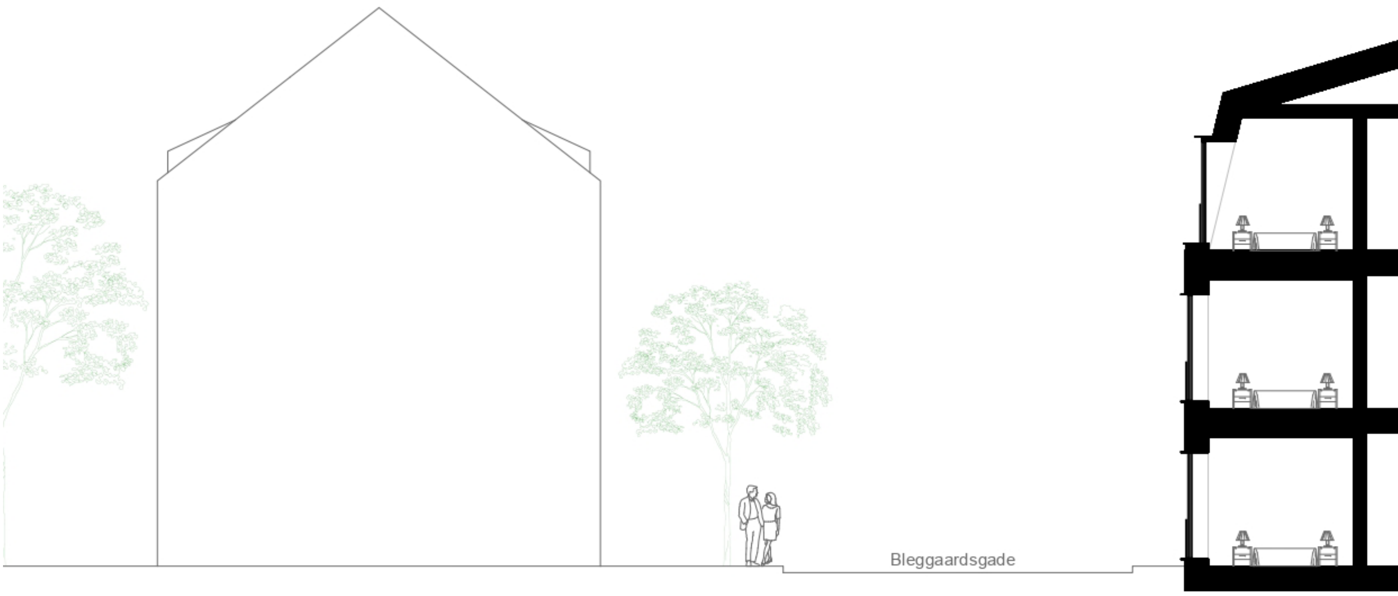


Fig 33: Cross section | Scale 1:150.

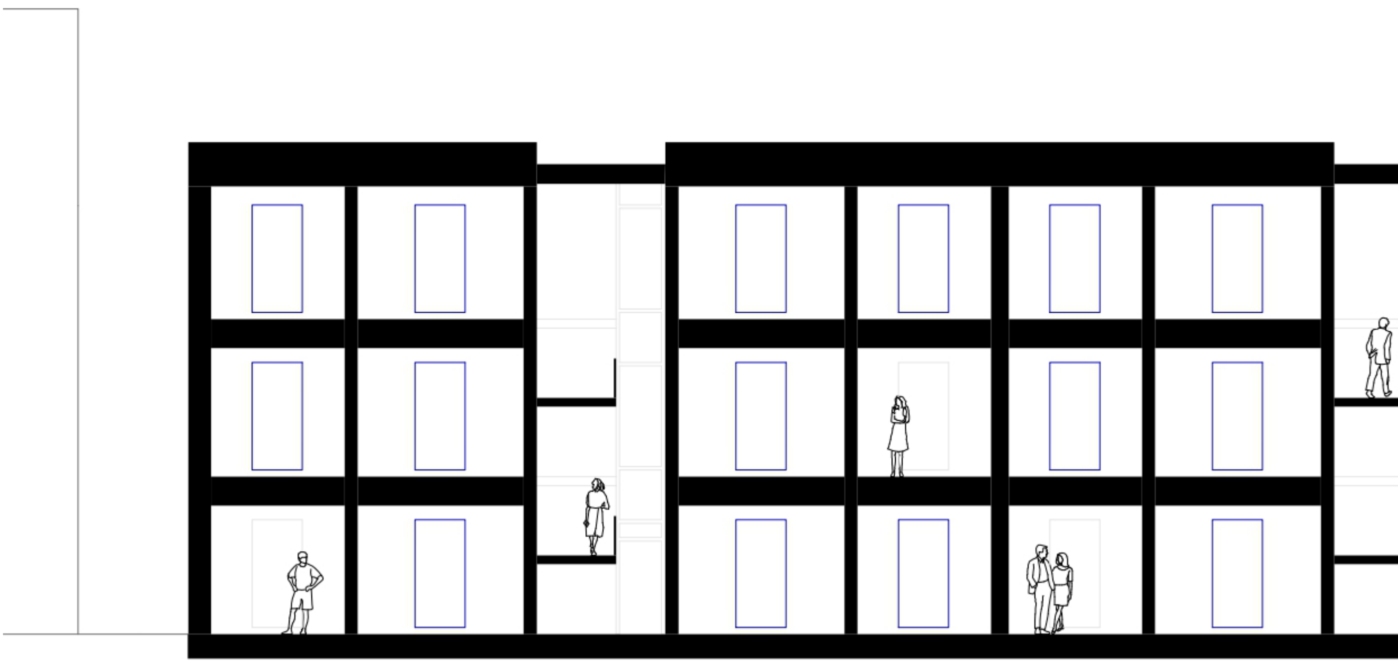
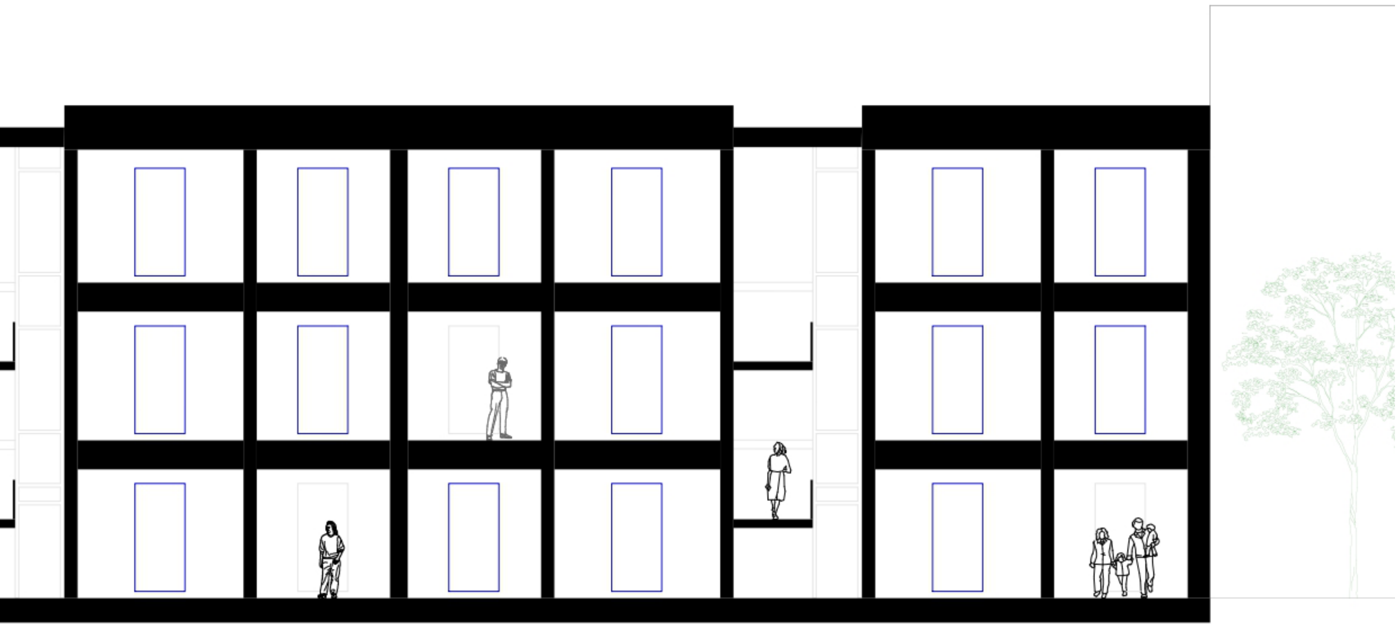


Fig 34: Longitudinal section section | Scale 1:150.



THERMAL THINKING STRATEGIES

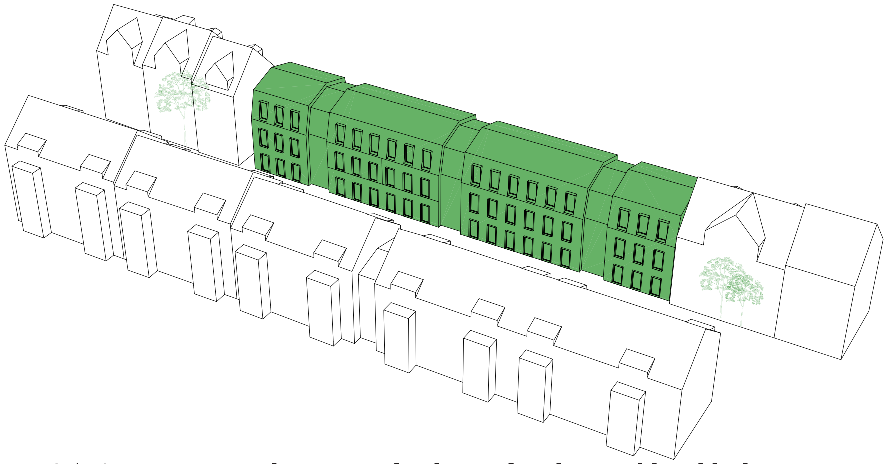


Fig 35: Axonometric diagram of volume for thermal load balance.

- Heat pump as source for heating and hot domestic water.
- Floor heating with heating set points per room.
- Increase of thermal resistance of partitions.
- Shading system to lock out summer sun and gain winter solar heat.
- Additional shading system with set points
- Closed volumes without air mixing between zones.
- Cold bedrooms occupied only for sleeping and no other function
- Centralized MVHR with 1ACH
- Venting with set points
- Night cooling with set points

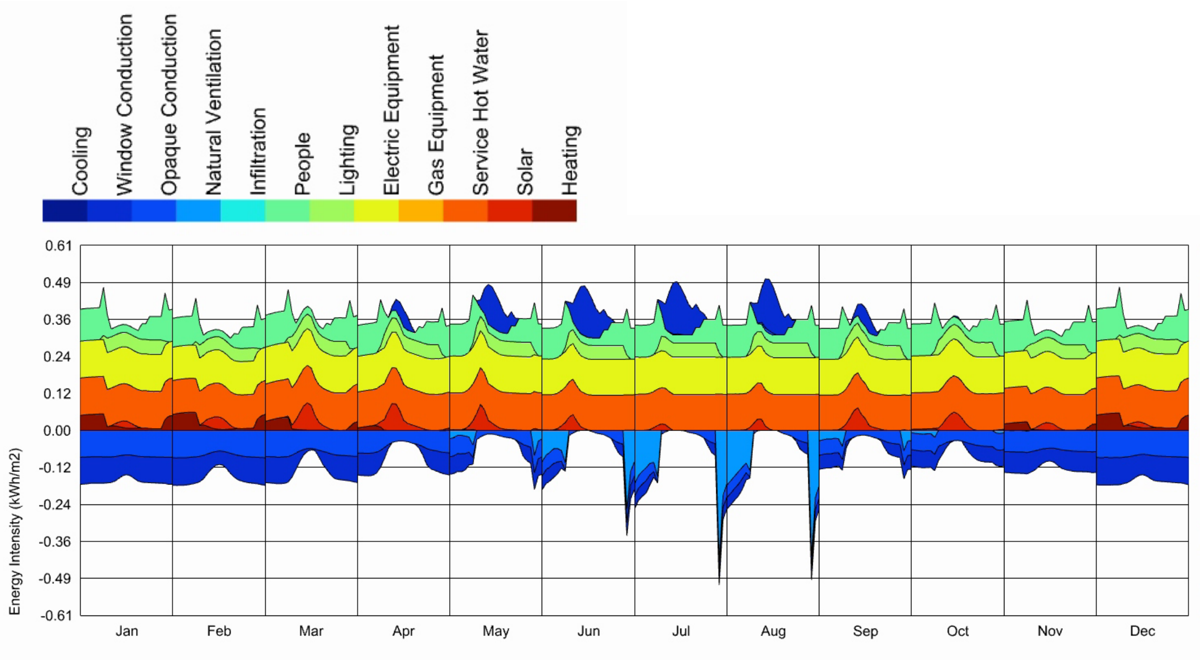


Fig 36: Proposal thermal load balance.

CONSTRUCTION PRINCIPLE

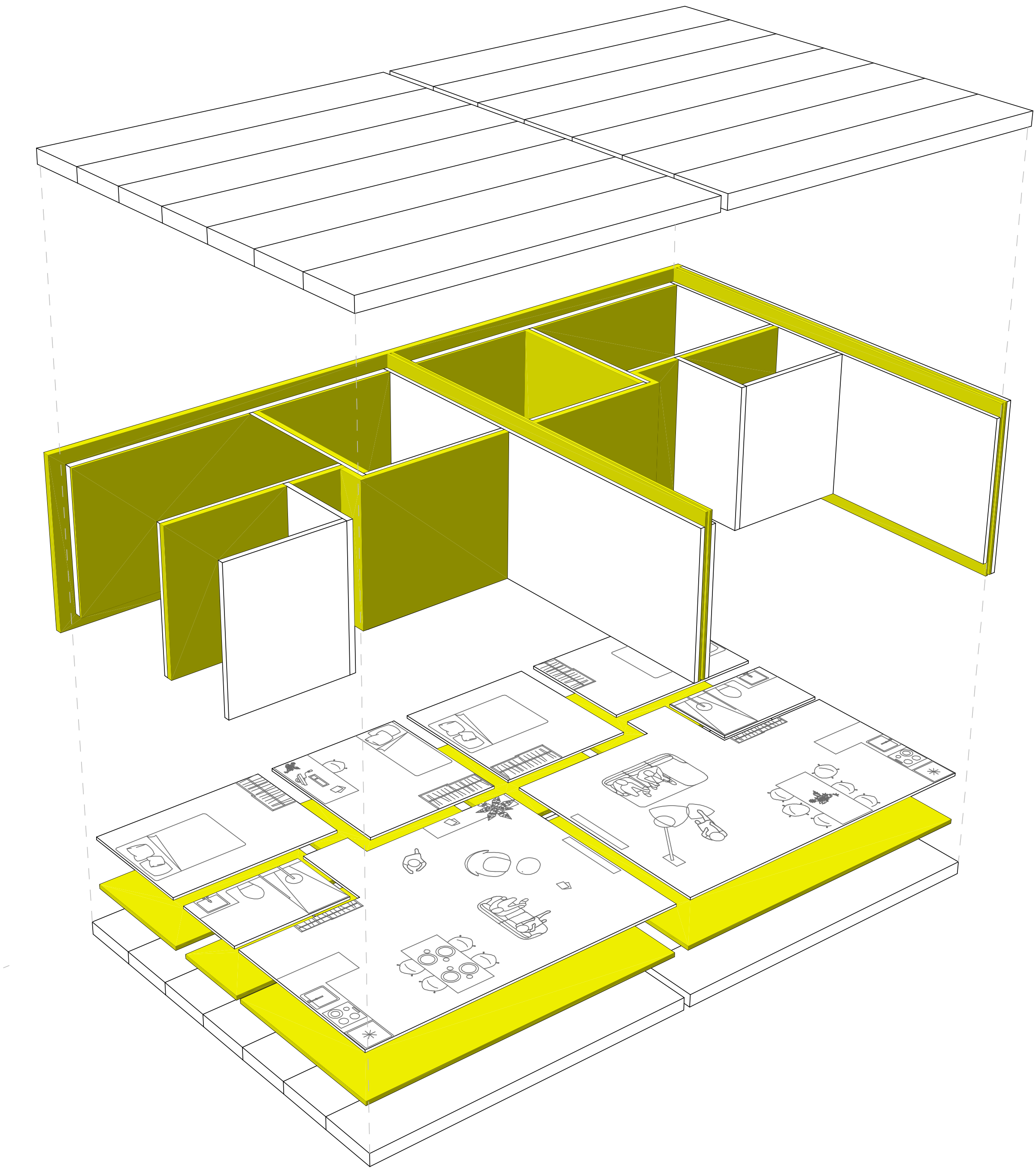


Fig 37: Proposal construction and insulation placement principle.

LEAST COMPACT UNIT

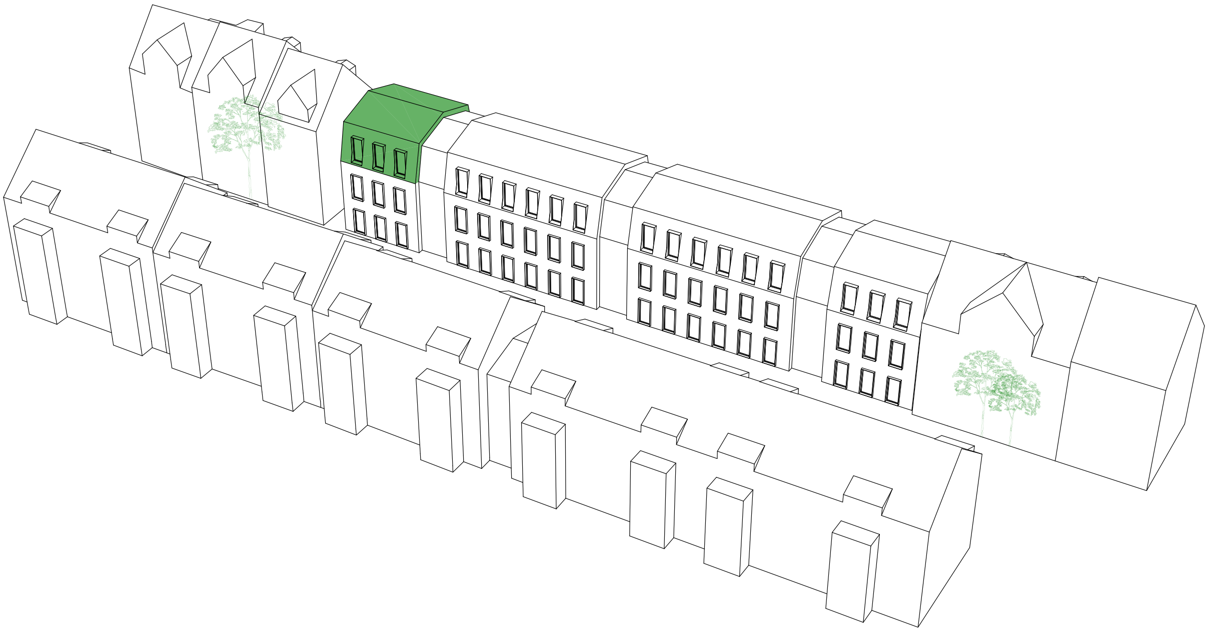
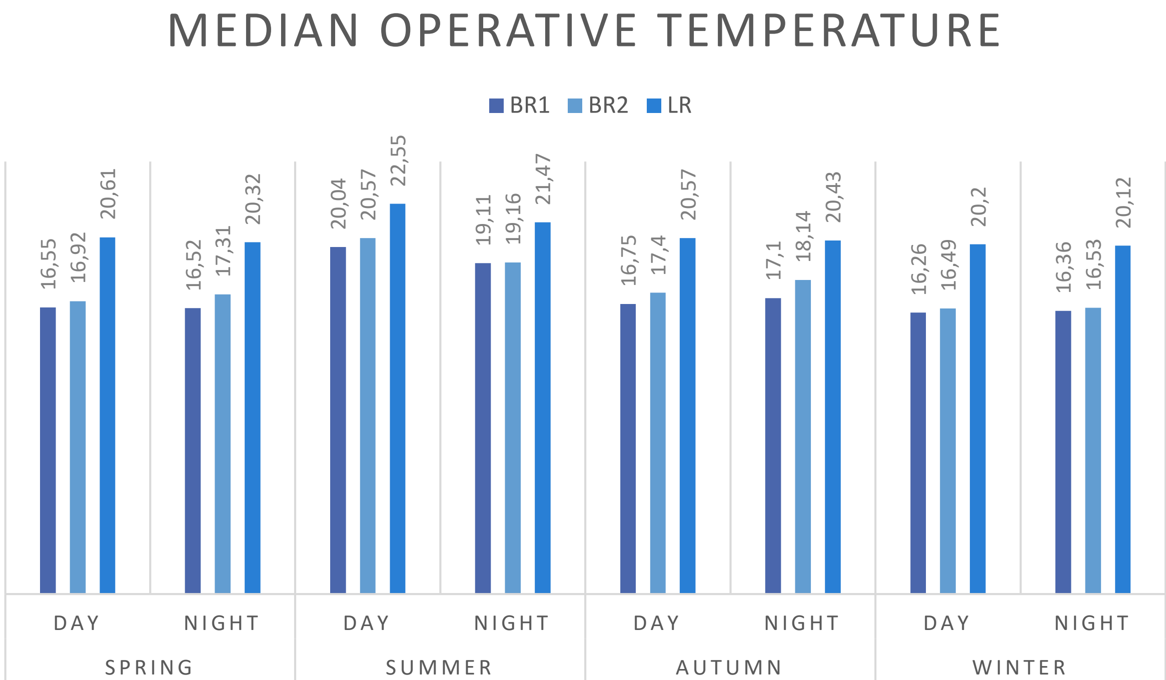


Fig 38: Axonometric diagram of volume for thermal load balance.



Cht 5: Median operative temperature chart.

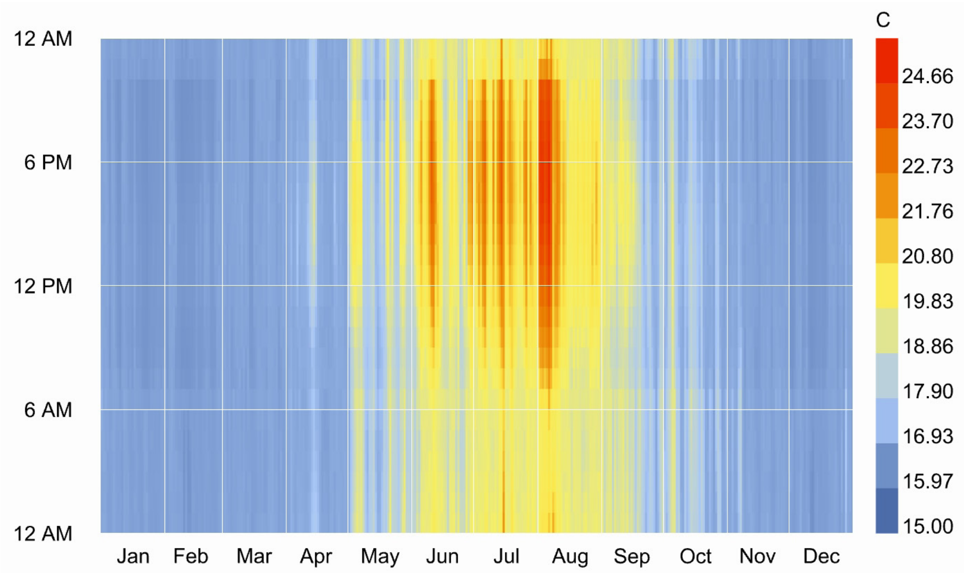


Fig 39: One-occupant bedroom operative temperature plot of annually hourly data.

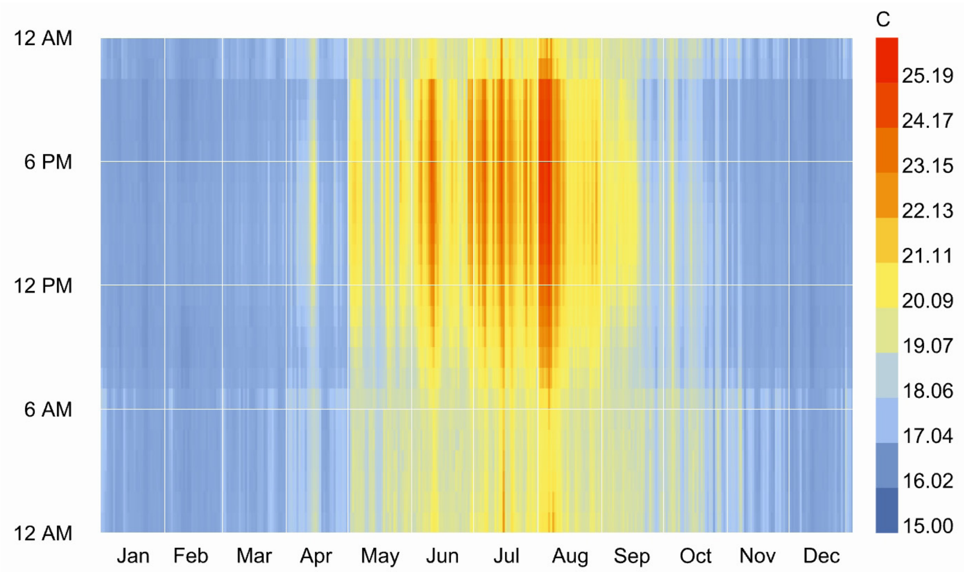


Fig 40: Two-occupant bedroom operative temperature plot of annually hourly data.

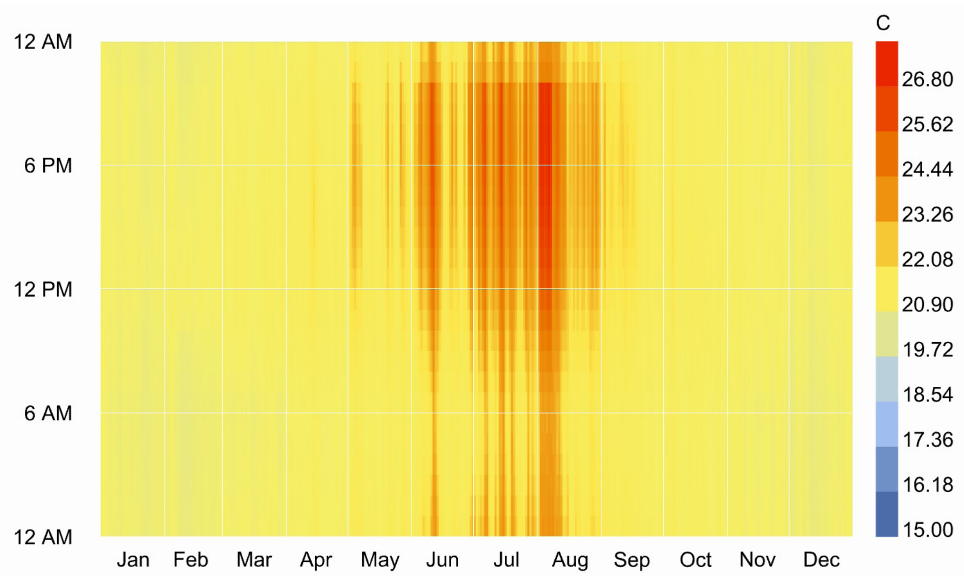


Fig 41: Living room operative temperature plot of annually hourly data.

MOST COMPACT UNIT

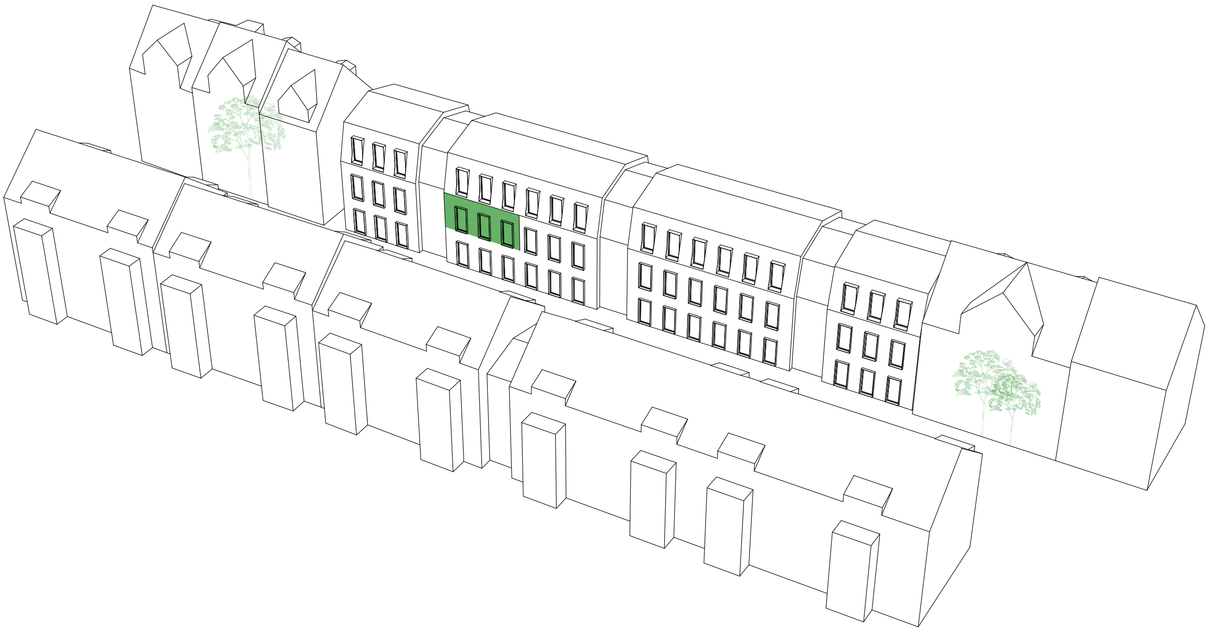
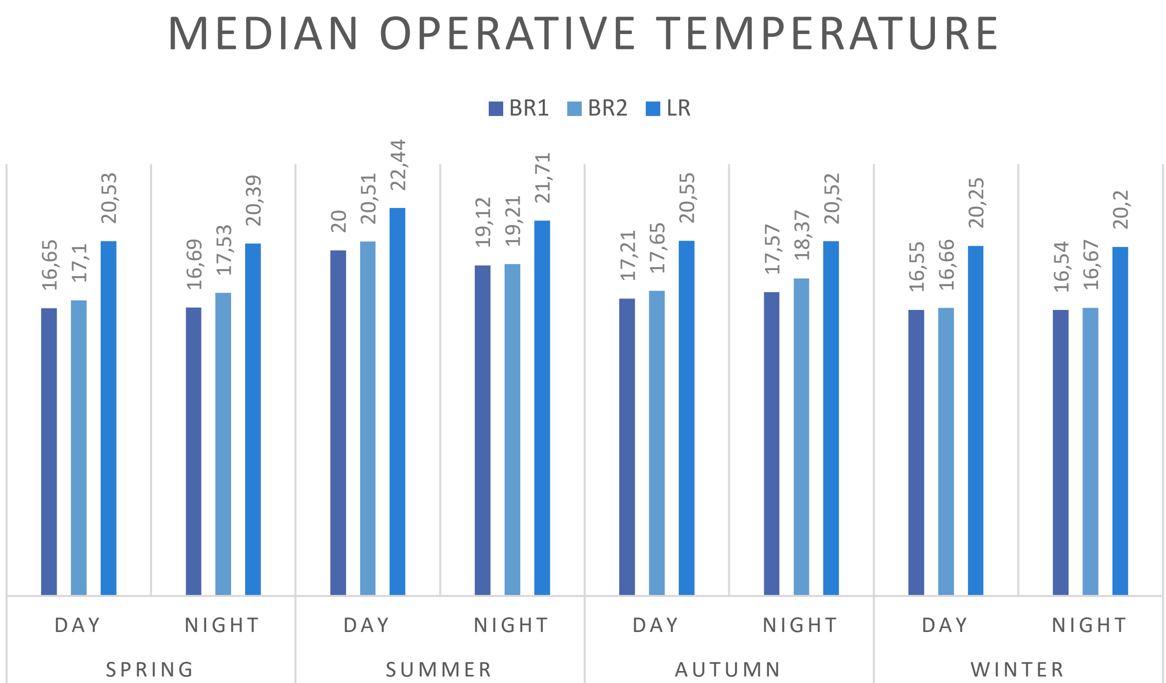


Fig 42: Axonometric diagram of volume for thermal load balance.



Cht 6: Median operative temperature chart.

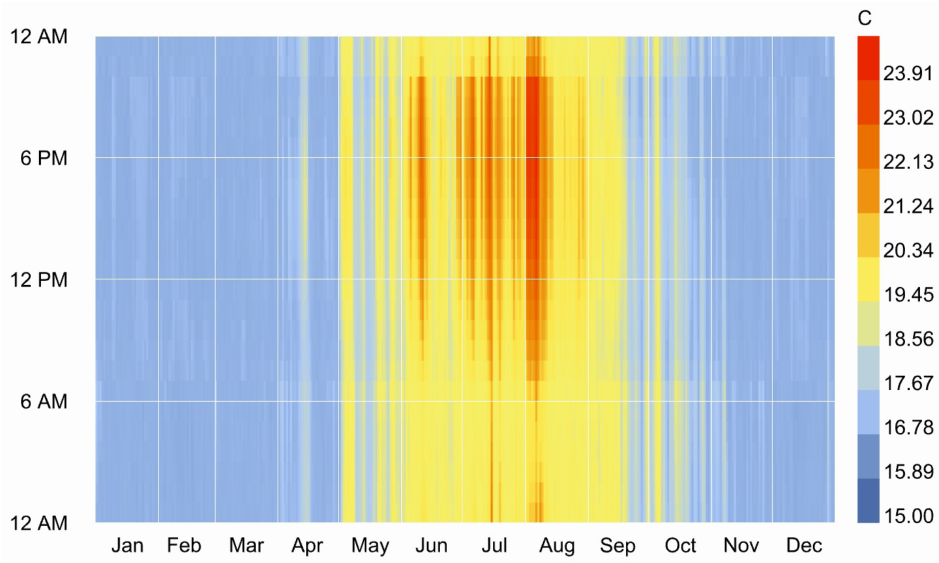


Fig 43: One-occupant bedroom operative temperature plot of annually hourly data.

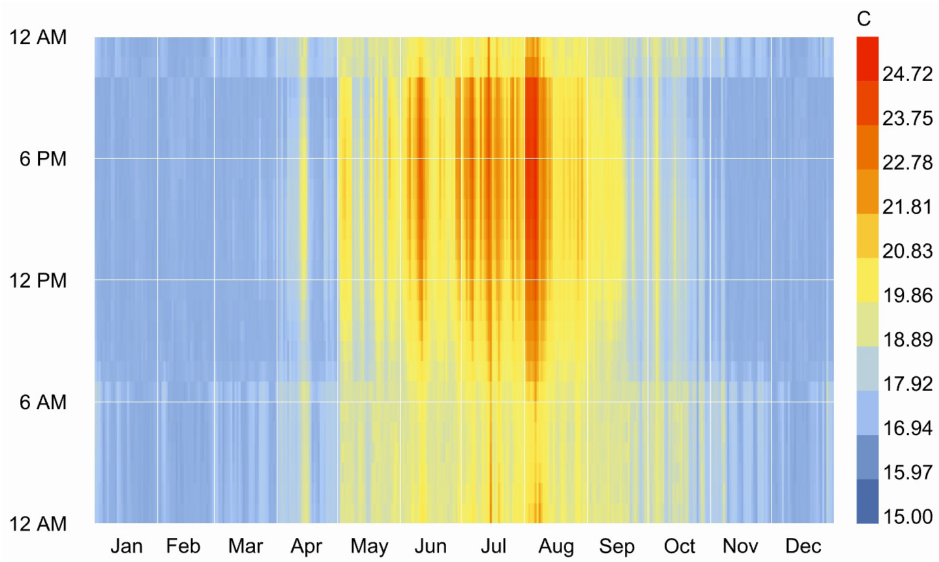


Fig 44: Two-occupant bedroom operative temperature plot of annually hourly data.

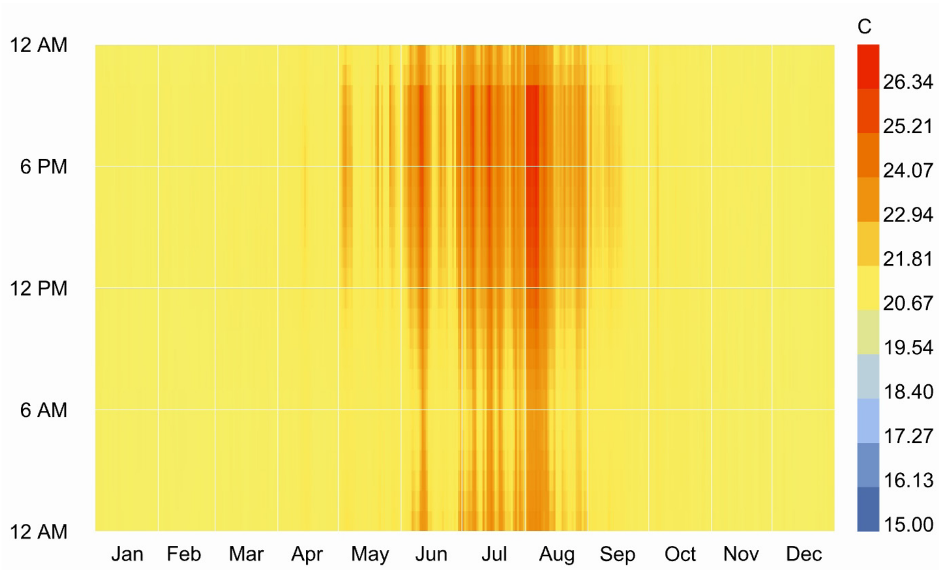


Fig 45: Living room operative temperature plot of annually hourly data.

CONCLUSIONS

This thesis has been an enormous expansion of the pool of knowledge through design-based research and its implementation into the research-based design. I am proud to conclude that it is partially possible to meet user demands without sacrificing building performance and, therefore, to enhance social and environmental sustainability simultaneously. Results suggest that creating two thermal zones into one residential unit is possible. Still, it is possible to meet user demand of temperature for winter T < 17 °C, and adaptive climate temperature is observed throughout the year. Weather adaptive indoor environment means that indoor temperatures are fallowing outdoor temperatures, and it is possible to create lower temperatures in winter than in summer.

How do we design residential architecture with two thermal zones to meet user demand for cold bedrooms? My answer is to follow good practice of low-energy housing when creating rooms with 5 °C temperature differences and supplement it with location-based, informed, and conscious integrated design decisions. Every design should be instructed on the early stages of location climatology, the orientation of the building and zones, shading and solar gain and material choices.

But how do we design flexible cold bedrooms to adapt to users' family configurations and accommodate new forms of co-living? After the project, I concluded that building envelope parameters are crucial and cannot be changed from high-performance residential architecture recommendation; for zones to changing function and thermal conditions. Instead, partition thermal resistance should be designed for a 5 °C temperature difference. Each room should be able to regulate and set up heating points to change the temperature and, therefore, be built with separate floor heating loops for each room. Furthermore, each zone should be designed with variable options to shade, open the window and close the area for the rest of the housing volume.

Complexity and sensibility of thermal environment and energy performance have been observed throughout the work process of this thesis. First, it has been designed and controlled by set points and sensors, while in real life, user behavior is unpredictable. Slightly changes made in a parametric digital building immediately informed its effect on these conditions, but it is not what is happening in real life. Visual communication through hourly plots and energy balances informed and trained my design choices. That makes me aware of how little the user is knowledgeable and even when willing to take responsible participation. In a digital world, we can design and establish desired user thermal demand or get close to it. Still, to ensure successful realization, architect, engineer, and tenant communication should be enhanced through educational manuals or digital platforms. For example, the final result would only work if bedrooms are only occupied for sleeping and without putting any extra electrical and equipment loads. Even more, rooms must be closed from other thermal zones. Therefore, at the end of the day, all must work together and be aware of their own participation and responsibility for meeting desired conditions.

REFLECTIONS

The research adds another layer of complexity to an already demanding thesis project. A diverse variety of expertise and skills are required to work with architecture, integrated design, research, and even more to present. Therefore, research and project work has been a personal challenge to accomplish as an individual project.

Luck of previse knowledge and skills of tools used in these projects has been another challenge to overcome. The lack of modern tutorials or books about Ladybug Tools has been missed and self-taught. Furthermore, verification tools were missed at the begging to ensure the correctness of results while design intuition and awareness were built. The practice of working with an enormous amount of data and analysing and communicating it was another dare.

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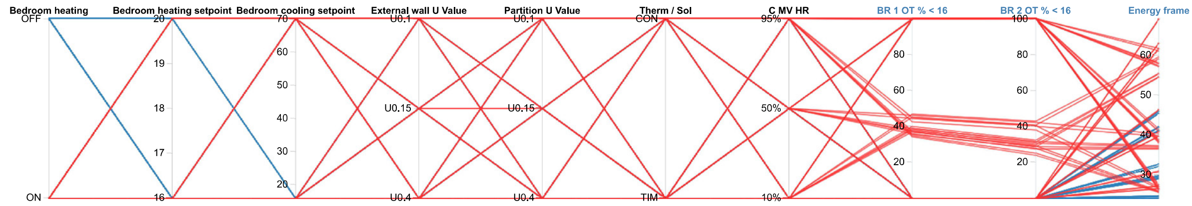
DETAILED RESEARCH SIMULATION RESULTS

CENTRALIZED MVHR WITH AIR OVERFLOW AND DISTRICT HEATING

https://tt-acm.github.io/DesignExplorer/?ID=BL_3SQGCV0



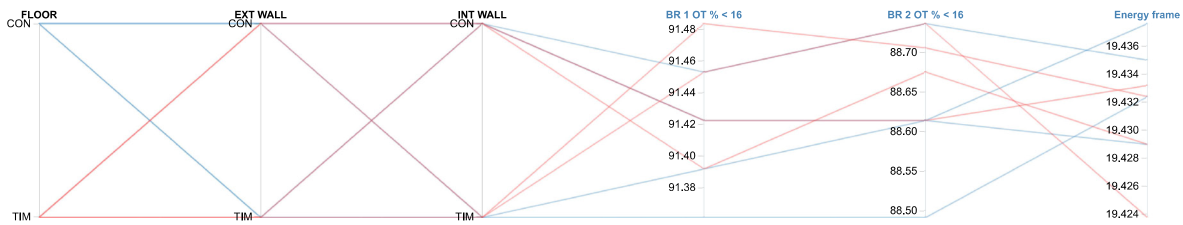
Cht 7: Design Explorer iterative design result chart.

Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9	Column10
in:Bedroom heating	in:Bedroom heating setpoint	in:Bedroom cooling setpoint	in:External wall U Value	in:Partition U Value	in:Therm / Sol	in:C MV HR	out:BR 1 OT % < 16	out:BR 2 OT % < 16	out:Energy frame
ON	16	70	U0.4	U0.4	CON	10%	46.855922	42.979243	59.568
ON	16	70	U0.4	U0.15	CON	10%	46.855922	42.979243	59.568
ON	16	70	U0.4	U0.1	CON	10%	46.855922	42.979243	59.568
ON	16	70	U0.4	U0.4	CON	50%	46.184371	42.307692	40.303
ON	16	70	U0.4	U0.15	CON	50%	46.184371	42.307692	40.303
ON	16	70	U0.4	U0.1	CON	50%	46.184371	42.307692	40.303
ON	16	70	U0.4	U0.4	TIM	10%	45.299145	40.842491	59.079
ON	16	70	U0.4	U0.15	TIM	10%	45.299145	40.842491	59.079
ON	16	70	U0.4	U0.1	TIM	10%	45.299145	40.842491	59.079
ON	16	70	U0.4	U0.4	CON	95%	44.810745	40.567766	26.976
ON	16	70	U0.4	U0.15	CON	95%	44.810745	40.567766	26.976
ON	16	70	U0.4	U0.1	CON	95%	44.810745	40.567766	26.976
ON	16	70	U0.4	U0.4	TIM	50%	44.444444	40.140415	39.725
ON	16	70	U0.4	U0.15	TIM	50%	44.444444	40.140415	39.725
ON	16	70	U0.4	U0.1	TIM	50%	44.444444	40.140415	39.725
ON	16	70	U0.4	U0.4	TIM	95%	42.612943	38.125763	26.599
ON	16	70	U0.4	U0.15	TIM	95%	42.612943	38.125763	26.599
ON	16	70	U0.4	U0.1	TIM	95%	42.612943	38.125763	26.599
ON	16	70	U0.15	U0.4	CON	10%	40.018315	32.417582	55.478
ON	16	70	U0.15	U0.15	CON	10%	40.018315	32.417582	55.478
ON	16	70	U0.15	U0.1	CON	10%	40.018315	32.417582	55.478
ON	16	70	U0.15	U0.4	TIM	10%	38.919414	31.410256	55.333
ON	16	70	U0.15	U0.15	TIM	10%	38.919414	31.410256	55.333
ON	16	70	U0.15	U0.1	TIM	10%	38.919414	31.410256	55.333
ON	16	70	U0.15	U0.4	CON	50%	38.858364	31.654457	37.354
ON	16	70	U0.15	U0.15	CON	50%	38.858364	31.654457	37.354
ON	16	70	U0.15	U0.1	CON	50%	38.858364	31.654457	37.354
ON	16	70	U0.1	U0.4	CON	10%	38.186813	29.945055	54.608
ON	16	70	U0.1	U0.15	CON	10%	38.186813	29.945055	54.608
ON	16	70	U0.1	U0.1	CON	10%	38.186813	29.945055	54.608
ON	16	70	U0.15	U0.4	TIM	50%	37.698413	30.769231	37.076
ON	16	70	U0.15	U0.15	TIM	50%	37.698413	30.769231	37.076
ON	16	70	U0.15	U0.1	TIM	50%	37.698413	30.769231	37.076
ON	16	70	U0.1	U0.4	TIM	10%	37.087912	28.754579	54.514
ON	16	70	U0.1	U0.15	TIM	10%	37.087912	28.754579	54.514
ON	16	70	U0.1	U0.1	TIM	10%	37.087912	28.754579	54.514
ON	16	70	U0.1	U0.4	CON	50%	37.057387	28.846154	36.78
ON	16	70	U0.1	U0.15	CON	50%	37.057387	28.846154	36.78
ON	16	70	U0.1	U0.1	CON	50%	37.057387	28.846154	36.78
ON	16	70	U0.15	U0.4	CON	95%	36.996337	29.334554	26.007
ON	16	70	U0.15	U0.15	CON	95%	36.996337	29.334554	26.007
ON	16	70	U0.15	U0.1	CON	95%	36.996337	29.334554	26.007
ON	16	70	U0.1	U0.4	TIM	50%	35.958486	27.533578	36.544
ON	16	70	U0.1	U0.15	TIM	50%	35.958486	27.533578	36.544
ON	16	70	U0.1	U0.1	TIM	50%	35.958486	27.533578	36.544
ON	16	70	U0.15	U0.4	TIM	95%	35.683761	27.899878	25.776
ON	16	70	U0.15	U0.15	TIM	95%	35.683761	27.899878	25.776
ON	16	70	U0.15	U0.1	TIM	95%	35.683761	27.899878	25.776
ON	16	70	U0.1	U0.4	CON	95%	34.981685	25.213675	25.887
ON	16	70	U0.1	U0.15	CON	95%	34.981685	25.213675	25.887
ON	16	70	U0.1	U0.1	CON	95%	34.981685	25.213675	25.887
ON	16	70	U0.1	U0.4	TIM	95%	34.249084	24.023199	25.686
ON	16	70	U0.1	U0.15	TIM	95%	34.249084	24.023199	25.686
ON	16	70	U0.1	U0.1	TIM	95%	34.249084	24.023199	25.686

Tbl 6: Iterative design CSV data.

THERMAL AND SOLAR ABSOEBANCE

https://tt-acm.github.io/DesignExplorer/?ID=BL_3UJwAqs



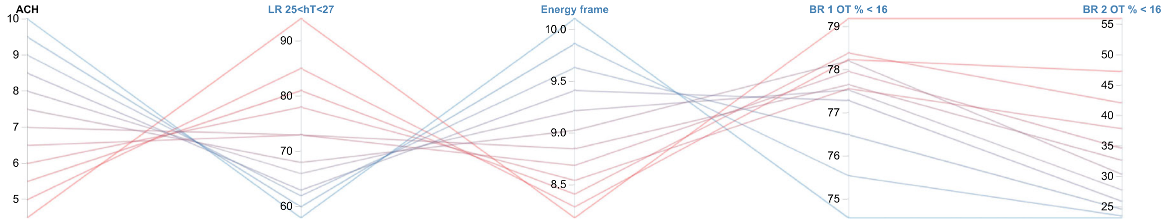
Cht 8: Design Explorer iterative design result chart.

Column1	Column2	Column3	Column4	Column5	Column6
in:FLOOR	in:EXT WALL	in:INT WALL	out:BR 1 OT % < 16	out:BR 2 OT % < 16	out:Energy frame
TIM	TIM	TIM	91.483516	88.705739	19.4324
CON	TIM	TIM	91.361416	88.492063	19.4324
TIM	CON	TIM	91.452991	88.736264	19.4238
CON	CON	TIM	91.391941	88.614164	19.429
TIM	TIM	CON	91.422466	88.614164	19.4332
CON	TIM	CON	91.422466	88.614164	19.4376
TIM	CON	CON	91.391941	88.675214	19.429
CON	CON	CON	91.452991	88.736264	19.435

Tbl 8: Iterative design CSV data.

ACH FOR THERMAL COMFORT REQUIREMENTS

https://tt-acm.github.io/DesignExplorer/?ID=BL_3fhYhGF



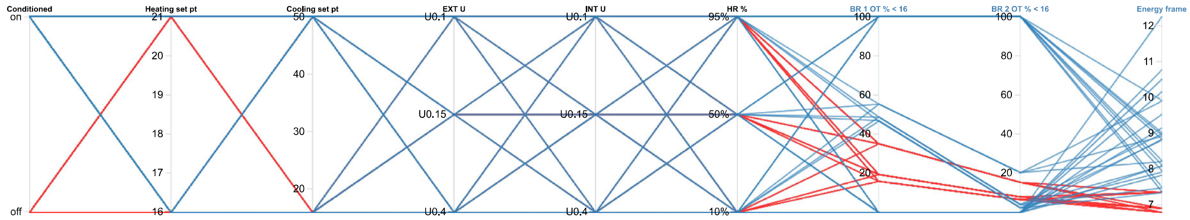
Cht 9: Design Explorer iterative design result chart.

Column1	Column2	Column3	Column4	Column5
in:ACH	out:LR 25<hT<27	out:Energy frame	out:BR 1 OT % < 16	out:BR 2 OT % < 16
0.5	4821	7.482	48.778999	3.724054
1	1237	7.5832	72.893773	45.39072
1.5	433	7.6534	83.363858	58.821734
2	239	7.729	87.240537	68.589744
2.5	168	7.807	89.407814	74.145299
3	134	7.8918	89.194139	77.808303
3.5	117	7.9826	86.416361	74.053724
4	107	8.0796	81.074481	64.529915
4.5	94	8.1816	79.181929	55.921856
5	85	8.2878	78.235653	47.252747
5.5	81	8.4104	78.388278	42.094017
6	78	8.5434	77.564103	37.881563
6.5	73	8.6874	77.960928	34.64591
7	73	8.8486	77.655678	32.692308
7.5	68	9.0252	78.205128	30.372405
8	66	9.2164	77.533578	27.808303
8.5	63	9.4118	77.289377	25.946276
9	62	9.6322	76.495726	24.664225
9.5	60	9.8636	75.549451	23.595849
10	58	10.1046	74.57265	23.260073

Tbl 9: Iterative design CSV data.

CENTRALIZED MVHR WITH AIRFLOW BALANCE

https://tt-acm.github.io/DesignExplorer/?ID=BL_3rd3BOq



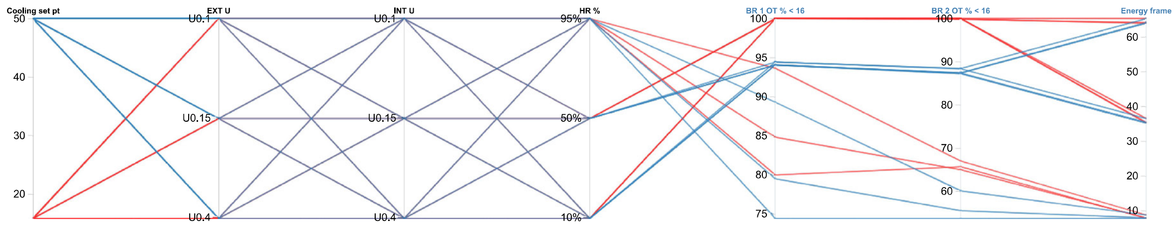
Cht 10: Design Explorer iterative design result chart.

Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9
in:Conditioned	in:Heating set pt	in:Cooling set pt	in:EXT U	in:INT U	in:HR %	out:BR 1 OT % < 16	out:BR 2 OT % < 16	out:Energy frame
on	16	50	U0.4	U0.4	10%	55.311355	20.32967	9.898
on	16	50	U0.4	U0.15	10%	55.311355	20.32967	9.898
on	16	50	U0.4	U0.1	10%	55.311355	20.32967	9.898
on	16	50	U0.4	U0.4	50%	55.311355	20.32967	8.918
on	16	50	U0.4	U0.15	50%	55.311355	20.32967	8.918
on	16	50	U0.4	U0.1	50%	55.311355	20.32967	8.918
on	16	50	U0.4	U0.4	95%	55.311355	20.421245	8.2176
on	16	50	U0.4	U0.15	95%	55.311355	20.421245	8.2176
on	16	50	U0.4	U0.1	95%	55.311355	20.421245	8.2176
on	16	50	U0.15	U0.4	10%	48.778999	4.090354	8.9892
on	16	50	U0.15	U0.15	10%	48.778999	4.090354	8.9892
on	16	50	U0.15	U0.1	10%	48.778999	4.090354	8.9892
on	16	50	U0.15	U0.4	95%	48.778999	3.785104	7.482
on	16	50	U0.15	U0.15	95%	48.778999	3.785104	7.482
on	16	50	U0.15	U0.1	95%	48.778999	3.785104	7.482
on	16	50	U0.15	U0.4	50%	48.717949	4.029304	8.083
on	16	50	U0.15	U0.15	50%	48.717949	4.029304	8.083
on	16	50	U0.15	U0.1	50%	48.717949	4.029304	8.083
on	16	50	U0.1	U0.4	50%	46.886447	2.350427	7.9236
on	16	50	U0.1	U0.15	50%	46.886447	2.350427	7.9236
on	16	50	U0.1	U0.1	50%	46.886447	2.350427	7.9236
on	16	50	U0.1	U0.4	10%	46.733822	2.411477	8.8092
on	16	50	U0.1	U0.15	10%	46.733822	2.411477	8.8092
on	16	50	U0.1	U0.1	10%	46.733822	2.411477	8.8092
on	16	50	U0.1	U0.4	95%	46.611722	2.258852	7.35
on	16	50	U0.1	U0.15	95%	46.611722	2.258852	7.35
on	16	50	U0.1	U0.1	95%	46.611722	2.258852	7.35
off	16	50	U0.4	U0.4	10%	35.042735	15.384615	7.3568
off	21	50	U0.4	U0.4	10%	35.042735	15.384615	7.3568
off	16	50	U0.4	U0.15	10%	35.042735	15.384615	7.3568
off	21	50	U0.4	U0.15	10%	35.042735	15.384615	7.3568
off	16	50	U0.4	U0.1	10%	35.042735	15.384615	7.3568
off	21	50	U0.4	U0.1	10%	35.042735	15.384615	7.3568
off	16	50	U0.4	U0.4	50%	35.042735	15.384615	6.9152
off	21	50	U0.4	U0.4	50%	35.042735	15.384615	6.9152
off	16	50	U0.4	U0.15	50%	35.042735	15.384615	6.9152
off	21	50	U0.4	U0.15	50%	35.042735	15.384615	6.9152
off	16	50	U0.4	U0.1	50%	35.042735	15.384615	6.9152
off	21	50	U0.4	U0.1	50%	35.042735	15.384615	6.9152
off	16	50	U0.4	U0.4	95%	35.042735	15.384615	6.8004
off	21	50	U0.4	U0.4	95%	35.042735	15.384615	6.8004
off	16	50	U0.4	U0.15	95%	35.042735	15.384615	6.8004
off	21	50	U0.4	U0.15	95%	35.042735	15.384615	6.8004
off	16	50	U0.4	U0.1	95%	35.042735	15.384615	6.8004
off	21	50	U0.4	U0.1	95%	35.042735	15.384615	6.8004
off	16	50	U0.15	U0.4	10%	19.383394	7.997558	7.3636
off	21	50	U0.15	U0.4	10%	19.383394	7.997558	7.3636
off	16	50	U0.15	U0.15	10%	19.383394	7.997558	7.3636
off	21	50	U0.15	U0.15	10%	19.383394	7.997558	7.3636
off	16	50	U0.15	U0.1	10%	19.383394	7.997558	7.3636
off	21	50	U0.15	U0.1	10%	19.383394	7.997558	7.3636
off	16	50	U0.15	U0.4	50%	19.383394	7.997558	6.9162
off	21	50	U0.15	U0.4	50%	19.383394	7.997558	6.9162
off	16	50	U0.15	U0.15	50%	19.383394	7.997558	6.9162

Tbl 10: Iterative design CSV data.

CENTRALIZED MVHR WITH AIRFLOW BALANCE AND ACH

https://tt-acm.github.io/DesignExplorer/?ID=BL_3Ri10Nt

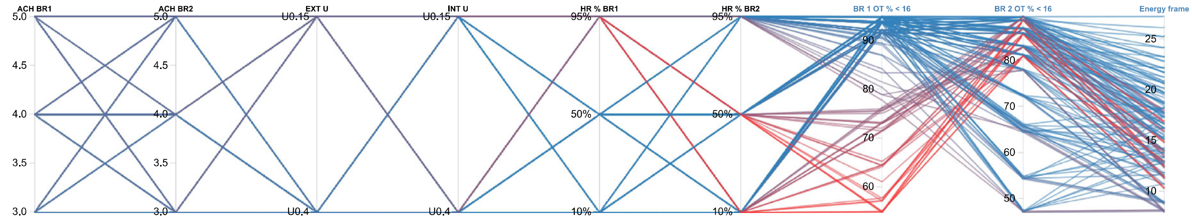


Cht 11: Design Explorer iterative design result chart.

Column1	Column2	Column3	Column4	Column5	Column6	Column7
in:Cooling set pt	in:EXT U	in:INT U	in:HR %	out:BR 1 OT % < 16	out:BR 2 OT % < 16	out:Energy frame
50	U0.4	U0.4	50%	94.474969	88.431013	36.6376
50	U0.4	U0.15	50%	94.474969	88.431013	36.6376
50	U0.4	U0.1	50%	94.474969	88.431013	36.6376
50	U0.4	U0.4	10%	94.474969	88.492063	65.3258
50	U0.4	U0.15	10%	94.474969	88.492063	65.3258
50	U0.4	U0.1	10%	94.474969	88.492063	65.3258
50	U0.15	U0.4	50%	94.108669	87.423687	35.5546
50	U0.15	U0.15	50%	94.108669	87.423687	35.5546
50	U0.15	U0.1	50%	94.108669	87.423687	35.5546
50	U0.15	U0.4	10%	94.108669	87.515263	64.2292
50	U0.15	U0.15	10%	94.108669	87.515263	64.2292
50	U0.15	U0.1	10%	94.108669	87.515263	64.2292
50	U0.1	U0.4	50%	94.078144	87.271062	35.319
50	U0.1	U0.15	50%	94.078144	87.271062	35.319
50	U0.1	U0.1	50%	94.078144	87.271062	35.319
50	U0.1	U0.4	10%	94.078144	87.454212	63.9892
50	U0.1	U0.15	10%	94.078144	87.454212	63.9892
50	U0.1	U0.1	10%	94.078144	87.454212	63.9892
50	U0.4	U0.4	95%	89.346764	60.286935	8.9926
50	U0.4	U0.15	95%	89.346764	60.286935	8.9926
50	U0.4	U0.1	95%	89.346764	60.286935	8.9926
50	U0.15	U0.4	95%	79.578755	55.738706	8.1808
50	U0.15	U0.15	95%	79.578755	55.738706	8.1808
50	U0.15	U0.1	95%	79.578755	55.738706	8.1808
50	U0.1	U0.4	95%	74.542125	53.937729	8.0332
50	U0.1	U0.15	95%	74.542125	53.937729	8.0332
50	U0.1	U0.1	95%	74.542125	53.937729	8.0332

Tbl 11: Iterative design CSV data..

DECENTRALIZED MVHR WITH AIRFLOW BALANCE AND ACH
https://tt-acm.github.io/DesignExplorer/?ID=BL_3SiMR3T



Cht 12: Design Explorer iterative design result chart.

Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9
in:ACH BR1	in:ACH BR2	in:EXT U	in:INT U	in:HR % BR1	in:HR % BR2	out:BR 1 OT % < 16	out:BR 2 OT % < 16	out:Energy frame
5	5	U0.4	U0.4	10%	10%	94.84127	89.468864	27.2016
5	5	U0.4	U0.15	10%	10%	94.84127	89.468864	27.2016
5	3	U0.4	U0.4	50%	10%	94.84127	83.180708	18.8066
5	5	U0.4	U0.4	50%	10%	94.84127	89.468864	22.7692
5	3	U0.4	U0.15	50%	10%	94.84127	83.180708	18.8066
5	5	U0.4	U0.15	50%	10%	94.84127	89.468864	22.7692
5	3	U0.4	U0.4	10%	50%	94.84127	83.089133	20.6772
5	3	U0.4	U0.15	10%	50%	94.84127	83.089133	20.6772
5	3	U0.4	U0.4	50%	50%	94.84127	83.089133	16.2448
5	3	U0.4	U0.15	50%	50%	94.84127	83.089133	16.2448
5	3	U0.4	U0.4	10%	10%	94.810745	83.211233	23.2374
5	3	U0.4	U0.15	10%	10%	94.810745	83.211233	23.2374
5	4	U0.4	U0.4	10%	50%	94.810745	86.904762	21.7446
5	5	U0.4	U0.4	10%	50%	94.810745	89.377289	22.8164
5	4	U0.4	U0.15	10%	50%	94.810745	86.904762	21.7446
5	5	U0.4	U0.15	10%	50%	94.810745	89.377289	22.8164
5	5	U0.4	U0.4	50%	50%	94.810745	89.377289	18.384
5	5	U0.4	U0.15	50%	50%	94.810745	89.377289	18.384
5	4	U0.4	U0.4	10%	95%	94.810745	66.086691	18.2434
5	4	U0.4	U0.15	10%	95%	94.810745	66.086691	18.2434
5	3	U0.4	U0.4	50%	95%	94.810745	72.191697	13.7398
5	5	U0.4	U0.4	50%	95%	94.810745	54.639805	13.8804
5	3	U0.4	U0.15	50%	95%	94.810745	72.191697	13.7398
5	5	U0.4	U0.15	50%	95%	94.810745	54.639805	13.8804
5	4	U0.4	U0.4	10%	10%	94.78022	87.057387	25.228
5	4	U0.4	U0.15	10%	10%	94.78022	87.057387	25.228
5	4	U0.4	U0.4	50%	50%	94.78022	86.874237	17.314
5	4	U0.4	U0.15	50%	50%	94.78022	86.874237	17.314
5	3	U0.4	U0.4	10%	95%	94.78022	72.435897	18.1712
5	5	U0.4	U0.4	10%	95%	94.78022	54.273504	18.3118
5	3	U0.4	U0.15	10%	95%	94.78022	72.435897	18.1712
5	5	U0.4	U0.15	10%	95%	94.78022	54.273504	18.3118
5	4	U0.4	U0.4	50%	95%	94.78022	65.445665	13.81
5	4	U0.4	U0.15	50%	95%	94.78022	65.445665	13.81
5	4	U0.4	U0.4	50%	10%	94.749695	87.057387	20.7956
5	4	U0.4	U0.15	50%	10%	94.749695	87.057387	20.7956
5	3	U0.15	U0.4	50%	10%	94.71917	81.288156	17.717
5	3	U0.15	U0.15	50%	10%	94.71917	81.288156	17.717
5	5	U0.15	U0.4	10%	50%	94.71917	88.644689	21.7318
5	5	U0.15	U0.15	10%	50%	94.71917	88.644689	21.7318
5	3	U0.15	U0.4	50%	50%	94.71917	81.105006	15.1784
5	3	U0.15	U0.15	50%	50%	94.71917	81.105006	15.1784
5	3	U0.15	U0.4	10%	50%	94.688645	81.135531	19.6124
5	3	U0.15	U0.15	10%	50%	94.688645	81.135531	19.6124
5	3	U0.15	U0.4	10%	95%	94.688645	78.113553	17.3166
5	5	U0.15	U0.4	10%	95%	94.688645	47.435897	17.4356
5	3	U0.15	U0.15	10%	95%	94.688645	78.113553	17.3166
5	5	U0.15	U0.15	10%	95%	94.688645	47.435897	17.4356
5	3	U0.15	U0.4	50%	95%	94.688645	77.930403	12.8824
5	5	U0.15	U0.4	50%	95%	94.688645	47.344322	13.0016

Tbl 12: Iterative design CSV data.

GRASSCHOPPER AND LADYBUG TOOL SCRIPT DEFINITION

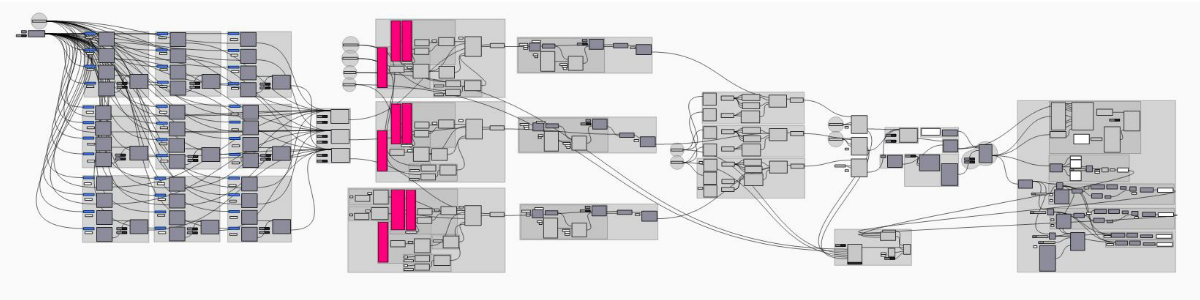


Fig 46: Grasshopper and ladybug tool script definition.

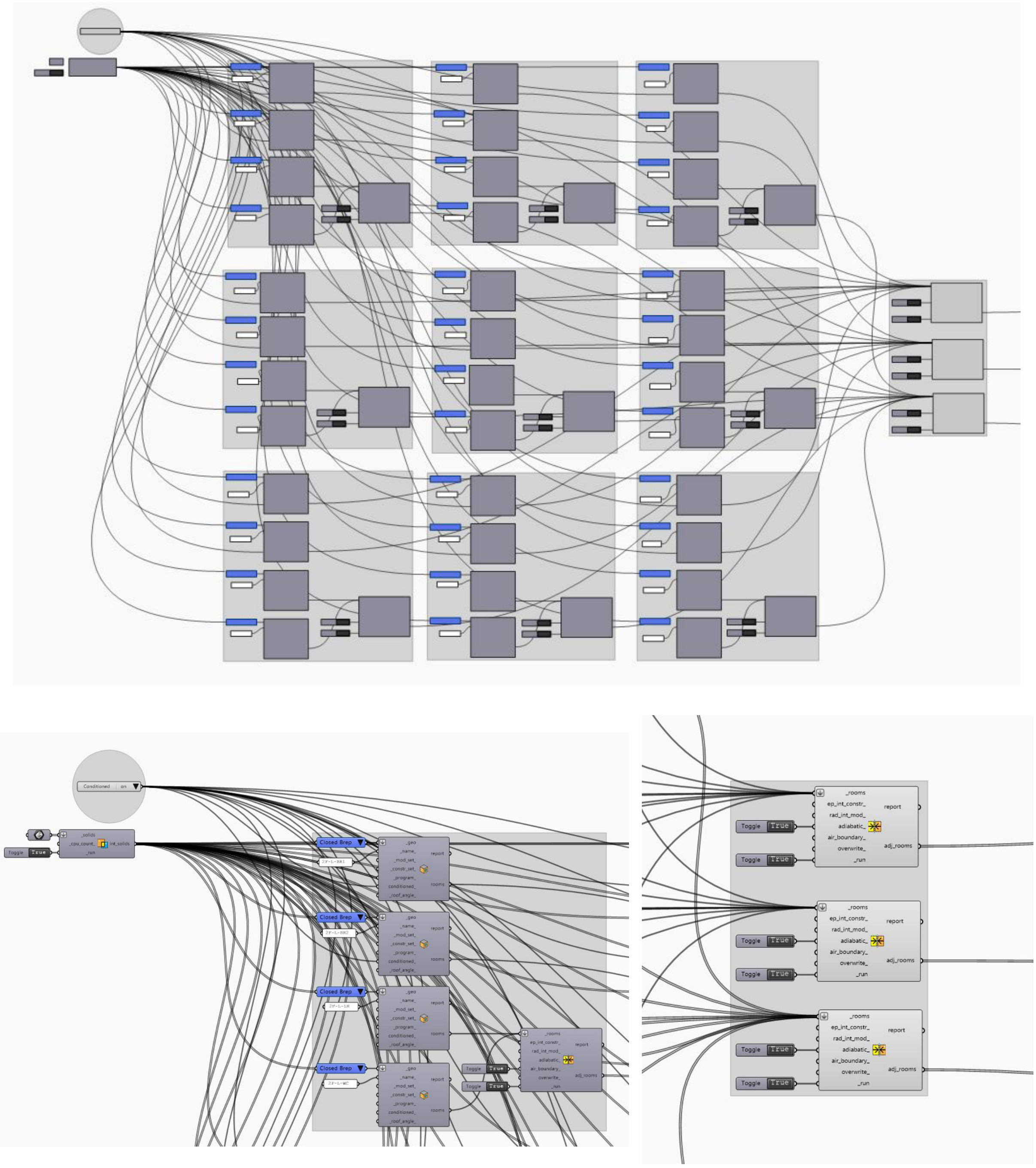


Fig 47: Room definition.

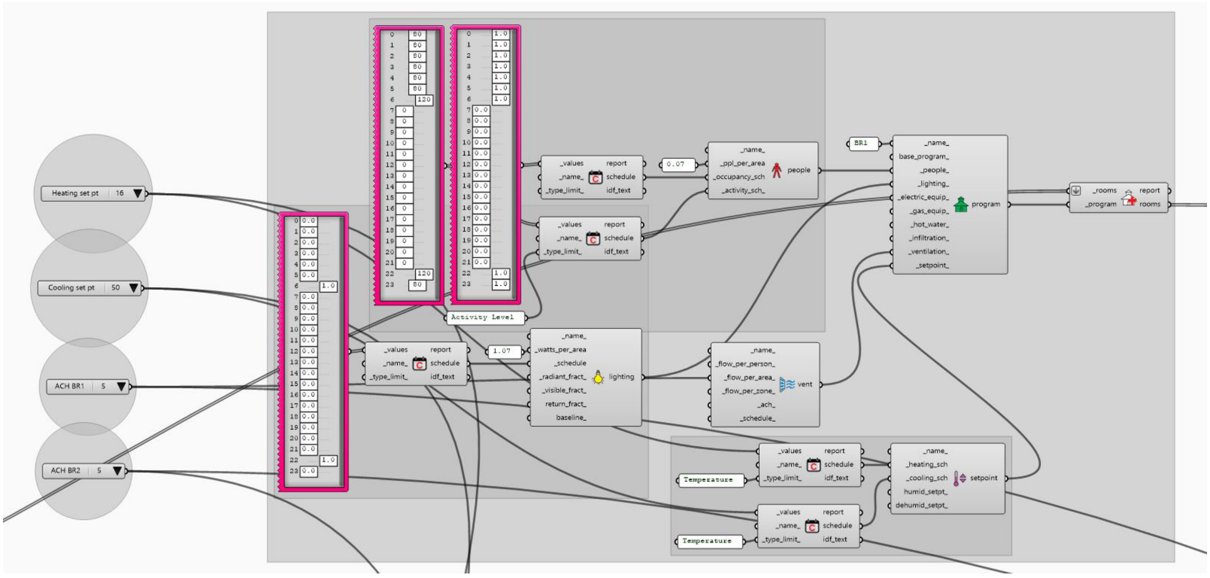


Fig 48: Bedroom programme definition.

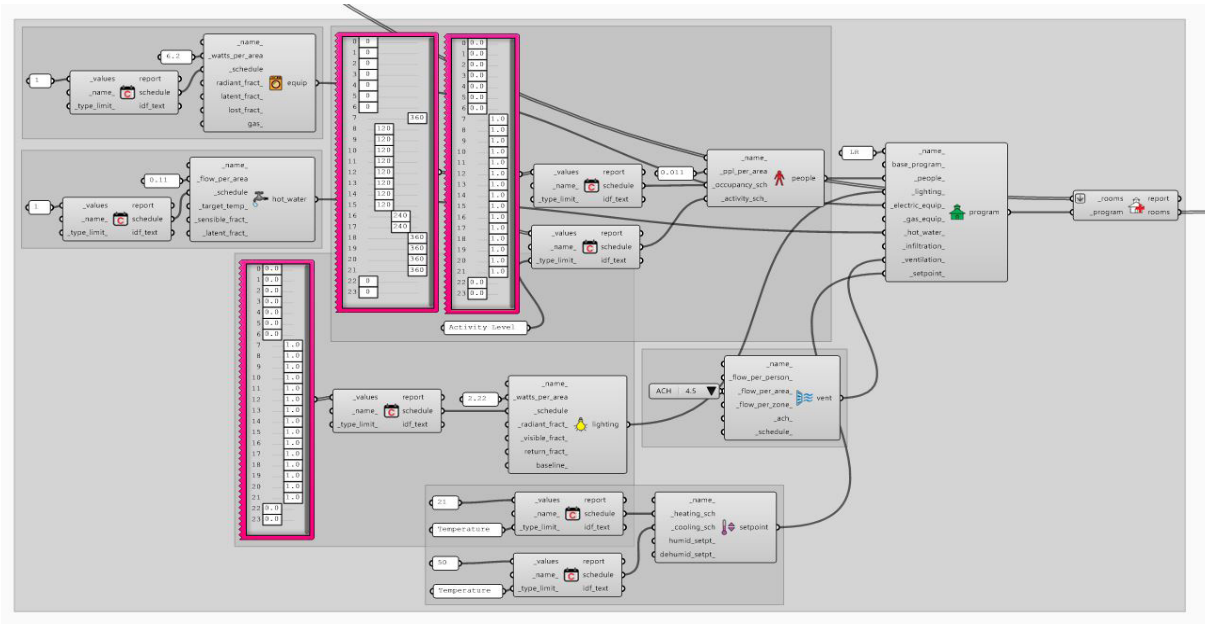


Fig 49: Living room programme definition.

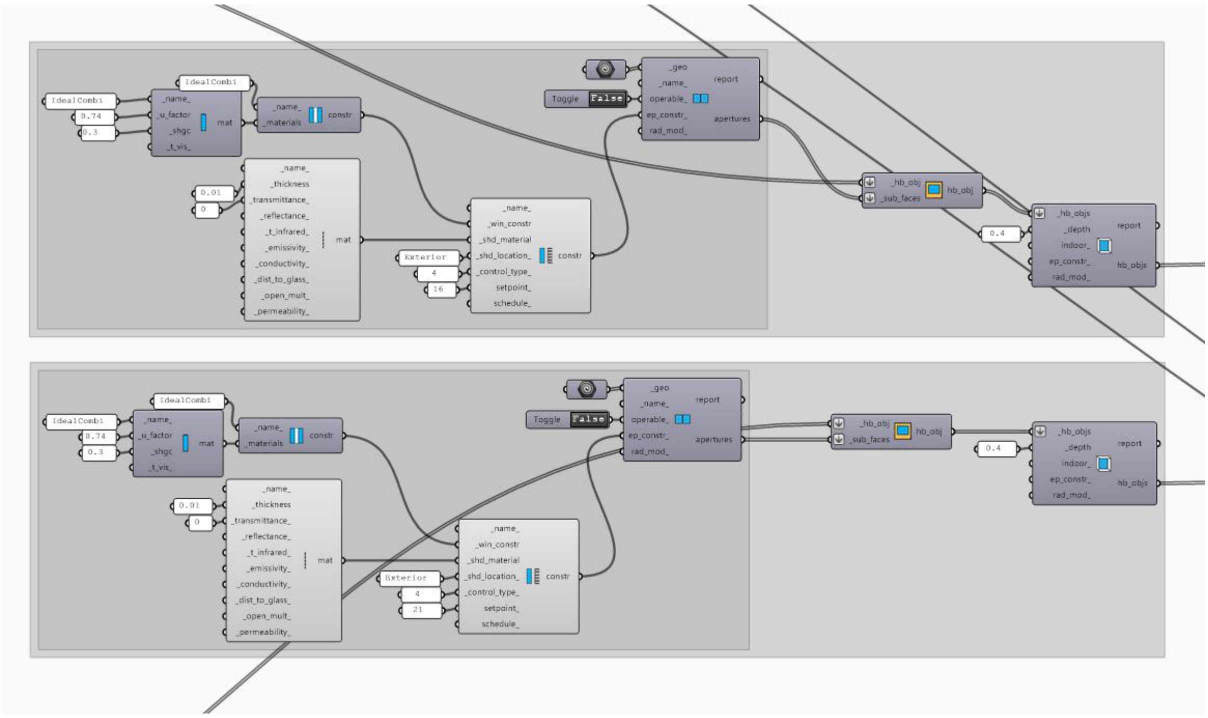


Fig 50: Window definition.

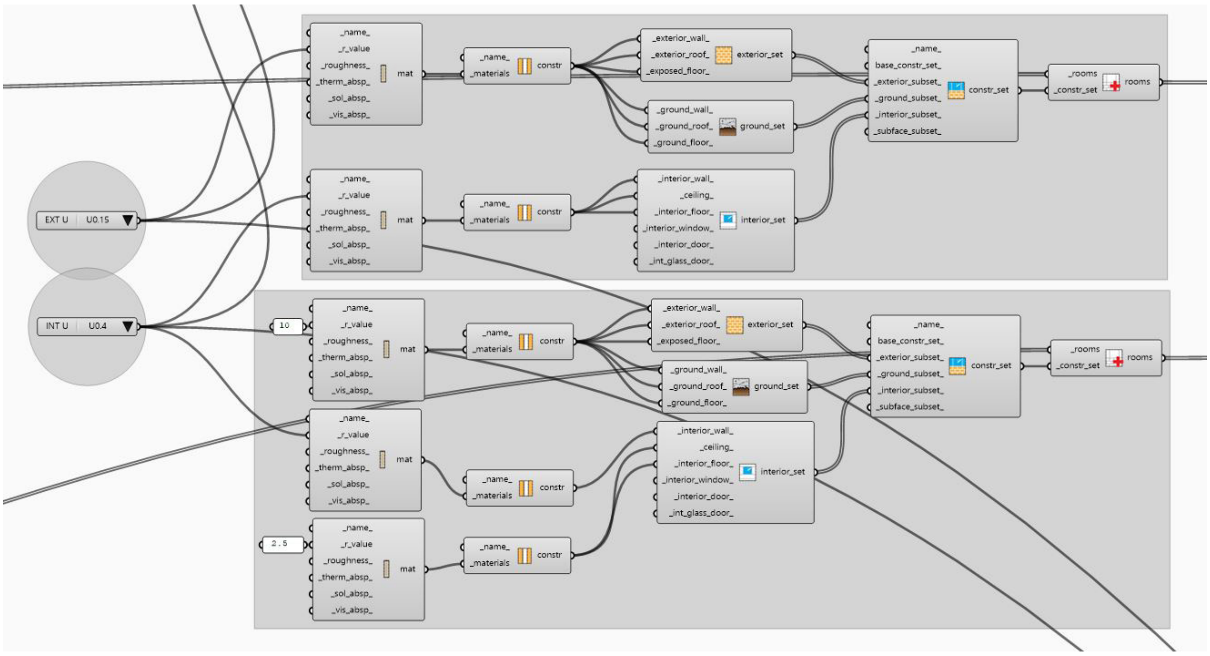


Fig 51: Construction definition.

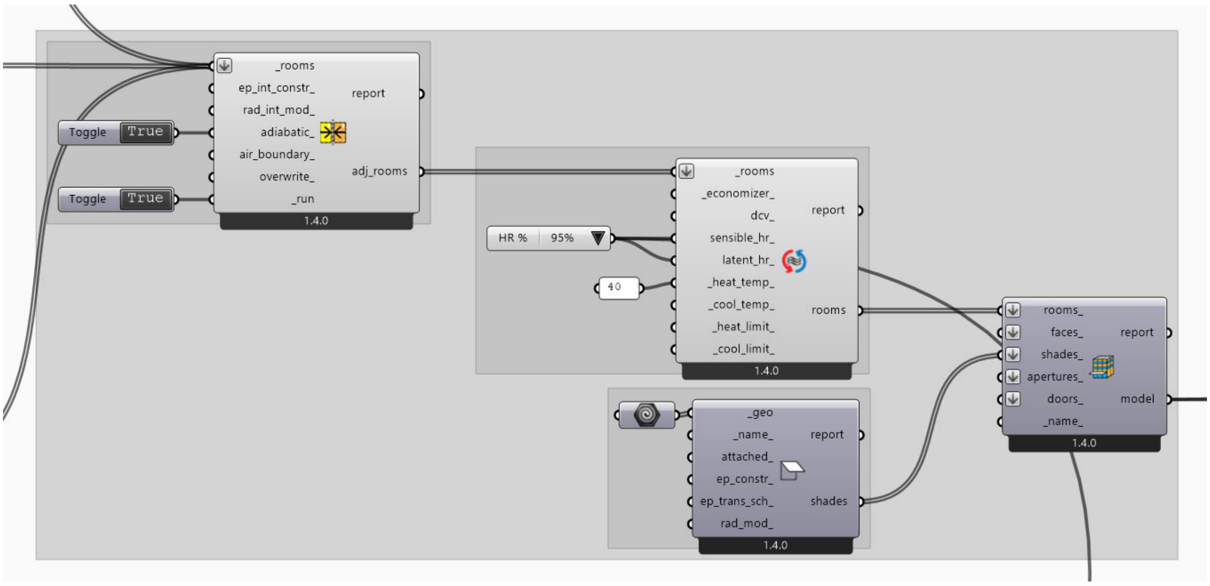


Fig 52: Centralized MVHR definition.

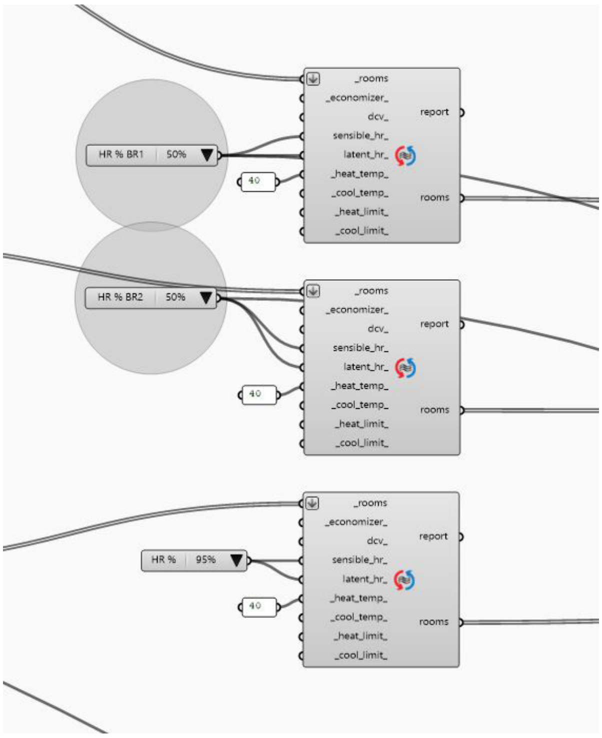


Fig 53: Decentralized MVHR definition.

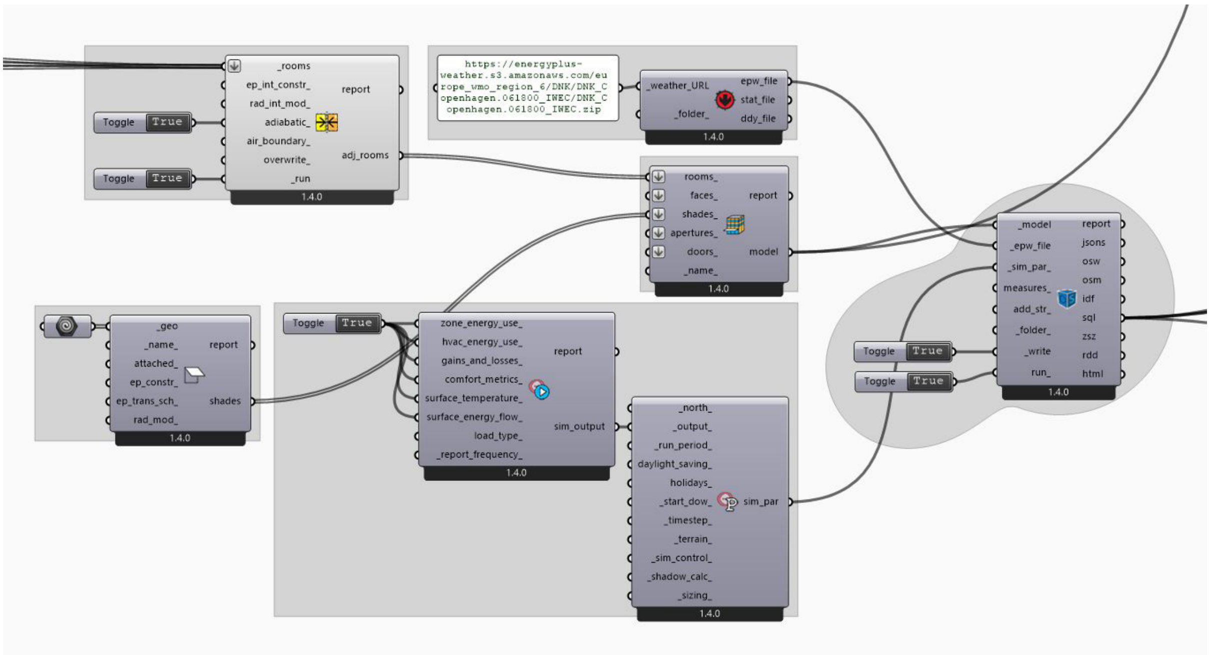


Fig 54: Model definition.

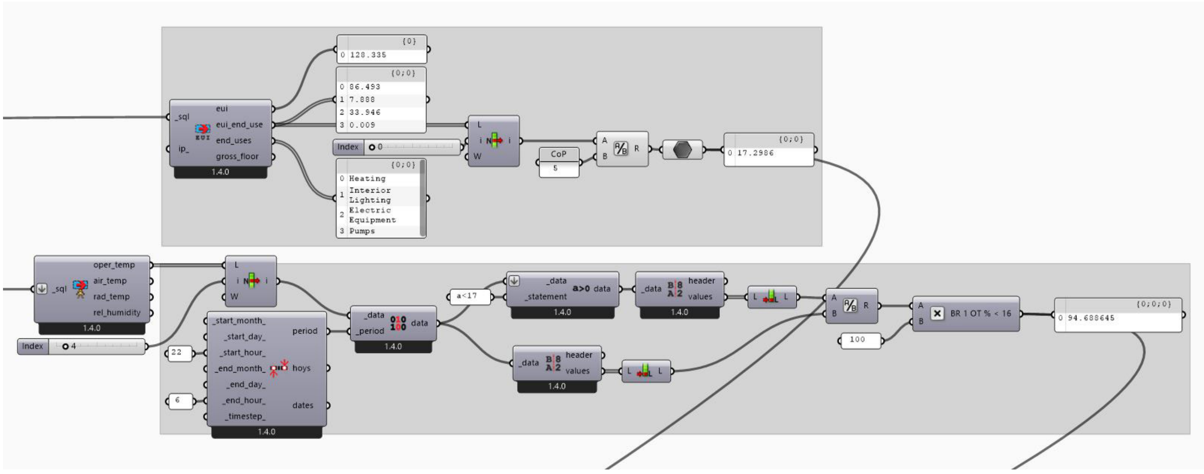


Fig 55: Output result definition.

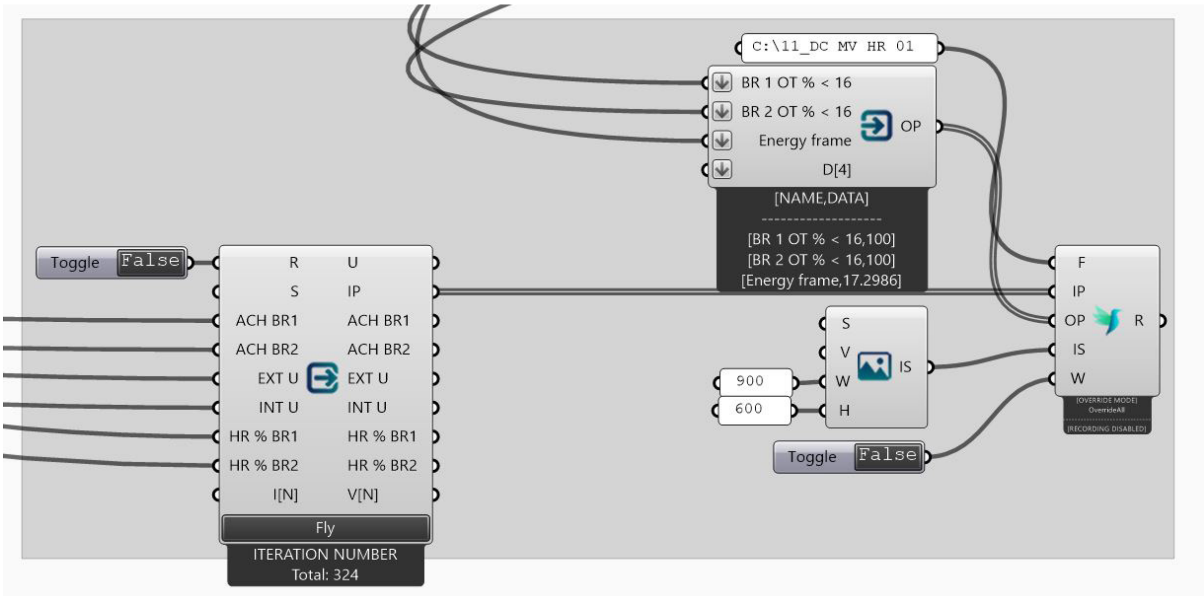


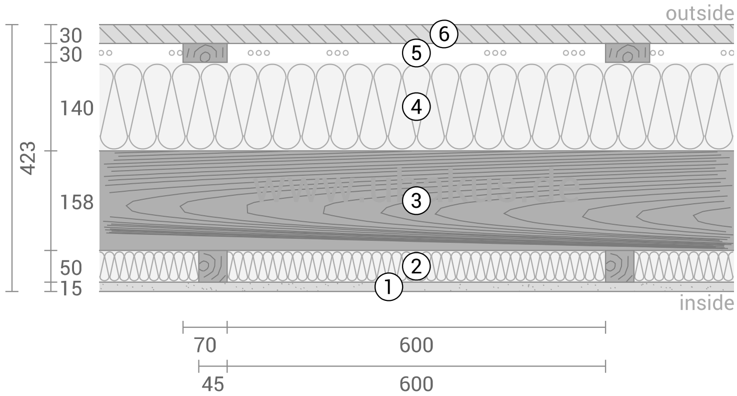
Fig 55: Automated iterative design definition.

CONSTRUCTION TECHNOLOGY

Thermal protection
U = 0,15 W/(m²K)
GEG 2020 Bestand*: U<0,24 W/(m²K)
excellent insufficient

Moisture proofing
No condensate
excellent insufficient

Heat protection
Temperature amplitude damping: >100
phase shift: non relevant
Thermal capacity inside: 106 kJ/m²K
excellent insufficient



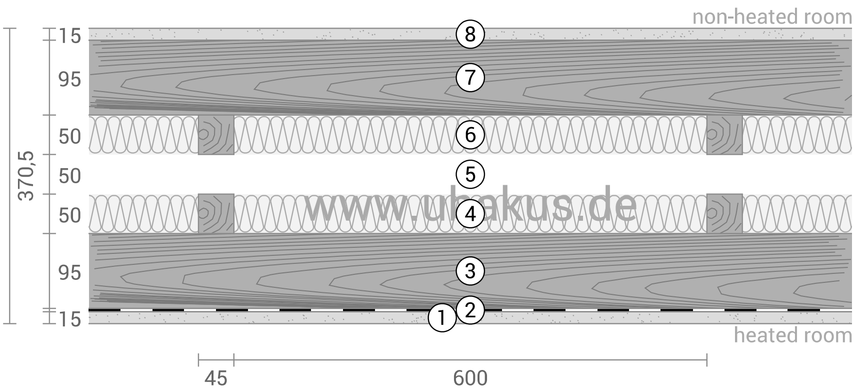
1. Fermacell Gypsum Fibre Board15mm (15 mm)
2. ROCKWOOL Klemmrock 035 (50 mm)
3. CLT (158 mm)
4. ROCKWOOL Kernrock 035 (140 mm)
5. Rear ventilated level (30 mm)
6. Clay bricks 1500kg/m³ (30 mm)

Fig 56: External wall construction.

ıermal protection
= 0,22 W/(m²K)
G 2020 Bestand*: U<0,3 W/(m²K)
:ellent insufficient

Moisture proofing
No condensate
excellent insufficient

Heat protection
Temperature amplitude damping: 67
phase shift: 15,0 h
Thermal capacity inside: 93 kJ/m²K
excellent insufficient



1. Fermacell Gypsum Fibre Board15mm (15 mm)
2. Vapor barrier sd=100m
3. CLT (95 mm)
4. ROCKWOOL Kernrock 035 (50 mm)
5. Stationary air (50 mm)
6. ROCKWOOL Kernrock 035 (50 mm)
7. CLT (95 mm)
8. Fermacell Gypsum Fibre Board15mm (15 mm)

Fig 57: Fire partition wall construction.

Thermal protection

U = 0,14 W/(m²K)

Heated on both sides: No requirement*

excellent insufficient

Moisture proofing

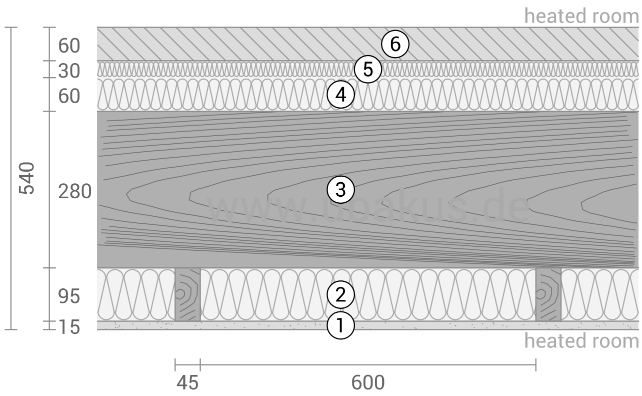
No condensate

excellent insufficient

Heat protection

Temperature amplitude damping: >100
phase shift: non relevant
Thermal capacity inside: 129 kJ/m²K

excellent insufficient



1. Fermacell Gypsum Fibre Board15mm (15 mm)
2. ROCKWOOL Klemmrock 035 (95 mm)
3. CLT (280 mm)
4. Knauf Insulation Supafil Loft Plus (60 mm)
5. Cork (30 mm)
6. Cement screed (60 mm)

Element free span 8m in order to fulfill to all regulations.

Fire class - R60 according to BR18.
Sound class - L'n,W>48dB according to DS490 Sound class A.
Load-bearing capacity - qk[kN/m2]=1.5, Qk[kN]=2 according to EN 1991-1-1 DK NA:2007
Imposed loads on floors A1 categories of use.
Vibration according to EN 1995-1-1 (f1 > 8 Hz).
Deformation according to EN 1995-1-1.

Fig 58: Floor partition construction.

Thermal protection

U = 0,14 W/(m²K)

Heated on both sides: No requirement*

excellent insufficient

Moisture proofing

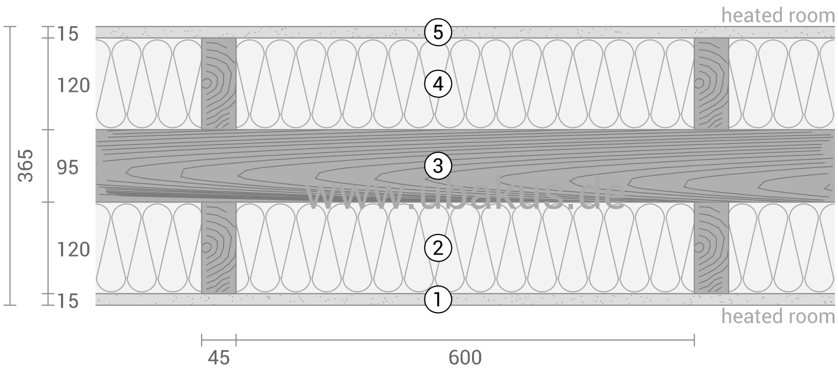
No condensate

excellent insufficient

Heat protection

Temperature amplitude damping: >100
phase shift: non relevant
Thermal capacity inside: 64 kJ/m²K

excellent insufficient



1. Fermacell Gypsum Fibre Board15mm (15 mm)
2. ROCKWOOL Kernrock 035 (120 mm)
3. CLT (95 mm)
4. ROCKWOOL Kernrock 035 (120 mm)
5. Fermacell Gypsum Fibre Board15mm (15 mm)

Fig 59: Partition wall construction.

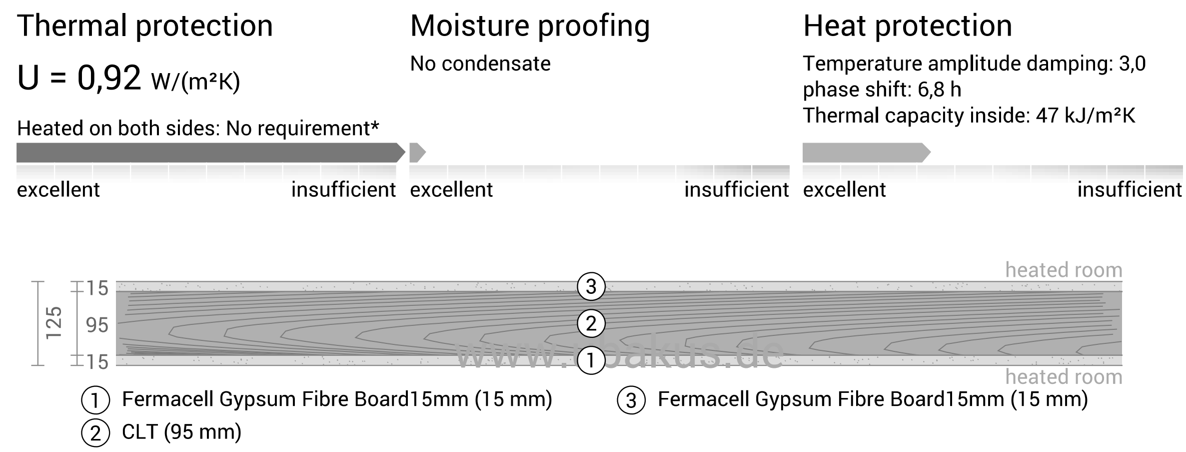


Fig 60: Partition wall construction.

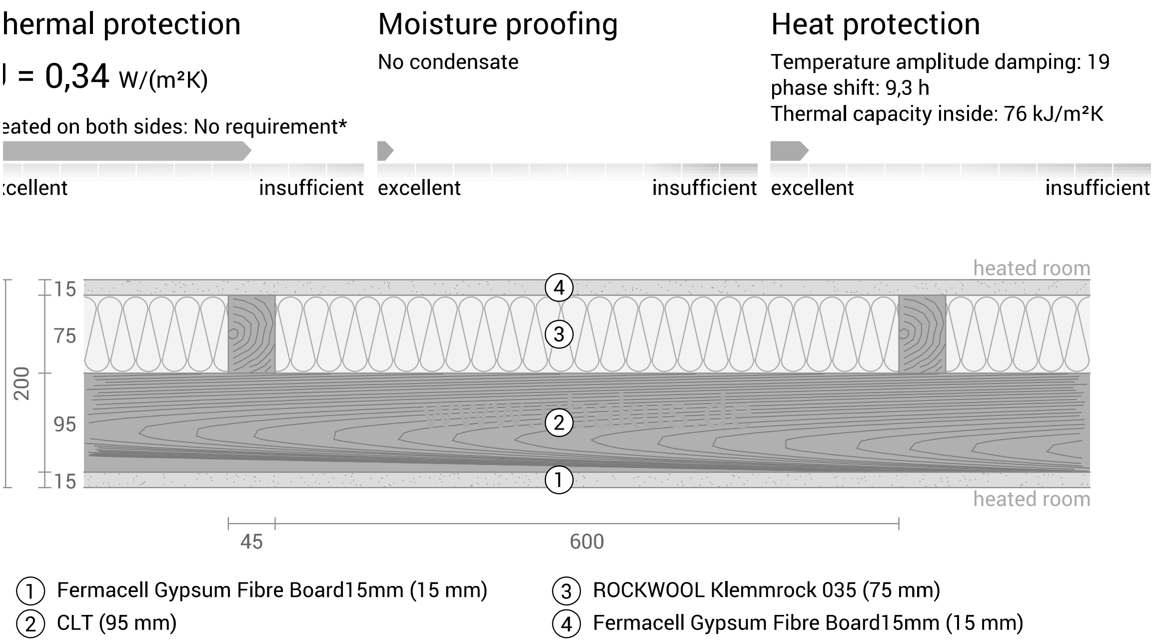


Fig 61: Partition wall construction.