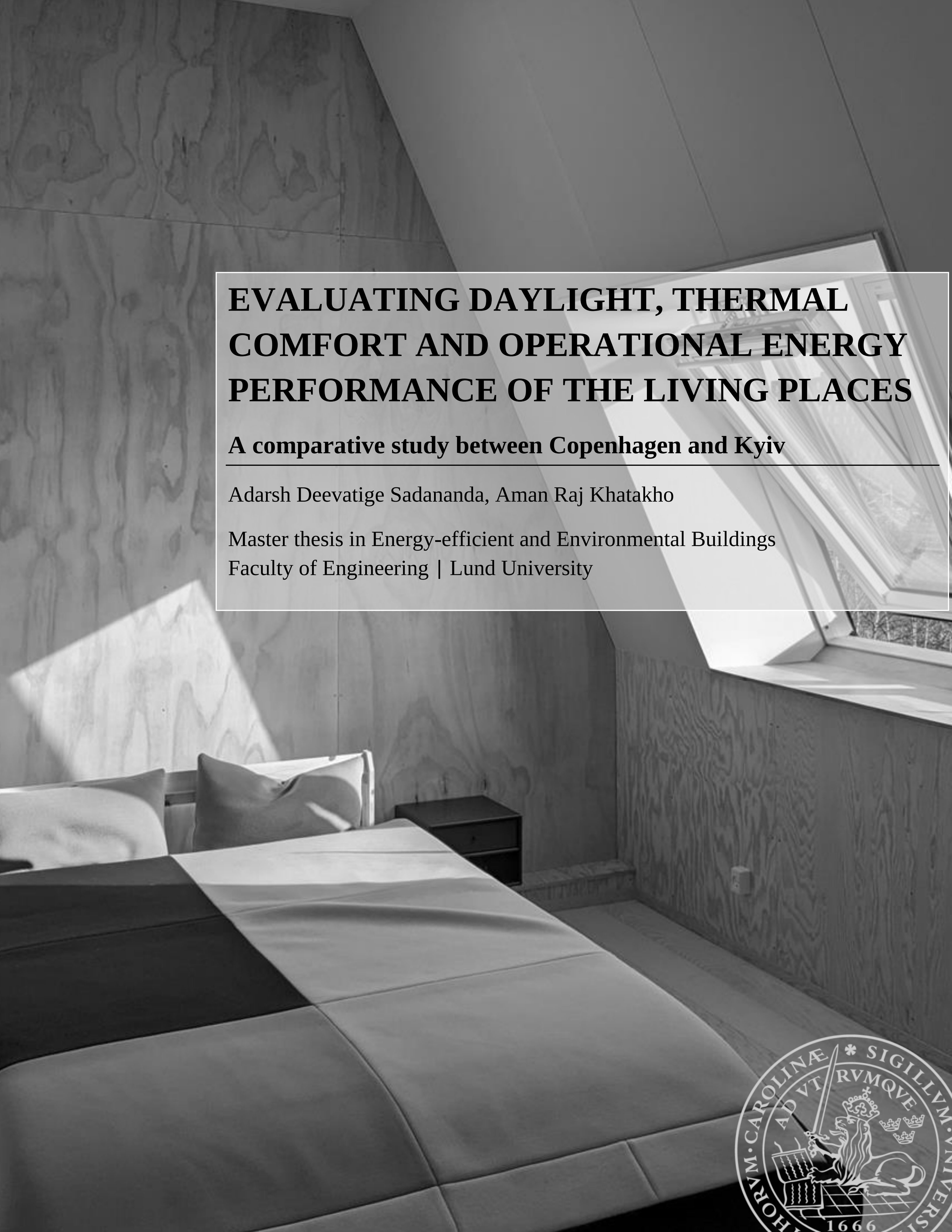

EVALUATING DAYLIGHT, THERMAL COMFORT AND OPERATIONAL ENERGY PERFORMANCE OF THE LIVING PLACES

A comparative study between Copenhagen and Kyiv

Adarsh Deevatige Sadananda, Aman Raj Khatakho

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and today has a total staff of 6 000 employees and 47 000 students attending 280 degree programs and 2 300 subject courses offered by 63 departments.

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The degree project is the final part of the master program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

The Energy Performance of Building Directive's (EPBD) guidelines to reach net zero emissions by 2030 for new constructions encourage energy efficiency amidst the ever-growing global building stocks. A prefabricated modular housing concept that can be optimised according to the climatic conditions that focus on sustainability and energy efficiency could address this situation while achieving high indoor comfort conditions for humans. This thesis is a comparative study of one such concept, The Living Places Copenhagen, to study its adaptability in a different climatic context, promoting visual and thermal comfort and calculating the environmental impact for the operational energy use phase of the building life cycle. This thesis aligns with the ongoing efforts to develop scalable building projects that prioritize occupant health and well-being with a minimal carbon footprint, to achieve carbon neutrality by 2050. Radiance based daylight simulations for Spatial Daylight Autonomy ($sDA_{300/50\%}$) and Energy-based simulations for annual percentage of adaptive comfort hours and Primary Energy (PE) demand were used as metrics to study the adaptation of the architecture and materials of the existing building in Kyiv. Parametric simulation was performed to assess the impact of parameters such as window sizes, glazing properties and the building orientation on daylight, thermal comfort, and energy demand of the building, to identify optimal cases in Kyiv and compare them with the building in Copenhagen, using the Active House specification developed by the International Active House Alliance. The study showed that window sizes had a positive effect on daylight with bigger window sizes bringing in more daylight indoors but also caused discomfort in both summer and winter due to heat gains and loss. The heat loss through the bigger windows had a higher impact on elevating the heating energy demand during winters. The study also showed that higher glazing transmittance (T_{vis}) which was also associated with higher solar heat gain coefficient (SHGC) had a positive effect on daylight and energy use but conversely caused discomfort due to summer heat gains. Rooms with window openings on single side showed more sensitivity toward orientation change pointing out the advantage of windows in multiple facades for multidirectional daylight. Hence the ideal window setup depends on the desired balance between daylight, thermal comfort, and energy demand.

A weighting method prioritizing, in the order, energy demand, thermal comfort and daylight was followed to compare the simulated cases against the base case. The optimal cases presented in this study all achieve $sDA_{300/50\%}$ >70% of the occupied floor area, adaptive thermal comfort hours >95% of the occupied hours and an average annual energy demand of 32.87 kWh/m²/y with a corresponding carbon footprint of 11.22 $kgCO_2$-eq./m²/y for operational energy use phase. For Kyiv that shared a climatic condition characterized by similar overcast sky conditions and daylight hours but higher summer and winter peaks, the building performed well achieving the highest Active House (AH) score for daylight while underperformed for thermal comfort and energy demand. The high energy factor and carbon emission factor for Kyiv associated to the electricity produced mainly from nuclear sources as opposed to hydro and wind sources in Copenhagen resulted in 2.8 times higher carbon footprint for operational energy use phase for the most optimal solutions.

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Abbreviation

AH	Active House
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BR18	Bygningsreglementet 18
BREEAM	Building Research Establishment Environmental Assessment Method
CBDM	Climate Based Daylight Modeling
CIE	Commission Internationale De I'Eclairage
CLT	Cross-Laminated Timber
CO_2	Carbon Dioxide
COP	Coefficient Of Performance
DA	Daylight Autonomy
DDM	Dynamic Daylight Metrics
DF	Daylight Factor
DHW	Domestic Hot Water
EMPS	European Multi-Area Power Market Simulator
EPBD	The Energy Performance Of Buildings Directive
EPW	Energy Plus Weather
EU	European Union
EUI	Energy Use Intensity
GHG	Greenhouse Gas
GWP	Global Warming Potential
IEQ	Indoor Environmental Quality
IES	Illuminating Engineering Society
ISO	International Standard
LCA	Life Cycle Assessment
LCEA	Life Cycle Energy Analysis
LEED	Leadership In Energy And Environmental Design
PE	Primary Energy
PEF	Primary Energy Factors
PMV	Predicted Mean Vote Model
PPD	Predicted Percentage of Dissatisfied
SGBC	Swedish Green Building Council
SHGC	Solar Heat Gain Coefficient
WSF	Window Scaling Factor
ZEB	Zero Energy Building

1 Introduction

The building sector accounts for over 40% of the final energy consumption and related Green House Gas (GHG) emissions in the European Union (EU) member states, of which residential buildings represents 63% of the total energy consumption (Balaras, et al., 2007) (Lee, Kim, Song, Kim, & Jang, 2017). These figures could further increase in the next decade as a consequence of the constant growth in buildings stocks, stressing the need to reduce carbon emission to reach sustainability goals.

Global conflicts cause damages to dwellings and land (Kulish, 2023), and there is an immediate need to provide shelter for the affected population. The eventual reconstruction puts more strain on the environment, contributing to increased carbon emissions. This has raised concerns emphasizing the need for a sustainable and energy efficient building approach to ensure high living conditions while minimizing impact on the resources. A prefabricated modular housing concept that can be optimised according to the climatic conditions that focus on sustainability and energy efficiency could address this immediate demand assisting the transition phase back to the normal life, while minimizing the environmental impacts. These buildings should aim at easing the transitional phase for the population affected by a conflict, in addition to minimal environmental impact, and must ensure healthy and comfortable living conditions for the residents, two key factors being the availability of daylight and indoor thermal comfort.

Living Places Copenhagen, a collaboration between VELUX Group, EFFEKT and Artelia, is a good example of such a concept. Living Places Copenhagen is an innovative architectural concept promoting sustainable buildability, prioritizing a healthy indoor climate through ample daylight and fresh air, achieving a remarkably low CO_2 footprint of 3.85 kg CO_2-eq/m²/year- three times below the current Danish legislative standard (Living Places, 2023). Living Places Copenhagen consists of seven buildings with different residential and non-residential uses. It offers context-responsive housing typologies ensuring flexibility, adaptability, and scalability in the Danish urban fabric (VELUX, 2023). The success of the Living Places in Denmark highlights the need for contextual adaptation when implementing this module in other settings. Given the ongoing conflict in Ukraine, the project's core principles could be strategically redeployed to support post-conflict reconstruction efforts in Kyiv.

To reach the scope, this thesis tailors a residential building module of Living Places Copenhagen to a new potential destination in Kyiv. The tailoring process includes architectural and material changes, such that the potential residential building in Kyiv could result in a similar high daylight, thermal and environmental performances as that in Copenhagen. In a larger context, this thesis is a part of a collective effort to address the need to scale projects that ensure healthy indoor living conditions for the occupant with low carbon footprint to attain carbon neutrality by 2050 (European Parliament, 2019). This research focuses on the implementation of a design strategy that promotes visual and thermal comfort, giving specific importance to environmental impact due to the operational energy use phase, as per the European EPBD guideline for zero-emission buildings by 2030 (The Energy Performance of Buildings Directive, 2024).

1.1 Objectives

The aim of this study is to adapt the Living Places- Pavilion 2, a three-story timber-framed single-family residential module in Copenhagen to the context of Kyiv, Ukraine. The process focuses on daylight, thermal comfort, and environmental performances in relation to operational energy use. The process is focused on an adaptation of the architecture and materials of the existing building, which is evaluated according to the Active House Specifications, 3rd Edition.

1.2 Research Questions

The study will attempt on answering the following questions to formulate a framework for the thesis:

a. How would Living Places module perform in a different climatic condition, a case of Kyiv, Ukraine, compared to the base case module in Copenhagen?
b. How can the base case module of Living Places be adapted to design an Active house suited for the climatic conditions of Kyiv?
c. How can the Indoor Environmental Quality (IEQ) be assured to the module in Kyiv?
d. How would the operational energy use and its environmental impact compare in these two climatic conditions?

1.3 Limitations

The study focuses on evaluating daylighting and its impact on the thermal comfort of the indoor environment, of Pavilion 2, among the total of seven different building modules of the Living Places Copenhagen. Living Places Copenhagen is an Active House (AH) rated building and hence the building performance is evaluated based on the AH standards for a fair comparison between the two cases, even though there are no specific guidelines available for Ukraine. The building is assessed only for a few selected subcategories under indoor comfort and energy categories from the Active House specification. The effects of dynamic shading were not considered in the simulations for their unpredictability in residential application as the use of interior shading devices like roller blinds and venetian blinds is significantly influenced by the user preferences. The study focuses on the calculation of carbon emission for the operational energy use phase (B6), to compare the impact of achieving similarly high indoor climate conditions on operational energy used in these two climatic conditions.

2 Background

2.1 Buildings for people

Humans spend most of their time indoors (Papadopoulos, et al., 2023) hence it is very important to ensure high level of indoor environmental quality, including thermal comfort, indoor air quality, illumination level and acoustics, which ensures healthy living conditions, higher productivity, and comfort for the occupants. The European standard EN 16798-1 specifies indoor environmental quality into four categories, based on the level of expectations the occupant may have. The comfort level for the occupants and the energy consumption of the building depends significantly on these categories' levels. Hence, several active and passive measures are implemented to ensure high indoor environmental quality while minimizing the energy consumption of buildings.

2.1.1 Daylight

A well day lit environment is a space primarily lit with natural light combined with high occupant satisfaction of visual and thermal environment with minimal energy use for heating, cooling, and lighting (Reinhart & Wienold, 2011). Inadequate exposure to daylight has a profound impact on the circadian rhythm, exerting adverse effects on sleep patterns, productivity, and the overall mental well-being of individuals (Nagare, et al., 2021). Daylight is highly valued by building occupants for its ability to efficiently illuminate indoor spaces and reduce reliance on electrical lighting. It offers high color rendering and variability, with daily and seasonal changes.

Several studies have described the development of daylight assessment metrics and calculation methods, due to the increased demand for accurate daylight assessment for creating energy efficient buildings while ensuring human comfort (Sokol & Martyniuk-Peczek, 2016). These daylight assessment metrics encompass aspects such as daylight provision and distribution, sunlight exposure, protection from glare and access to view towards the outdoor.

Daylight provision is often assessed via Daylight Factor (DF), namely the ratio between indoor and outdoor horizontal illumination under CIE overcast sky condition (Gentile, et al., 2016). Daylight Factor (DF) is, therefore, insensitive to building orientation, location, season, time of day and sun availability. These DF limitations have led to the development of advanced dynamic methods called Dynamic Daylight Metrics (DDM) which require advanced computer simulations often referred to as Climate Based Daylight Modeling (CBDM). Prediction of daylight performance is delivered by CBDM using weather data derived from standard meteorological datasets (Climate-Based Daylight Modelling, 2017). Within the dynamic daylight metrics (DDM), Daylight Autonomy (DA) is a widely employed metric, which quantifies the percentage of occupied hours in a year where a point or grid of points within a space achieves the minimum illuminance threshold solely through daylight (Reinhart C. , 2004). It serves as a key indicator of a building's reliance on artificial lighting for illumination. Spatial Daylight Autonomy (sDA) is another method approved by the Illuminating Engineering Society (IES) for standardized daylight provision assessment. It quantifies the percentage of a designated analysis area that receives a minimum level of horizontal daylight illuminance (e.g. 300lux) for a specified duration (e.g. 50%) of the annual occupied hours (Dubois, Gentile, Laike, Bournas, & Alenius, 2019). Spatial Daylight Autonomy assesses the adequacy and distribution of natural light within a space throughout the year.

National building codes generally set requirements on daylight provision based on DF approaches. Voluntary building performance rating systems such as BRE Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) seek excellence by setting requirements based on daylight metrics, such as Spatial Daylight Autonomy (sDA). In Europe, the European daylight standard EN 17037 proposes a scheme based on DA or on a 'climatized' version of DF. The Active House (AH) standard also integrates daylight provision under its certification criteria, the calculation of which is based on methods described in EN 17037:2018. Coherently, the Active House specifies two quantitative criteria evaluation methods for daylight assessment based on Daylight Factor (DF) and Daylight Autonomy (DA).

2.1.2 Thermal Comfort

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines thermal comfort as '*the condition of mind which expresses satisfaction with the surrounding environment of the occupants*.' Thermal comfort relates human sensation and perception with several environmental and physical parameters (Fanger, 1970). Thermal comfort, mainly, is an individual's state of feeling satisfied in an environment, hence it might differ from person to person. Thermal discomfort affects productivity along with health and well-being (Rupp, Vásquez, & Lamberts, 2015). Apart from the impacts on health of humans, buildings performing poorly in respect to thermal aspects e.g. because of cold draft may increase the load of the ventilation, leading to an increased energy use, making the building less energy efficient (Veitch & Galasiu, 2012).

Thermal comfort conditions are influenced by environmental factors such as relative humidity, air speed, air temperature and mean radiant temperature and human factors such as metabolic rates and clothing levels. Various comfort models have been developed to analyse these thermal comfort conditions. The Predicted Mean Vote (PMV) model, a static model of thermal comfort based on Fanger's principles of heat balance and experimental data collected in a controlled climate chamber under steady-state conditions, is perhaps the most recognized (Fanger, 1970). For a mechanically ventilated building, the PMV model recommends a consistent indoor temperature with small adjustments to account for seasonal clothing level in summer and winter. Research argue that this static method ignores important cultural, climatic, social, and contextual dimensions of comfort (Kempton & Lutzenhiser, 1992). Such considerations have prompted interest in a variable indoor temperature standard to supplement the current standard. This adaptive model of thermal comfort is based on the idea that occupants dynamically interact with their environment and control it by the combination of behavioural, physiological, and psychological adjustments such as clothing, operable windows, fans, and shading devices (de Dear & Brager, 1998). The adaptive model is applied to buildings that are naturally ventilated and have no mechanical systems in operation.

The PMV and PPD (Predicted Percentage of Dissatisfied) indices are used by the international standard ISO 7730 to predict the thermal sensation of occupants in an indoor environment and specify different levels of the acceptable thermal comfort conditions (Peeters, Dear, Hensen, & D'haeseleer, 2009). The European Standard EN 16798:2019 specifies various categories of criteria for thermally comfortable indoor environment. Building performance rating systems such as BREEAM and LEED also award credits to buildings with good thermal comfort. The Active House (AH) standard recommends adequate thermal comfort, both during summer and winters, for human comfort and energy efficiency. The evaluation of thermal comfort for AH is based on indoor operative temperature. For indoor environment regulated by mechanical ventilation, a static approach of maximum (summer) and minimum (winter) operative room temperature is employed. Conversely, a dynamic adaptive comfort approach of maximum operative temperature is adapted by AH for the summer months, particularly when relying on natural ventilation.

2.2 Environmental Buildings

Buildings designed to be operated with a focus on minimizing their negative impact on the environment while offering comfortable indoor environment to the occupants can be defined as environmental buildings. Carbon emission of building materials, the energy use and the disposal of building materials inform about the different environmental impacts of a building. The method used to identify and evaluate the environmental impacts of a building throughout its life span, ranging from materials manufacturing, construction, use and maintenance and end of life is called Life Cycle Assessment (LCA) (Charlene, Gamble, Russell, & Joshi, 2010). All energy requirements associated with the building life cycle, termed as life cycle energy, include embodied energy and operational energy. Energy used for space heating and cooling, ventilation, lighting, domestic hot water, and running electrical equipment in the dwelling falls under operational energy while embodied energy is the energy used during materials manufacturing and construction phases of the building project. Life cycle energy analysis (LCEA) helps in identification of high energy demand stages for reducing the primary energy use and their emission (Ramesh, Prakash, & Shukla, 2010). Consequently, greenhouse gas emissions will be reduced. For reduction of the life cycle energy of buildings, the traditional focus has been on reducing operational energy use over time through building design or equipment efficiency. While these efforts to optimize the operational energy usually add up the total embodied energy of the buildings, the overall impact of the building is lowered (Karimpour, Belusko, Xing, & Bruno, 2014).

The proposed new EPBD guidelines outline the enhanced climate and energy ambition of the European Union through the vision of zero-emission buildings by 2030 for new buildings. The concept necessitates newly constructed buildings with minimal energy demand, zero on-site carbon emissions from fossil fuels and very low operational greenhouse gas emissions (The Energy Performance of Buildings Directive, 2024). Based on their sources and energy mix, the energy use of the buildings can be converted to carbon emissions, often denoted as Global Warming Potential (GWP). There are certifications schemes, in addition to LEED and BREEAM, which account for 'climate-neutral buildings' such as NollCO_2 from the Swedish Green Building Council (SGBC), Zero Emission Buildings (ZEB) from the Norwegian Research Institute, including the Active House. The Active House follows the well-established framework set up by the European standard EN 15978 for life cycle assessment and requires the assessment of the buildings under different impact categories of emissions for energy use and environmental impact.

2.3 Active House Standards

The Active House (AH) standard is a voluntary building certification protocol, developed by the International Active House Alliance, designed to enhance the well-being of occupants, and promote environmental sustainability. The vision of Active House establishes ambitious long-term goals for the building stock, aiming to unite stakeholders through a holistic approach to building design and performance (Active House, 2024). The certification label is granted to buildings meeting the Active House specifications and minimum requirements, based on the evaluation of three key quantitative indicators: indoor comfort, energy efficiency, and environmental impact, which are further categorized into nine interdependent subcategories, as shown in the AH radar in Figure 1. The Active House standard emphasizes a balance between categories, acknowledging contextual implications that may lead a project to excel in some areas while performing less optimally in others. The standard envisions buildings that enhance occupants' lives without adverse environmental impact, representing the next generation of sustainable structures that prioritize energy efficiency, comfort, and environmental considerations.

An Active House integrates these factors to create a healthy and sustainable living space. Each of the nine subcategories is associated with ranking criteria used to determine the Active House ambitions for a design project, with four classes or scores (1-4) where 1 represents the highest and 4 the lowest passing level. If a building falls outside these classes, it is deemed unclassifiable as an Active House. These criteria have both qualitative and quantitative aspects, where the qualitative aspects influence the initial building design process. Table 1 describes the ranking criteria for the relevant quantitative categories for this thesis, which is part of the Active House specifications, as shown in Appendix A.

Table 1: Active House quantitative criteria evaluation method for relevant categories in the study.

Category	Subcategory	Aspect	Class: Criteria
Comfort	Daylight	Target daylight level per room	The amount of daylight in a room is evaluated through daylight levels with a target illuminance of 300 lux in dwellings ($DA_{300/50}$) 1: > 70% of the occupied space 2: > 60% of the occupied space 3: > 50% of the occupied space 4: > 40% of the occupied space
	Thermal Environment	Minimum operative temperature per room	The minimum indoor temperature limits apply in winter periods with an outside T_{rm} of 12°C or less. For living rooms, kitchens, study rooms, bedrooms, etc. in dwellings, requirement met for 95% of the occupied hours. 1: $T_{i,o} > 21$°C 2: $T_{i,o} > 20$°C 3: $T_{i,o} > 19$°C 4: $T_{i,o} > 18$°C
		Maximum operative temperature per room	The maximum indoor temperature limits apply in summer periods with an outside T_{rm} of 12°C or more. For naturally ventilated rooms, requirement met for 95% of the occupied hours. 1: $T_{i,o} < 0.33 * T_{rm} + 20.8$°C 2: $T_{i,o} < 0.33 * T_{rm} + 21.8$°C 3: $T_{i,o} < 0.33 * T_{rm} + 22.8$°C 4: $T_{i,o} < 0.33 * T_{rm} + 23.8$°C
Energy	Energy Demand	Annual energy demand	1: < 40 kWh/m² 2: < 60 kWh/m² 3: < 80 kWh/m² 4: < 100 kWh/m²
	Primary energy performance	Annual non-renewable primary energy performance	1: 0 kWh/m² 2: < 50 kWh/m² 3: < 100 kWh/m² 4: < 130 kWh/m²

All buildings can receive an Active House (AH) rating if they demonstrate an overall good performance. Although emphasis on criteria may vary, provided that the average score of all nine subcategories is 2.5 or less for new construction, as calculated using equation (1), the building qualifies as an Active House.

$$Overall\ AH\ score = \frac{Sum\ of\ total\ scores\ of\ all\ 9\ AH\ parameters}{9} \leq 2.5 \tag{1}$$

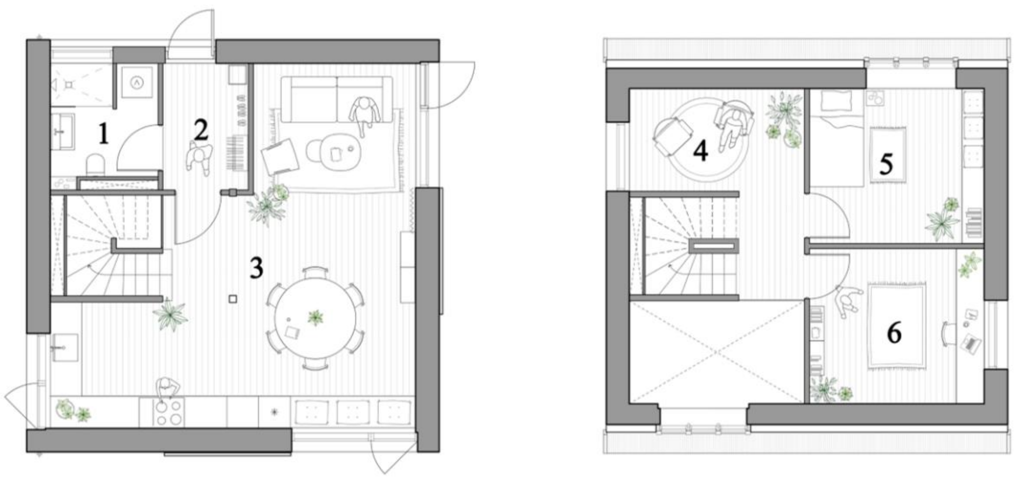
Figure 1: Active House Radar (adapted from International Active House Alliance)

2.4 Living Places Copenhagen: Pavilion 2

Pavilion 2 shown in Figure 2, also named the Hygge House, is a three-story fully functional timber frame construction. It is built as a '*post and beam*' structure, which consists of vertical and horizontal linear elements that require incorporating stability planes and is one of the most traditionally used building techniques. It is a residential prototype ideally designed for a single family of four with a total heated floor area, A_{temp} of approximately 110 m². The floor layout of the building can be seen in Figure 3. The module is designed elegantly supported on a screw pile foundation. It is equipped with an air-to-water heat pump to fulfill heating requirements. The building has four VELUX windows with dynamic solar shading that operate with indoor temperature and Carbon-di-Oxide sensors (AirBird, 2020) to regulate the indoor thermal comfort. Additionally, this module is equipped with 11 m² of solar panels to produce its electricity demands.

The Hygge House is one of the two residential modules for a single-family home in Living Places Copenhagen, the other being Pavilion 5, a module in cross-laminated timber (CLT) with hybrid ventilation, also known as the Haven House. The Hygge house uses the least quantity of materials, takes approximately 10 days of assembly time, and has a low carbon footprint, estimated to be 3.8 kg CO_2-eq/m²/year. The cost of construction of the Hygge House is estimated to be 13 900 DKK/m² (VELUX, 2023).

Figure 2: Living Place Copenhagen, Pavilion 2: The Hygge House



1	Bathroom
2	Foyer
3	Living and Kitchen
4	Study
5	Bedroom 1
6	Bedroom 2
7	Master Bedroom

Figure 3: The Hygge House: Ground floor plan (Top Left), First floor plan (Top Right) and Second floor plan (Bottom Left)

3 Methodology

Pavilion 2, the Hygge House, was chosen for assessment among the seven prototypes of Living Places Copenhagen as it is among the two residential modules for single-family homes with the lowest carbon footprint and cost of construction (VELUX, 2023). A digital model along with a set of reference drawings of the assessed building was provided by VELUX. Comprehensive data collection regarding the thermal characteristics of the construction was carried out. This information was used to construct a simplified energy model and a daylight model, using Rhinoceros 7. These models were simulated for daylight, energy use and thermal comfort analysis using Honeybee in Grasshopper and compared against the monitored results provided by VELUX. A site was proposed in Kyiv, in a low-density location similar to the one chosen for Living Places in Copenhagen. This allows for a fairer comparison between the performances of the module in these two different climatic conditions. The Active House (AH) scores for the simulated results were compared with the building in Copenhagen. Based on the performance compared to the Copenhagen model, various passive measures were adapted to enhance the performance. Parametric studies were performed using Colibri for Grasshopper aiming at optimal solutions for daylighting performance, and related indoor thermal comfort conditions. The checked parameters included the window sizes, glazing properties, and building orientation. These cases were first weighted among themselves to identify the cases with highest daylight and thermal comfort conditions. A second weighing was done, incorporating the energy use intensity (EUI), to compare these top cases against the Copenhagen model to highlight the best performing cases. Finally, carbon emissions for the optimum solutions were calculated using the energy carrier emission factor to compare with the Copenhagen model. A workflow diagram for the methods followed is illustrated in Figure 4.

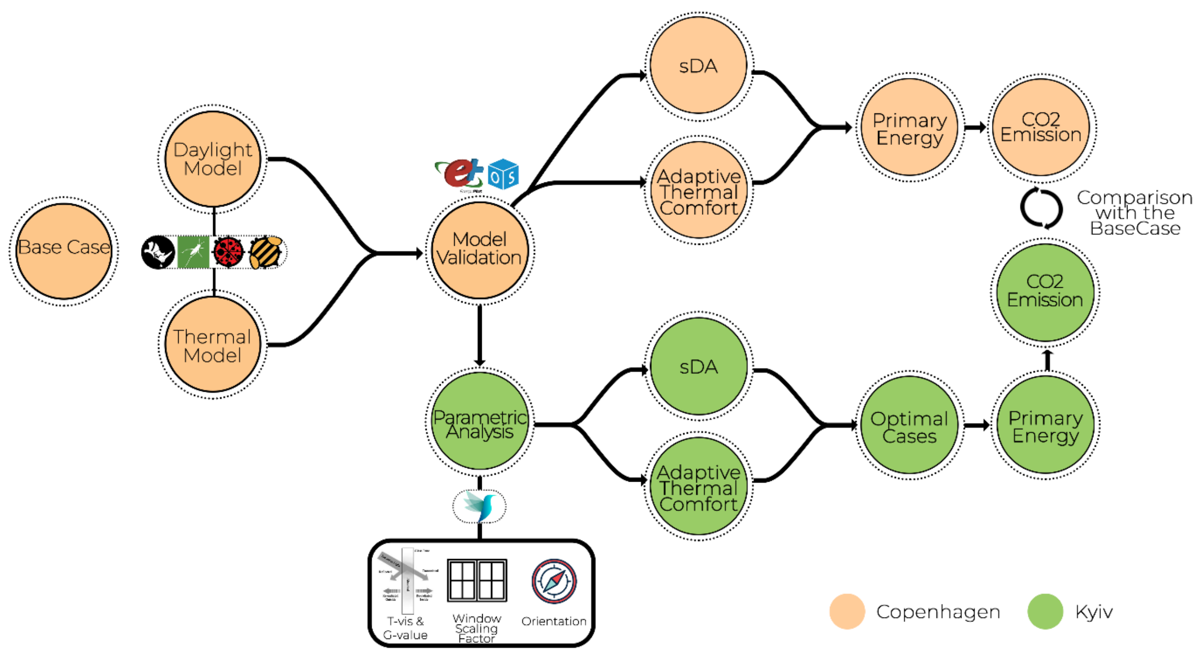


Figure 4: Methods flow diagram.

3.1 Site Selection

Analysis of different interactive city maps of Kyiv (LUN city, 2024) aided to narrow down a site proposal for the residential module in Kyiv. The maps included information regarding the pollution level, noise level, city thermal islands, built up density and neighborhood with major investment in the public facilities. These criteria were used to identify a low-density residential neighborhood within the proximity of Central Kyiv, which would offer essential services and recreational activities for a comfortable urban lifestyle as indicated as in Figure 5.

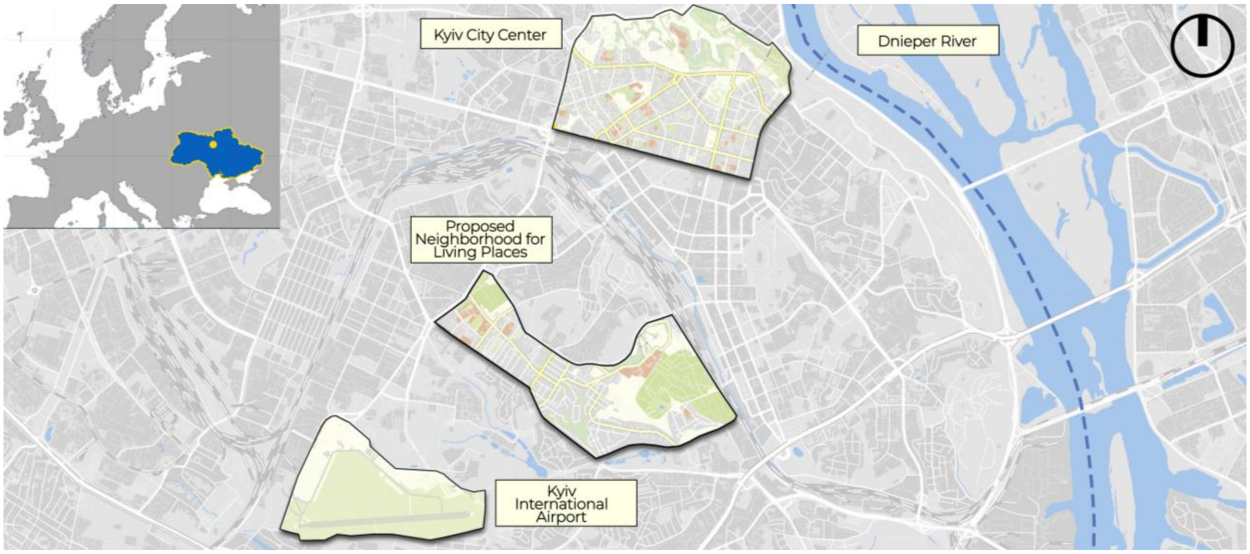


Figure 5: Proposed neighborhood for Living Places in Kyiv.

3.2 Climate Characterization

Characterization of climate was done via Köppen Geiger climate classification method (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). Both Copenhagen and Kyiv show a humid continental climate with large seasonal temperature differences such as warm to hot summers and cold to snowy winters. Despite sharing a comparable climate classification, these locations exhibit distinct weather conditions. Copenhagen experiences a peak summer temperature of 27.2°C and a peak winter temperature of -12.2°C, with an annual average of 9°C and approximately 1097 hours of sunshine throughout the year out of the total 4406 daylight hours. This translates to 75.1% of the daylight hours being characterized by cloudy or overcast skies. In contrast, Kyiv experiences a summer peak of 32.5°C and a winter peak of -22.2°C with an annual average of 8.9°C, and approximately 1189 hours of available sunshine during the year out of 4399 daylight hours. This results in 72.9% of the daylight hours being overcast. Thus, the two locations have similar average temperatures and overcast daylight hours, but most likely different requirements for heating and cooling peak loads.

3.3 Active House Assessments

The analysis of daylight, thermal, and energy performance focuses on the AH standard, and it thus follows the calculation methodologies provided by the Active House Standard.

3.3.1 Daylight and Thermal Comfort

The criteria for comfort were weighted according to the predicted or actual use. When assessing daylight, only occupied daylit hours were taken into account. However, for thermal comfort, all hours were included in the assessment. The calculation method for the total average score of the building for the assessed category is shown in Table 2. A weighting method defined by the AH standard, as shown in equation (2), was used to calculate the Active House score for each room of the building. The intensity of use hours for typical room types for residential buildings is shown in Appendix B. The total averaged score of all the rooms results in the Active House score for the building under each category as shown in equation (3).

Table 2: Example calculation of average score for the assessed category using default values for different rooms in a house (Active House, 2024).

Room Types	Category Score	Intensity of Use	No. of People	Weighted Score
Kitchen	3	2.5	3	22.5
Living Room	2	3	3	18
Bedroom (Parents)	2	0.5	2	2
Bedroom (Kids)	2	1.5	1	3
Sub Total		19		45.5
Total Average Score				2.4

$$Weighted\ Score = Score\ x\ Intensity\ of\ Use\ x\ No.of\ People$$

(2)

$$Total\ Average\ Score = \frac{Total\ Weighted\ Score}{Total\ Use\ Hours}$$

(3)

3.3.1.1 Daylight

A climate-based daylight performance metric method of illuminance levels on the reference plane 0.85 m above the floor was used for assessing the daylight qualities. The calculation preconditions for assessing DA were based on the method described in EN 17037- Daylight in Buildings, Daylight provision calculation method 2. EN 17037 verifies criteria for 50% of the daylight hours. The sun-up hours from the weather file were adopted as daylight hours for analysis and the amount of daylight in a room was evaluated based on the daylight levels with a target illuminance level of 300 lux for dwellings. The percentage of occupied space area achieving the criterion set ($sDA_{300/50\%}$) was used to determine the class of daylight provision as specified by AH standard (see Table 1).

3.3.1.2 Thermal Environment

Active House standard specifies indoor operative temperatures for naturally ventilated buildings as a function of the outdoor running mean temperature (T_{rm}) with a deviation from the EN 16798-1:2019. It only specifies the minimum operative temperature for winter and maximum operative temperature for summers for residential buildings as described in Table 1. For naturally ventilated buildings during summer seasons when T_{rm} is 12°C or higher, an adaptive model is applied in which the maximum indoor operative temperature changes with the outdoor temperature. The requirements for indoor operative temperature should be met for a minimum of 95% of occupied time.

3.3.2 Energy

Active House assesses the annual energy demand of the building, including energy demand for space heating, ventilation, air conditioning including cooling, domestic hot water, and lighting, following the national calculation methodology. To enable a comparison of the building module in Copenhagen and Kyiv, the energy framework for homes and dormitories specified in Danish Building Standards BR18 was referred to, which suggests the building's annual energy demand should not exceed 30 kWh/m² plus 1 000 kWh per heated floor area (A_{temp}). This specification aligns with the highest grade for annual energy demand criteria for AH (see Table 1). Primary energy and their corresponding carbon emissions were calculated (see 3.4.3) to determine the primary energy performance and the carbon emission of the building's operational energy use.

3.4 Simulations

3.4.1 Daylighting

The building model was simplified in Rhinoceros 7, where the daylighting simulations were performed in Grasshopper using Honeybee, a Radiance-based plugin from Ladybug tools. A climate-based simulation using the Energy Plus Weather (EPW) files was carried out following the calculation method specified by EN 17037- Daylight in Buildings, Daylight provision calculation method 2 for 50% of the daylight hours. The daylight hours retrieved from the EPW files for Copenhagen and Kyiv were 4406 hours and 4399 hours respectively. The simulations results obtained were expressed as Spatial Daylight Autonomy (sDA) values for each individual room, with the illuminance threshold set to 300 lux for all the occupied spaces for at least 50% of the daylight hours.

Analysis points were distributed in a grid of 0.5 m, at 0.85 m above the floor plane as specified by EN 17037. The effects of dynamic shading on daylight were not considered in the simulations for their unpredictability in residential application as the use of interior shading devices like roller blinds and venetian blinds is significantly influenced by the user preferences. The glazing transmittance (T_{vis}) of 0.62 and Solar Heat Gain Coefficient (SHGC) value of 0.44 were used for the four VELUX windows installed in the building while other façade windows had a T_{vis} of 0.65 and SHGC of 0.35. The optic properties of the building surfaces used in the simulations are shown in Table 3 below, as per the material list from the drawing set provided by VELUX.

Table 3: Surface properties of the building envelope used in simulation.

Building Envelop	Materials	Reflectance
Wall	White pine plywood	0.57
	Fiber gypsum board	0.70
Ceiling	White pine plywood	0.57
	Fiber gypsum board	0.70
Floor	WIKING ask select	0.46
Door/Window Frames	Timber	0.40
	Aluminum	0.89
Ground	Timber	0.40 – 0.20

3.4.2 Thermal Comfort

A dynamic thermal simulation was performed using the Ladybug-tools: Honeybee-Energy plug-in on Grasshopper, to determine hourly values of indoor operative temperature in all the rooms. The thermal model was assigned with the same construction materials used in the Living Places Copenhagen- Pavilion 2. The thermal conductivity (U-value) of the building façade used in the simulation is shown in Table 4. The VELUX windows installed in the building module were replicated in the thermal model, with the thermal conductivity of 0.60 W/m²/K of the triple glazing and 1.0 W/m²/K for the overall window along with the frames and a SHGC of 0.44. The skylights were modeled with the same thermal properties.

Table 4: Thermal properties of the building envelop used for simulation.

Building Envelop	Thermal Conductivity (W/m²/K)
Wall	0.11
Roof	0.09
Floor	1.93
Ground	0.09
Interior Walls	1.96
Windows/ Skylights	1.00
Doors	1.89

Coherently with the daylight analysis, the thermal comfort analysis excluded the impact of dynamic shadings such as rolling blinds or venetian blinds. The heating set point was fixed to 21°C, disregarding the cooling setpoint for the naturally ventilated residential module, as specified by Active House Standard. The sedentary activity level of 1.2 met and clothing level of 0.5 clo and 1.0 clo, for summer and winter respectively, were used according to EN 16798-1:2019. People and equipment load for different room types used for simulations are shown in Table 5 where the equipment load accounts for the artificial light load as well. The occupancy and equipment schedules were specified in accordance with the Danish Standards for Indoor Climate Calculation outlined in Branchevejledning for Indeklimaberegninger for residential buildings where the schedule for equipment load is turned on with occupancy (Vorre, et al., 2017). A constant domestic hot water (DHW) load of 3.40 kWh/m² was used, for an average of 144 liters per person per day supplied to households in Europe (Water use in Europe — Quantity and quality face big challenges, 2023)

Table 5: Loads for different room types used in simulations.

Room Types	People Load (W/person)	Equipment Load (W/m²)
Bedroom	80	6
Kitchen	100	10
Living	100	5

Natural ventilation was set to be operated based on indoor CO_2 levels and operative temperature for the façade and roof windows. The windows were simulated so that 50% of the window areas could be opened. All the operable windows were set to open with the indoor CO_2 level exceeding 550 ppm above the typical outdoor CO_2 concentration of 400 ppm. Additionally, a temperature sensor triggers the window to open if the indoor temperature rises above 24°C. The validation of the base case resulted in the choices of thresholds for the CO_2 and temperature sensors. An Energy Management System (EMS) code, as shown in Appendix C, was written as an additional string on EnergyPlus program. This code integrates the CO_2 and temperature sensor control system for window operation with a 1-hour time step, translating that the windows remain open for an hour on reaching either of these conditions.

Overheated hours were calculated to quantify the risk of overheating for summer as well as for winter as Active House does not specify the maximum indoor temperature in winter, which could potentially cause overheating risks in a well-insulated building in winter (Huang & Zhai, 2020). The percentage of comfort hours were calculated using the adaptive comfort metric to quantify the thermal comfort conditions throughout the year. The Danish Building Standards BR18 was used to assess the overheating hours that recommends that the indoor operative temperature can exceed the value of 27°C for 100 hours of the year and 28°C for 25 hours of the year, which also complies with the maximum operative temperature in summer criteria for Class 1 (see Table 1) (Bygningsreglementet, 2018).

3.4.3 Energy Use

The annual energy demand of the building was simulated using the Ladybug-tools: Honeybee-Energy plug-in on Grasshopper to determine the Energy Use Intensity (EUI) of the building. The thermal properties of the building facades are shown in Table 4. The Primary Energy (PE) for the simulated annual energy demand in Copenhagen was calculated using the Primary Energy Factors (PEF) specified in the BR18. The recommended factors are 1.90 for electricity, 0.85 for district heating, and 1.00 for other forms of energy sources (Bygningsreglementet, 2023). The PEF for electricity was used assuming electricity as the primary energy source with a heat pump of COP 4.2 to fulfill the heating requirements of the building in both locations (Sprsun, 2021). In absence of a standardized PEF for electricity in Ukraine, the energy mix for electricity production (IEA 50, 2021) and their corresponding PEFs (Saprunov, 2017) were used to calculate the approximate PEF, as shown in Table 6. The calculated PEF is, however, higher than the European Energy Efficiency Directive's suggested PEF for Electricity of 2.10 (Energy Efficiency Directive, 2023). The primary energy was then calculated by multiplying the EUI of the building with the PEF.

Table 6: Primary energy factor calculation for electricity in Ukraine

Energy Source	**Mix (%)**	**Primary Energy Factor (PEF)**
Coal	23.10	2.45
Natural Gas	9.10	1.89
Nuclear	54.60	3.50
Hydro	6.50	1.00
Solar PV	4.20	1.00
Other Sources	2.50	1.00
PEF: Electricity		**2.78**

A study carried out by SINTEF Energi AS, using the European Multi-Area Power Market Simulator (EMPS), presented five distinct scenarios, Red, Yellow, Blue, Green and Ultra Green as shown in Figure 6, to model the evolution of the energy mix for electricity production from 2010 to 2050, with the goal of achieving net-zero carbon emissions by 2050 (Graabak & Feilberg, 2011). The most optimistic scenario (Ultra Green), as shown in Figure 7, predicts that emissions will reach zero by 2054. This scenario was assumed for the calculation in this thesis.

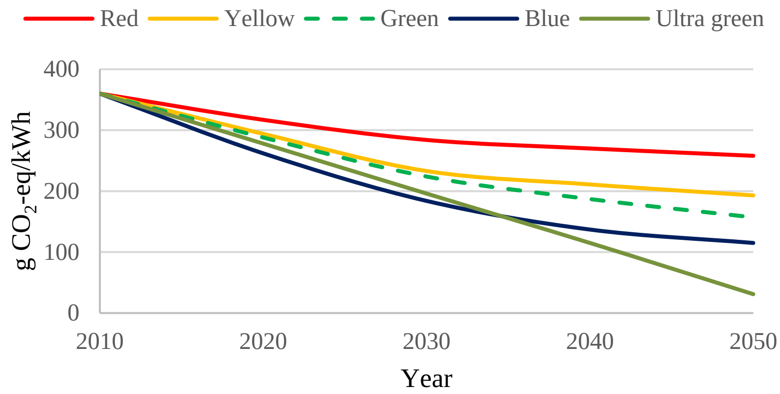


Figure 6: Development of average specific CO_2 emissions for all scenarios (Graabak & Feilberg, 2011)

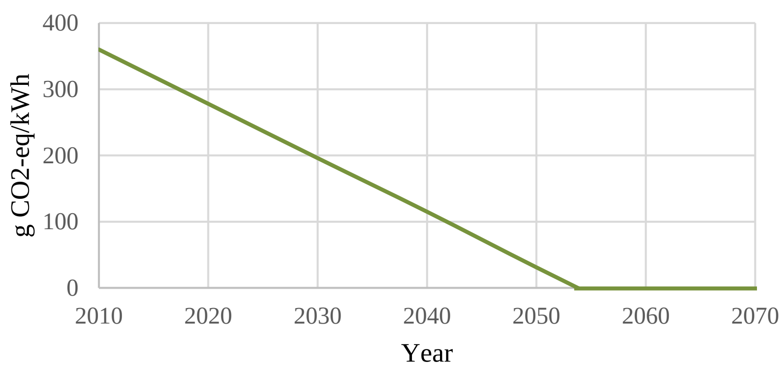


Figure 7: Simulated and extrapolated specific CO_2 emissions from the European Energy Mix from 2010-2070 (Dokka, 2011)

Based on these extrapolated data, an average specific CO_2 emission factor for electricity was estimated for the building life span of 50 years. The calculation was simplified with the assumption that the annual energy use of the building is constant throughout its lifespan (Dokka, 2011). Due to lack of CO_2 emissions data for Electricity in Ukraine pre-2016, the CO_2 emissions of 2016 was considered for Denmark as well. The specific CO_2 emission for electricity for both locations was calculated using the equation (4), which are shown in Table 7.

$$K_{el} = \frac{CO_2\ Emissions\ Factor\ at\ 2016}{2} \times \frac{2054 - 2016}{Building\ life\ span} \tag{4}$$

K_{el} = Average Carbon Emissions Factor (kg CO_2-eq. /kWh/y)

Table 7: CO_2 emission factor for 2016 and their corresponding calculated average annual CO_2 emission factor for the two locations.

Location	CO_2 Emission Factor for 2016 (kg CO_2-eq./kWh)	Average Annual CO_2 emission factor (kg CO_2-eq./kWh/y)
Copenhagen	0.193 (Bastos, Monforti-Ferrario, & Melica, 2024)	0.073
Kyiv	0.362 (IRENA Energy Profile - Ukraine, 2024)	0.137

Finally, Primary Energy was multiplied with the average carbon emission factor to calculate the carbon emission for the two locations for comparison.

3.5 Study Parameters

Building apertures that allow daylight into the buildings, also called daylighting systems, are major factors in daylighting and the overall energy performance of the buildings. In order to be able to estimate the contributions to a building's thermal balance, it is necessary to define visual and thermal transmittance characteristics of glazing area. Different parameters for the building apertures were studied for their impact in the daylight provision and thermal comfort conditions along with their operational energy demand.

3.5.1 Window Sizes

Solar Centre-Pivot VELUX windows were proposed for all the operable windows for Kyiv for their advantages of monitoring temperature and CO_2 levels in individual rooms and creating a healthier indoor climate for the occupants. The window sizes were altered in ratios compared to the existing window to find the optimum window dimension to later propose a suitable panel size for the Solar Centre-pivot windows. The windows were centrally positioned on the façade as the centrally placed windows were found to produce better sDA than lateral positions (Vogiatzi, 2018). The sill at 815 mm and height of the windows, 1400 mm were kept constant as they offered better visual connection to the outside. The width of the windows was altered in the ratio of 0.33, 0.5, 0.66, 1.0, 1.33, 1.5 and 1.66 as permitted by the exposed façade. The size of three windows, as shown in Figure 8, remained fixed to keep the room layout unaltered.

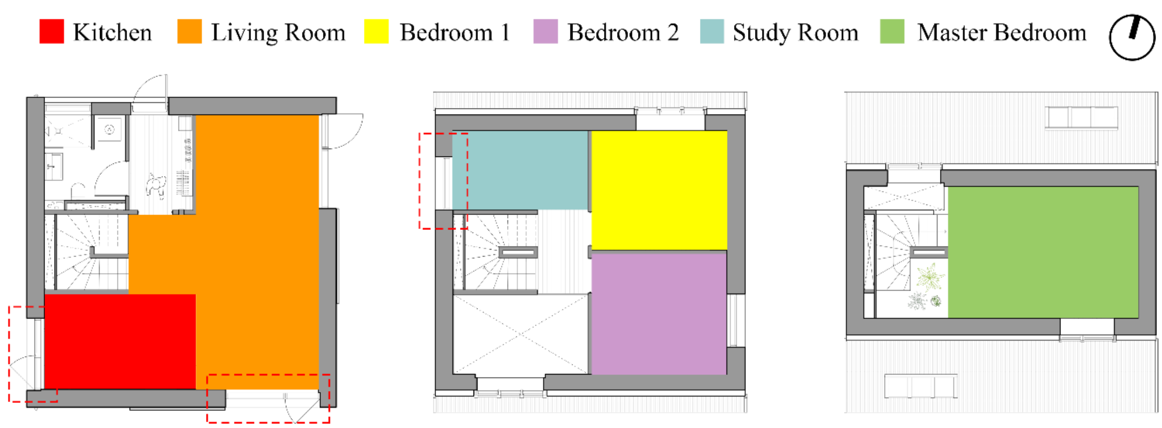


Figure 8: Floor plans of the Hygge House highlighting the three windows that remain fixed for the parametric study. From left to right: Ground floor plan, First floor plan and Second floor plan

3.5.2 Glazing Properties

Building apertures allow daylight along with solar heat gains to the indoor. Daylight is needed, however excessive solar heat gains are usually undesirable as it would create overheating and a high cooling demand. To counteract this phenomenon, high performance glazing assemblies that generally admit more daylight and less heat than a typical glazing assembly are used. These glazing units are coated with low e-coat and/or solar control coats which typically have a light transmittance that is twice as high as the solar transmittance (Dubois, Gentile, Laike, Bournas, & Alenius, 2019). 54 different combinations of low-e coat and solar control coats were compared using the Guardian Glass Analytics, a comprehensive web-based tool complaint with EN 410 and EN 673, that calculates the thermal and optical properties of insulated glazing units (IGU) (Guardian Glass Analytics®, 2024). The triple glazed IGU with coating combinations having higher T_{vis} and lower SHGC than the installed VELUX windows were selected for analysis. However, some combinations with lower T_{vis} and higher SHGC were also considered for a broader study of the impact of glazing transmittance and solar heat gain in daylight provision, thermal comfort, and the energy demand. The studied coating combinations are shown in Table 8.

Table 8: Optical and thermal properties of triple glazed units proposed for study. The coats are applied to surfaces #2 and #5 in the IGU respectively. All the coating named ClimaGuard along with Guardian Sun indicate low-e coat and SunGuard indicate solar control coat.

S. No	Coating Combination	Glazing Transmittance (%)	SHGC
1	Guardian Sun 39, ClimaGuard Premium 2	63.80	0.36
2	ClimaGuard 1.0+, ClimaGuard 1.0+	63.30	0.39
3	ClimaGuard 1.0+, ClimaGuard Premium 2	68.30	0.44
4	ClimaGuard Premium 2, ClimaGuard Premium 2	73.70	0.53
5	SunGuard SNX 50, ClimaGuard 1.0+	41.60	0.20
6	SunGuard SNX 60, ClimaGuard Premium 2 + T	53.50	0.27
7	SunGuard SNX 70, ClimaGuard Premium 2	60.40	0.31

The thermal conductivity of glazing for all the studied coating combinations was 0.60 W/m²/K, equal to the glazing of VELUX windows. As the window frames were not included in the study, the overall U-value for these windows was considered to be a constant value of 1.0 W/m²/K.

3.5.3 Orientation

Building orientation plays a significant role in daylighting as well as the thermal comfort, more so in low density environments, where the buildings are not shaded by adjacent buildings, vegetation, or landscape (Dubois, Gentile, Laike, Bournas, & Alenius, 2019). The building context of Living Places hence requires assessing the optimal orientations for the building. The building orientation was studied for all the cardinal directions between 0° and 360° in an increment of 45° in the counterclockwise direction. As all the rooms had window openings in different orientations (see Figure 9), rotation angle was preferred as a study parameter over cardinal directions to avoid confusion. The building orientation was later determined on the basis of the most critical room performances. The daylighting and thermal comfort analysis were performed for individual rooms to find the best overall orientation for the building without altering the room arrangements.

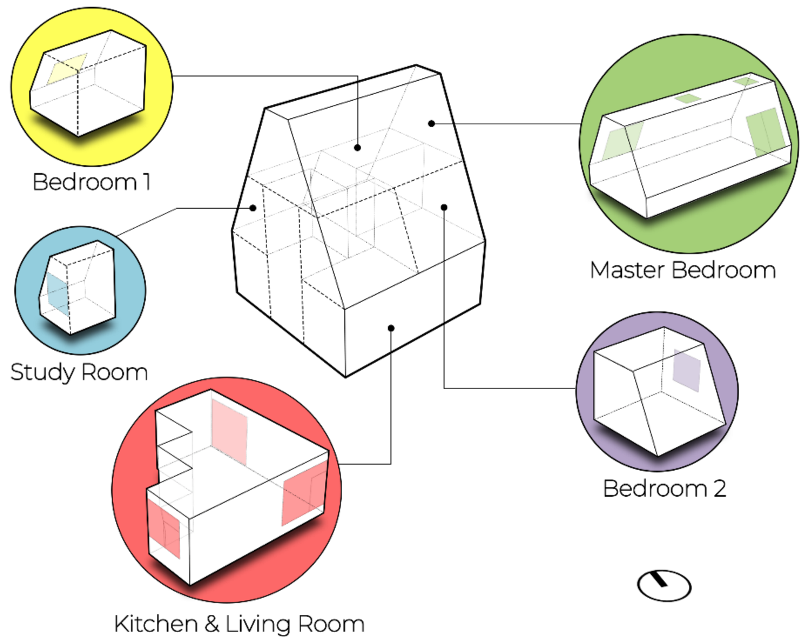


Figure 9: 3D diagram of the Living Places Copenhagen Pavilion 2

3.6 Weighting System

To compare different iteration cases with varying daylighting qualities, thermal comfort conditions and energy use, a weighting system was used to assign relative importance to each of these performance metrics. This was done in two steps, with the first only comparing daylight and thermal comfort conditions. Daylight and thermal comfort conditions for individual rooms were internally normalized and weighted against each other to identify the top iteration cases. For this thesis, a weighting system of 30-70% was proposed giving greater importance to thermal comfort as the requirements for thermal comfort cover at least 95% of the total occupied hours while daylight metric only considers the daylight hours. The iterations with highest daylighting and thermal comfort conditions with their corresponding energy use were further weighted including the Copenhagen model in 50-50%, with the EUI given 50% weightage compared to a combined 50% for daylight and thermal comfort conditions. This resulted in final scores which could be used to compare the proposed optimal cases in Kyiv against the Copenhagen model. It must be noted that the weighting system used for this study does not affect the results but merely serves as a selection tool to navigate all the simulated cases, and it can be subjected to change.

4 Results

4.1 Living Places Copenhagen

The validated base case model in Copenhagen displayed high quality for daylight as well as thermal comfort as shown in Figure 10. Bedrooms 1 and 2, having windows in a single façade display lower daylight provision in comparison to other rooms with windows in multiple façades highlighting the impact of multi-directional daylighting solutions for higher and uniform daylight distribution in the rooms. The roof window in bedroom 1 resulted in higher $sDA_{300/50\%}$ than bedroom 2 as sloped window collect zenithal and low angle daylight specially in Nordic skies dominated by overcast sky conditions (Dubois, Gentile, Laike, Bournas, & Alenius, 2019). These rooms, on the other hand, had higher comfort hours compared to kitchen and living room, study room and master bedroom. The kitchen and living room had the lowest comfort hours of all the room types indicating the higher heat losses from the big windows on multiple facades, contributing to more cold hours. This resulted in higher EUI for the kitchen, living and the master bedroom for heating up the cold hours (see Appendix D). Bedroom 1 had more cold hours than bedroom 2 indicating the north-oriented roof window in bedroom 1 allowed lower solar heat gains compared to the east oriented façade window in bedroom 2. The windows operating on temperature sensors helped in keeping the hot hours close to zero. However, the indoor CO_2 sensor meant that there were hours during winter when the windows were opened causing cold draught, resulting in higher cold hours than hot hours.

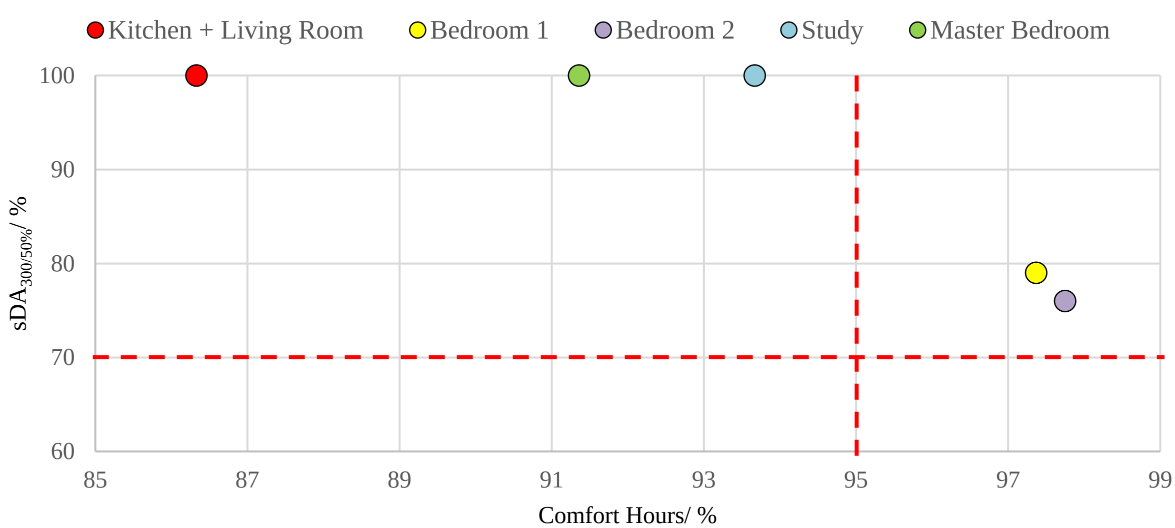


Figure 10: Daylight and thermal comfort of different rooms in Living Places Copenhagen. The horizontal and vertical red dotted lines indicate the minimum requirements for AH score 1 for daylight and adaptive thermal comfort respectively.

The simulated EUI was 28.40 kWh/m²/y, for the building that used an air-water heat pump of COP 4.2 to fulfill the heating requirements. Using the energy carrier factor of 1.90 for electricity, the total calculated primary energy demand was 53.96 kWh/m²/y that translated to a carbon emission of 3.93 $kgCO_2$-eq./m²/y. Figure 11, illustrates the AH radar for the Copenhagen model showing the AH scores of the four relevant criteria to this thesis. The Primary Energy Performance under the AH radar receives a rating of 1 assuming all the supplied energy to the building was from renewable sources. The table with the calculation of the AH score is attached in Appendix E.

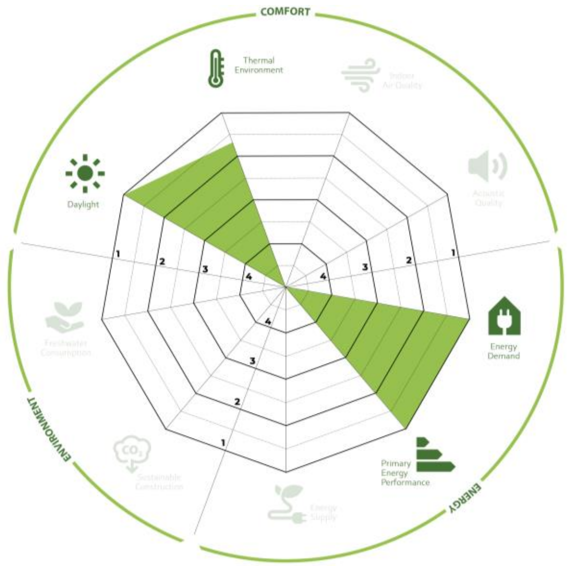


Figure 11: Active House Radar for Living Places Copenhagen, Pavilion 2. The radar presents the scores only for the criteria assessed in this thesis.

4.2 Living Places Kyiv

4.2.1 Window Sizes

The range of $sDA_{300/50\%}$ results of all the assessed cases for different rooms in the building are shown as boxplot diagram in Figure 12, which includes all the parameter iterations i.e. the glazing transmittance and orientation for various window scaling factors as compared to the existing windows. The average $sDA_{300/50\%}$ value is indicated by the 'x' markers in the figure. Bedrooms 1 and 2 were the most critical rooms where the daylight autonomy was significantly impacted by the sizes of the window opening due to a single window bringing in all the daylight in the room. Bedroom 1 having a roof window, at an inclination of 65°, displayed higher sDA compared to bedroom 2 having a window on a vertical facade for the same window scaling factor as the roof window could benefit from the zenithal illumination and low angle sunlight in Kyiv which is dominated by overcast sky conditions. The kitchen, living and study room did not have significant impact of varying window sizes as they had at least one window that did not change in size as shown in Figure 8.

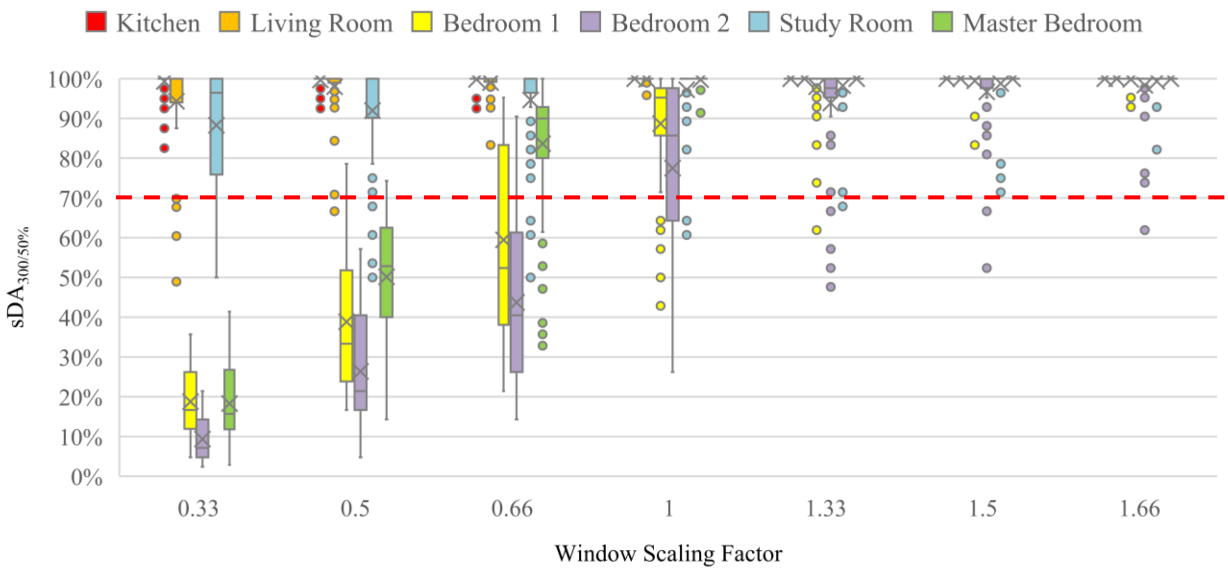


Figure 12: Spatial daylight autonomy for different window sizes. The red dotted line indicates the requirement to be met for the AH score 1 for daylight provision.

Figure 13 illustrates the distribution of comfort hours in a boxplot for all the rooms for varying window sizes, which showed the inverse relationship between window sizes and the comfort hours. The increase in window sizes allows more solar gains indoors hence increases the hot hours during summers. During winters, the windows mainly operated with CO_2 sensor. In hours when the indoor CO_2 level was higher than 950 ppm, bigger windows allowed higher volume of cold outdoor air causing a cold draught and reducing the comfort hours. The figure showed that bedroom 1 had lower comfort hours in comparison to bedroom 2. This can be characterized by a higher amount of heat loss to the outdoor through the roof windows as it has been seen that thermal transmission of windows increases with decrease in inclination angle for glazing, as the rate of convection in the interspace increases resulting into higher heat transmission from the inner to the outer pane (Guardian GlassTime- Technical Manual, 2022). Figure 13 also indicated kitchen and living room as the critical room with the lowest comfort hours compared to all other rooms. However, most of the iterations resulted in comfort hours higher than the AH score 2 threshold. The larger window area in this space along with the higher equipment loads contributed to higher solar heat gains during summer increasing the hot hours while also allowing heat loss during the winters increasing the cold hours. This resulted in higher discomfort than other room types.

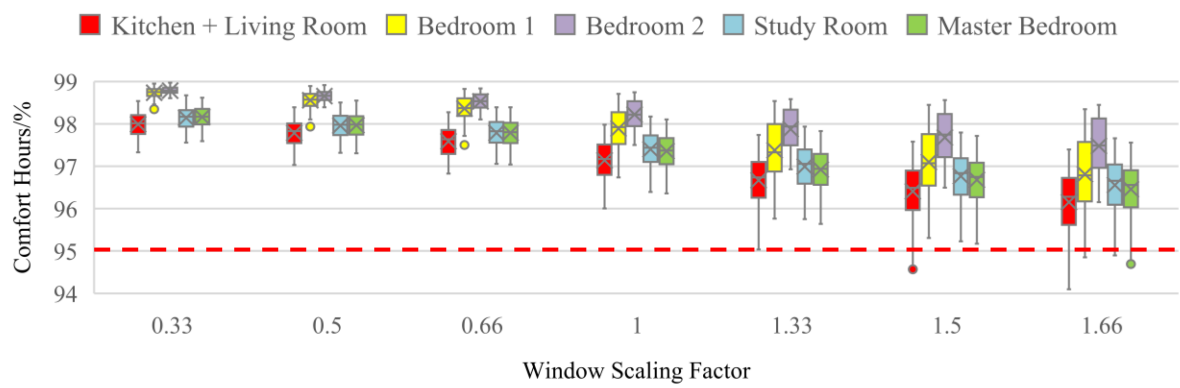


Figure 13: Thermal comfort for varying window sizes. The red dotted line indicates the minimum requirement of comfort hours to be met for AH score 2 for operative temperature.

The energy use of all the rooms varied directly with the window sizes. Figure 14 illustrates the increase in annual heating energy demand in all the rooms for increased window sizes, with kitchen and living along with the master bedroom having higher heating demand. This could be attributed to the higher window-to-wall ratio resulting in larger heat losses during winter. Increase in the window sizes increased the annual heat gains and losses from the window, with the summer months contributing more to the gains and the losses during the cold seasons. The higher heat loss for bigger windows resulted in increased heating energy demand for the building.

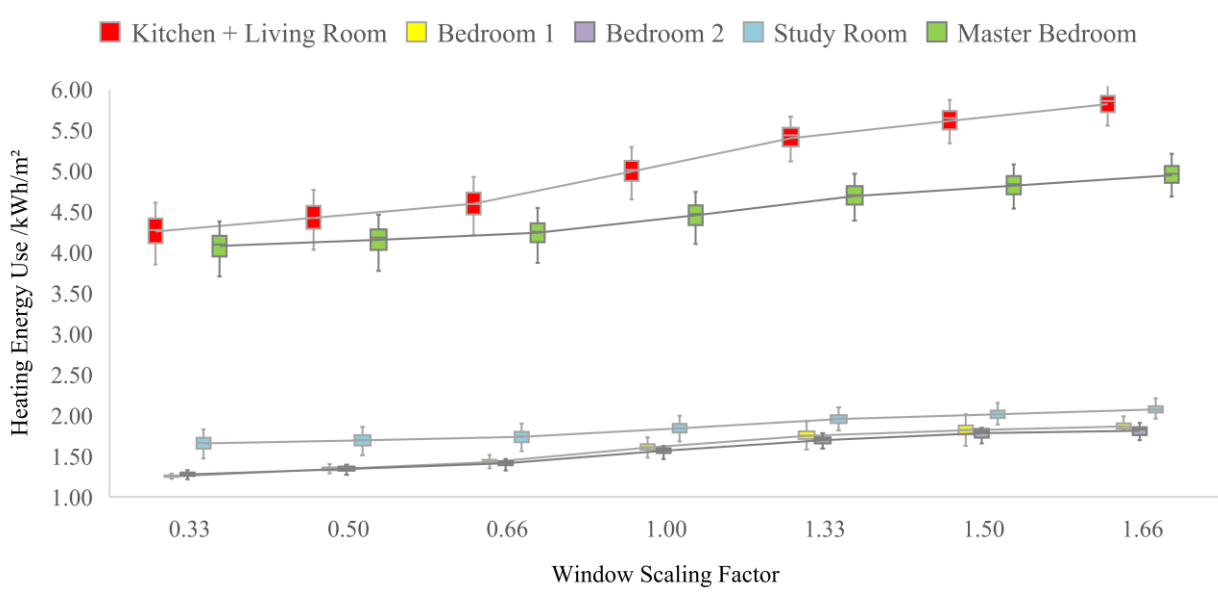


Figure 14: Heating energy demand for different rooms for varying window sizes.

4.2.2 Glazing Properties

The Figure 15 below shows the distribution of the iteration results for $sDA_{300/50\%}$ for varying T_{vis} for all the window sizes and orientations in different rooms. It was evident that higher T_{vis} value of the windows improved the daylight autonomy in the rooms. The effect of T_{vis} was minimal for rooms such as kitchen, living room and study room, that have higher window to wall area ratio along with an already higher spatial daylight autonomy.

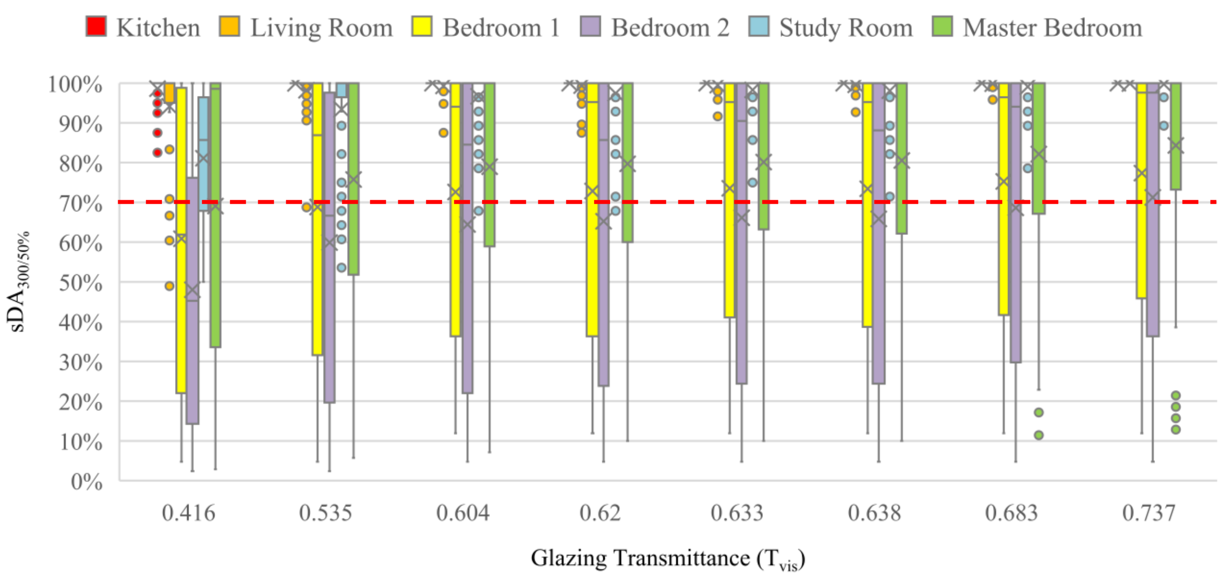


Figure 15: Spatial daylight autonomy for different glazing transmittance. The red dotted line indicates the requirement to be met for the AH score 1 for daylight provision.

Figure 16 illustrates the inverse relationship between SHGC and indoor thermal comfort. The iterations with higher SHGC resulted in high solar heat gains and eventually increased the hot hours reducing the comfort hours compared to iterations with lower SHGC. Bedroom 1 with roof window allowed more solar heat gains during summer increasing the hot hours and heat loss during winters contributing to higher cold hours, for the iterations with the same SHGC than the bedroom 2 with a façade window, resulting in overall lower comfort hours.

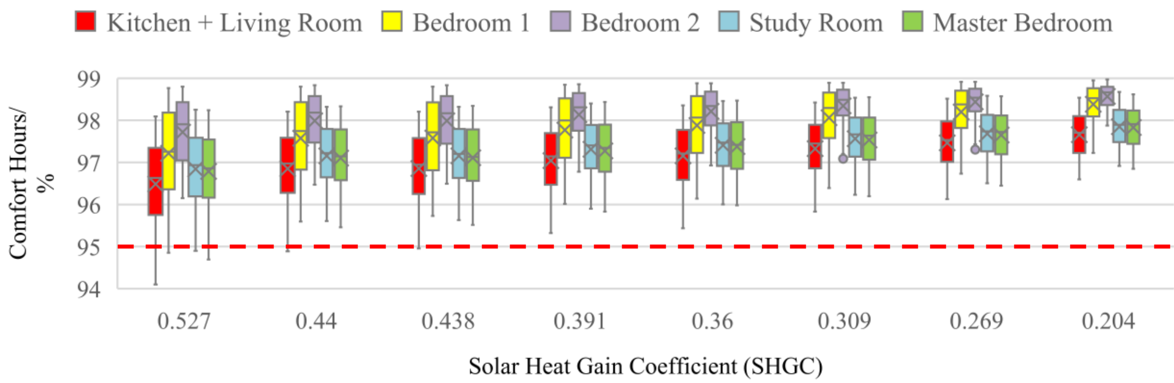


Figure 16: Thermal comfort for varying SHGC. The red dotted line indicates the minimum requirement of comfort hours to be met for AH score 2 for operative temperature.

For the building, which is naturally ventilated, the annual heating load plays the most important role in optimizing the energy use for the building, as other equipment loads remained constant. Hence, it was seen that the iterations with higher SHGC value had lower EUI compared to the cases with lower SHGC. This could be attributed to the heat gains allowed by windows with higher SHGC reducing the cold hours and eventually decreasing the annual heating demand of the building.

4.2.3 Orientation

The $sDA_{300/50\%}$ for all the rooms for varying rotation angle of 45° in counterclockwise direction, for all window sizes and glazing properties, is illustrated in Figure 17. The starting orientation 0°, has the building with its main entrance towards North as shown in Figure 18. Bedroom 1 and 2 that have windows on a single façade were significantly impacted by the orientation. Kitchen, living, and study rooms were not affected by the orientation due to distribution of higher wall to window area ratio in multiple facades. The presence of at least one fixed window size (see Figure 8) also resulted in a consistently high daylight availability for different orientations. The master bedroom, even though having roof windows in multiple facades along with the skylights, displayed lower daylight autonomy for rotation angle between 135°-225°, 180° being the worst case where the roof window bringing in direct daylight into the reference plane was oriented to the north. Bedroom 1 had the highest number of cases that achieved AH score 1 for daylight autonomy when rotated 180° with the roof window oriented towards south, followed by southwest and southeast respectively. Bedroom 2 displayed a similarly higher volume of cases that achieved AH score 1 when rotated by 225° and 270°, when the window was oriented southwest and south respectively.

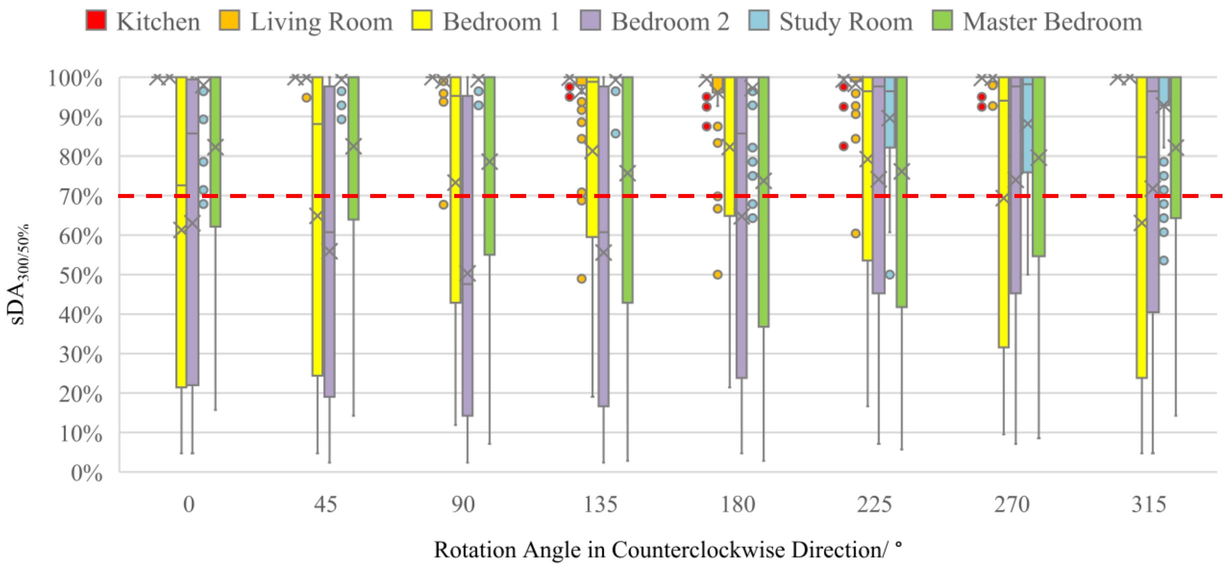


Figure 17: Spatial daylight autonomy for different rotation angles. The red dotted line indicates the requirement to be met for the AH score 1 for daylight provision.

Figure 18: Floor plan showing the starting orientation of the building module in Kyiv.

Figure 19 illustrates the iteration cases for all the rooms for varying rotation angles. The building was designed to maximize the ventilation potential through stack effect. Hence the kitchen, living, study room and master bedroom that allow constant exchange of air between themselves followed a similar pattern of comfort hours when subjected to different rotation angles, rotation angle of 135° having the overall higher set of iterations with higher comfort hours. Bedroom 2 also displayed higher comfort hours when rotated by 135°, where the window was oriented northwest. Bedroom 1 had the highest average comfort hours in the original orientation, where the roof window was oriented north, followed by rotation angle of 315°, with the roof window-oriented northeast.

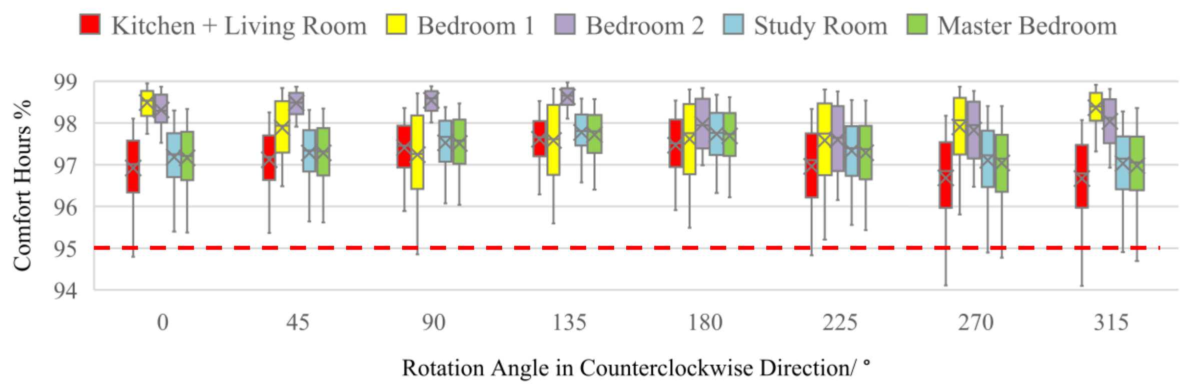


Figure 19: Thermal comfort for different rotation angles. The red dotted line indicates the minimum requirement of comfort hours to be met for AH score 2 for operative temperature.

The impact of orientation on the heating energy demand of the individual rooms can be seen in Figure 20. The rotation angle of 90° displayed the highest annual heating demand followed by 45°. Similarly, when the building was rotated 270° counterclockwise, the overall heating demand was the lowest closely followed by 315° counterclockwise rotation. Bedroom 1 and 2 showed higher sensitivity to change in orientation as they have windows in a single façade compared to other rooms with windows in multiple facades. This meant that the orientation in which the windows were facing south benefitted from the solar heat gains hence reduced the annual heating hours.

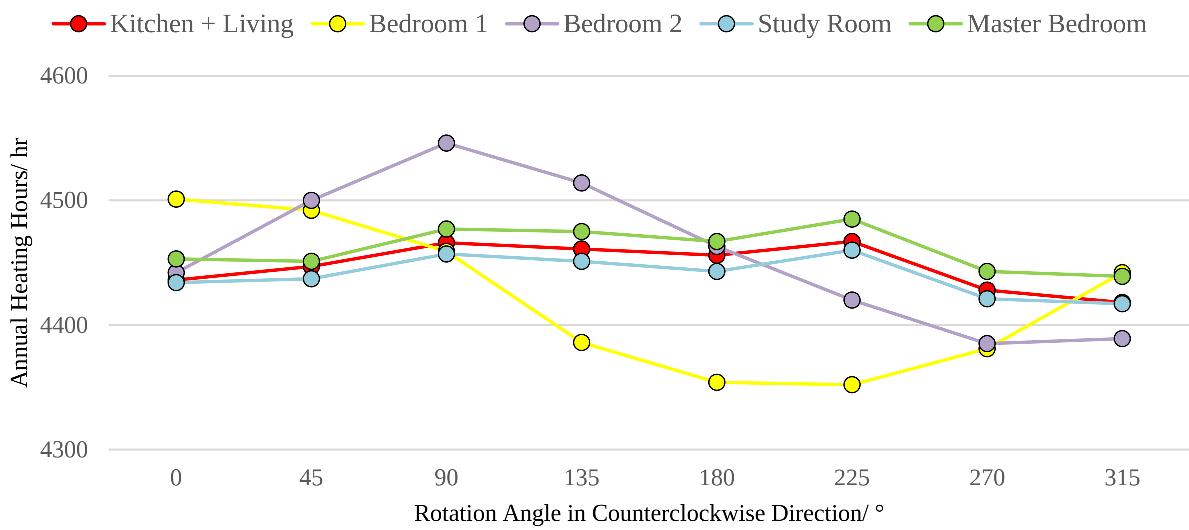


Figure 20: Annual heating hours for all room types for existing window size and glazing properties.

4.2.4 Optimal Cases

Out of the total 448 iterations, 227 cases complied with the daylight requirement set for AH score 1 of at least 70% of occupied floor area achieving $sDA_{300/50\%}$. The number of iterations filtered down to 213, which also complied with the adaptive thermal comfort requirements set for AH score 2 at 95% of the occupied hours within the comfortable temperature range. Approximately 80% of these cases had bigger window sizes indicating the huge impact of window sizes to the daylight and thermal comfort conditions in the building. However, the cases were evenly distributed among the other two study parameters, glazing properties and the orientation of the building. Hence, the results were grouped into cases with common window sizes and compared against each other using a weighting system of 30-70% for daylight performance and thermal comfort to identify the optimal cases for these parameters for all the rooms. This resulted in 34 optimal cases for different window sizes, which is attached in Appendix F. Figure 21 highlights the top 3 cases that have higher daylighting and thermal comfort conditions than the Copenhagen model. The common characteristics of these cases were bigger windows, lower T_{vis} and SHGC values than the base case. However, these were among the cases that had the highest EUI and CO_2 emissions which were approximately 2.8 times higher than the base case Copenhagen model.

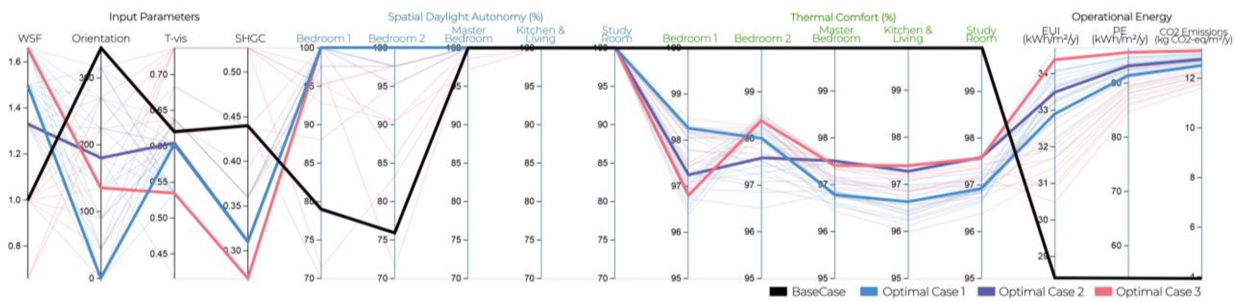


Figure 21: Comparison between 34 optimal iteration cases with the base case after 30-70% weighting system for daylight and thermal comfort conditions. The base case iteration refers to Copenhagen and the optimal cases represent Kyiv. All the cases are rated AH score 1 for daylight and AH score 2 for thermal comfort.

These cases were further compared with the building in Copenhagen, using a weighting system of 50-50%, with the EUI given 50% weightage compared to a combined 50% for daylight and thermal comfort conditions. Figure 22 highlights the top iteration cases for Kyiv compared to the base case in Copenhagen. Inversely, the current window size with higher T_{vis} and SHGC values than the base case were the common parameter characteristics for the top cases with the lowest EUI. Optimal Case A proves to be the ideal choice due to a low EUI of 31.28 kWh/m²/y and CO_2 emission of 11.91 $kgCO_2$-eq/m²/y while providing comfortable indoor environment.

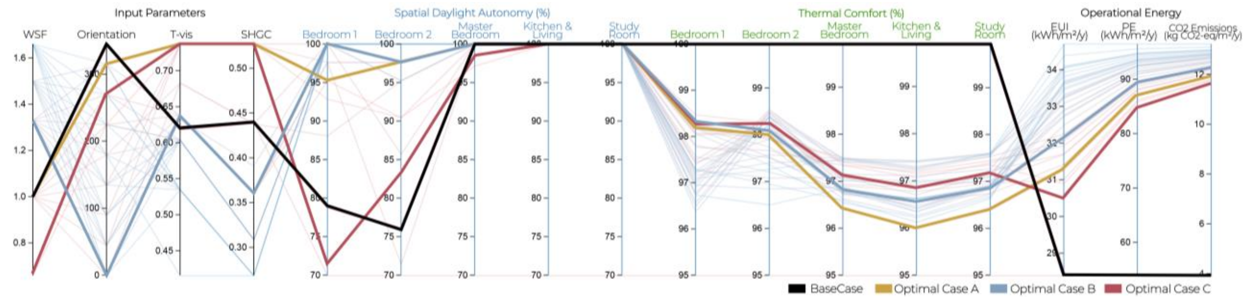


Figure 22: Comparison between 34 optimal iteration cases with the base case after 50-50% weighting system, with 50% for EUI and combined 50% for daylight and thermal comfort conditions. The base case iteration refers to Copenhagen and the optimal cases represent Kyiv. All the cases are rated AH score 1 for daylight and AH score 2 for thermal comfort.

Figure 23 compares the AH score of the optimal Case A in Kyiv with the base case in Copenhagen. The table with the calculation of the AH score is attached in Appendix G. As the climatic condition of Kyiv is more extreme, the optimal iteration cases could not reach the overall AH score for thermal comfort criteria as in Copenhagen. While the overall daylighting performance of all the rooms was higher in Kyiv, both these cases scored the same highest AH score 1 for daylight autonomy. Similarly, both these cases complied with the highest AH score 1 for energy demand, even though the building in Kyiv used 31.28 kWh/m²/y compared to 28.40 kWh/m²/y in Copenhagen. The contrast was however more visible in the primary energy performance criteria as both the energy carrier factor (see Table 6) and average annual emission factor (see Table 7) were significantly higher in Kyiv, resulting in the AH score of 2.5 in Kyiv as against AH score 1 in Copenhagen.

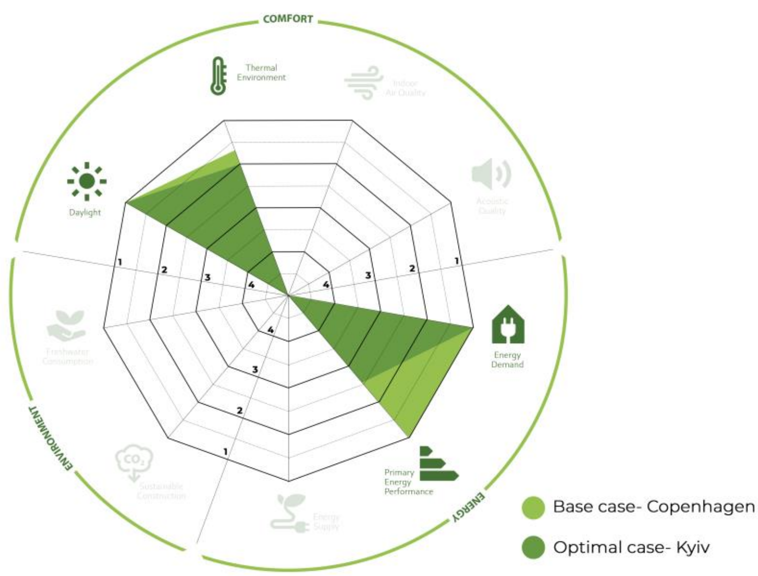


Figure 23: Comparative Active House Radar for Copenhagen and Kyiv

5 Discussions

Larger windows allowed more daylight indoors improving the $sDA_{300/50\%}$ but had a negative effect on thermal comfort and energy demand, as dynamic shading were not incorporated in the study. Larger window openings allowed higher solar heat gains in the rooms during summer increasing the hot hours and caused higher heat loss during the winter for more cold hours, eventually degrading the annual comfort conditions. While the heat gained from the windows during summer months did not increase the cooling demand for the building as it is naturally ventilated, the heat loss from bigger windows caused higher heating demand during winters. The glazing transmittance (T_{vis}) of the windows affected the daylight while Solar Heat Gain Coefficient (SHGC) affected the thermal comfort conditions and energy demand in the rooms. Windows with higher glazing transmittance allowed more daylight indoors improving the daylight availability and vice versa. SHGC, however, is inversely related to thermal comfort and energy demand. While higher SHGC allowed solar heat gains indoor, lowering the heating demand during the winter months, it also increased the hot hours during the summer months degrading the annual thermal comfort conditions. Building orientation played a major role in daylight and thermal environment of the building. Rooms with windows on a single façade were more sensitive to orientation, while rooms that have multiple windows in more than one façade were obviously less reactive to change in orientation. In general, the rooms with windows oriented between Northeast and Northwest had lower daylight availability but higher thermal comfort conditions as they avoided solar gains. These rooms, however, had higher heating energy demand for the same reason.

The proposed Solar Centre-Pivot VELUX windows incorporating CO_2 sensor to regulate the indoor environment by opening the windows when the indoor CO_2 level reaches 950 ppm, helped in maintaining a high level of indoor air quality. This, at times during winter, caused the window to open bringing in cold draft leading to an increased number of cold hours. This is one of the major reasons the optimal cases failed to achieve the AH score 1 for adaptive thermal comfort. The optimal cases presented in this study are based on specific assumptions made during the process and the higher weightage provided to one performance metric than the others for a tradeoff between them. The optimal cases that displayed the highest daylight and thermal comfort conditions were subjected to a weighting system where energy demand had a bigger weight, hence the selected cases strived, in order, for the lowest energy demand, highest thermal comfort and finally the highest daylight provision.

6 Conclusion

In this study, a comparative analysis was conducted for a modular residential building of Living Places Copenhagen in two different climatic contexts. Simulations were conducted to assess the daylighting, thermal comfort, and environmental performance of the building in relation to the operational energy, evaluated according to the Active House Specifications. The performance metrics used in this study were $sDA_{300/50\%}$ for daylight, percentage of annual comfort hours for adaptive thermal comfort conditions and carbon emission measured in $kgCO_2$-eq./m²/y for the environmental performance of the operational energy use, as specified by the AH. The accessed building in Living Places Copenhagen is a well-designed residential module that has an AH score 1 - on a scale between 1 and 4, where 1 is best - on all the studied categories except thermal comfort where it receives a score of 1.7. It must be noted that the presented results were achieved without considering dynamic shadings for the windows. With similar overcast sky conditions, daylight hours and slightly higher sunshine hours, the model performed better in Kyiv for daylight but underperformed for thermal comfort due to the fact that Kyiv had higher summer and winter peaks compared to Copenhagen, also increasing the energy demand. A parametric analysis carried out looking at window sizes, glazing properties and the building orientation on the daylight, thermal comfort, and energy demand of the building in Kyiv, using the Active House scoring method, demonstrated the need for a contextual adaptation for Kyiv. Bigger windows resulted in higher daylight performance and lower thermal comfort while also increasing the energy use. However, the current window sizes when combined with higher T_{vis} and SHGC could maintain the daylight and indoor thermal comfort conditions, additionally reducing the energy demand of the building. Even though the EUI in both locations were similar, the building in Kyiv would have approximately 2.8 times larger carbon footprint for the operational energy use phase due to the energy mix primarily including non-renewable sources.

With the need for more energy efficient buildings that have comfortable indoor environments while having minimum environmental impacts, the contextual adaptation of Living Places Copenhagen could be a solution. This study provides insight into one of the several ways the module could be optimized to ensure a healthy indoor environment for occupants.

7 Reflection and Future Works

To have a further understanding of the building performance, a comprehensive study of the energy use and the environmental impact has to be conducted for a precise comparison. Additionally, a whole Life Cycle Analysis would aid in the comparison of emissions for the embodied energy. This could include but is not limited to an assumption that the building material is sourced from Denmark, translating to an additional environmental impact for transportation. Furthermore, an intensive study of the building materials available in Ukraine to construct a similarly high-performing modular building should be done. These results could bring in a fairer comparison of the overall carbon footprint of the building in two climates.

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9 Appendices

Appendix A

Appendix Table 1: Active House quantitative criteria evaluation method (Active House, 2024)

Category	Subcategory	Aspect	Class: Criteria
Comfort	Daylight	Daylight Factor DF per room calculated using a validated daylight simulation program according to EN 17037	The amount of daylight in a room is evaluated through the fraction of the room, $F_{plane\%}$, that have a DF higher than the target daylight factor (D_T)[1] 1: > 70% of the occupied space 2: > 60% of the occupied space 3: > 50% of the occupied space 4: > 40% of the occupied space
		Target Daylight Level per room	The amount of daylight in a room is evaluated through daylight levels with a target illuminance of 300 lux in dwellings ($DA_{300/50}$) 1: > 70% of the occupied space 2: > 60% of the occupied space 3: > 50% of the occupied space 4: > 40% of the occupied space
	Thermal environment	Minimum Winter Operative Temperature per room	For living rooms, kitchens, study rooms, bedrooms, etc in dwellings, requirement met for 95% of operative hours. 1: $T_{i,o} > 21$℃ 2: $T_{i,o} > 20$℃ 3: $T_{i,o} > 19$℃ 4: $T_{i,o} > 18$℃
		Maximum Summer Operative Temperature	Requirement met for 95% of the operative hours. For rooms mechanically ventilated, 1: $T_{i,o} < 25.5$°C 2: $T_{i,o} < 26$°C 3: $T_{i,o} < 27$°C 4: $T_{i,o} < 28$°C For rooms naturally ventilated, 1: $T_{i,o} < 0.33 * T_{rm} + 20.8$°C 2: $T_{i,o} < 0.33 * T_{rm} + 21.8$°C 3: $T_{i,o} < 0.33 * T_{rm} + 22.8$°C 4: $T_{i,o} < 0.33 * T_{rm} + 23.8$°C
	Indoor air quality	Standard fresh air supply per room	Hourly concentration of CO_2 inside the rooms, requirement met for 95%. 1: < 400 ppm above outdoor CO_2 concentration 2: < 550 ppm above outdoor CO_2 concentration 3: < 800 ppm above outdoor CO_2 concentration 4: < 1100 ppm above outdoor CO_2 concentration
		Inside system noise	The limit values are: 1: < 25 dB 2: < 30 dB 3: < 35 dB 4: < 40 dB
		Outside noise	The maximum indoor noise levels from outdoor sources are: 1: < 25 dB 2: < 30 dB 3: < 35 dB

			4: < 40 dB
		Acoustic privacy	For connected dwellings, such as apartment buildings, the limit values for airborne sound ($D_{nT;A}$) and contact sound ($L_{nt;A}$) are: 1: $D_{nT;A} \geq 62$ dB and $L_{nt;A} \leq 43$ dB 2: $D_{nT;A} \geq 57$ dB and $L_{nt;A} \leq 48$ dB 3: $D_{nT;A} \geq 52$ dB and $L_{nt;A} \leq 53$ dB 4: $D_{nT;A} \geq 47$ dB and $L_{nt;A} \leq 58$ dB
Energy	Energy Demand	Annual energy Demand	1: < 40 kWh/m² 2: < 60 kWh/m² 3: < 80 kWh/m² 4: < 100 kWh/m²
	Energy Supply	Origin of energy supply	Energy produced on the plot or in a nearby system is able to cover the total energy used in the building for 1: > 100% 2: > 75% 3: > 50% 4: > 10%
	Primary energy performance	Annual non-renewable primary energy performance	1: 0 kWh/m² 2: < 50 kWh/m² 3: < 100 kWh/m² 4: < 130 kWh/m²
Environment	Sustainable Construction	Recycled content	Percentage of the recycled or reused materials for all building material by weight 1: > 20% 2: > 10% 3: > 5% 4: > 0%
		Recyclable or reusable virgin content	Percentage of recyclable or reusable content for all building materials by weight 1: > 50% 2: > 30% 3: > 10% 4: > 5%
		Responsibly sourced wood	Percentage of (FSC, PEFC) certified wood 1: > 75% 2: > 50% 3: > 25% 4: > 0%
		Declared origin	Percentage of new materials with certified EPD 1: > 75% 2: > 50% 3: > 25% 4: > 0%
	Environmental loads	Global warming potential (GWP) during building's life cycle	1: < -30 kgCO2-eq/m² 2: < 10 kgCO2-eq/m² 3: < 40 kgCO2-eq/m² 4: < 50 kgCO2-eq/m²
	Freshwater consumptions	Toilet water use	Toilet water usage 1: < 4 liter per flush 2: < 6 liter per flush 3: < 9 liter per flush 4: < 12 liter per flush
		Shower water use	Flowrate of showerhead 1: < 6 liter per minute

		2: < 8 liter per minute 3: < 10 liter per minute 4: < 12 liter per minute
	Tap water use	Tap flow rate. 1: < 3 liter per minute 2: < 5 liter per minute 3: < 7 liter per minute 4: < 9 liter per minute

Appendix B

Appendix Table 2: Default values for intensity of use hours for different rooms in a residential building (Active House, 2024)

Room Types	**Daylight (hours)**	**Thermal Environment (hours)**
Kitchen	2.5	3.5
Living Room	3.0	5.0
Bedroom (Parents)	0.5	8.5
Bedroom (Kids)	1.5	11

Appendix C

```
!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:SENSOR ===========

EnergyManagementSystem:Sensor,
    EMS_CO2_Sensor02,        !- Name
    AtticBedroom,   !- Output:Variable or Output:Meter Index Key Name
    Zone Air CO2 Concentration;  !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    Temperature_Sensor02,        !- Name
    AtticBedroom,   !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;  !- Output:Variable or Output:Meter Name

!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:ACTUATOR
===========

EnergyManagementSystem:Actuator,
    OpenFactor01,           !- Name
    Window_4_Opening,  !- Actuated Component Unique Name
    Zone Ventilation,       !- Actuated Component Type
    Air Exchange Flow Rate;  !- Actuated Component Control Type

!-   ===========  ALL OBJECTS IN CLASS:
ENERGYMANAGEMENTSYSTEM:PROGRAMCALLINGMANAGER ===========

EnergyManagementSystem:ProgramCallingManager,
    CO2 Control01,          !- Name
    BeginTimestepBeforePredictor,  !- EnergyPlus Model Calling Point
    CO2_Sensor01;           !- Program Name 1

!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAM ===========

EnergyManagementSystem:Program,
```

```
CO2_Sensor01,           !- Name
IF (EMS_CO2_Sensor02 > 950) || (Temperature_Sensor02 >= 24),  !- Program Line 1
        SET OpenFactor01 = 1.0, !- Program Line 2
ELSE,  !- A4
SET OpenFactor01 = 0.0,  !- A5
ENDIF;  !- A6
```

Appendix D

Appendix Table 3: Breakdown of EUI for each room in Living Places Copenhagen

Thermal Zones	**Heating Energy Use (kWh/m²/y)**	**Equipment Energy Use (kWh/m²/y)**	**Total EUI (kWh/m²/y)**
Kitchen & Living	3.95	9.91	13.86
Bedroom 1	1.04	0.60	1.64
Bedroom 2	1.10	0.67	1.77
Master Bedroom	3.19	0.79	3.96
Study Room	1.44	1.40	2.84

Appendix E

Appendix Table 4: AH score calculation for daylight for Copenhagen module

Room Types	**$sDA_{300/50\%}$ (%)**	**AH Score**	**Occupied Hours**	**Occupants Number**	**Weighted Score**
Kitchen	100	1	3	4	12
Living Room	100	1	2.5	4	10
Bedroom 1	79	1	1.5	1	1.5
Bedroom 2	76	1	1.5	1	1.5
Study Room	100	1	3	2	6
Master Bedroom	100	1	0.5	2	1
Sub total			32		32
Total Average Score					1

Appendix Table 5: AH score calculation for thermal comfort for Copenhagen module

Room Types	**Comfort Hours (%)**	**AH Score**	**Occupied Hours**	**Occupants Number**	**Weighted Score**
Kitchen	99.50	2	5	4	40
Living Room		2	3.5	4	28
Bedroom 1	97.80	1	11	1	11
Bedroom 2	99.70	1	11	1	11
Study Room	99.20	2	5	2	20
Master Bedroom	95.90	2	8.5	2	34
Sub total			83		144
Total Average Score					1.7

Appendix F

Appendix Table 6: Optimal cases chosen using weighting system of 30-70% for daylight and thermal comfort.

WSF	Orientation (°)	T_{vis}	SHGC	EUI (kWh/m²/y)	Primary Energy (kWh/m²/y)	CO2 Emissions ($kgCO_2$-eq/m²/y)
0.66	225	0.737	0.527	30.90	85.91	11.76
0.66	270	0.737	0.527	30.49	84.77	11.61
1	345	0.620	0.44	28.40	53.96	03.93
1	315	0.737	0.527	31.28	86.96	11.91
1	270	0.638	0.36	31.71	88.16	12.07
1	45	0.737	0.527	31.43	87.38	11.97
1	225	0.638	0.36	32.08	89.19	12.21
1	180	0.683	0.438	32.26	89.67	12.28
1	135	0.737	0.527	31.94	88.78	12.16
1	90	0.737	0.527	31.70	88.13	12.07
1	0	0.683	0.438	31.02	86.23	11.81
1.33	0	0.638	0.36	32.18	89.46	12.25
1.33	315	0.638	0.36	32.50	90.35	12.37
1.33	270	0.604	0.309	32.73	90.99	12.46
1.33	45	0.638	0.36	32.76	91.08	12.47
1.33	225	0.604	0.309	33.09	91.98	12.60
1.33	90	0.633	0.391	32.91	91.49	12.53
1.33	135	0.638	0.36	33.25	92.43	12.66
1.33	180	0.604	0.309	33.51	93.16	12.76
1.5	0	0.604	0.309	32.89	91.44	12.52
1.5	315	0.535	0.269	33.24	92.40	12.65
1.5	270	0.535	0.269	33.29	92.55	12.67
1.5	45	0.638	0.36	33.33	92.64	12.69
1.5	225	0.604	0.309	33.61	93.42	12.79
1.5	135	0.604	0.309	33.82	94.02	12.88
1.5	90	0.604	0.309	33.63	93.50	12.80
1.5	180	0.535	0.269	34.08	94.74	12.97
1.66	0	0.535	0.269	33.47	93.03	12.74
1.66	315	0.535	0.269	33.66	93.58	12.82
1.66	270	0.535	0.269	33.70	93.68	12.83
1.66	45	0.604	0.309	33.94	94.35	12.92
1.66	90	0.604	0.309	34.10	94.79	12.98
1.66	225	0.535	0.269	34.04	94.64	12.96
1.66	135	0.535	0.269	34.39	95.60	13.09
1.66	180	0.416	0.204	34.70	96.47	13.21

Basecase | Optimal Case A | Optimal Case B | Optimal Case C | Optimal Case 1 | Optimal Case 2 | Optimal Case 3

Appendix G

Appendix Table 7: AH score calculation for daylight for Kyiv- Optimal case A

Room Types	$sDA_{300/50\%}$ (%)	AH Score	Occupied Hours	Occupants Number	Weighted Score
Kitchen	100	1	3	4	12
Living Room	100	1	2.5	4	10
Bedroom 1	95.2	1	1.5	1	1.5
Bedroom 2	97.6	1	1.5	1	1.5
Study Room	100	1	3	2	6
Master Bedroom	100	1	0.5	2	1
Sub total			32		32
Total Average Score					1

Appendix Table 8: AH score calculation for thermal comfort for Kyiv- Optimal case A

Room Types	Comfort Hours (%)	AH Score	Occupied Hours	Occupants Number	Weighted Score
Kitchen	96	2	5	4	40
Living Room		2	3.5	4	28
Bedroom 1	98.2	2	11	1	22
Bedroom 2	98	2	11	1	22
Study Room	96.4	2	5	2	20
Master Bedroom	96.4	2	8.5	2	34
Sub total			83		166
Total Average Score					2

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