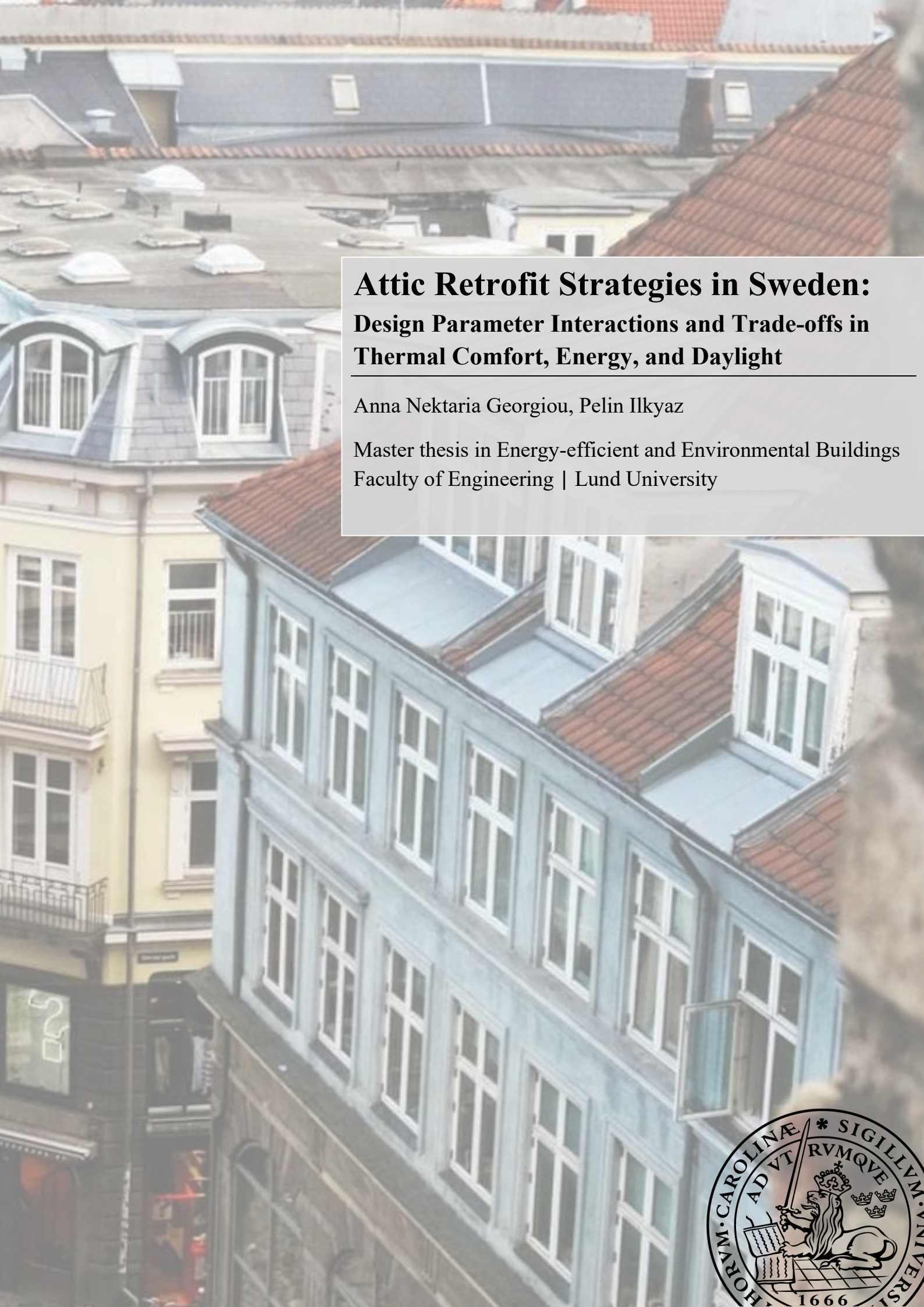




Attic Retrofit Strategies in Sweden: Design Parameter Interactions and Trade-offs in Thermal Comfort, Energy, and Daylight

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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 centres 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 has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

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This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

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

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Abstract

The renovation and adaptive reuse of existing buildings is increasingly recognised as a strategy to address both housing shortage and climate targets in Europe. In Sweden, there is a large potential in converting cold attic spaces in mid-twentieth-century multi-family buildings which offers increased housing capacity without new construction. However, attic retrofits involve complex interactions between energy demand, thermal comfort, daylight availability, while overheating becomes an increasing concern under future climate conditions.

This study investigates how retrofit design parameters influence the energy performance, thermal comfort, and daylight availability of residential attic spaces in Sweden. A simulation-based parametric approach was applied in IDA ICE to evaluate the effects of glazing configuration and orientation on heating energy demand, daylight provision, and thermal comfort, as well as the effects of shading strategies and natural ventilation controls on overheating risk. Daylight performance was assessed according to EN 17037, while thermal comfort and overheating risk were evaluated using the adaptive comfort model according to EN 16798-1. The analysis was conducted on a representative Swedish attic apartment under present climate conditions, while future climate conditions (2050, SSP2-4.5 scenario) were assessed specifically in relation to overheating risk. Both typical and advanced renovation contexts were considered, corresponding to different envelope structures.

The results show that glazing-related parameters have the strongest influence on performance, although their impact varies across the evaluated aspects. Roof windows were the main drivers of daylight availability and thermal comfort, with increased number of roof window improving daylight provision while also increasing overheating risk. In contrast, façade windows had a stronger influence on heating energy demand. Compared to the typical renovation context, the advanced renovation context reduced heating energy demand while increasing overheating and slightly reducing daylight availability. The effectiveness of the control strategies varied depending on window type: shading was more effective for roof windows, while natural ventilation was more effective for façade windows. The combined application of both strategies resulted in the lowest overheating levels. Under future climate conditions, overheating increased across all analysed cases, and shading strategies used alone were less effective. Natural ventilation therefore played a greater role in maintaining acceptable indoor temperatures, while the combined application of smart shading and smart natural ventilation controls resulted in the best thermal performance.

Overall, the study contributes to the understanding of multi-performance attic retrofit design by balancing daylight provision, thermal comfort, and energy performance, while highlighting the increasing role of shading and natural ventilation control strategies in maintaining acceptable indoor conditions, especially under future climate scenarios.

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1 Introduction

Buildings are responsible for about 40% of the EU's energy use, but only 1% of buildings undergo energy-efficient renovation every year (European External Action Service, 2020). The total building stock of the European Union's Member States is estimated at approximately 131 million buildings, with residential buildings accounting for the largest share (Royal Institution of Chartered Surveyors, 2020). At the same time, Europe faces an increasing housing crisis, with the European Commission projecting that more than 2 million new homes per year will be needed through 2035 to meet demand and tackle the housing crisis (Joint Research Centre, 2026). As a result, property prices are rising and contributing to affordability challenges, with the European Parliament claiming that 10% of the households are spending over 40% of their income on housing (European Parliament, 2026).

The affordable housing initiative, which was announced in the Commission's Renovation Wave strategy for Europe, intends to at least double renovation rates in the EU, renovating 35 million buildings by 2030 and ensure renovations lead to higher energy and resource efficiency. This initiative was a response to the underlying energy poverty, with nearly 34 million Europeans unable to afford adequate heating for their homes (European External Action Service, 2020). Within this context, the adaptive reuse of existing building spaces represents a promising opportunity to increase housing supply while minimising the need for new construction. Renovating residential buildings, particularly when undertaken on a large scale, has the potential to reduce emissions significantly while also enhancing thermal comfort, supporting occupant health, and improving the resilience of homes to future climate conditions (Klemm et al., 2025). These improvements are particularly important in the context of global climate targets. Meeting the targets of the Paris Agreement, which aims to limit global warming to well below 2 °C, requires significant reductions in greenhouse gas emissions and energy use (United Nations Framework Convention on Climate Change, 2015). Rising temperatures associated with climate change are increasing the risk of overheating and also energy use for cooling in buildings across Europe in the upcoming decades. While buildings can be designed to protect occupants from heat, inadequate design strategies, particularly in relation to solar gains, ventilation, and internal loads, can lead to elevated indoor temperatures. This effect can be especially pronounced in well-insulated buildings, where reduced heat loss may intensify overheating. Overheating is not only a matter of thermal discomfort but also poses health risks, including heat stress and the aggravation of existing medical conditions (European Environment Agency, 2022). In this context, strategies that simultaneously address housing demand and building performance under changing climate conditions become particularly relevant.

One promising option is the conversion of cold attics into residential spaces, as these areas represent a large and often unused spatial potential that could help address the housing shortage associated with growing urban populations. A cold attic is an unheated space surrounded by a pitched roof, gable walls, and a thermally insulated ceiling of the highest floor of the building (Richter et al., 2020). The roof is one of the most exposed elements of the building envelope, and especially during summer months, pitched roofs typically receive higher solar radiation than vertical surfaces (Fantucci & Serra, 2019). This phenomenon can strongly affect the thermal performance of attic spaces, increasing their vulnerability to overheating, a condition that is projected to intensify under future climate change scenarios. The thermal behaviour of cold attics also influences the building's overall energy performance. If the ceiling separating the attic from the heated rooms below is insufficiently insulated, significant heat losses can occur, increasing the heating demand of the dwellings beneath the attic (Archesso, 2025).

Furthermore, cold attics are often identified as moisture-prone spaces in buildings, often experiencing condensation and mold development associated with inadequate ventilation and high humidity levels within the roof space. Over time, these conditions may damage timber structural elements and enable mould spores to migrate into neighbouring indoor areas, potentially affecting the health of occupants (Richter et al., 2020).

In addition to thermal performance and moisture-related considerations, daylight availability is another important aspect of indoor environmental quality in attic spaces. Daylight exposure in buildings is an important factor influencing occupant health, circadian rhythm regulation, and overall well-being. Adequate access to natural light has been shown to support healthy sleep patterns and enhance productivity, while insufficient daylight may negatively affect physical and mental health. In addition to supporting occupant health, daylight can decrease the demand for artificial lighting and therefore reduce overall building energy use (Šprah & Košir, 2020).

Façade windows are the primary source of daylight in buildings. However, attic spaces also allow daylight through roof windows. The design of these openings' influences daylight distribution, solar gains, and indoor conditions. While roof windows can improve daylight availability, they may also increase heat gains, requiring a balance between daylight and thermal comfort.

Achieving a balance between thermal comfort, daylight availability, and energy performance is a complex design challenge in attic retrofits, particularly under projected future climate conditions. To better understand these interactions, this study evaluates the combined influence of design strategies on the indoor performance of residential attic spaces.

1.1 Project Aim

While attic conversions offer significant potential for increasing housing capacity within existing buildings, their performance in terms of energy demand, thermal comfort, and daylight availability, greatly depends on early design decisions. Specifically, glazing configuration, building orientation, shading and ventilation strategies influence solar gains, indoor temperatures, daylight distribution, and the overall performance of attic spaces.

The aim of this study is to investigate how retrofit design parameters influence energy demand, thermal comfort, and daylight availability in residential attic spaces in Sweden. Using a parametric simulation approach, the study evaluates the effects of window configuration, orientation, shading and natural ventilation strategies on these performance indicators under two different envelope renovation levels representing usual and advanced renovation contexts.

The analysis is conducted for a generic typology representing an attic apartment in Sweden under present and future climate conditions. The findings aim to support performance-informed design decisions for residential attic retrofits, considering the need for climate-responsive and future-proof solutions. The study therefore investigates: (1) the effects of glazing configuration and orientation on attic performance regarding energy demand, thermal comfort, and daylight, (2) the influence of shading and natural ventilation control strategies on thermal comfort performance, and (3) the robustness of selected retrofit strategies under future climate conditions.

2 Background

2.1 Housing Shortage and Urban Densification

The conversion of attic spaces into liveable spaces is a usual practice in European countries, and it leads to an increase in urban population density, avoiding the new constructions (Fantucci & Serra, 2019).

According to the Swedish National Board of Housing, Building and Planning (Boverket), approximately 60.000 new homes need to be constructed annually between 2021 and 2030 to accommodate projected population growth and address the housing shortage caused by the past 15 years of housing construction not keeping pace with population increases. Nearly three-quarters of this housing demand is concentrated in the three metropolitan regions (Boverket, 2021).

Research examining urban development at the rural–urban fringe in the Netherlands shows that Dutch planning has historically promoted the concept of the compact city, which encourages development within existing urban areas rather than expansion into surrounding rural land. This approach aims to limit uncontrolled suburban growth while protecting natural landscapes and recreational spaces around cities. By retaining development closer to existing urban centres, travel distances get shortened and more efficient use of infrastructure, such as transport networks and public services are supported (Nabielek et al., 2013).

Green space plays an important role in urban environments. Data from Swedish Statistical Office indicate that approximately 63% of the land within Swedish urban areas consisted of green space in 2015. The report also identifies a relationship between the size of urban areas and the proportion of green space, showing that smaller urban areas generally contain a higher share of green areas than larger cities (Statistics Sweden, 2019).

A review of comprehensive plans from Swedish municipalities shows that densification is frequently presented as a strategy to support sustainable urban development. The motivations for densification vary between municipalities, with urban areas often emphasising land-use efficiency, access to green spaces, and water management, while less urbanised municipalities focus more on development feasibility. While these motives are generally framed positively in planning documents, the study also notes that some of the commonly cited benefits of densification have limited empirical support in the scientific literature, suggesting that the sustainability outcomes of densification may depend on the specific context in which it is implemented (Haupt et al., 2020).

The compact city model is widely linked to sustainability objectives in urban planning. Increasing development density within established urban areas may contribute to reduced travel demand, lower car dependency, decreased energy use, and the protection of green and natural spaces by limiting outward urban expansion (Bibri et al., 2020). However, urban densification may also have unintended consequences for daylight access in buildings. One of the negative affiliations of urban densification is the potential unintended consequences for daylight access in buildings. Increased building density and height, deeper floor plans, and reduced glazing areas can lead to diminished indoor daylight availability (Jin et al., 2025). This highlights a potential trade-off between densification and indoor environmental quality, as efforts to accommodate growing urban populations may negatively affect daylight conditions within dwellings.

Urban densification itself can take different forms, including “soft densification,” which focuses on increasing housing capacity within the existing built environment without substantially altering the urban form. Such interventions may include adding additional living spaces to existing buildings through refurbishment processes (Asfour, 2022).

In the context of a growing urban population, the demand for additional housing space increases, while available land for new construction is often limited. As a result, strategies for urban densification have become greatly important. One potential approach is the extension or conversion of attic spaces, which can create additional

residential units while making use of existing buildings. In several European cities, attic extensions have already been implemented in the refurbishment of late 19th-century buildings, particularly in privileged city locations, where high real estate values make such interventions economically attractive. However, the potential of buildings belonging to other construction periods has not yet been fully recognised (Jaksch et al., 2016).

2.2 Swedish Housing Stock and Renovation Needs

Energy poverty has historically been considered a relatively limited issue in Sweden compared with many other European countries. This has partly been attributed to the relatively high energy performance of the housing stock and a strong social welfare system that helps households manage housing and heating costs. However, recent increases in electricity prices have exposed vulnerabilities among some households, highlighting that energy affordability can become a challenge under changing energy market conditions (von Platten, 2022).

At the same time, the Swedish residential building stock faces increasing renovation needs. According to a study by RISE cited in Sweden's national strategy for energy-efficient renovation, there is a renovation deficit among Swedish apartment buildings. Although the renovation rate for apartment buildings has increased in recent years, it remains lower than the number of buildings reaching an age when major renovation is typically required (around 50 years). As a result, the renovation deficit in the building stock continues to increase (Ministry of Infrastructure, 2020).

Housing shortages remain a challenge in many Swedish cities, particularly for young people and students. Legislative changes introduced in 2014 simplified the creation of small apartments of up to 35 m² in existing buildings (Boverket, 2014a; Tengdelius, 2015). In addition, Boverket's Building Regulations allow deviations from accessibility and usability requirements when attics are converted into dwellings not exceeding 35 m² (Boverket, 2019). This provision can facilitate the conversion of attics into smaller apartments, as it may reduce the need for major structural interventions.

Demographic trends in Europe also indicate a growing number of single-person households. Between 2015 and 2024, the number of single-person households without children in the European Union increased by 16.9%, compared with an increase of 5.8% for households overall. This trend contributes to growing demand for smaller housing units such as studios and one-room apartments (Eurostat, 2025).

2.3 Swedish Residential Building Typologies

During the post-war period, a large part of the population moved to the big cities and due to the following housing shortage, new residential areas were planned to be built. The multi-family buildings represented 86% of the total number of buildings, with linear block buildings being the most common form. It is estimated that around 40.000 apartments were built annually during the 1940s-1960s (Björk et al., 1983). Swedish Statistical Office's dwelling stock data, as presented in Figure 1, show that the largest number of multi-dwelling buildings in Sweden was constructed between 1961 and 1970, including the buildings from a massive public housing project known as the Miljonprogrammet (the Million Programme) (Boverket, 2014b; Statistics Sweden, 2024). The following period of the largest building stock is 1951–1960, indicating that a great share of the existing multi-family housing stock originates from the mid-twentieth century. In recent years, they account for approximately 52% of the residential dwelling stock as of 2024 (Statistics Sweden, 2024).

Regarding the Swedish multi-dwelling typologies, during the 1950s decade residential construction adopted industrialised building systems and prefabricated components and roof geometries gradually shifted toward lower slopes and nearly flat configurations. The earlier Lammellhus typology, which was widely adopted during the 1940s-1950s, contained gable roofs finished with clay tiles. These buildings were typically low-rise buildings, generally three to four storeys in height and used brick as the main façade material. Their layout often formed open courtyards, while building depths remained relatively narrow, with values of around 10–11 meters (Björk et al., 1983).

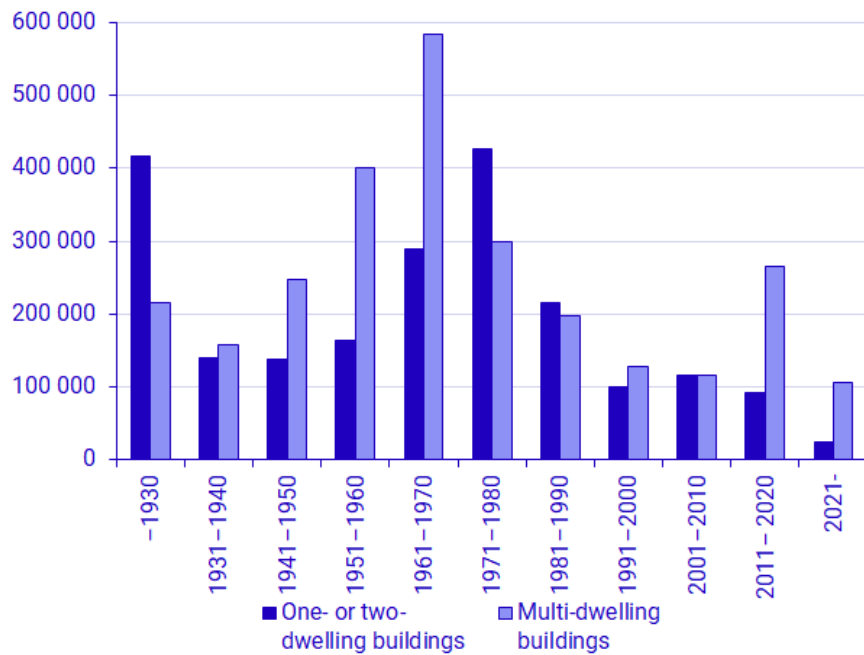


Figure 1: Number of dwellings by type of building and period of construction (Statistics Sweden, 2024)

2.4 Energy Performance of Buildings

Building energy regulations and minimum performance requirements are becoming increasingly stricter in many countries, while the adoption of energy-efficient and renewable building technologies continues to grow. However, there is an urgent need for progress in the building sector to accelerate significantly in order to align with the Net Zero Emissions by 2050 (NZE) pathway. Developed by the International Energy Agency (IEA), the NZE pathway describes a route to achieving net-zero emissions by 2050 consistent with limiting global warming to 1.5°C. For the building sector, this will require a significant acceleration in decarbonization efforts (International Energy Agency, 2021). The current decade is particularly critical, as major actions are required to ensure that all new constructions and at least 20% of the existing building stock can operate by 2030 as highly energy-efficient, using renewable energy or relying on a source of energy that can be fully decarbonised (International Energy Agency, 2023).

The reduction of energy use and greenhouse gas emissions from buildings is guided at the European level through the Energy Performance of Buildings Directive (EPBD), which establishes a policy framework. The directive encourages member states to balance efforts to decarbonise energy supply with measures that lower the overall energy demand of buildings. In order to achieve this, it is required that they develop long-term renovation strategies that outline actions and policy measures to improve the energy performance of the building stock. These strategies typically include milestones for the short, medium and long term (around 2030, 2040 and 2050, respectively), providing a roadmap for transforming existing buildings into highly energy-efficient and low-carbon structures. Member states are also expected to monitor progress through national indicators that reflect local conditions and policies (European Parliament and Council of the European Union, 2018).

Alongside efforts to reduce operational energy use, increasing attention has also been given to life-cycle carbon emissions in buildings. In particular, emissions associated with construction materials and processes, commonly referred to as embodied carbon, are estimated to account for 10–20% of a building's total carbon footprint, a proportion that is expected to rise as operational emissions decrease through energy-efficiency measures more rapidly than embodied emissions (Green Transition Denmark, 2024). European policy developments emphasise the life-cycle emissions, including the integration of whole life carbon considerations into the revised EPBD, as well as national initiatives such as climate declarations in Sweden. In February 2022, the Swedish government

commissioned Boverket to develop proposals aimed at accelerating the implementation of limit values for the climate impact of buildings and expanding the use of climate declarations.

In this context, reducing the need for new construction becomes a key strategy for lowering overall climate impact. The adaptive reuse of existing buildings, including the conversion of cold attic spaces into habitable areas, therefore represents an approach aligned with these objectives by increasing housing capacity while limiting additional carbon emissions associated with new construction.

At the same time, improving building performance, whether in new constructions or renovation of existing buildings, has direct implications for indoor environmental conditions. While these policies primarily focus on reducing energy use and emissions, measures such as increased insulation and airtightness can affect indoor temperature, air quality, and moisture levels. Therefore, energy performance improvements must be considered alongside indoor quality.

2.5 Indoor Climate and Thermal Comfort

Although outdoor air quality and its health impacts are often emphasised, people spend around 90% of their time indoors, making indoor air quality equally important for health and well-being. Improvements in energy efficiency have resulted in buildings that are increasingly airtight, which can reduce uncontrolled heat losses but may also limit natural air exchange. As a result, indoor pollutants originating from building materials, furnishings, and consumer products may accumulate if adequate ventilation is not provided (Harrison, 1998). Ventilation plays an important role in maintaining healthy indoor environments by diluting and removing indoor contaminants (Smith & Wiech, 1994). In addition to improving indoor air quality, ventilation also contributes to thermal comfort by removing excess heat and providing cooling effects (Liddament, 1996).

The overall comfort of the environment is critical for human health. When negative health effects occur, they are often linked to deficiencies in building design or operation. Thermal comfort is defined as “the state of mind that expresses satisfaction with the thermal environment”, according to standards such as ASHRAE 55 and ISO 7730. Nevertheless, the application of passive design approaches is strongly influenced by climatic conditions, and therefore the passive thermal comfort measures applied in Northern Europe differ considerably from those required in the warmer climates, where mechanical cooling is frequently necessary to maintain comfortable indoor conditions. Thermal comfort plays an important role in building energy use, as occupants who experience discomfort often adjust heating or cooling systems to non-optimal settings in order to improve indoor conditions (Al horr et al., 2016).

In addition to general thermal comfort considerations, overheating has become an increasingly relevant issue in buildings, particularly in the context of changing climatic conditions. Overheating risk is influenced not only by external temperatures but also by the characteristics of the existing building stock. A large proportion of European buildings were constructed before the introduction of modern thermal standards and may present limitations such as insufficient insulation and inadequate ventilation, which can reduce their ability to respond effectively to heat events. Overheating is not limited to older buildings and may also occur in newly constructed or retrofitted buildings when design strategies do not adequately account for the interaction between solar gains, internal heat loads, and ventilation. In response, current approaches emphasise the importance of context-specific cooling strategies that prioritise passive measures and consider building characteristics, local environmental conditions, and future climate conditions (European Environment Agency, 2022).

2.5.1 Adaptive Comfort Model

In this context, understanding how occupants perceive and adapt to thermal conditions becomes essential. The early studies of thermal comfort focused mainly on laboratory experiments examining heat exchange between the human body and the surrounding thermal environment and the physiological conditions needed for human comfort. These investigations resulted in the development of rational thermal comfort indices, including

Fanger's Predicted Mean Vote (PMV) model, based on which several thermal comfort standards have been established, including ISO 7730, ASHRAE 55 Standard and EN 15251 (Humphreys & Nicol, 1998; Yang et al., 2015). However, evidence from field studies has questioned the accuracy of the PMV index, indicating that it may over- or under-predict occupants' thermal sensations, which led to the development of the adaptive comfort principle. Humphreys & Nicol (1998) proposed the adaptive thermal comfort model, which suggests that occupants can achieve thermal comfort by adapting to changes in their thermal environment through behavioural, physiological, and psychological responses. They further explain that when individuals experience thermal discomfort, they tend to respond through different forms of adaptation aimed at restoring comfort, including behavioural, physiological, psychological, social, or technological actions that help adjust the thermal environment (Humphreys & Nicol, 1998). This adaptive approach has also been incorporated into European standards, such as EN 16798-1, which defines acceptable indoor operative temperature ranges for free-running buildings (buildings without mechanical cooling in summertime) as a function of the running mean outdoor temperature (Nicol & Humphreys, 2010; Olesen, 2024).

2.6 Daylight in Buildings

Recent research has highlighted the important role that light and darkness play in regulating human physiological processes. Exposure to varying lighting conditions throughout the day influences circadian rhythms, including patterns of hormone secretion, bodily functions, and levels of activity (Veitch, 2007).

Lighting in buildings has traditionally been designed to support visual tasks. However, light also influences human health and well-being and should therefore be considered in the design of both electric lighting and daylighting systems. Daylight originates from the sun and consists of electromagnetic radiation within the visible spectrum (approximately 400–700 nm), which corresponds to the range of wavelengths detectable by the human visual system (Webb, 2006).

Daylight conditions in Nordic regions vary significantly throughout the year, with particularly large seasonal differences at higher latitudes. During winter, limited daylight and prolonged periods of darkness can negatively affect both physical and psychological well-being. Insufficient sunlight exposure has been associated with reduced vitamin D levels and conditions such as winter depression, which affect a large part of the population. Although increasing the use of daylight in buildings is often promoted as a strategy to reduce electric lighting energy use, excessively large glazed areas are not necessarily an appropriate design solution. Very large windows can lead to issues such as glare, increased heat losses, and excessive solar heat gains, which may ultimately increase cooling demand in buildings (Dubois et al., 2019).

Natural daylight can be introduced into buildings through several architectural strategies. The most common strategy is side-lighting, which uses windows located in exterior façades to bring daylight into interior spaces. The effectiveness of this approach depends on a range of design parameters, including the climatic context, site conditions, building orientation, and the dimensions and placement of window openings. Other factors, such as glazing characteristics, shading systems, and the reflectance of surrounding interior and exterior surfaces, also influence how daylight enters and spreads within a space. In addition, architectural elements such as window frames, reveals, and the configuration of interior partitions can affect the distribution of daylight throughout the room. Another commonly used architectural strategy is top-lighting, which includes elements such as skylights and atria. Unlike façade windows, which receive light primarily from the horizon, roof openings capture daylight from the sky dome above. For this reason, top-lighting systems can provide relatively high levels of illumination even under overcast sky conditions and can distribute daylight more uniformly (Dubois et al., 2019). Nevertheless, if daylight openings are not carefully designed, they may lead to undesirable effects such as glare or excessive solar heat gains, which can negatively affect both visual and thermal comfort in buildings.

Daylighting design in buildings has usually been evaluated using a limited number of quantitative indicators, primarily daylight factor (DF), access to views to the outside, and, in some cases, the avoidance of direct

sunlight. Among these indicators, the daylight factor has been widely applied as a measure of daylight availability within interior spaces. The daylight factor describes the relationship between the illuminance measured at a point inside a building and the unshaded outdoor horizontal illuminance under a standard CIE overcast sky, expressed as a ratio (Reinhart et al., 2006).

However, because the daylight factor is calculated under a standard overcast sky, it does not account for the effects of building orientation, geographic location, or varying sky conditions. As a result, the metric cannot fully represent the dynamic nature of daylight and its availability indoors. To address these limitations, more advanced daylight evaluation methods have been developed, such as the Climate-Based Daylight Modelling (CBDM), which estimates daylight levels in buildings by using simulation models that incorporate local climate data and orientation. Unlike traditional daylight factor calculations, which rely on a single overcast sky condition, CBDM considers the influence of direct sunlight and varying sky conditions throughout the year. By accounting for factors such as geographic location, solar position, and building geometry, this method can predict realistic indoor daylight illuminance values. As a result, CBDM enables a more detailed and comprehensive assessment than the daylight factor approach (Mardaljevic et al., 2011).

Within climate-based daylight assessment, metrics have been developed to evaluate daylight conditions over an annual period using simulation methods. One of these metrics is Spatial Daylight Autonomy (sDA), which represents the percentage of floor area in a space where a specified daylight illuminance level is achieved for a defined fraction of the annual occupied hours. For example, sDA300/50% indicates that an illuminance of at least 300 lux is reached for 50% of the occupied hours during the year. The metric is typically evaluated together with Annual Sunlight Exposure (ASE), which assesses the potential for excessive direct sunlight within a space (Illuminating Engineering Society, 2012).

In Sweden, daylight requirements are regulated through BBR, which requires adequate access to daylight in regularly occupied spaces (Boverket, 2019). Compliance is commonly demonstrated through a daylight factor of approximately 1%. However, the European standard SS-EN 17037:2018+A1:2021 provides a more comprehensive framework for daylight assessment, including both daylight factor targets and climate-based daylight metrics (Swedish Institute for Standards, 2021).

2.7 Performance Interactions in Attic Spaces

In attic spaces, thermal comfort, daylight availability, and energy performance are closely interrelated. Design decisions such as the configuration and type of openings, shading and ventilation strategies directly influence solar gains, indoor temperatures, and daylight distribution. These interactions can create conflicting relationships among these aspects, as measures that improve daylight conditions may increase overheating risk, while strategies aimed at reducing heat gains can limit daylight availability. Therefore, attic retrofit design requires a balanced approach that considers these trade-offs in order to achieve energy efficiency and acceptable indoor environmental conditions.

Research highlights the role of roof windows in shaping these interactions. Studies on attic classrooms indicate that roof windows are necessary to provide sufficient daylight in deeper areas of spaces, while their configuration influences daylight uniformity and the achievement of required illumination levels. However, the study also reports overheating during summer conditions, highlighting the need for additional measures such as shading or mechanical cooling. The results further show that combining façade and roof windows improves daylight performance, while façade windows had a limited influence on summer temperature increases in the analysed case (Dolnikova et al., 2020). Therefore, the design and selection of façade and roof windows represent critical factors influencing the overall energy performance of buildings.

In addition to window configuration, control strategies play a crucial role in managing attic performance. Psomas et al. (2017) examined the performance of natural ventilation and shading strategies in a renovated single-family house under summer conditions, with particular focus on roof windows. Their findings indicate

that manually operated natural ventilation and shading systems may not consistently maintain acceptable indoor environmental conditions, especially in spaces exposed to high solar gains. In contrast, automated roof window control systems were shown to reduce overheating risk and improve thermal comfort without negatively affecting indoor air quality. These results highlight the importance of control strategies in managing solar gains and natural ventilation in spaces where roof openings play a significant role.

These findings demonstrate that both design parameters and operational strategies influence not only indoor environmental conditions but also overall energy performance, as increased solar gains may reduce heating demand while simultaneously increasing cooling needs.

2.8 Building Performance under Future Climate Conditions

In Nordic countries such as Sweden, residential buildings have traditionally been characterised by the absence of active cooling systems, as current climatic conditions generally do not lead to significant overheating problems and buildings can often be cooled through natural ventilation. However, climate change introduces uncertainty regarding the future performance of buildings, particularly in relation to potential increases in cooling demand. This highlights the importance of assessing building performance under future climate scenarios in order to understand how these conditions may evolve (Nik & Sasic Kalagasidis, 2013).

Future climate projections are developed using scenario-based approaches, such as the Shared Socioeconomic Pathways (SSPs), which combine assumptions about emissions, land use, and socio-economic development and are used to support analyses of climate change impacts and adaptation (O'Neill et al., 2016). Accordingly, climate projections indicate that buildings will be exposed to more frequent and severe heat events, particularly during summer periods, which can lead to increased overheating risk. At the same time, existing renovation practices have primarily focused on reducing heating demand and may not adequately address summer performance. This raises concerns about the long-term effectiveness of current retrofit approaches and highlights the need to reassess building design strategies to ensure acceptable indoor conditions in a changing climate (Hostein et al., 2024).

3 Methodology

3.1 Research Approach

This study adopted a quantitative, simulation-based approach to investigate the influence of retrofit design parameters on thermal comfort, daylight availability, and energy performance in residential attic spaces in Sweden, with particular focus on the trade-offs between these performance criteria and on quantifying the impact of individual design parameters on the assessed metrics. The analysis primarily considered present climate conditions, while selected variations were further evaluated under future climate conditions to assess their sensitivity to climate change.

To systematically analyse the influence of multiple variables, referred to as design parameters, a Design of Experiments (DoE) framework was applied. In this context, discrete parameter values were defined as configurations or levels, and each unique combination of these constituted a distinct variation (Montgomery, 2022).

A multi-level full factorial design was employed, in which all possible combinations of parameters and their configurations or levels were explicitly generated and simulated. Factorial designs are particularly suitable for studies involving multiple design parameters, as they enable the investigation of both main and interaction effects (Janković et al., 2025; Montgomery, 2022). The full factorial design ensured complete coverage of the discrete design space, allowing direct comparison of all retrofit variations without approximation (Janković et al., 2025). The framework was implemented through parametric building performance simulations, which are commonly used to analyse the influence of design parameters on building performance (Hopfe & Hensen, 2011). The specific design parameters considered in the analysis are defined in the following sections.

3.2 Reference Building and Representative Attic Model

A reference building was used as the basis for the development of a representative attic model. The geometry of the model was derived from the selected building and informed by relevant provisions for attic spaces defined in the Boverket Building Regulations (BBR). The reference building selected for this study was based on a low-rise multi-family residential typology from the 1940s, as presented in Figure 2, commonly referred to as a lamellhus. These buildings are characterised by linear building forms, relatively narrow depths, and gable roof geometries. The selection was based on the tendency of later building typologies to adopt flatter roof geometries, which reduce the feasibility and spatial potential of attic conversions into habitable areas. The selected building corresponded to a three-storey slatted house with continuous apartments, as documented in typological descriptions of Swedish residential buildings (Björk et al., 1983; Stockholms läns museum, 2023). The geometry of this building type was used as the basis for the development of the representative attic model.



Figure 2: Floor plans of 1940s laminated timber houses. Source: Stockholms läns museum (n.d.), based on Tidstypiskt (2022).

In this study, only one attic studio apartment was evaluated, representing a corner unit, with approximately 35 m² of habitable floor area. The decision to model a corner unit was based on the flexibility to incorporate façade windows without increasing the knee wall height, as full-height knee walls are not typically found in attic apartments. The size was selected in accordance with the BBR, which allow deviations from accessibility requirements for attic dwellings not exceeding 35 m², thereby enabling conversion without major structural interventions (Boverket, 2019). In accordance with BBR definitions, areas with a ceiling height below 1.9 m are not considered habitable and therefore, while the habitable area was limited to approximately 35 m², the total floor area of the attic was 46 m² (Boverket, 2014a). The choice also reflects the increasing demand for smaller housing units, particularly in urban contexts, where housing shortages and demographic trends have led to a growing number of single-person households (Eurostat, 2025). The roof inclination in the model was defined as 30°, corresponding to typical roof pitches for this building typology from the 1940s–50s, which is characterised by relatively low-pitched gable roofs (Björk et al., 1983). Figure 3 and Figure 4 illustrates the location of the studied attic apartment within the building and its floor plan.

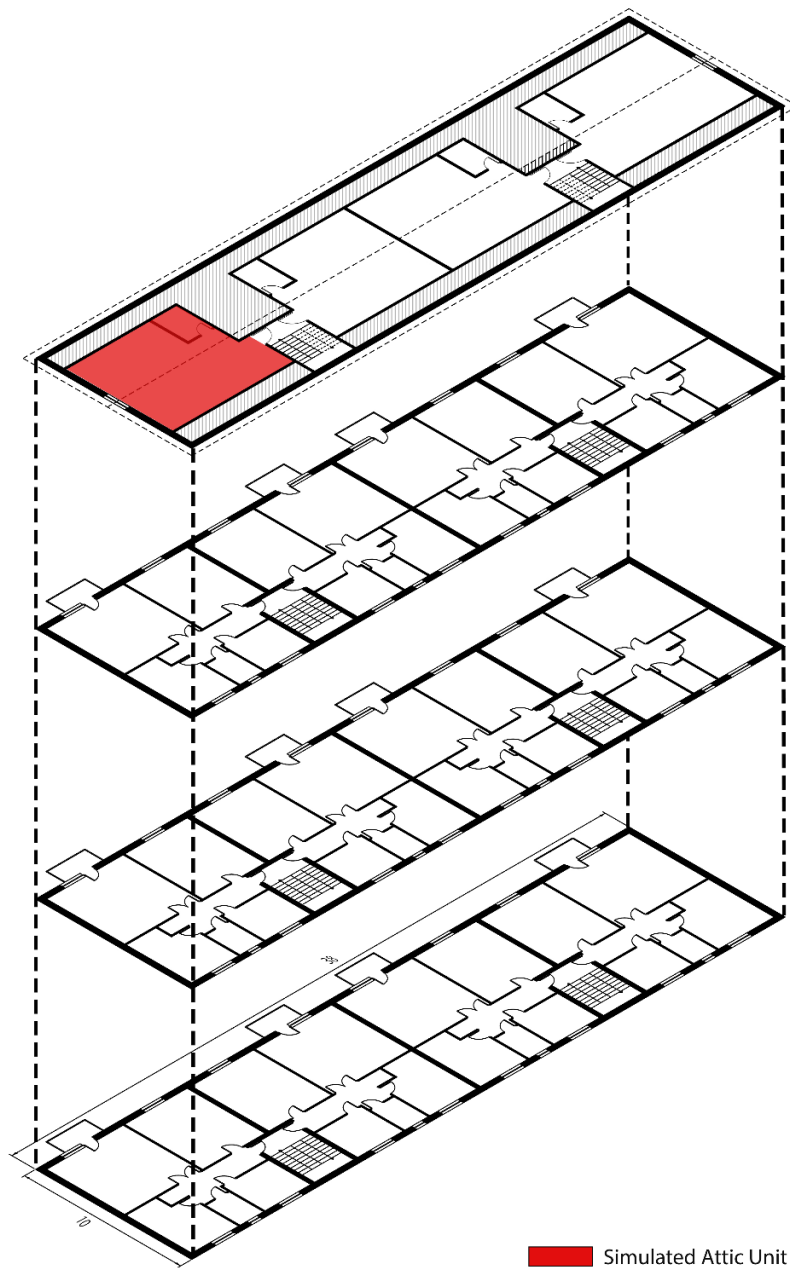


Figure 3: Illustration of the assessed attic unit within the building

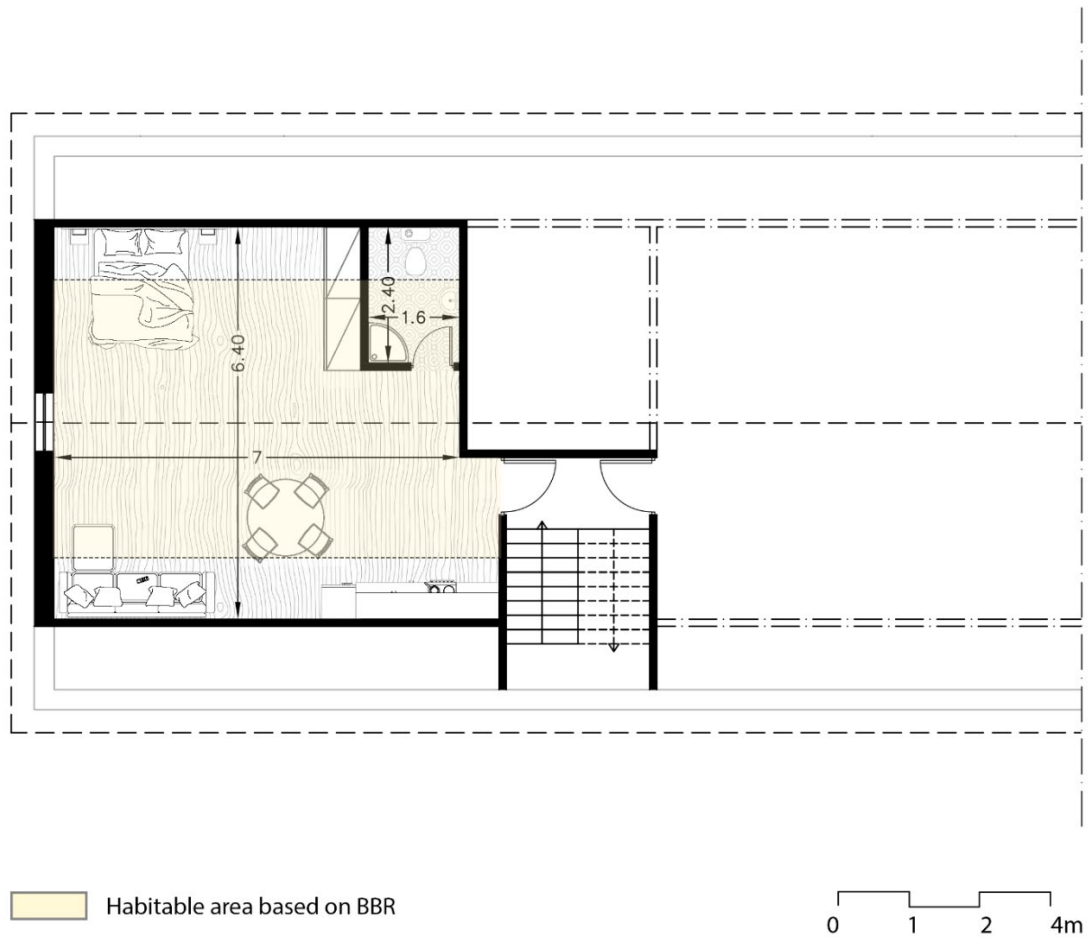


Figure 4: Floor Plan of the studied attic

The building envelope was defined based on a representative Swedish lamellhus archetype from the 1940s–1950s, as described in Björk et al. (1983). These buildings are characterised by load-bearing brick masonry external walls with plaster finishes and timber roof structures with roof boarding and clay tile roofing (Björk et al., 1983).

The thermal performance of the envelope was improved through the addition of thermal insulation as part of the retrofit strategy. Two renovation contexts (typical and advanced) were defined by varying the insulation thickness and airtightness, while maintaining consistent construction principles.

For the external walls, the retrofit was defined through the application of external insulation to the existing masonry structure. This approach reduces thermal bridging and improves hygrothermal performance. Internal insulation in solid masonry constructions, in contrast, requires careful design due to reduced drying potential and increased moisture risk (Bjarløv et al., 2015). It should be noted that the selection of the insulation strategy focused on the thermal performance of the retrofit and did not evaluate architectural or heritage preservation constraints associated with the application of external insulation, which can be considered as a limitation of the study. The typical and advanced contexts were represented by different external insulation thicknesses applied to the same base wall construction.

Internal insulation can present challenges in masonry walls, whereas insulation between rafters is a common solution in pitched timber roofs when combined with a vapour barrier and a ventilated air cavity. Additional continuous insulation layers may be introduced to further improve thermal performance and reduce thermal bridging (ROCKWOOL, 2026).

The roof was defined as a ventilated pitched assembly. In the typical renovation context, insulation was placed between the rafters with a ventilated air layer above and a continuous vapour barrier on the interior side. In the advanced context, an additional continuous insulation layer was introduced above the rafters. A service cavity was included on the interior side to accommodate building services without compromising the airtight layer.

Within the attic space, only the gable wall was treated as an external envelope element, as it is directly exposed to outdoor conditions. The remaining side walls were considered as internal partitions. The section of the attic and the typical renovation configuration are illustrated in Figure 5.

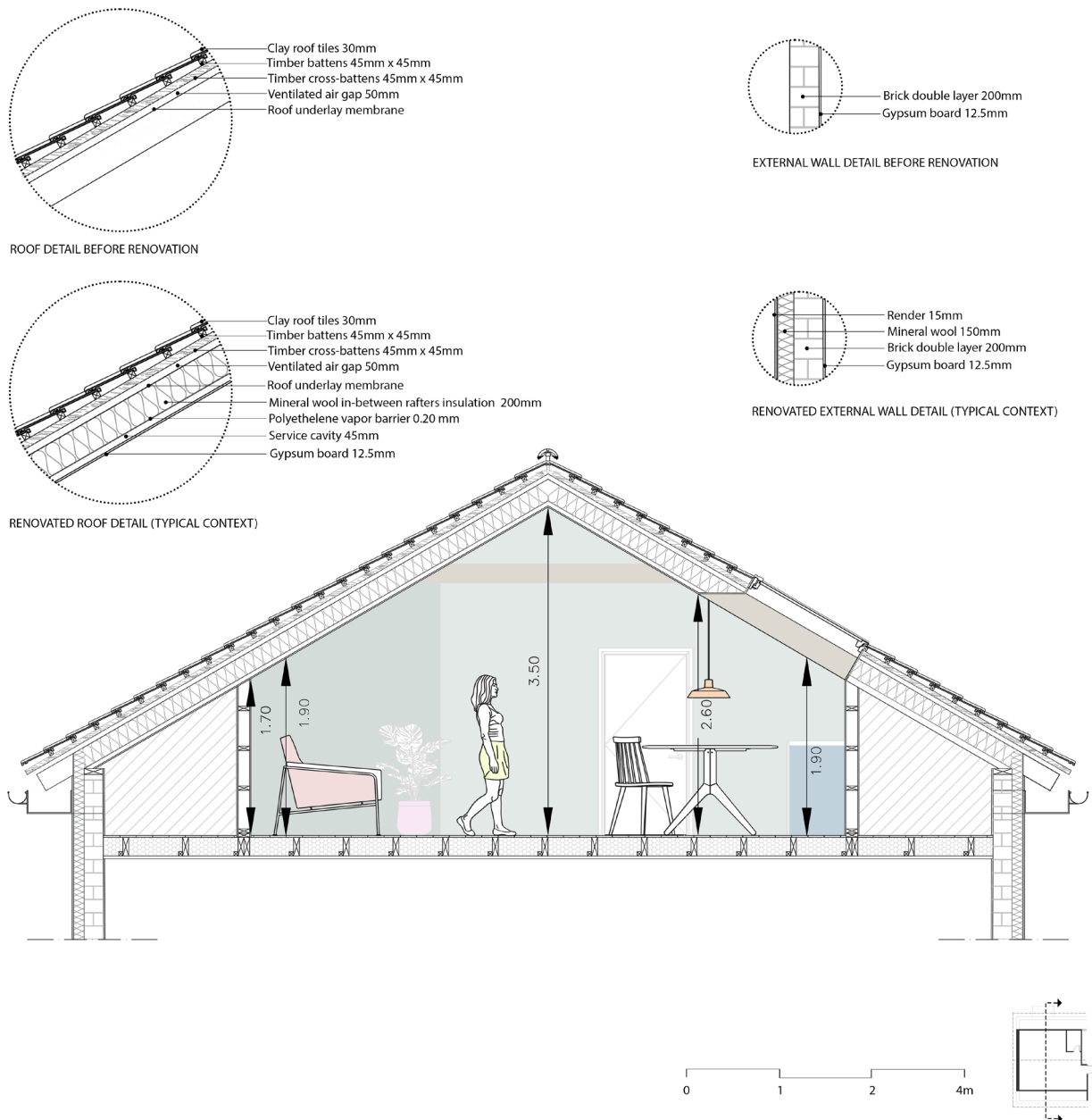


Figure 5: Section and construction details of the attic in typical renovation context

3.3 Parametric Study Framework

The research was structured into three sequential studies, referred to as Study A, Study B, and Study C. The first study, Study A, examined the influence of geometric design parameters, specifically roof and facade window configurations and building orientation, on thermal comfort, daylight availability, and energy performance, evaluated within the two renovation contexts, corresponding to two different envelope (external walls and roof) structures. The second study, Study B, was focused on operational strategies, evaluating the effects of shading and natural ventilation controls on thermal comfort. The analysis was conducted on a subset of representative variations selected from Study A based on their performance on overheating hours. The third study, Study C, extended the analysis by assessing selected variations, a set of representative control strategies used in Study B, under future climate conditions to evaluate their future performance. Further explanation on the selected variations for each study will be presented in detail in the results section.

The simulation setup and evaluation criteria applied across all studies are described in the following sections. The overall methodological workflow is illustrated in Figure 6.

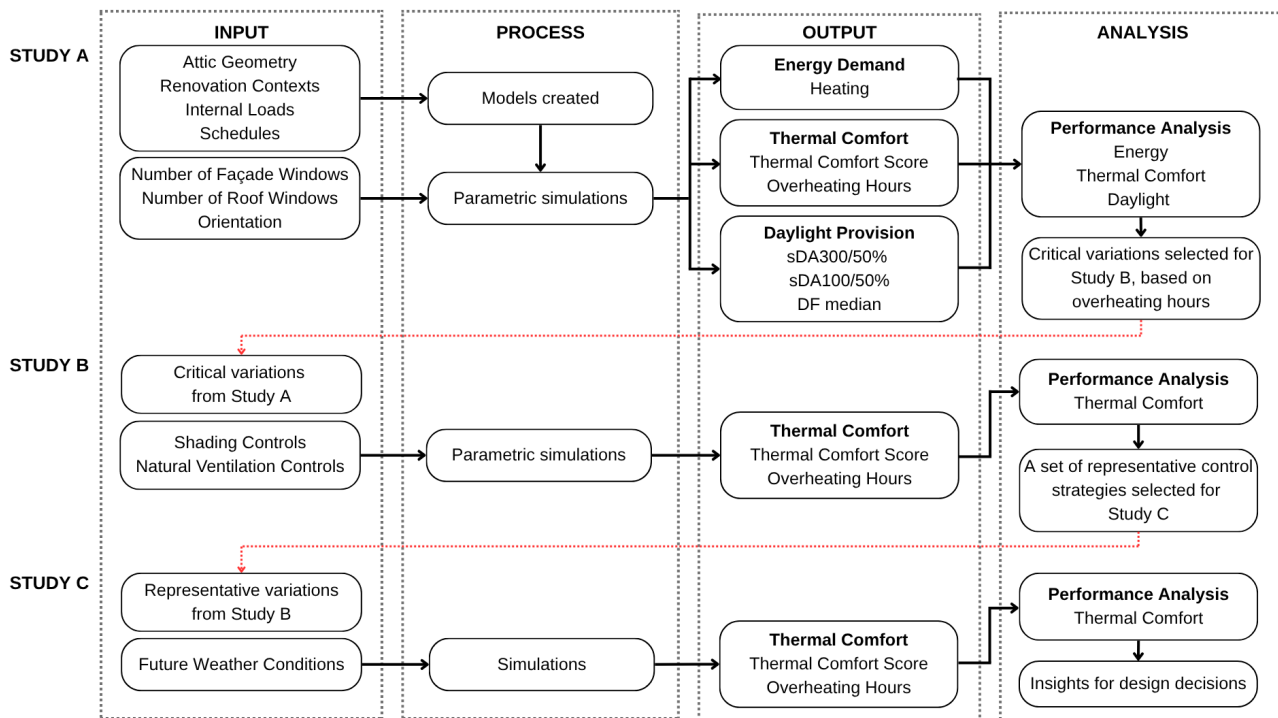


Figure 6: Methodological workflow

3.3.1 Simulation Setup

The simulations were performed using IDA ICE (Indoor Climate and Energy), developed by EQUA. Weather data for Stockholm, Arlanda (SWE_STOCKHOLM-ARLANDA_024600_IW2) were used for both present climate conditions, based on EnergyPlus Weather (EPW) file formats. Future climate data were generated for the same location using Meteonorm, representing the year 2050 under the SSP2-4.5 scenario, a medium-emission pathway within the Shared Socioeconomic Pathways framework, characterised by intermediate greenhouse gas emissions and moderate climate mitigation efforts (O'Neill et al., 2016).

The modelled attic unit was divided into two thermal zones: the living area and the bathroom. Both zones were included in the energy simulations, while only the living area was considered for the thermal comfort and daylight analyses. Two envelope configurations were considered, representing different renovation contexts and referred to as a typical and an advanced configuration. These configurations differed in their thermal transmittance (U-values), as presented in Table 1.

Table 1: U-values of typical and advanced renovation contexts

Building Element	Typical Renovation U-Value [W/m ² K]	Advanced Renovation U-Value [W/m ² K]
External walls	0.29	0.09
Roof	0.12	0.06
Intermediate Floor	0.16	0.16
Partition Walls	1.71	1.71
Façade windows	1.10	1.10
Roof windows	1.20	1.20

Internal partitions and intermediate floor elements were assigned identical U-values in both renovation configurations, as they were modelled as adiabatic in the energy model and therefore did not contribute to heat transfer between zones. The thermal properties of opaque elements were derived from the TABULA WebTool, based on typical renovation scenarios for Swedish multi-family buildings constructed before the 1960s (TABULA, 2017).

The thermal and optical properties of both façade and roof windows were derived from the specifications of the VELUX GGL SK08 68 roof windows, representing a centre pivot, triple glazed unit, as seen in Figure 7. To ensure consistency across the study, identical geometrical dimensions and performance characteristics were applied to both window types for both typical and advanced renovation levels. The complete set of parameters, including window size, thermal transmittance (U-value of window (U_w), U-value of glazing (U_g)), solar heat gain coefficient (g-value), and visible transmittance (T_{vis}), is presented in Table 2 and is based on the manufacturer's technical data (VELUX, 2026a). Derived from the same dataset, for roof windows, the U-value was adjusted to account for the effect of the roof slope. While the dataset provided values for overall thermal performance, frame-specific U-values were not directly adopted; instead, adjustments were implemented within the simulation model to achieve the target U-values for both façade and roof windows.



Figure 7: VELUX GGL SK08 68 centre pivot roof window (VELUX, 2026b)

Table 2: Thermal and optical properties of the selected window

Window model	Size [m]	Area [m ²]	U _w (90°) [W/m ² K]	U _w (30°) [W/m ² K]	U _g [W/m ² K]	U _f for roof windows [W/m ² K]	U _f for facade windows [W/m ² K]	g [%]	T _{vis} [%]
VELUX SK08 GGL 68	1.14 × 1.398	1.59	1.10	1.20	0.70	2.23	1.87	49	68

The envelope constructions were implemented in IDA ICE as simplified layered assemblies defined to achieve the target U-values for each renovation level. Secondary construction elements, such as battens, roof tiles, vapour control layers, and surface finishes, were not explicitly included, as their influence on thermal transmittance is negligible.

The roof construction was modelled as an insulated timber assembly, allowing the attic space to be incorporated within the heated building volume. The insulation was represented as timber framing (cc600) with light insulation, accounting for the thermal effect of the rafters through equivalent thermal properties. In the advanced configuration, an additional continuous light insulation layer was included to reflect the improved thermal performance.

Rather than modelling the complete construction layer compositions, simplified equivalent constructions were used to represent the thermal performance of the renovation variations. The insulation thicknesses were adjusted to achieve the target U-values and therefore differ from reference values reported in the TABULA WebTool. These values should be interpreted as modelled equivalents rather than exact representations of construction practice.

The resulting constructions provide thermally equivalent envelope performance, ensuring consistency in the comparative analysis. The layer compositions implemented in the IDA ICE model are presented in Table 3 and Table 4, with material names retained exactly as specified in the software. In this context, “Light insulation (example)” in IDA ICE refers to a standard lightweight, highly permeable bulk insulation material (such as mineral wool or fiberglass).

Table 3: Renovated attic’s external wall simplified structure (IDA ICE model)

Material	Typical envelope thickness [m]	Advanced envelope thickness [m]
Brick masonry	0.20	0.20
Light insulation (example)	0.10	0.35
TOTAL	0.30	0.55

Table 4: Renovated attic’s roof simplified structure (IDA ICE model)

Material	Typical envelope thickness [m]	Advanced envelope thickness [m]
Light Insulation (example)	-	0.25
Frames (cc600) insulation (example)	0.35	0.35
TOTAL	0.35	0.60

The air infiltration was specified for each configuration to account for differences in airtightness between typical and advanced renovation levels. Lower infiltration rates were assigned to the advanced configuration to reflect improved airtightness. The selected values are 0.80 l/s·m² for the typical configuration, which corresponds to an older version of BBR requirements, and 0.60 l/s·m² for the advanced configuration (Bold, 2022).

Regarding the transmission losses, thermal bridge effects were included in the model as aggregated heat loss coefficients for key building junctions. These values were defined in accordance with ISO 14683 and are presented in Table 5, aligning in advance with Miljöbyggnad Ombyggnad 4.0, stating that the losses from the thermal bridges correspond to approximately 30% of all losses in the building, as it is considered a good practice (Sweden Green Building Council, 2025; Swedish Institute for Standards, 2017).

Table 5: Linear thermal transmittance (Ψ -values) for building envelope junctions

Junction type	Ψ -values [W/m ² ·K]
Roof - External Walls	0.40
External Walls - External Walls	0.05
Windows and Doors - External Walls	0.10
Ground Slab - External Walls	0.55
Intermediate Floors - External Walls	0.45

Internal heat gains, occupancy schedules and domestic hot water (DHW) use remained constant for all simulated variations and were defined according to the Sveby standard profiles for residential buildings (Sveby, 2024). These included heat gains from occupants, lighting, and equipment, as well as corresponding daily and weekly schedules. The specific values for the internal gains applied in the simulations are presented in Table 6, occupancy activity level represented by a metabolic rate of 1 Met. Additionally, the occupancy schedule was defined from 17:00 to 07:00 daily, and the schedule for lighting and equipment can be seen in Table 7. The lighting and equipment schedules were based on commonly adopted residential occupancy and usage patterns, intended to represent typical household behaviour throughout the day. The fraction of internal gains to heat was set to 70%.

Table 6: Internal Gains

Internal Gains	Value
Number of Occupants [person]	1.42
Lighting and Equipment Loads [kWh/m ²]	21.0
Domestic Hot Water [kWh/m ²]	21.0

Table 7: Lighting and Equipment Schedule

Daily Schedule	Load Fraction [-]
22:00-06:00 & 7:00-17:00	0.5
6:00-7:00 & 17:00-22:00	1.0

Natural ventilation and shading systems were implemented in the simulation model with predefined operational modes. The same control strategies, described in the following sections, were applied to both roof and façade windows. For natural ventilation modelling, the effective opening area was defined for façade windows as 30% of the maximum relative opening width. For roof windows, which were selected as top-operated centre-pivot type, the opening was set to 30% of the maximum relative opening height.

The shading devices applied to both façade and roof windows were modelled based on the technical characteristics of integrated soft shutters provided by VELUX. Although the application of the same shading system to both window types does not reflect typical construction practice, this assumption was adopted to ensure consistency across all simulation variations. The impact of shading on the thermal transmittance (U-value) and solar heat gain coefficient (g-value) is presented in Table 8.

Table 8: Effect of shading on window thermal and solar properties

Window type	Uw (no shading) [W/m ² K]	Uw (with shading) [W/m ² K]	g (no shading) [%]	g (with shading) [%]
Facade window	1.20	1.06	49.0	4.9
Roof window (30°)	1.30	1.14	49.0	4.9

Both shading and natural ventilation represent passive strategies. However, their performance is influenced by the level of control, ranging from no control and manual operation to smart (automated) control based on environmental and occupancy conditions. Three control levels were defined for both systems: no control, manual control, and smart control. The smart control strategy was based on occupancy, indoor air temperature (Tzone), outdoor air temperature (Tout), incident solar radiation on the window (Gwindow) and CO₂ concentration levels (CO₂), depending on the specific control logic applied. The specifications applied to each control system are described in Table 9.

Table 9: Control strategies for shading and natural ventilation

System	Control mode	Activation conditions
Shading	No control	No shading applied
	Manual	Space occupied AND Tzone > 23°C
	Smart	Tzone > 23°C OR Gwindow > 150 W/m ²
Natural ventilation	No control	Windows remain closed
	Manual	Space occupied AND Tzone > 23°C AND Tout: 14°C < Tout < 31°C
	Smart	Tzone > 23°C AND 14°C < Tout < 31°C OR CO ₂ > 900 ppm AND 14°C < Tout < 31°C

In Study A, both shading and natural ventilation were operated under manual control and were therefore kept constant across all variations. These control levels were subsequently varied in Study B, where they were treated as parameters within the experimental design. All parameters described above were kept constant unless explicitly defined as parameters within a given study.

Mechanical ventilation was modelled as an exhaust-only system with a constant ventilation rate of 0.35 l/s·m², reflecting typical ventilation strategies applied in residential spaces in Sweden (Boverket, 2019). Space heating

was included to maintain indoor thermal conditions at a setpoint of 20 °C and was modelled using an ideal heating system with a coefficient of performance (COP) of 1. This approach ensures that the results reflect the building heating demand independently of system performance, allowing differences to be attributed only to the iterated design variables. The heating system was set to operate only during winter months, specifically from 1st October to 30th April. Mechanical cooling was not applied as it is not a common practice in residential spaces in Sweden.

Daylight performance was evaluated on a horizontal work plane positioned at 0.8 m above floor level, using a grid spacing of 0.5 m and an offset of 0.5 m from surrounding walls. Furniture was not included in the daylight model, as the analysis focuses on envelope-related design parameters. The sill height of facade windows was set to 0.6m, and the roof windows were placed at a ceiling height of 2.6 m. Simulations were performed in IDA ICE using the Radiance engine. Surface reflectance values were defined to represent typical residential conditions and are summarised in Table 10. Additionally, Radiance settings used can be seen in Table 11.

Table 10: Surface properties for daylight simulations

Surface type	Material description	Reflectance, ρ [-]
Ceiling	White painted surface	0.70
Walls	White painted surface	0.70
Floor	Clear oak flooring	0.36
Window Frame	White-painted timber	0.80
Ground (external)	-	0.20

Table 11: Radiance settings

Radiance Parameters	Values
Radiance Preset	High Precision
Ambient Divisions	2048
Ambient Super-samples	1024
Ambient Bounces	7
Ambient Accuracy	0.1

Two sky models were applied depending on the daylight metric: Daylight Factor (DF) was calculated under a standard CIE overcast sky, while Spatial Daylight Autonomy (sDA) was evaluated using a Perez all-weather sky model. Shading devices were not included in the daylight simulations in order to assess daylight availability under unobstructed conditions. The daylight performance metrics used in the analysis are described in detail in the following section.

To represent realistic urban conditions, surrounding buildings with a uniform height of 10 m, equal to that of the reference building, were modelled as shading objects in IDA ICE, as illustrated in Figure 8.

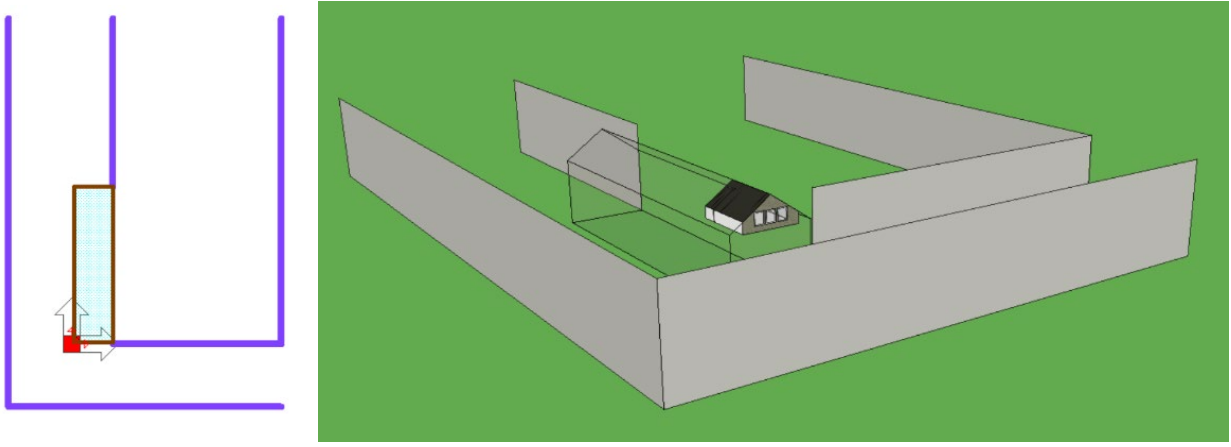


Figure 8: IDA ICE model with surrounding shading objects

3.3.2 Performance Metrics and Evaluation Criteria

The indicators applied in this study for the assessment of energy performance, daylight availability, and thermal comfort are described in detail in this section.

3.3.2.1 Energy Performance

In Sweden, the energy performance of buildings is commonly evaluated using the primary energy number (EP_{pet}), as defined in the building regulations issued by Boverket. This indicator represents the annual primary energy use of a building per unit of heated floor area, accounting for different energy carriers through weighting factors (Boverket, 2017).

However, EP_{pet} is defined at the whole-building level and is primarily used to assess whether a building meets the maximum allowable energy performance requirements defined in the regulations. Since this study focuses on a single attic apartment within a parametric framework, a full building-level representation was not considered, as the objective is to compare the relative impact of design parameters rather than evaluate overall building compliance. Therefore, the EP_{pet} indicator was not applied.

Instead, energy performance was evaluated based on the simulated annual heating energy demand per unit floor area ($kWh/m^2 \cdot year$) of the attic apartment ($46 m^2$). Only heating demand was considered in the comparison, while domestic hot water, lighting, and equipment were kept constant across all variations.

3.3.2.2 Thermal Comfort

Thermal comfort was evaluated using the adaptive comfort model defined in EN 16798-1:2019, which defines acceptable indoor operative temperature ranges for free-running buildings as a function of the running mean outdoor temperature (θ_{rm}) (Swedish Institute for Standards, 2019). In this approach, acceptable indoor operative temperatures are determined as a function of the running mean outdoor temperature. The running mean outdoor temperature is calculated using a weighted average of the daily mean outdoor temperatures of previous days, as seen in Equation 1, where θ_{ed-i} represents the daily mean outdoor temperature of the i -th previous day.

$$\theta_{rm} = \frac{(\theta_{ed-1} + 0.8 \cdot \theta_{ed-2} + 0.6 \cdot \theta_{ed-3} + 0.5 \cdot \theta_{ed-4} + 0.4 \cdot \theta_{ed-5} + 0.3 \cdot \theta_{ed-6} + 0.2 \cdot \theta_{ed-7})}{3.8} [^{\circ}C] \quad (1)$$

Based on θ_{rm} , the neutral (comfort) operative temperature (θ_c) is defined as seen in Equation 2.

$$\theta_c = 0.33 \cdot \theta_{rm} + 18.8 [^{\circ}C] \quad (2)$$

It should also be noted that there are requirements for a day to be assessed using the adaptive comfort model. Firstly, the building should be free-running, meaning that there cannot be a mechanical cooling system in the building. Secondly, the adaptive comfort criteria can be applied outside the winter season, when the heating

systems are active. The definition of heating season in this study is the days between 1st October and 30th April. During these days, the limits presented in Table 12 were applied, which correspond to the heating season limits for residential buildings with mechanical cooling systems, as recommended by the EN 16798-1:2019. Lastly, the adaptive comfort model can be applied only on the days where θ_{rm} is between 10°C and 30°C. Therefore, the days which are not in the heating season, but do not comply with this criterion, were disregarded in the thermal comfort model definition.

Table 12: Comfort Categories in Heating Season (EN 16798-1)

Category	Description	Minimum Temperature
Category I	High level of expectation (sensitive or vulnerable occupants)	21°C
Category II	Normal level of expectation	20°C
Category III	Moderate, acceptable level of comfort	18°C
Category IV	Outside acceptable limits	Outside Category III range

The acceptable indoor operative temperature is defined through a categorisation system consisting of three acceptable comfort categories and a fourth category representing unacceptable conditions. These categories reflect different levels of thermal expectation, with Category I corresponding to a high level of comfort intended for sensitive or vulnerable occupants, Category II representing the normal level of expectation, and Category III indicating a moderate but still acceptable level of comfort.

According to EN 16798-1:2019, the acceptable temperature ranges are defined relative to the neutral operative temperature (θ_c), as shown in Table 13. These category definitions were used for both the current climate file and the future climate file to define the upper and lower limits of comfort. The visual representation of the comfort model can also be seen in Figure 9.

Table 13: Adaptive Comfort Categories in Non-Heating Season (EN 16798-1)

Category	Description	Temperature range
Category I	High level of expectation (sensitive or vulnerable occupants)	$\theta_c + 2^\circ\text{C}$ to $\theta_c - 3^\circ\text{C}$
Category II	Normal level of expectation	$\theta_c + 3^\circ\text{C}$ to $\theta_c - 4^\circ\text{C}$
Category III	Moderate, acceptable level of comfort	$\theta_c + 4^\circ\text{C}$ to $\theta_c - 5^\circ\text{C}$
Category IV	Outside acceptable limits	Outside Category III range

In this study, Category II was adopted as the target comfort level, as it represents a typical level of expectation in building design, while Category I is associated with more stringent requirements for sensitive or vulnerable occupants.

To enable a consistent and comparable assessment of performance, the results were further evaluated using the Active House Specifications (Active House Alliance, 2020). Within this framework, the temperature limits are expressed in a form directly derived from the EN 16798-1 adaptive comfort model, where the upper temperature thresholds are written as a function of the running mean outdoor temperature (θ_{rm}).

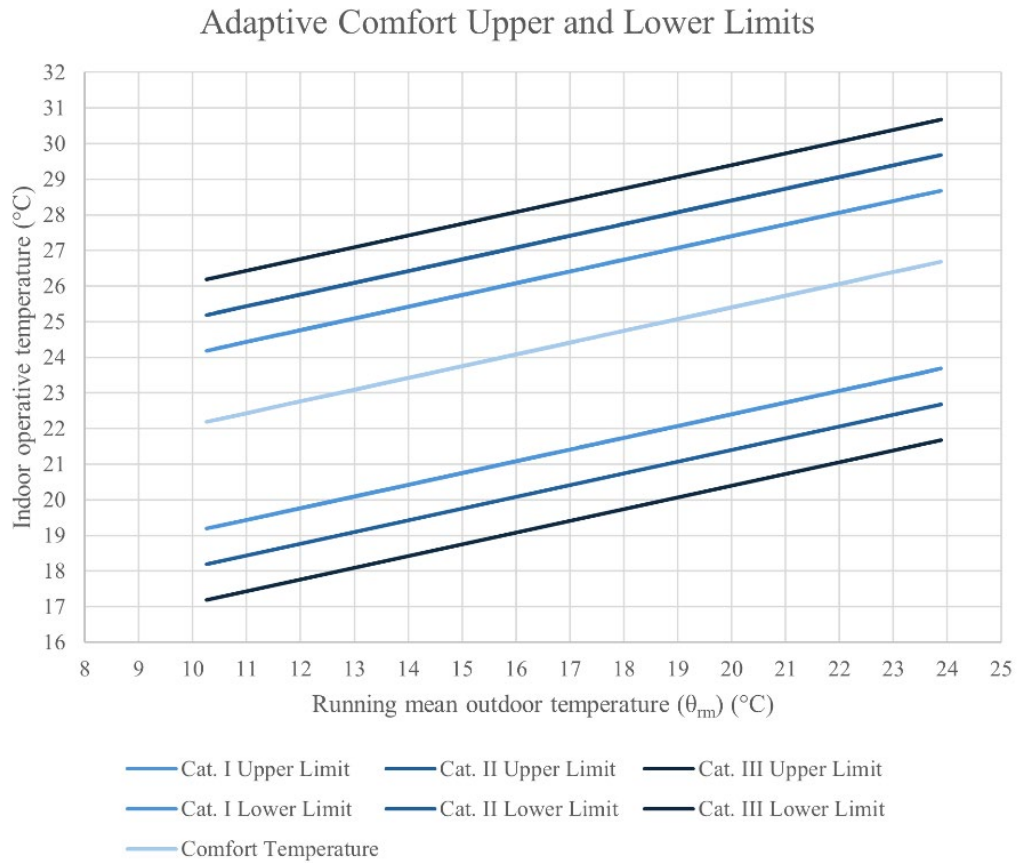


Figure 9: Adaptive comfort upper and lower limits

Hourly indoor operative temperatures were compared against the applicable comfort thresholds and classified according to the corresponding comfort category for each time step. Each eligible hour was then assigned a numerical score based on Table 14, and the overall thermal comfort score was calculated as the annual average of these hourly values.

Table 14: Thermal comfort scoring

Comfort category	Description	Score (per hour)
Category I	Highest comfort level	1
Category II	Target comfort level	2
Category III	Lowest acceptable comfort level	3
Category IV	Unacceptable comfort level	4

The evaluation was performed for all hours throughout the year, excluding days that did not satisfy the applicability criteria of the adaptive comfort model. The resulting score ranges from 1 to 4, where 1 represents the highest comfort level and 4 represents unacceptable conditions. Since Category II is commonly regarded as the target comfort category, a score of 2 was adopted as the benchmark for acceptable thermal comfort performance.

3.3.2.3 Daylight

Due to its more comprehensive assessment framework and detailed daylight performance criteria, SS-EN 17037:2018+A1:2021 was selected as the primary benchmark for daylight evaluation in this study. Two daylight metrics were applied to evaluate the performance of retrofit strategies related to window configuration and building orientation, in accordance with the European Standards (Swedish Institute for Standards, 2021).

Daylight provision was assessed using a climate-based illuminance method defined in the standard, using annual simulations under the Perez all-weather sky model. According to EN 17037, daylight provision is verified by assessing whether specified illuminance thresholds are achieved over a given proportion of the floor area for at least 50% of daylight hours (SS-EN 17037:2018+A1:2021). Following EN17037, a target level of 300 lux over at least 50% of the floor area and a minimum level of 100 lux over at least 95% of the area were considered. These criteria were evaluated using sDA, specifically sDA300/50% and sDA100/95%, which quantify the percentage of floor area receiving at least the specified illuminance level for at least 50% of the daylight hours.

In addition, the daylight factor method was applied as a simplified, static approach under a standard CIE overcast sky. In EN 17037, the target daylight factor (D_t) is defined as the DF value required to achieve a given indoor illuminance level over at least 50% of the reference plane for more than half of daylight hours (SS-EN 17037:2018+A1:2021). This value is derived by relating the target indoor illuminance to the median diffuse outdoor illuminance ($E_{v,d,med}$). For the studied location, where $E_{v,d,med}$ is 12100 lux, the target illuminance of 300 lux corresponds to a daylight factor of 2.5%, calculated using Equation 3.

$$DF = (E_{target}/E_{v,d,med}) \cdot 100 [\%] \quad (3)$$

Accordingly, a DF threshold of 2.5% was adopted as the target daylight provision level, corresponding to achieving 300 lux over at least 50% of the floor area. While the standard also defines a minimum threshold of 0.8% (corresponding to 100 lux over 95% of the area), only the target level was considered in the DF-based evaluation, as the compliance with the targets was already checked using the illuminance level method, using the sDA values. Therefore, DF was used only as an additional analysis metric in this study.

DF values were calculated at each grid point, and the DF median was used as a representative indicator of performance, as it corresponds to the value exceeded by 50% of the analysed area. The analysis was conducted for the main living area of the attic space, excluding the bathroom, as it is not considered a regularly occupied space.

3.3.3 Description of Parametric Studies

The following studies apply the defined simulation setup and performance indicators to evaluate the impact of design and operational parameters on the performance of attic retrofit strategies.

3.3.3.1 Study A: Window Configuration and Orientation

Study A investigated the influence of geometric design parameters on thermal comfort, daylight availability, and energy performance in the developed attic model. The analysis focused on window configuration, specifically the number of roof windows and façade windows, as well as building orientation, which were systematically varied using a multi-level full factorial design to evaluate their individual effects and interactions, as described in the previous sections.

The study was conducted within two renovation contexts, named typical and advanced, representing different envelope structures. These contexts differed in the thermal properties of the external wall and the roofs, but were not treated as parameters within the factorial design. Instead, the influence of the geometric design parameters was evaluated separately within each renovation context.

The design parameters considered in Study A included the number of roof and façade windows, as well as the building orientation. The number of façade windows (FW) varied between 0 and 3, while the number of roof windows (RW) also varied between 0 and 3. Façade windows followed the building orientation, whereas roof

windows were aligned with the roof slope and therefore faced different directions, as presented in Figure 10. In addition, these geometrical variations were tested in all four orientations, namely north, south, east, and west.

All parameters were fully crossed, such that each configuration of one parameter was combined with all configurations of the others. This resulted in a complete enumeration of all possible geometric variations for each renovation context. In total, 60 variations were generated per renovation context, disregarding the ones with no roof or façade windows from each orientation, resulting in 120 simulation variations.

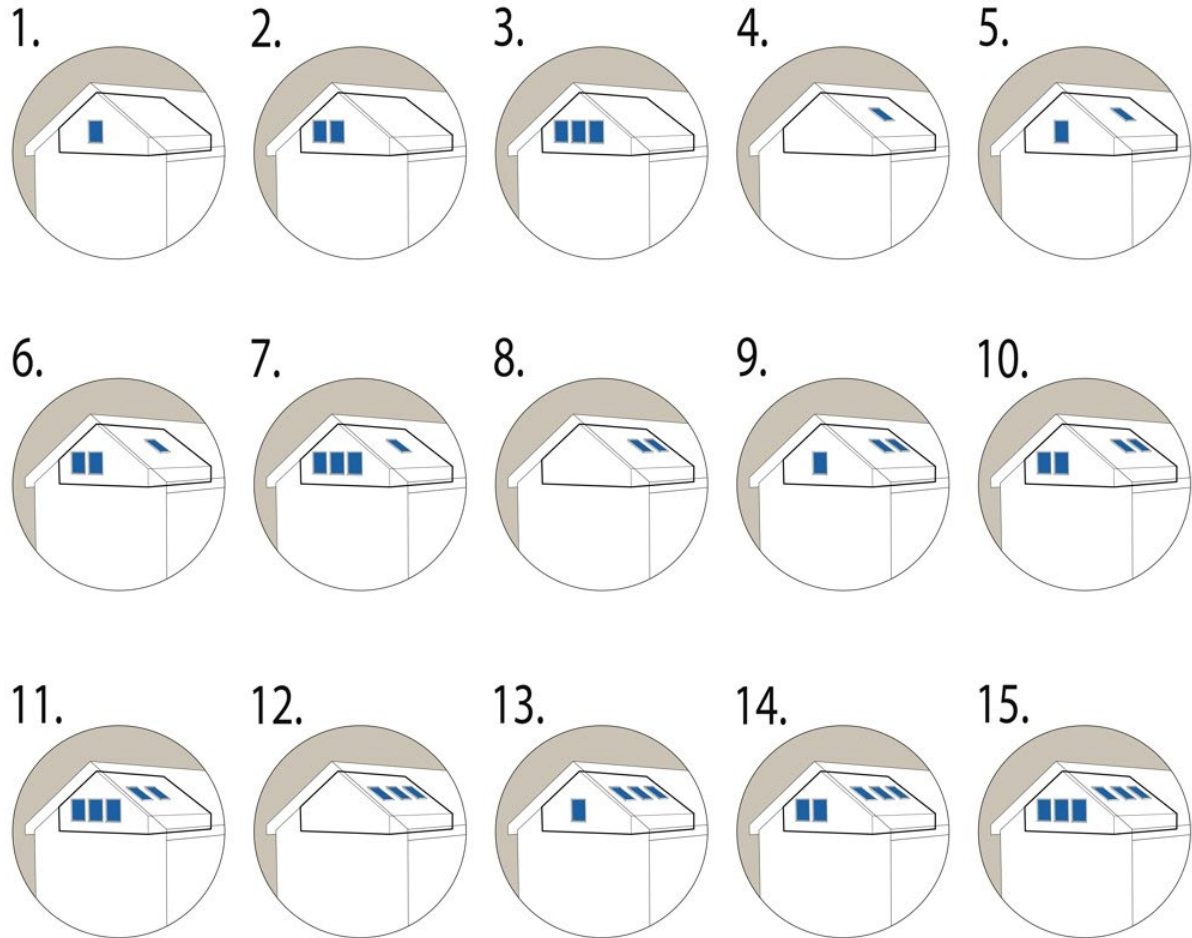


Figure 10: Variation of window configurations in Study A

The following parameters were kept constant across all variations in Study A: internal loads and occupancy schedules, natural ventilation strategy, shading configuration, and envelope properties within each renovation context. In Study A, both shading and natural ventilation were assumed to operate under manual control as described, based on predefined user-driven actions rather than automated control strategies.

Following the completion of Study A, critical variations were selected to be further evaluated in terms of shading and natural ventilation control strategies in Study B. During the selection of variations, the ones with the highest overheating results were chosen, in order to provide conditions where the effects of the control strategies can be the most measurable. Specifically, both shading and natural ventilation controls were expected to primarily affect thermal comfort performance, while having minimal influence on daylight provision and energy demand. Therefore, thermal comfort was selected as the main focus for critical variation selection. This selection process can be seen in Figure 11.

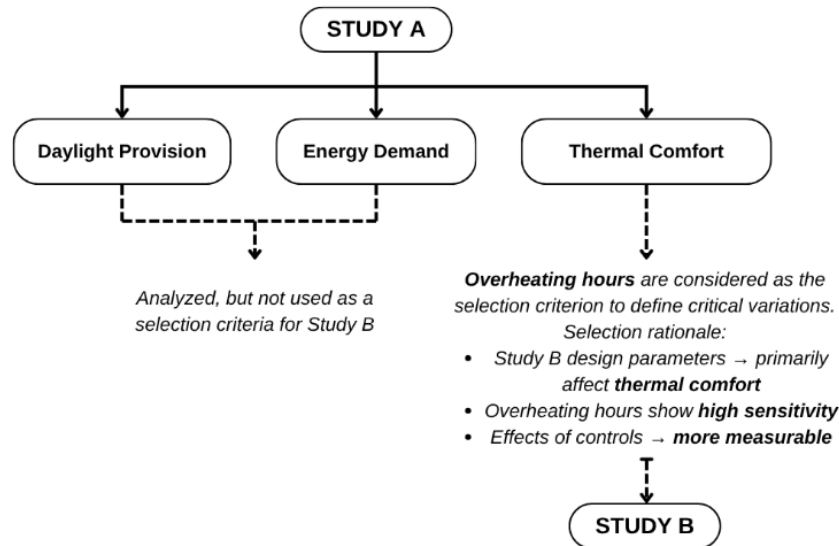


Figure 11: Critical variation selection process

3.3.3.2 Study B: Shading and Natural Ventilation Strategies

Study B investigated the influence of operational strategies on thermal comfort, focusing on shading and natural ventilation controls on roof and facade windows. In this study, shading and natural ventilation were treated as the varied design parameters of the parametric study, while all geometric characteristics, including window configuration and orientation, as well as envelope properties, remained fixed. Three shading control levels were considered, including no shading, manual control, and smart control. Similarly, three natural ventilation control levels were evaluated, including no natural ventilation, manual control, and smart control. All combinations of these strategies were systematically explored, resulting in a complete set of 81 operational variations for each renovation context, as seen in Figure 12.

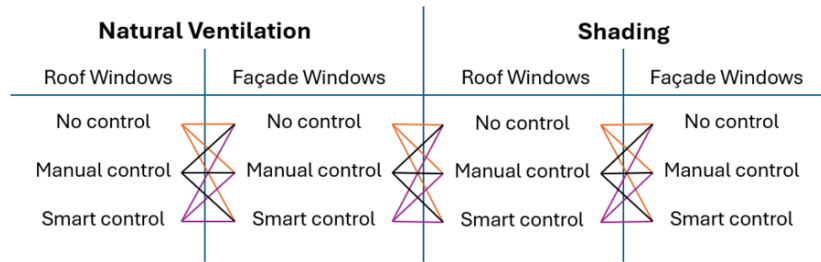


Figure 12: Natural ventilation and shading control strategies investigated in Study B

Each variation was simulated to assess the effects and interactions of shading and natural ventilation on thermal comfort. Based on the results, critical variations were selected to be further evaluated in future climate conditions. The variations were selected to have a set of representative control strategies to be able to evaluate their sensitivity to the future climate. These variations were chosen to represent the full range of control levels, from no control to fully smart control, enabling a direct comparison between shading and natural ventilation strategies and an analysis of the robustness of control levels.

3.3.3.3 Study C: Future Climate Conditions

Study C evaluated selected variations under future climate conditions to examine how their thermal comfort performance changed compared to present conditions. In this study, all design and operational parameters remained unchanged, and only the climate data were modified.

First, an analysis was conducted on the created future climate file that corresponds to the predicted 2050 climate under the SSP2-4.5 scenario. This analysis included changes in temperature and natural ventilation potential. Natural ventilation potential was defined as the number of hours during which ventilation controls could be activated, based on outdoor temperature criteria ($14^{\circ}\text{C} < T_{\text{out}} < 31^{\circ}\text{C}$).

The selected variations were simulated, and the results were analysed to assess the impact of future climate conditions on thermal comfort and the effectiveness of shading and natural ventilation controls. Each variation was compared under both current and future climate scenarios, and between variations, to inform design insights for future performance.

3.4 Post-Processing of Simulation Data

The simulation outputs from IDA ICE were exported and post-processed using Microsoft Excel and statistical analysis tools. For all studies (A, B, and C), the simulation results were first organised and processed in Microsoft Excel. The performance indicators used in the study, including heating annual energy demand, daylight metrics, overheating hours, and thermal comfort scores, were derived from the simulation outputs. Microsoft Excel was also used to structure the datasets and generate part of the graphs used in the analysis. However, the majority of the graphs were created using IBM SPSS Statistics, while Matplotlib in the Python environment was used to analyse future climate data in Study C.

In Study A, a multiple linear regression analysis was selectively applied using IBM SPSS Statistics to further quantify the relative influence of the design parameters on the selected performance indicators. Regression analysis is used to examine how variations in independent variables influence a dependent variable (Montgomery, 2022).

To ensure the reliability of the regression model, multicollinearity between the independent variables was assessed using the Variance Inflation Factor (VIF). The VIF quantifies how much the variance of regression coefficients is increased due to correlations between variables. A VIF value equal to 1 indicates that there is no correlation between a variable and the other variables (Penn State, 2018). Due to the full factorial design of Study A, all parameters were varied independently across the simulated variations, and therefore, low levels of multicollinearity were expected.

To evaluate the performance of the regression models, the coefficient of determination (R^2) and adjusted R^2 values were considered. These metrics indicate the proportion of variance in the dependent variable explained by the independent variables, with adjusted R^2 accounting for the number of predictors in the model. This provides a more reliable measure of model fit when comparing models with multiple variables, allowing the comparison of the explanatory powers of the models (Weisberg, 2014).

In this regression analysis, the number of façade windows, the number of roof windows, and the building orientation represented the independent variables, while the dependent variables included the selected performance indicators. The results were interpreted using standardised regression coefficients (β values) and p-values. The β values indicate the relative influence of each design parameter, allowing direct comparison of their importance, while p-values were used to assess statistical significance, with a threshold of $p < 0.05$ adopted, as it is commonly used in statistical analysis to identify significant effects (Nieminen, 2022).

4 Results

4.1 Study A: Window Configuration and Orientation

Study A results are presented across three performance categories: energy demand, thermal comfort, and daylight provision. Within each category, the influence of the design variables (number of façade windows, number of roof windows, and orientation) is reflected in the distribution of performance outcomes across 60 design variations for each renovation context. The definition of each simulated variation can be found in Appendix A, while the full results of Study A are presented in Appendix B, Appendix C, and Appendix D for heating energy demand, thermal comfort, and daylight performance, respectively.

Variance inflation factor (VIF) values ranged between 1 and 1.02 across all models, indicating negligible multicollinearity among the design variables.

4.1.1 Heating Energy Demand

The distribution of heating energy demand was analysed as a function of façade window configurations across both renovation contexts, as shown in Figure 13. Each boxplot aggregates results across all tested orientations and roof window configurations. Heating energy demand generally increased with a higher number of façade windows. In addition, the performance range widened while the number of facade windows was increased, indicating greater variation in energy demand for variations with more façade windows. Across all façade window configurations, variations in the advanced renovation context consistently exhibited lower heating energy demand than those in the typical context.

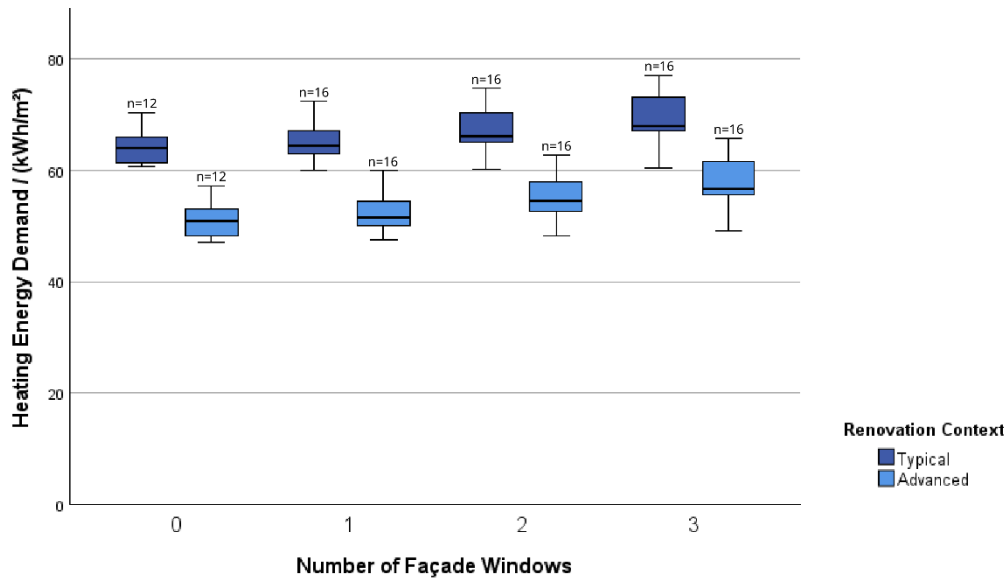


Figure 13: Distribution of heating energy demand by façade window configuration

A similar analysis was conducted for the roof windows, as shown in Figure 14, where heating energy demand is examined in relation to the number of roof windows for both renovation contexts. Each boxplot represents the distribution of results across all tested façade window configurations and orientations. The results follow trends comparable to those observed for the number of façade windows as a design parameter, with both heating energy demand and the spread of results increasing as the number of roof windows increases. Across all roof window configurations, variations in the advanced renovation context consistently exhibited lower heating energy demand than those in the typical context.

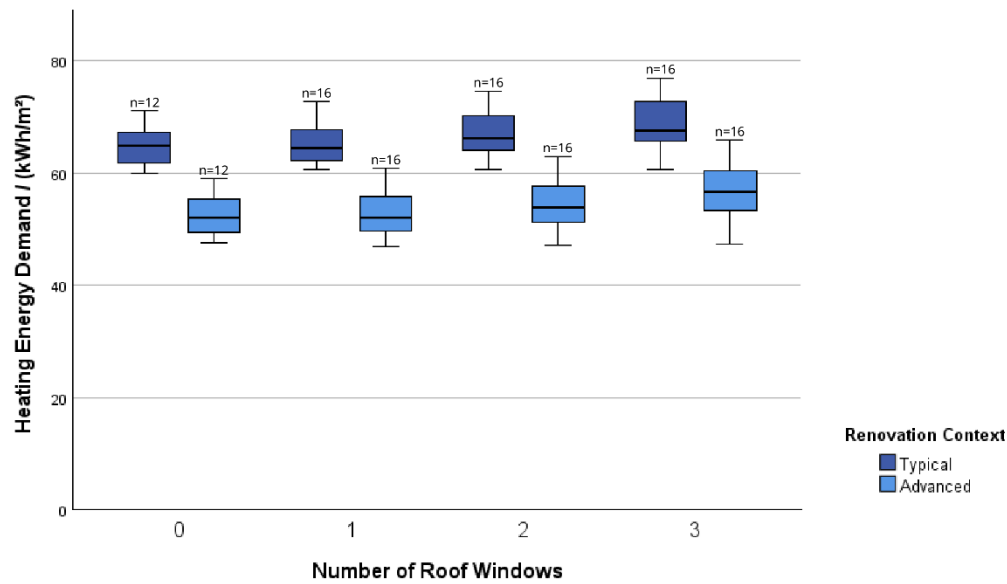


Figure 14: Distribution of heating energy demand by roof window configuration

The distribution of heating energy demand was also analysed with respect to orientation, as shown in Figure 15, where results are grouped by orientation for both renovation contexts. Each distribution reflects the range of outcomes across all tested façade and roof window configurations. Variations in both median heating energy demand and the spread of results were observed between orientations. The set of variations with façade windows facing east and north, and roof windows facing north and west, exhibited higher heating energy demand and wider performance ranges. Across all orientations, the variations included in the advanced renovation context consistently resulted in lower heating energy demand, in line with the trends observed for the other parameters.

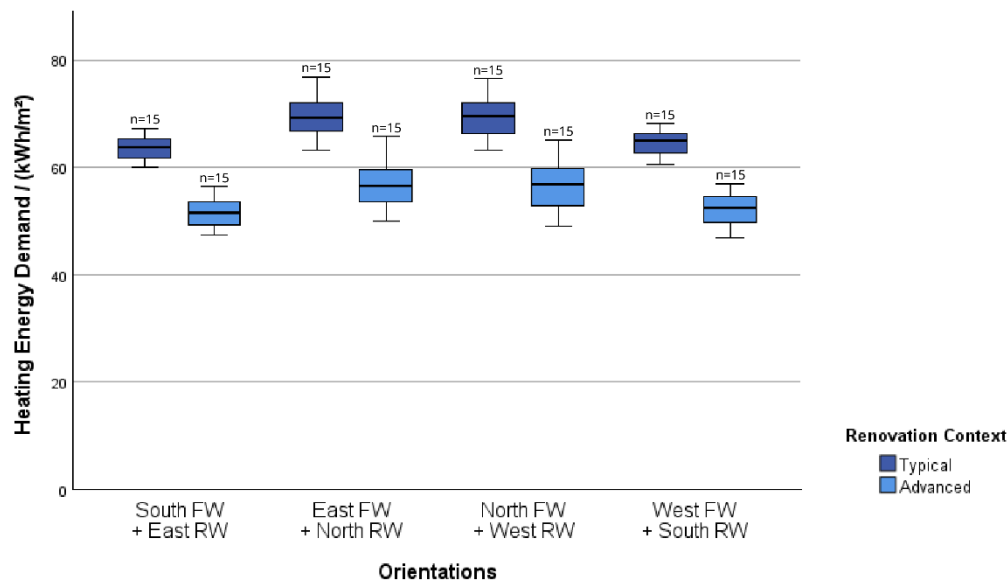


Figure 15: Distribution of heating energy demand by orientation

Finally, the relative influence of the design parameters on energy performance was evaluated using regression analysis, as shown in Figure 16. The analysis was based on heating energy demand, with the number of façade windows, the number of roof windows, and orientation as predictors.

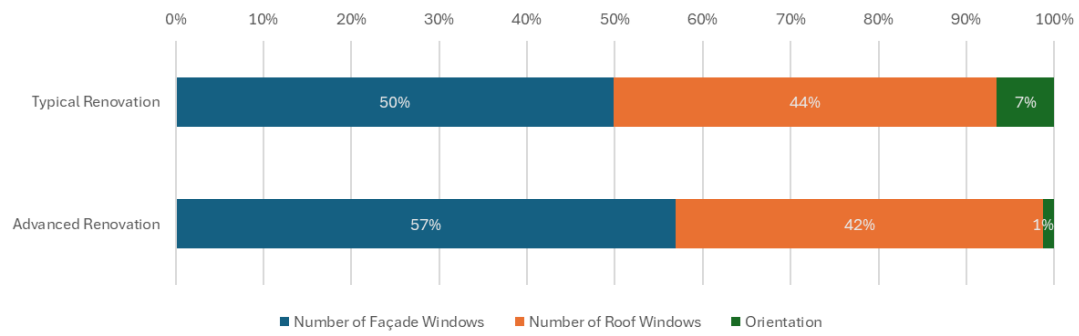


Figure 16: Relative influence of design parameters on heating energy demand

The results indicate that the number of roof and façade windows accounts for the majority of the variation in heating energy demand across both renovation contexts. The model achieved an adjusted R^2 of 0.39 for the typical renovation context and 0.53 for the advanced renovation context. Both values fall within a moderate range, with the advanced renovation context showing a somewhat higher degree of explained variation.

Table 15 presents the regression results, including standardised β coefficients and p-values. For heating energy demand, the number of façade and roof windows had a significantly stronger influence than orientation in both renovation contexts. However, the extent of their impact varies between the two contexts.

Table 15: Regression Results for Heating Energy Demand

	Typical Renovation		Advanced Renovation	
	β Value	p-value	β Value	p-value
Number of Façade Windows	0.523	0.000	0.643	0.000
Number of Roof Windows	0.458	0.000	0.473	0.000
Orientation	0.069	0.500	0.014	0.874

Overall, the results indicated that glazing-related parameters, particularly the number of roof windows, were the primary drivers of heating energy demand, while orientation had a limited influence. Additionally, advanced renovation consistently resulted in lower heating energy demand across all variations.

4.1.2 Thermal Comfort

Thermal comfort results for Study A are presented using annual overheating hours and a thermal comfort score, derived from the EN 16798-1 adaptive comfort model and Active House specifications.

The distribution of annual overheating hours across façade window configurations is shown in Figure 17, where results are grouped by the number of façade windows for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested orientations and roof window configurations. A clear increasing trend is observed, with overheating hours rising as the number of façade windows increases. The spread of results also widens for a higher number of windows, indicating greater sensitivity to other design parameters. Differences between the renovation contexts are evident, with the variations in the advanced context generally exhibiting a higher overheating risk than those in the typical context.

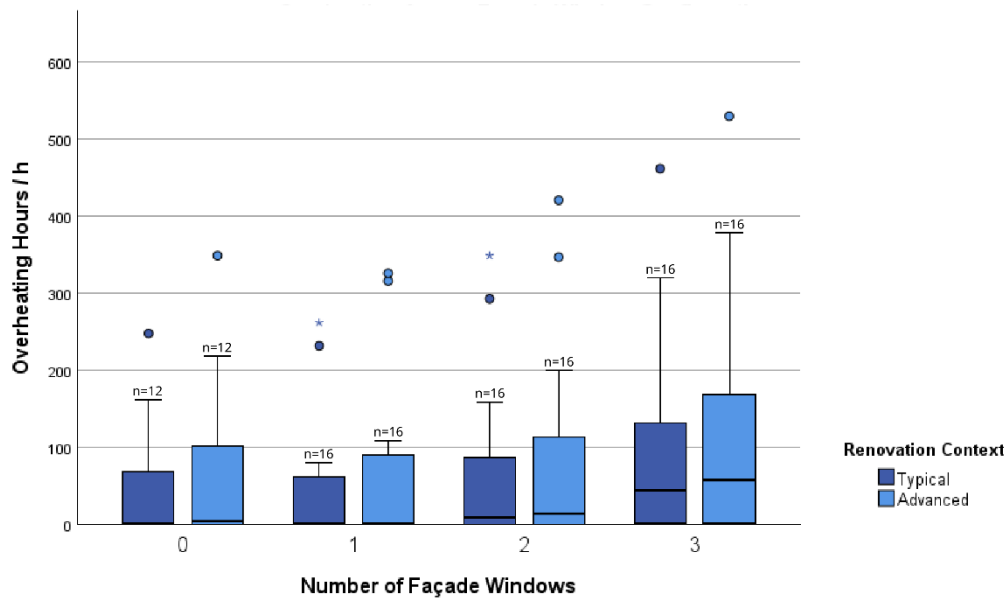


Figure 17: Distribution of overheating hours by facade window configuration

The distribution of overheating hours in relation to roof window number is shown in Figure 18, where results are grouped by roof window configurations for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested façade window configurations and orientations. Overheating hours show a steeper upward trend with an increasing number of roof windows compared to façade windows. In addition, the spread of results widens for a higher number of roof windows, indicating a greater influence of other design parameters under these conditions. Higher numbers of roof windows are also associated with extreme overheating cases, with extreme values (upper range of the distribution) exceeding 400 hours. Similar to the trends observed for façade windows, the variations in the advanced renovation context consistently exhibit higher overheating risk across all roof window configurations.

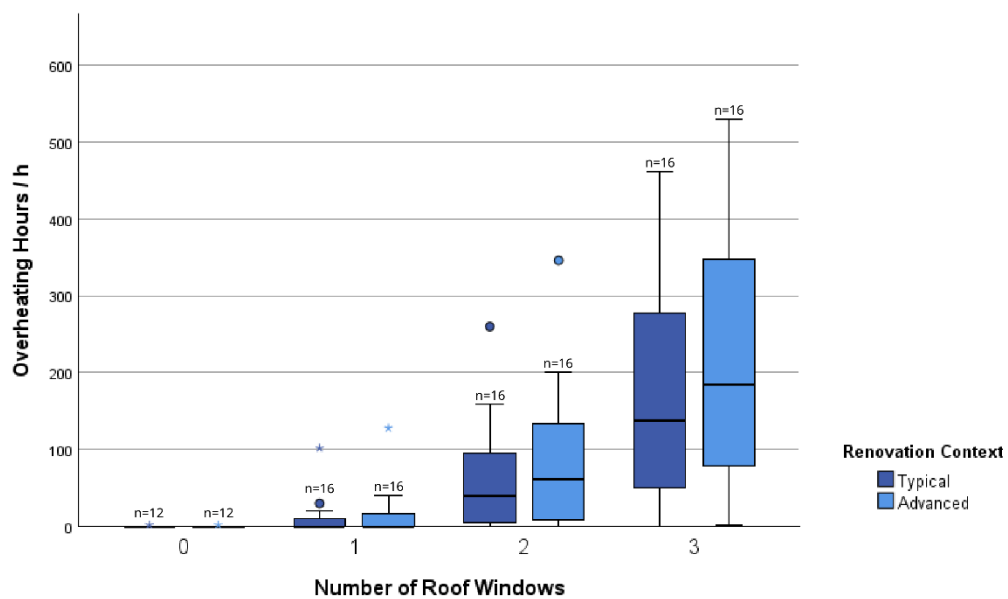


Figure 18: Distribution of overheating hours by roof window configuration

The distribution of overheating hours across orientations is shown in Figure 19, where results are grouped by orientation for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested

façade and roof window configurations. Clear differences in overheating performance are observed between orientations. In particular, higher overheating risk is associated with variations featuring façade windows facing south and roof windows facing east, as well as façade windows facing west and roof windows facing south. The spread of results follows a similar pattern across orientations, with wider distributions indicating a greater influence of other design parameters under certain orientation combinations. Across all orientations, the variations in the advanced renovation context consistently exhibit higher overheating hours.

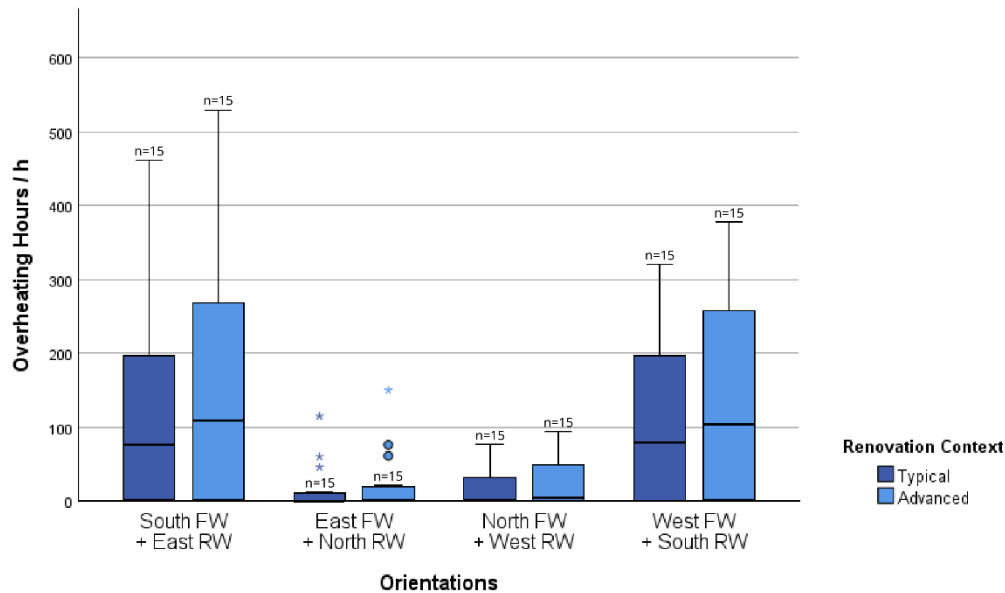


Figure 19: Distribution of overheating hours by orientation

Finally, the relative influence of the design parameters on overheating hours is presented in Figure 20. The results show that the number of roof windows accounts for the largest share of variation, followed by the number of façade windows, while orientation has only a minor effect. This pattern is consistent across both the typical and advanced renovation contexts. The regression model yields an adjusted R^2 of 0.42 for the typical renovation and 0.43 for the advanced renovation, indicating moderate explanatory power in both renovation contexts.

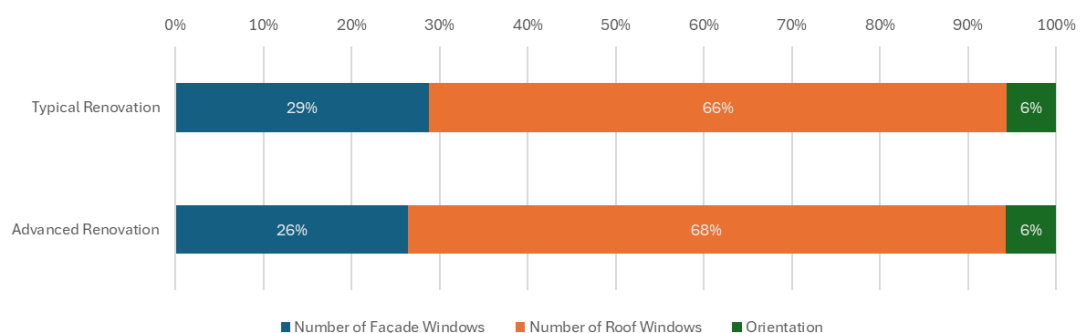


Figure 20: Relative influence of design parameters on overheating

Table 16 presents the results of the regression analysis, including the standardised β coefficients and p-values. These findings confirm that glazing-related design parameters are the primary drivers of thermal comfort performance, while orientation contributes to variability between specific design combinations rather than exhibiting a consistent overall trend.

Table 16: Regression Results for Overheating Hours

	Typical Renovation		Advanced Renovation	
	β Value	p-value	β Value	p-value
Number of Façade Windows	0.282	0.007	0.256	0.013
Number of Roof Windows	0.644	0.000	0.657	0.000
Orientation	-0.055	0.583	-0.056	0.573

Following the analysis of overheating hours, thermal comfort performance was further evaluated using the thermal comfort score. The distribution of the score across the number of façade windows is shown in Figure 21, where results are grouped by façade window configurations for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested orientations and roof window configurations. Only minor differences are observed between façade window configurations, with the overall variation in results remaining limited. A clearer distinction, however, emerges between the renovation contexts. In contrast to the overheating hours results, the variations in the advanced renovation context generally demonstrate improved thermal comfort, as indicated by lower scores.

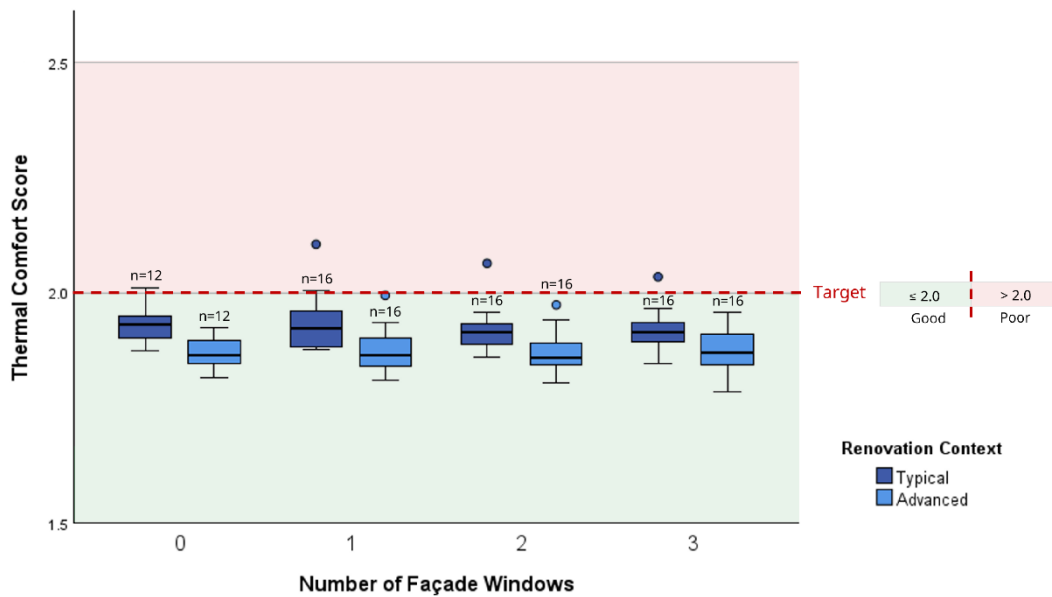


Figure 21: Distribution of thermal comfort score by facade window configuration

A comparable pattern is observed in roof window configurations, as shown in Figure 22, where each distribution includes all façade window configurations and orientations. As with façade windows, the overall variation in thermal comfort score remains relatively small, indicating limited sensitivity to the tested design parameters. However, the influence of the number of roof windows is slightly more pronounced, with fewer roof windows generally associated with higher thermal discomfort. Consistent with the previous results, the variations within the advanced renovation context exhibit better thermal comfort performance across all roof window configurations.

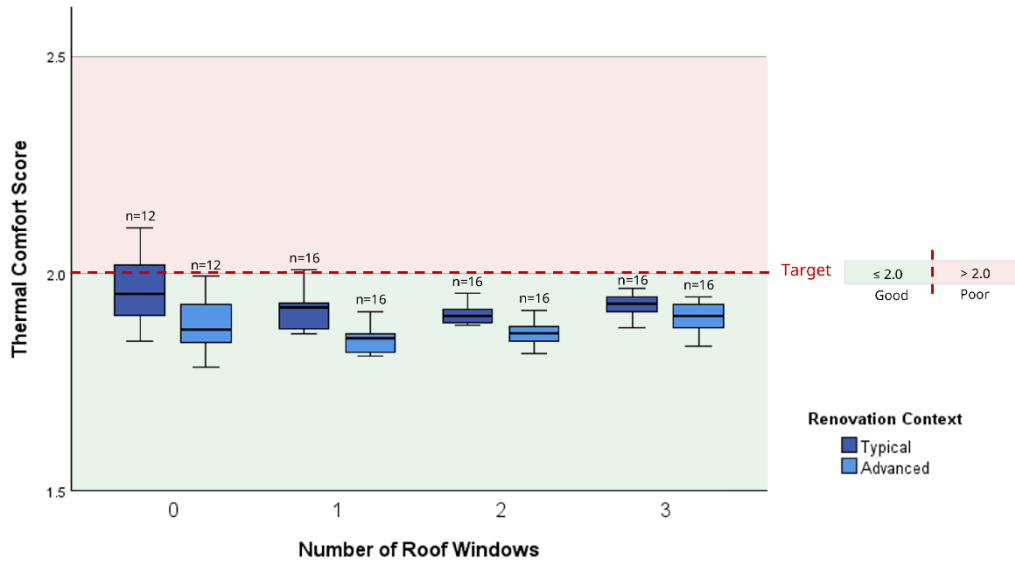


Figure 22: Distribution of thermal comfort score by roof window configuration

The distribution of thermal comfort score across orientations is shown in Figure 23, where results are grouped by orientation for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested façade and roof window configurations. Overall, only limited variation is observed between orientations. While certain orientations exhibit slightly lower scores and a slightly wider spread, the overall impact of orientation on thermal comfort score remains small. Consistent with previous findings, the variations within the advanced renovation context demonstrate improved thermal comfort performance across all orientations.

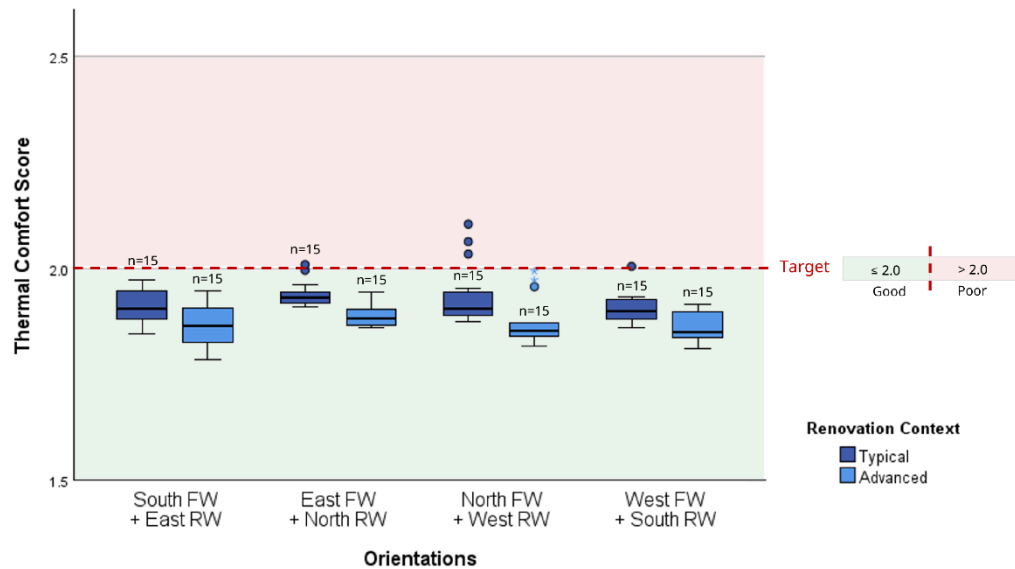


Figure 23: Distribution of thermal comfort score by orientation

The relative influence of design parameters on thermal comfort score was further analysed through regression analysis, as seen in Figure 24. The results indicated that the number of roof windows contributed the most to the variation, while the orientation played a bigger role compared to the overheating analysis, even surpassing the number of façade windows in the advanced renovation context. However, the explanatory power of the model is low, with an adjusted R^2 of 0.03 for the typical renovation and 0.002 for the advanced renovation. These results suggest that the variation in thermal comfort score is not well explained by the investigated design parameters alone.

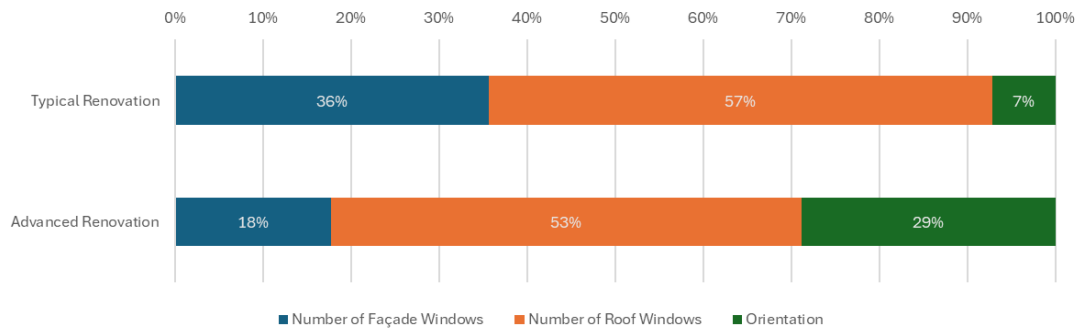


Figure 24: Relative influence of design parameters on thermal comfort score

Table 17 presents the results of the regression analysis, including the standardised β coefficients and p-values. The findings indicate that the design parameters do not exhibit a statistically significant effect on the thermal comfort score. This contrasts with the overheating hours analysis, which showed a clear sensitivity to glazing-related design parameters.

Table 17: Regression Results for Thermal Score

	Typical Renovation		Advanced Renovation	
	β Value	p-value	β Value	p-value
Number of Façade Windows	-0.154	0.240	0.067	0.612
Number of Roof Windows	-0.248	0.061	0.201	0.131
Orientation	-0.031	0.811	-0.109	0.406

Overall, the results showed that overheating hours were strongly influenced by glazing-related parameters, particularly roof windows, while orientation played a minor role. In contrast, the thermal comfort score exhibited limited sensitivity to these parameters, highlighting a clear difference between the two comfort indicators. Additionally, the overheating hours analysis showed that variations within the advanced renovation context resulted in higher overheating hours, while the thermal comfort score analysis indicated lower thermal comfort scores for the same variations, suggesting an overall improvement in comfort levels.

4.1.3 Daylight Provision

Daylight performance was assessed using sDA300/50%, sDA100/95%, and median daylight factor (DF). However, only sDA300/50% and DF are presented in the main analysis, as the results in Appendix D indicate that variations meeting the 300 lux threshold also consistently satisfied the 100 lux requirement. Therefore, sDA300/50% was considered sufficient to represent daylight performance in the subsequent analysis.

The distribution of sDA300/50% across façade window configurations is shown in Figure 25, where results are grouped by façade window configurations for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested orientations and roof window configurations. An overall increasing trend is observed, with daylight availability improving as the number of façade windows increases. The spread of results also widens for a higher number of façade windows, indicating a greater influence of other design parameters on daylight performance under these conditions. Across all façade window configurations, the variations in the advanced renovation context consistently exhibit lower daylight performance.

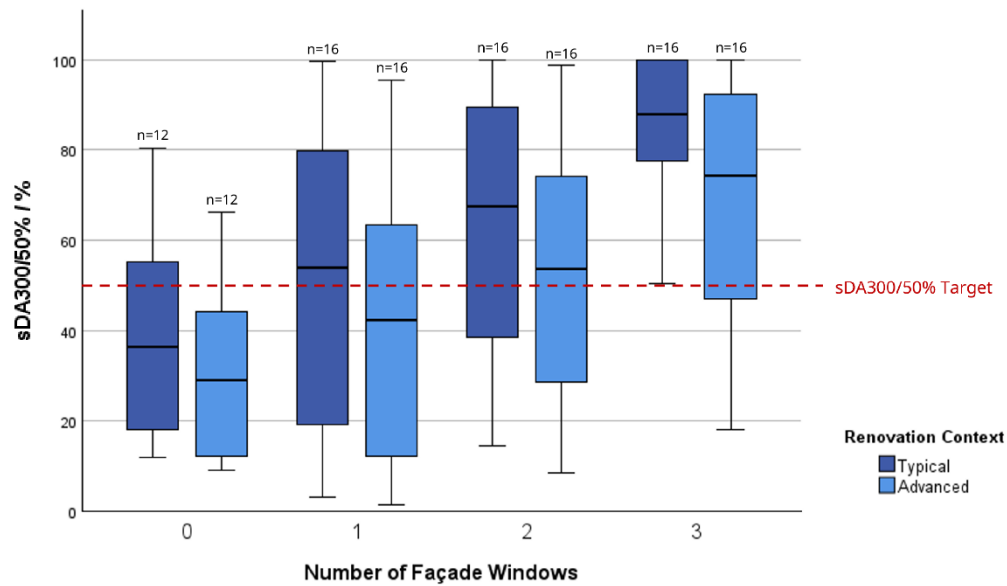


Figure 25: Distribution of sDA300/50% by facade window configuration

The distribution of sDA300/50% values across roof window configurations is shown in Figure 26, where results are grouped by roof window number for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested façade window configurations and orientations. An increasing trend is observed, with higher sDA300/50% values as the number of roof windows increases. The spread of results also widens for a higher number of roof windows, indicating a greater influence of other design parameters on daylight performance under these conditions. This increase is more pronounced compared to that observed for façade windows. Across all configurations, the variations with the advanced renovation context consistently exhibit lower sDA300/50% values than those within the typical context.

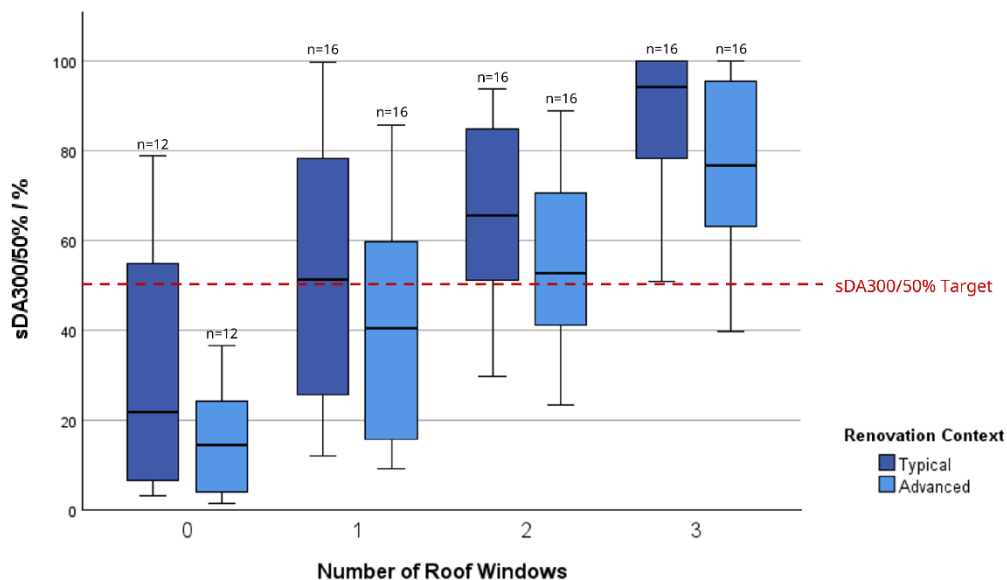


Figure 26: Distribution of sDA300/50% by roof window configuration

In terms of the effect of orientation on sDA300/50% values, variations were observed across different orientations, as seen in Figure 27. However, the resulting trend was less systematic compared to the design parameter of the window configuration. Additionally, the variations within performance ranges were smaller

between different orientations. As with the analysis of façade and roof windows, the orientation analysis showed that variations within the typical renovation context perform better than those in the advanced context.

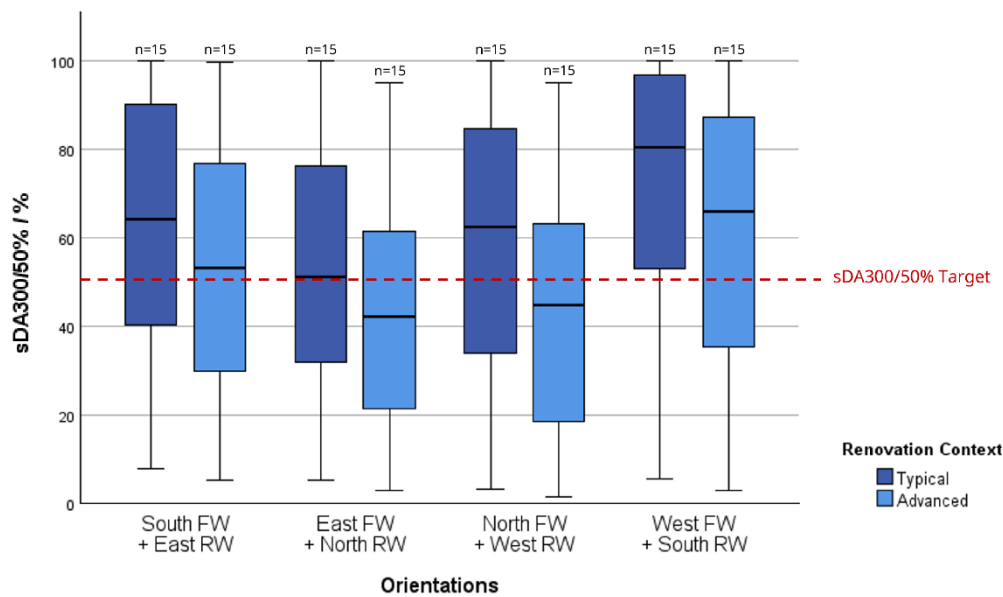


Figure 27: Distribution of sDA300/50% by orientation

Finally, the relative effect of design parameters on daylight performance was analysed using a regression modelling method, which can be seen in Figure 28. The results show that the number of roof windows accounted for the highest variation across all daylight performance metrics, which was followed by the number of façade windows, while the orientation had a lower impact. These trends were consistent between the different renovation contexts. This regression model had an adjusted R^2 value of 0.85 for the typical renovation context and 0.89 for the advanced renovation context, indicating a high explanatory power.

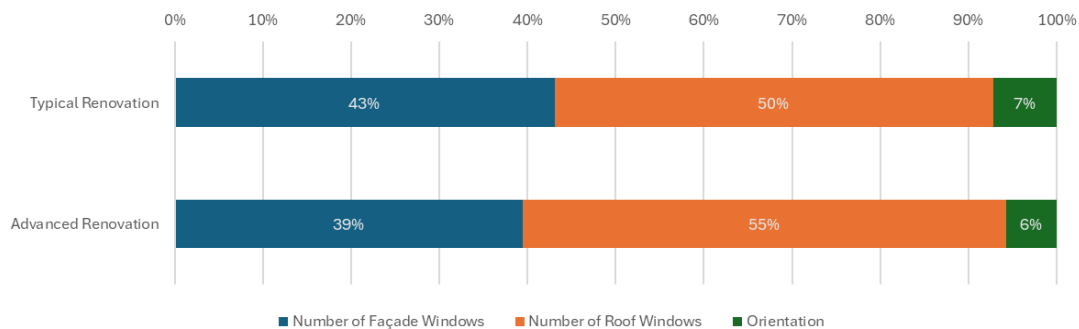


Figure 28: Relative influence of design parameters on sDA300/50%

Table 18 presents the results of the regression analysis, including standardised β coefficients and p-values. The findings indicate that the number of façade and roof windows is the primary driver of daylight performance metrics, demonstrating consistently high impact alongside low p-values across different metrics and renovation contexts. In contrast, building orientation exhibited a comparatively smaller effect. Although its influence was statistically significant, particularly within the typical renovation context, its overall contribution to variations in daylight provision remained limited when compared to glazing-related parameters.

Table 18: Regression Results for sDA300/50%

	Typical Renovation		Advanced Renovation	
	β Value	p-value	β Value	p-value
Number of Façade Windows	0.649	0.000	0.589	0.000
Number of Roof Windows	0.748	0.000	0.818	0.000
Orientation	0.108	0.035	0.085	0.057

In addition to the sDA300/50% analysis, daylight provision was further examined using the median daylight factor (DF). As DF is independent of orientation, no orientation-based distribution is presented for this metric.

The distribution of DF median values across façade window configurations is shown in Figure 29, where results are grouped by the number of façade windows for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested roof window configurations. A clear upward trend is observed, with higher DF median values as the number of façade windows increases. The spread of results also widens for a higher number of façade windows, indicating a greater influence of roof window configurations under these conditions. Across all façade window configurations, the ones within the advanced renovation context generally exhibit lower DF median values.

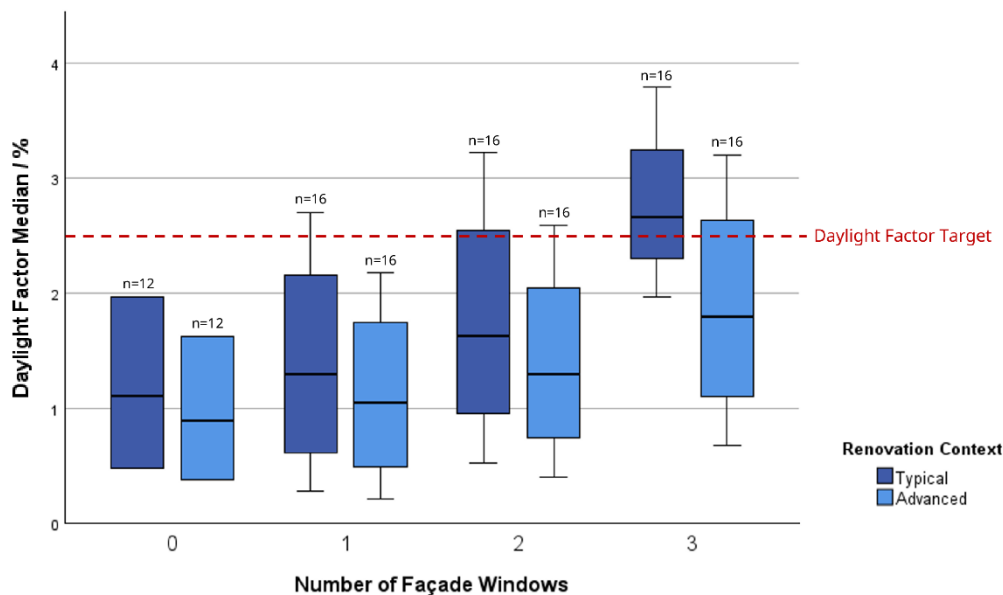


Figure 29: Distribution of DF median by facade window configuration

The distribution of DF median values across roof window configurations is shown in Figure 30, where results are grouped by roof window number for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested façade window configurations. A trend similar to that observed for façade windows is evident, with DF median values increasing as the number of roof windows rises. The spread of results also widens for a higher number of roof windows, indicating a greater influence of façade window configurations under these conditions. This increase is more pronounced compared to that observed for façade windows. Consistent with the previous daylight metrics, the variations in the advanced renovation context systematically exhibit lower DF median values.

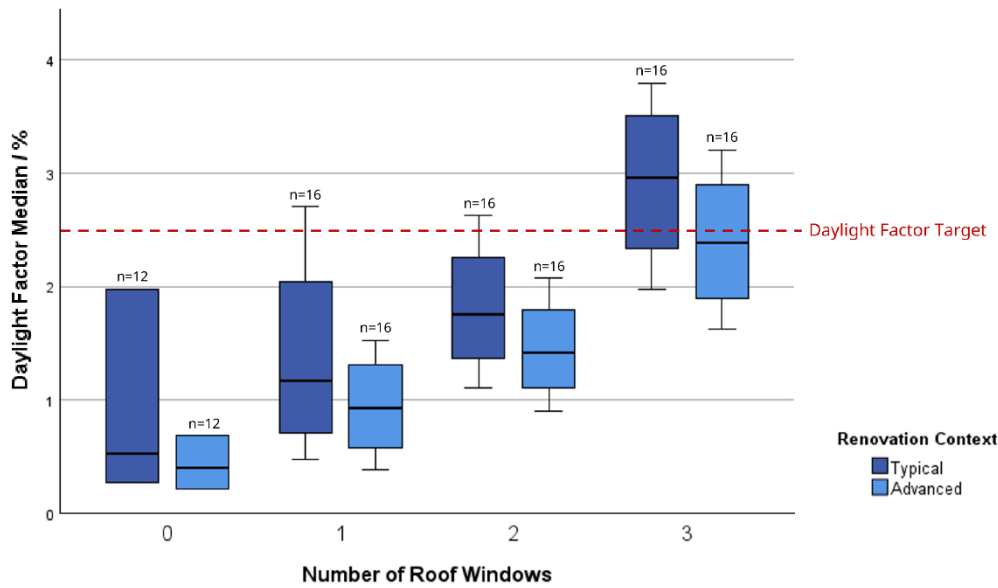


Figure 30: Distribution of DF median by roof window configuration

The assessment results for both sDA300/50% and DF median across the roof façade window configurations indicate that a greater number of variations meet the sDA300/50% performance target than the median DF target.

The relative influence of design parameters on DF median results was further examined using regression analysis, as presented in Figure 31. The results indicate that the number of roof windows as a design parameter had the strongest impact on DF, followed by façade windows. Orientation had no effect, in line with the technical definition of the metric. The regression model showed a high explanatory power, as it had an adjusted R^2 value of 0.93 for the typical renovation context and 0.97 for the advanced renovation context.

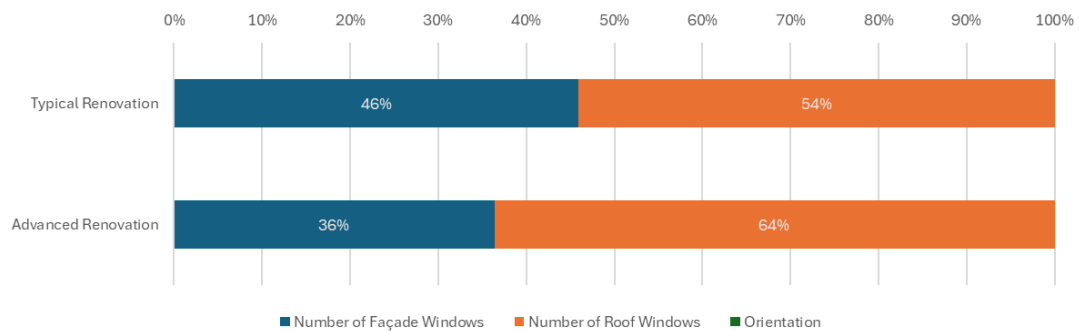


Figure 31: Relative influence of design parameters on DF median

Table 19 presents the results of the regression analysis, including standardised β coefficients and p-values. The findings confirm that both the number of roof and façade windows are the primary drivers of DF performance, each demonstrating strong effects accompanied by low p-values across both renovation contexts. Among these variables, roof windows exhibit the greatest influence. As discussed previously, orientation does not affect this metric, as DF is inherently independent of orientation; this is further supported by the regression results, which indicate no statistically significant effect.

Table 19: Regression Results for DF median

	Typical Renovation		Advanced Renovation	
	β Value	p-value	β Value	p-value
Number of Façade Windows	0.672	0.000	0.521	0.000
Number of Roof Windows	0.790	0.000	0.911	0.000
Orientation	0.000	1.000	0.000	1.000

Overall, it was seen that the daylight performance was primarily driven by glazing-related parameters, with roof windows showing the strongest influence, followed by façade windows, while orientation had a comparatively minor effect. The variations in the advanced renovation context consistently exhibited lower daylight performance than those in the typical context.

4.1.4 Interaction Between Categories

Figure 32 summarises the relative influence and statistical significance of the design parameters across all performance categories, providing an overall synthesis of the results. The classifications were based on the regression analysis results, specifically the standardised β values and the p-values. These findings showed the key trends and differences between metrics and parameters to be clearly identified. This synthesis highlighted the overall dominant role of glazing-related parameters and the varying sensitivity of performance indicators.

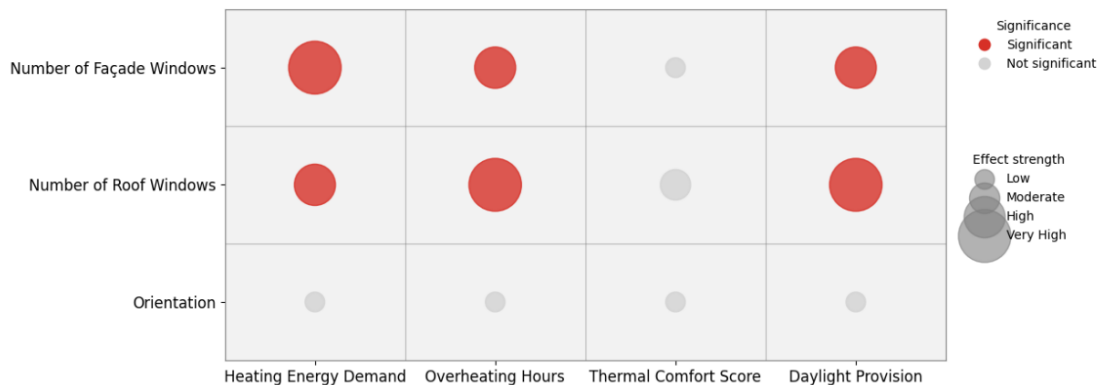


Figure 32: Relative Effect and Statistical Significance of Design Parameters

The results indicated that glazing-related parameters, especially the number of roof windows, are the dominant drivers across most performance categories. In contrast, the orientation generally showed a limited influence, with its impact varying depending on the metric. It should be noted that within the daylight provision category, the effect of orientation is metric-dependent, showing no influence in DF and minor influence in sDA300/50%. Therefore, it was classified as not significant in the synthesis table.

In addition, the interactions between energy performance, thermal comfort, and daylight provision were analysed. Figure 33 and Figure 34 illustrate the relationship between daylight availability (sDA300/50%) and thermal comfort score for variations in both typical and advanced renovation contexts, alongside heating energy demand.

The results indicate no strong correlation between daylight availability and thermal comfort score, as the data points are widely distributed along the daylight axis while remaining relatively clustered with respect to thermal comfort. This suggests that the thermal comfort score is not significantly influenced by the investigated parameters, in contrast to overheating hours, as demonstrated in the previous results.

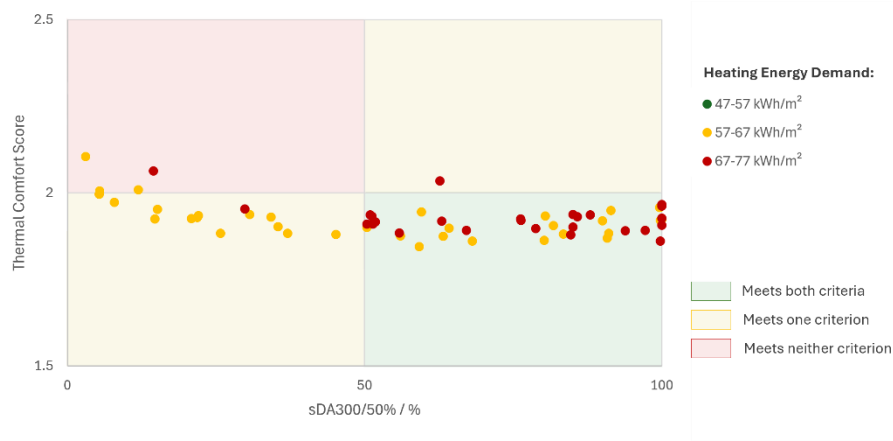


Figure 33: Relationship between sDA300/50% & thermal comfort score in typical renovation context

Additionally, differences in heating energy demand were observed across the variations; however, these did not correspond to significant differences in thermal comfort score. Comparing the typical and advanced renovation contexts, the latter demonstrated consistently lower energy demand and a slightly lower range of thermal comfort scores. However, the overall trends, including the lack of strong correlation between the performance categories, remained consistent between the renovation contexts.

Based on these observations, the thermal comfort score was found to lack sufficient sensitivity to differentiate between variations. Therefore, overheating hours were also considered as the primary performance indicator for comparison and selection of critical variations.

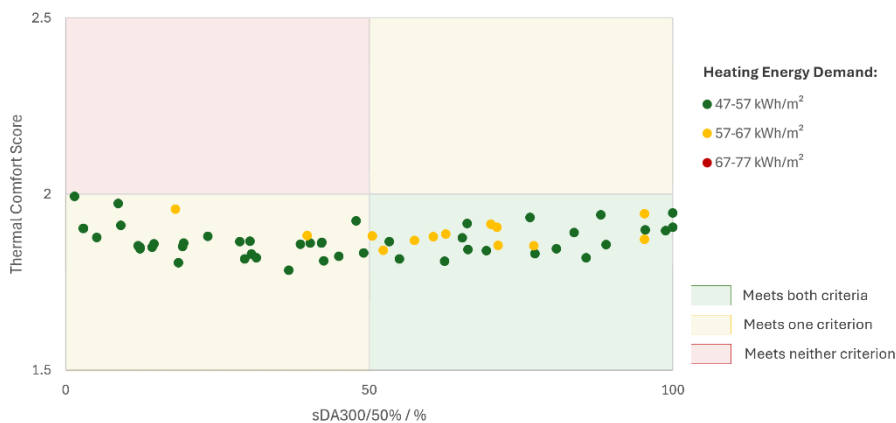


Figure 34: Relationship between sDA300/50% & thermal comfort score in advanced renovation context

4.1.5 Selection of Critical Variations

As demonstrated in the previous sections, the thermal comfort score showed limited sensitivity to the tested parameters and did not provide sufficient differentiation between results, whereas overheating hours exhibited clear variability and a strong dependence on the design parameters. Consequently, overheating hours were adopted as the primary performance indicator for identifying critical variations. In addition, the selected variations were required to meet the daylight performance benchmark criteria. Heating energy demand was not considered as a selection criterion, in line with the methodological framework, due to the absence of a regulatory reference within the scope of this study.

Based on these criteria, variations exhibiting the highest overheating hours while still satisfying daylight performance requirements were identified as critical. This approach ensured that the selected variations represent high-risk scenarios and are particularly suitable for evaluating the effectiveness of shading and natural

ventilation control strategies in improving indoor environmental conditions. Figure 35 and Figure 36 present the variations identified as critical based on the defined selection criteria.

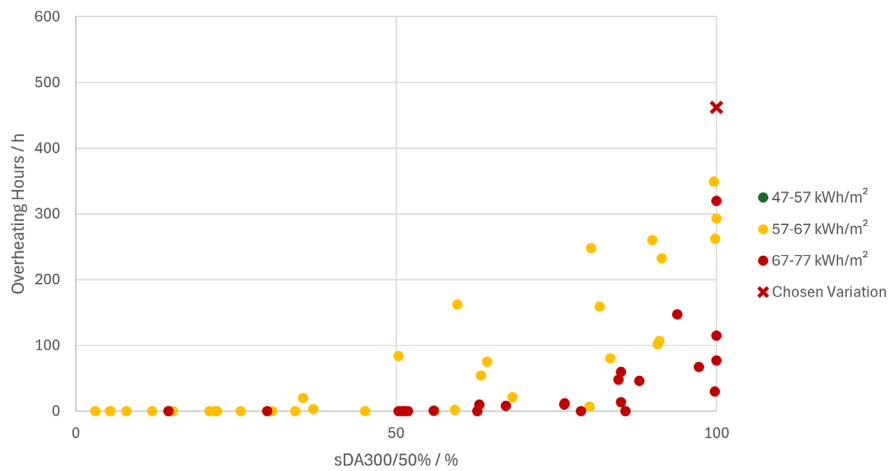


Figure 35: Relationship between sDA300/50% and overheating hours in typical renovation context

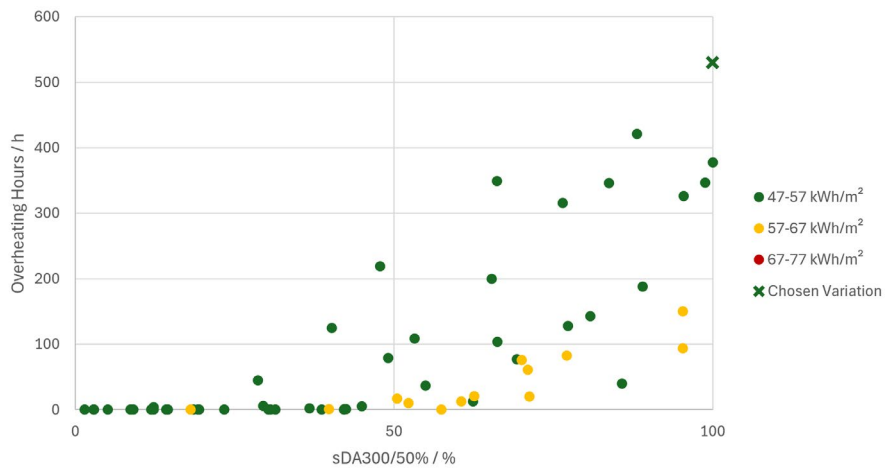


Figure 36: Relationship between sDA300/50% and overheating hours in advanced renovation context

Following these criteria, Variation 15 was identified as the most critical variation for both the typical and advanced renovation contexts and was selected for further analysis in Study B. The properties and performance results of these variations are presented in Table 20.

Table 20: Selected Variations and Their Properties

Variation and Description	Heating Energy Demand [kWh/m ²]	sDA300/50% [%]	DF median [%]	Thermal Comfort Score [-]	Overheating Hours [h]
Variation 15 – Typical - South Facade Window + East Roof Window 3 Roof Windows & 3 Facade Windows	67.2	100	3.8	1.97	462
Variation 15 – Advanced - South Facade Window + East Roof Window 3 Roof Windows & 3 Facade Windows	56.5	100	3.2	1.95	530

4.2 Study B: Shading and Natural Ventilation Strategies

This section presents the performance of the selected critical variations under different shading and natural ventilation control strategies, resulting in a total of 81 assessed variations for each renovation context. The focus is on thermal comfort outcomes, evaluating how the applied control strategies affect overheating hours and thermal comfort scores. The definition of each simulated variation can be found in Appendix E, while the full results of Study B in terms of thermal comfort performance are presented in Appendix F.

4.2.1 Shading Controls

The effect of shading control strategies on thermal comfort is evaluated through overheating hours. The distribution of overheating hours across roof window shading control levels is shown in Figure 37, where results are grouped by shading control strategy for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested design parameter configurations. A clear reduction in overheating hours is observed with increasing control level. While variations using no control and manual control show similar distributions, the introduction of smart shading control results in a substantial decrease in overheating hours across all cases. The spread of results also decreases with higher control levels, indicating reduced sensitivity to other design parameters under more advanced control levels.

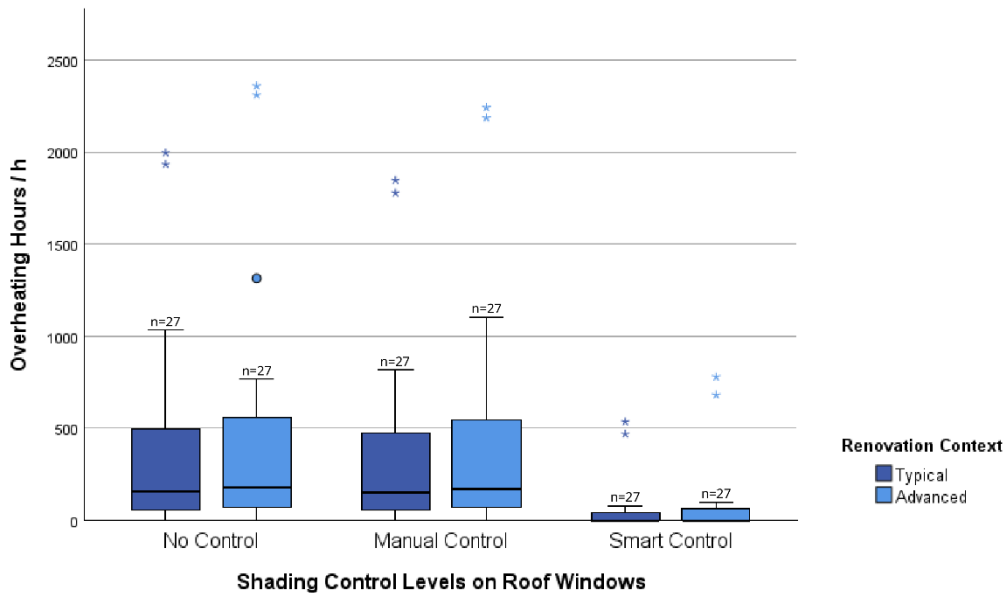


Figure 37: Distribution of overheating hours by shading control levels on roof windows

A similar pattern is observed for façade window shading controls, as shown in Figure 38, where results are grouped by shading control strategy for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested design parameter configurations. As with roof window shading, the introduction of smart shading control results in a notable reduction in overheating hours, while variations using no control and manual control exhibit similar distributions. However, the overall reduction in overheating hours is less pronounced compared to that observed for roof window shading. The spread of results remains relatively consistent across control levels, indicating a more limited influence of façade shading on the variability of overheating performance.

When comparing renovation contexts, the variations within the advanced generally exhibit slightly higher overheating hours; however, the trends across shading control levels remain consistent between the two contexts.

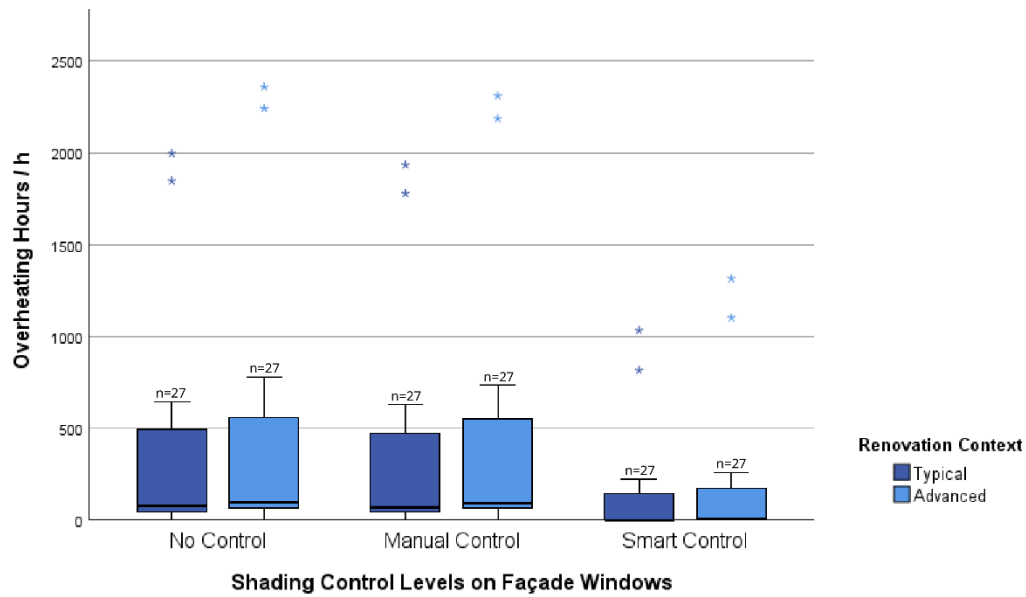


Figure 38: Distribution of overheating hours by shading control levels on façade windows

In terms of thermal comfort score, a similar pattern to that observed for overheating hours is evident for both roof and façade window shading controls, as shown in Figure 39 and Figure 40.

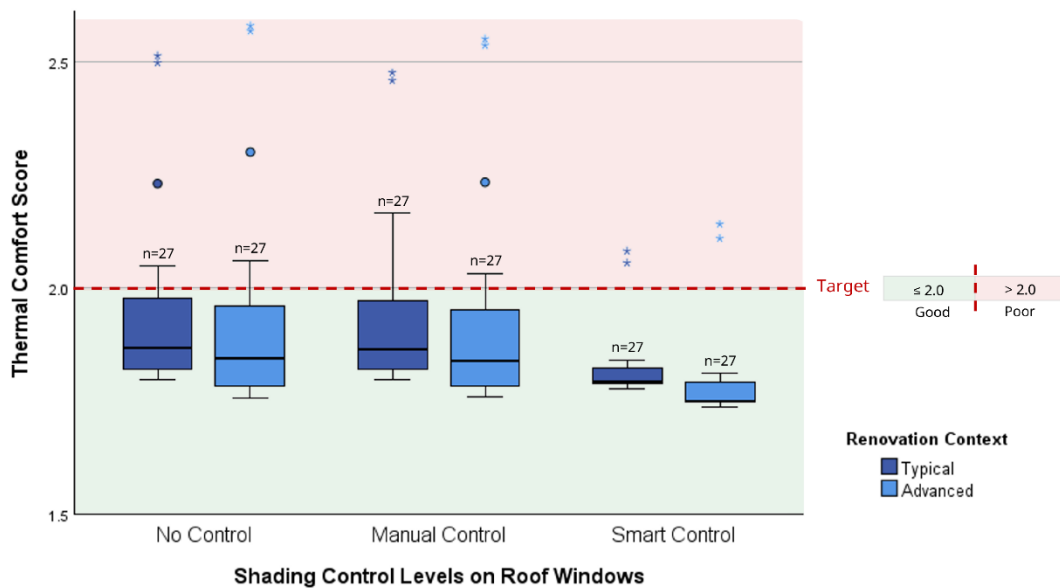


Figure 39: Distribution of thermal comfort score by shading control levels on roof windows

In both cases, results are grouped by shading control strategy, and each boxplot represents the distribution of outcomes across all tested design parameter configurations. Lower thermal comfort scores are observed with increasing control level, indicating improved thermal comfort performance. However, the differences between control strategies are less pronounced than those observed for overheating hours, and the spread of results remains relatively limited, indicating lower sensitivity of the thermal comfort score to shading controls.

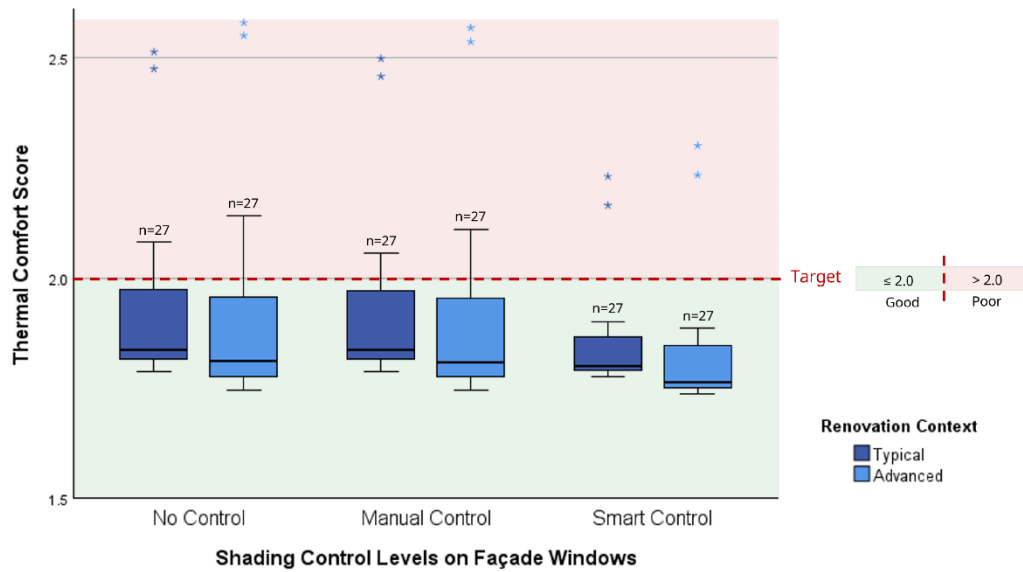


Figure 40: Distribution of thermal comfort score by shading control levels on facade windows

4.2.2 Natural Ventilation Controls

The effect of natural ventilation control strategies on thermal comfort is evaluated through overheating hours. The distribution of overheating hours across natural ventilation strategies on roof windows is shown in Figure 41, where results are grouped by control level for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested design parameter configurations. A clear reduction in overheating hours is observed with increasing control level. While variations using manual control show some improvement compared to no control, the introduction of smart natural ventilation control results in a substantial decrease in overheating hours. The spread of results also decreases with higher control levels, indicating reduced sensitivity to other design parameters under more advanced natural ventilation levels.

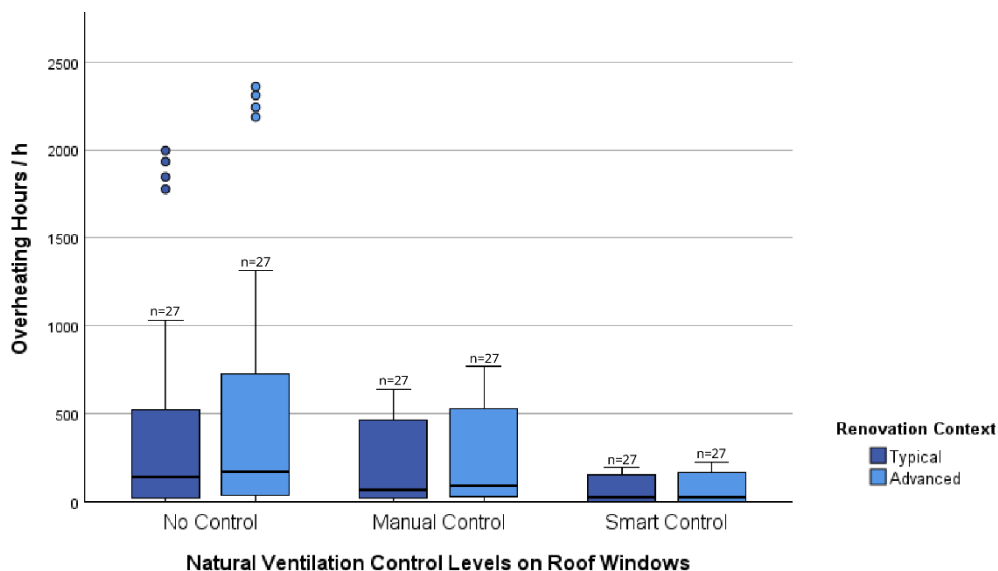


Figure 41: Distribution of overheating hours by natural ventilation control levels on roof windows

A similar pattern to that observed when assessing the natural ventilation controls on roof windows is evident for natural ventilation controls on façade windows, as shown in Figure 42, where results are grouped by control level for both renovation contexts. Each boxplot represents the distribution of outcomes across all tested design

parameter configurations. Increasing the control level results in a consistent reduction in overheating hours, with smart control achieving the lowest values. Compared to the implementation of natural ventilation controls on roof windows, applying them on the façade windows appears slightly more effective, as lower overheating hours and a narrower spread of results are observed across the control levels.

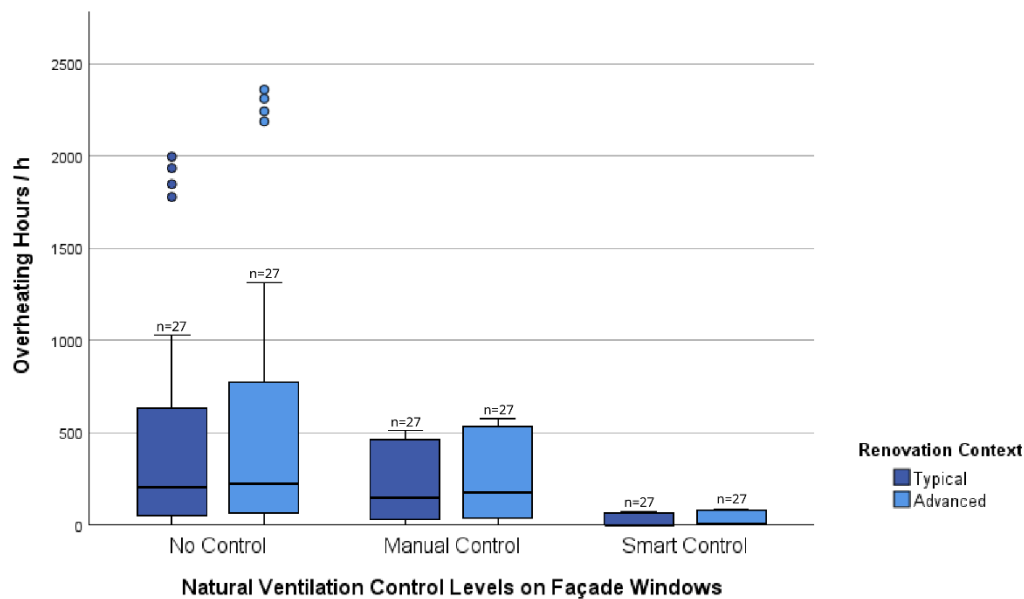


Figure 42: Distribution of overheating hours by natural ventilation control levels on façade windows

Comparing renovation contexts, advanced renovation variations generally exhibited slightly higher overheating hours; however, the overall trends across natural ventilation control levels remained consistent between the two renovation contexts.

In terms of thermal comfort score, a similar pattern to that observed for overheating hours is evident for natural ventilation controls applied on both roof and façade windows, as shown in Figure 43 and Figure 44.

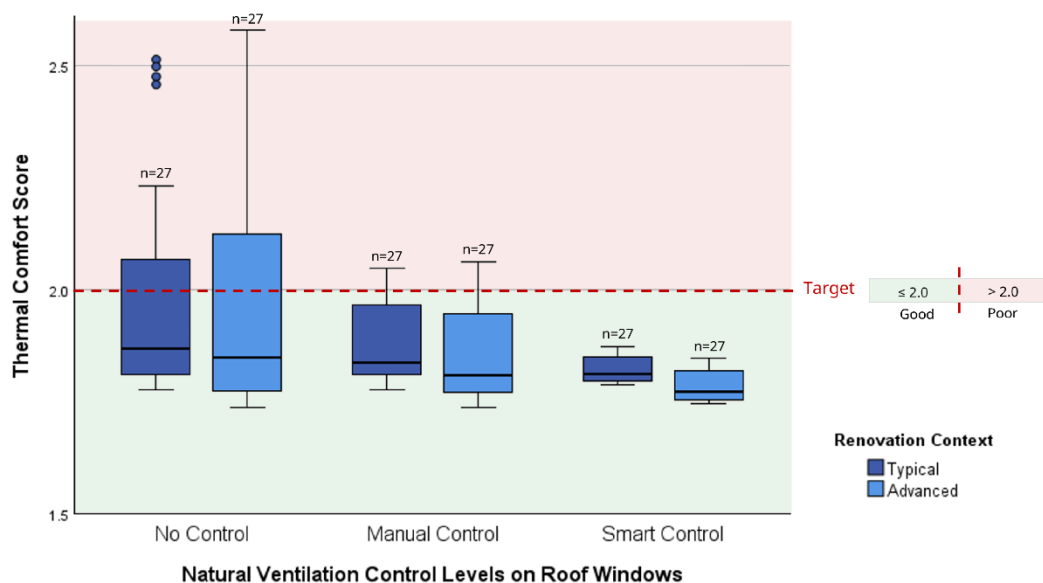


Figure 43: Distribution of thermal comfort score by natural ventilation control levels on roof windows

In both cases, results are grouped by control level for each renovation context, and each boxplot represents the distribution of outcomes across all tested design parameter configurations. Increasing the control level is associated with lower thermal comfort scores, indicating improved thermal comfort performance. In line with the overheating results, the implementation of natural ventilation controls on façade windows exhibited slightly lower scores and a narrower spread of results compared to those applied on roof windows, indicating more consistent performance. However, the differences between control levels remain less pronounced than those observed when assessing overheating hours, confirming that the thermal comfort score is less sensitive to changes in natural ventilation control levels.

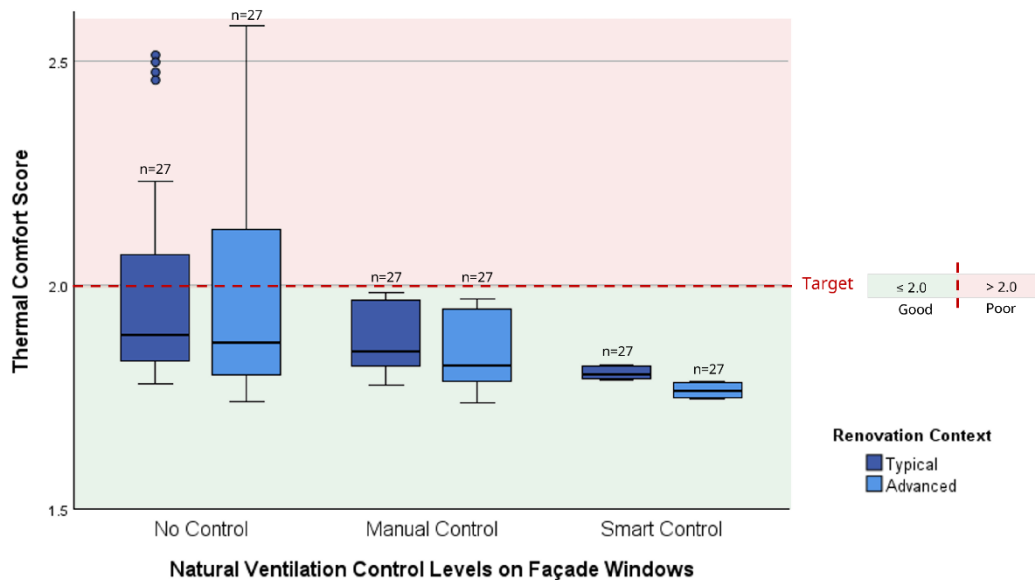


Figure 44: Distribution of thermal comfort score by natural ventilation control levels on façade windows

4.2.3 Comparison of Control Strategies

To enable a direct comparison between shading and natural ventilation strategies, the distribution of overheating hours across control strategies and window types is presented in Figure 45 and Figure 46. In both figures, results are grouped by control level and window type for each renovation context, and each group represents the distribution of outcomes across all tested design parameter configurations. Overheating hours were selected as the primary performance indicator, as previous analyses demonstrated their higher sensitivity to control strategies compared to the thermal comfort score. While the majority of cases show relatively low overheating hours, the distributions also include a number of extreme cases with very high values, reaching up to nearly 2500 hours. These cases are important in identifying critical design conditions and are generally associated with the variations where no control strategies are applied to one or both window types.

Comparing the window types, different patterns are observed for shading and natural ventilation strategies with regard to different control levels. For shading controls, roof windows exhibit a stronger reduction in overheating hours when smart controls are applied, compared to façade windows. In contrast, for natural ventilation controls, façade windows show lower overheating hours and a narrower spread of results than roof windows, indicating more stable and consistent performance across control levels. Under smart control conditions, applying controls on both façade and roof windows results in the lowest overheating hours for both shading and natural ventilation strategies. In contrast, at the no control and manual control level, overheating is presented as more pronounced when the control is applied to both facade and roof windows compared to single window configurations.

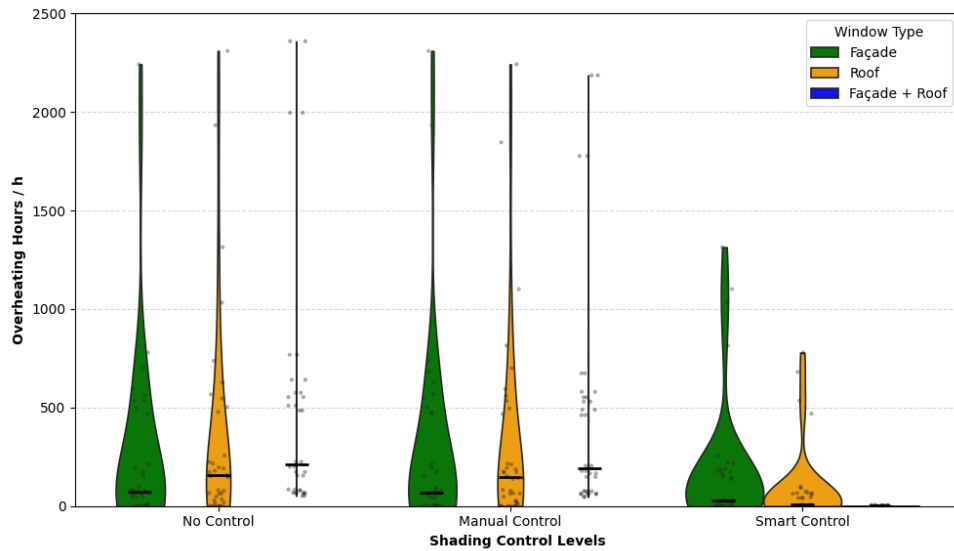


Figure 45: Distribution of overheating hours by shading control levels on window configurations

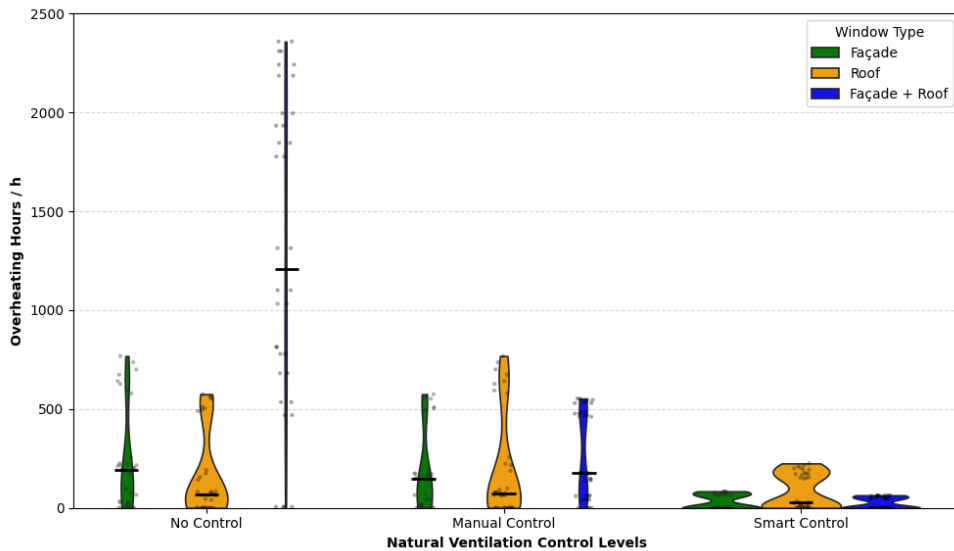


Figure 46: Distribution of overheating hours by natural ventilation control levels on window configurations

In terms of control levels, smart control consistently results in the lowest overheating hours across both strategies and window types. Manual control shows a notable improvement for natural ventilation, but only a limited effect for shading when compared to no control.

Overall, natural ventilation control strategies demonstrate a more pronounced effect on reducing overheating hours compared to shading controls. While both strategies show improvements with increasing control levels, natural ventilation leads to substantially lower overheating values across all control levels, particularly for manual and smart control. In contrast, shading control strategies exhibit limited improvement under manual control, with significant reductions observed primarily in variations using smart control.

However, these comparisons are based on the independent evaluation of shading and natural ventilation strategies across all tested variations. The combined effect of both control strategies is further explored in the following section.

4.2.4 Interactions Between Controls

To further investigate the combined effects of shading and natural ventilation strategies, the interaction between control levels was analysed using average overheating hours, as shown in Figure 47 for the roof windows and Figure 48 for the façade windows.

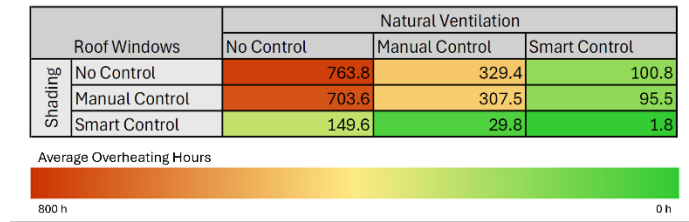


Figure 47: Interaction of Shading and Natural Ventilation Controls on Overheating (Roof Windows)

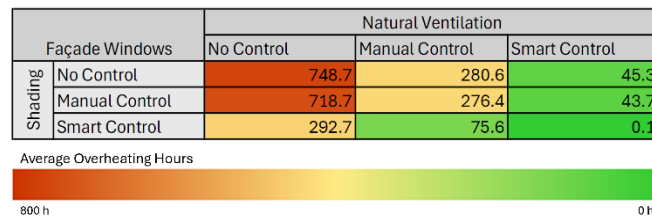


Figure 48: Interaction of Shading and Natural Ventilation Controls on Overheating (Facade Windows)

The results of Study B indicate that the effectiveness of shading strategies is strongly dependent on the control level. Under manual control, shading has only a marginal impact on overheating, reducing average overheating hours by approximately 3% when applied to façade windows, and 7% when applied to roof windows. In contrast, under smart control, shading becomes significantly more effective, with total reductions reaching approximately 66% when applied to façade windows and 85% when applied to roof windows. This corresponds to an additional reduction of around 65% and 84%, respectively, when transitioning from manual to smart control, highlighting the strong dependence of shading performance on automatic operation.

Natural ventilation, in comparison, already achieves substantial reductions under manual control, decreasing overheating by approximately 64% when applied to façade windows and 59% when applied to roof windows. The transition to smart control further improves performance, with total reductions increasing to approximately 95% and 88%, corresponding to additional reductions of around 86% when applied to façade windows and 70% when applied to roof windows relative to manual control.

However, the most notable effect is observed when both strategies are combined using smart controls. Under manual control, the combined application of shading and ventilation provides only limited additional benefit compared to ventilation alone, with total reductions of approximately 60% when applied to roof windows and 63% when applied to façade windows, closely matching the performance of ventilation as a standalone strategy. In contrast, under smart control, the combined strategy results in near-complete elimination of overheating, with reductions reaching approximately 99.8% when applied to roof windows and 99.99% when applied to façade windows. While individual strategies under smart control already achieve substantial reductions (approximately 80–87% when applied to roof windows and 61–94% when applied to façade windows), their combination leads to a significantly greater overall effect, highlighting a strong synergy between solar gain reduction and heat removal when operated responsively.

4.2.5 Selection of Critical Variations

Following the analysis of shading and natural ventilation control strategies and their interactions, a set of representative variations was identified for further evaluation under future climate conditions in Study C. The selected seven variations and their corresponding results from Study B are presented in Table 21 and Table 22.

Table 21: Selected Variations and their Study B findings - Typical Renovation

Variation Number	Natural Ventilation Controls		Shading Controls		Overheating hours [h]	Thermal Comfort Score
	Roof	Façade	Roof	Façade		
1	None	None	None	None	1996	2.51
5	None	None	Manual	Manual	1777	2.46
37	Manual	Manual	None	None	485	1.97
41	Manual	Manual	Manual	Manual	462	1.97
9	None	None	Smart	Smart	5	1.80
73	Smart	Smart	None	None	52	1.81
81	Smart	Smart	Smart	Smart	0	1.79

Table 22: Selected Variations and their Study B findings - Advanced Renovation

Variation Number	Natural Ventilation Controls		Shading Controls		Overheating hours [h]	Thermal Comfort Score
	Roof	Façade	Roof	Façade		
1	None	None	None	None	2359	2.58
5	None	None	Manual	Manual	2186	2.54
37	Manual	Manual	None	None	553	1.96
41	Manual	Manual	Manual	Manual	530	1.95
9	None	None	Smart	Smart	5	1.76
73	Smart	Smart	None	None	64	1.77
81	Smart	Smart	Smart	Smart	0	1.75

These variations span the full range of control levels, from no control to fully smart control, enabling a direct comparison between shading and natural ventilation strategies. The same set of variations was applied to both typical and advanced renovation contexts, ensuring consistency in the subsequent analysis.

4.3 Study C: Future Climate Conditions

Study C results show the performance of the selected variations under future climate conditions, allowing a direct comparison with current climate results and highlighting the robustness of different control strategies. The definition of each simulated variation can be found in Appendix G, while the full results of Study C in terms of thermal comfort performance are presented in Appendix H.

4.3.1 Future Climate Scenario Analysis

A comparison between the future and current climate scenarios is presented to support the interpretation of results in Study C. Carpet plots illustrating the two climates are shown in Figure 49. The results indicated a general increase in outdoor dry-bulb temperature, with the annual mean rising from 6.64°C to 9.18°C, corresponding to an increase of 2.54°C. In addition, a slight increase in outdoor temperature variability was observed, as the standard deviation increased from 8.11 to 8.41.

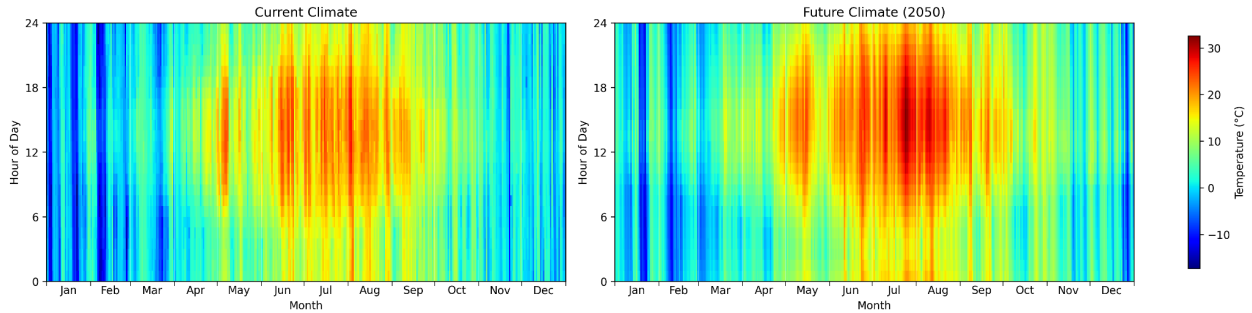


Figure 49: Comparison of current and future climate temperature profiles

A seasonal comparison between heating and non-heating periods shows that the outdoor dry-bulb temperature increase is consistent throughout the year. During the heating season, both mean and extreme outdoor temperatures increase, while in the non-heating season, higher maximum outdoor temperatures are observed.

Additionally, the analysis of outdoor temperature thresholds reveals a significant increase in the frequency of high-temperature periods. The number of hours above 25°C increases in the future scenario, as shown in Figure 50, along with increases in hours above 28°C and 30°C. Specifically, an increase of 2.5% is observed over the year for hours above 25°C. In contrast, the number of hours below 0°C and -5°C decreases.

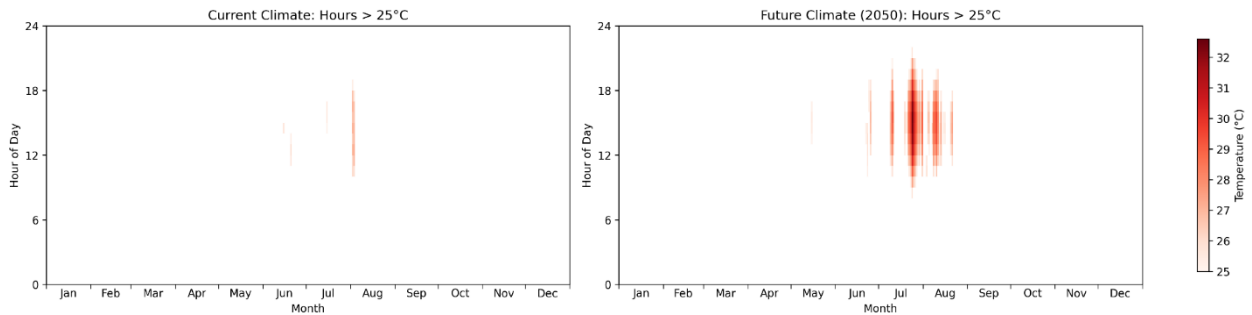


Figure 50: Increase in hours above 25°C under future climate conditions

These results indicate that while average outdoor temperature increases were moderate, the frequency and intensity of extreme heat conditions increased significantly in the projected future climate.

In terms of thermal comfort modelling, the number of hours assessed using the adaptive comfort model increased from 3264 hours to 3600 hours. This suggests that adaptive conditions became applicable over a longer period of the year. Additionally, a shift in comfort temperature definitions was observed, with higher upper limits for acceptable indoor temperatures in the future scenario. Although the average shift in comfort temperatures was relatively small, with a 0.68°C increase, the overall increase in maximum upper limits indicated that higher indoor temperatures are more likely to occur in the future.

Finally, changes in the natural ventilation potential, regarding the outdoor temperature conditions, were investigated between the current and future climate. The natural ventilation potential was defined according to the temperature limits used in the natural ventilation control strategy ($14^{\circ}\text{C} < T_{out} < 31^{\circ}\text{C}$), representing the

hours during which the controls would permit window opening. It was seen that this potential increased from 1794 hours to 2619 hours, corresponding to 825 hours, approximately 9.4% of the year. The visual comparison showing this difference can be seen in Figure 51. This indicated that, despite the increased risk of overheating, the potential for natural ventilation also increases under future climate conditions.

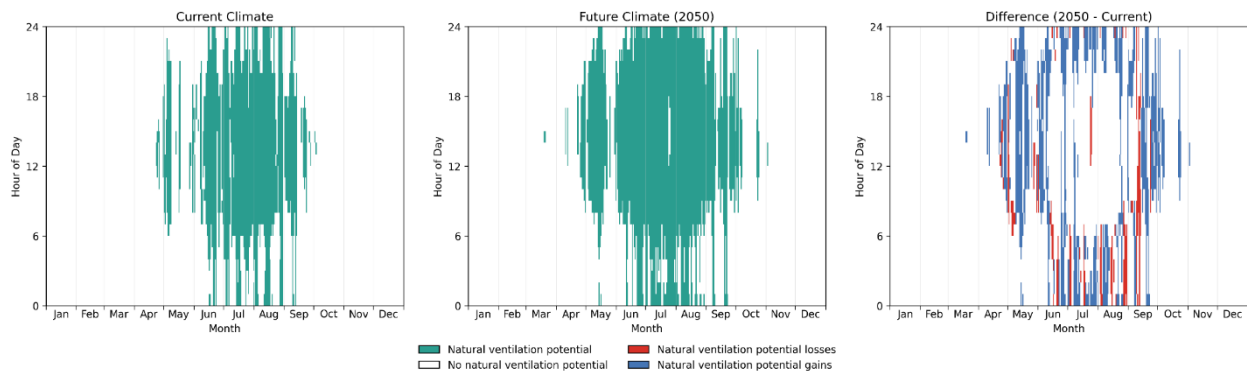


Figure 51: Natural ventilation potential in current and future climate conditions

4.3.2 Performance of Selected Variations in the Future

The impact of future climate conditions on overheating performance was evaluated by comparing the selected control strategy variations under current and future scenarios, in both typical and advanced renovation contexts, as seen in Figure 52 and Figure 53, respectively. Comparing the renovation contexts, variations with typical renovation generally maintained lower overheating hours than the advanced variations under both climate conditions.

Across all variations, an increase in overheating hours was observed under future climate conditions. On average, overheating hours increased by approximately 20-30%, indicating a general deterioration in thermal comfort performance. However, the extent of increase varied significantly depending on the applied control strategy. Variations with no or limited control exhibited the highest absolute increases and remained the worst-performing cases.

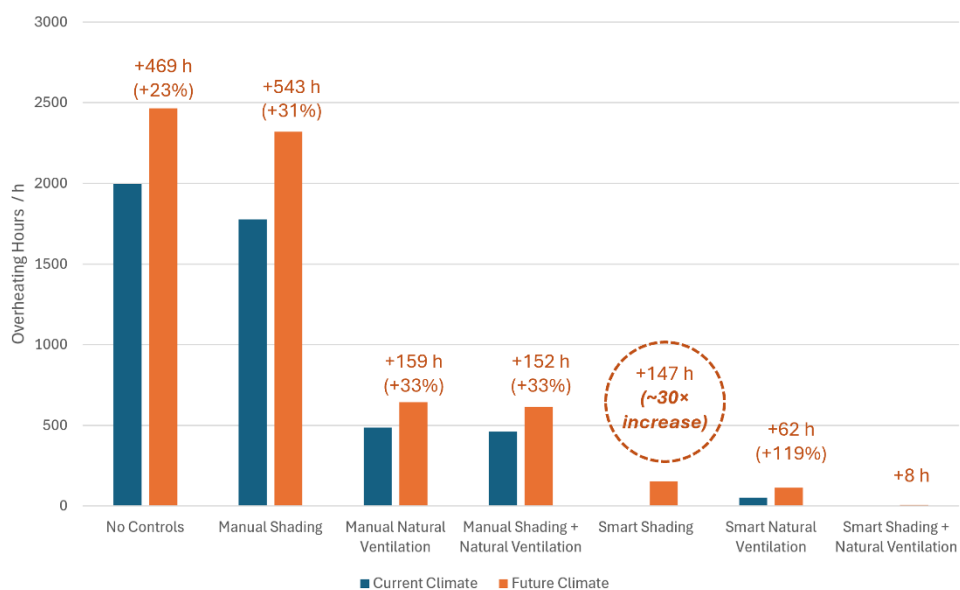


Figure 52: Overheating hours under current and future climate conditions for different control strategies (typical renovation)

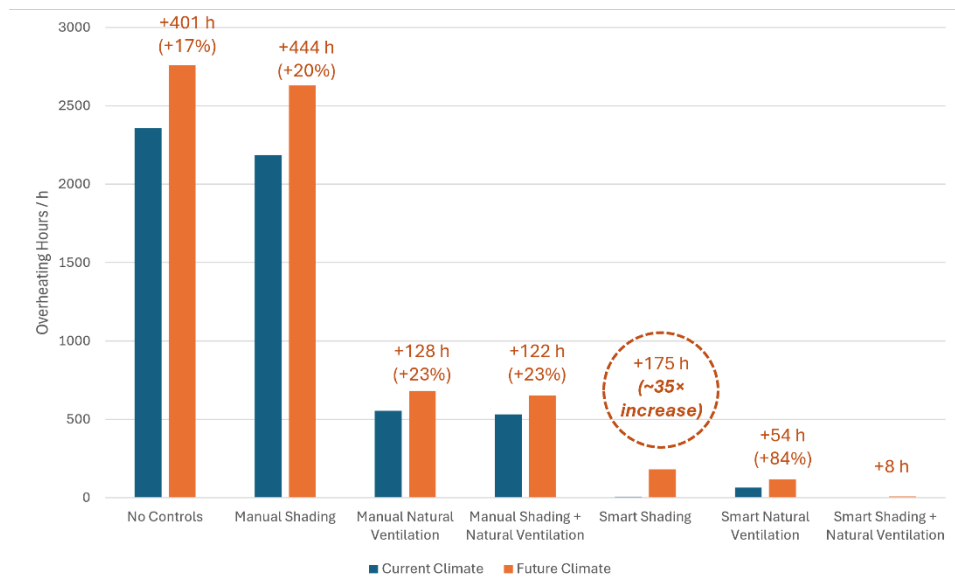


Figure 53: Overheating hours under current and future climate conditions for different control strategies (advanced renovation)

Additionally, the variations relying on shading controls showed a disproportionate increase in overheating hours. For example, variations only with smart shading, which demonstrated near-zero overheating in the current conditions, showed a significant increase under future climate conditions. This indicated a reduced effectiveness of applying only shading strategies in the projected future scenario. In contrast, the implementation of only natural ventilation control strategies demonstrated a greater robustness. Variations incorporating natural ventilation controls showed comparatively smaller increases in overheating hours, maintaining lower overall values under future conditions.

The thermal comfort score also showed a slight increase across all variations under future conditions, indicating a general decline in thermal comfort performance. However, the range of the thermal comfort score values between variations remained relatively limited compared to overheating hours, confirming the lower sensitivity of this metric. The comparison of the thermal comfort score between current and future climate across variations can be seen in Figure 54 and Figure 55, for typical and advanced renovation contexts, respectively.

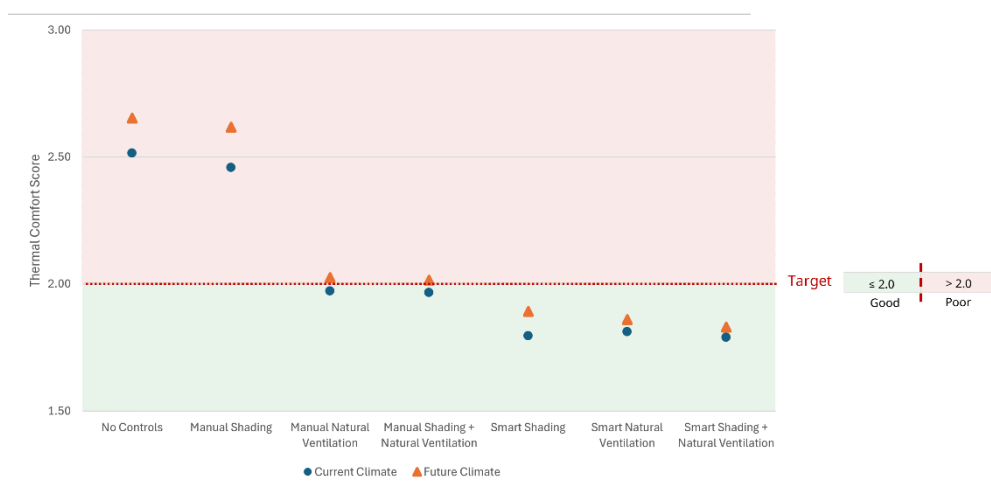


Figure 54: Thermal comfort score across different control strategies under present and future climate (typical renovation)

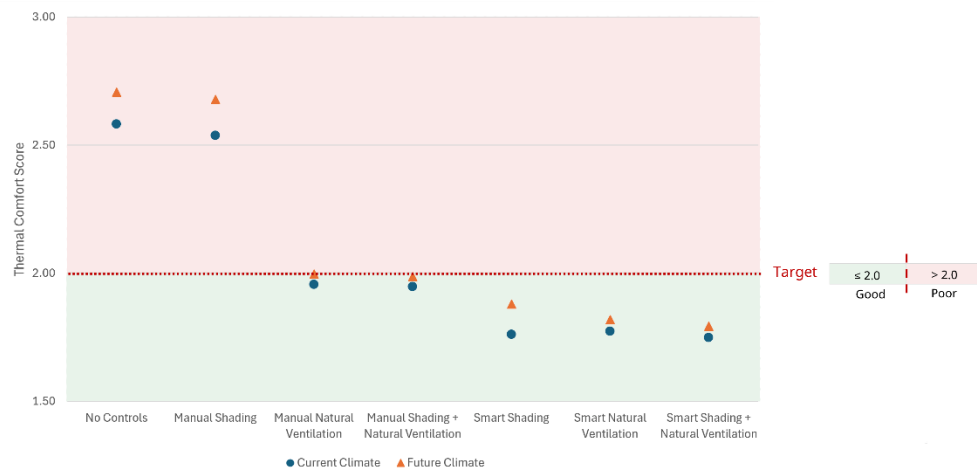


Figure 55: Thermal comfort score across different control strategies under present and future climate (advanced renovation)

5 Discussion

5.1 Study A: Window Configuration and Orientation

The results demonstrate that glazing-related parameters are the primary drivers of attic performance, although their influence varies across performance categories. Roof windows have the strongest influence on daylight provision and overheating due to their direct exposure to solar radiation and the sky dome, allowing deeper and more uniform daylight penetration while simultaneously increasing solar heat gains. Façade windows also contribute to all performance categories but exhibit a slightly stronger influence on heating energy demand, reflecting the dominant role of transmission heat losses. Compared to roof windows, façade windows receive lower solar exposure and may be partially affected by surrounding obstructions, resulting in a more consistent contribution to heat losses than solar gains. Orientation introduces some variability across the analysed metrics but does not act as a consistent driver of performance. This is likely related to the geometric configuration of the attic, where façade and roof windows are oriented differently within the same variation, reducing the consistency of solar exposure patterns and limiting the overall influence of orientation on the results.

The influence of these parameters is further affected by the renovation context. Variations within the advanced renovation context consistently exhibit lower heating energy demand due to improved insulation and airtightness, which reduce heat losses through the building envelope. However, these same measures also limit the dissipation of excess heat, leading to increased overheating hours. In addition, daylight performance is slightly reduced as thicker constructions create deeper window reveals, reducing visible sky exposure and limiting daylight penetration. As a result, the relative importance of roof windows becomes even more pronounced in the advanced renovation context, particularly for daylight-related metrics. The regression analysis further highlights that glazing-related parameters explain a substantial proportion of the variation in daylight performance, whereas heating energy demand and overheating are influenced by a broader range of interacting factors beyond the investigated design parameters. This distinction suggests that daylight performance is largely governed by geometry, while thermal performance depends on a more complex interaction between design parameters and dynamic environmental conditions.

The relationships between daylight, thermal comfort, and energy performance reveal clear trade-offs between performance categories. Higher daylight availability is generally associated with increased overheating, reflecting their shared dependence on solar radiation. Similarly, increased glazing area, particularly through roof windows, improves daylight provision but may also increase overheating risk and, to a lesser extent, heating energy demand. The relationship between daylight and heating energy demand further demonstrates that the benefits of additional solar gains are often outweighed by the corresponding increase in heat losses through glazing. A comparable trade-off is observed between renovation contexts, where the advanced renovation level improves energy performance while simultaneously increasing overheating. These findings demonstrate that design decisions cannot be evaluated through a single performance metric and highlight the importance of balancing daylight, energy, and thermal comfort objectives during attic retrofit design.

A notable observation is the difference between the two thermal comfort indicators used in the study. Overheating hours exhibit a wide performance range and respond strongly to changes in glazing configuration and renovation context, whereas the thermal comfort score remains within a relatively narrow band. This reflects the aggregated and category-based nature of the thermal comfort score, which reduces its sensitivity to peak conditions and short-term temperature variations. The effect is particularly evident in the advanced renovation context, where higher overheating hours can coincide with improved thermal comfort scores due to a reduction in underheating during the shoulder seasons. Consequently, overheating hours provide a more sensitive representation of peak thermal conditions, while the thermal comfort score offers a broader assessment of overall comfort performance. Together, the two metrics provide a more comprehensive evaluation of thermal conditions than either metric alone, and demonstrate how the choice of metric can influence the interpretation of design performance.

5.2 Study B: Shading and Natural Ventilation Strategies

Both shading and natural ventilation reduce overheating, although their effectiveness differs. Smart controls consistently outperform manual controls, while manual shading provides only limited benefits due to its dependence on occupant presence during periods of peak solar gains. Across both renovation contexts, natural ventilation emerges as the more influential individual strategy, suggesting that the removal of accumulated heat plays a greater role in controlling overheating than limiting solar gains alone.

The effectiveness of the strategies is also influenced by window type. Shading is particularly effective when applied to roof windows, reflecting their dominant contribution to solar heat gains. In contrast, natural ventilation through façade windows shows a slightly stronger influence on overheating reduction, which may be related to the airflow patterns generated by the simulated window configuration. Nevertheless, the lowest overheating levels are achieved when both façade and roof windows are controlled simultaneously under smart operation.

The interaction between shading and natural ventilation demonstrates that the two strategies are complementary rather than independent. While both reduce overheating individually, their combined effect is greater than their individual contributions. Natural ventilation emerges as the more influential individual strategy, as substantial reductions in overheating are achieved even at lower shading levels. In contrast, improvements in shading alone result in more moderate reductions, particularly when natural ventilation is limited. This suggests that the removal of accumulated heat plays a more critical role than solely limiting solar gains.

However, the results also indicate that the effectiveness of each strategy depends on the performance of the other. Shading is most effective when combined with higher levels of ventilation, while ventilation performs best when solar gains are simultaneously controlled. This reflects the complementary roles of the two strategies: shading limits heat gains, whereas natural ventilation removes accumulated heat. As a result, neither strategy fully addresses overheating on its own. The lowest overheating levels are consistently observed when both façade and roof windows operate under smart control conditions, highlighting the importance of integrated control approaches rather than relying on a single passive measure.

5.3 Study C: Future Climate Conditions

Future climate conditions lead to a consistent deterioration in thermal comfort performance, with higher outdoor temperatures resulting in increased overheating across all analysed variations. Although adaptive comfort limits become slightly more permissive under warmer conditions, this adjustment is insufficient to compensate for the increase in extreme heat events.

The results also demonstrate that climate change affects the relative effectiveness of control strategies. Variations relying primarily on shading experience larger increases in overheating, whereas those incorporating natural ventilation remain comparatively resilient. This can be attributed to the increase in ventilation potential under future climate conditions, which expands the period during which natural ventilation can effectively remove excess heat.

Overall, the findings indicate that the effectiveness of design strategies is climate dependent. While overheating risk increases under future conditions, strategies based on active heat removal remain more robust than those relying solely on limiting heat gains. This suggests that future attic retrofit designs should place greater emphasis on ventilation-based approaches alongside solar gain control measures.

6 Limitations

This study is subject to several limitations related to modelling assumptions, simplifications, and the defined scope of the analysis. These limitations influence the interpretation and generalisability of the results and should be considered when applying the findings to real-world conditions. The following points outline the key constraints associated with the modelling approach, input assumptions, and the selected study configurations.

A key limitation of the study relates to the simplifications applied in the modelling process. While reference values from the TABULA database were used to define target U-values, the actual constructions were simplified and adapted within the simulation environment to match these values. As a result, the model does not fully represent the complexity of real building assemblies, and the findings should therefore be interpreted as indicative of general performance trends rather than exact real-world outcomes.

The applicability of external insulation strategies in existing buildings with brick façades is also a concern. While improving the thermal performance of the envelope is an important aspect of attic retrofits, the addition of external insulation layers may be difficult in practice, particularly in buildings with architectural or cultural heritage value, where preserving the original façade appearance is often a key consideration. Therefore, the feasibility of such renovation measures may vary depending on the specific architectural and regulatory context of the building.

Assumptions associated with the selected climate data and location conditions can be another limitation. Different weather files and climatic datasets may influence the simulation results and lead to variations in the predicted building performance.

Another limitation of the study is that the analysis was conducted using a single attic geometry, represented by a corner studio apartment. Different attic configurations may influence the absolute performance outcomes related to daylight provision, thermal comfort, and energy demand, limiting the direct generalisability of the numerical results. However, the aim of the study was not to evaluate all possible attic forms, but rather to investigate the general trends, parameter interactions, and trade-offs between glazing design, renovation context, and control strategies under a controlled geometric framework.

The selected geometry was based on a corner unit, as this allowed greater flexibility for incorporating façade windows without increasing the knee wall height, which is uncommon in attic apartments. In addition, the corner configuration represents a relatively exposed attic condition due to its multiple external façades. While this may increase daylight availability and ventilation potential, it may also lead to higher heat losses, greater solar exposure, and increased sensitivity to external conditions. As a result, the geometry can be considered representative of a more performance-sensitive case, allowing the effects of the investigated parameters to become more visible within the analysis. Maintaining a constant geometry throughout the study also improved the comparability of variations and the interpretability of the identified trends and trade-offs.

The definition of design parameters also introduces certain limitations. In order to isolate the impact of glazing area, the same window products were used across both façade and roof applications, as well as in both renovation contexts. While this approach ensures comparability between cases, it does not account for potential differences in window properties, such as glazing performance or frame characteristics, which may influence real-world performance.

In addition, the geometric configuration of the analysed attic imposes constraints on the ventilation behaviour. Both façade and roof windows are arranged on a single orientation of the building, preventing ventilation types such as cross-ventilation. As a result, airflow is characterised by a combination of wind-driven and buoyancy-driven effects rather than fully developed cross-ventilation. This may lead to different airflow patterns and ventilation effectiveness compared to buildings with alternative window configurations.

Another source of uncertainty arises from the use of predefined occupancy and operation schedules, which are based on standardised assumptions and therefore do not reflect the variability of real occupant behaviour. This limitation is particularly relevant for the manual control scenarios in Study B, where shading and ventilation operation depend on occupant presence. In the analysed cases, occupancy schedules did not coincide with peak overheating periods, resulting in limited activation of the control strategies during the most critical hours. Consequently, manual control cases showed performance patterns similar to the no-control scenarios, particularly for shading. Since real occupant behaviour may differ significantly from the assumed schedules, the actual effectiveness of manual control strategies may vary in practice.

A further limitation of Study B relates to the consideration of a single orientation configuration for the analysed case. The selected variation includes façade windows oriented towards the south and roof windows oriented towards the east, representing a specific solar exposure condition. While this allows for a consistent comparison of control strategies, it does not account for the variability in solar gains and daylight availability associated with different orientations. As a result, the effectiveness of shading and natural ventilation strategies, particularly their interaction with solar radiation, may differ under alternative orientation scenarios. This limits the generalisability of the findings to buildings with different orientation configurations.

A critical limitation of Study B is that the daylight performance assessment did not account for the operation of the shading controls examined, which can be misleading especially for smart control shading scenarios. The daylight simulations were conducted under unobstructed glazing conditions, meaning that the potential reduction in daylight availability caused by activated shading devices was not evaluated. In practice, especially during warm periods with high solar exposure, shading operation may significantly decrease indoor daylight levels and therefore influence daylight compliance. As a result, the reported daylight performance should be interpreted as the maximum potential daylight provision of the examined configurations rather than the daylight conditions continuously experienced during shading operation. Future studies could further investigate the dynamic interaction between daylight availability and shading control strategies to better capture these trade-offs.

Another limitation relates to the evaluation of energy performance. Swedish energy regulations, including the EP_{pet} framework in BBR, are defined at the whole-building level and therefore fall outside the scope of this study, which focuses exclusively on the analysed, converted attic unit. As a result, no direct regulatory energy benchmark was applied in the assessment. The reported heating energy demand values should therefore be interpreted as comparative indicators between design variations rather than as measures of regulatory compliance.

Moisture safety considerations were also outside the scope of this study. While the analysis focuses on daylight, thermal comfort, and energy performance, attic conversions are also strongly influenced by moisture-related risks, including condensation and mould growth. In particular, increased insulation levels and changes in airtightness may affect hygrothermal behaviour. Since these aspects were not evaluated, the findings should not be interpreted as a complete assessment of retrofit suitability. Future studies could therefore incorporate moisture safety and hygrothermal analysis to provide a more comprehensive evaluation of attic retrofit performance.

Finally, the sequential structure adopted between Studies A, B, and C represents a limitation of the study. Due to the large number of possible parameter combinations, it was not feasible within the scope of the thesis to evaluate all glazing configurations together with all control strategies and future climate scenarios across all performance categories. Instead, a staged approach was adopted, where the findings of each study informed the selection of cases for the following stage. Additionally, the future climate analysis was limited to a selected subset of design variations, and uniform control strategies were applied across both façade and roof windows, meaning that mixed control configurations were not explored. While this staged methodology allowed for a more focused investigation within practical time and computational constraints, it may introduce a risk of sub-

optimisation. Alternative configurations or control combinations not included in the later stages may respond differently under future climate conditions, potentially leading to additional or different conclusions.

7 Conclusions

Attic retrofit design requires an integrated consideration of daylight provision, thermal comfort, and energy performance, as these aspects are interdependent and governed by shared design parameters. This is particularly critical in cold climates such as Sweden, where limited daylight availability and high heating demand coexist with an increasing risk of overheating in attic spaces. The results of this study demonstrate that early-stage design decisions play a decisive role in shaping the overall performance of residential attic retrofits.

A central finding of the study is that glazing design cannot be evaluated in relation to a single performance aspect. The influence of roof and façade windows varies depending on the evaluated metric and the properties of the envelope construction. Roof windows were found to have the strongest influence on daylight provision and overheating due to their high solar exposure, while façade windows showed a comparatively stronger influence on heating energy demand and a more consistent contribution across performance categories. These findings highlight the presence of clear trade-offs between daylight availability, thermal comfort, and energy performance, demonstrating the need for a multi-criteria design approach.

The results further show that the effectiveness of passive strategies depends strongly on both their application and control logic. Smart control strategies consistently resulted in the lowest overheating levels, substantially outperforming manual controls. While smart shading achieved reductions in overheating of up to 85%, natural ventilation proved to be the more influential individual strategy, with smart ventilation reducing overheating by up to 95%. The most effective thermal performance was achieved through the combined application of shading and natural ventilation, particularly under smart controls, where overheating was reduced to near-zero levels in several cases. These findings demonstrate that robust thermal performance requires both the limitation of solar heat gains and the active removal of accumulated heat.

Under future climate conditions, overheating risk increased across all analysed variations, indicating a general deterioration in thermal comfort performance. At the same time, the relative effectiveness of the investigated strategies changed. Approaches relying primarily on limiting solar gains became less robust, while natural ventilation remained effective due to the increased number of operable hours under warmer conditions. Variations combining smart shading and natural ventilation controls showed only minimal increases in overheating under the future climate scenario, indicating a higher level of resilience to climate change.

The renovation context was also found to significantly influence performance outcomes. While improved insulation and airtightness reduced heating energy demand, they also increased overheating risk by limiting heat dissipation, highlighting a clear trade-off between winter and summer performance. In addition, the advanced renovation context resulted in slightly lower daylight performance. These findings demonstrate that improving one aspect of performance may lead to compromises in others, reinforcing the need for balanced and integrated retrofit strategies.

The study also demonstrates that the interpretation of thermal performance is sensitive to the selected evaluation metric. Overheating hours showed strong sensitivity to glazing configuration and control strategies, providing a detailed representation of peak thermal conditions. In contrast, the thermal comfort score exhibited lower variability and masked some critical differences between variations due to its aggregated nature. This highlights the importance of evaluating thermal comfort using multiple complementary metrics rather than relying on a single indicator.

Overall, the findings demonstrate that the performance of residential attic retrofits depends on integrated early-stage design decisions. Glazing configuration, shading, natural ventilation, and renovation level should therefore be considered jointly rather than as isolated parameters. The study shows that cold attic spaces can be successfully converted into habitable residential environments in Swedish climates, provided that effective glazing and control strategies are implemented. In particular, the combination of smart shading and natural ventilation controls enables overheating to be reduced from several hundred hours to near-zero levels while

maintaining acceptable daylight and energy performance. These findings support the potential of attic retrofits as a viable and future-oriented strategy for increasing housing capacity within the existing building stock under both present and future climate conditions.

8 Usage of Generative AI Tools

During the preparation of this report, generative AI tools such as ChatGPT and Claude were used to edit wording and improve readability. After it was implemented, the text was reviewed and edited as needed to ensure the quality and accuracy of the report. Additionally, the utilisation of Python to create figures and plots in the Matplotlib environment was assisted by an AI tool, namely ChatGPT.

9 References

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10 Appendix

10.1 Appendix A

Table A1: Design Variations of Study A

Variation Number	Number of Façade Windows	Number of Roof Windows	Orientation
01	1	0	South Façade Window & East Roof Window
02	2	0	
03	3	0	
04	0	1	
05	1	1	
06	2	1	
07	3	1	
08	0	2	
09	1	2	
10	2	2	
11	3	2	
12	0	3	
13	1	3	
14	2	3	
15	3	3	
16	1	0	East Façade Window & North Roof Window
17	2	0	
18	3	0	
19	0	1	
20	1	1	
21	2	1	
22	3	1	
23	0	2	
24	1	2	
25	2	2	
26	3	2	
27	0	3	
28	1	3	
29	2	3	
30	3	3	
31	1	0	North Façade Window & West Roof Window
32	2	0	
33	3	0	
34	0	1	
35	1	1	
36	2	1	
37	3	1	
38	0	2	
39	1	2	
40	2	2	
41	3	2	

42	0	3	
43	1	3	
44	2	3	
45	3	3	
46	1	0	West Façade Window & South Roof Window
47	2	0	
48	3	0	
49	0	1	
50	1	1	
51	2	1	
52	3	1	
53	0	2	
54	1	2	
55	2	2	
56	3	2	
57	0	3	
58	1	3	
59	2	3	
60	3	3	

10.2 Appendix B

All tables follow the variation numbering defined in Appendix A.

Table B1: Energy performance results of Study A – Typical Renovation

Variation Number	Heating Energy Demand [kWh]	Heating Energy Demand [kWh/m²]
01	2762.1	60.0
02	2766.3	60.1
03	2780.3	60.4
04	2844.1	61.8
05	2845.7	61.9
06	2856.5	62.1
07	2877.4	62.6
08	2931.4	63.7
09	2939.7	63.9
10	2957	64.3
11	2983.8	64.9
12	3018	65.6
13	3032.6	65.9
14	3056.7	66.5
15	3089.5	67.2
16	2902.9	63.1
17	2999.5	65.2
18	3099.6	67.4
19	2948.1	64.1
20	3043.8	66.2
21	3142.1	68.3
22	3243.8	70.5
23	3089.5	67.2
24	3186.8	69.3
25	3286.8	71.5
26	3390.8	73.7
27	3231	70.2
28	3329.7	72.4
29	3431.5	74.6
30	3537.1	76.9
31	2979.6	64.8
32	3124	67.9
33	3269.1	71.1
34	2902.5	63.1
35	3048.9	66.3
36	3195.7	69.5
37	3343	72.7
38	2976.7	64.7
39	3126.3	68.0
40	3278.5	71.3
41	3427.9	74.5
42	3057.8	66.5
43	3210.1	69.8
44	3364.6	73.1

45	3516.7	76.5
46	2896.4	63.0
47	2991.1	65.0
48	3088.7	67.1
49	2785.7	60.6
50	2882.8	62.7
51	2983.4	64.9
52	3090.5	67.2
53	2785.1	60.5
54	2891.6	62.9
55	3003.3	65.3
56	3115.3	67.7
57	2788	60.6
58	2901.5	63.1
59	3016.7	65.6
60	3133.1	68.1

Table B2: Energy performance results of Study A – Advanced Renovation

Variation Number	Heating Energy Demand [kWh]	Heating Energy Demand [kWh/m²]
01	2184.1	47.5
02	2216.8	48.2
03	2259.6	49.1
04	2247.1	48.9
05	2276.7	49.5
06	2316.8	50.4
07	2366.6	51.4
08	2342.5	50.9
09	2379.5	51.7
10	2426.9	52.8
11	2483.7	54.0
12	2438.2	53.0
13	2483.1	54.0
14	2537.5	55.2
15	2599.7	56.5
16	2299.3	50.0
17	2426.7	52.8
18	2557.9	55.6
19	2324.1	50.5
20	2450.2	53.3
21	2579.5	56.1
22	2712.6	59.0
23	2475.3	53.8
24	2603.2	56.6
25	2734.6	59.4
26	2869.4	62.4
27	2626.7	57.1
28	2756.2	59.9
29	2889.4	62.8
30	3026.3	65.8

31	2359.9	51.3
32	2536.3	55.1
33	2713.1	59.0
34	2259.2	49.1
35	2437.9	53.0
36	2616.8	56.9
37	2796.3	60.8
38	2342.7	50.9
39	2524.6	54.9
40	2708.8	58.9
41	2890.5	62.8
42	2435.8	53.0
43	2620.5	57.0
44	2807.2	61.0
45	2991.4	65.0
46	2294.6	49.9
47	2419.6	52.6
48	2548.1	55.4
49	2158.6	46.9
50	2286.8	49.7
51	2419.7	52.6
52	2558.9	55.6
53	2166.2	47.1
54	2305.4	50.1
55	2447.8	53.2
56	2590.3	56.3
57	2179.7	47.4
58	2324.8	50.5
59	2471	53.7
60	2617.5	56.9

10.3 Appendix C

All tables follow the variation numbering defined in Appendix A.

Table C1: Thermal Comfort performance results of Study A – Typical Renovation

Variation Number	Category I Hours [%]	Category II Hours [%]	Category III Hours [%]	Category IV Hours [%]	Overheating Hours [h]	Underheating Hours [h]	Thermal Comfort Score
01	26.4%	38.6%	27.7%	2.7%	0	233	1.97
02	31.8%	35.4%	26.9%	1.2%	0	107	1.88
03	34.1%	34.0%	26.6%	0.6%	2	51	1.84
04	28.3%	39.2%	25.7%	2.2%	0	191	1.92
05	31.7%	35.8%	26.6%	1.2%	0	106	1.88
06	33.6%	33.6%	27.3%	0.8%	21	51	1.86
07	33.7%	33.2%	26.9%	1.5%	102	31	1.87
08	30.7%	36.2%	26.8%	1.7%	20	129	1.90
09	31.9%	34.1%	27.7%	1.7%	75	72	1.90
10	32.0%	33.7%	27.4%	2.2%	159	38	1.91
11	32.6%	32.1%	27.3%	3.3%	260	25	1.92
12	29.8%	34.8%	27.9%	2.8%	162	86	1.94
13	30.4%	33.4%	28.4%	3.1%	232	40	1.95
14	30.9%	32.6%	27.5%	4.3%	349	27	1.96
15	31.6%	31.6%	26.6%	5.5%	462	20	1.97
16	24.9%	39.9%	27.3%	3.3%	0	286	2.00
17	29.3%	37.1%	26.4%	2.5%	0	220	1.93
18	30.8%	35.6%	26.8%	2.2%	0	189	1.91
19	24.7%	40.1%	26.2%	4.3%	0	380	2.01
20	28.7%	38.3%	25.5%	2.8%	0	241	1.93
21	30.7%	36.0%	26.5%	2.2%	0	196	1.91
22	30.5%	35.0%	27.6%	2.1%	12	174	1.92
23	27.9%	38.5%	25.5%	3.5%	0	306	1.95
24	29.9%	37.0%	26.0%	2.5%	0	215	1.92
25	30.4%	35.8%	27.0%	2.2%	10	187	1.92
26	30.0%	34.8%	28.1%	2.5%	60	158	1.94
27	29.2%	37.0%	26.0%	3.1%	0	269	1.94
28	29.6%	36.6%	26.7%	2.3%	10	195	1.92
29	29.5%	35.8%	27.5%	2.5%	46	174	1.94
30	29.1%	34.6%	28.6%	3.0%	115	148	1.96
31	21.2%	40.4%	26.4%	7.3%	0	640	2.10
32	22.9%	39.6%	27.0%	5.8%	0	508	2.06
33	24.4%	38.8%	27.2%	5.0%	0	436	2.03
34	27.1%	39.4%	26.1%	2.7%	0	240	1.95
35	28.4%	38.3%	25.9%	2.8%	0	241	1.94
36	29.0%	37.5%	26.0%	2.8%	0	244	1.93
37	29.4%	36.8%	26.2%	2.9%	0	250	1.93
38	31.1%	37.2%	25.3%	1.7%	3	150	1.88
39	31.5%	36.4%	25.5%	1.9%	1	162	1.88
40	31.4%	36.0%	25.9%	2.0%	8	167	1.89
41	31.2%	35.6%	26.3%	2.2%	14	176	1.90
42	32.1%	35.9%	25.8%	1.6%	54	82	1.87
43	32.1%	35.5%	26.1%	1.6%	48	90	1.88

44	31.7%	35.3%	26.4%	1.9%	67	101	1.89
45	31.3%	35.0%	26.7%	2.3%	77	121	1.91
46	24.9%	39.7%	26.7%	4.0%	0	350	2.01
47	28.6%	38.2%	25.9%	2.7%	0	235	1.93
48	30.9%	37.0%	25.1%	2.4%	0	207	1.90
49	28.7%	38.0%	26.7%	1.9%	0	170	1.93
50	31.8%	36.3%	25.8%	1.4%	1	123	1.88
51	32.8%	35.3%	26.0%	1.2%	7	101	1.86
52	33.1%	35.1%	25.7%	1.4%	30	91	1.86
53	31.9%	33.9%	27.8%	1.7%	84	67	1.90
54	32.8%	34.0%	27.0%	1.6%	80	56	1.88
55	32.7%	34.1%	26.7%	1.8%	107	50	1.88
56	32.8%	33.8%	26.6%	2.3%	147	51	1.89
57	31.1%	33.4%	27.8%	3.0%	248	15	1.93
58	32.2%	32.8%	27.1%	3.2%	262	18	1.92
59	32.4%	32.5%	26.9%	3.6%	293	21	1.92
60	32.6%	32.2%	26.7%	3.9%	320	22	1.93

Table C2: Thermal Comfort performance results of Study A – Advanced Renovation

Variation Number	Category I Hours [%]	Category II Hours [%]	Category III Hours [%]	Category IV Hours [%]	Overheating Hours [h]	Underheating Hours [h]	Thermal Comfort Score
01	30.3%	38.1%	26.5%	0.4%	0	38	1.88
02	35.1%	35.2%	25.0%	0.0%	0	0	1.80
03	37.0%	33.7%	24.6%	0.0%	2	0	1.78
04	31.8%	37.9%	24.9%	0.7%	0	64	1.85
05	34.3%	35.4%	25.6%	0.0%	0	1	1.82
06	35.2%	34.4%	25.3%	0.4%	37	0	1.82
07	35.5%	33.4%	25.0%	1.5%	128	0	1.83
08	32.1%	36.0%	26.4%	0.8%	45	21	1.86
09	33.0%	34.7%	26.4%	1.2%	109	0	1.87
10	33.5%	33.7%	25.9%	2.3%	200	0	1.88
11	34.5%	31.9%	25.0%	3.9%	346	0	1.89
12	30.8%	34.4%	27.6%	2.5%	219	0	1.92
13	31.2%	33.8%	26.7%	3.6%	316	0	1.93
14	31.8%	33.1%	25.6%	4.8%	421	0	1.94
15	32.9%	31.7%	24.7%	6.0%	530	0	1.95
16	28.5%	40.2%	25.1%	1.5%	0	128	1.90
17	32.3%	36.6%	25.2%	1.2%	0	102	1.86
18	32.4%	35.6%	26.3%	1.0%	0	90	1.87
19	28.0%	40.6%	25.0%	1.8%	0	154	1.91
20	31.7%	37.7%	24.8%	1.2%	0	102	1.86
21	32.4%	36.1%	25.8%	1.0%	0	90	1.86
22	31.6%	35.3%	27.2%	1.2%	21	82	1.89
23	30.6%	38.3%	25.0%	1.5%	0	129	1.88
24	31.7%	37.3%	25.3%	1.0%	1	86	1.86
25	31.4%	36.2%	26.6%	1.1%	17	80	1.88
26	30.5%	35.3%	27.8%	1.8%	76	79	1.91
27	30.7%	37.8%	25.7%	1.2%	1	108	1.88
28	31.0%	37.1%	26.2%	1.0%	13	78	1.88

29	30.4%	36.1%	27.2%	1.6%	61	77	1.91
30	29.7%	34.8%	28.3%	2.6%	150	78	1.94
31	24.4%	40.7%	27.3%	2.9%	0	256	1.99
32	25.9%	39.7%	26.9%	2.8%	0	249	1.97
33	27.2%	38.8%	26.4%	2.9%	0	255	1.96
34	31.3%	39.3%	23.9%	0.8%	0	68	1.85
35	32.1%	37.6%	24.8%	0.9%	0	76	1.85
36	32.3%	36.8%	25.3%	1.0%	0	91	1.86
37	31.9%	36.6%	25.5%	1.3%	0	118	1.87
38	33.9%	36.9%	24.1%	0.4%	6	29	1.82
39	33.9%	36.4%	24.5%	0.5%	5	43	1.82
40	33.3%	36.1%	25.2%	0.8%	10	56	1.84
41	32.8%	35.9%	25.6%	1.0%	20	67	1.85
42	33.8%	36.2%	24.4%	1.0%	79	8	1.83
43	33.7%	35.7%	24.8%	1.1%	77	20	1.84
44	33.0%	35.9%	25.1%	1.3%	83	32	1.85
45	32.5%	35.3%	25.9%	1.6%	94	43	1.87
46	28.1%	40.9%	24.9%	1.4%	0	127	1.90
47	31.9%	38.1%	24.3%	0.9%	0	83	1.85
48	33.7%	36.5%	24.4%	0.8%	0	70	1.83
49	32.6%	36.6%	25.9%	0.3%	4	18	1.84
50	34.5%	36.1%	24.5%	0.2%	1	16	1.81
51	34.9%	35.5%	24.6%	0.3%	13	14	1.81
52	34.7%	35.4%	24.6%	0.6%	40	16	1.82
53	32.9%	35.6%	25.4%	1.4%	125	0	1.86
54	34.2%	34.4%	25.5%	1.2%	104	0	1.84
55	34.5%	34.2%	25.0%	1.6%	143	0	1.84
56	34.4%	33.8%	25.0%	2.2%	188	4	1.86
57	32.4%	33.6%	25.4%	4.0%	349	0	1.92
58	33.6%	32.8%	25.3%	3.7%	326	0	1.90
59	33.9%	32.5%	25.0%	4.0%	347	0	1.90
60	33.7%	32.3%	25.0%	4.3%	378	0	1.91

10.4 Appendix D

All tables follow the variation numbering defined in Appendix A.

Table D1: Daylight performance results of Study A – Typical Renovation

Variation Number	sDA100/95% [%]	sDA300/50% [%]	DF median [%]
01	41.6	7.9	0.3
02	81.7	25.7	0.5
03	100.0	59.2	2.0
04	45.8	14.7	0.5
05	97.4	45.2	1.0
06	100.0	68.1	1.4
07	100.0	90.8	2.7
08	93.5	35.5	1.1
09	99.2	64.2	1.6
10	100.0	81.8	1.9
11	100.0	90.0	2.6
12	100.0	59.6	2.0
13	100.0	91.4	2.7
14	100.0	99.6	3.2
15	100.0	100.0	3.8
16	38.2	5.3	0.3
17	83.6	21.8	0.5
18	100.0	50.4	2.0
19	38.6	11.9	0.5
20	94.3	34.2	1.0
21	99.7	51.4	1.4
22	100.0	76.3	2.7
23	85.5	29.9	1.1
24	98.3	51.8	1.6
25	100.0	63.0	1.9
26	100.0	85.1	2.6
27	100.0	51.0	2.0
28	100.0	76.2	2.7
29	100.0	88.0	3.2
30	100.0	100.0	3.8
31	25.9	3.1	0.3
32	67.2	14.5	0.5
33	100.0	62.7	2.0
34	48.3	15.2	0.5
35	94.6	30.7	1.0
36	99.9	51.3	1.4
37	100.0	85.8	2.7
38	94.3	37.1	1.1
39	98.0	55.9	1.6
40	100.0	67.1	1.9
41	100.0	85.1	2.6
42	100.0	63.2	2.0
43	100.0	84.7	2.7
44	100.0	97.2	3.2

45	100.0	100.0	3.8
46	39.6	5.4	0.3
47	83.7	22.0	0.5
48	100.0	78.8	2.0
49	67.9	20.9	0.5
50	99.5	56.1	1.0
51	100.0	80.2	1.4
52	100.0	99.7	2.7
53	98.3	50.4	1.1
54	100.0	83.5	1.6
55	100.0	91.1	1.9
56	100.0	93.9	2.6
57	100.0	80.4	2.0
58	100.0	99.8	2.7
59	100.0	100.0	3.2
60	100.0	100.0	3.8

Table D2: Daylight performance results of Study A – Advanced Renovation

Variation Number	sDA100/95% [%]	sDA300/50% [%]	DF median [%]
01	27.33	5.107	0.2115
02	67.17	18.54	0.4038
03	86.34	36.76	0.683
04	35.71	11.91	0.3797
05	90.77	31.37	0.7775
06	98.14	54.96	1.082
07	100	77.28	1.525
08	79.38	28.68	0.8999
09	95.52	53.26	1.316
10	99.93	65.3	1.515
11	100	83.71	2.07
12	99.51	47.84	1.618
13	100	76.46	2.177
14	100	88.12	2.585
15	100	99.97	3.2
16	24.6	2.896	0.2115
17	69.32	14.51	0.4038
18	92.95	30.34	0.683
19	29.91	9.078	0.3797
20	84.2	19.44	0.7775
21	96.41	42.13	1.082
22	99.99	62.59	1.525
23	60.29	23.37	0.8999
24	94.09	42.19	1.316
25	98.72	50.5	1.515
26	100	70.06	2.07
27	90.12	39.79	1.618
28	100	60.53	2.177
29	100	71.01	2.585
30	100	95.32	3.2

31	15.61	1.449	0.2115
32	47.95	8.648	0.4038
33	79.19	18.06	0.683
34	36.68	12.26	0.3797
35	85.87	19.26	0.7775
36	95.48	38.68	1.082
37	99.9	57.45	1.525
38	80.96	29.5	0.8999
39	95.15	44.98	1.316
40	98.96	52.3	1.515
41	100	71.24	2.07
42	99.69	49.1	1.618
43	100	69.3	2.177
44	100	77.08	2.585
45	100	95.32	3.2
46	24.82	2.959	0.2115
47	73.82	14.24	0.4038
48	92.84	30.6	0.683
49	36.68	12.26	0.3797
50	95.66	42.49	0.7775
51	100	62.4	1.082
52	100	85.74	1.525
53	94.51	40.24	0.8999
54	99.66	66.24	1.316
55	100	80.81	1.515
56	100	89.02	2.07
57	100	66.15	1.618
58	100	95.46	2.177
59	100	98.8	2.585
60	100	100	3.2

10.5 Appendix E

Control strategies are represented using abbreviations: NC (No Control), MC (Manual Control), and SC (Smart Control).

Table E1: Design Variations of Study B

Variation Number	Natural Ventilation - Roof Window Control	Natural Ventilation – Façade Window Control	Shading - Roof Window Control	Shading - Façade Window Control
1	NC	NC	NC	NC
2	NC	NC	NC	MC
3	NC	NC	NC	SC
4	NC	NC	MC	NC
5	NC	NC	MC	MC
6	NC	NC	MC	SC
7	NC	NC	SC	NC
8	NC	NC	SC	MC
9	NC	NC	SC	SC
10	NC	MC	NC	NC
11	NC	MC	NC	MC
12	NC	MC	NC	SC
13	NC	MC	MC	NC
14	NC	MC	MC	MC
15	NC	MC	MC	SC
16	NC	MC	SC	NC
17	NC	MC	SC	MC
18	NC	MC	SC	SC
19	NC	SC	NC	NC
20	NC	SC	NC	MC
21	NC	SC	NC	SC
22	NC	SC	MC	NC
23	NC	SC	MC	MC
24	NC	SC	MC	SC
25	NC	SC	SC	NC
26	NC	SC	SC	MC
27	NC	SC	SC	SC
28	MC	NC	NC	NC
29	MC	NC	NC	MC
30	MC	NC	NC	SC
31	MC	NC	MC	NC
32	MC	NC	MC	MC
33	MC	NC	MC	SC
34	MC	NC	SC	NC
35	MC	NC	SC	MC
36	MC	NC	SC	SC
37	MC	MC	NC	NC
38	MC	MC	NC	MC
39	MC	MC	NC	SC
40	MC	MC	MC	NC

41	MC	MC	MC	MC
42	MC	MC	MC	SC
43	MC	MC	SC	NC
44	MC	MC	SC	MC
45	MC	MC	SC	SC
46	MC	SC	NC	NC
47	MC	SC	NC	MC
48	MC	SC	NC	SC
49	MC	SC	MC	NC
50	MC	SC	MC	MC
51	MC	SC	MC	SC
52	MC	SC	SC	NC
53	MC	SC	SC	MC
54	MC	SC	SC	SC
55	SC	NC	NC	NC
56	SC	NC	NC	MC
57	SC	NC	NC	SC
58	SC	NC	MC	NC
59	SC	NC	MC	MC
60	SC	NC	MC	SC
61	SC	NC	SC	NC
62	SC	NC	SC	MC
63	SC	NC	SC	SC
64	SC	MC	NC	NC
65	SC	MC	NC	MC
66	SC	MC	NC	SC
67	SC	MC	MC	NC
68	SC	MC	MC	MC
69	SC	MC	MC	SC
70	SC	MC	SC	NC
71	SC	MC	SC	MC
72	SC	MC	SC	SC
73	SC	SC	NC	NC
74	SC	SC	NC	MC
75	SC	SC	NC	SC
76	SC	SC	MC	NC
77	SC	SC	MC	MC
78	SC	SC	MC	SC
79	SC	SC	SC	NC
80	SC	SC	SC	MC
81	SC	SC	SC	SC

10.6 Appendix F

All tables follow the variation numbering defined in Appendix E.

Table F1: Thermal Comfort performance results of Study B – Typical Renovation

Variation Number	Category I Hours [%]	Category II Hours [%]	Category III Hours [%]	Category IV Hours [%]	Overheating Hours [h]	Underheating Hours [h]	Thermal Comfort Score
1	12.9%	31.7%	27.9%	22.9%	1996	6	2.51
2	13.3%	31.6%	28.3%	22.1%	1933	6	2.50
3	20.5%	34.0%	28.8%	12.1%	1032	26	2.23
4	13.8%	31.9%	28.5%	21.1%	1846	6	2.48
5	14.1%	32.3%	28.6%	20.4%	1777	7	2.46
6	22.4%	34.2%	29.2%	9.6%	814	25	2.17
7	24.4%	35.4%	29.3%	6.3%	535	16	2.08
8	25.3%	35.3%	29.2%	5.5%	469	15	2.06
9	37.8%	31.1%	26.0%	0.4%	5	28	1.80
10	30.9%	31.8%	26.7%	6.0%	510	18	1.98
11	31.1%	31.8%	26.6%	6.0%	503	19	1.98
12	34.3%	32.1%	26.8%	2.1%	157	26	1.87
13	31.2%	31.8%	26.5%	5.9%	495	19	1.98
14	31.3%	31.7%	26.5%	5.8%	489	19	1.98
15	34.5%	32.1%	26.8%	1.9%	142	26	1.87
16	35.9%	32.3%	26.4%	0.8%	45	21	1.83
17	36.0%	32.2%	26.4%	0.7%	41	23	1.83
18	39.1%	30.4%	25.6%	0.3%	0	29	1.78
19	36.8%	31.4%	26.0%	1.2%	69	32	1.82
20	36.9%	31.2%	26.1%	1.1%	66	32	1.82
21	37.1%	31.9%	25.9%	0.4%	0	32	1.80
22	36.8%	31.3%	26.1%	1.1%	65	32	1.82
23	36.8%	31.3%	26.1%	1.1%	63	32	1.82
24	37.2%	31.9%	25.9%	0.4%	0	32	1.80
25	37.7%	31.9%	25.3%	0.4%	0	32	1.79
26	37.7%	31.8%	25.5%	0.4%	0	31	1.79
27	38.1%	31.3%	25.6%	0.4%	0	31	1.79
28	28.0%	32.6%	27.2%	7.5%	641	13	2.05
29	28.3%	32.6%	27.1%	7.3%	627	14	2.04
30	33.1%	32.6%	26.8%	2.8%	223	26	1.90
31	28.9%	32.4%	27.1%	6.9%	594	13	2.03
32	29.3%	32.2%	27.0%	6.8%	580	14	2.02
33	33.6%	32.3%	27.0%	2.4%	187	26	1.89
34	35.4%	32.4%	26.5%	1.1%	74	19	1.84
35	35.4%	32.4%	26.5%	1.0%	66	19	1.84
36	39.0%	30.4%	25.6%	0.3%	0	29	1.78
37	31.5%	31.6%	26.5%	5.8%	485	19	1.97
38	31.5%	31.7%	26.5%	5.7%	477	20	1.97
39	34.5%	32.1%	26.8%	2.0%	147	26	1.87
40	31.6%	31.7%	26.5%	5.6%	468	20	1.97
41	31.6%	31.6%	26.6%	5.5%	462	20	1.97

42	34.7%	31.9%	26.8%	1.9%	138	26	1.87
43	36.1%	32.2%	26.3%	0.7%	42	22	1.82
44	36.1%	32.1%	26.3%	0.7%	41	22	1.82
45	39.1%	30.3%	25.6%	0.3%	0	30	1.78
46	36.9%	31.2%	26.1%	1.1%	66	32	1.82
47	36.9%	31.2%	26.0%	1.1%	65	32	1.82
48	37.2%	31.9%	25.8%	0.4%	0	32	1.80
49	36.9%	31.3%	26.1%	1.1%	64	32	1.82
50	36.9%	31.3%	26.1%	1.1%	62	32	1.82
51	37.2%	31.9%	25.9%	0.4%	0	32	1.80
52	37.8%	31.7%	25.5%	0.4%	0	32	1.79
53	37.7%	31.7%	25.5%	0.4%	0	31	1.79
54	38.1%	31.2%	25.7%	0.4%	0	31	1.79
55	34.6%	31.9%	26.2%	2.6%	200	28	1.87
56	34.8%	31.8%	26.2%	2.6%	196	28	1.87
57	36.2%	31.8%	26.6%	0.7%	29	32	1.82
58	34.8%	31.7%	26.2%	2.5%	193	28	1.87
59	35.0%	31.7%	26.3%	2.3%	178	27	1.87
60	36.3%	31.8%	26.5%	0.7%	25	32	1.82
61	37.4%	31.8%	25.8%	0.4%	8	30	1.80
62	37.4%	31.7%	25.9%	0.4%	5	30	1.80
63	38.1%	31.2%	25.6%	0.4%	0	32	1.79
64	35.7%	31.5%	26.1%	2.1%	155	27	1.85
65	35.6%	31.6%	26.0%	2.1%	153	28	1.85
66	36.5%	31.9%	26.4%	0.5%	15	32	1.82
67	35.7%	31.6%	26.1%	2.0%	151	27	1.85
68	35.7%	31.5%	26.1%	2.0%	148	28	1.85
69	36.5%	31.9%	26.4%	0.5%	11	32	1.82
70	37.5%	31.7%	25.7%	0.4%	1	31	1.80
71	37.5%	31.8%	25.7%	0.4%	1	30	1.80
72	38.0%	31.3%	25.8%	0.4%	0	32	1.79
73	37.1%	31.7%	25.6%	1.0%	52	32	1.81
74	37.0%	31.6%	25.7%	0.9%	48	32	1.81
75	37.5%	31.7%	25.8%	0.4%	0	32	1.80
76	37.1%	31.5%	25.8%	0.9%	48	32	1.81
77	37.1%	31.6%	25.8%	0.9%	47	32	1.81
78	37.5%	31.7%	25.8%	0.4%	0	32	1.80
79	37.9%	31.7%	25.3%	0.4%	0	32	1.79
80	37.9%	31.6%	25.5%	0.4%	0	31	1.79
81	38.1%	31.3%	25.6%	0.4%	0	31	1.79

Table F2: Thermal Comfort performance results of Study B – Advanced Renovation

Variation Number	Category I Hours [%]	Category II Hours [%]	Category III Hours [%]	Category IV Hours [%]	Overheating Hours [h]	Underheating Hours [h]	Thermal Comfort Score
1	11.9%	31.1%	25.4%	26.9%	2359	0	2.58
2	12.0%	31.4%	25.5%	26.4%	2310	0	2.57
3	18.4%	34.0%	27.9%	15.0%	1314	0	2.30
4	12.4%	31.5%	25.8%	25.6%	2242	0	2.55

5	12.8%	31.6%	26.0%	25.0%	2186	0	2.54
6	20.4%	34.3%	28.0%	12.6%	1101	1	2.23
7	22.9%	34.9%	28.6%	8.9%	779	0	2.14
8	23.8%	35.2%	28.6%	7.8%	681	0	2.11
9	39.4%	31.2%	24.6%	0.1%	5	4	1.76
10	31.9%	31.9%	25.0%	6.6%	575	0	1.97
11	32.0%	31.8%	25.0%	6.5%	567	0	1.97
12	35.2%	32.3%	25.7%	2.2%	191	1	1.86
13	32.2%	31.8%	24.9%	6.4%	559	0	1.96
14	32.4%	31.7%	24.9%	6.3%	552	0	1.96
15	35.3%	32.3%	25.7%	2.0%	174	1	1.85
16	37.6%	32.0%	25.0%	0.8%	68	0	1.80
17	37.6%	32.1%	24.9%	0.7%	65	0	1.79
18	41.0%	30.2%	24.1%	0.0%	0	4	1.74
19	38.7%	31.2%	24.5%	1.0%	84	2	1.78
20	38.7%	31.1%	24.6%	0.9%	81	2	1.78
21	39.1%	31.6%	24.6%	0.0%	1	3	1.76
22	38.8%	31.0%	24.6%	1.0%	82	2	1.78
23	38.8%	31.0%	24.7%	0.9%	77	2	1.78
24	39.1%	31.5%	24.8%	0.0%	0	2	1.76
25	40.0%	31.3%	24.0%	0.0%	0	2	1.75
26	39.9%	31.4%	24.0%	0.0%	0	2	1.75
27	40.1%	31.0%	24.2%	0.0%	0	2	1.75
28	27.9%	32.9%	25.8%	8.8%	768	0	2.06
29	28.4%	32.7%	25.7%	8.4%	737	0	2.05
30	33.8%	32.6%	25.9%	2.9%	257	1	1.89
31	29.0%	32.9%	25.5%	8.0%	700	0	2.03
32	29.4%	32.7%	25.5%	7.7%	674	0	2.02
33	34.4%	32.6%	25.9%	2.5%	216	1	1.87
34	36.9%	32.1%	25.2%	1.1%	98	0	1.81
35	37.0%	32.2%	25.1%	1.1%	92	0	1.81
36	40.9%	30.2%	24.1%	0.0%	0	4	1.74
37	32.6%	31.6%	24.8%	6.3%	553	0	1.96
38	32.6%	31.7%	24.8%	6.2%	546	0	1.95
39	35.4%	32.3%	25.6%	2.1%	179	1	1.85
40	32.8%	31.7%	24.7%	6.1%	535	0	1.95
41	32.9%	31.7%	24.7%	6.0%	530	0	1.95
42	35.5%	32.3%	25.6%	2.0%	172	1	1.85
43	37.8%	31.9%	24.9%	0.7%	63	0	1.79
44	37.8%	32.0%	24.9%	0.7%	60	0	1.79
45	41.0%	30.2%	24.1%	0.0%	0	4	1.74
46	38.7%	31.1%	24.6%	0.9%	80	2	1.78
47	38.8%	31.1%	24.6%	0.9%	78	2	1.78
48	39.2%	31.4%	24.7%	0.0%	1	2	1.76
49	38.8%	31.0%	24.6%	0.9%	78	2	1.78
50	38.9%	30.9%	24.7%	0.9%	75	2	1.78
51	39.2%	31.4%	24.8%	0.0%	0	2	1.76
52	40.0%	31.3%	24.1%	0.0%	0	2	1.75

53	39.9%	31.3%	24.0%	0.0%	0	2	1.75
54	40.1%	30.9%	24.4%	0.0%	0	2	1.75
55	36.0%	32.0%	24.8%	2.6%	225	1	1.85
56	36.1%	31.8%	24.9%	2.5%	216	1	1.84
57	38.0%	31.5%	25.4%	0.4%	34	3	1.79
58	36.3%	31.7%	25.0%	2.4%	211	1	1.84
59	36.4%	31.6%	24.9%	2.3%	204	1	1.84
60	38.1%	31.4%	25.5%	0.3%	26	3	1.79
61	39.5%	31.2%	24.6%	0.1%	8	1	1.76
62	39.5%	31.3%	24.5%	0.1%	6	2	1.76
63	40.1%	31.0%	24.2%	0.0%	0	3	1.75
64	37.2%	31.6%	24.6%	2.0%	173	1	1.82
65	37.2%	31.5%	24.6%	2.0%	173	1	1.82
66	38.4%	31.4%	25.3%	0.2%	18	3	1.78
67	37.2%	31.5%	24.6%	2.0%	171	1	1.82
68	37.2%	31.5%	24.7%	1.9%	166	1	1.82
69	38.4%	31.4%	25.3%	0.2%	16	3	1.78
70	39.7%	31.2%	24.4%	0.0%	2	2	1.75
71	39.7%	31.2%	24.4%	0.0%	2	2	1.75
72	40.0%	31.0%	24.4%	0.0%	0	3	1.75
73	39.0%	31.5%	24.1%	0.8%	64	2	1.77
74	39.0%	31.3%	24.3%	0.7%	63	2	1.77
75	39.5%	31.3%	24.5%	0.0%	0	2	1.76
76	39.1%	31.2%	24.3%	0.7%	63	2	1.77
77	39.1%	31.2%	24.3%	0.7%	61	2	1.77
78	39.4%	31.2%	24.7%	0.0%	0	2	1.76
79	40.1%	31.2%	24.0%	0.0%	0	2	1.75
80	40.1%	31.2%	24.0%	0.0%	0	2	1.75
81	40.1%	30.9%	24.2%	0.0%	0	2	1.75

10.7 Appendix G

Control strategies are represented using abbreviations: NC (No Control), MC (Manual Control), and SC (Smart Control).

Table G1: Design Variations of Study C

Variation Number	Natural Ventilation - Roof Window Control	Natural Ventilation – Façade Window Control	Shading - Roof Window Control	Shading - Façade Window Control
0	NC	NC	NC	NC
1	NC	NC	MC	MC
2	MC	MC	NC	NC
3	MC	MC	MC	MC
4	NC	NC	SC	SC
5	SC	SC	NC	NC
6	SC	SC	SC	SC

10.8 Appendix H

All tables follow the variation numbering defined in Appendix G.

Table H1: Thermal Comfort performance results of Study C – Typical Renovation

Variation Number	Category I Hours [%]	Category II Hours [%]	Category III Hours [%]	Category IV Hours [%]	Overheating Hours [h]	Underheating Hours [h]	Thermal Comfort Score
0	16.6%	27.1%	27.3%	28.1%	2465	0	2.65
1	17.4%	27.5%	27.8%	26.5%	2320	1	2.62
2	37.0%	28.4%	26.3%	7.5%	644	9	2.02
3	37.3%	28.4%	26.3%	7.1%	614	9	2.02
4	40.6%	28.9%	27.7%	1.9%	152	11	1.89
5	41.4%	30.1%	26.2%	1.4%	114	12	1.86
6	42.2%	30.4%	26.4%	0.3%	8	14	1.83

Table H2: Thermal Comfort performance results of Study C – Advanced Renovation

Variation Number	Category I Hours [%]	Category II Hours [%]	Category III Hours [%]	Category IV Hours [%]	Overheating Hours [h]	Underheating Hours [h]	Thermal Comfort Score
0	16.2%	26.0%	25.5%	31.5%	2760	0	2.71
1	16.6%	26.5%	26.0%	30.0%	2630	0	2.68
2	39.0%	27.7%	24.7%	7.8%	681	1	2.00
3	39.2%	27.8%	24.7%	7.5%	652	1	1.99
4	41.1%	29.4%	26.6%	2.1%	180	0	1.88
5	43.8%	29.4%	24.6%	1.4%	118	4	1.82
6	44.0%	30.3%	24.7%	0.2%	8	6	1.79



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