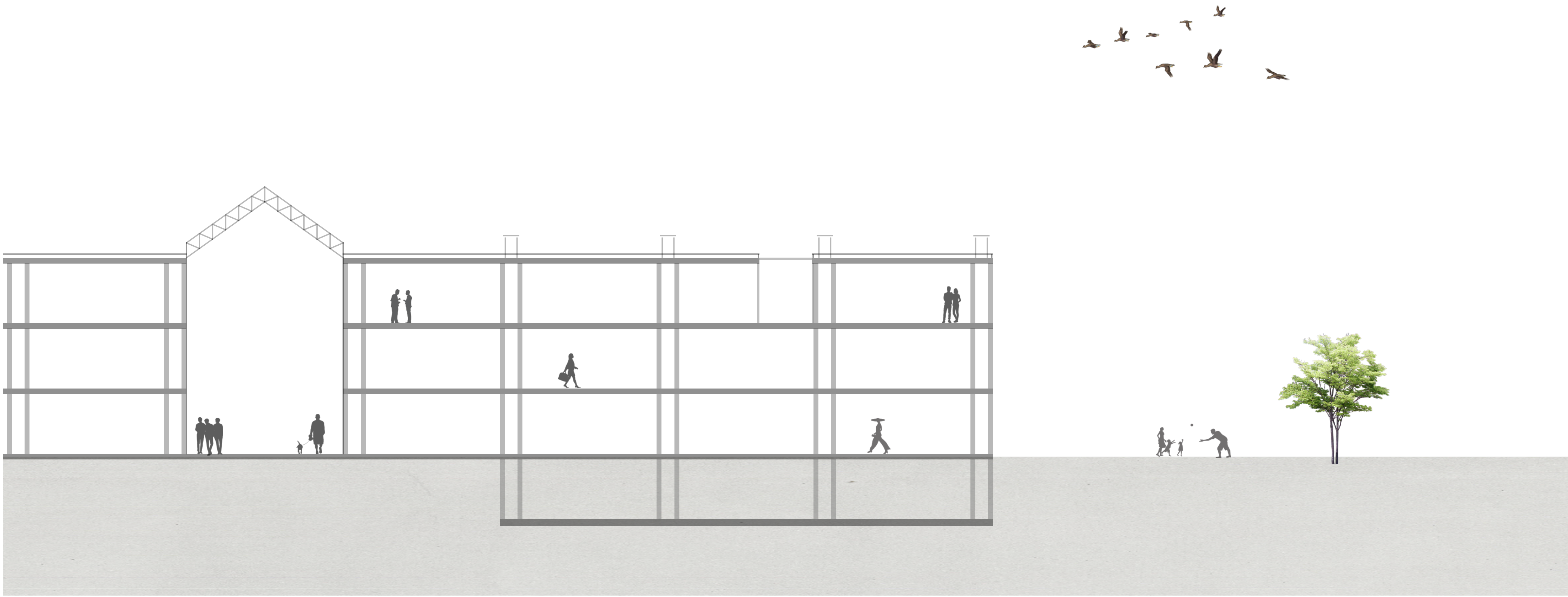
DRAGVOLL TRANSFORMATION PROJECT

Master‘s Thesis in Sustainable Architecture
Supervisors: Per Monsen & Luca Finocchiaro

David Garlick
2021



NTNU
Norwegian University of Science and Technology

ABSTRACT

Dragvoll campus contains a series of individual buildings connected by glass covered streets, creating a city within a city. The structure was purpose built to house NTNU and has done so since its construction in 1978.

NTNU plans to consolidate its campuses to a central location. As a result, the campus at Dragvoll will be vacated and in need of a new function if it is to avoid demolition.

This thesis investigates the possibility of transforming the space into apartments and shared workspace, focusing on one building in detail. Detailed energy and daylight analysis were used to drive design decisions.

The deep building provided challenges with apartments only having access to one outer façade. To resolve this, terraces and atriums were introduced to increase daylight. The result is two apartment designs that are energy efficient, have good daylight qualities and comfortable indoor environments.

The historical Dragvoll campus has a great potential to continue to service the community and provide an alternative to city living.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

INTRODUCTION

Dragvoll campus currently houses several faculties of the Norwegian University of Science and Technology (NTNU). Consisting of a series of individual buildings connected by glass covered streets, the structure was purpose built to house the expanding university located in Trondheim and has done so since its construction in 1978.

NTNU plans to consolidate its campuses in Trondheim to a central location around the existing Gløshaugen campus to improve interdisciplinary cooperation. As a result, the campus at Dragvoll will be vacated and in need of a new function if it is to avoid demolition.

BACKGROUND

The Dragvoll site and its surrounding area has been farmland since the 15th century. In 1968 it was purchased by the University of Trondheim to build a new campus on the outskirts of the city. The location was chosen for several reasons, mainly the availability of surrounding land and proximity to nature. This availability allowed for future expansion, which planned to include parks, sporting venues and student housing. The surrounding land was to remain agricultural until expansion of the campus required its acquisition. Original plans provided 500,000 m^2 of campus area and 25,000 students. This location allowed for the freedom and flexibility to enable Dragvoll to develop as required over time.

Dragvoll was designed by Danish architect Henning Larsen in conjunction with local firm PKA Arkitekter. Larsen's vision at Dragvoll draws both criticism and praise. The daylight qualities within the streets are exceptional and the flexibility of the structure evident. While students complain of a confusing layout and streets too cold in winter and too hot in summer, long term occupation of the streets was not the intention.

Ultimately Dragvoll did not become the large city within a city that was envisioned. One possible reason is the demand for the urban lifestyle among students. Universities and the student population it brings can transform cities and make them more vibrant. In Trondheim students tend to move away from student villages to more central locations. While enjoying a vibrant city lifestyle, access to the forest and cross-country tracks remain a short bus journey. The Dragvoll area has however become an attractive place for families in need of more space and wanting to escape the city.

Regardless, Dragvoll has served its purpose as a university campus for 43 years and will do so until at least 2027 when NTNU's campus development plan is scheduled for completion. During this period Dragvoll campus has become part of Trondheim's cultural heritage.

NTNU plans to build a host of new energy efficient buildings, however, the most sustainable building is the one already built. A report by the US National Trust for Historic Preservation concluded "reusing an existing building and upgrading it to be as efficient as possible is almost always the best choice regardless of building type and climate" [1]. 2021 Pritzker Prize winners, Lacaton & Vassal, have built an office around the principle of "never demolish". Giving value to what exists before making changes and doing more with what exists [2]. Society can no longer continue to build new buildings to solve the climate crisis, regardless of their energy efficiency. Improving and upgrading existing buildings must play a major part in society if the UN sustainability goals are to be achieved. Additionally, disassembly and reuse of construction material, especially reinforced concrete is not yet common practise and requires further investigation. To demolish the campus at Dragvoll would be a setback for the sustainability record of Norway.

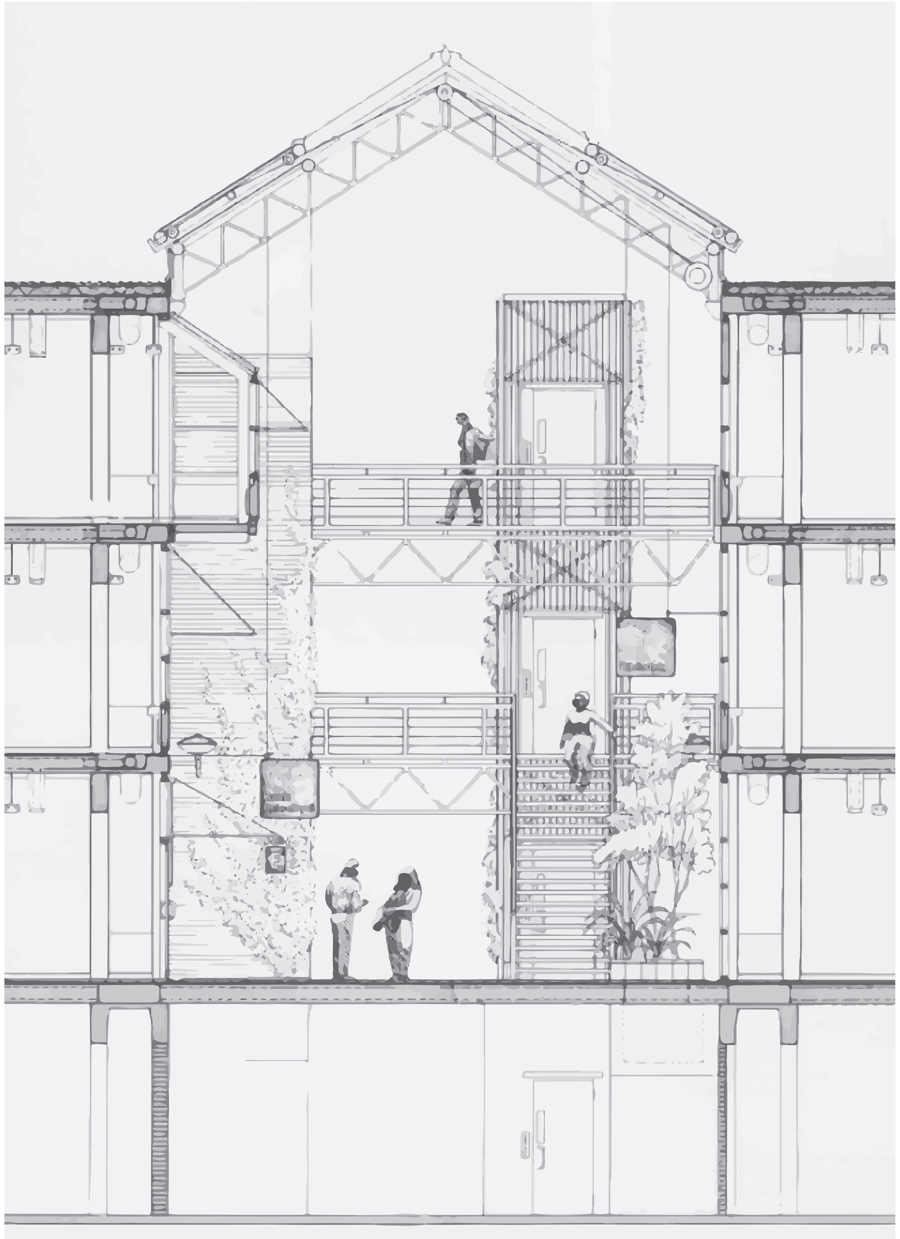


Figure 1. Street Section [3]

Figure 2. Street Perspective [3]

INTRODUCTION

SCOPE

The scope of this thesis was to investigate in detail to what extent the structure can accommodate different functions. It examined if the integrated structural and technical system could be re-purposed effectively, and what is the minimum façade renovation required to improve energy efficiency.

After the initial investigation into the site, building history and structure, building 8 level 3 (Figure 3) was used as a case study and analysed and designed in detail.

Once functions were proposed, daylight and energy simulations drove the design in a quantitative aspect to reduce energy demand. Floor plans were created to ensure architectural qualities were maintained.

Specific goals of this thesis:
Create a hub for people in the area to have a place to work without needing to commute to the city each day.
Design two different sized apartments that would allow different sized families and incomes to live in the building.
Create a sense of community living.
Ensure daylight quality is achieved.
Minimise new materials.
Ensure architectural quality is achieved.

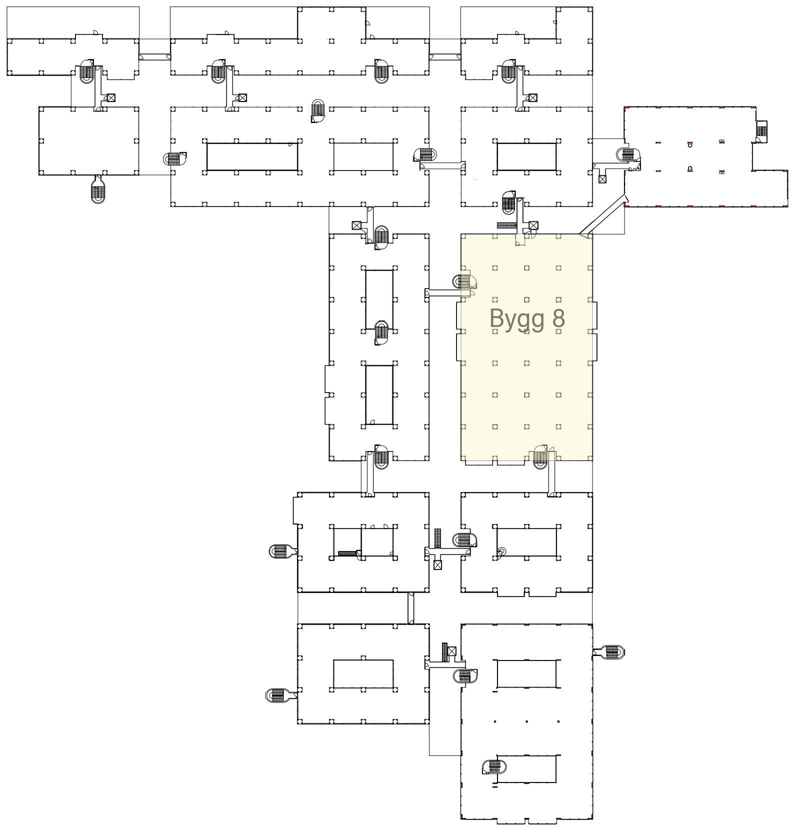


Figure 3. Dragvoll Campus 1:2000

Figure 4. Interior atrium

Figure 5. Dragvoll exterior [3]

INTRODUCTION

METHODOLOGY

To assess if the campus can be effectively transformed to serve a new function, an integrated energy design (IED) process was followed:

1. Literature review
2. Site analysis
3. Building history
4. Understanding of structural system
5. Function proposal
    a. Overall campus
    b. Building 8, general
    c. Building 8 level 3, specific
6. Daylight analysis
7. Energy Analysis
8. Floor plan design
9. Iterative design process repeating steps 6,7 & 8
10. Final design & final analysis

The initial stage of this thesis was to analyse the site, surrounds, and buildings. This included contacting PKA Arkitekter, NTNU Dragvoll campus facility managers and Trondheim commune for information and drawings. In addition, site visits to the campus were made and included questioning students in regard to their experience on campus.

Once the structural systems and functionality of the campus was examined, potential new functions were investigated for the entire campus. The project then focused on building 8 as it is the largest building without an existing atrium, thus providing some design challenges.

After the functions were proposed, daylight and energy analysis was completed to drive design of the floor plans. Floor plans were created to ensure architectural qualities were maintained, while simulations provided quantitative results to reduce energy demand and improve daylight. An iterative design process, with simulations driving major design decisions was formed.

Simulations were completed in Honeybee for Rhino. Version 1.2.0 for energy and version 0.0.69 for daylight. Floor plans and modelling was completed in Archicad, and construction sections in AutoCAD.

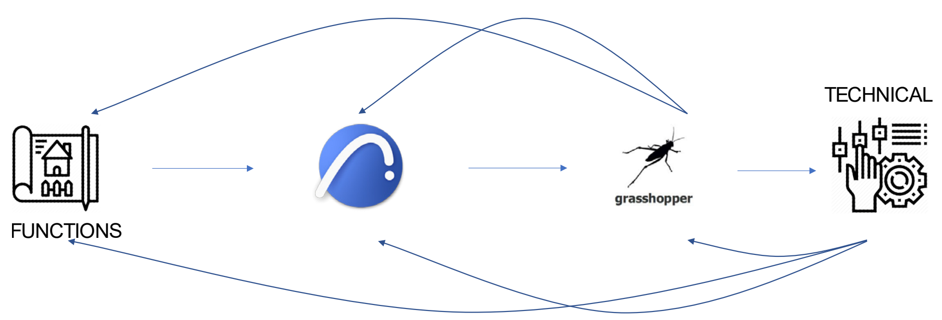


Figure 6. Work flow

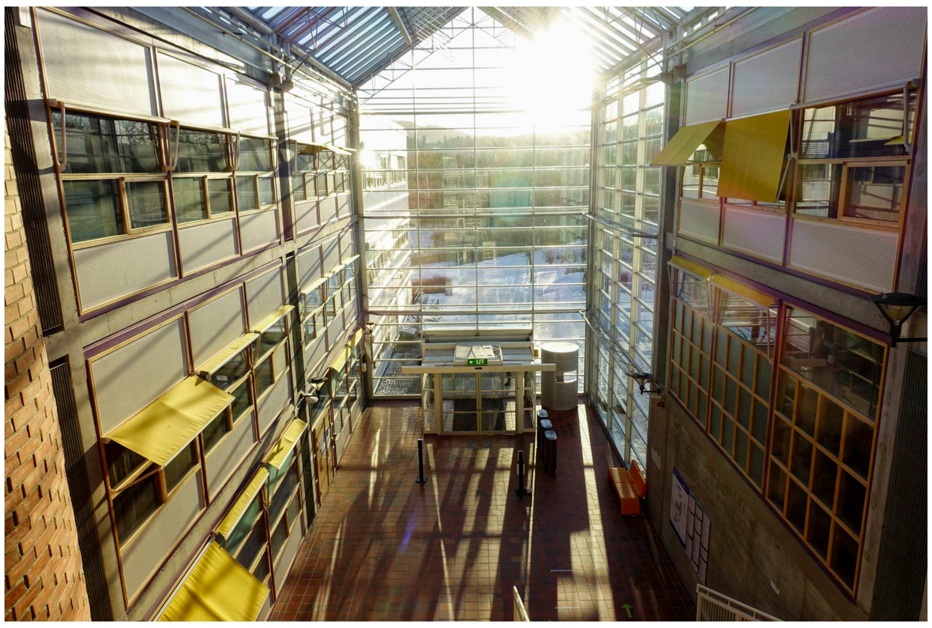


Figure 7. Dragvoll south entrance

Figure 8. Dragvoll interior [3]

2. SITE & CONTEXT

SITE & CONTEXT

SITE ANALYSIS

Dragvoll is located on the outskirts of Trondheim, 4.5 km from the city centre. It is surrounded by residential developments and close to the Estenstadmarka forest – popular for recreational activities. The site has good existing infrastructure, with frequent bus connections to the city centre (circa 15 minutes), large car parks, bicycle parking and electric vehicle charging stations. It is located near the national E6 highway, 30 minutes from the airport, and existing services including supermarkets, schools, and kindergartens.

The advantage of the site location is the close proximity to the city while having the benefits of countryside living – open space, quiet, nearby forests. It is an ideal area for families looking to escape the city life while maintaining access to essential services. There is evidence of a trend in the global north for counter-urbanisation, with young urban professional parents looking to sub-urban areas as more suitable and affordable location for raising children [4].

Current municipality zone planning shows that the surrounding area will increase in residential and commercial developments, while at the same time preserving the forest boundary from development. Figure 10 is an extrapolation based on current planning.

Dragvoll provides a great opportunity to bring value to the surrounding area and its growing population. With the use of shared office space, it can create an area where professionals can live outside the city without the need for commuting to the city for work every day, increasing family and leisure time.

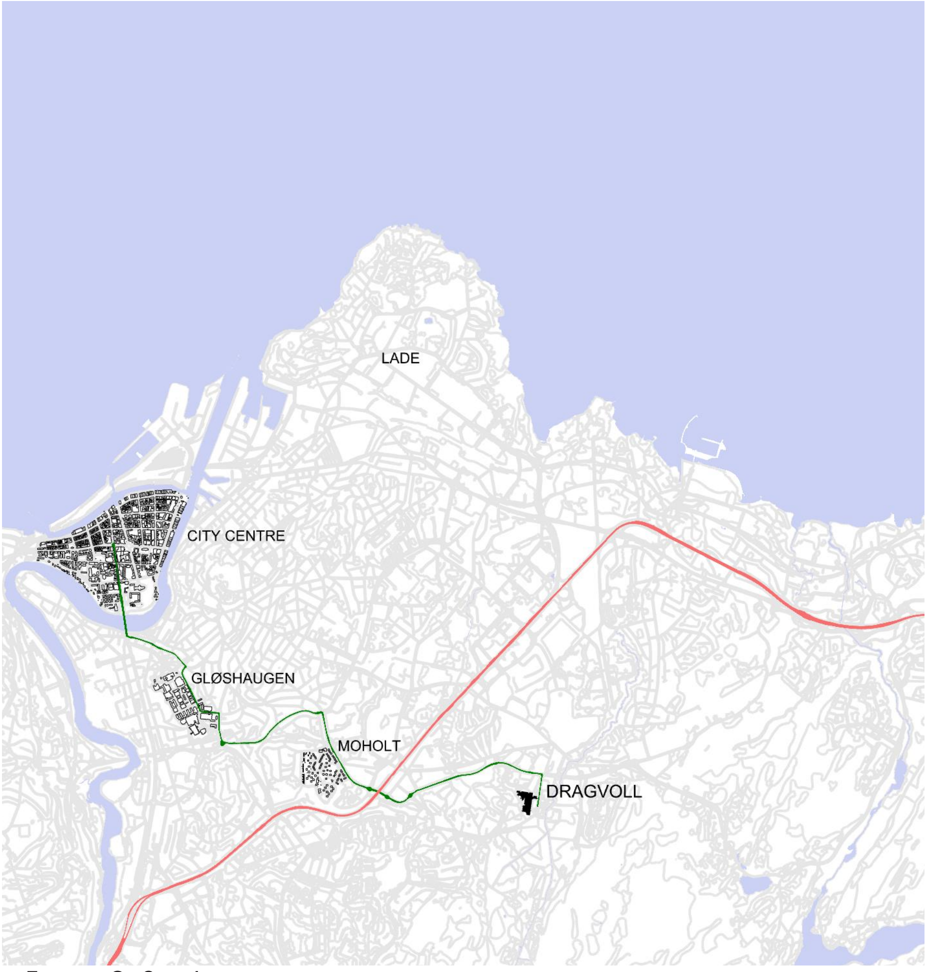


Figure 9. Site Location

CLIMATE

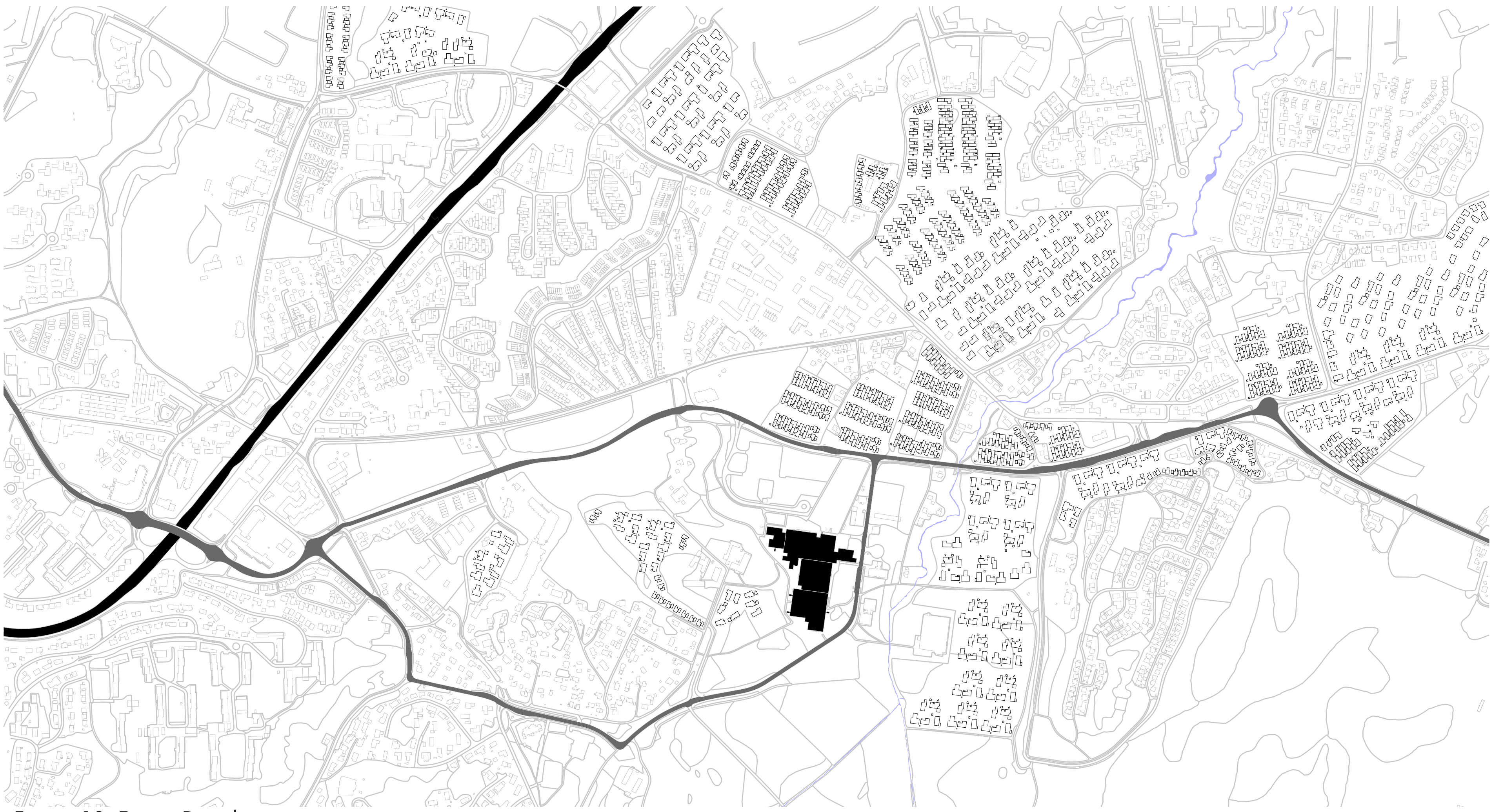


Figure 10. Future Development

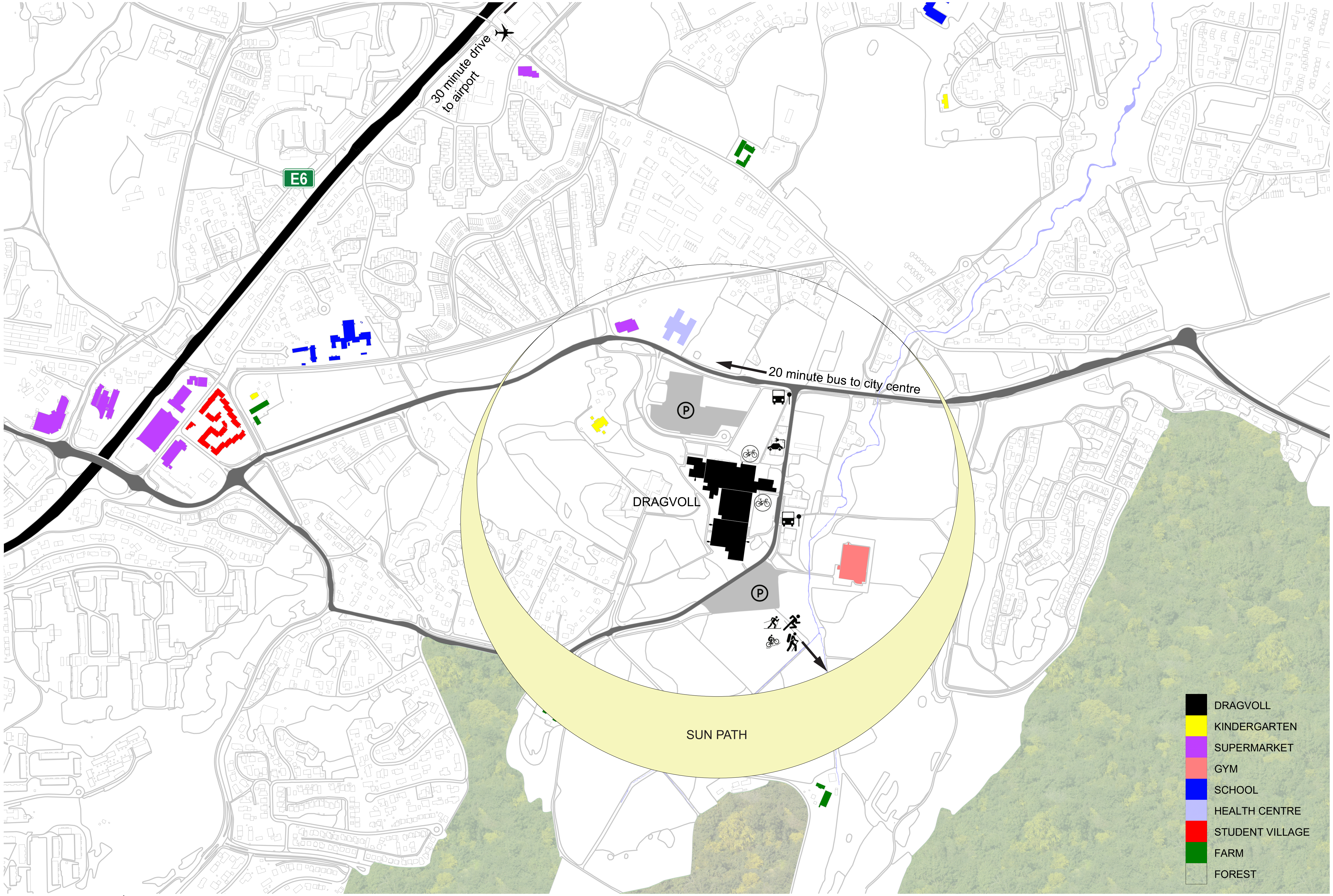


Figure 11. Site Analysis 1:10000

SITE & CONTEXT

Trondheim experiences long cold winters and short cool summers. The average annual dry bulb temperature is 6.4 degrees Celsius with temperatures averaging a minimum of -1°C in February and a maximum of +15°C in July. Annual average sky cover is 68% with Trondheim experiencing consistent precipitation throughout the year approximately, 900mm. Wind is common throughout the year, with dominating from east-south-east to west-south-west (Figure 12).

Dragvoll is located at 160m above sea level and a high point in relation to its surrounding area. As a result, it benefits from views of the fjord to the north and the forest to the east and south. Unobstructed views have the added benefit of increasing solar radiation to the building with shading only caused by other campus buildings. Figure 13 & 14 show the high level of radiation experienced by the eastern façade, roof, and the street glazing.

The climate in Trondheim makes traditional open campus design less attractive. Larsen's solution of glass covered streets creates a climatic refuge for users to commute between buildings with ease.

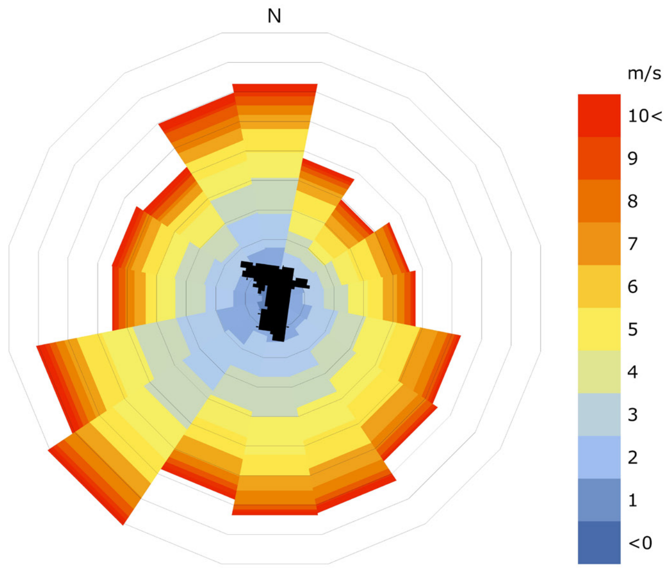


Figure 12. Trondheim Average Annual Wind Speed & Direction

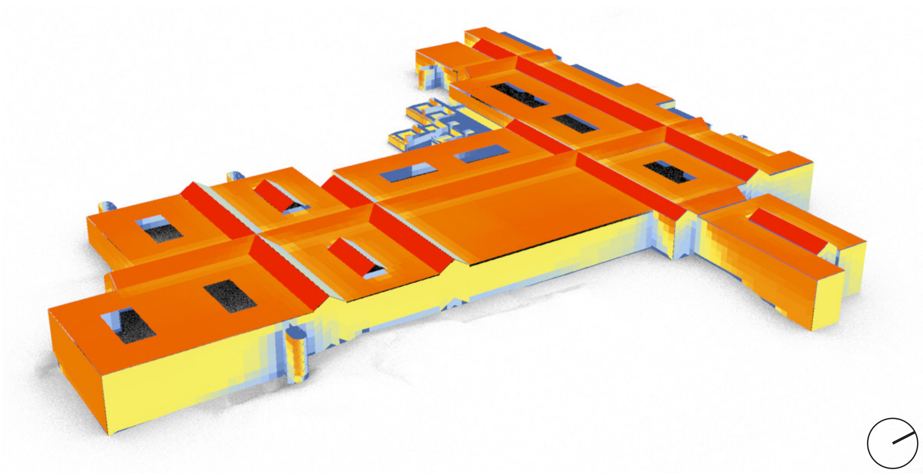


Figure 13. Solar Radiation Analysis

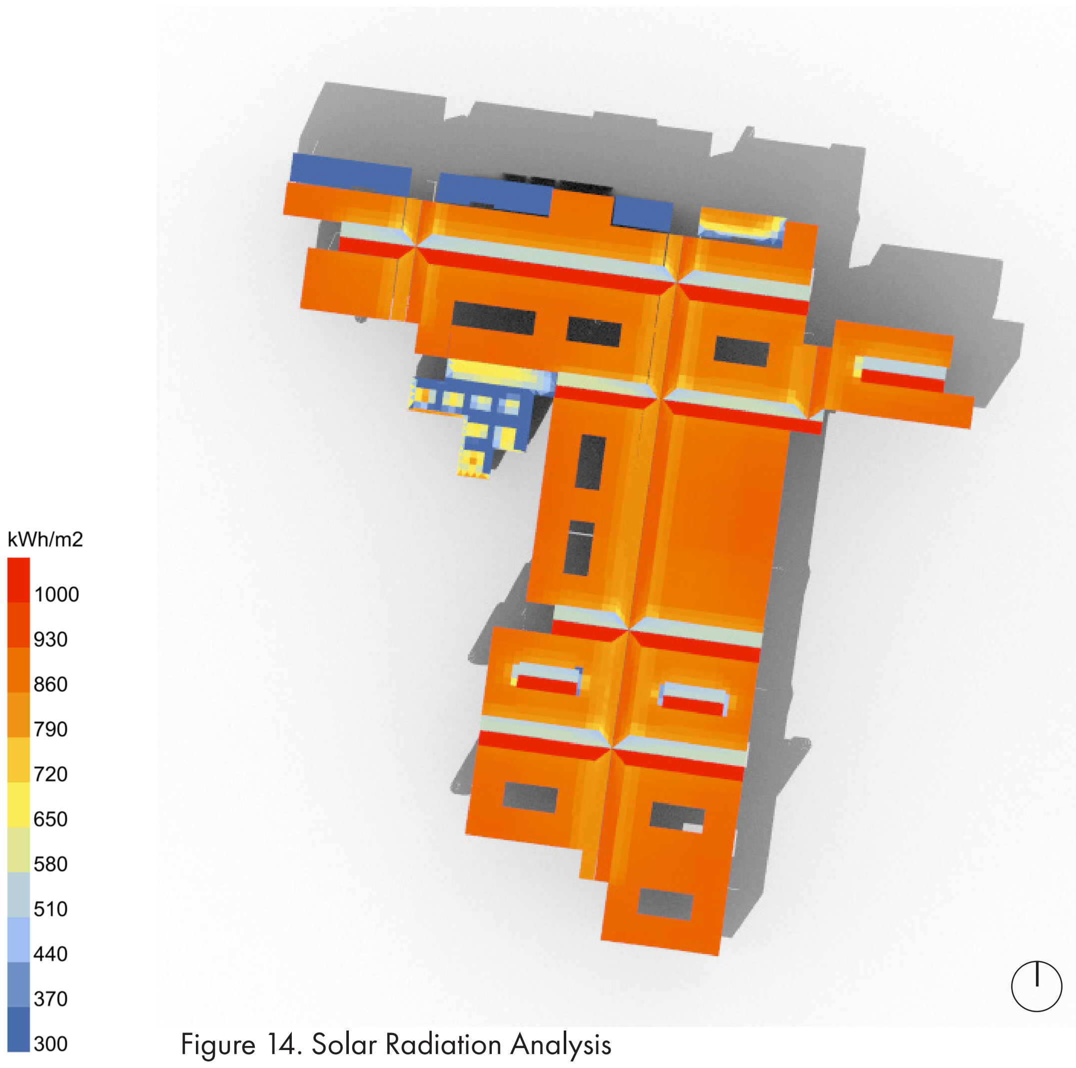


Figure 14. Solar Radiation Analysis

SITE & CONTEXT

CAMPUS

Larsen envisioned a city within a city, an independent university town. To do this, a series of independent modular buildings following a strict grid system was proposed.

The campus consists of low-rise buildings with well-developed communication and a series of covered streets linking the buildings (Figure 15). These covered streets would earn Dragvoll its nickname "Drivhuset" (the greenhouse) and provide an informal space for students to meet and interact, creating a life within the campus. Public functions such as canteens, shops and auditoriums are located on the ground floor with more private functions as office and research labs located in the upper floors.

Known as the "master of light" [5], Henning Larsen placed great emphasis on ensuring good daylight quality within the campus. In addition to the glazed streets which experience good daylight conditions (Figure 7), most individual buildings contain internal atriums introducing light into the compact buildings (Figure 3).

The glazed street roof acts to create a relatively comfortable climatic zone for pedestrians year-round, without obstructing the flow of movement. Heated air from adjacent buildings is exhausted into the street when heating is required. In cooling periods, the glazed roof is partially operable providing the ability to ventilate excess warm air. This creates the occasional inconvenience when rain occurs on a warm summer day. The presence of the glazed streets allows for non-traditional exterior walls on the façades facing internally, reducing cost. External façades were modularised to reduce cost.

Located outside the city centre, transport connection to the city is of importance. Larsen developed a plan to fully integrate Dragvoll into the city. Large car parks were built to accommodate commuters and today major bus routes efficiently connect the campus to the city centre.

STRUCTURAL SYSTEM

The campus currently consists of 13 individual buildings, built in four phases between 1978 and 2007. The reinforced concrete super structure comprises of a strict column grid with horizontal beams and slabs (Figure 16). The structural system was designed to allow for the ease of expansion for future buildings.

Columns forming the grid comprise of four individual columns with a cavity in the centre which is used to run services vertically from a central technical room located in the basement. This gives a great degree of flexibility to the structure and allows for future buildings to run services through new columns. Figure 17 illustrates the integration of services into the structure.

It can be argued that the cavity is no longer large enough for modern requirements of ventilation ducts and technical services, reducing flexibility of the design. Modern requirements for indoor air quality result in increasingly larger ducts. Furthermore, the square columns are large, at 1.2m wide, and prove a challenging obstruction when designing floor plans.

A lack of structural walls allows for flexibility within each building as functions can easily be changed without obstructing services. With stairs and lifts located on the perimeter of each building, central cores are not required, adding to the flexibility within each building.

Research suggests adaptable structures require several key components, including [6]:

- Increase in regularity in building patterns
- Simplicity in systems and materials
- Use modular coordinate system
- Use prefabricated components design over capacity
- Increase system predictability
- Improve flow through system layout
- Avoid running services through structural sections
- Restrict distribution of function and facilities

Adaptable design increases the life of a building by enabling the building to adapt to new technical and functional requirements. To create an adaptable building, the architect must predict the future use of the building. Deciding the location of mechanical systems limits flexibility to a degree. Columns providing mechanical services cannot be relocated, whereas a structural wall can be replaced, though not without difficulty.

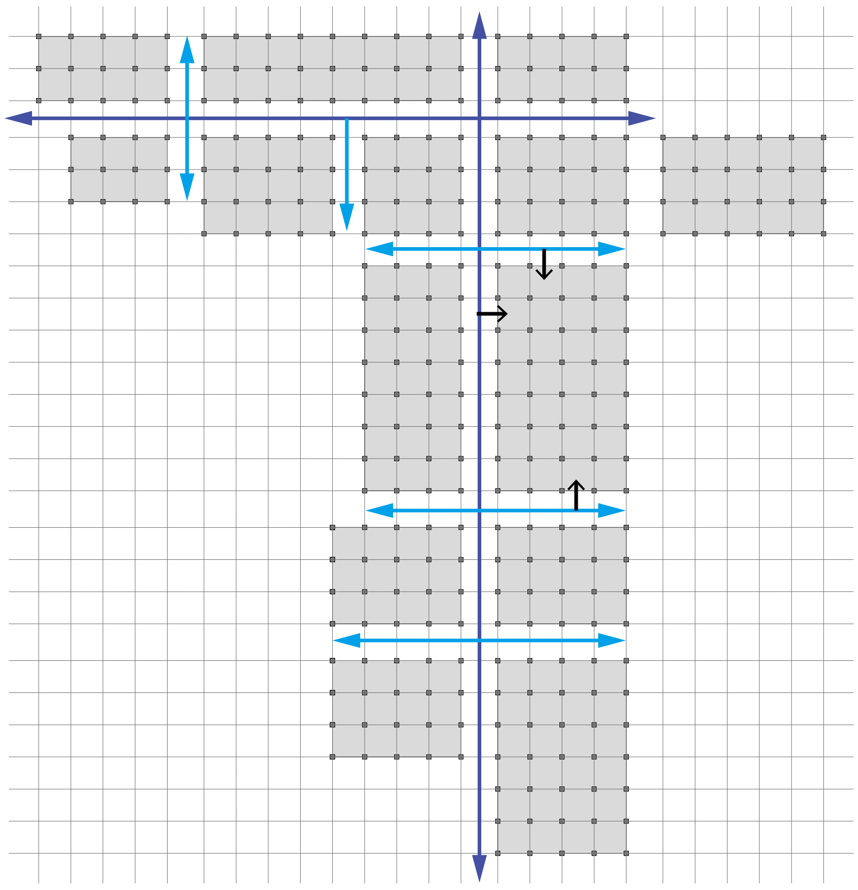


Figure 15. Communication 1:2000

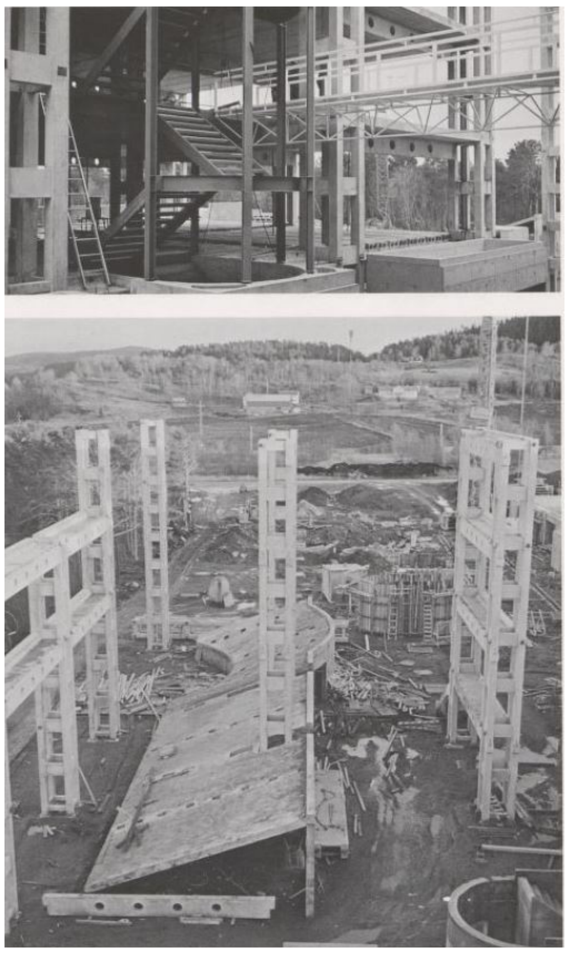


Figure 16. Concrete structure shown during construction

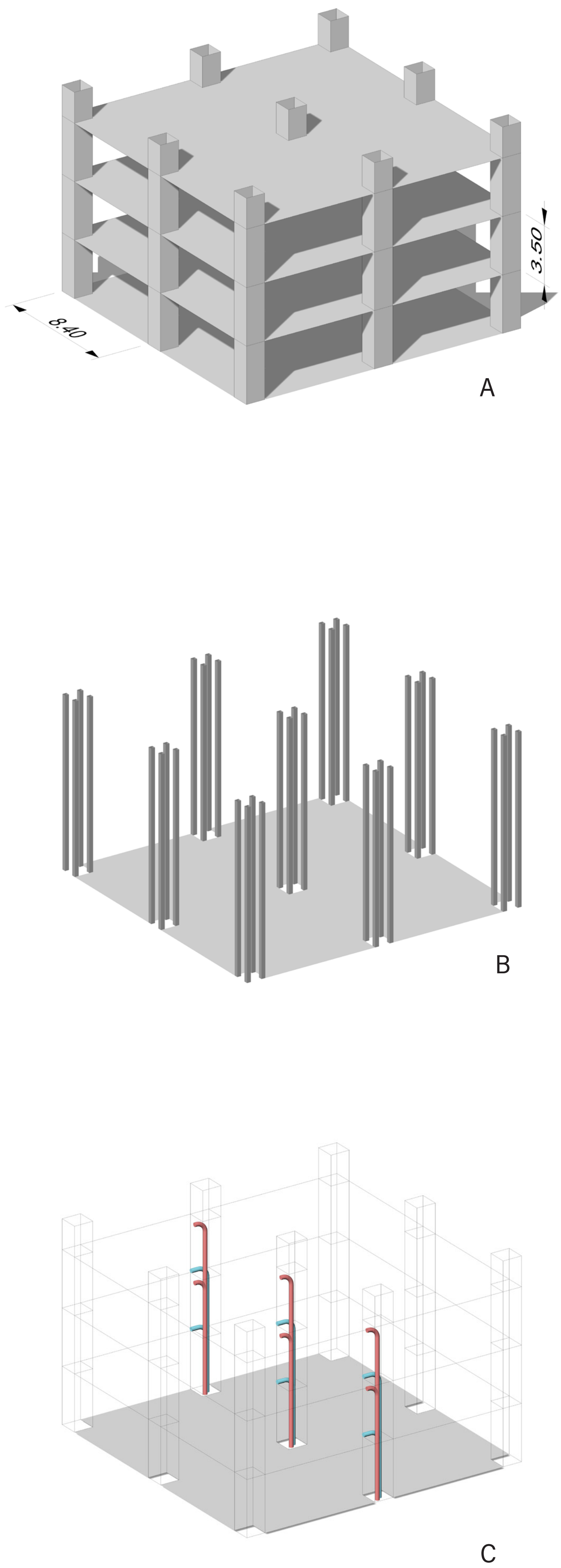


Figure 17. Structural System Breakdown

A. column and slab system
B. structural columns (4 off 250mm reinforced concrete)
C. service pipes located in the central cavity of columns

3. DESIGN

PROGRAM

There is great potential for Dragvoll to become a service hub for the surrounding community. To understand how it could serve the community, the overall potential of Dragvoll was assessed and new functions proposed. Resulting in a combination of public functions on the street level and private functions in the upper floors.

Building 8's proposed functions aim to accommodate young families looking to live out of the city, near the forest, but still in need of the amenities a city provides – workspace, cafés, library.

Utilising the view, on the top-level accommodation & shared working spaces are located on the façades and a mix of services for the residents (storage, gym, self-maintenance workshops) in the centre. On the second level, a mix of shared and company office space to accommodate the increase in home office demand and companies wanting to set up satellite offices for their employees. On the ground floor, services to accommodate the residents, office workers and locals; cafés, restaurants, library/bookstore, kiosk, etc. The technical equipment remains located in the basement.

Figure 18. Building 8 Program

APARTMENT DESIGN

Building 8 is the largest building on campus without an internal atrium. The eastern façade overlooks the forest while other façades face the internal street. Column grid spacing follows the standard of 8.4 metre centres. It is 60 metres long and 35 metres in width, resulting in a lack of daylight in the centre of the building.

Due to the depth, apartments could not utilise both east and west façades, resulting in limited façade area and reduced daylight. Additional design constraints included the large 1.2 metre square columns. Though advantageous to the design, these large columns proved challenging in the designing of the smaller apartment due to the large space they occupied. It was therefore important to ensure they added value to the design through the technical system.

Floor three contains apartments located on the eastern façade, shared office space on the western, and a corridor with services runs between. Aiming to create a community among residents, several shared facilities are located on the floor. These services create a space for residents to meet formally and informally. The large kitchen can be used for large celebrations, while the workshop allows residents to share knowledge and assist fellow neighbours. A small atrium is located to introduce light into the corridor/common space and provide an outdoor area.

TERRACE APARTMENT

Common solutions for improving apartments include the use of terraces and balconies. This thesis chose to investigate the use of the terrace, as the porosity of terraces increase available daylight deeper into the space and does not induce shading on lower levels.

Through an integrated energy design process, the result is a large apartment design with two bedrooms and a small internal atrium to the rear. The terrace creates a large outdoor space (23m^2) adequate to entertain guests, watch the sunrise, and enjoy meals outdoors while enjoying forest views.

A retractable shading device covers the terrace, providing protection from rain, and reducing overheating and glare in warmer months. Meanwhile an atrium (8.2m^2) to the rear introduces daylight into the second bedroom, creates a private outdoor space and induces natural cross ventilation.

The apartment is 114m^2 BRA (heated useful floor area) and are mirrored, allowing for the possibility of a shared terrace space.

ATRIUM APARTMENT

To satisfy the goal of designing two apartments with alternative sizes, a smaller, slender apartment was designed. The limited façade resulted in a distinct lack of daylight into the space. To solve this, a small atrium was introduced in the middle of the apartment. This ensures good daylight levels in the bedroom and living area. The atrium provides opportunity for natural cross ventilation in warmer months. Connected to the bedroom, it creates an outdoor space that can be used for eating, relaxing and occasionally sleeping in good weather.

The apartment is 64m^2 BRA, and the atrium is 7.6m^2 and are mirrored with both bathroom and kitchen located near the structural service columns allowing for easy access to water and services.

To maximise thermal gains and utilise the existing heavy concrete structure, exposed concrete flooring has been used.

OFFICES

The shared office space creates a professional environment close to home. The space includes two kitchens, the southern with a terrace to enjoy the street life below, sunshine, and introduce daylight into the space. The north kitchen creates an informal workspace and meeting area.

Floor three aims to create a sense of community among residents and provide a professional workspace for locals.

Figure 19. Terrace apartment floor plan 1:100

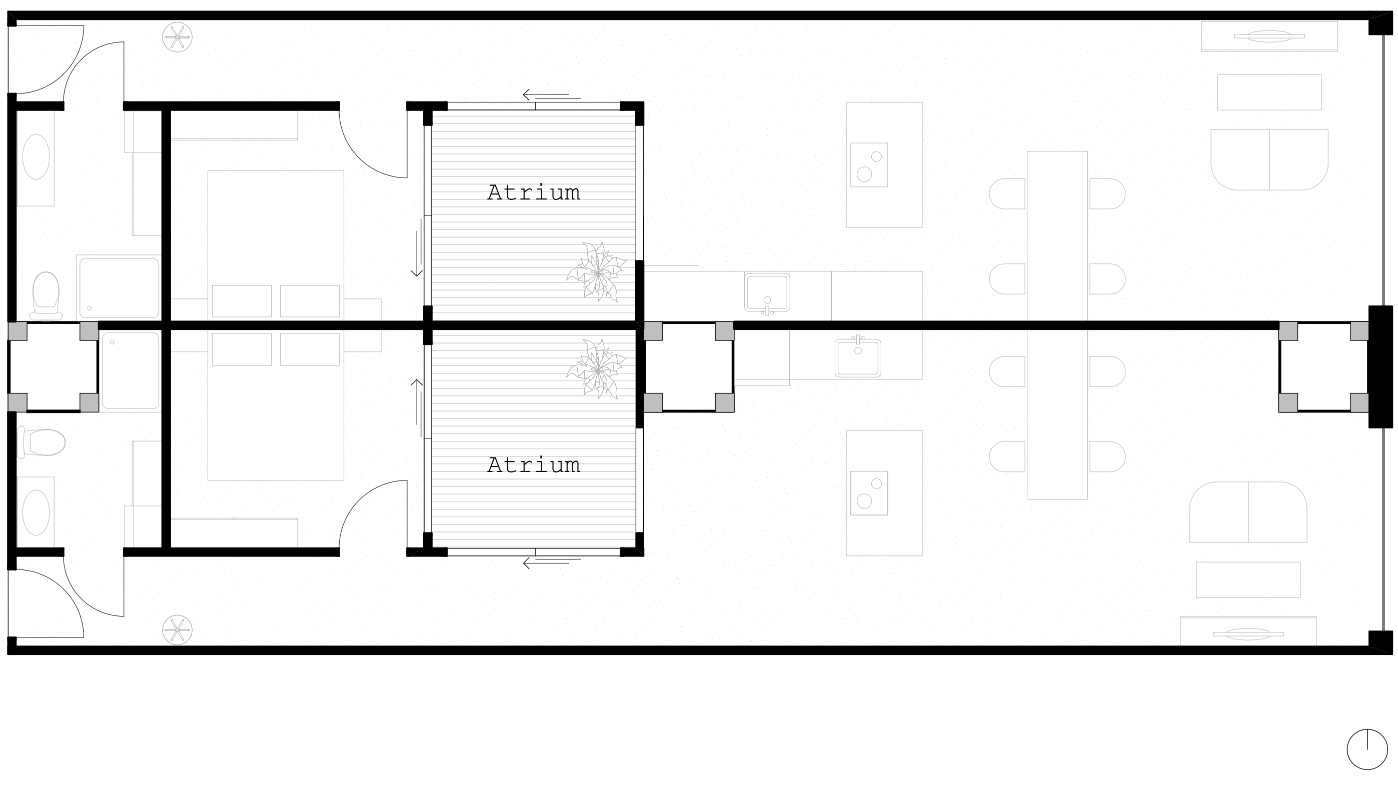


Figure 20. Atrium apartment floor plan 1:100

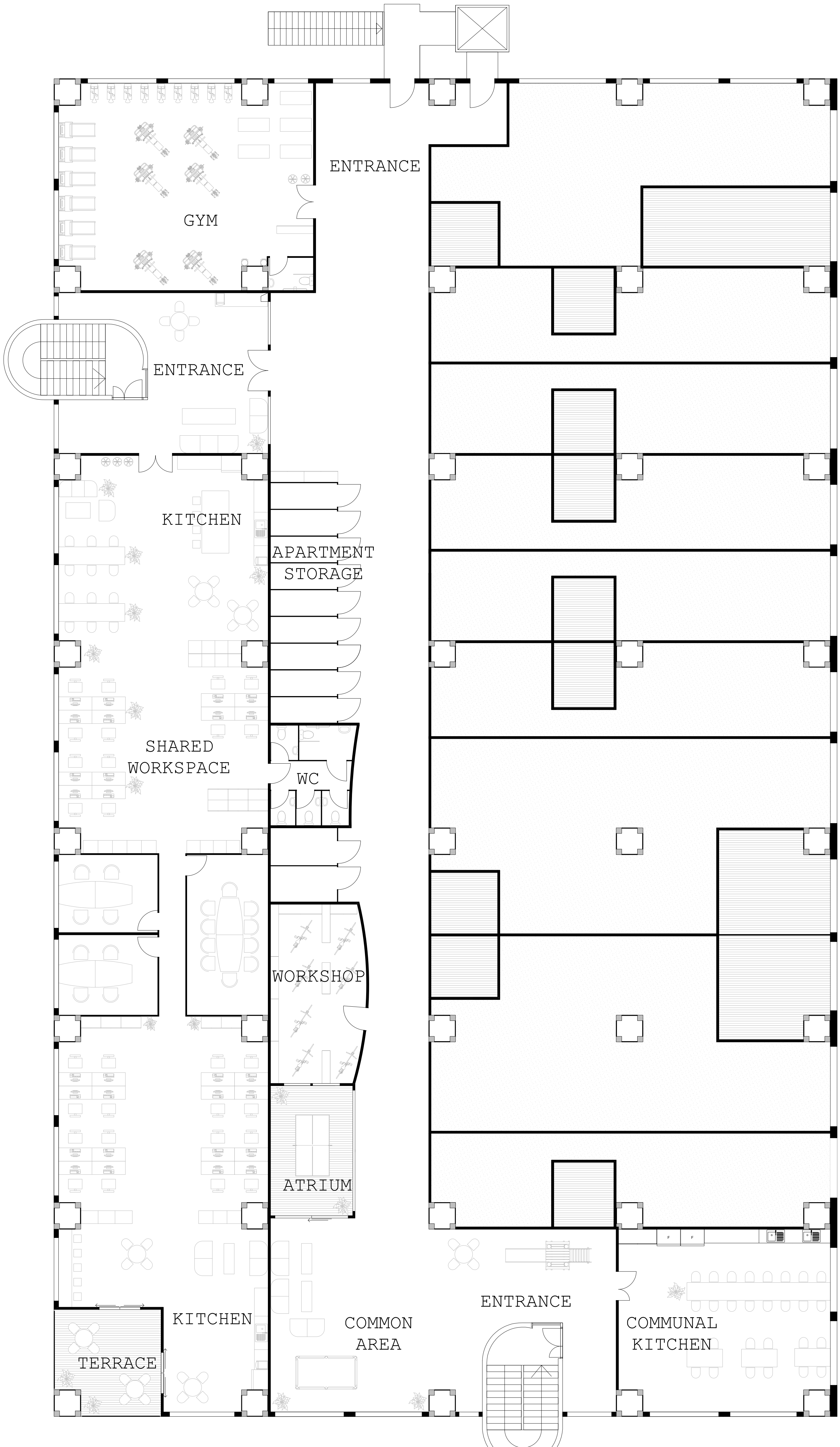


Figure 21. Level 3 floor plan 1:200

Figure 22. Atrium Apartment

Figure 23. Atrium Apartment

MATERIAL CONSTRUCTION

As the reinforced concrete super structure is to be reused, the primary materials that require replacement include insulation, glazing, and the façade. To adhere to the project goal of limiting renovation and new material use, insulation thickness was optimised using energy analysis. The façade panels are modularised, easing disassembly and renovation.

The renovated façade is shown in Figure 26. 200mm of glass wool insulation (λ 0.032 W/mK) is used in the outer façade and 250mm in the roof. Pine wood has been used for the outer façade panels and triple glazed low-e glazing has been used.

To ensure airtightness of the building envelope, vapour barriers and wind barriers are installed. Vapour barriers stop water vapour from entering the wall, prevent warm air from escaping, and reduce the draft potential in the building. Wind barriers prevent outside water from entering, while allowing water retained within the wall to escape.

Figure 25 shows the thermal flux (W/m^2) of the existing section and the new section. This simplified analysis shows a reduction in heat flow rate intensity in the new section.

While a complete life cycle analysis (LCA) for the renovation was not included in the scope of this thesis, LCA tools were used to aid material choices. LCA shows Glava glass wool has a lower life cycle impact than rock wool and wood fibre alternatives, for a site in Trondheim (Figure 24). Wood for the outer façade and battens are supplied by Støren Treindustri, located 53km south of Trondheim.

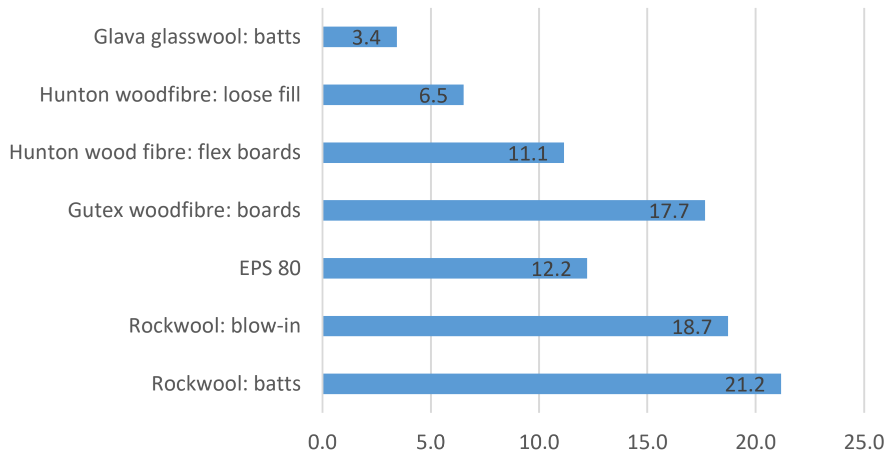


Figure 24. Insulation Emissions A1-A4 (kgCO_2eq)

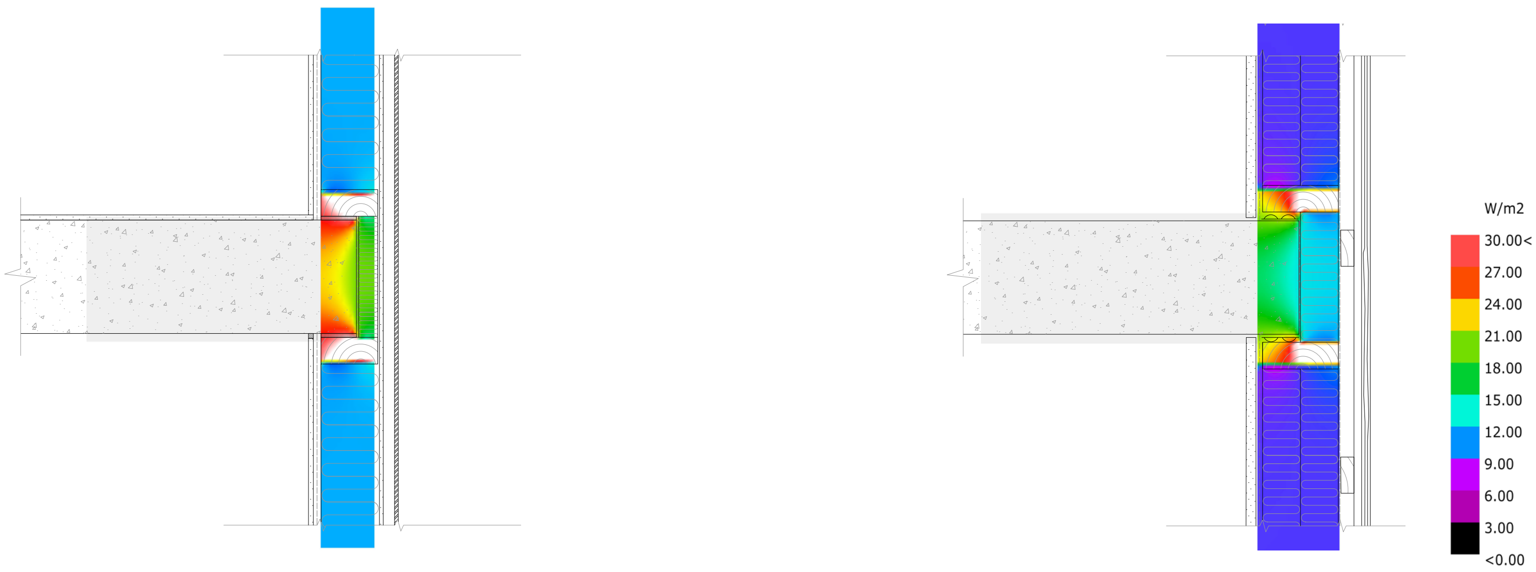
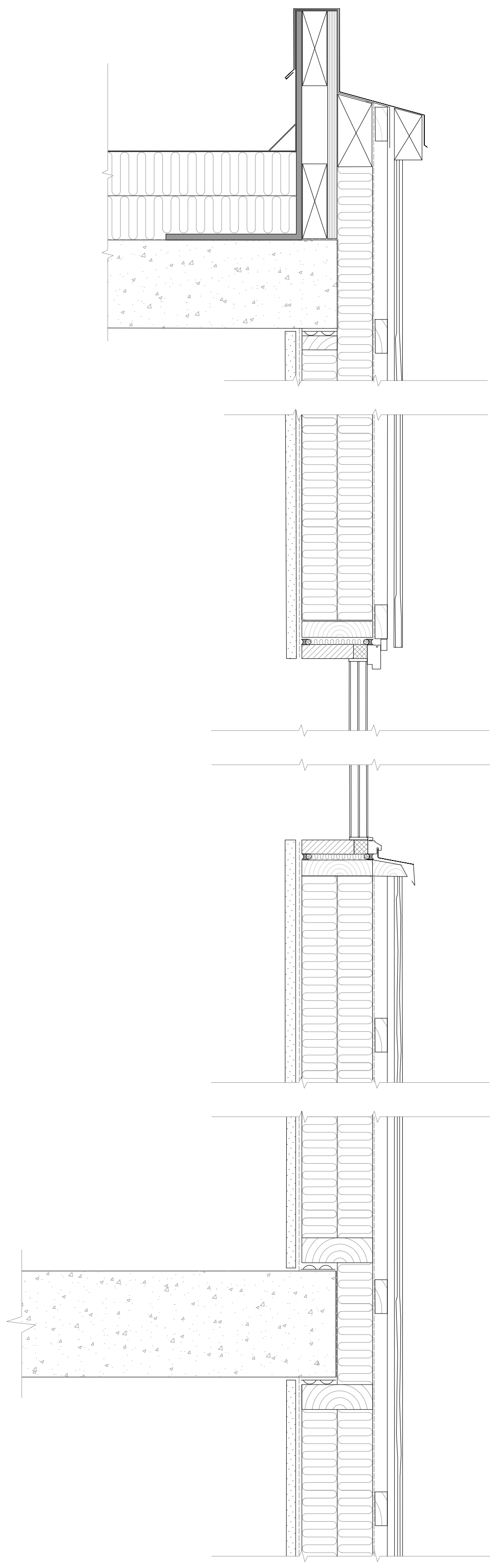


Figure 25. Thermal Flux - before and after renovation

MATERIAL CONSTRUCTION

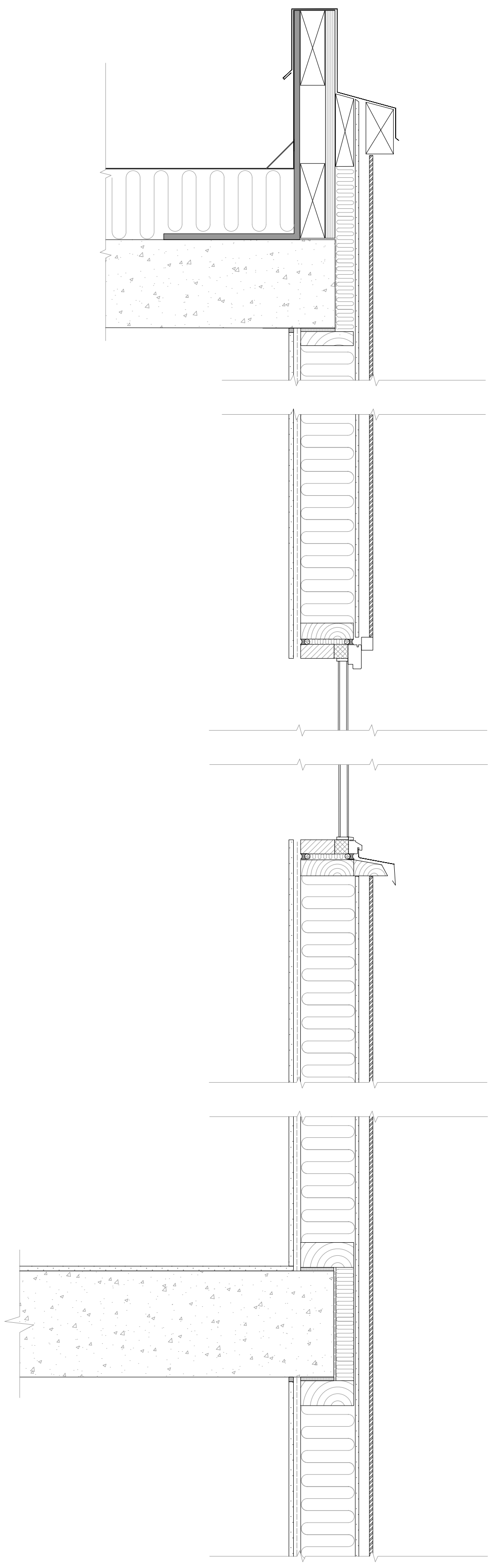


NEW WALL SECTION 1
EXTERNAL FACADE
SCALE 1:20

Exterior cladding	22mm
Ventilation gap	20mm
Battens	35mm
Wind barrier board	25mm
Insulation Glass wool	200mm
Vapour barrier	0.2mm
Internal cladding	30mm

U-value: 0.15 W/(m^{2}K)

Figure 26. Construction section - new



EXISTING WALL SECTION 1
EXTERNAL FACADE
SCALE 1:20

Facade plate	10mm
Ventilation gap	30mm
Plaster board	10mm
Wind barrier	30mm
Insulation mineral wool	150mm
Vapour barrier	0.2mm
Gypsum board	13mm

U-value: 0.25 W/(m^{2}K)

Figure 27. Construction section - existing

TECHNICAL SYSTEM

The ventilation strategy for the building uses a hybrid system. Natural ventilation can be utilised in the warmer months when heating demand is lower, and mechanical ventilation used in the cooler months. Hybrid systems decrease energy demand over the year, however, require a more advanced control system.

A variable-air-volume system with a heat recover unit (HRU) of 85% efficiency located in the basement is used to provide ventilation and space heating to the building. Figure 30 & 31 show the simplified diagrammatic heating and cooling principles for the building.

During periods of heating, inlet air is heated in the basement, distributed through the existing vertical shaft within the columns and supplied into the space through diffusers on the floor. Exhaust air is transported down alternate columns and sent to the HRU. Fans located in the columns assist extraction of exhaust air (Figure 32). In addition, excess exhaust air not required for heat recovery is exhausted into the covered street to create comfortable conditions for users.

During cooling periods air is supplied through the vertical columns and exhaust air is ventilated up through the columns. Chimneys located on the roof raise the neutral axis and help drive the exhaust air. Solar radiation entering the building through the atriums and terraces passively heat the space. To avoid overheating, excess heat or CO_2 in the covered street can be exhausted through the glazed cover.

Natural ventilation reduces energy demand by ventilating and cooling the space using fresh air. Windows located on one side of the building can lead to poor natural ventilation qualities. Therefore, apartment atriums are used to induce cross ventilation and actively ventilate and cool the space.

Figure 28 & 29 shows the location of ventilation ducts within the columns, entering the room at the far end of the apartment.

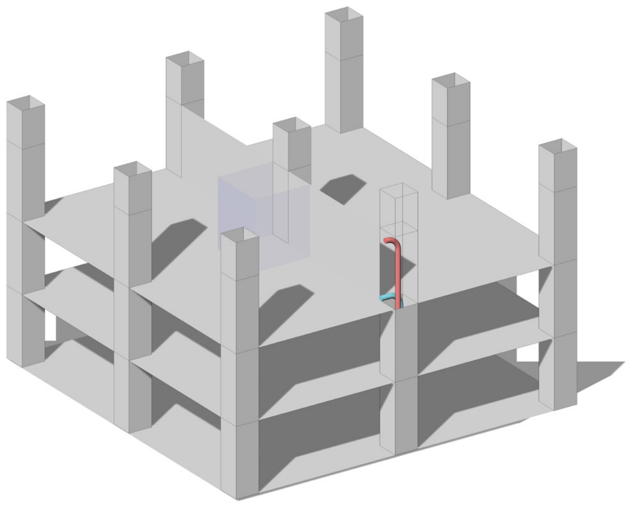


Figure 28. Structural system showing services - Atrium apartment

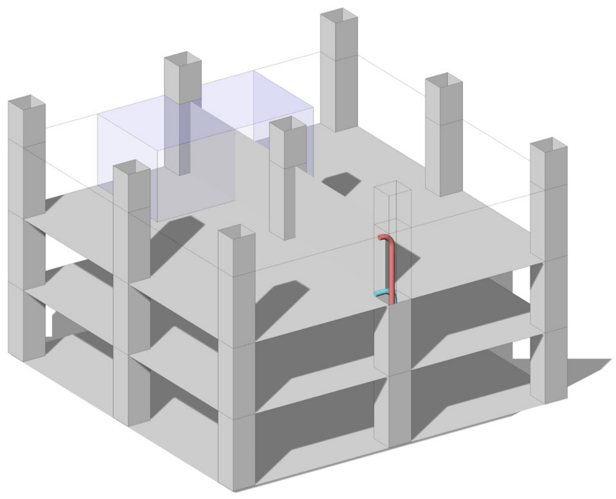


Figure 29. Structural system showing services - Terrace apartment

TECHNICAL SYSTEM

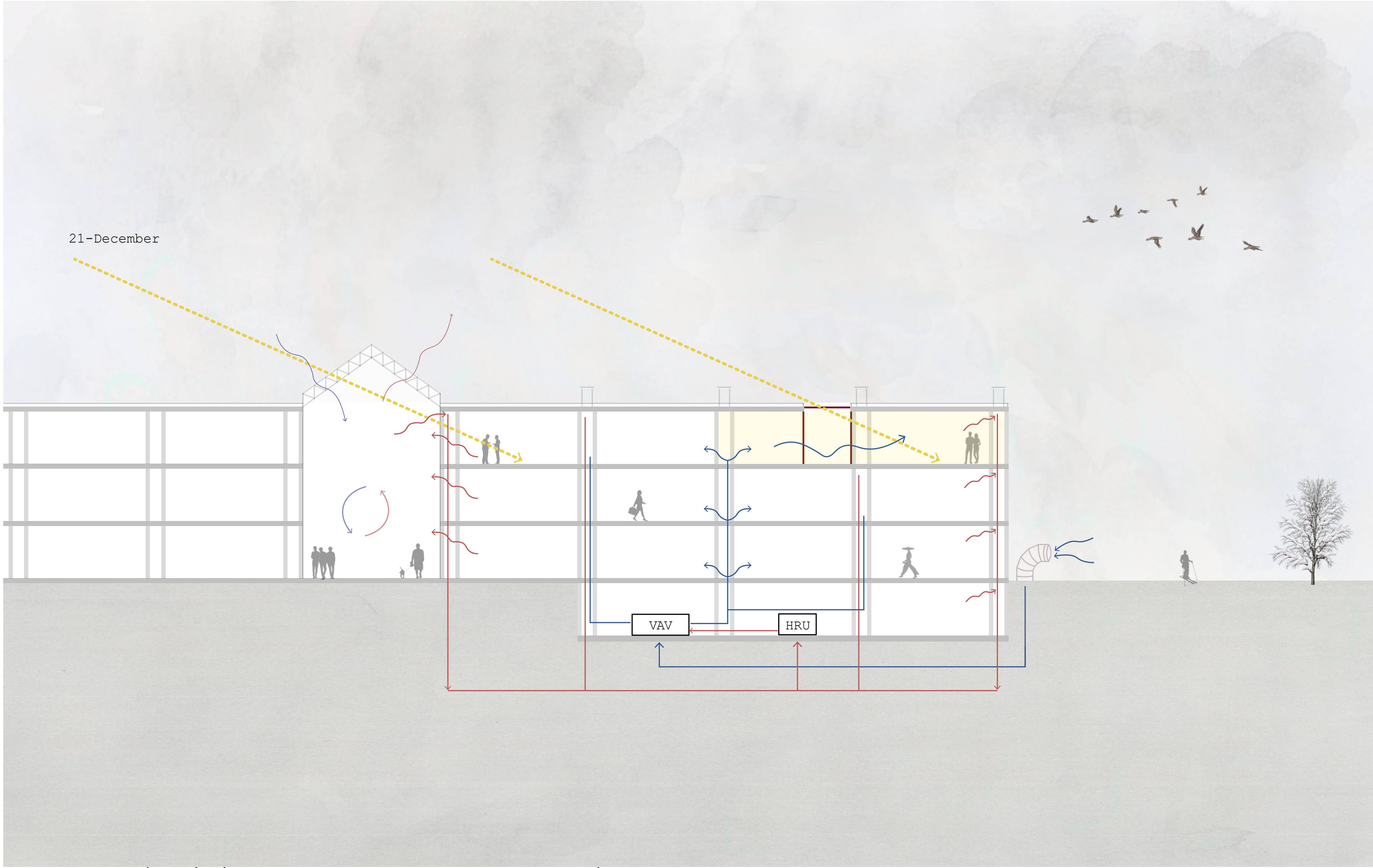


Figure 30. Technical schematic atrium apartment - Heating period

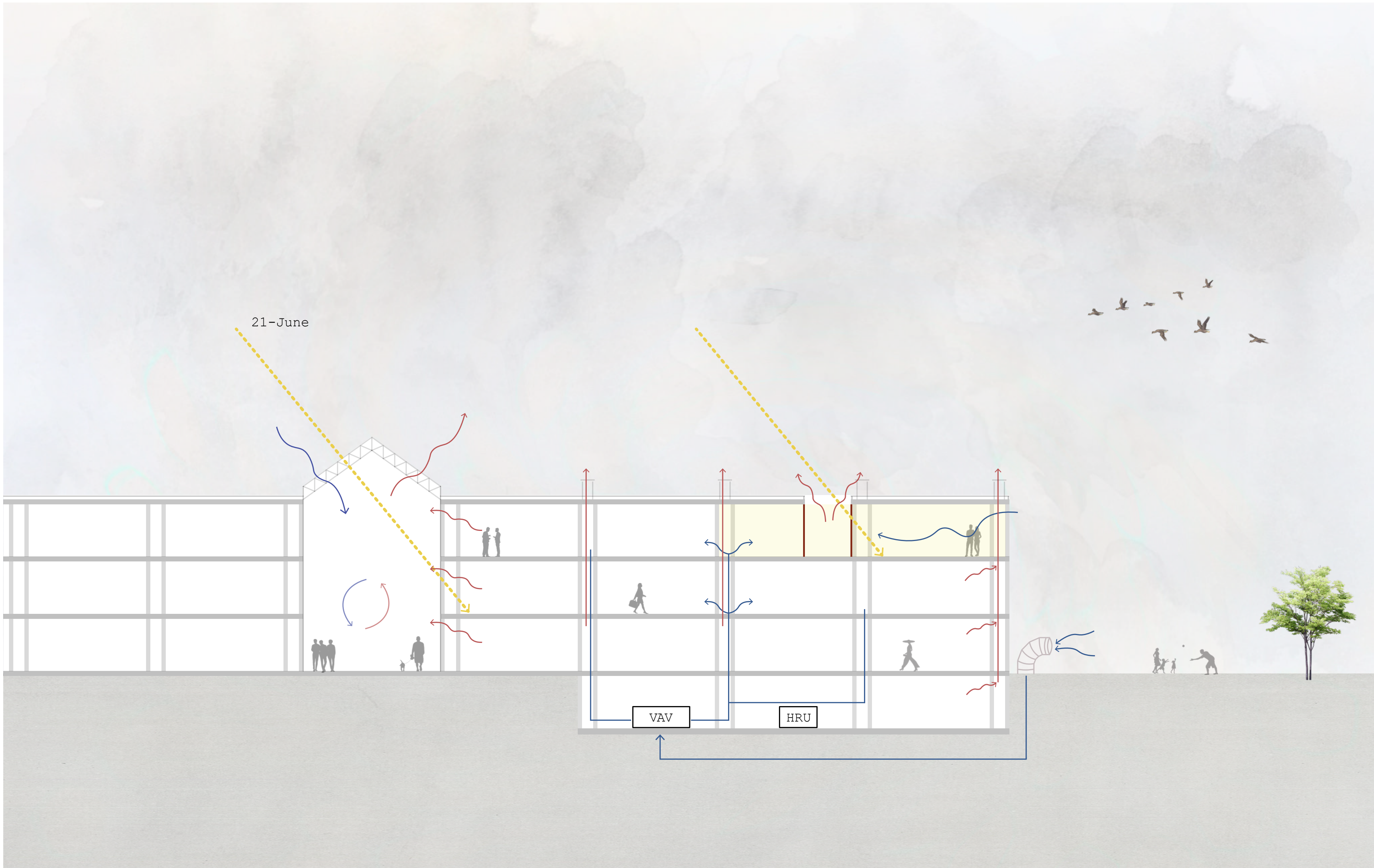


Figure 31. Technical schematic atrium apartment - Cooling period

TECHNICAL SYSTEM

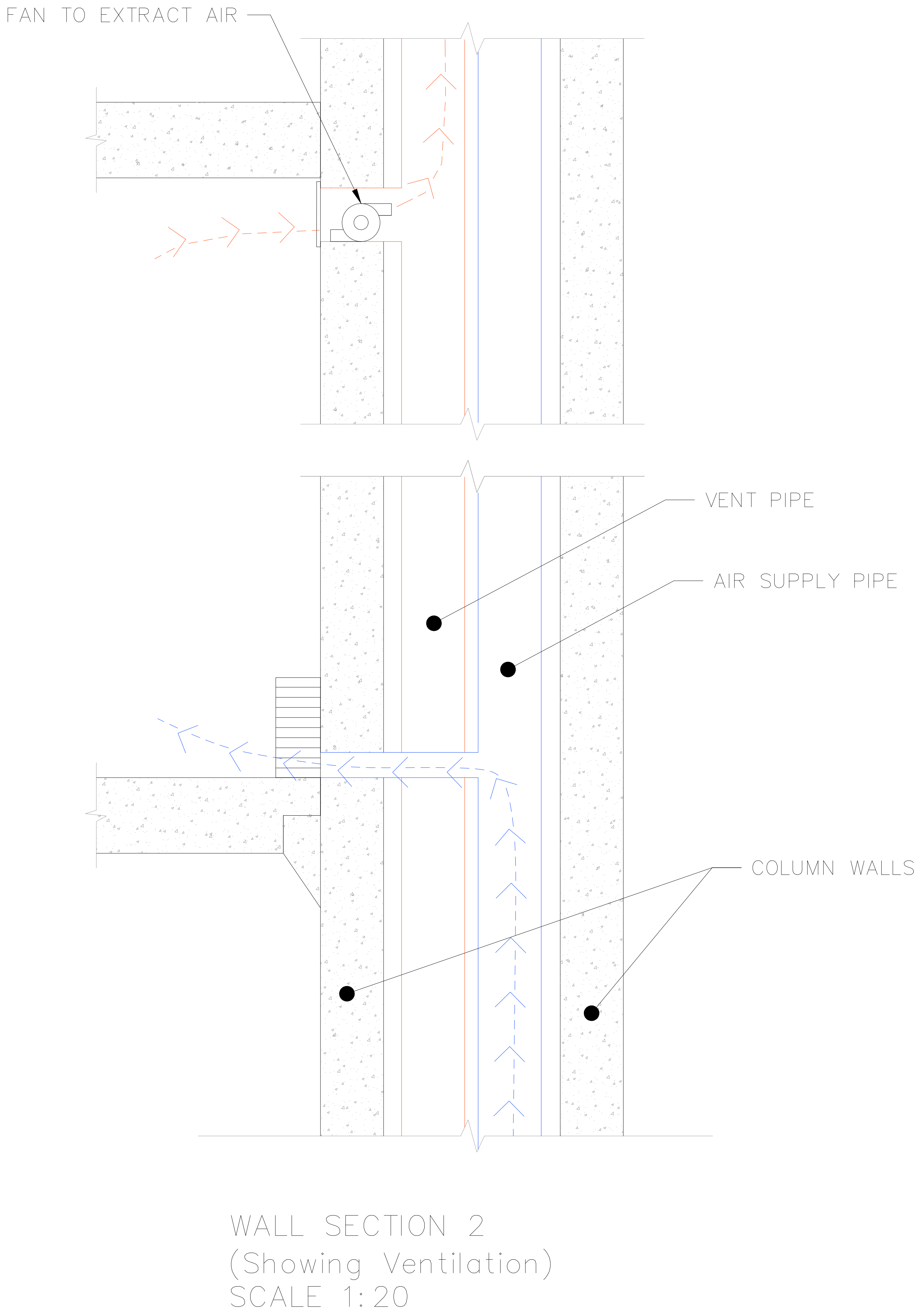


Figure 32. Section through column showing ventilation principle 1:20

DAYLIGHT ANALYSIS

The first stage of the design was to complete a daylight analysis of building 8 level 3 with the existing facade layout, to assess the daylight depth and potential for apartment layouts.

FLOOR 3
Figure 33 shows that the daylight depth >2% is limited to approximately 5m from the facade. To increase daylight depth and quality into the space, the façades current 1.3-metre-high windows should be replaced with larger windows. The size and material of the new windows has been designed for daylight and optimised using energy analysis.

Level 3 currently functions as a library which occupies the darker central areas, while office spaces utilise the eastern façade and study rooms the western façade facing into the campus. As the building is purpose built, no means of providing daylight into the centre was added and is currently occupied by bookshelves.

TEK 17 cl 13.7(2) [7] stipulates a minimum daylight factor of 2.0% is required for occupied areas. To achieve this, additional light sources are needed to increase daylight opportunity.

ATRIUM APARTMENT
For the smaller apartment, an atrium was introduced to provide daylight to the centre of the space. A parametric analysis of potential atrium locations was completed using daylight simulations. The results formed the basis of the floor plan design. The location of the atrium was set out according to the apartment program and room size requirements. Its central location provides daylight to the bedroom and kitchen and ensures TEK 17 requirements are met as shown in Figure 35.

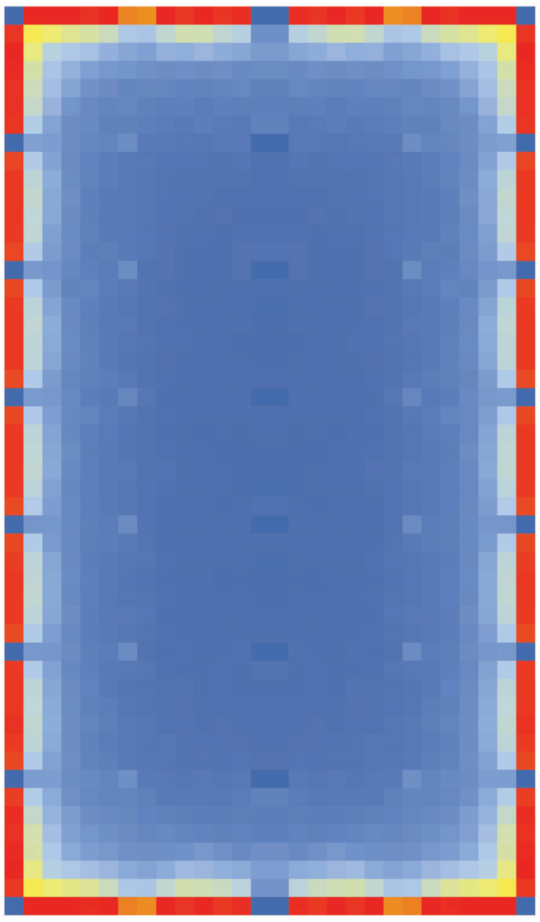


Figure 33. Daylight Factor - Floor 3 Existing 1:500

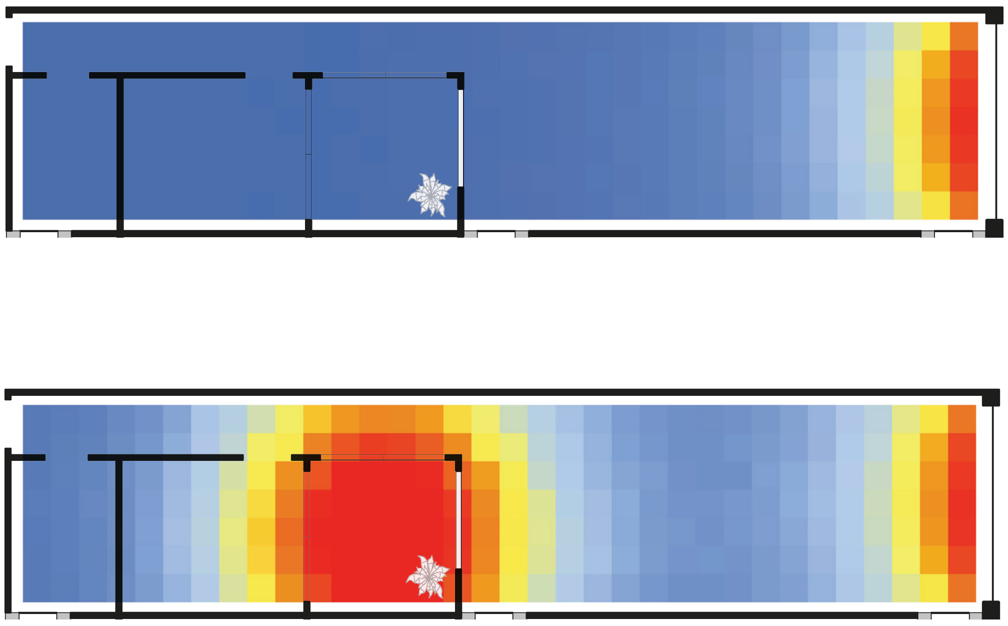


Figure 34. Design progression - Atrium apartment

DAYLIGHT ANALYSIS

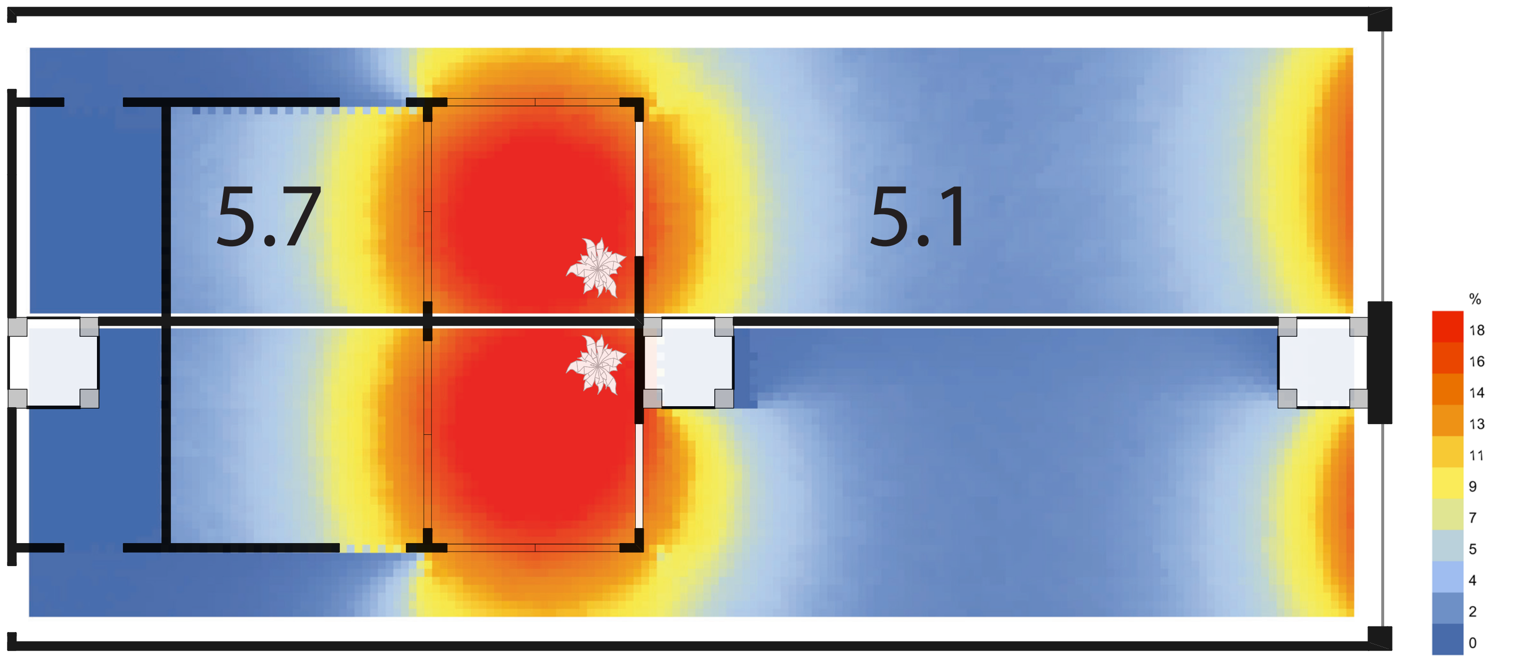


Figure 35. Daylight Factor - Atrium apartment design 1:100

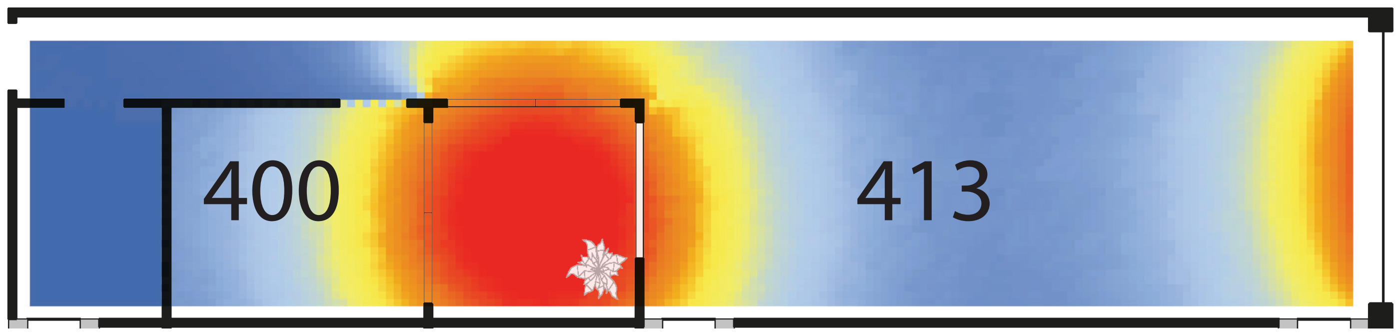


Figure 36. Illuminance - Atrium apartment design 1:100

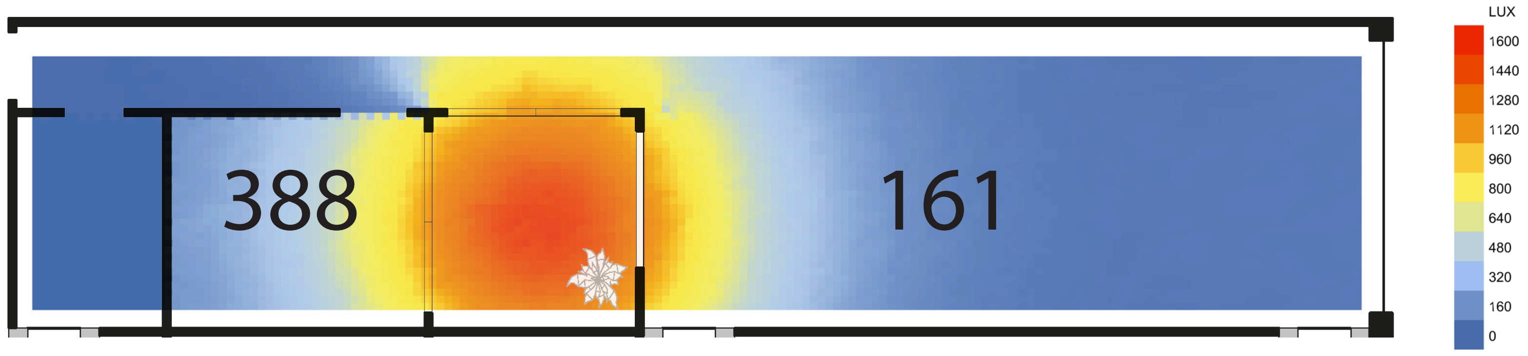


Figure 37. Illuminance - Atrium apartment design - internal shading active 1:100

DAYLIGHT ANALYSIS

TERRACE APARTMENT

Figure 38 shows the progression of the terrace apartment design based on simulations. The large terrace was initially designed to introduce daylight further into the apartment (B). Subsequent results of the energy analysis indicated that a smaller terrace with less glazed area could reduce energy heating demand (Table 4). The smaller terrace reduced daylight into the apartment and created more dark space to the rear of the apartment (C). In addition to the lack of daylight, from the floor plan design it became clear that there was wasted space in the large apartment and a second bedroom was necessary. Therefore the final design included a small atrium to introduce light into the second bedroom (D).

The resulting daylight factors are shown in Figure 39. Both bedrooms and living area achieve DF levels above 2%, complying with TEK 17.

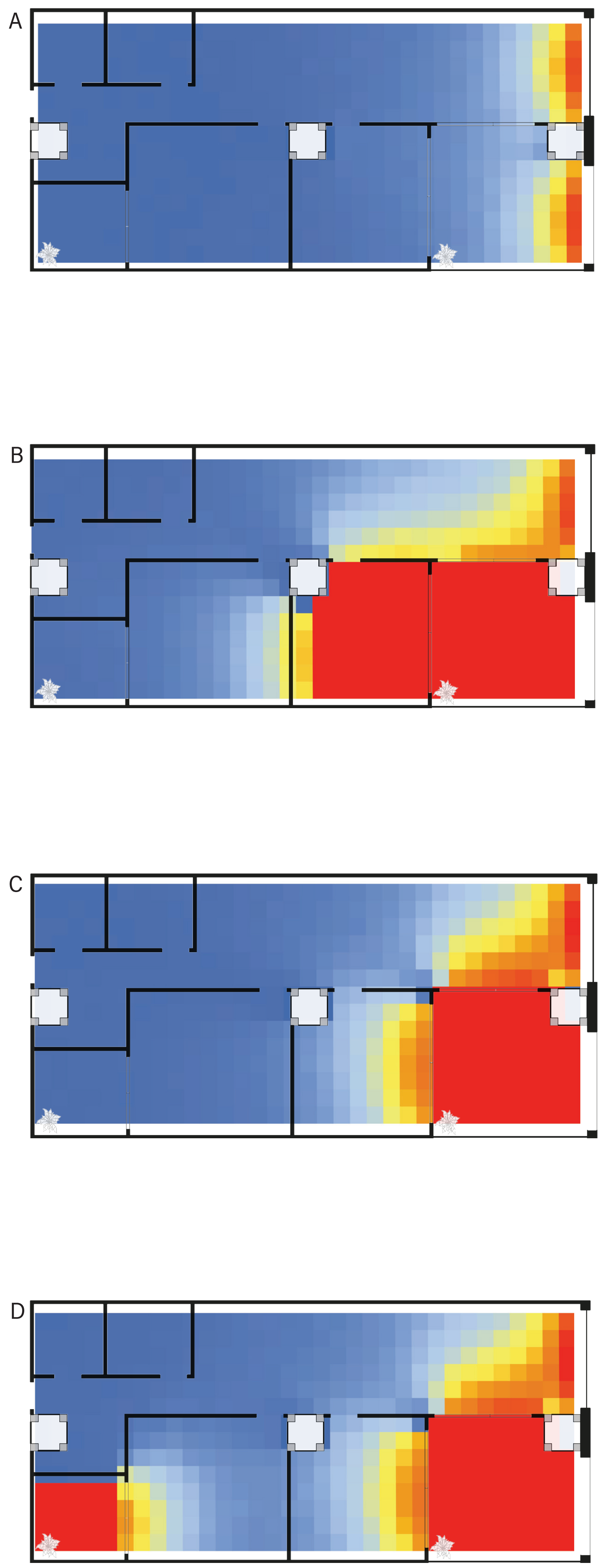


Figure 38. Design progression - Terrace Apartment

A. larger window
B. large terrace
C. small terrace
D. small terrace & atrium

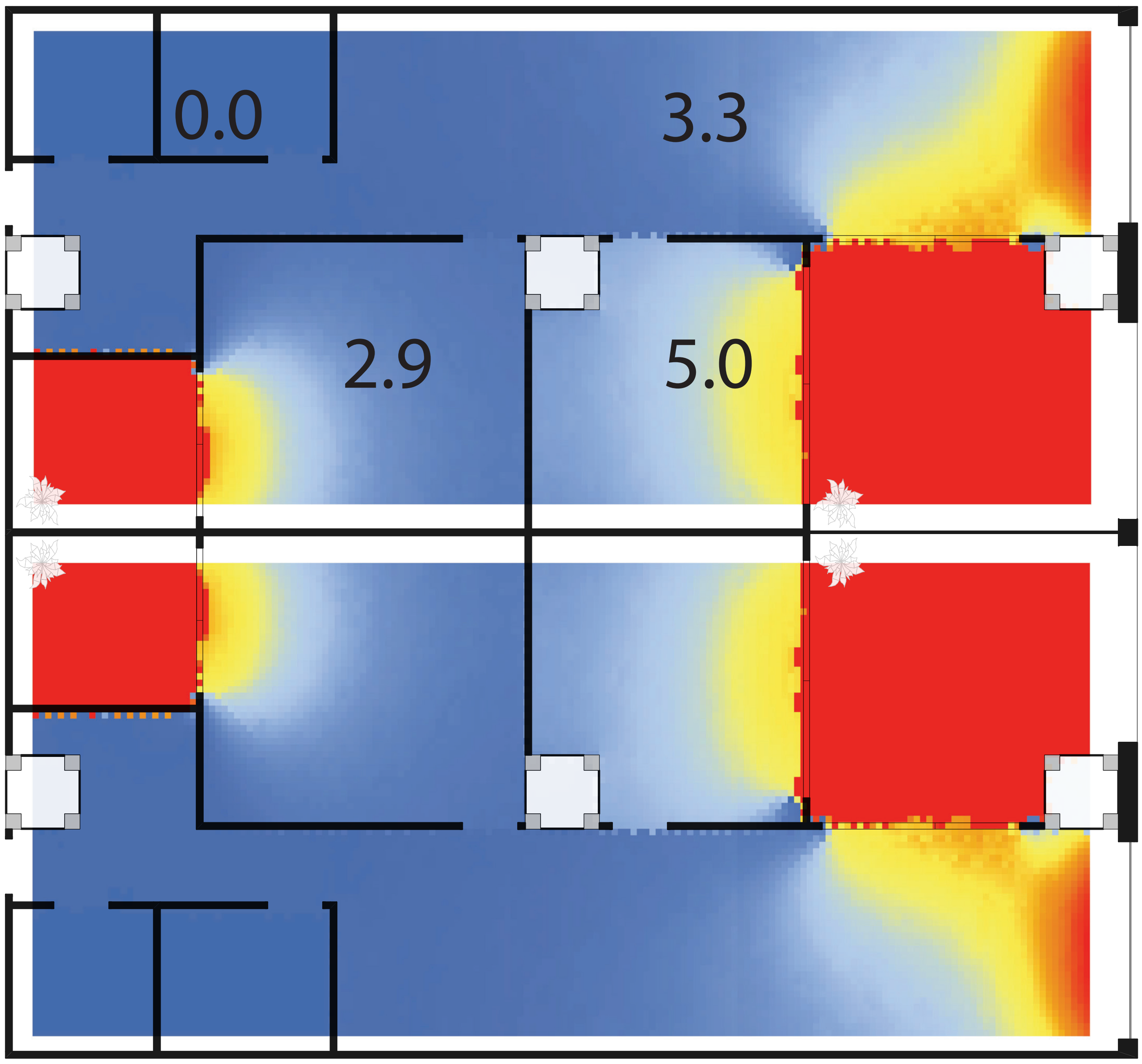


Figure 39. Daylight Factor - Terrace apartment design - terrace shading 1:100

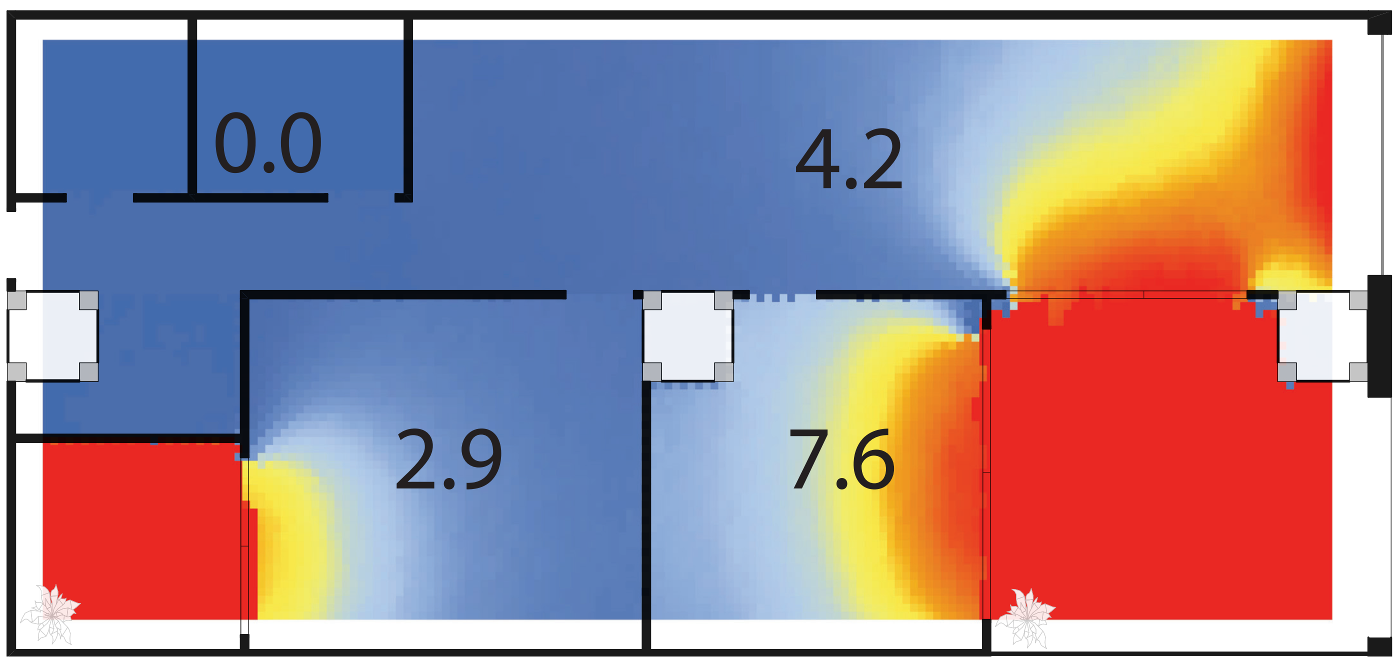


Figure 40. Daylight Factor - Terrace apartment design - no shading 1:100

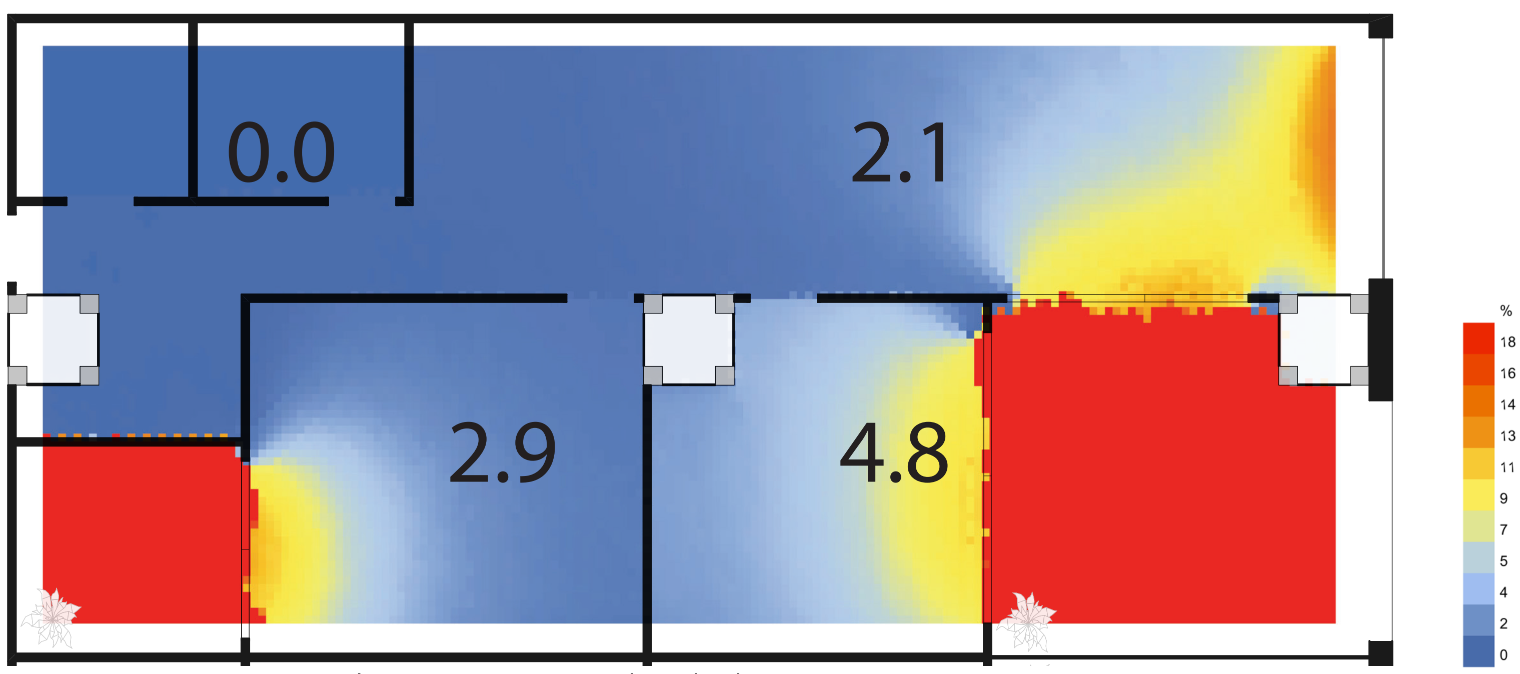


Figure 41. Daylight Factor - Terrace apartment design - terrace & window shading 1:100

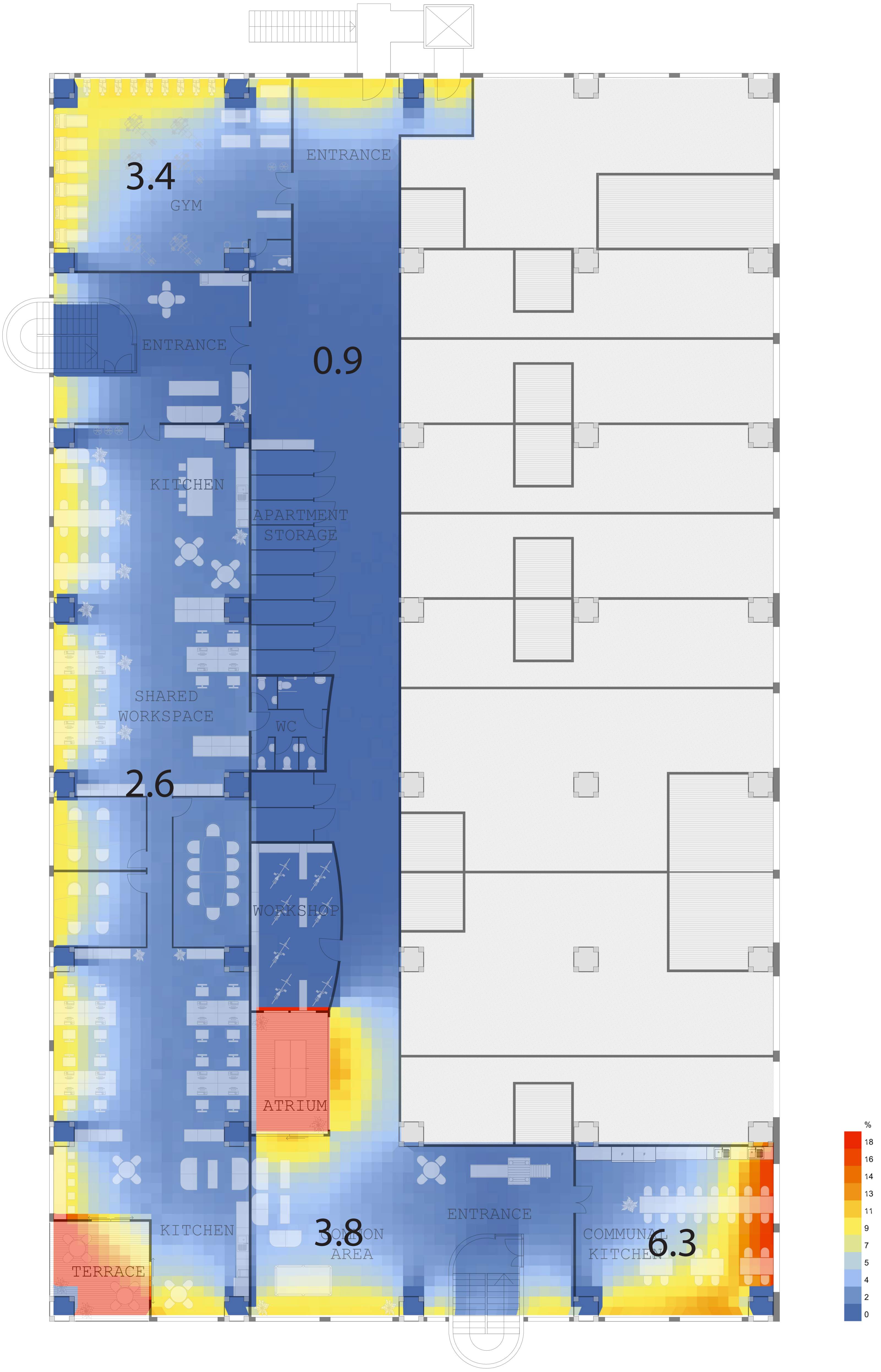


Figure 42. Dayilght Factor - Floor 3 1:200

DAYLIGHT ANALYSIS

GLARE

Excessive daylight factors on the eastern façade indicate the potential for glare within the apartment. A glare analysis was completed to assess when levels were intolerable and to test measures to reduce perceived glare.

Daylight glare probability (DGP) levels are defined in Honeybee/Radiance as:

- DGP < 0.35 imperceptible
- 0.35 < DGP < 0.40 perceptible
- 0.40 < DGP < 0.45 disturbing
- 0.45 < DGP intolerable

The glare probability due to daylight was tested in the following cases:

- 21 June @ 12:00 – assess DGP created by atrium & terrace
- 21 Sept @ 8:00 – assess DGP of morning sun during breakfast

Analysis confirmed intolerable glare levels (DGP 0.54) experienced in the living room of the terrace apartment due to the uncovered terrace (Figure 44). The addition of shading covering the terrace area reduced glare to acceptable levels (DGP 0.38) (Figure 45) while maintaining good daylight levels within the space (Figure 39).

This glare analysis was run at 21-June at 12:00 when the sun is highest. A terrace shading device is not required year-round and use of shading in winter would reduce beneficial solar gains. The shading device is therefore designed as retractable, ideally programmable to prevent excess solar gains and glare in warmer months but allow solar gains in the colder months.

The east facing façade of both apartments leads to a high glare potential in the morning hours. To prevent unwanted glare blinds have been installed as an internal shading device. Figure 46 & 47 show the DGP within the space with and without the blinds activated. Figure 37 shows sufficient daylight is available to the space when blinds are active, due to daylight emitted from the atrium.

An additional glare analysis was completed to assess whether the atrium caused glare and if shading devices were required. Results show that at 12:00 on 21-June glare is not perceivable from the bedroom or kitchen area (DGP 0.25) and shading devices not required.

Figure 48 & 49 show the sunlight progression in each apartment through the day for September 21. The eastern facade gains morning sun and glare potential early in the day. Later in the day the sunlight enters the space through the atrium and terrace.

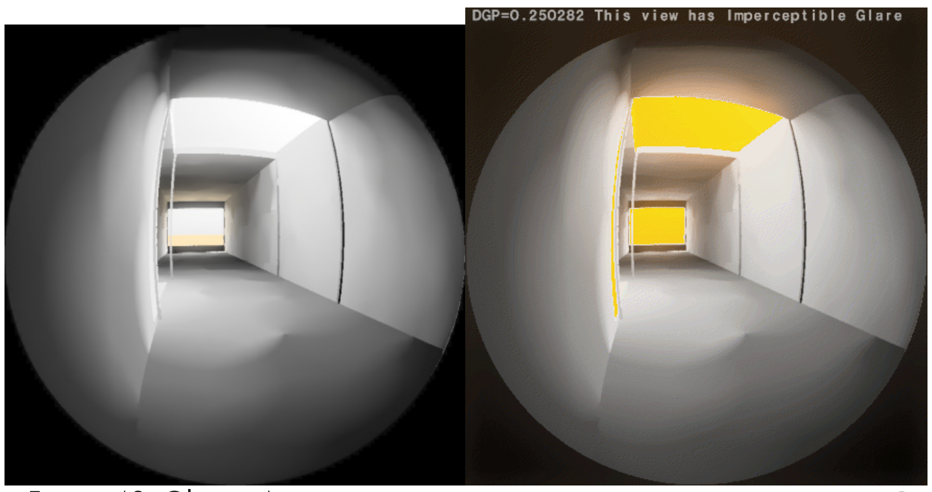


Figure 43. Glare - Atrium apartment (from bedroom looking east)

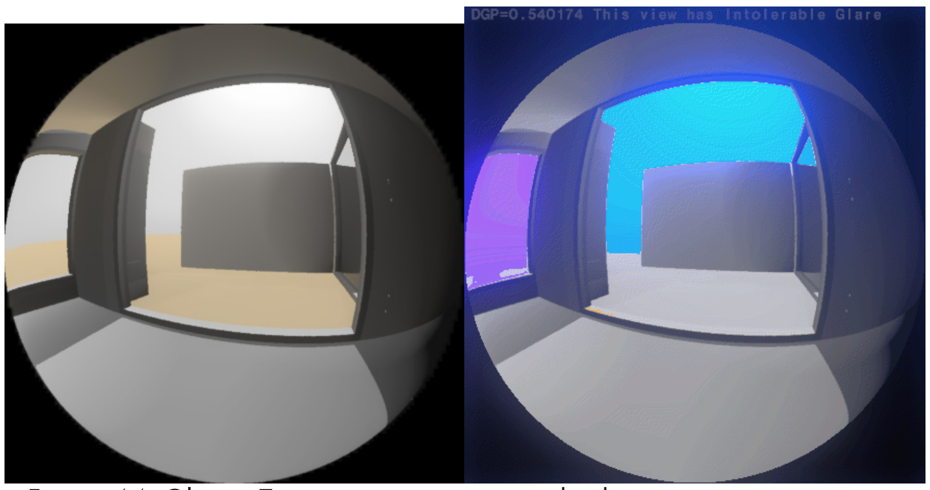


Figure 44. Glare - Terrace apartment - no shading

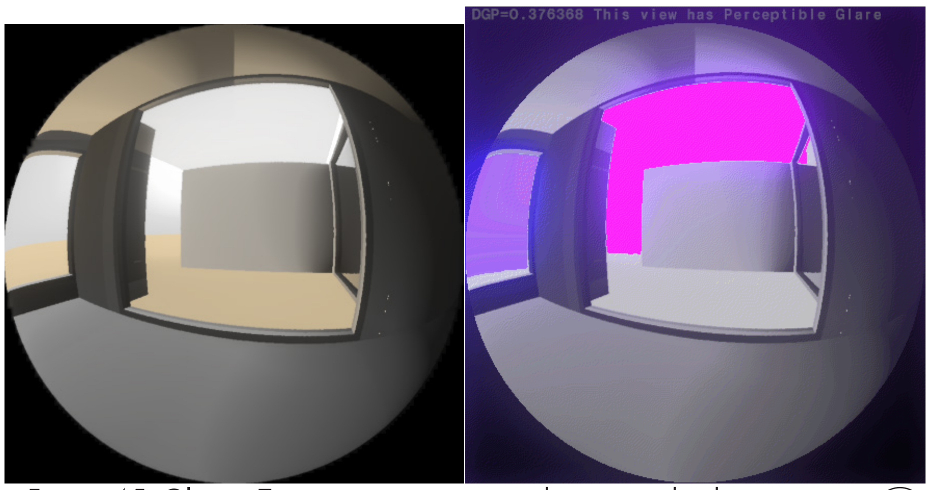


Figure 45. Glare - Terrace apartment - with terrace shading (looking out to terrace looking east)

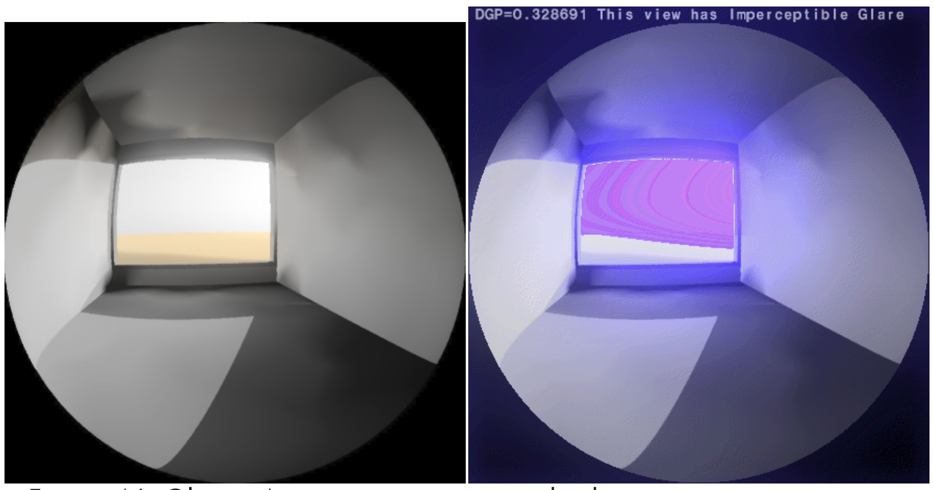


Figure 46. Glare - Atrium apartment - no shading

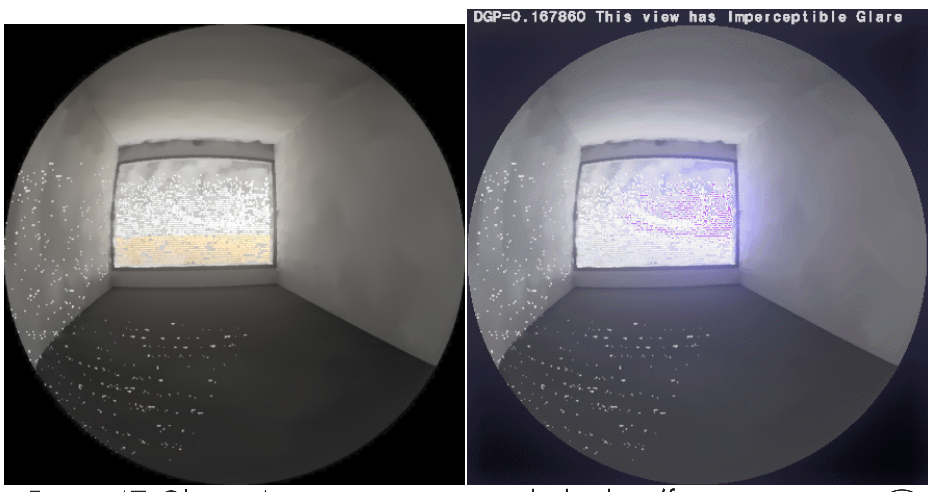


Figure 47. Glare - Atrium apartment - with shading (from dining room looking east)

DAYLIGHT ANALYSIS

06:00

09:00

12:00

15:00

21:00

Figure 48. Daily sunlight - Terrace apartment (Sept 21) (from living room looking east)

Figure 49. Daily sunlight - Atrium apartment (Sept 21) (from bedroom looking east)

DAYLIGHT ANALYSIS

DAYLIGHT AUTONOMY

Daylight autonomy (DA) and useful daylight index (UDI) are dynamic analysis used to forecast energy savings more accurately than daylight factor analysis. The annual DA calculates the number of hours a room receives illuminance above 300 lux during waking/working hours. UDI calculates the number of hours which a room receives useful illuminance values between 100-2000 lux. Based on occupant preferences, above 2000 lux is generally disturbing while below 100 lux is insufficient. Table 1 summarises the results for the office and apartments. The results are on the lower side, with the Illuminating Engineering Society of North America (IESNA, 2013) recommending a DA of 50%. The limited available sunlight, surrounding buildings and single façade contribute to the low values. Energy analysis shows that increasing the DA/UDI through larger atriums/terraces increases heating demand. Analysis resulted in a balance between DA and energy, while ensuring DF requirements from TEK 17 were met.

Table 1. Daylight autonomy

	OFFICE	ATRIUM	TERRACE
DA	43%	38%	28%
UDI	54%	39%	26%
Analysis period	07:00-18:00	06:00-23:00	
Electric lighting hours (annual)	2305	3841	4471

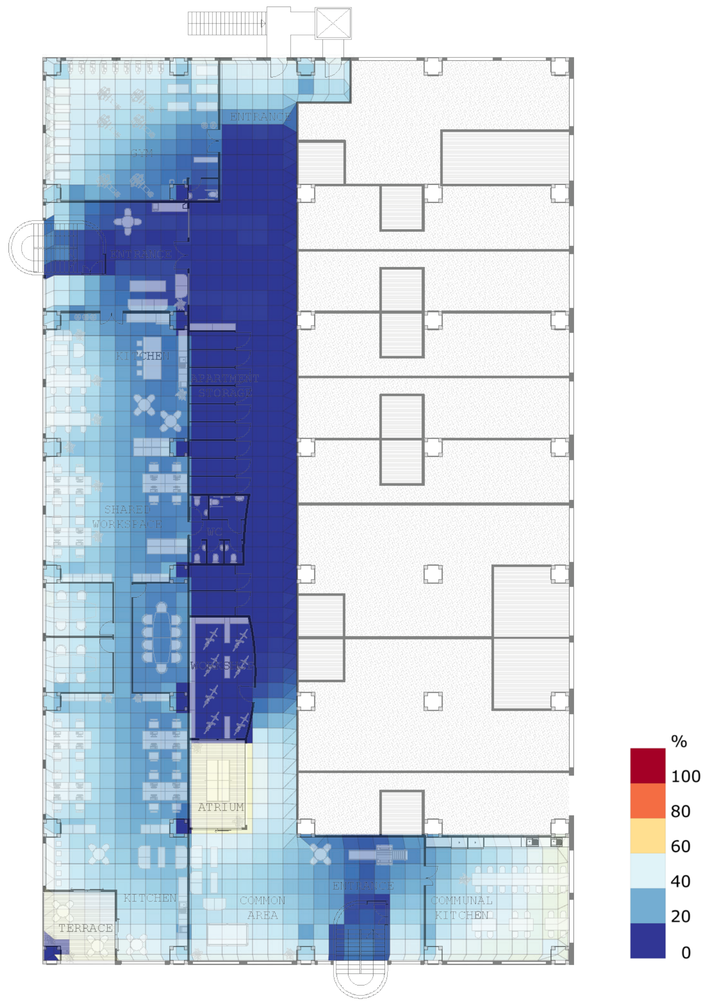


Figure 50. Daylight Autonomy - Floor 3 1:500

PARAMETERS

Final daylight simulations used a test grid of 0.1m at 0.8m above the floor and 4 light bounces. Standard CIE sky condition of overcast sky was used. Other parameters follow recommendation of the software (Radiance). Parameters for transmissivity/reflectance of materials is shown in Table 2.

The results verify adequate daylight levels are achieved throughout the apartments and office space.

Table 2. Reflectance/Transmissivity

OBJECT	MATERIAL TYPE	RGB REFLECTANCE / TRANSMISSIVITY
Glazing_outer facade	Transparent glass	0.65
Glazing_atrium	Transparent glass	0.65
Floor_grey	Opaque	0.20
Ceiling_white	Opaque	0.70
WindowFrame	Opaque	0.30
InnerWalls	Opaque	0.60
ShadingDevice	Opaque	0.30
GroundSurface	Opaque	0.30
SurroundingBuildings	Opaque	0.30
SurroundingBuildings	Transparent Glass	0.65

ENERGY ANALYSIS

Following the initial design of floor plans based on daylighting, detailed energy simulations were completed to verify and progress the design by assessing different design options. Final verification of the design was completed to ensure indoor air quality and comfort was acceptable while keeping energy demand to a minimum.

Simulations completed in Honeybee for Rhino were used to investigate the effects of different sizes and layouts of atriums and terraces, while ensuring indoor comfort levels are maintained. Materials, shading devices, and ventilation techniques were also investigated.

Wall and roof insulation thickness was optimised based on energy demand, balanced with indoor air quality, while ensuring compliance with TEK 17. Windows conservatively met the minimum requirements for TEK 17. Refer Table 3 for U-values.

Table 3. U-values

U-VALUES (W/m²K)	CURRENT	RENOVATION	TEK 17
Outer wall	0.25	0.15	0.18
Roof	0.15	0.12	0.13
Windows	2.36	0.80	0.80

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Table 4 summarises the heating and cooling demand of the various apartment designs proposed during the design process. For the terrace apartment design, the initially large terrace (to maximise daylight deep into the apartment) was found to have higher heating demand when compared to the smaller terrace. The smaller terrace also allowed for an additional bedroom. The necessary introduction of the rear atrium increased the heating demand slightly but remained lower than the initial large terrace design. And as expected, the most energy efficient design contained no atrium or terrace.

Simulations shows by increasing the insulation thickness and improving its properties, the heating demand is reduced by around half. Over insulating led to overheating within the apartment. The optimal insulation thickness was determined using energy analysis.

The heating and cooling demand for the terrace apartment is 23 & 21 kWh/m² respectively, and 25 & 17 kWh/m² for the atrium apartment. Energy balance graphs indicate the effective use of natural ventilation for cooling and high solar gains (Figure 51 & 53).

Both apartments have been designed to maintain a comfortable temperature throughout the year, ranging from 19°C to 24.5°C (Figure 52 & 54). This temperature range was found to produce a good balance between energy use and comfort levels. Predicted mean vote (PMV) is used to gauge the comfort level of a user in the space. It is based on a scale ranging from -3 to +3, with 0 as neutral where the user is neither cold nor hot. The yearly PMV for the terrace and atrium apartment is -0.48 and -0.26 respectively - based on a clothing level of 0.8 clo (long sleeved shirt and pants). The PMV indicates the space is slightly cold, however the use of wall mounted radiators and additional clothing can be used to increase warmth as desired. Summarised in Table 5, Figure 55 & 56 shows the average temperature values for both apartments for summer, winter and the year. Results show consistent temperatures throughout the space, increasing slighting near the eastern façade due to solar radiation.

Although not conditioned, the atriums provide a warmer space compared to the outdoor temperature (Figure 52 & 54). The temperature within the atrium is controlled through natural ventilation of the space, preventing over heating in summer and reducing energy loss in winter. Removing the operable atrium roof and having it permanently open greatly increased energy heating demand for both apartments as heat loss through the glazing increased (Table 4). All windows in the apartments are operable and control temperatures for natural ventilation was studied in detail. A balance was determined individually for each apartment design to ensure unnecessary ventilation in winter did not increase heating demand while reducing mechanical cooling demand in summer.

An infiltration rate of 0.0001 m³/s per m² façade (tight buildings) was used. Building program and schedule was set based on mid-rise apartments and modified as needed.

Majority of the heat loss is through the glazing, with losses increased due to the atrium (Figure 57 & 58). The compact form of the apartments and the single façade reduces the exposed surfaces of the apartments to minimise heat loss.

The retractable terrace shading device required for daylight conditions has a net benefit to the energy demand, greatly decreasing cooling demand (19 vs. 42 kWh/m²) but increasing heating demand (23 vs. 14 kWh/m²). Shading for the façade and atrium glazing was investigated but found to have minimal effect on energy demand and omitted from the design.

The measures taken as a result of the energy analysis act to reduce GHG emissions and costs (renovation, operation & maintenance); both essential characteristics to ensure the transformation of Dragvoll is attractive for stakeholders.

Table 4. Energy Demand Results

DESIGN	HEATING (kWh/m²)	COOLING (kWh/m²)
Atrium_no atrium	9	28
Atrium_open atrium	31	28
Atrium_final design	25	17
Atrium_original materials	41	22
Terrace_no terrace	11	33
Terrace_large	29	19
Terrace_small	20	19
Terrace_small & atrium_noshade	14	42
Terrace_small & atrium_shaded	23	21
Terrace_original materials	41	41
Large Atrium	17	45

Table 5. PMV & Average Temperature Results

DESIGN	PMVyr	Temperature yearly (°C)	Temperature Summer (°C)	Temperature Winter (°C)
Atrium	-0.26	22	25	19
Terrace	-0.48	20	24	18

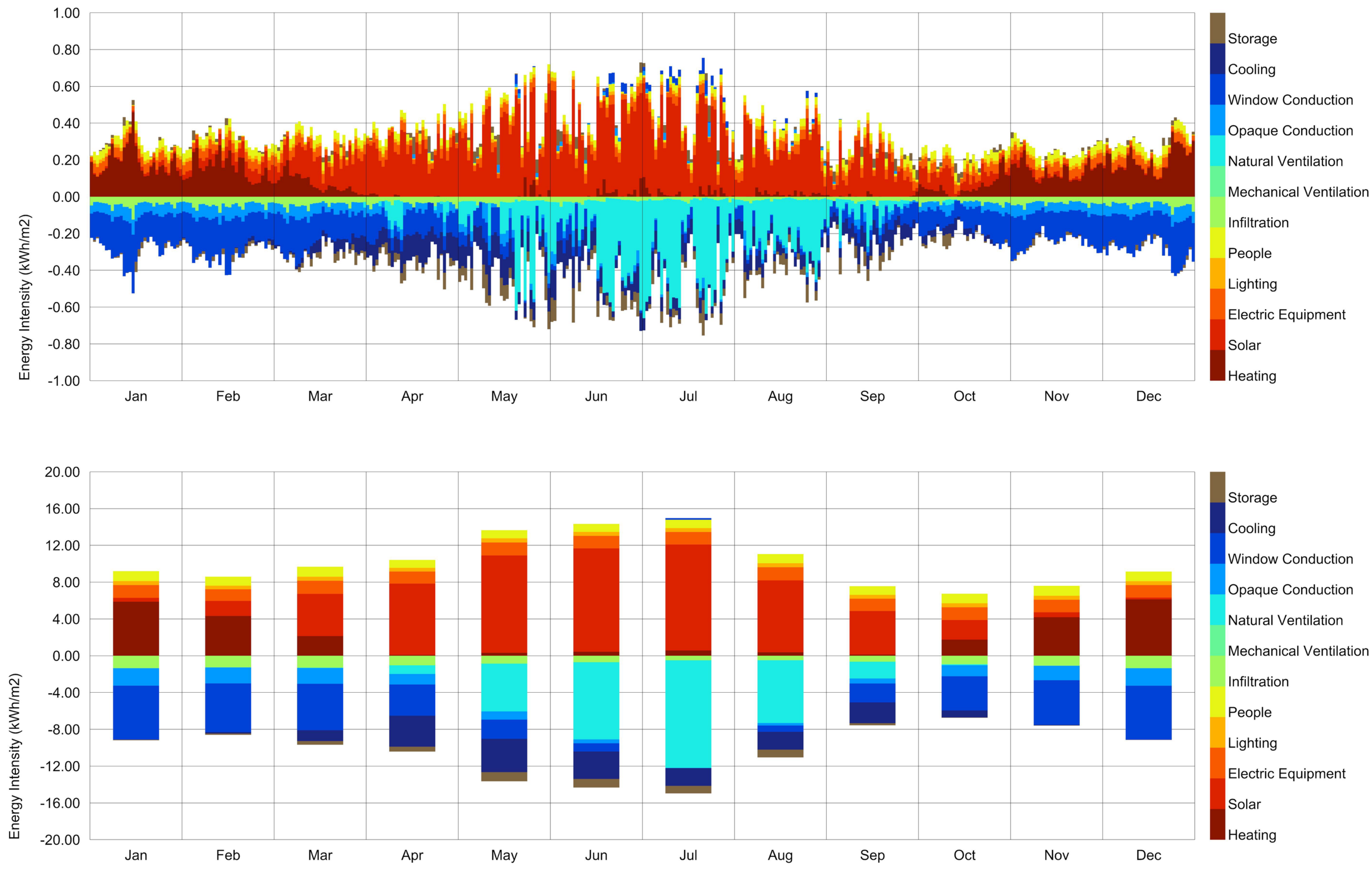

Figure 51. Energy Balance - Atrium Apartment (daily & monthly)

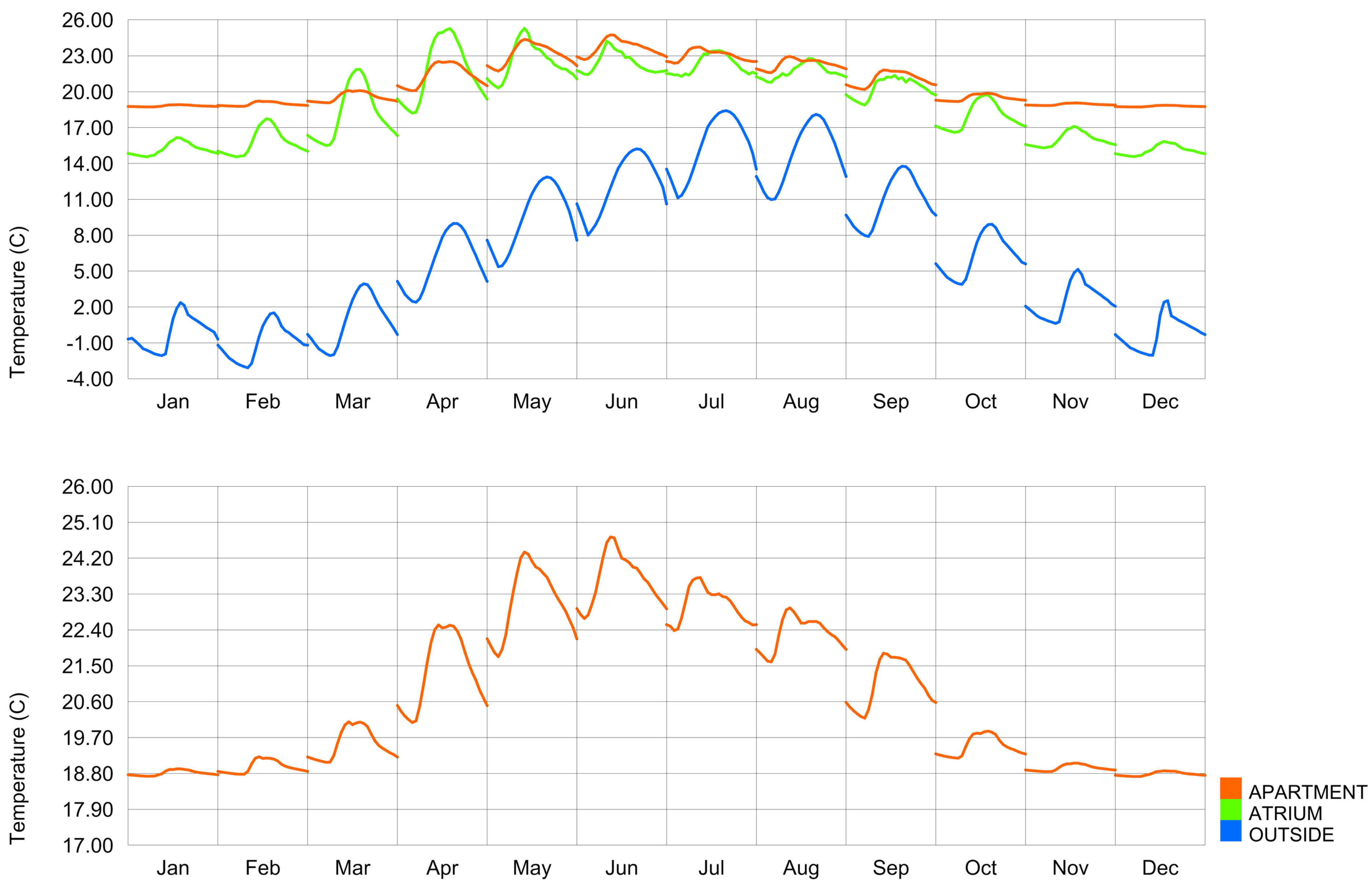

Figure 52. Operative Temperature - Atrium apartment

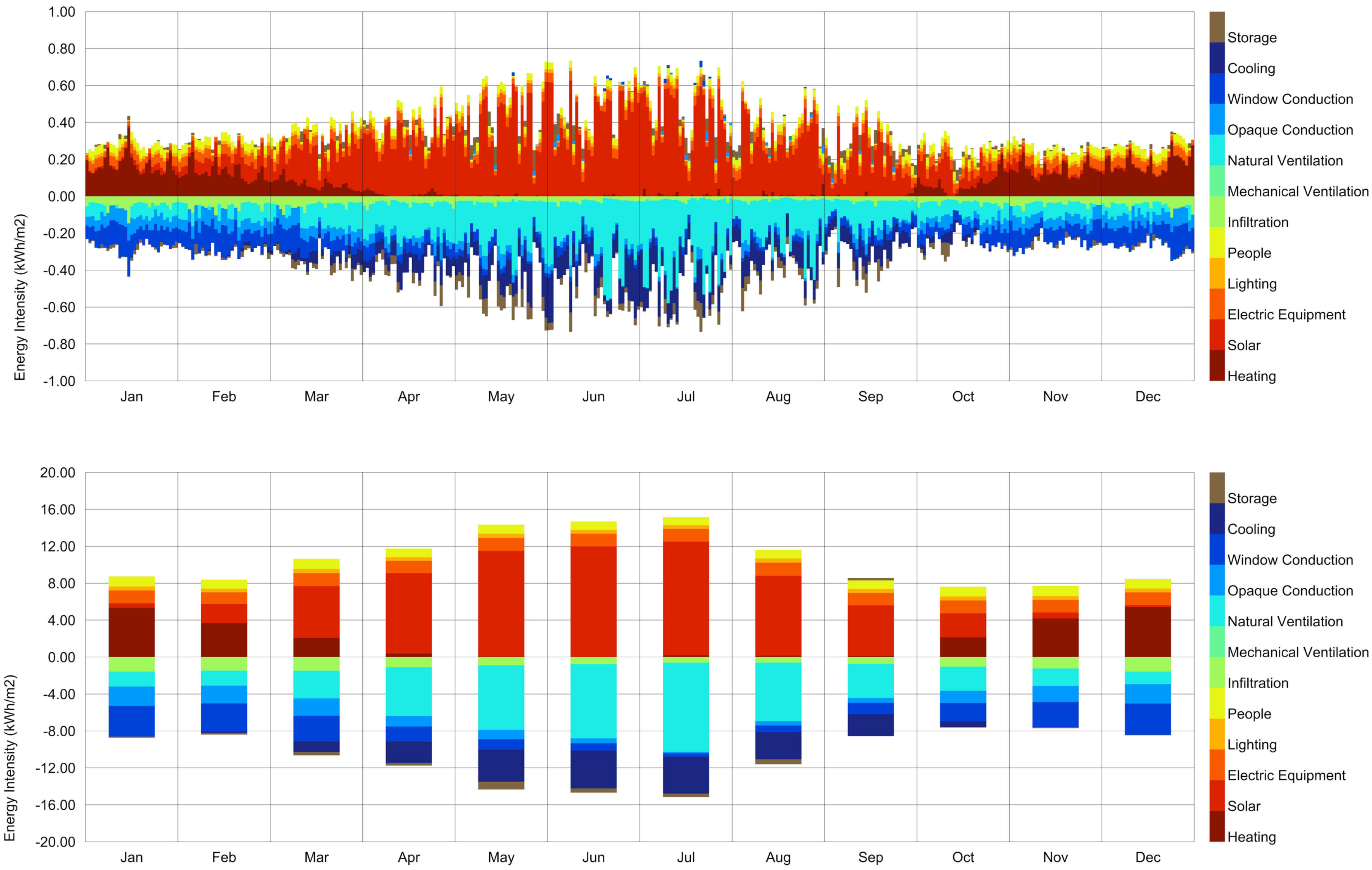

Figure 53. Energy Balance - Terrace Apartment (daily & monthly)

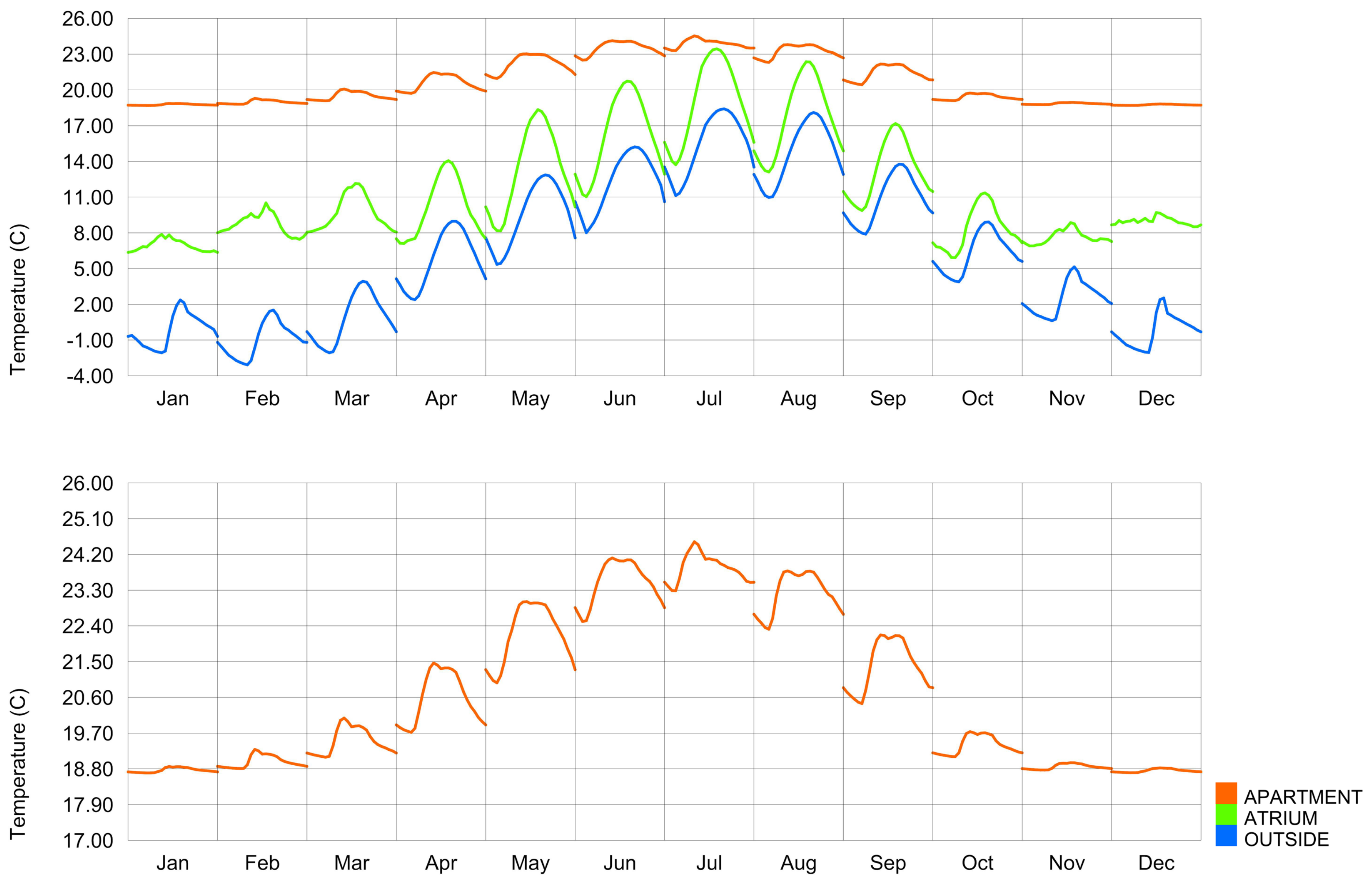

Figure 54. Operative Temperature - Terrace apartment

ENERGY ANALYSIS

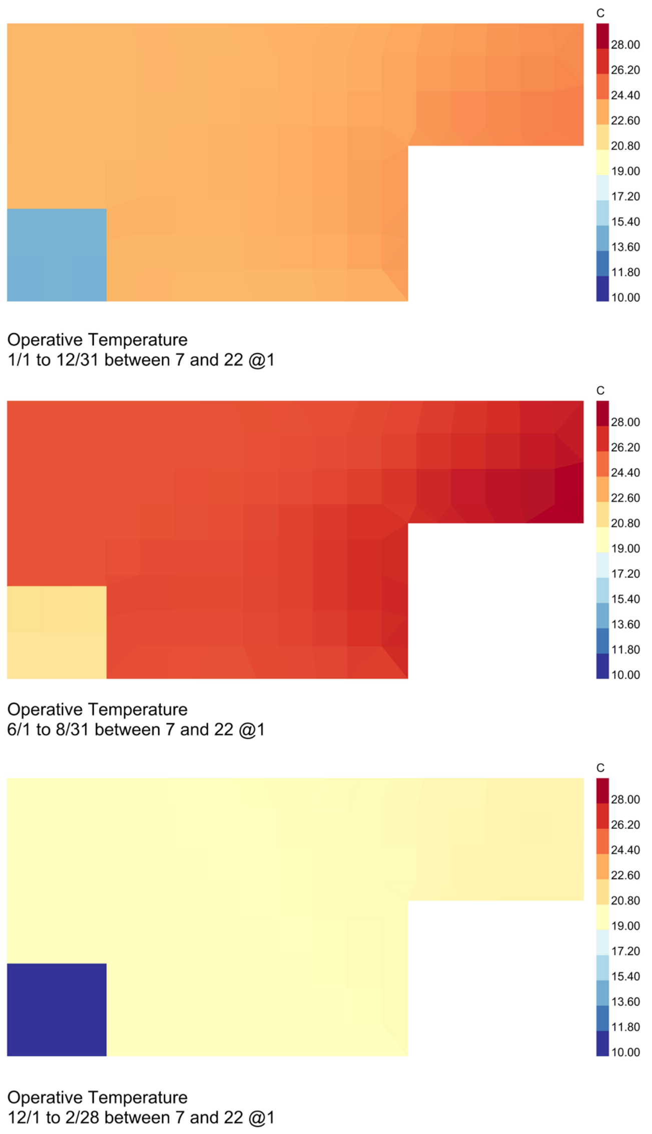

Figure 55. Operative Temperature - Terrace Apartment

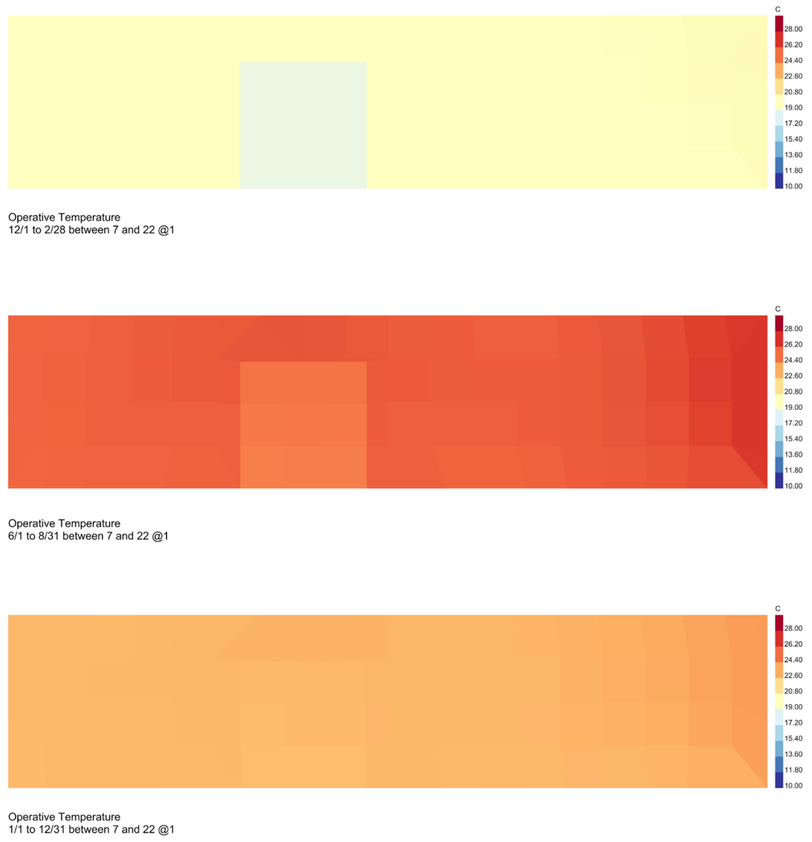

Figure 56. Operative Temperature - Atrium Apartment

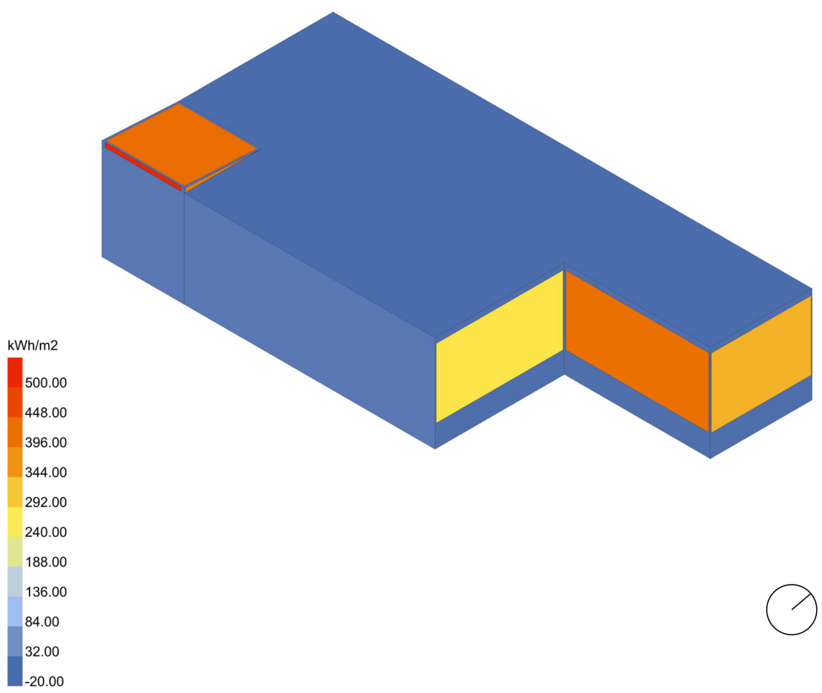

Figure 57. Surface Heat Loss - Terrace Apartment

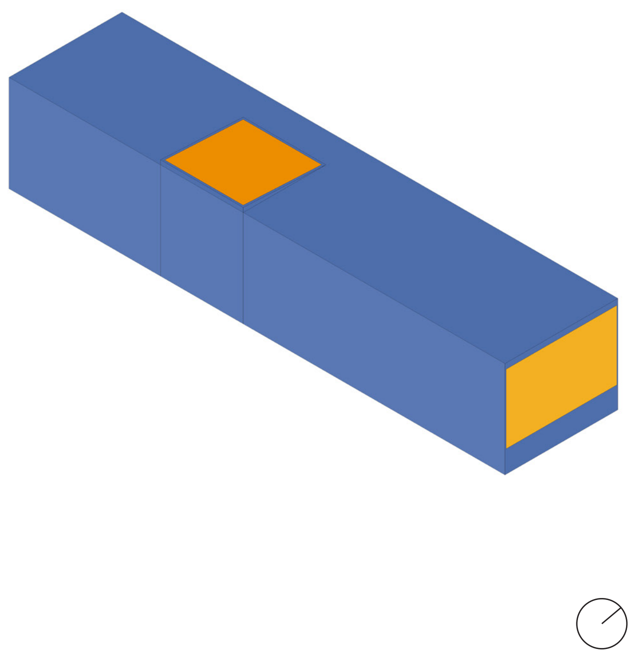

Figure 58. Surface Heat Loss - Atrium Apartment

ENERGY ANALYSIS

RADIATION STUDY

To utilise the thermal mass of the concrete building, a radiation study was completed to investigate the potential of increasing sun radiation through the atrium to the exposed concrete floor. Early results showed that utilising the radiation through the atrium required a larger apartment. This led to the apartment size increasing from 72m^2 to 146m^2 (gross).

Energy analysis showed that the increase in solar radiation reduced heating demand but increased cooling demand (refer 'Large Atrium' in Table 5), creating a net increase in demand. For this reason, and to satisfy the original goal of designing different sized apartments, the apartment with large central atrium was not further investigated. Figure 60 shows the results of different atrium shapes investigated. Results show a linear relationship between atrium size and solar radiation reaching the apartments exposed concrete floor (Figure 59). The optimal size and location of the atrium for solar gains vs. daylight and energy demand could warrant further investigation.

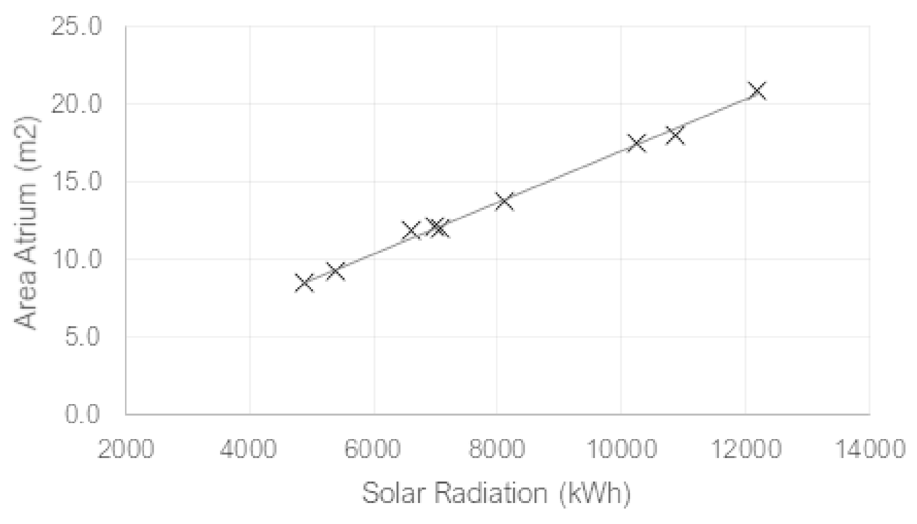

Figure 59. Solar Radiation vs Atrium Area

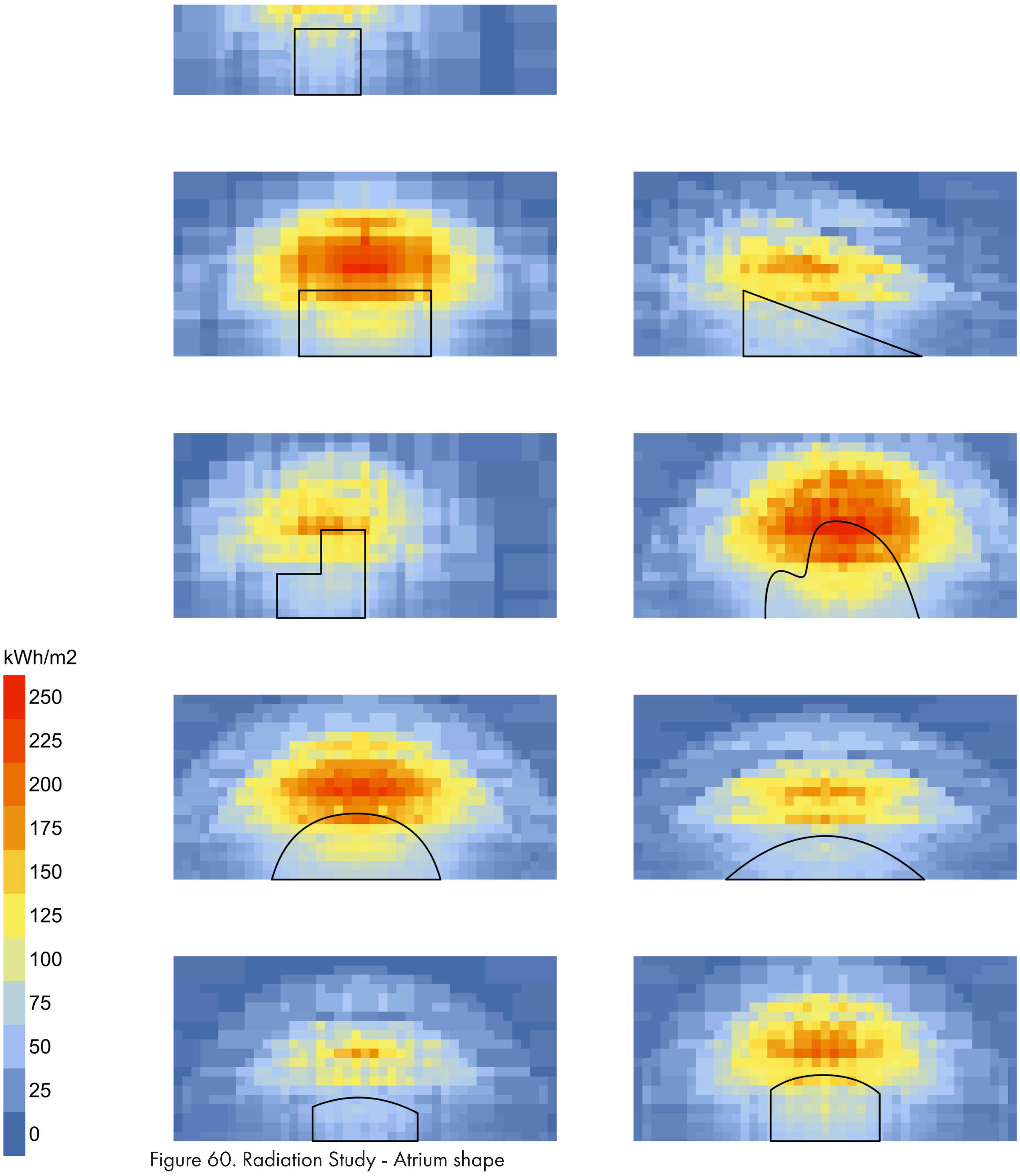

Figure 60. Radiation Study - Atrium shape

4. CONCLUSION

CONCLUSION

This thesis has investigated the potential reuse of Dragvoll university campus. It has considered if the purpose-built campus has potential to serve the community by accommodating alternative functions. Combining residential and office space as an example, the environmental consequences of making necessary modifications to the building was assessed through energy analysis.

For the proposed functions to work, introducing daylight into the centre of the space was of primary importance. This was done using atriums and terraces. Development of floor plans ensured architectural qualities were maintained.

The result is the design of two possible apartment layouts varying in size, with shared functions for the residents. The design integrates the use of natural ventilation to reduce energy usage and create a good indoor climate while utilising the existing technical infrastructure to provide mechanical services. Office space accompanies the apartments, completing the floor layout.

Design shows that with relatively minor modifications, daylight could be introduced into the space without significant consequences to the energy demand. The introduction of atriums to the central space results in sufficient daylight conditions. Reuse of the super structural and technical infrastructure reduces the environmental impact of the renovation as modifications to the super structure is reduced.

A limitation of this project is the level of scope. Dragvoll is a large and complex structure with multiple buildings. It would be interesting to continue the project with an interdisciplinary team of architects and engineers and an increased scope. Future work specific to this thesis could therefore include detailing the technical system, completing a full energy analysis on building 8, or continuing the design and analysis on the other floors. The integration of LCA and use of photovoltaics to determine the overall energy balance of the renovation would create a more quantifiable argument for the reuse of Dragvoll.

The topic of adaptable design, and the assessment of the success of Dragvoll and the reasons that the vision was not realised, could also be further investigated to gain lessons learnt for future architectural projects.

5. REFERENCES

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