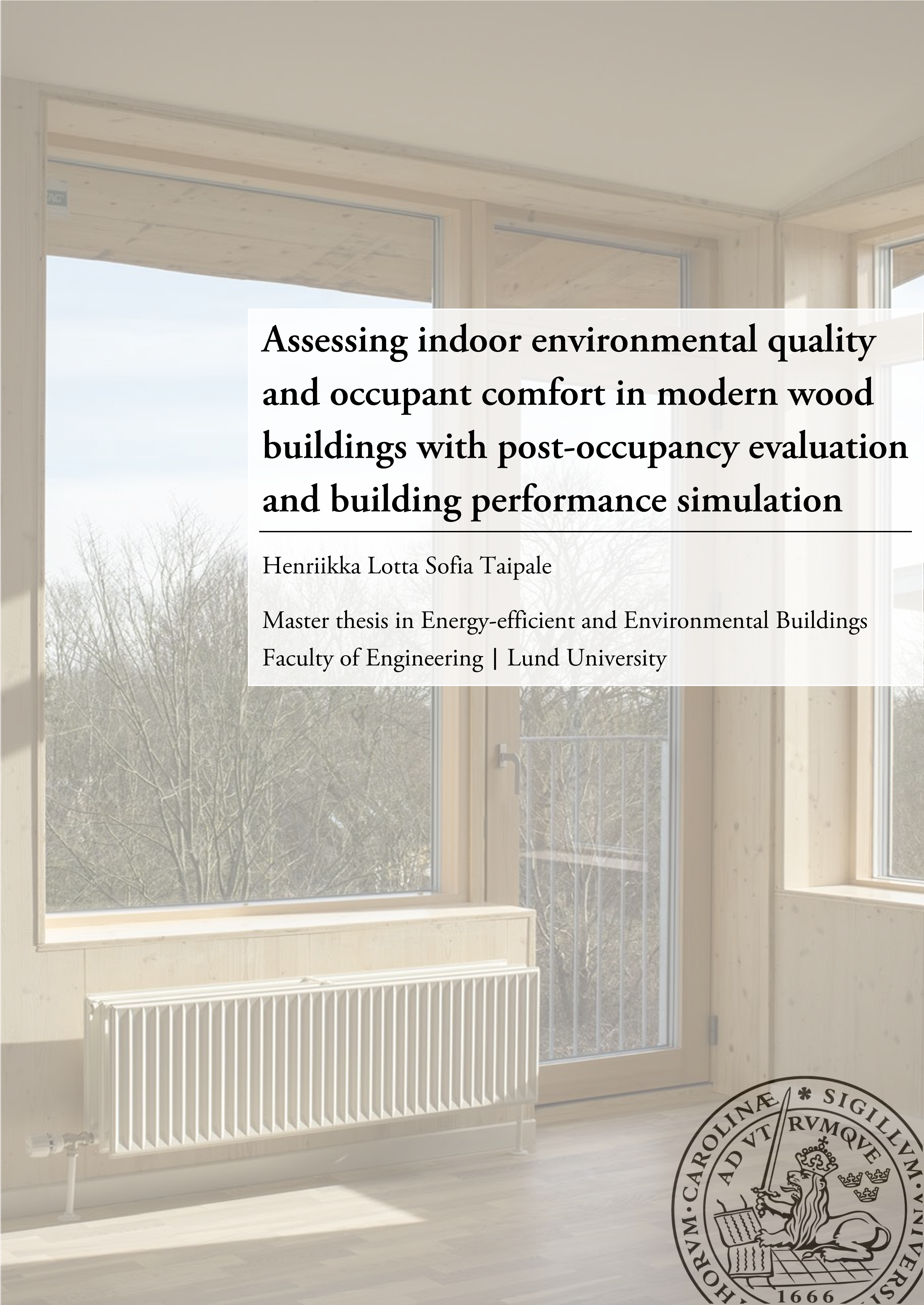

Assessing indoor environmental quality and occupant comfort in modern wood buildings with post-occupancy evaluation and building performance simulation

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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.

Master Programme in Energy-efficient and Environmental Building Design

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' behavior 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 European building sector is a source of significant negative environmental impacts, and large part of its carbon emissions can be attributed to heating, cooling and lighting of buildings – in other words, regulating buildings' indoor environments. As people spend most of their lives indoors, there is a great challenge to create comfortable indoor environments, while also striving for further energy-efficiency and lower environmental impact. There is a growing interest in natural and renewable building materials such as wood that can address these challenges, while simultaneously substituting other, more harmful materials.

This study investigates the attributes affecting indoor environmental quality in multi-story wood buildings and evaluates the performance of a case study building in Aarhus, Denmark. The parameters included in the study are thermal comfort, indoor air quality, acoustic performance and daylight availability. These indoor environmental conditions are assessed on the basis of a post-occupancy evaluation survey, simulated building performance data and recorded measurements. Based on the findings, suitable methods for predicting and evaluating indoor environmental performance in the design phase for future wood buildings are identified, and the usability of the occupant survey is reviewed.

The post-occupancy evaluation generated valuable insight into the subjective perceptions of the occupants, and pinpointed problem areas on different levels. The building performance simulations accurately predicted the thermal discomfort experienced by the occupants, and should be incorporated into early design stages of future projects to help mitigate issues. The demand for better occupant control over indoor conditions, as well as opportunities for design optimization within acoustic and daylight performance were identified. Analyzing the diurnal latent heat and moisture flux of the wood surfaces is proposed as future work on the subject.

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In regards to the case study building, the author gratefully acknowledges permission to use the DGNB documentation from the building owner Al2Bolig.

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Nomenclature

ASE	Annual sunlight exposure
BPS	Building performance simulations
BR10/BR15	The Danish building regulations
CLT	Cross-laminated timber
DfD	Design for Disassembly
DGNB	The German sustainable building council
DLT	Dowel-laminated timber
EU	European Union
EWP	Engineered wood products
GDPR	The General Data Protection Regulation
GHG	Greenhouse gas
GLT	Glued laminated timber, “glulam”
IAQ	Indoor air quality
IEQ	Indoor environmental quality
IES	The Illuminating Engineering Society
IPCC	Intergovernmental Panel on Climate Change
LBL	Laminated bamboo lumber
LCA	Life-cycle assessment
LCI	Lowest concentration of interest
LVL	Laminated veneer lumber
OTS	Observed thermal sensation
PMV	Predicted mean vote
POE	Post-occupancy evaluation
PPD	Predicted percentage of dissatisfied
RH	Relative humidity
sDA	Spatial daylight autonomy
SDG	Sustainable Development Goals
TMY	Typical meteorological year
TVOC	Total volatile organic compound
UN	The United Nations
WLT	Wave-layered timber
WWR	Window-to-wall ratio

Notation

°C	Degrees Celsius	[-]
K	Degrees Kelvin	[-]
r_s	Spearman’s rank correlation coefficient	[-]
SHGC / g-value	Solar energy transmittance	[%]
T_a	Temperature, indoor air	[°C]
T_c	Temperature, indoor operative	[°C]
T_o	Temperature, outdoor mean	[°C]
ΔT	Temperature difference	[K]
U-value	Thermal conductance	[W/m²·K]
T_{vis}	Visible transmittance	[%]

1 Introduction and problem motivation

The European building sector is responsible for half of all extracted materials, half of the total energy consumption, a third of water consumption and a third of all waste generation when considering a building's full lifecycle (European Commission, 2021). People spend more than 90 % of their lives indoors (WHO, 2013). The COVID-19 pandemic has further increased the time spent indoors, which might not be a temporary effect due to people getting used to working from home, substituting business travel with virtual meetings, and favoring online shopping.

In efforts to mitigate a climate crisis, increasingly stringent national and international measures have been introduced to increase energy-efficiency and reduce carbon emissions of the built environment. The green transition has been further driven by the increasing adoption of building certification systems. This development has had a fundamental impact on design choices and performance objectives of modern construction projects, and resulted in a shift concerning material consumption.

To address the environmental challenges and occupant well-being, there is an increasing interest in using natural and renewable building materials, and ensuring a healthy indoor environment. Over the past two decades, timber has been re-emerging in new, technologically advanced forms. Structural massive wood elements have become popular, often remaining exposed as finished interior surfaces. The exposed wood surfaces have been shown to impact a building's indoor environmental quality, energy performance as well as comfort, wellbeing and health of the occupants.

The impact of wooden materials on measured and perceived indoor environmental quality, energy performance and occupant comfort has been explored by a growing number of studies. Particularly the emissions of chemical compounds, the moisture buffering capacity and the latent heat of sorption, as well as the psychological effects on thermal comfort have been investigated, among various other aspects.

Post-occupancy evaluation has been used as a research method to assess the occupant behavior and perceptions of the indoor environment in conjunction with building performance assessments. Post-occupancy evaluations for different types of buildings can have very different purposes and methods and as such, no post-occupancy evaluation framework for multi-story timber buildings has yet been developed and made publicly available. Investigating the properties of indoor environmental quality in wooden buildings with post-occupancy evaluations is a new field pioneered by few studies so far.

1.1 Aims of the study

The main aim of this study is to assess the variables and properties affecting the indoor environmental quality (IEQ) in wood buildings, and to find a method to holistically evaluate the building performance of a case study building utilizing a cross-analysis of a post-occupancy evaluation survey (POE) with simulated and measured data.

The second aim is to find suitable methods for predicting and evaluating the IEQ in a wood building in the design phase to achieve optimal performance and occupant comfort in the operational phase, and to find a common method for POEs of modern wood buildings.

1.2 Goals and objectives

The objective is to (i) carry out a literature review summarizing the status quo of research on the attributes impacting IEQ and occupant comfort in wood buildings, (ii) find out if there is a suitable POE method or if a method can be suggested for multi-story timber buildings (iii) carry out a case study POE and compare the findings against simulated and measured data, and (iv) propose suitable methods for evaluating the IEQ of wood buildings.

This study combines a POE with simulation-based analyses and calculation methods to answer the following research questions:

- What is the current state of the art on the properties affecting the IEQ and occupant comfort in multi-story wood buildings?
- Is there a common method for carrying out POE for indoor climate investigations in multi-story wood buildings?
- Does the case study data correlate with simulated and surveyed results?

Additionally, the following questions are answered based on the findings of the study:

- Can a method for carrying out POEs in multi-story wood buildings be suggested?
- Can suitable methods for predicting and evaluating the IEQ of multi-story wood buildings in the design phase be suggested?

1.3 Scope and limitations

The study investigated one individual building and only a part of it, so findings and conclusions may not be applicable for other buildings. Building performance simulations were based on a simplified model of the case study building and using a single software without being validated by other methods. Furthermore, the study included newly introduced methods and theories that have not yet been fully validated, and should therefore be critically assessed.

2 Theoretical background

2.1 Climate change

Climate change, or as increasingly referred to, the climate crisis is one of the greatest challenges humankind has had to face and poses an existential threat to the planet. The latest Intergovernmental Panel on Climate Change special report on Global Warming (IPCC, 2018) states that warming greater than the global annual average is being experienced in many land regions and urban environments, and that temperature extremes and the number of hot days on land are projected to increase more than on ocean regions. *Figure 1* effectively summarizes the estimated rise in global surface air temperature relative to the 1850–1900 reference period.

In the Northern Hemisphere, where the four seasons were once observed in a predictable pattern, the summers are getting longer and hotter, while winters get shorter and warmer. A recent study found that without further climate change mitigation efforts, summers in the Northern Hemisphere's mid-latitudes may span six months by the year 2100, causing significant environmental and health risks (Wang et al., 2021).

The rising outdoor temperatures also increase the incidence of overheating in buildings. Excessive indoor temperatures affect the health and wellbeing of occupants and can lead to premature mortality. Extreme historical examples worth mentioning are the European heatwaves of 2003 with an estimated 70 000 casualties (Watts et al., 2017) and 2019, with a record temperature of 45,9 °C measured in France (Mitchell et al., 2019). The year 2020 was the warmest on record in Europe, and one of the three warmest years on record globally (Copernicus Climate Change Service (C3S), 2021). The evidence is clear that severe heatwaves will become more frequent as the climate continues to warm, which means that the buildings used as shelter from the elements need to adapt accordingly.

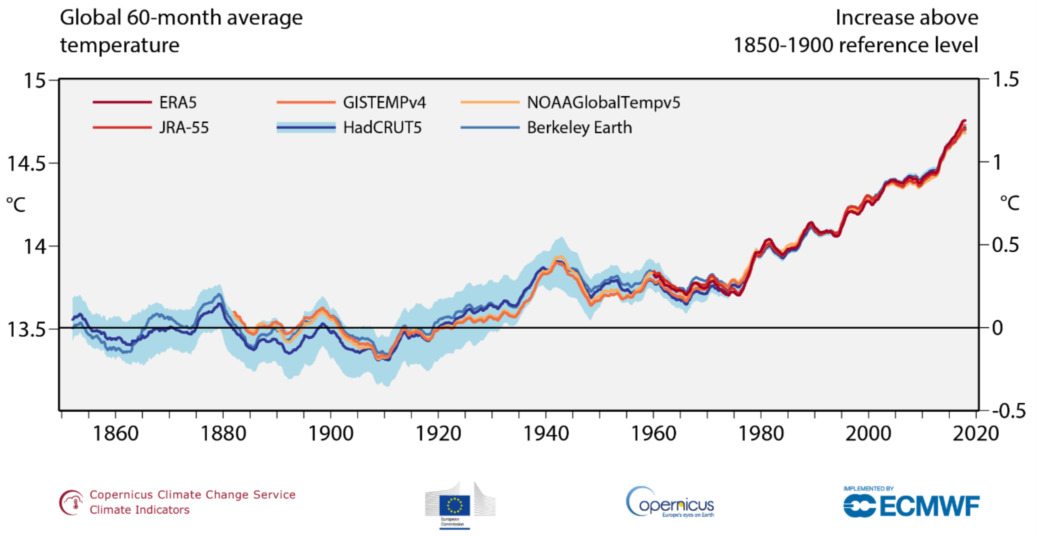


Figure 1. The estimated difference in global surface air temperature relative to the 1850–1900 reference period, according to six datasets. Source: C3S/ECMWF.

Environmental concerns have been driving the building industry to strive for higher energy-efficiency especially by means of reducing heat loss or gain. In heating-dominated climates, this can often effectively be achieved by increasing the insulation of the building envelope and reducing infiltration with air-tight seals. In latitudes with cold winters, the attention has been on retaining heat within the buildings, but evidence suggests it will be equally if not more important to equip buildings for summertime overheating in the coming decades.

2.2 Embodied impacts and material depletion

The building industry is responsible for 39 % of global carbon emissions and 28 % is resulting from operational emissions from the energy used for heating, cooling and lighting of buildings (WorldGBC, 2019) – in other words, regulating buildings' indoor environments. The other 11 % comes from embodied carbon relating to the greenhouse gas (GHG) emissions of materials and processes accumulated throughout a building's lifecycle. An estimated 80 % of the embodied carbon emissions originate from the structural frame, making the informed choice of structural materials a crucial step in determining the environmental impact of a building.

The scientific methodology of life-cycle assessment (LCA) determines the embodied carbon of a product, service or process over declared life-cycle stages. It has become a widely adopted tool for quantifying the potential environmental impact in the building industry, especially in Northern Europe, and has been included in many building certification schemes. With LCA, it has become easy to critically compare the impacts of all the stages of a building process; from raw material extraction to the manufacturing of the construction products, through the building process and the operational stage, all the way to demolition or preferably reuse, repurposing or recycling of materials.

By carrying out such environmental impact assessments it has become evident that traditional mineral-based building materials, such as steel and concrete, cause a tremendous environmental impact. Reports show that the raw ingredients required to produce said mineral-based materials are being depleted at an alarming rate. Primary metal supplies are projected to be exhausted within 50 years (Jowitt et al., 2020), and sand and gravel are being extracted at a rate far greater than their renewal, causing massive destruction to biodiversity and climate (Peduzzi, 2014).

Bio-based building materials have therefore become the subject of extensive research and scrutiny in search of alternative methods for building, renovating and extending our buildings. The main benefits of bio-based building materials are seen in renewability, low environmental impact and carbon storage capacity. There is a new understanding that instead of emitting GHG and contributing to the climate crisis, the built environment has the potential to store embedded carbon and act as a carbon sink. Another aspect to consider is the substitution effect: a quantifiable amount of GHG emissions is avoided when a bio-based material is chosen over a mineral-based alternative.

One of the widely available, traceable, bio-based materials today is wood. The following chapter will examine the properties of wood as a construction material and how modern wood products may contribute to not only achieving the common environmental goals, but also a better indoor environment.

2.3 Wood as a construction material

Wood is one of the longest-standing building materials in existence, as using wood can be traced back thousands of years. In forested regions, wood has been used for shelter building and structures such as bridges, and in areas with less timber supply, combined with materials like brick and clay.

Following numerous city fires in the 19th century, wood used to be feared for its combustibility and several European countries introduced regulations to limit the usage of wood in construction. These regulations considerably hindered multi-story timber construction, leading to a decline of skill and experience among building professionals. In the 20th century, steel and reinforced concrete became state of the art construction materials, further diminishing structural timber construction to mainly small-scale light-weight constructions, sports halls and log houses (Brandner et al., 2016).

Prefabricated engineered timber products were developed in the 1990s in Alpine Europe as a result of research by the sawmill industry aiming to utilize the surplus of low-grade timber produced (Falk, 2013). The development was driven by the Austrian and German timber industries, where suitable softwoods such as spruce and pine were widely available (Dickson & Parker, 2014). The continuous development has produced a range of products with high dimensional stability and load-bearing capacity, resulting in an increasing market share. This has enabled completely new technical solutions and building systems that make it possible to raise tall buildings with structural timber frames. Although there is no common definition for a modern wood building, the term typically refers to buildings where the main load-bearing structure is predominantly built with wood.

The climate crisis and environmental concerns are also driving the increase of wood in the construction sector. As buildings become more energy-efficient and the operational emissions are reduced, the embodied carbon emissions become more prominent in the overall carbon footprint of a building. Trees sequester carbon dioxide from the atmosphere during their growth phase, and once the trees are felled and processed into lumber or veneered wood, the carbon remains embedded in the end product. When the wood product is used in a building designed for long service life, the building becomes a carbon sink where the embedded carbon is retained for the lifetime of the building.

2.3.1 Engineered wood products

Over the past few decades, timber has regained market share from traditional mineral-based construction materials such as steel and concrete. This development can at least in part be credited to the advancements in wood technology and increasing commercial availability of the first engineered wood products (EWPs), such as glue-laminated timber (GLT), laminated veneer lumber (LVL) and cross-laminated timber (CLT) panels.

GLT, or glulam, is made by bonding together layers of solid timber boards with structural adhesives where each board runs parallel to the longitudinal axis of the element. Glulam elements are typically used as load-bearing joists, beams and columns. LVL is made with rotary peeled parallel-running wood veneers that have been sliced to thin layers and are bonded under heat and pressure. LVL elements are typically used as load-bearing beams, trusses and rafters. CLT is made by bonding together an odd number of softwood layers with structural adhesive under pressure, where each layer is placed at a right angle in relation to the previous one. CLT panels are typically used as load-bearing wall, floor and roof elements. The above-mentioned EWPs have become widely available in the European construction market, and further innovations such as dowel-laminated timber (DLT), wave-layered timber (WLT) and laminated bamboo lumber (LBL) are being developed worldwide.

As part of the European Green Deal goal of becoming climate neutral by 2050, the EU established a goal of designing buildings aligning with the circular economy. That entails choosing materials that last for a long time and repurposing them at the end of their service life. While no single material should be hailed as the ultimate answer to net-zero carbon emissions, bio-based products such as EWPs can play an important role in advancing the circular economy.

2.4 Indoor environmental quality

A building’s indoor environment is a complex concept affected by various physical, chemical and biological factors. In turn, the indoor environment affects the health, productivity and comfort of its occupants. As people in Western countries spend most of their lives indoors, it is a relevant goal to provide indoor environments that benefit physical and mental health, and the overall wellbeing of the occupants.

There are many definitions for the indoor environment, or indoor climate, some of them considering details such as ergonomics of the occupants, vibrations of the building structure, and electrical or magnetic fields generated within a building. In this study, the indoor environmental quality (IEQ) parameters considered are those of the thermal environment (including heat, cold, draughts and humidity), the atmospheric environment (including emissions and air quality), the acoustic environment (airborne and impact noise) and visual environment (daylight availability).

To understand how individual indoor environmental factors impact human health and well-being, and how to identify components needed to advance research, Wierzbicka et al. (2018) explored interactions between different factors and potential risks involved. Four themes were identified: (i) the bio-psycho-social aspects of health; (ii) interaction between occupants, buildings and the indoor environment; (iii) climate change and its impact on indoor environment quality, thermal comfort and health; and (iv) energy-efficiency measures and indoor environment. The latter two have already been briefly discussed in this chapter, and the first two are further explored in the following chapters.

2.4.1 Thermal environment

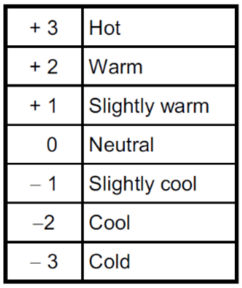
Thermal comfort is defined as the condition of mind that expresses satisfaction with the thermal environment, and therefore is a highly subjective experience. For many building occupants, thermal comfort is more important than visual and acoustic comfort, and good air quality (Frontczak & Wargocki, 2011). When people feel thermal discomfort, their actions depend on the available opportunities to increase comfort, and their understanding of the likely impact of taking that action (Lomas & Porritt, 2017).

The classic understanding of human thermal comfort is that thermal comfort is the result of the body’s heat exchange with its environment. For the past five decades, international standards for thermal comfort such as ISO 7730 (2006), ASHRAE 55 (2017), and EN 16798

(2019), have been based on the steady-state human body heat balance that suggests the optimal occupant comfort state is when a person is feeling neither warm nor cold (Fanger, 1970). Fanger's classic comfort theory is based on the seven-point scale of thermal sensation registering a predicted mean vote (PMV), as shown in *Figure 2*.

According to the ASHRAE definition, thermal comfort is influenced by the four environmental factors of air temperature, radiant temperature, air speed and humidity, and the two personal factors of metabolic rate and clothing insulation. Therefore, all the above-described factors need to be considered when seeking to achieve thermal comfort.

Thermal comfort can be expressed as PMV, which consists of a 7-point scale describing how a group of people experience thermal comfort in given conditions. The PMV can be used to check whether a given thermal environment complies with comfort criteria, and to establish requirements for different levels of acceptability. The goal is that at least 80 % of occupants are satisfied. Consequently, the proportion of respondents dissatisfied with the thermal comfort conditions is expressed as Predicted Percentage of Dissatisfied (PPD).



+ 3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral
− 1	Slightly cool
−2	Cool
− 3	Cold

Figure 2. The 7-point thermal sensation scale. Source: EN ISO 7730.

In the past two decades, there has been increasing consensus that psychological effects such as a person's thermal history and adaptation level also influence the perception of thermal comfort in a space (de Dear et al., 2016). The resulting theory is referred to as the adaptive thermal comfort model, which relates the acceptable indoor temperature ranges to the mean outdoor temperature, which varies for the different seasons of the year. The adaptive thermal comfort theory presumes that occupants respond to changing environmental conditions by adjusting their behaviors and expectations. Therefore, moderate temperature variations are well tolerated, because they can easily be countered to regain thermal comfort, for instance by removing a sweater when it gets too warm.

Personal preferences and experience influencing one's expectations are therefore better understood to impact the perceived thermal comfort. For instance, the relative humidity (RH) of the indoor air is affected by the moisture content of outdoor air, ventilation rate and the dynamic sources of moisture, such as occupants and activities. Research has shown that at high levels, RH can impact thermal comfort, perceived IAQ, occupant health, durability of building materials, material emissions and energy consumption (Simonson et al., 2002). For health and hygiene purposes, the ideal range for indoor RH is between 30 % and 55 %.

Increasing air velocity with fans can be used to manipulate thermal comfort. According to The Chartered Institution of Building Services Engineers (CIBSE), a ceiling fan generating a 0,5 m/s air speed over a person could be used when temperatures exceed 25 °C to give an improvement in thermal comfort equivalent to reducing the space temperature by about 2 K (CIBSE, 2015). Similarly, the ASHRAE Standard 55 has determined that the upper threshold of acceptable indoor temperature can be increased if the airflow in the occupied zone of a naturally ventilated building is increased. If the indoor operative temperature is > 25 °C, the upper acceptability limits in the adaptive comfort standard can be increased according to Table 1. The EN 16798 also proposes that with indoor operative temperatures

> 25 °C, artificially increased air velocity can be used to compensate for increased air temperatures, and refers to the temperature correction values introduced in *Table 1*.

Table 1. *Indoor operative temperature correction for occupant-controlled, naturally conditioned spaces resulting from increasing air speed. Source: ASHRAE Standard 55 & EN Standard 16798.*

Average air speed [m/s]	**Indoor *Tc* correction [°C]**
0,6	1,2
0,9	1,8
1,2	2,2

The PMV and PPD have been the most widely used thermal comfort indices, yet their performance remains a contested topic. The prediction accuracy of the PMV/PPD methodology was recently tested against a sample size of nearly 85 000 records from the ASHRAE Global Thermal Comfort Database II (Cheung et al., 2019). The accuracy of PMV in predicting observed thermal sensation (OTS) was 34 %, meaning that the thermal sensation is incorrectly predicted two out of three times. The findings were similar for air-conditioned, naturally ventilated and mixed-mode buildings. Additionally, the PPD was found not to be able to predict the dissatisfaction rate.

In a recent review of six existing thermal comfort indices and five new indices, Li et al. (2020) found that most existing thermal comfort indices, especially those based on PMV and PPD, have a weak correlation with subjective long-term thermal satisfaction. Instead, the best performing indices were those that combined the frequency of temperature variations falling outside a comfort range and the frequency of large daily temperature variations. It was concluded that occupants' long-term thermal comfort is more influenced by temperature variations than the average experience over time.

Most thermal comfort standards list indoor operative temperature (Tc) as the required input parameter because it includes both air temperature (Ta) and mean radiant temperature (MRT). However, Li et al. (2020) found that half of the existing indices better predict occupant satisfaction using Ta, and further testing suggests that Ta is sufficient as an input parameter for calculating said indices when Tc has not been measured.

According to ASHRAE 55, the PMV/PPD model is best applied to indoor environments with a stable climate, such as air-conditioned buildings, whereas the adaptive thermal comfort model performs better for naturally ventilated buildings. There is no consensus about which comfort model should be applied for partially air-conditioned buildings.

2.4.1.1 Overheating

The energy-optimization of modern buildings, and the consequent reduction in operational energy demand, have been achieved through improvements in the building envelope to minimize heat transfer. However, lower U-values and infiltration rates combined with larger windows increase the risk of overheating, as the window glazing allows short wavelength solar radiation to enter the building and heat the interior surfaces, which then radiate long infrared waves that cannot escape through the window, causing the heat to get trapped indoors.

Overheating of buildings has been investigated since the late 1980s, but no universally robust definition has been developed to date (Lomas & Porritt, 2017). CIBSE in the UK has developed criteria for assessing overheating risk in residential buildings, but the static model does not consider threshold temperatures as a function of ambient temperature, which makes it incompatible with the adaptive comfort models. The CIBSE TM59 Overheating Methodology (CIBSE, 2017) determines the following compliance criteria:

- For naturally ventilated living rooms, kitchens and bedrooms: The number of hours during which the change in temperature (ΔT) is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 3 % of occupied hours.

- For naturally ventilated bedrooms: To guarantee comfort during the sleeping hours the operative temperature in the bedroom from 10 pm to 7 am shall not exceed 26 °C for more than 1 % of annual hours.

- For mechanically ventilated rooms: All occupied rooms should not exceed an operative temperature of 26 °C for more than 3 % of the annual occupied hours.

Another static method of evaluating overheating is by using the Passivhaus Planning Package (PHPP) criteria (Passivhaus Institut, 2012). The international Passivhaus Standard defines overheating as when indoor temperatures exceed 25 °C, and evaluates performance based on the following criteria describing the time exceeded during occupied hours, as described in *Table 2*.

Table 2. The International Passivhaus Standard evaluation criteria for overheating.

Occupied hours exceeding 25 °C	0 %–2 %	2 %–5 %	5 %–10 %	10 %–15 %	> 15 %
Performance criterion	Excellent	Good	Acceptable	Poor	Catastrophic

At the time of the design process of the case study building, the Danish building regulations stated that the thermal comfort on sunny days must be documented and may not exceed 26 °C for more than 100 h/year, nor 27 °C for more than 25 h/year during occupied hours (Danish Transport, Building and Housing Authority, 2010). Since then, the building regulations have been changed and no longer specify such a range, but more generally describe that a satisfactory thermal indoor climate must be maintained without risk to occupants' health or comfort.

With the introduction of adaptive thermal comfort models in the ANSI/ASHRAE 55 and EN 16798 standards, it has become possible to combine overheating criteria with weather data, whereby the temperature thresholds increase with the mean of the ambient temperature and the threshold is determined by the occupants' thermal sensitivity. The latter defines three IEQ categories: I, II and III, representing high, medium and moderate levels of occupant expectation, respectively. Category IV also exists for values that do not meet the three categories, but should not be accepted for more than part of the year. The discussed thermal comfort and overheating limits are summarized in *Figure 3*.

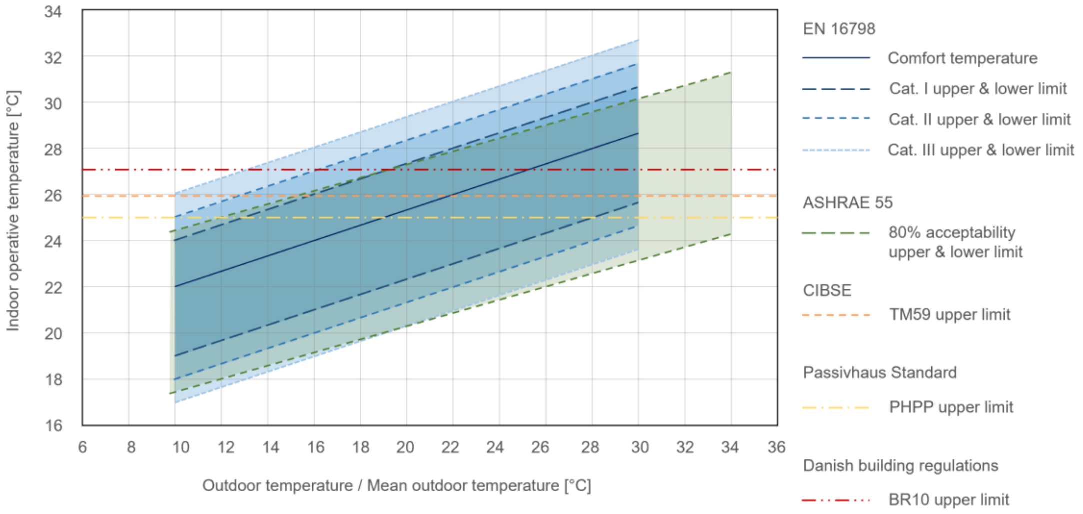


Figure 3. Upper and lower thermal comfort limits for the adaptive thermal comfort standards of EN 16798 and ASHRAE 55. Overheating limits for CIBSE, Passivhaus and BR10.

Dynamic thermal modeling makes it possible to include information on the thermodynamic processes involved and predict outcomes of overheating in buildings, but is dependent on accurate occupancy and internal gain profiles as well as weather data models.

Another approach for investigating overheating is using on-site sensors, which until recently has typically been considered too expensive. Using sensor technology for real-time monitoring and trend-casting combined with a building performance management system could be harnessed to react to the changes in climate conditions and mitigate overheating.

2.4.1.2 Thermal alliesthesia

The psychophysiological concept of alliesthesia challenges the mainstream thermal comfort principles and suggests that thermal perception is more than an outcome of a steady-state heat balance (Cabanac, 1971; de Dear, 2011). Thermal alliesthesia hypothesizes that “any peripheral (skin) thermal stimulus that offsets or counters a thermoregulatory load-error will be pleasantly perceived” or, more simply put, cold stimuli will be perceived as pleasant if the body’s core temperature is elevated above normal temperatures, and warm stimuli will be experienced as pleasant if the body’s core temperature is below normal temperatures. Inversely, a warm peripheral stimulation when the subject’s whole body thermal state is warmer-than-neutral or cool peripheral stimulation when cooler-than-neutral will lead to negative alliesthesia – which is unpleasant (Parkinson & de Dear, 2014).

Parkinson & de Dear point out that all classic human-subject studies of local discomfort, including investigations on radiant temperature asymmetry, draught, vertical air temperature difference and floor surface temperature in practice explored the minimization of negative alliesthesia, but overlooked the aspect of positive alliesthesia, or thermal pleasure.

Thermal alliesthesia is proposed as the more suitable framework for understanding thermal perception under dynamic or non-isothermal conditions. Parkinson suggests that the potential for nonsteady-state indoor thermal environments to lift occupant satisfaction rates could be achieved by catering to the expectations and preferences of individual occupants by creating bespoke microclimates with personalized environmental controls (Parkinson, 2016).

2.4.2 Atmospheric environment

Wood is often referred to as having a pleasant smell, which is due to wood naturally emitting various organic chemical substances. Some of these substances are Volatile Organic Compounds (VOCs) and formaldehyde (Skulberg et al., 2019), which are considered to be pollutants when exceeding certain concentrations in indoor air. The majority of the VOCs are emitted during wood's drying process and generally decrease over time.

With the introduction of massive wood elements in construction, there has been an increased interest in exposing the solid wood surfaces in the interior spaces. This has been especially the case for CLT constructions, where visible CLT wall and ceiling surfaces have been extensively utilized as finished surfaces. While the exposed wood surfaces may contribute to an elevated architectural expression, allow for easy mounting of installations or furniture, and amount to savings in material costs due to omitted conventional surface coverings, the surfaces can also considerably contribute to emissions to the indoor air.

In the European market, massive wood elements are typically manufactured with locally available certified softwoods, such as pine, considered a high-emitting wood species, and spruce, which is considered a low-emitting wood species (Skulberg et al., 2019). The VOC emissions from these softwoods are mostly terpenes, namely α-pinene, β-pinene, 3-carene, as well as hexanal and limonene, as listed in *Table 3* (Alapieti et al., 2020). Terpenes are also the chemical compounds responsible for wood's characteristic odor (Nore et al., 2017).

Table 3. Most abundant emission products from Norway spruce and Scots pine. Adapted from (Alapieti et al., 2020).

Wood species	Most abundant emission products
Norway spruce (*Picea abies*)	α-pinene, β-pinene, 3-carene, hexanal, acetaldehyde, limonene, acetic acid, camphene
Scots pine (*Pinus sylvestris*)	α-inene, β-pinene, 3-carene, hexanal, pimaral

When glues are added to the wood material, other compounds as formaldehyde and aromatic hydrocarbons may be emitted from the wood-based material. Formaldehyde, classified as carcinogenic, is a strong sensory irritant released from many wood species.

The possible adverse effects from indoor emissions on perceived IEQ range from unpleasant odors to sensory irritation in eyes and airways, and reported health effects, such as negative moods, stress, and environmental worry (Wolkoff, 2013). Studies have shown that odor thresholds can be significantly lower than sensory irritation, in the case of α-pinene for instance. The measured indoor air concentrations were found to be close to or above the odor thresholds, which influence the perceived IEQ (Wolkoff & Nielsen, 2017).

On the other hand, terpenes have also been linked to psychological and physiological benefits. Studies on olfactory stimulation from d-limonene and α-pinene were found to increase the parasympathetic nervous activities, resulting in decreased heart rates and a ‘comfortable’ feeling among the study subjects (Joung et al., 2014; Ikei et al., 2016). Harb et al (2018) studied the VOC emissions from wood-based materials for a three-week time period and concluded that the emissions impact indoor air quality (IAQ) in newly built environments, and that construction materials have to be considered as main determinants of IAQ. In contrast, an exposure chamber study of thirty healthy individuals by Skulberg et al. (2019) showed that VOC exposure from pine and spruce yielded no inflammatory reactions or sensory irritation.

To harmonize the measurement and evaluation methods for emissions from building products, a common European list of substances and associated emission limits, known as the EU-LCI values, has been developed (European Commission, 2020). It is based on the concept of Lowest Concentration of Interest (LCI) for the potential risks to health arising from inhalation exposure to individual VOCs. The agreed EU-LCI values have been used as the reference range for emissions in this study.

Another emission parameter often used in the context of indoor emissions is Total Volatile Organic Compounds (TVOC). It comprises an undefined mix of compounds of varying or poorly defined toxicity, and is not a reliable indicator of impact on human health (CEN, 2020), but is generally used as a mass metric or a hygienic guidance value for indoor air (Skulberg et al., 2019). No internationally recognized limit value for TVOC has been established, but for example the DGNB certification requires that the total TVOC concentration does not exceed 3 000 $\mu g/m^3$.

The climate crisis also leads to direct and indirect consequences for indoor emissions. Increased temperatures contribute to an increase in outdoor air pollution levels, and when occupants in naturally ventilated buildings attempt to improve the indoor climate by opening a door or a window, the increased emissions are introduced to the indoor air (Wierzbicka et al., 2018).

In summary, as the VOCs are continuously emitted, the initial load in the material mass decreases, and the emission rates lower over time. The indoor environmental conditions, such as RH and the chemical composition of indoor air, affect the nature and concentration of emissions. In Europe, the harmonized LCI limits offer a reliable framework for assessing the potential effects of indoor emissions on human health and wellbeing.

2.4.3 Acoustic environment

The acoustics in a space can be determined by how sound waves are affected when hitting the walls, ceiling, floor or furniture. This naturally places some expectations on indoor surface materials. Wood has an inherently low sound absorption coefficient and is thereby sound reflecting. The sound insulation performance of wood compared to other common building materials is often cited as its greatest weakness.

The unwanted acoustic reflection in the indoor environment can be addressed with board resonators, where a porous absorption material with an air gap is placed behind the wooden surface, or with a perforated resonator, by introducing holes or three-dimensional patterns on the wooden surface (Asdrubali et al., 2017).

With applications where the wooden surface is both a structural member and an interior surface, such as with exposed CLT, the acoustic performance needs to be carefully addressed in the design phase. Wood constructions have been seen to present problems with both airborne sound insulation and impact sound insulation in buildings. Some proposed solutions to mitigate the issues include self-supporting suspended ceilings and different timber-concrete composite solutions (Martins et al., 2015).

In the context of an apartment block, the main acoustic objectives are to provide insulation against airborne and impact sound. Airborne sound can travel both horizontally and vertically through structural elements between apartments and rooms, whereas impact sound is the result of motion activity such as footsteps, and travels downwards through story partition elements. Both can be experienced as disturbing by the building's occupants. For several decades, only a handful of European countries had determined acoustic descriptors and limit values, but these differed wildly across the different countries. Only now in 2021, the ISO insulation standard for acoustic classification of dwellings was published (CEN, 2021). The standard aims to make it easier for developers to specify a classified level of acoustic quality for a dwelling, and help users and builders be informed about the acoustic conditions and define increased acoustic quality.

2.4.4 Visual and tactile environment

Traditionally, visual comfort in an indoor space is determined by available daylight and view to the outside, and the absence of glare. However, when considering the visual comfort in an indoor environment with visible wood surfaces, the bio-psycho-social aspects become more pronounced. Findings from the field of environmental psychology show that humans are aesthetically attracted to natural contents, but as a consequence of urbanization, opportunities for direct contact with nature are becoming less frequent (Joye, 2007). It has been suggested that integrating natural elements such as wood into the built environment can increase the subjective experience of being closer or more connected to nature.

Wood is generally perceived as a positive and natural material, and some studies suggest that intermediate levels of wood are preferred over extensive use or no wood at all. Due to wood's low thermal conductivity, touching wooden surfaces causes lower variations in the skin temperature than touching tiles, metals or concrete. Although many studies of physiological responses on exposure to wood in indoor environments have been introduced, many had small or homogenous sample sizes, or short exposure times, and might not well reflect real-life situations with long-term exposure (Alapieti et al., 2020).

2.5 The physical impact of wood on IEQ

The building physical mechanisms in wood buildings are less well understood, but becoming increasingly relevant and more frequent in academic research. In this chapter, the thermodynamic processes of moisture and heat flux of wood are briefly introduced in the context of IEQ.

2.5.1 Hygroscopicity and moisture buffering capacity

Wood is a hygroscopic material, which means that it can attract and hold water as liquid or as vapor from the surrounding atmosphere. Controlling the indoor humidity of a building typically takes place with ventilation efforts. However, an indoor environment’s moisture behavior is also affected by the moisture buffering capacity of the materials exposed to the indoor climate. This moisture buffering is the result of absorption and desorption of water vapor due to humidity variations in the ambient air.

The phenomenon of wooden interior surfaces as moisture buffers has been gaining research interest alongside the increase of modern timber construction in general. Studies have shown that it is possible to reduce the diurnal peak variations in indoor humidity with hygroscopic materials, and that the moisture buffering effect depends on the surface area’s exposure to indoor air, vapor permeability, coating, sorption capacity, diffusion coefficient and the material thickness (Osanyintola & Simonson, 2006).

Moisture transfer between wood-based structures and indoor air has been found to reduce the peak indoor RH by as much as 35 % and increase the minimum indoor humidity by up to 15 % (Simonson et al., 2002). The moisture buffering properties of wood further depend on the species of wood used and its direction towards the indoor environment. The longitudinal direction of wood has higher moisture buffering capacity than the transverse direction, which is determined to be approximately 1 mm for daily humidity variations (Hameury, 2005). Research results show that in a room with low ventilation and a large surface area of wood exposed to surrounding humidity, the buffering effect can considerably reduce the daily humidity fluctuations, which can improve the perceived IAQ without increasing ventilation (Simonson et al., 2001, 2002; Hameury, 2005; Nore et al., 2017).

In an effort to define the moisture transmitting and buffering properties of absorbent, porous building materials, a Nordic research group developed the concept of moisture buffer value. The moisture buffer value (MBV) indicates the amount of moisture uptake or release by a material when it is exposed to repeated daily variations of high humidity (8h, 75 % RH) and low humidity (16h, 33 % RH) (Rode et al., 2006). Wood products from Finland, Denmark and Norway were included in the initial tests and compared against concrete, gypsum and brick. The required specimen thickness was the moisture penetration depth for daily humidity variations, or 10 mm, whichever was larger. Wooden materials like untreated spruce and birch boards, as well as cellular concrete performed best, while materials like brick and concrete were able to buffer less than half of what the best performing materials could buffer. The results were translated into a MBV classification representing ranges for practical moisture buffer value classes for building materials, shown in *Figure 4*.

Another factor influencing the moisture buffering performance is the ventilation rate and moisture load. Simonson et al. (2002) found that increased ventilation rate decreases the effects of hygroscopic materials, but with higher moisture loads, their effects in fact increase.

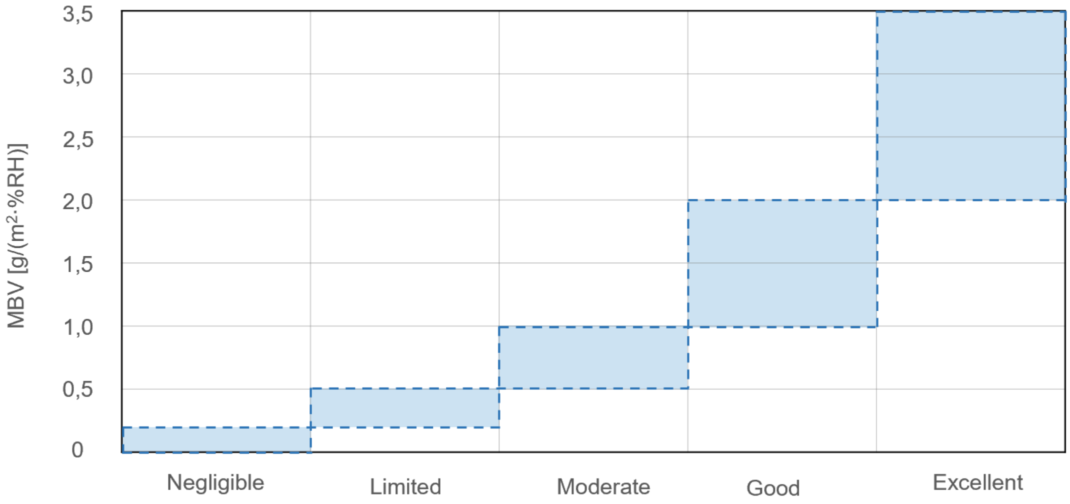


Figure 4. Ranges for practical moisture buffer value (MBV) classes for absorbent, porous building materials, adapted from Rode et al. (2006).

2.5.2 Thermal mass, latent heat of sorption and energy-saving potential

The characteristic material properties of wood vary across different wood species and their strength classes. Wood used in the European EWPs is typically locally sourced pine or spruce. A research project analyzing measured densities of Scots Pine (*n* = 327) and Norway Spruce (*n* = 317) samples collected from southern Finland concluded an average density of 412,6 kg/m³ and 385,3 kg/m³ respectively (Repola, 2006). Therefore, when comparing to the density of cured concrete, typically 2400 kg/m³, wood is approximately six times lighter. Due to being a comparatively lightweight material, wood lacks the thermal mass to mitigate temperature fluctuations caused by heat gains.

However, moisture transfer between hygroscopic materials and indoor air also impacts the indoor temperature because of phase change and the latent heat phenomenon (Hameury, 2005; Kraniotis et al., 2016; Nore et al., 2017). When moisture is absorbed in wood, its temperature rises and when the wood dries, the temperature decreases, which can potentially be utilized to reduce energy consumption for heating, cooling and ventilation. Osanyintola and Simonson (2006) investigated this potential with a numerical model and concluded that potential energy savings are the highest for buildings in hot and humid climates with mechanical cooling equipment, but energy-saving seems possible in all climates. Overall, the estimated energy saving potential was higher for cooling energy (5 % - 30 %) than heating energy (2 % - 3 %). Further savings from reduction in ventilation ranged from 5 % to 20 %. A similar Danish study found that the thickness of the material affected by the phase change in typical Danish climate is limited to 20 mm - 30 mm, and dependent on sufficiently high temperature fluctuations (Rose et al., 2009). Wooden indoor surfaces are therefore considered to have the potential to store surplus heat gains, release the thermal energy during nighttime and reduce overheating risks in summer.

2.6 Post-occupancy evaluations

While the above-mentioned building physical properties are relatively well understood and methodologies to quantify and qualify their performance have been established, an undisputable element in final building performance is the impact of occupant perception.

Predicting building performance and occupant satisfaction is a complex subject, and depends on various factors, such as culture, location and personal preferences. Research into user perceptions has been gaining popularity over the past decades. This has paved the way to developing post-occupancy evaluation (POE) frameworks that investigate the building performance from the perspective of the buildings' occupants, and compare the results with the buildings' quantitative data. This methodology is referred to as environmental assessment including observer-based environmental assessments (OBEAs) and technical environmental assessments (TEAs).

As building certification systems are primarily used in the design phase, POE can be an essential tool in verifying whether the buildings are performing as intended. The history of POE dates back to the 1960s US and England, but became more mainstream along with the first published textbook on the subject by Preiser, Rabinowitz & White (1988). Two decades ago, POE first received an industry-accepted definition as "*any activity that originates out of an interest in learning how a building performs once it is built (if and how it has met expectations) and how satisfied building users are with the environment that has been created*" (National Research Council & Federal Facilities Council, 2002). An extensive state-of-the art review by Li et al. (2018) found that the number of POE-related scientific publications increased dramatically around 2010, and has been growing since.

Few pioneering studies have combined POE frameworks with investigations of the IEQ in wood buildings. Adekunle & Nikolopoulou (2016) combined POE, thermal comfort surveys, monitoring and simulation for two multi-story wood buildings to investigate the indoor thermal conditions and overheating risk in prefabricated timber buildings in the UK. Watchman et al. (2017) attempted to understand how occupants perceive wood in built environments and whether its indoor use influenced the satisfaction of occupants. An exploratory comparative study within a POE framework investigated the subjective perception of occupants in relation to physical comfort factors in Québec, Canada. In a study by Stenson et al. (2019), building performance monitoring, sampling, and evaluation was conducted periodically after construction and spanning more than a year, for an occupied office building constructed using mass timber elements. IAQ, bacterial community composition, vibrational comfort and VOCs were assessed for an office building in Oregon, USA. Adekunle & Nikolopoulou (2020) carried out another case study of three prefabricated structural timber housing developments in the UK to investigate occupants' perception of comfort, adaptation to the thermal environment, and seasonal performance of the buildings.

POE frameworks, or protocols, have been developed by various entities for a range of applications. According to the literature, the most broadly adopted tools are the Building Use Studies (BUS) methodology, acquired by Arup in 2009, and the one developed by the Center for the Built Environment (CBE) at UC Berkeley. Other examples include the Building Occupants Survey System Australia (BOSSA), the National Environmental Assessment Toolkit (NEAT), the ASHRAE Performance Measurement Protocols for

Commercial Buildings (PMP), and the European Comfortmeter. These already established frameworks have accumulated extensive databases for benchmarking, comparison and analysis of buildings, but are fully commercialized solutions and as such not available to all interested industry actors.

On the contrary, the ASHRAE Global Thermal Comfort Database II is an open-source database with over 100 000 records from more than 50 field studies available online. The data is collected exclusively from field experiments as opposed to climate chamber tests, the original raw data files of the researchers, and peer-reviewed journals and conference papers (Földváry Ličina et al., 2018). Of the 1 242 survey samples of multifamily housing in Europe, all cases are from naturally ventilated buildings, whereas from offices and classrooms, data on air-conditioned and mechanically ventilated buildings are also available. Filtering for wood buildings is not possible, but a simple search of the study titles would indicate that the database does not include open-source data on wood buildings.

Through a case study, this study aims to present the findings of a POE to understand occupants’ perceptions on the indoor environment, personal adaptation and seasonal performance of their apartments, located in the first multi-story wood building in Denmark.

3 Methodology

The overall aim was to examine the relationship between the measured, simulated and experienced indoor environmental conditions of a case study residential wood building located in Aarhus, Denmark (lat. 56.2° N, long. 10.1° E). The geographical location of the case study buildings is depicted in *Figure 5*.

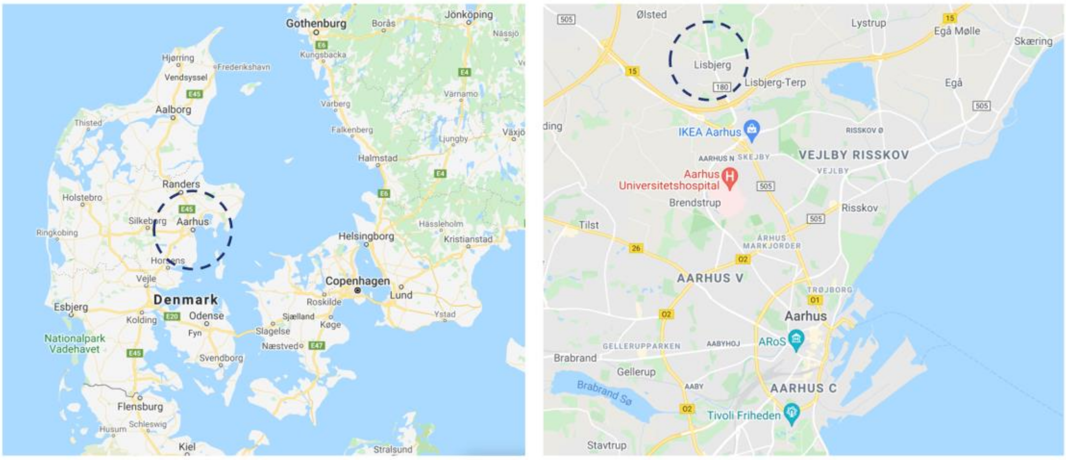


Figure 5. *The geographical location of the case study building at Lisbjerg Bakke in Aarhus, Denmark.*

The first phase of the project was to carry out a literature review on current research pertaining to indoor environmental conditions of wood buildings and the status quo of POE. In the following phase, quantitative data on the building's geometrical dimensions and physical properties were collected. Next, a POE survey was designed and employed to gain qualitative data on the occupants' experience of the indoor environment. Building performance simulations were carried out to generate granular data on the predicted performance of the apartments. Finally, the findings were analyzed and learnings for upcoming POEs of wooden buildings were identified. *Figure 6* describes the process in a simplified linear format.

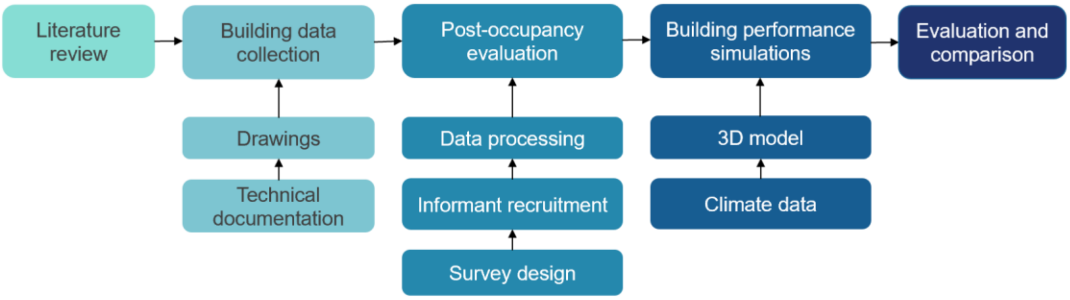


Figure 6. *Linear representation of the project process.*

3.1 Assumptions

A level of uncertainty in the simulation results may be credited to differences in the weather file dataset (for years 2004 through 2018) and the current climate conditions. Similarly, the occupancy, equipment and lighting schedules developed by the Swiss Society of Engineers and Architects used in the study might considerably vary from the actual occupancy patterns at the case study building. Finally, there will always be unaccounted for discrepancies due to behavior of individual occupants.

To delimit the scope of this study, certain subtopics that undeniably impact the IEQ of buildings have been delimited or excluded. This delimitation is graphically expressed in *Figure 7*. Greater attention has been given to the thermal and atmospheric indoor conditions, and the acoustic and visual environments have been considered less. This is due to a lack of reliable calculation and simulation methods to compare against the measured acoustic performance, and due to daylight simulations already being such a well-documented subject. Furthermore, the impacts of possible variable configurations for the HVAC systems, the internal geometries of the apartments nor the effects of common indoor emissions such as dust and pollen, radon nor CO_2 have not been included in this study.

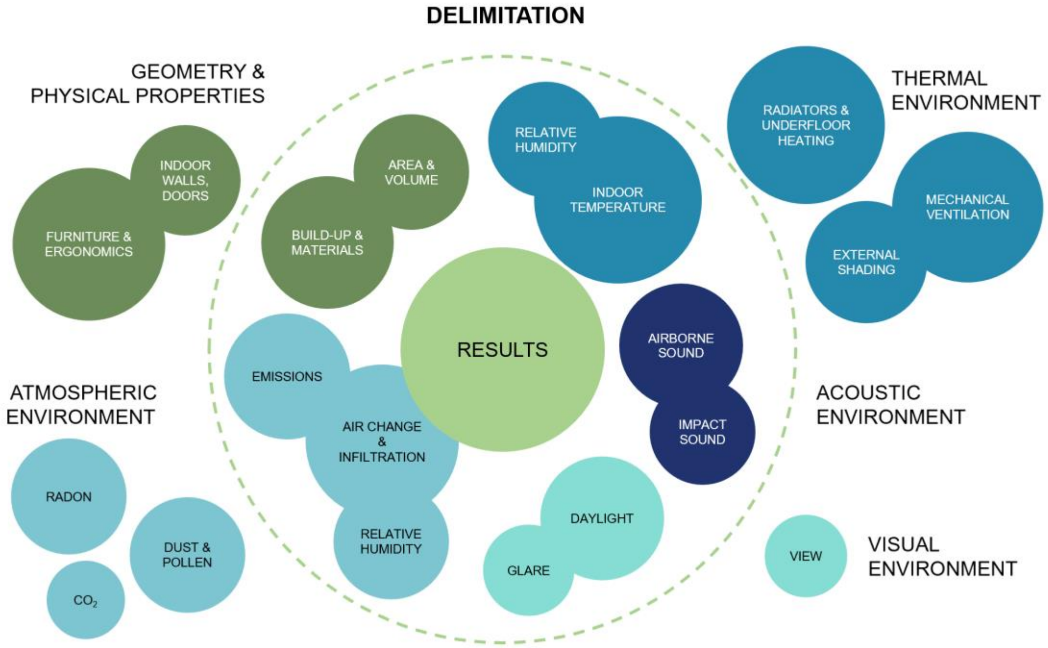


Figure 7. Delimitation of the study scope.

3.1.1 Climate model

The climate conditions used in the simulations are based on an EnergyPlus weather file including weather data collected at Aarhus Syd weather station, Denmark, between 2004 and 2018. The data set represents a so-called typical meteorological year (TMY) and is derived from hourly weather data in the US NOAA's Integrated Surface Database (ISD) using the TMY/ISO 15927-4:2005 methodologies.

Historical open-source weather data from Aarhus before the turn of the millennium has not been made available. It should also be noted that, due to climate change, historical data is likely not representative of the future climate conditions.

On the Köppen-Geiger climate classification, Aarhus is placed in the Cfb category, representing the marine west coast variety of temperate oceanic climates. It is characterized by moderate temperatures, the absence of a dry season, predominantly cloudy weather and constant rainfall. The annual outdoor dry-bulb temperature and RH are listed in *Table 4* and graphically expressed in *Figure 8*.

Table 4. Annual mean outdoor temperature and RH for Aarhus, Denmark.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Mean *To* **[°C]**	1,1	1,5	3,3	6,9	11,0	13,7	16,4	15,9	13,4	9,1	5,5	3,7
Mean RH [%]	91,4	89,2	80,3	81,3	75,7	77,6	84,4	84,0	80,9	87,3	90,9	91,7

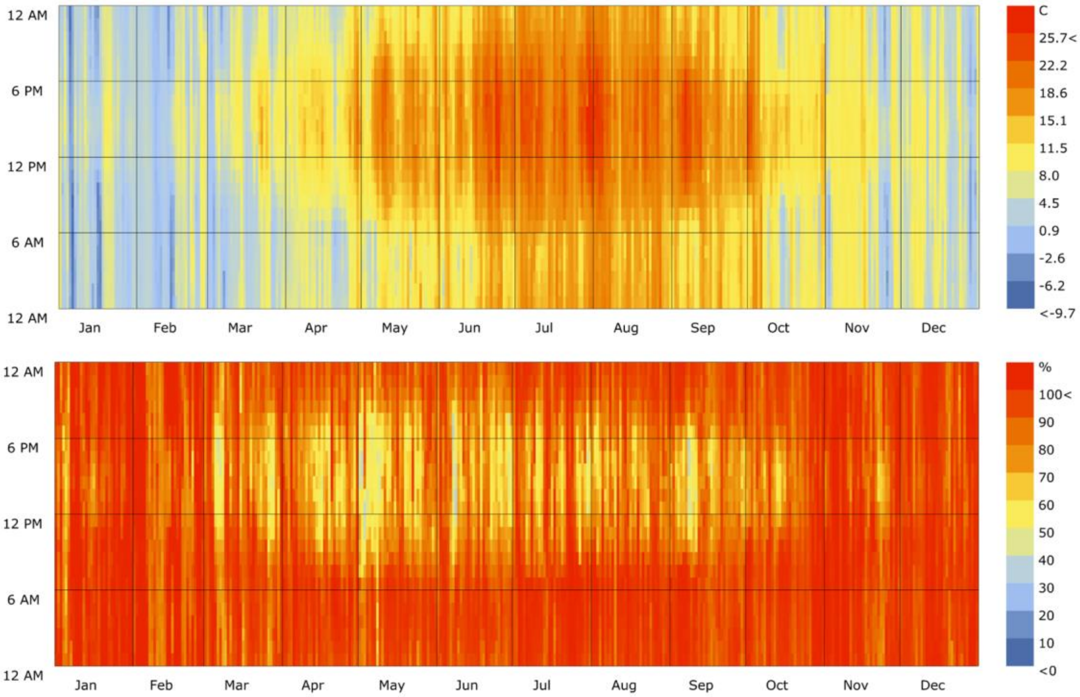


Figure 8. Annual outdoor air dry-bulb temperature (°C, above) and RH (%, below) at an hourly resolution for Aarhus, Denmark.

3.2 Case study: Lisbjerg Bakke apartments

Due to the investigations in this paper being part of a broader research project where the case study building is one of the subjects, detailed information on the building properties, such as precise geometry, thermo-physical parameters of materials, and measured data on infiltration rate and acoustics was available. This information, recorded in the DGNB[1] documentation, has been an invaluable source of data for analyzing the case study building.

Lisbjerg Bakke is a residential complex located in the city of Aarhus, in western Denmark. It consists of six freestanding apartment blocks, three to four stories tall, with a total of 40 apartments for state-subsidized rental housing. The situation plan is presented in *Figure 9*.

In 2013, the Danish Ministry of Cities, Housing and Rural areas, the city of Aarhus, and a non-profit housing administrator Al2Bolig launched an open competition for a series of demonstration housing schemes with the headline ‘The sustainable non-profit housing of the future’. The winning concept was designed by Vandkunsten architects and completed in 2018. The project was realized following the DGNB framework for achieving environmental, social and economic sustainability.

In 2019, Lisbjerg Bakke was awarded with DGNB GOLD certification. The project is also the recipient of the 2019 Matilde Baffa Ugo Rivolta Award for European Architecture for the best European social housing project, presented every two years.

Figure 9. Left: Situation plan and numbering convention for the six buildings. Source: Al2Bolig. Right: Aerial view of the realized project in the context of the site. Source: Google Maps.

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[1] Deutsche Gesellschaft für Nachhaltiges Bauen, German Sustainable Building Council (DGNB) is an internationally recognized certification benchmark for sustainability in the built environment sector.

3.2.1 Technical building data

The 40 apartments represent 27 different apartment types in one, two and three stories. The buildings are primarily constructed of massive wood elements. The load-bearing structure consists of LVL beams and glulam columns, and story partition and partition walls of CLT. Detailed drawings for standard constructions are included in Appendix D.

The project is designed with principles of Design for Disassembly (DfD), meaning that the configuration allows for easy disassembly and repurposing of the structural materials at the end of the building’s life (Moffatt & Russell, 2001). With DfD, the main focus is on component preservation (reuse, repurposing) before material preservation (recycling).

The facade is clad with untreated Norway spruce paneling. A total of 863 m^3 of wood was used in the project, 84 % of which is PEFC[2] or FSC[3] certified. Concrete has been used for the stairway and elevator shafts, and as a screed layer on the floor build-up for acoustic purposes.

To avoid an accumulation of moisture in the structure, no vapor barrier has been installed. On the interior, CLT has been left exposed and wooden paneling has been installed on the inner leaf of the exterior walls, and the rest are clad in gypsum, as seen in *Figure 10*. White-lacquered ash parquet flooring has been installed throughout the apartments.

Figure 10. The indoor environment of an apartment in the case study building. Source: Al2Bolig.

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[2] The Programme for the Endorsement of Forest Certification (PEFC) is an international, non-profit, non-governmental organization promoting sustainable forest management through independent third-party certification.
[3] The Forest Stewardship Council (FSC) is an international, non-profit, non-governmental organization which identifies forest products made with materials from well-managed forests and/or recycled sources.

3.2.2 Post-occupancy evaluation

To evaluate the building performance in a broader sense, a user perspective study was carried out at the case study building. This post-occupancy evaluation (POE) complements the technical data obtained from the building documentation and helps identify subjective experiences of the building's occupants that cannot otherwise be measured.

Due to the global COVID pandemic, the occupants were approached via a postal letter and invited to partake in an online survey. Each of the 40 households received an invite, and the responses were collected during the period March 26 - April 11, 2021.

The evaluation questionnaire was specifically developed for assessing the IEQ of multi-story wood buildings, and was informed by previous POEs and evaluations of wood buildings found in academic literature, especially those works detailed in chapter 2.6. For most questions, the answer options included a 7-point scale including a neutral answer option as recommended by ASHRAE Standard 55, which assumes that "*occupants by nature can recall instances or periods of thermal discomfort, identify patterns in building operation, and provide overall or average comfort votes*".

The questionnaire was structured around two types of categorical variables:

1) Nominal variables, such as open-ended questions and answers by selection of one predefined answer.

2) Ordinal variables as ranked scales, such as satisfaction ranging from very satisfied to very unsatisfied. The descriptors varied depending on the nature of the question.

The questions were divided into the following subtopics:

A. Background

B. Thermal comfort

- Thermal sensation vote, the indoor temperature in the summer
- Thermal sensation vote, the indoor temperature in the winter
- Satisfaction with indoor temperature in the summer
- Satisfaction with indoor temperature in the winter
- Agreeability with the availability of controls for adjusting temperature conditions
- Preferred method(s) of adjusting temperature conditions
- Presence of draught

C. IAQ

- Overall IAQ in the summer
- Overall IAQ in the winter
- Satisfaction with IAQ y & humidity in the summer
- Satisfaction with IAQ & humidity in the winter
- Satisfaction with odors in the indoor air
- Agreeability with the availability of controls for improving IAQ
- Preferred method(s) of improving IAQ

D. Acoustic performance

- Satisfaction with noise originating from the apartments above and/or below
- Satisfaction with noise originating from the apartments on the same level
- Satisfaction with acoustic performance within the apartment, such as echoing
- Satisfaction with noise originating from the apartment installations
- Satisfaction with noise originating from outside of the apartment
- Subjective assessment of the overall noise disturbance

E. Daylight quality

- Satisfaction with daylight availability during summer
- Satisfaction with daylight availability during winter
- Subjective assessment of glare/visual disturbance

F. Other

Additionally, the occupants were asked about their age group, length of occupancy on the building, and whether their decision to move into the building had been affected by the fact that the building was primarily made of wood. Finally, the respondents were invited to describe some positive and negative aspects of their apartments in their own words.

Some previous studies have cited that women are more susceptible to disturbances in the indoor environment and more likely to experience fatigue, headache and irritation. However, in the light of the findings by Kraus and Novakova (2019) on gender differences in perception of IEQ, the perceived quality of the indoor environment is not affected by gender, and therefore the gender metric was excluded from this survey.

With respect to the European General Data Protection Regulation (GDPR), the personal data collected from the occupants were kept to a minimum, and therefore the participants were not asked to identify themselves. Instead, they were asked to confirm the address of their dwelling, which was then located on the site for simulation purposes, but not reported in this paper to ensure the participants’ anonymity. The questionnaire in its entirety can be viewed in Appendix A, followed by the responses in Appendix B.

Before processing the POE survey results, a design prediction was made based on the PMV/PPD method pertaining to the EN 16798 indoor thermal comfort categories, with reference to the acceptable summer indoor temperature range shown in *Table 5*, and the look-up tables in EN 7730 Annex E.

Table 5. The default design values for indoor thermal environment categories, PPD and acceptable summer indoor temperatures for buildings without mechanical cooling systems as per EN 16798.

EN 16798 IEQ category	**Level of occupant expectation**	**Fanger method**		**Adaptive method**
		PPD [%]	**PMV**	***Tc* variance [°C]**
I	High	≤ 6	-0,2 ≤ PMV ≤ +0,2	Upper limit: $T_c = 0{,}33 \cdot T_o + 18{,}8$ + 2 Lower limit: $T_c = 0{,}33 \cdot T_o + 18{,}8$ - 3
II	Medium	≤ 10	-0,5 ≤ PMV ≤ +0,5	Upper limit: $T_c = 0{,}33 \cdot T_o + 18{,}8$ + 3 Lower limit: $T_c = 0{,}33 \cdot T_o + 18{,}8$ - 4
III	Moderate	≤ 15	-0,7 ≤ PMV ≤ +0,7	Upper limit: $T_c = 0{,}33 \cdot T_o + 18{,}8$ + 4 Lower limit: $T_c = 0{,}33 \cdot T_o + 18{,}8$ - 5
IV	Low	≤ 25	-1,0 ≤ PMV ≤ +1,0	

With the PMV determined, the PPD was calculated with equation 1.

$$PPD = 100 - 95 \cdot exp(-0{,}03353 \cdot PMV^4 - 0{,}2179 \cdot PMV^2) \qquad (1)$$

After receiving the POE responses, the case study apartments could be identified, and relevant information for modeling the building and the apartments were sourced from the DGNB documentation.

3.2.3 Simulated technical data

Dynamic building performance simulations (BPS) were conducted to generate hourly simulation data for assessing the building. A 3D model of the building was created with Rhinoceros 6, which is a commercial 3D computer graphics and computer-aided design application software. The Rhinoceros-compatible plugin ClimateStudio, built on the EnergyPlus simulation engine and a novel Radiance-based path tracing technology, was used for environmental performance analysis with two sub-models – one for thermal analysis and another for daylight analysis.

The dynamic thermal model was based on the fundamental thermo-physical processes of conduction, convection and radiation and aimed to predict the impact of the ambient outdoor conditions on the heat flux through the thermal envelope. Therefore, the input data was reliant on accurate modeling geometry, but also building envelope details. The climate conditions simulated were based on a weather file including historical weather data for Aarhus, Denmark, representing a typical meteorological year (TMY) (Crawley & Lawrie, 2019).

The 3D model of the building was drafted based on the DGNB documentation, and simplified to reduce computational resource demand. Each case study apartment was drawn as a single shoebox zone, excluding the footprint of the bathroom, except for the two-story apartment, in which case each story was drawn as its own zone. The windows and balcony doors were also simplified. No interior walls, doors, furniture nor shading for the windows were included in the 3D model, which is shown in *Figure 11*. Simulation inputs for the building model properties are shown in *Table 6*, and for the environmental performance analysis in *Table 7*.

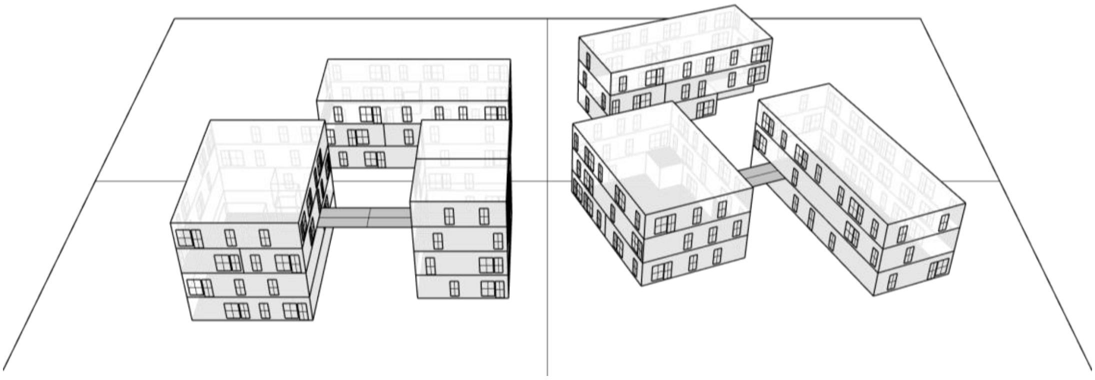

Figure 11. The simplified Rhinoceros 3D model used for the building performance and daylight simulations.

The occupancy, equipment and electrical lighting schedules were based on the Swiss Society of Engineers and Architects (Schweizerischen Ingenieur-und Architektenverein (SIA), (2016) Merkblatt 2024, as no locally applicable schedules were found. As heat losses from occupant activity and subsequent clothing are an essential input to the indoor climate, the internal heat gains from occupancy were calculated based on the estimated metabolic activity and body surface area (Ahmed et al., 2017).

The thermal insulation of occupant clothing can be estimated based on Annex C of the European Standard ISO 7730, but ClimateStudio uses a non-adjustable built-in dynamic clothing model based on the ASHRAE 55 standard.

For the illuminance target, affecting the electrical lighting load, there is no general recommendation when it comes to residential buildings. For offices, the recommendation is 500 lux for task areas and 300 lux for the office overall (CEN, 2011), and therefore 300 lux was also chosen for this residential case study.

The infiltration rate was given as the mean leakage of all the blower door tests carried out at the building site.

Table 6. Simulation inputs for building model properties.

Simulation input	Input value	Data source
U-value, exterior wall [W/m²·K]	0,12	DGNB documentation
U-value, roof [W/m²·K]	0,08	DGNB documentation
U-value, slab on ground [W/m²·K]	0,08	DGNB documentation
U-value, storey partition [W/m²·K]	0,13	DGNB documentation
U-value, window [W/m²·K]	0,80	DGNB documentation
U-value, glazing [W/m²·K]	0,53	DGNB documentation
SHGC/g-value, glazing [%]	53	DGNB documentation
Window T_{vis} [%]	71	DGNB documentation

Table 7. Simulation inputs for environmental performance analysis.

Simulation input	Input value	Data source
Occupant density [persons/m²]	0,025	SIA Merkblatt 2024
Occupant metabolic rate [met]	1,20	Ahmed et al. 2017
Occupant body surface area [m²]	1,80	Ahmed et al. 2017
Clothing insulation [clo]	Dynamic	ASHRAE 55 model in ClimateStudio
Equipment load [W/m²]	2,00	SIA Merkblatt 2024
Electrical lighting load [W/m²]	9,50	SIA Merkblatt 2024
Illuminance target [lux]	300	EN 12464-1:2011
Heating setpoint [°C]	20,0	DGNB documentation
Mechanical ventilation supply airflow [l/s/m²]	0,45	DGNB documentation
Mechanical ventilation heat recovery [-]	0,82	DGNB documentation
Infiltration rate [q_{50}, l/s/m²]	0,87	DGNB documentation

The following output data was generated at an hourly resolution:

- Outdoor T_a [°C]
- Outdoor air RH [%]
- Zone air T_a [°C]
- Zone air MRT [°C]
- Zone air T_c [°C]
- Zone air RH [%]
- Heat gain through windows [J]
- Heat loss through windows [J]
- Conduction heat gain of opaque indoor surfaces [J]
- Conduction heat loss of opaque indoor surfaces [J]

Additionally, the daylight performance was simulated with ClimateStudio's built-in function geared towards LEED[4] certification of buildings. The simulation inputs are shown in *Table 8*. The tool reports two daylight metrics: spatial daylight autonomy (sDA) and annual solar exposure (ASE). The window properties were limited to an existing library of products on the market, so an example window was chosen. The U-value, g-value and T_{vis} are therefore not completely accurate.

Table 8. Simulation inputs for daylight performance analysis.

Simulation input	**Input value**
Sensor spacing [mm]	600
Sample rays / sensor / pass [-]	64
Ambient samples [-]	6400
Ambient bounces [-]	6
Max. number of passes [-]	20
Radiance parameters	-ab 6, -lw 0,01, -ad 1
Interior surface material reflectance [%]	42
Window U-value [W/m^2·K]	0,85
Window g-value / SHGC [%]	52
Window T_{vis} [%]	55

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[4] Leadership in Energy and Environmental Design (LEED) is a national certification system developed by the U.S. Green Building Council (USGBC) to encourage the construction of energy and resource-efficient buildings that are healthy to live in.

The sDA calculates the percentage of an analysis area meeting a minimum horizontal daylight illuminance level of 300 lux for 50 % of the operating hours per year. The operating time is fixed at 8.00 - 18.00 every day of the year, totaling 3 650 h. The Illuminating Engineering Society (IES) has defined two success criteria for sDA: < 75 % results in ‘preferred’, which translates to occupants finding the daylight level sufficient to work without the need of electrical lights, and 55 % - 74 % results in ‘nominally accepted by occupants’, which is considered the minimum goal for areas where some daylight is important.

The ASE calculates the number of hours per year where direct sunlight is incident on the interior surface, and the percentage of analysis points with ≤ 1 000 lux for at least 250 operating hours/year. It complements the sDA in describing the potential for visual discomfort indoors. The IES has defined three performance criteria for ASE: < 3 % results in ‘clearly acceptable’, < 7 % is considered ‘nominally acceptable’, and > 10 % results in ‘unsatisfactory visual comfort’ (IES, 2012).

It should be noted that the sDA and ASE results would in reality be somewhat lower because interior walls would hinder the incidence of solar radiation in the apartments.

MS Excel was used for data processing and analysis of the results.

3.2.4 Measured technical data

Measurements performed at the building site immediately after project completion and before occupancy have been used as input data in this paper. The work has not been done by the author of this report, but by the relevant specialists. The data consists of acoustics results, including airborne and impact data measurements, infiltration results achieved with blower-door tests, as well as measurements for TVOCs and formaldehyde in the indoor air.

The acoustic measurements were carried out with a handheld sound analyzer (model nr. 140), a sound calibrator (model nr. 1251), a tapping machine (model nr. 277), a power amplifier (model nr. 280) and a dodecahedron loudspeaker (model nr. 276) from Norsonic.

The blower door tests were carried out at blocks 2, 5 and 6 with a manometer and a ventilator (equipment not specified in the documentation), and measured airflow at 50 Pascals.

The indoor air emission measurements were collected with GilAir Plus sampling pumps, SKC sorbent tubes for collection of formaldehyde and Tenax TA tubes for collection of VOCs.

In all cases, a number of sample tests were carried out, rather than testing each apartment individually, due to which the data can only be evaluated on a general level.

3.3 Comparative analysis

According to the building’s DGNB documentation, the objective for the T_c was fulfilling the EN 16798 category I, which defines the acceptable range as 21 °C – 25 °C. However, the setpoint temperature for heating in the winter period was declared to be 20 °C. Therefore, unless otherwise stated, an acceptable range of 20 °C – 25 °C has been used in the following considerations.

3.3.1 Long-term evaluation of the general thermal comfort conditions

Annex H of the EN 7730 standard lists five methods to evaluate the comfort conditions over time based on data measured in real buildings or dynamic computer simulations. Method A is used here. The method calculates the number or percentage of occupancy hours during which the PMV or the T_c is outside a specified range. In this case, the number and percentage of hours outside the range of 20 °C – 25 °C was calculated. However, considering the findings of Li et al. (2020), the same was calculated for mean T_a.

3.3.2 Adaptive thermal comfort

The adaptive thermal comfort temperature range for the summer season was calculated, and then compared against overheating hours for predetermined limit ranges.

The European thermal adaptive comfort standard EN 16798 is based on ASHRAE 55, and the comfort temperature is calculated with similar equations but with different coefficients. The adaptive thermal comfort temperature upper and lower limits for a naturally ventilated category I building are calculated through equations 2 and 3.

$$T_c = 0{,}33 \cdot T_o + 18{,}8 + 2 \tag{2}$$

$$T_c = 0{,}33 \cdot T_o + 18{,}8 - 3 \tag{3}$$

where,

T_o is the outdoor mean temperature [°C]

T_c is the indoor operative temperature [°C].

The resulting range determines the adaptive thermal comfort 80 % acceptability limits inside the building where at least 80 % of the occupants are satisfied. The adaptive comfort temperature range was calculated accordingly and compared to the simulated annual T_c of the apartments, as well as the thermal sensation vote of the POE.

At the time of the design process of the case study building, the Danish building regulations stated that the thermal comfort must be documented and may not exceed 26 °C for more than 100 h/year, nor 27 °C for more than 25 h/year during occupied hours. Since then, the building regulations have been changed and no longer specify such a range. To evaluate the overheating potential of the case study building apartments, the amount of annual overheating hours exceeding 25 °C, 26 °C and 27 °C were simulated. The results were also projected against the CIBSE and Passivhaus overheating limits.

3.3.3 Daily temperature range index

A comparative study of the existing thermal comfort indices by Li et al. (2020) found that a newly proposed index based on daily temperature range had the strongest correlation and outperformed all existing indices. The study showed that EN ISO 7730 class II T_a range (23 °C – 26 °C for summer and 20 °C – 24 °C for winter) with a 2 °C threshold for the daily range are the best indices to estimate occupant thermal satisfaction. It was concluded that increases increments in the daily occurrences of T_a >2 °C are highly correlated with lower occupant thermal satisfaction.

To test this theory, equation 4 by Li et al. (2020) was used to calculate the performance concerning the daily temperature range for each apartment.

$$index = \frac{\%T_a\ outside\ specified\ ranges + \%T_a\ daily\ range > a\ threshold}{2} \tag{4}$$

The resulting index was then compared against the occupants' thermal satisfaction votes to investigate possible correlation.

3.3.4 Correlation

To evaluate the relationship between the quantitative POE survey results and the simulated and measured data, several correlation calculations were made in Excel utilizing Spearman's rank correlation coefficient.

Spearman's rank correlation coefficient is a tool for exploratory data analysis, and measures the strength and direction of association between two ranked variables. It is the nonparametric version of Pearson correlation, which determines the strength and direction of the linear relationship between two variables. Spearman's rank correlation coefficient (r_s) was also selected for its suitability for ordinal data and small sample sizes. It can easily be applied to any number of responses with ordinal data. The null hypothesis (H_0) is that there is no association between the two variables.

There are two methods to calculate r_s depending on whether the data has tied ranks or not. When there are no tied ranks, equation 5 is used.

$$r_s = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{5}$$

where,

d_i is the difference in paired ranks

n is the number of data pairs.

When there are tied ranks, equation 6 is used.

$$r_s = \frac{\sum_i (x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_i (x_i-\bar{x})^2 \sum_i (y_i-\bar{y})^2}} \tag{6}$$

where i is the paired score.

The result will always be between 1,0 (a perfect positive correlation) and -1,0 (a perfect negative correlation), where 0 indicates no association between the ranks. There is no consensus on what is considered a strong Spearman's rank correlation, and the interpretation varies between fields and depends on the aims of the study. For this study, the correlation results were interpreted according to *Table 9*.

Table 9. Interpretation of Spearman's rank correlation results used in this study. Adapted from Akoglu (2018).

Correlation r_s (positive or negative)	**Interpretation**
<0,20	Insignificant correlation
0,20 - 0,39	Weak correlation
0,40 - 0,59	Moderate correlation
0,60 - 0,79	Strong correlation
0,80 - 0,99	Very strong correlation

The level of significance (α) of any discovered correlation was then calculated to obtain how likely an observed correlation is due to chance, and whether there is therefore evidence to reject the null hypothesis. This was done by comparing the r_s to the critical values in *Table 10*. The critical values are adapted from Zar (1971) where the lowest considered sample size is 4. If the absolute value of r_s is larger than the critical value, the correlation is considered significant.

Table 10. Critical values for Spearman's rank correlation coefficient for n=6. Adapted from Zar (1971).

Critical value for n = 6	0,371	0,657	0,829	0,886	0,943	1,000
Level of significance (α)	0,25	0,10	0,05	0,025	0,01	0,005
Probability level of confidence [%]	75,0	90,0	95,0	97,5	99,0	99,5

Literature suggests that significant correlation is achieved at or below $\alpha = 0{,}05$ where there is at least 95 % probability that the null hypothesis is wrong, that the data is statistically significant and that they show a true relationship. Therefore, only results with $\alpha \leq 0{,}05$ in this study are considered for rejecting the null hypothesis.

As a secondary measure to objectively estimate whether or not a relationship exists between two variables, the correlation coefficient rule of thumb (Krehbiel, 2004) was applied to results with $\alpha \leq 0{,}05$. The rule of thumb is calculated with equation 7.

$$\text{If } |r| \geq \frac{2}{\sqrt{n}}\text{, then a relationship exists.} \qquad (7)$$

If $\alpha \leq 0{,}05$ and the rule of thumb test is passed, the alternative hypothesis (H_1) is that there is a relationship between the two variables. This indicates that changes in one variable are associated with changes in the other variable.

4 Results

The results are primarily reported following the same structure as the methodology chapter. An exception is the chapter on technical building data, for which the results are reported after the results of the POE survey.

4.1 Case study: Lisbjerg Bakke apartments

The results for the individual apartments were evaluated in relation to each other. The overarching goal was to identify any observable associations between the different data.

4.1.1 PMV/PPD prediction

Before processing the POE survey results, a design prediction was made based on the PMV/PPD equation presented in the EN ISO 7730 standard, the EN 16798 indoor thermal comfort categories and the look-up tables in EN 7730 Annex E. The look-up tables include the *Tc* at intervals of 2 degrees Celsius, so the values have been rounded to the closest bracket. The prediction results are detailed in *Table 11*.

Table 11. Predicted PMV based on mean indoor T_c, an activity level of 1,2 met (or 69,6 W/m²), clothing level of 1,0 clo (or 0,155 m²·K/W), RH of 50 % and relative air velocity of 0,1 m/s.

Apartment	Mean *Tc*, summer [°C]	PMV, summer	Mean *Tc*, winter [°C]	PMV, winter	Mean annual *Tc*, [°C]	PMV overall
B1-A1	24,6 → 24	0,54	20,1 → 20	–0,33	22,4 → 22	0,10
B1-A2	24,2 → 24	0,54	20,1 → 20	–0,33	22,3 → 22	0,10
B2-A1	23,8 → 24	0,54	20,2 → 20	–0,33	22,0 → 22	0,10
B3-A1	24,6 → 24	0,54	20,3 → 20	–0,33	22,5 → 22	0,10
B4-A1	23,6 → 24	0,54	20,2 → 20	–0,33	21,9 → 22	0,10
B5-A1	23,1 → 24	0,54	19,9 → 20	–0,33	21,5 → 22	0,10

For a PMV of +0,10 the resulting PPD was 5,2 %. Therefore, the prediction is that the thermal comfort category I is met.

4.1.2 Post-occupancy evaluation

The POE survey was distributed to all 40 apartments at Lisbjerg Bakke. By the deadline, a total of 9 responses had been received, of which two were duplicates and excluded. Of the remaining 7 responses, one respondent had not correctly filled in their address, which meant that the answers could not be used in the analysis based on simulations of the occupant’s apartment. However, the answers were included in the overall evaluation of the survey results. An overview of the survey response rate is shown in *Table 12*.

Table 12. Overview of POE survey response rate.

Level of response		**Respondent alias**	**Apartment location known?**	**Apartment reference**
Completed questionnaires	n = 8 of which eligible 6	A	Yes	B1-A1
		B	Yes	B1-A2
		C	Yes	B2-A1
		D	Yes	B3-A1
		E	Yes	B4-A1
		F	Yes	B5-A1
Partially completed questionnaires	n = 1	G	No	N.A.
Non-contacts	n = 33	-	-	-

The simple response rate for the survey was 17,5 %. If considering the American Association for Public Opinion Research (AAPOR, 2016) definitions, and the Response Rate 2 also accounting for partially completed questionnaires, the response rate is calculated as per equation 8.

$$RR2 = \frac{(I+P)}{(I+P)+(R+NC+O)+(UH+UO)} \qquad (8)$$

where,

I is the number of completed responses

P is the number of partially completed responses

R is the number of refusals

NC is the number of non-contacts

O is other

UH is unknown if the household is occupied

UO is unknown, other,

in which case the AAPOR RR2 response rate is 20 %.

All the respondents had lived in the building for one year or longer, which was interpreted as all occupants being acclimatized to their indoor environments.

The survey results for the ordinal variable questions are presented with a 7-point scale, with the exception of question 5, which measured OTS based on the PMV scale. The mean OTS vote was +1,9 for the summer season and +0,1 for the winter season. Three of the occupants found the temperature conditions in their apartment ‘hot’ in summer, and the rest also reported neutral, warm or somewhat warm summer conditions. Two occupants found the temperature conditions in winter to be somewhat warm, and four voted ‘neutral’. When asking about the occupants' satisfaction with said temperature conditions, the respondents who found summer conditions to be 'hot' also reported being unsatisfied or very unsatisfied. Occupants were generally more satisfied with the temperature conditions in winter than in summer. Satisfaction with the floor temperature was also relatively high, although one occupant was 'somewhat unsatisfied'. Results for questions 5 and 6 are shown in *Figure 12*.

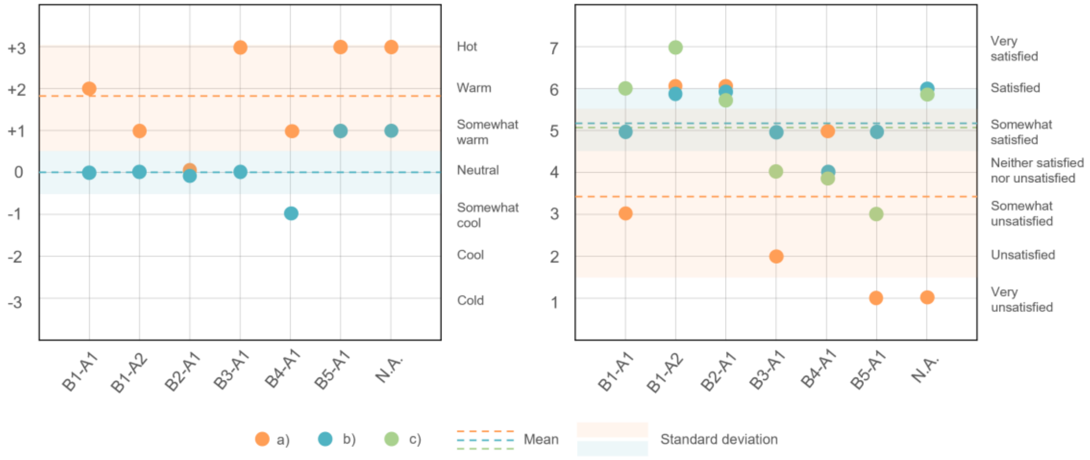

Figure 12. POE survey results for questions 5. (How would you generally describe the temperature conditions in your apartment? a) In the summer, b) In the winter) and 6. (How satisfied are you with the temperature conditions in your apartment? a) In summer, b) In winter, c) The floor temperature).

Answers on the occupants' level of control over the temperature conditions in their apartments yielded more spread-out results (*Figure 13*). Approximately half of the respondents found it both easy to adjust the indoor temperature conditions in their apartment and were satisfied with the level of control available. The other half voted quite the opposite, disagreeing or strongly disagreeing with the proposed statements.

A follow-up question encouraged the occupants to describe in their own words how they adjust the temperature in their apartment. Turning the radiators up or down, and opening the windows were mentioned by most, three of whom also named cross-ventilation. Two respondents specified that in summer it can be difficult or not possible to achieve cooling at all.

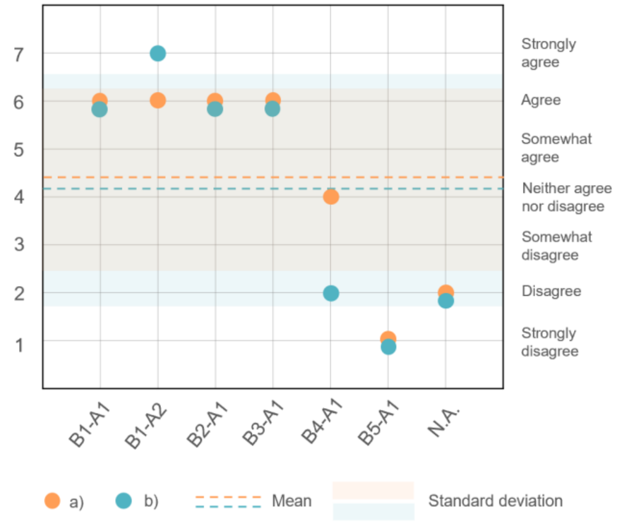

Figure 13. *POE survey results for question 9. (To what extent do you agree with the following statements? a) I can easily control the indoor temperature in my apartment, b) I am satisfied with the level of control available to adjust the indoor temperature).*

Six out of seven respondents found the IAQ of their apartments in the summertime to be pleasant or very pleasant. Most voted similarly for air quality in winter. On the contrary, one occupant reported IAQ to be unpleasant in summer and very unpleasant in winter. The answers were nearly identical when asked about the satisfaction of the IAQ (see *Figure 14*).

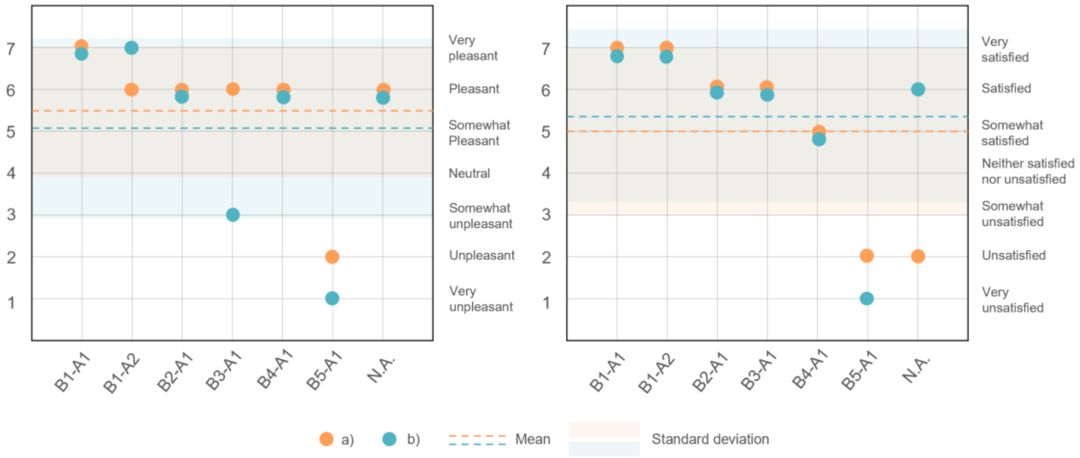

Figure 14. *POE survey results for questions 11. (How would you generally describe the indoor air quality in your apartment? a) In summer, b) In winter) and 12. (How satisfied are you with the indoor air quality in your apartment? a) In summer, b) In winter).*

Indoor air humidity perceptions vastly divided the respondents, as can be seen in *Figure 15*. Some found the humidity conditions satisfactory, all year round, whereas one occupant was satisfied with humidity conditions in summer but unsatisfied in winter. The same respondent that was the most unsatisfied with IAQ was also the most unsatisfied with the indoor air humidity and odors in their apartment. Otherwise, the question on satisfaction in regards to odors received votes from neutral to very satisfied.

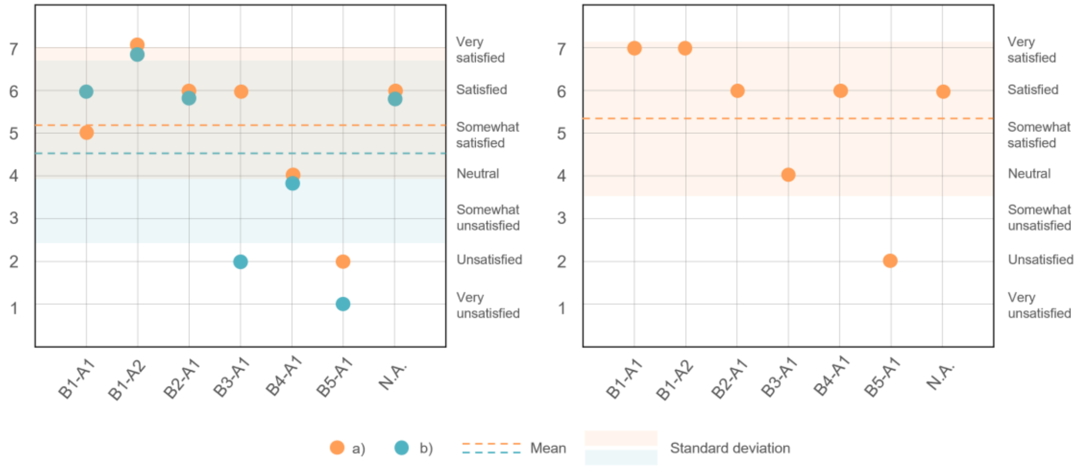

Figure 15. POE survey results for questions 12. (How satisfied are you with the indoor air humidity in your apartment? c) In summer, d) In winter and e) How satisfied are you with odors in your apartment?).

Agreeability over the ease and satisfaction of occupants’ control to improve air quality received somewhat low votes (*Figure 16*). Only one occupant voted to agree that they can easily improve the IAQ in their apartment and are satisfied with the level of control available.

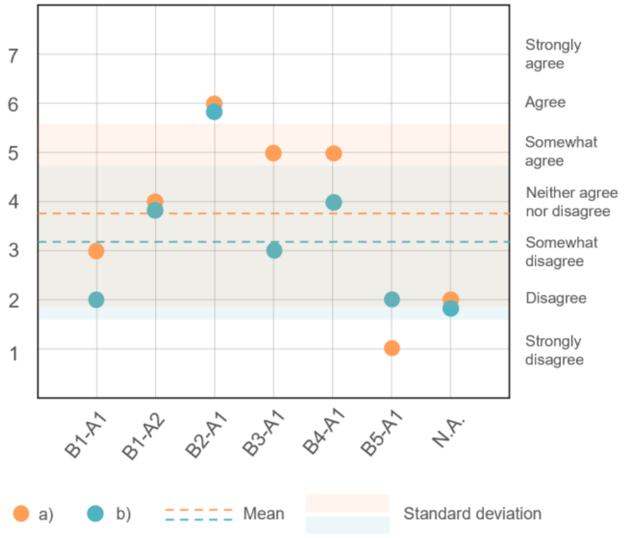

Figure 16. POE survey results for questions 13. (To what extent do you agree with the following statements? a) I can easily improve the indoor air quality in my apartment, b) I am satisfied with the level of control available to improve the indoor air quality).

Perhaps unsurprisingly, the occupants were more satisfied with noise coming from neighbors on the same floor than from neighbors above or below their apartment. One respondent found both conditions very unpleasant. The overall acoustics in the apartment were found satisfactory, except for two apartments where the respondents voted to be 'very unsatisfied'. Satisfaction with noise from within the apartments, such as noise associated with technical installations, received spread out votes across the scale. It was mentioned that the architectural "visor" running along the story partition to lead water away from the façade structure generates a loud noise when rain or hail is falling on it. Apart from one occupant, the respondents were generally satisfied with noise from outside the apartments. Acoustics responses are compiled in *Figure 17*.

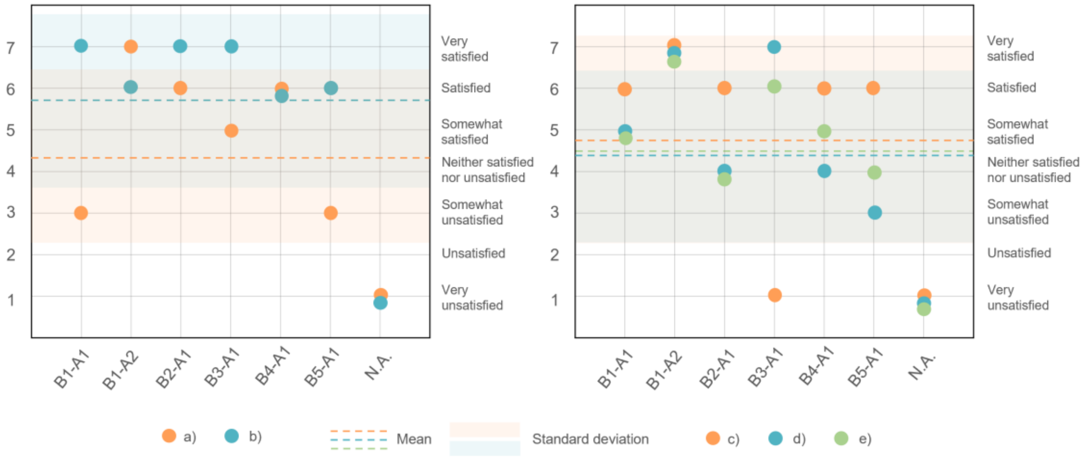

Figure 17. *POE survey results for question 15. (How satisfied are you with the acoustic conditions in your apartment? a) Noise from neighbors above/below, b) Noise from neighbors on the same level) and (c) Overall acoustics, f.ex. echoing, d) Noise from within the apartment, f.ex. from technical installations, e) Noise from outside the apartment, f.ex. traffic noise).*

Three occupants found the overall acoustic conditions disturbing due to the ventilation system and neighbors' activities, but also the construction works taking place outside the building.

The responses regarding daylight availability were by far the most unanimous in the POE survey. All occupants were satisfied or very satisfied with daylight in summer and winter (see *Figure 18*). One occupant did also find the daylight disturbing, and reported using curtains for adjusting the conditions.

In the final part of the IEQ survey, the occupants were asked to freely name positive and negative attributes about their apartment. Repeating positive mentions included good light conditions, the wooden walls and their scent, the layout of the apartment and positive/warm/natural feel. However, the positive comments were fewer than the negative ones. The noise was again mentioned most frequently as a negative attribute. Thermal comfort issues and overheating were also named. Ventilation installations taking a lot of floor space in the apartments and generating noise disturbance, as well as functioning poorly in the bathroom were described by the occupants. On a more functional level, comments mentioned that technical installations such as sprinklers and radiators were inconveniently positioned for decorating purposes, and that it wasn't allowed to hang things on the wooden walls. One occupant reported that the ground floor apartments have silverfish (*Ctenolepisma longicaudatum*), which is a type of pest insect commonly found in residential environments with humidity.

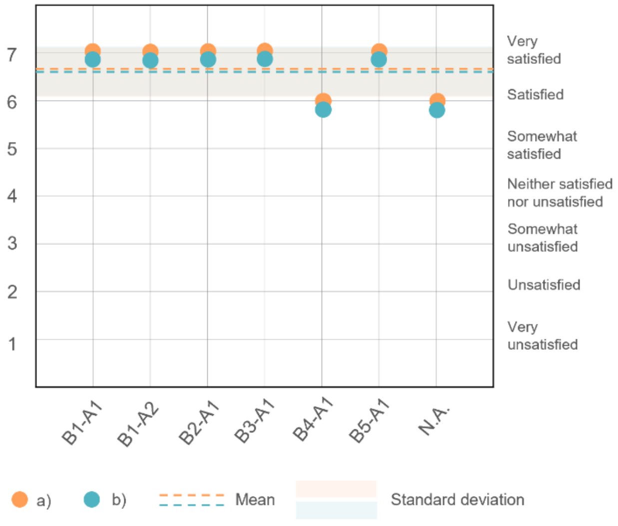

Figure 18. *POE survey results for question 18. (How satisfied are you with the daylight conditions in your apartment? a) Daylight availability in summer, b) Daylight availability in winter).*

The summarized POE survey responses can be viewed in Appendix B.

4.1.3 Technical building data

The POE survey responses from the six apartments represent five of the six blocks at Lisbjerg Bakke, therefore covering a broad sample of the overall building project. The site orientation and numbering convention of the different blocks were introduced in Figure 6 and the case study apartments were named after the block they belong to. Two of the apartments are situated within the same block (B1-A1 and B1-A2), and one of the apartments (B3-A1) consists of two stories. The general geometric properties of the case study apartments are summarized in *Table 13*.

Table 13. Geometric properties of the case study apartments.

Apartment	Floor area [m^2]	Floor-to-ceiling height [m]	Number of windows & window orientations						WWR [%]	Interior walls with wood [%]
			NW	SE	SW	S	E	NE		
B1-A1	50,2	2,56	-	2	-	-	-	3	17	43
B1-A2	50,2	2,56	2	-	2	-	-	-	28	47
B2-A1	94,8	2,56	2	-	3	-	4	-	18	40
B3-A1	115,3	2,56 – 3,38	3	5	-	4	-	-	19	68
B4-A1	94,8	2,56	2	-	3	-	-	4	18	40
B5-A1	114,4	2,56	3	3	3	-	-	-	8	52

The layout drawings, including orientation in reference to true north, window placement and wooden indoor wall surfaces for each apartment are detailed in Appendix C.

4.1.4 Simulated technical data

Simulation data relating to thermal comfort was divided into bi-seasonal segments as many of the POE questions were divided into ‘summer’ and ‘winter’ questions. The summer season was considered to be April 1 – September 30, and the winter period October 1 – March 31. The results are presented in *Table 14* and *Table 15*. The metrics chosen for daylight availability evaluation were sDA and ASE, and the results are given in *Table 16*. Graphical results are included in Appendix C.

Apartment B3-A1 was a two-story apartment, due to which the apartment was divided into two thermal zones for the BPS. The two sets of results were then combined to ensure that the results from all of the apartments can be compared against each other.

Table 14. Bi-seasonal results of mean dry-bulb, radiant and operative indoor temperatures.

Apartment	Mean *Ta*, summer [°C]	Mean *Ta*, winter [°C]	MRT, summer [°C]	MRT, winter [°C]	Mean *Tc*, summer [°C]	Mean *Tc*, winter [°C]
B1-A1	23,8	20,1	25,5	20,1	24,6	20,1
B1-A2	23,4	20,1	25,1	20,6	24,2	20,3
B2-A1	22,9	20,0	24,6	20,3	23,8	20,2
B3-A1	23,6	20,1	25,5	20,6	24,6	20,3
B4-A1	22,8	20,1	24,5	20,4	23,6	20,2
B5-A1	22,3	20,0	23,8	19,7	23,1	19,9

Table 15. Results on peak dry-bulb temperature, overheating hours and bi-annual mean RH.

Apartment	Peak *Ta*, summer [°C]	*Ta* Number of hours > 25 °C	*Ta* Number of hours > 26 °C	*Ta* Number of hours > 27 °C	Mean RH, summer [%]	Mean RH, winter [%]
B1-A1	32,4	1519	1107	754	42,1	33,0
B1-A2	31,4	1353	890	529	42,8	32,9
B2-A1	31,4	1043	658	406	44,2	33,0
B3-A1	33,8	2840	1985	1304	42,3	32,8
B4-A1	31,1	970	606	365	44,4	33,0
B5-A1	29,5	691	370	164	45,7	33,0

Table 16. Results on the simulated daylight performance metrics sDA and ASE.

Apartment	sDA [%]	ASE [%]
B1-A1	51,8	5,9
B1-A2	36,1	18,1
B2-A1	74,5	7,4
B3-A1	82,4	23,2
B4-A1	10,0	1,7
B5-A1	6,7	1,1

To begin to understand the heat flux of the apartments and the latent heat storage behavior of the indoor wood surfaces, data on the heat gain and heat loss through the windows, as well as heat gain and heat loss of the opaque indoor surfaces were simulated. Results are shown in *Figure 19*.

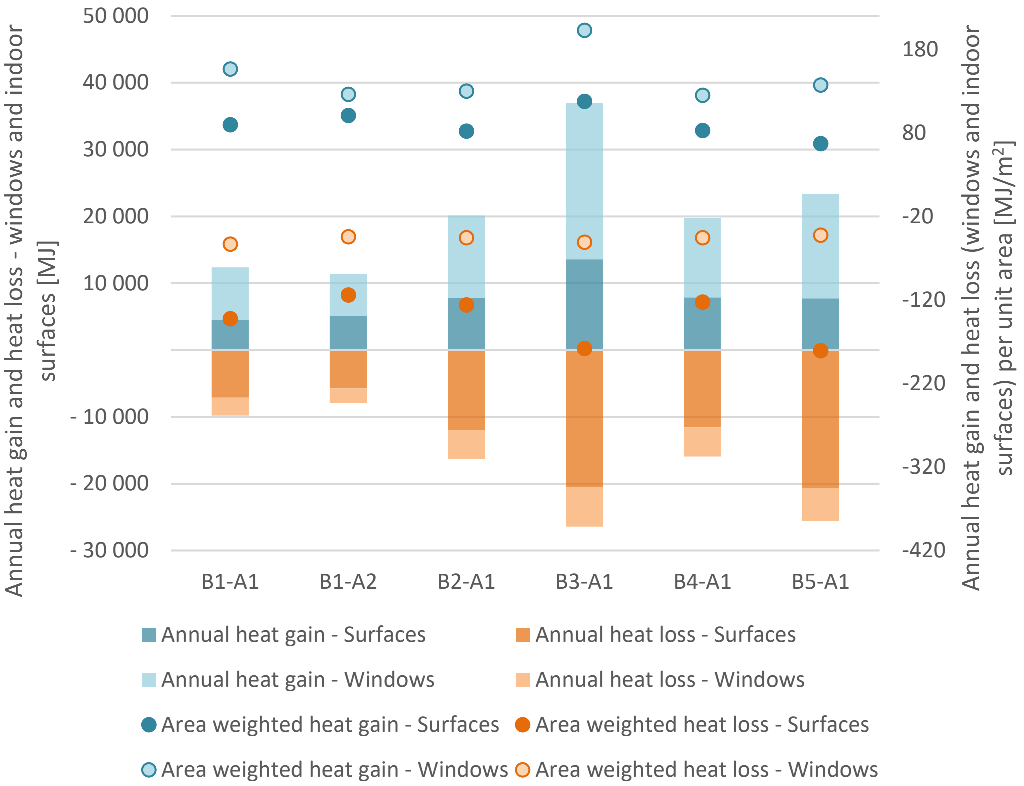

Figure 19. Annual heat gain and heat loss for windows and opaque indoor surfaces of the case study apartments.

4.1.5 Measured technical data

The acoustic performance was measured from all six buildings and a total of 77 samples were recorded. Airborne sound insulation was measured with 15 samples, impact sound insulation was measured with 21 samples, one sample measured reverberation time, and 40 samples measured noise from technical installations. Results for airborne sound insulation are detailed in *Figure 20* and for impact sound insulation in *Figure 21*. Reverberation time in a common room was measured to be 0,5 seconds, where the acceptable limit was 0,6 seconds. Results for noise from technical installations were not included, but it was noted that of the 40 measurements, 21 fulfilled the required levels stated in the Danish building regulations BR15, valid at the time (Danish Transport, Building and Housing Authority, 2018).

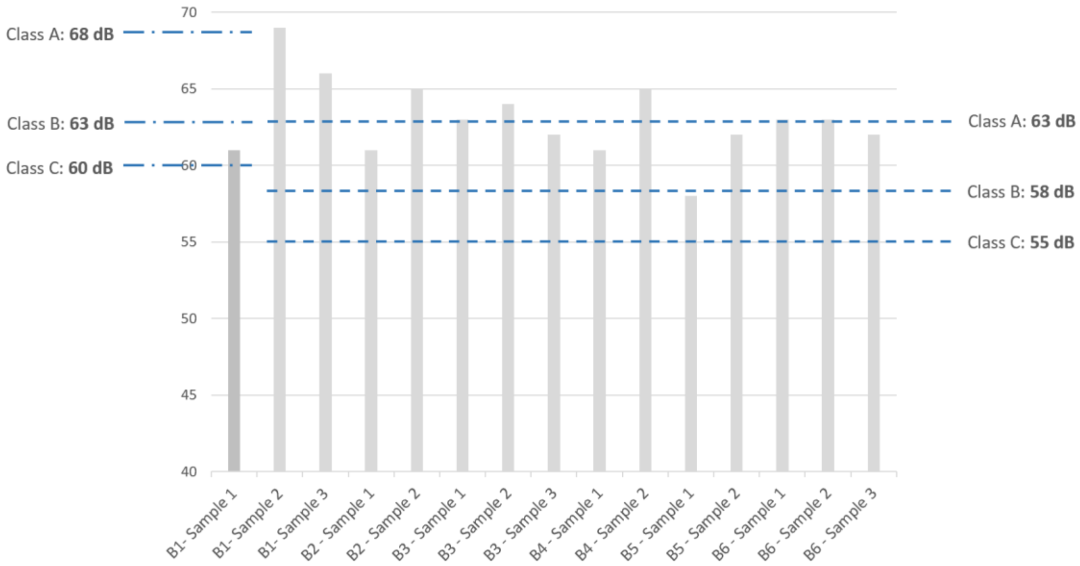

Figure 20. *Measured airborne sound insulation. 'B1 – Sample 1' is for the common room and has higher limit values than the rest of the measurements which are for the apartments. A higher value indicates higher performance. Data source: Lisbjerg Bakke DGNB documentation.*

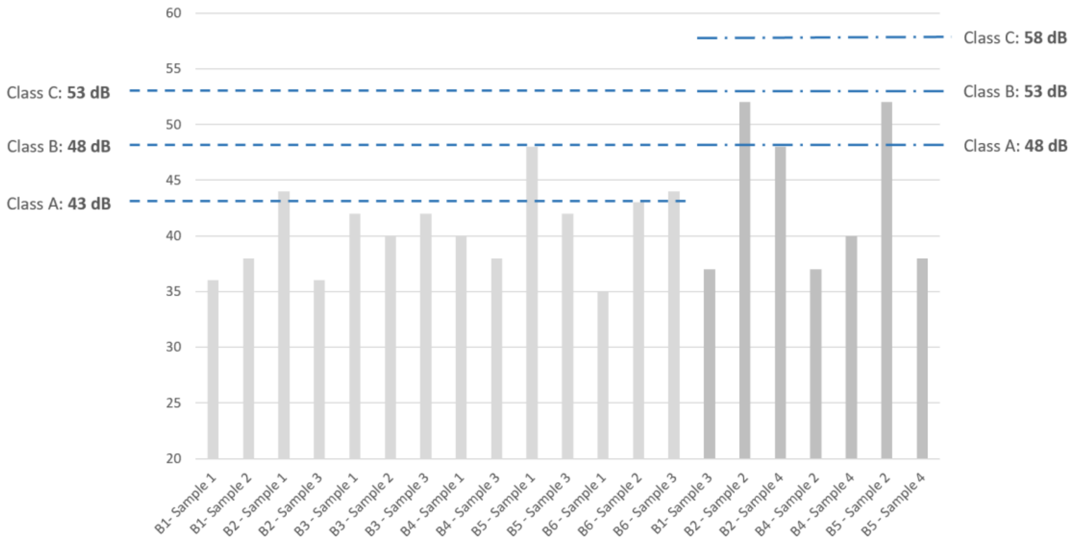

Figure 21. *Measured impact sound insulation. 'B1 – Sample 1' to 'B6 – Sample 3' are from bedrooms, living rooms and kitchens, and 'B1 – Sample 3' to 'B5 – Sample 4' are from bathrooms and common stairways, which have higher limit values. A lower value indicates higher performance. Data source: Lisbjerg Bakke DGNB documentation.*

To evaluate the acoustic performance, sound insulation design criteria were compared against the expected percentage of occupants in dwellings finding the conditions satisfactory, introduced by Rasmussen & Rindel (2005). The reference ranges are shown in *Table 17*. The new ISO/TS 19488 classification was also consulted, but the limit values were less rigorous than presented here, and hence not used.

Table 17. Relation between acoustic sound insulation design criteria for dwellings and the expected percentage of people finding the conditions satisfactory. Adapted from Rasmussen & Rindel (2005).

Occupants finding acoustic conditions satisfactory [%]	Airborne sound insulation $R'_w + C_{50\text{-}3150}$ [dB]	Measured results, airborne sound [%]	Impact sound pressure level $L'_{n,w} + C_{i,50\text{-}2500}$ [dB]	Measured results, impact sound [%]
80	63	53	48	90
60	58	47	53	10
40	53	-	58	-
20	48	-	63	-

Indoor air emissions were evaluated against samples from three buildings and six representative rooms, collected on-site before 28 days had passed from the construction completion. The samples were analyzed for TVOCs and formaldehyde, and the results are listed in *Table 18*.

Table 18. Indoor emission measurements carried out on-site after building completion. Data source: Lisbjerg Bakke DGNB documentation.

Sample source	TVOC [µg/m³]	Formaldehyde [µg/m³]
B1 – Sample 1	270	14
B1 – Sample 2	290	16
B4 – Sample 1	270	17
B4 – Sample 2	240	19
B6 – Sample 1	120	14
B6 – Sample 2	51	22

For TVOCs, no internationally established guideline value exists. However, the DGNB certification scheme requires that the total TVOC concentration does not exceed 3 000 µg/m³, which the measurements fulfilled by an order of magnitude.

The measured in-situ concentrations of formaldehyde were below the EU-LCI limit value of 100 µg/m³.

4.2 Comparative analysis

The following chapters demonstrate the numerical findings achieved through the various investigations.

4.2.1 Long-term evaluation of the general thermal comfort conditions

The number and percentage of occupancy hours during which the T_c and mean T_a are outside the specified range of 20 °C – 25 °C is shown in *Table 19*.

Table 19. The number and percentage of occupancy hours during which the T_c and T_a are outside 20 °C – 25 °C.

Apartment	T_c outside of 20 °C – 25 °C [h]	T_c outside of 20 °C – 25 °C [%]	T_a outside of 20 °C – 25 °C [h]	T_a outside of 20 °C – 25 °C [%]
B1-A1	4262	48,7	1519	17,3
B1-A2	2192	25,0	1353	15,4
B2-A1	2839	32,4	1043	11,9
B3-A1	6445	73,6	2856	32,6
B4-A1	2649	30,2	970	11,0
B5-A1	4224	48,2	691	7,9

4.2.2 Adaptive thermal comfort

The adaptive comfort temperature range for summer was calculated to have a lower limit of 20,0 °C and an upper limit of 25,0 °C. The range was compared to the simulated annual T_c of the apartments, as well as the thermal sensation votes of the POE, and the results are shown in *Table 20*.

Table 20. Comparison of mean annual Tc of the apartments and the difference to the calculated adaptive comfort range upper limit, as well as the thermal sensation votes recorded in the POE survey.

Apartment	Mean annual T_c [°C]	Difference to adaptive comfort temperature range upper limit [°C]	Thermal sensation vote, summer	Thermal sensation vote, winter
B1-A1	22,4	-2,6	Warm (+2)	Neutral (0)
B1-A2	22,3	-2,7	Somewhat warm (+1)	Neutral (0)
B2-A1	22,0	-3,0	Neutral (0)	Neutral (0)
B3-A1	22,5	-2,5	Hot (+3)	Neutral (0)
B4-A1	21,9	-3,1	Somewhat warm (+1)	Somewhat cool (-1)
B5-A1	21,5	-3,5	Hot (+3)	Somewhat warm (+1)

4.2.3 Daily temperature range index

The calculated indices for the daily temperature range introduced in section 3.2.3 are shown in *Table 21*.

Table 21. The calculated daily temperature range index based on the T_a exceeding the specified ranges and thresholds.

Apartment	T_a outside specified ranges [h]	T_a outside specified ranges [%]	T_a daily range > threshold [h]	T_a daily range > threshold [%]	Calculated index
B1-A1	3079	35,1	478	5,5	0,203
B1-A2	3038	34,7	271	3,1	0,189
B2-A1	3124	35,7	214	2,4	0,191
B3-A1	3044	34,7	405	4,6	0,197
B4-A1	3156	36,0	192	2,2	0,191
B5-A1	3172	36,2	62	0,7	0,185

4.2.4 Correlation

The above-mentioned index was analyzed against the summer vote, winter vote and combined mean annual vote of the thermal satisfaction POE survey results to evaluate correlation. The resulting correlation coefficients and α-values are reported in *Table 22*.

For the comparisons where $\alpha \leq 0{,}05$, the rule of thumb calculation was also true, with one exception. For the case ‘Satisfaction with indoor air quality vs. mean relative humidity in summer’, the rule was not fulfilled.

Table 22. Correlation analysis for daily temperature range index and thermal satisfaction votes from the POE survey.

	Correlation coefficient r_s [-]	**Correlation interpretation**	**α-value [-]**	**Level of confidence [%]**
Daily temperature range index vs. Thermal satisfaction in summer	-0,84	Strong	0,05	95,0
Daily temperature range index vs. Thermal satisfaction in winter	-0,13	Insignificant	> 0,05	< 90,0
Daily temperature range index vs. Mean annual thermal satisfaction	-0,70	Strong	0,10	90,0

In an exploratory approach, various measured, simulated and surveyed results were analyzed together to identify possible correlations. The data pairs with very strong correlation and their results are summarized in *Table 23*, and an overview of the correlation results of all investigated data pairs are shown in *Figure 22*. Appendix E includes fully detailed results of the correlation analysis including α-value and level of confidence for each data pair.

Table 23. Correlation analysis of various measured, simulated and surveyed results from Lisbjerg Bakke resulting in a very strong correlation with $\alpha \leq 0{,}05$.

	Correlation coefficient r_s [-]	**Correlation interpretation**	**α-value [-]**	**Level of confidence [%]**
Ease of temperature control vs. indoor MRT in summer	0,87	Very strong	0,050	95,0
Ease of temperature control vs. Mean *Ta* in summer	0,86	Very strong	0,050	95,0
Ease of temperature control vs. Mean *To* in summer	0,87	Very strong	0,050	95,0
Ease of temperature control vs. Satisfaction of temp. control	0,91	Very strong	0,025	97,5
Satisfaction with IAQ vs. Mean indoor RH in summer	-0,80	Very strong	0,050	95,0
Satisfaction with odors vs. Satisf. with indoor RH in summer	0,87	Very strong	0,050	95,0
Satisfaction with odors vs. Satisf. with indoor RH in winter	0,93	Very strong	0,025	97,5

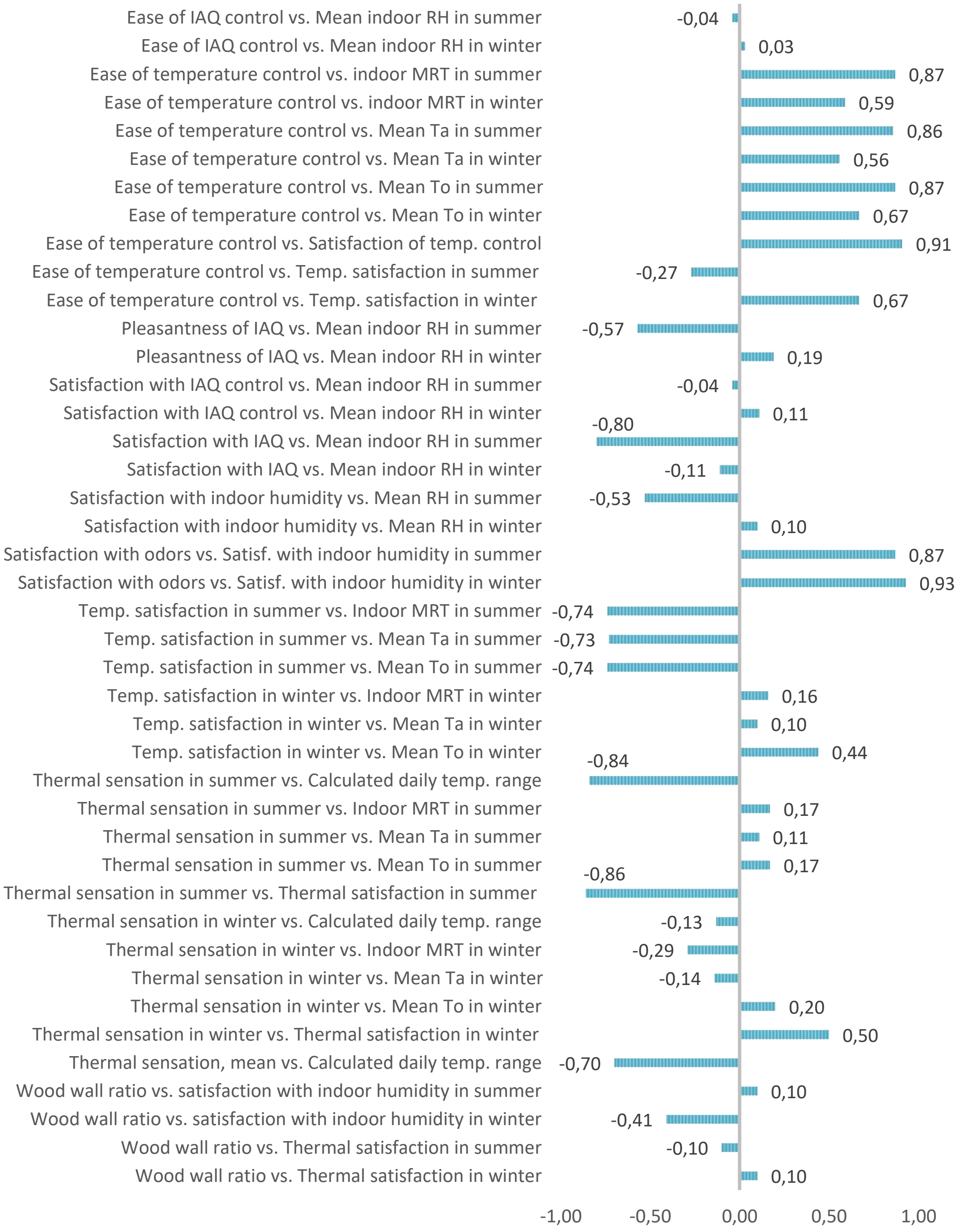

Figure 22. Correlation analysis of various surveyed, simulated and measured results from Lisbjerg Bakke.

5 Discussion

This study pursued identifying the properties affecting the indoor environmental quality (IEQ), and finding a method to holistically evaluate the performance and occupant comfort in modern wood buildings. By combining post-occupancy evaluation (POE) and building performance simulation (BPS), the obtained knowledge could be used as input for designing wooden multi-story buildings with comfortable indoor environments in the future.

No common method for POEs in multi-story wood buildings existed, so a methodology was designed as part of this study. The designed POE survey was successfully distributed digitally and performed relatively well. Using the 7-point answer scale yielded a wide range of perceptions, and allowed for comparing many different sets of perceptions with other ordinal variables.

The case study building at Lisbjerg Bakke was the first multi-story wood building in Denmark. It was designed and built to meet a range of criteria stipulated in the DGNB sustainability certification scheme. It was also built as a subsidized housing complex with a rigorous budget. While efforts were made to ensure that the requirements for social, environmental and economic sustainability were met, the building seems to suffer from performance issues, some of which could have been predicted with BPS.

The POE of the case study building identified invaluable insight into the performance of the building. The initial predicted mean vote (PMV) indicated that the building would comply with environmental category I, but the actual results placed the building in category IV, considered not acceptable. The findings thereby confirm that the PMV/PPD as such might be an unreliable metric for predicting thermal sensation, at least in a partially air-conditioned building such as Lisbjerg Bakke, and when the sample size is small.

Due to the small sample size achieved, the POE results were not normally distributed, but Spearman’s rank correlation coefficient was identified as a suitable data analysis method. Correlations between various data pairs were discovered, but should be interpreted with caution, as correlation does not equal causation. Only further research can prove that one thing affects the other.

The simulations and calculations carried out for this study showed that overall, there is a clear connection between the thermal sensation votes of the occupants and the simulated thermal performance of the apartments, and especially in summer months, the indoor temperatures regularly exceed comfort levels. These results are in agreement with previous findings from three prefabricated multi-story wood buildings by Adekunle & Nikolopoulou. For many apartments, the indoor environment was perceived to be uncomfortably warm during the summer period, but neutral and satisfying during the winter period. This result was supported by the BPS results, which exposed high mean temperatures and a large number of predicted overheating hours during summer. None of the apartments met the overheating limits considered in this study. When examining the overheating results together with the high daylight penetration, it can be argued that an effective improvement could be achieved with different window dimensioning and placement. Another suggestion is to prioritize user control and the possibility of cross-ventilation, and introduce user-operable external shading devices. The importance of such passive heat rejection measures would be even more pronounced for similar buildings located in areas affected by the urban heat island effect.

The calculated daily temperature range index showed a strong negative correlation coefficient with the occupants' thermal sensation in the summertime. When calculating the same for the winter season, no correlation was found. When combining and averaging the summer and winter votes, a negative yet weaker correlation was found, but it did not pass the rule of thumb test. These findings support the theory proposed by Li et al. for summertime thermal performance, and the calculation method can be recommended for future predictions.

Indoor air quality (IAQ) was generally assessed to be pleasant, and occupant satisfaction with air quality and air humidity indoors was high. The simulated results relatively dry ambient conditions, especially compared to the high mean outdoor realtive humidity (RH). The humidity fluctuations may be reduced by the moisture buffering effect of the large wooden surfaces of the apartments, as previously found by Simonson et al., Hameury, and Nore et al., but it is not possible to conclude without more detailed investigations. Comparison against long-term on-site measurements would be highly useful to validate the accountability of the results.

For acoustic conditions, the results showed that although the structural design achieved the highest category of performance in many cases, the occupants still expressed dissatisfaction with noise. With the measured results, 60 % - 80 % of the occupants were expected to find the conditions satisfactory, and summing up the results from the POE survey on satisfaction with acoustic conditions received an average satisfaction of 72 %. Although the six buildings were built with the same structural principles, materials and assumingly by the same construction crews, the measured airborne and especially impact sound insulation results varied between the apartments. In modern wood buildings, acoustic performance is one of the most debated subjects and the findings of this study confirm that work remains to be done to provide satisfactory acoustic indoor environments for the occupants.

All occupants reported high satisfaction with the daylight availability in their apartments. The simulations suggested much more varying performance. Only two of the six apartments reached the recommended spatial daylight autonomy (sDA) ranges, but had unsatisfactory annual solar exposure (ASE) results, and three apartments fell within an acceptable ASE range, but did not reach desired sDA levels. It should be noted that the sDA schedule is set to 8 am – 6 pm, a timeframe many people are away from home, which might in part explain the dissimilarity of the simulated results and occupant satisfaction on daylight conditions. Comparing the very high satisfaction with daylight conditions with the overheating and the area-weighted heat gains from the windows suggest that there is room for design optimization for providing better thermal performance. Evaluating daylight performance in residential environments could be revisited to propose as detailed reference frameworks as currently exist for offices.

Previous studies have shown that the level of occupant control has a considerable impact on the IEQ satisfaction. At the case study building, the survey responses revealed a lack of control availability and perhaps also knowledge, which could explain some of the low satisfaction votes. The finding follows Lomas & Porritt's claim that people's actions on improving thermal discomfort depend on the available opportunities to increase comfort, and understanding of the likely impact of taking the action. Rather than seeking to increase the ventilation rate and increase energy consumption, more knowledge on how to make local adjustments and consider alternatives such as fans could lead to higher efficiency and occupant satisfaction.

Among the various correlation calculations, a handful of relationships were found. The highest positive correlation coefficients were found between ‘satisfaction with odors’ and ‘satisfaction with indoor air humidity in winter’, and ‘ease of temperature control’ and ‘satisfaction of temperature control’. ‘Ease of temperature control’ strongly correlated with ‘Mean Tc in summer’, ‘indoor MRT in summer’, and ‘Mean Ta in summer’. The highest negative correlation was found between ‘satisfaction with indoor air quality’ and ‘mean relative humidity in summer’.

No significant correlation between the ratio of indoor wood surfaces in the apartments and the thermal sensation votes nor indoor humidity votes were found. However, the apartments with the largest ratio of wood surfaces per wall area also had the largest area-weighted indoor surface heat loss, which could indicate that there is a relationship between the quantity of wood used on the interior, the actual indoor temperature conditions and the resulting comfort experience of the occupants.

Overall, the simulation results reflected the surveyed occupant responses, which suggests that carrying out holistic BPS studies in the design phase can help mitigate suboptimal IEQ performance. However, the results achieved have been limited by the methods applied. While simulations offer an affordable, low threshold approach to evaluating a building’s performance, the greatest benefit would be achieved by combining the data to long-term on-site measurements of actual conditions. This would also enable collecting data on indoor emissions, which cannot be estimated using simulations. Furthermore, analyzing the diurnal variations would provide a more detailed understanding of the processes involved, and allow observations on the latent heat storage and moisture buffering of the wood surfaces.

Modern building performance management systems with built-in sensor technology and big data analytics have the potential to revolutionize the methods and norms relating to the indoor environment as we know it. This technology is already being pioneered, for example in schools where real-time feedback on IEQ parameters such as temperature, RH and CO_2 levels are continuously displayed and paired with nudges for the occupants to open windows to air out when the indoor climate quality declines. Over time, the accumulated data and knowledge on building performance parameters could be employed to develop transparent and easy to understand information for the building occupants, similar to the label currently used for communicating energy efficiency of appliances across Europe. As a consumer, being able to compare for instance the thermal, acoustic and daylight performance of prospective rental apartments, houses or offices could further increase demand for healthier, better performing buildings.

At a time of accelerated change and unprecedented challenges, the future success of our species depends on science-based decision-making, leading by example and setting the bar higher than the bare minimum. For the built environment, the transformation toward less resource and energy-demanding industry is backed up with policies requiring regions and nations to act now, and well-recognized frameworks, such as the UN Sustainable Development Goals and the 2050 carbon neutrality goal. The increasing attention on natural resource scarcity, biodiversity loss and climate change should not lull us into a false sense of security that something is being done, but remind us that finding the best solutions to continue thriving on this planet is a mutual responsibility of us all.

6 Conclusions

The current state of the art on attributes affecting indoor environmental quality (IEQ) and occupant comfort in modern wood buildings were identified and many were investigated in this study.

As no established method for post-occupancy evaluation (POE) in wood buildings was found, one was developed as part of this study and employed at a case study building. The POE survey revealed valuable insight into the building performance and some of the attributes that are appreciated in the wood building, such as light, airiness and the natural presence of wood, as well as the undesirable side effects, such as design choices that generate disturbing noise. The POE method can be repeated for future investigations on indoor environmental quality in multi-story wood buildings.

The surveyed occupant perceptions mostly aligned with the building performance simulation (BPS) data. Several strongly correlating data pairs were identified and the validity of the findings was tested. The predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) failed to estimate the observed mean thermal sensation vote, but adaptive thermal comfort indices performed better and are recommended to be used for similar buildings. The occurrence of daily temperatures exceeding a set range correlated with occupant thermal satisfaction during the cooling period.

Based on the findings of this study, the IEQ of a wood building in the design phase can be predicted and evaluated with BPS and calculations. Generating apartment-specific annual data on temperature ranges, humidity levels and overheating hours is highly recommended early on in any design process to make data-driven decisions. The simulation model accuracy can be further fortified by introducing a higher level of input detail, such as case-specific occupancy, equipment and lighting schedules.

6.1 Future work

For future applications, the POE methodology could be divided into separate versions for buildings with and without exposed indoor wood surfaces. If there are no visible wood surfaces on the interior of a wood building, the investigations shift focus as there will not be a similar thermodynamic exchange of moisture and heat, and other IEQ parameters might be experienced differently. Where possible, the survey should be combined with qualitative interviews with the occupants and/or physical on-site measurements where further relevant and critical information could be collected.

A continuation to the research in this paper could be a detailed investigation of the diurnal surface moisture flux and latent heat flux of the exposed wood surfaces in the apartments, paired with long-term measurements of the on-site thermal conditions. In this context, developing a location-specific future weather file including data on both long-term average conditions and the incidence of heatwaves would be beneficial.

Contribution to open-source data accumulation of the IEQ in buildings is recommended to provide data for all building stakeholders, including residents, to encourage demand for healthier, better performing buildings.

7 Summary

The European building sector is responsible for extensive energy consumption, material extraction, water consumption and waste generation. In efforts to mitigate a climate crisis, measures have been introduced to increase energy-efficiency and reduce the carbon emissions of the built environment. Due to the environmental challenges and concerns for occupant well-being in buildings, there is an increasing interest in using natural and renewable building materials, such as wood. The impact of wooden materials on measured and perceived IEQ, energy performance and occupant comfort has been explored by a growing number of studies.

The main aim of this study was to assess the variables and properties affecting the IEQ in wood buildings, and to find a method to holistically evaluate the building performance of a case study building with a POE survey, simulated data and measured data. The second aim was to propose suitable methods for predicting and evaluating the IEQ of a wood building in the design phase to achieve optimal performance and occupant comfort in the operational phase, and to review the suitability of the POE survey for future investigations. In this study, the IEQ parameters considered were the thermal environment (including heat, cold, draughts and humidity), the atmospheric environment (including emissions and air quality), the acoustic environment (airborne and impact noise) and the visual environment (daylight availability).

An occupied multi-story wood building was examined in great detail. For each case study apartment studied, hourly annual data on thermal and daylight properties were generated with a dynamic simulation model, taking into account the local climate conditions. Documented on-site measurements on acoustics, indoor emissions and leakage were also incorporated.

Both the classic thermal comfort theory on the steady-state heat balance of the human body with its environment, and the adaptive thermal comfort theory were investigated. Long-term thermal comfort was evaluated in light of annual overheating hours. A newly proposed theory based on the correlation of the occurrence of daily temperature ranges exceeding a set range versus occupant thermal satisfaction was also calculated. To evaluate the relationships between the POE survey results, and the measured and simulated data, several correlation calculations were made.

Despite the low response rate, the POE survey findings were interesting. The largest problems identified were with the thermal conditions and overheating in summer. The occupants were generally satisfied with the IAQ, but rather unsatisfied with the acoustic performance. All occupants reported high satisfaction with the daylight availability in their apartments. It was found that both the level of control available to adjust the temperature and air quality in the apartments, and the occupants' knowledge on the effectiveness of making local adjustments was low. The small sample size was one of the drawbacks of the study.

With minor adjustments, the developed POE survey can be deployed to upcoming investigations of wooden multi-story buildings. The predictive methods tested in this study are recommended for design-phase investigations of modern wood buildings.

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Appendices

Appendix A – POE survey

This appendix presents the full structure of the post-occupancy evaluation questionnaire discussed in the paper.

A. Background

1. What is your address? [Free text]

2. What is your age group? [Answer options: 18-24, 25-34, 35-44, 45-54, 55-64, 65+, Prefer not to answer]

3. How long have you lived in your current apartment? [Free text]

4. Was your choice to move into the building influenced by the fact that it was built in wood? [Yes/No]

B. Thermal comfort

5. How would you describe the overall temperature conditions in your apartment?

a) In the summer

b) In the winter

	Cold	**Cool**	**Slightly cool**	**Neutral**	**Slightly warm**	**Warm**	**Hot**
Ordinal rank	-3	-2	-1	0	+1	+2	+3

6. How satisfied are you with the overall temperature conditions in your apartment?

a) Indoor temperature in the summer

b) Indoor temperature in the winter

c) Temperature of the floor

	Very unsatisfied	**Unsatisfied**	**Somewhat unsatisfied**	**Neither unsatisfied nor satisfied**	**Somewhat satisfied**	**Satisfied**	**Very satisfied**
Ordinal rank	1	2	3	4	5	6	7

7. Do you experience a feeling of draft within your apartment? [Answer options: Yes/No]

8. If you answered ’Yes’ to question 7, where in the body do you feel the draft? [Free text]

9. To what extent do you agree with the following statements?

a) I can easily control the indoor temperature in my apartment

b) I am satisfied with the controls available to adjust the indoor temperature in my apartment

	Strongly disagree	**Disagree**	**Somewhat disagree**	**Neither disagree nor agree**	**Somewhat agree**	**Agree**	**Strongly agree**
Ordinal rank	1	2	3	4	5	6	7

10. With your own words, describe how you adjust the indoor temperature in your apartment. [Free text]

C. Indoor air quality

11. How would you describe the overall indoor air quality in your apartment?

a) In the summer

b) In the winter

	Very unpleasant	**Unpleasant**	**Somewhat unpleasant**	**Neither unpleasant nor pleasant**	**Somewhat pleasant**	**Pleasant**	**Very pleasant**
Ordinal rank	1	2	3	4	5	6	7

12. How satisfied are you with the overall indoor air quality in your apartment?

a) Indoor air quality in the summer

b) Indoor air quality in the winter

c) Indoor air humidity in the summer

d) Indoor air humidity in the winter

e) Odors in the apartment

	Very unsatisfied	**Unsatisfied**	**Somewhat unsatisfied**	**Neither unsatisfied nor satisfied**	**Somewhat satisfied**	**Satisfied**	**Very satisfied**
Ordinal rank	1	2	3	4	5	6	7

13. To what extent do you agree with the following statements?

a) I can easily improve the indoor air quality in my apartment

b) I am satisfied with the controls available to improve the indoor air quality in my apartment

	Strongly disagree	**Disagree**	**Somewhat disagree**	**Neither disagree nor agree**	**Somewhat agree**	**Agree**	**Strongly agree**
Ordinal rank	1	2	3	4	5	6	7

14. With your own words, describe how you improve the indoor air quality in your apartment. [Free text]

D. Acoustic quality

15. How satisfied are you with the acoustic conditions in your apartment?

a) Noise from neighbors above/below

b) Noise from neighbors on the same level

c) Overall acoustics in the apartment, f.ex. echoing

d) Noise from within the apartment, f.ex. from technical installations

e) Noise from outside the apartment, f.ex. traffic noise

	Very unsatisfied	**Unsatisfied**	**Somewhat unsatisfied**	**Neither unsatisfied nor satisfied**	**Somewhat satisfied**	**Satisfied**	**Very satisfied**
Ordinal rank	1	2	3	4	5	6	7

16. Do you experience the acoustic conditions in your apartment as disturbing? [Answer options: Yes/No]

17. If yes, describe the disturbing noise, f.ex. loud music from neighbors, footstep from the apartment above, ventilation system noise, traffic noise. [Free text]

E. Daylight quality

18. How satisfied are you with the daylight conditions in your apartment?

a) Daylight availability in the summer

b) Daylight availability in the winter

	Very unsatisfied	**Unsatisfied**	**Somewhat unsatisfied**	**Neither unsatisfied nor satisfied**	**Somewhat satisfied**	**Satisfied**	**Very satisfied**
Ordinal rank	1	2	3	4	5	6	7

19. Do you experience the daylight conditions in your apartment as disturbing? [Answer options: Yes/No]

20. If yes, describe how you adjust the daylight conditions in your apartment.

F. Other

21. In your own words, describe some positive attributes about your apartment.

22. In your own words, describe some negative attributes about your apartment.

23. Please enter your email address if we may contact you to elaborate on your answers.

Appendix B – POE survey results

This appendix presents the summarized results of the post-occupancy evaluation questionnaire discussed in the paper.

Resp. alias	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Apt. alias	B1-A1	B1-A2	B2-A1	B3-A1	B4-A1	B5-A1	N.A.
Q #	**Responses**						
2.	18-24	25-34	45-54	35-44	25-34	55-64	5-34
3.	1-2 years	1-2 years	2-3 year	1-2 years	> 3 years	> 3 years	2-3 years
4.	No	No	No	No	No	No	No
5.a	6	5	4	7	5	7	7
5.b	4	4	4	4	3	5	4
6.a	3	6	6	2	5	1	1
6.b	5	6	6	5	4	5	6
6.c	6	7	6	4	4	3	6
7.	Yes	No	Yes	No	No	No	Yes
8.	A little bit around the windows, otherwise only around the ventilation unit		It depends on where I am in reference to the ventilation unit in the ceiling				All over, it comes from the windows and the technical room
9.a	6	6	6	6	4	1	2
9.b	6	7	6	6	2	1	2

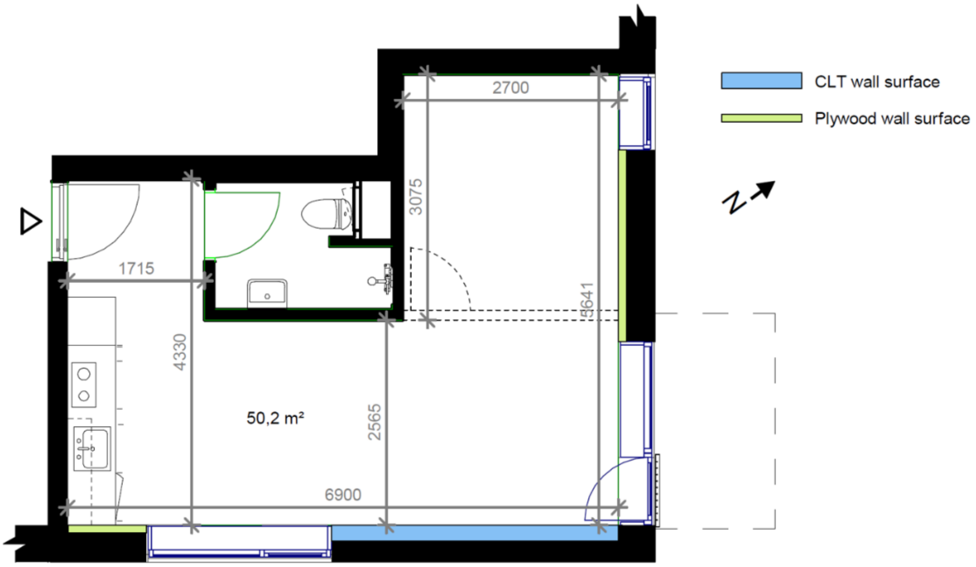
10.	If I think it's too cold, I can turn up the radiators which are conveniently placed in the apartment and if it gets too hot in the summer, I can open more windows and use cross-ventilation if that's what I want.	In the summer, it can be difficult to do anything other than open a window, as there is no AC. In winter by underfloor heating and radiators.	Open or close windows/doors or turn the radiator up or down.	With radiator and windows, and ventilation in winter as cross-ventilation is difficult.	With radiators.	It cannot be controlled - there are radiators that are always at almost a minimum - the only option for cooling is to close the curtains or open windows/balcony doors to get cross-ventilation - in the summer it is not possible to get cooling at all.	Open windows or turn on the radiators.
11.a	7	6	6	6	6	2	6
11.b	7	7	6	3	6	1	6
12.a	7	7	6	6	5	2	2
12.b	7	7	6	6	5	1	6
12.c	5	7	6	6	4	2	6
12.d	6	7	6	2	4	1	6
12.e	7	7	6	4	6	2	6
13.a	3	4	6	5	5	1	2
13.b	2	4	6	3	4	1	2
14.	I have some plants so they can improve the air and in addition I also have a ventilation system which probably has many settings but I'm not sure how it works or what it can do.	There is central ventilation which controls everything, I cannot do anything other than open a window.	I'm not doing much.	It is easy to ventilate, but it is difficult to change the humidity in winter without buying a humidifier.	By opening windows/balcony doors.	This can only be done by airing out. There has been a centrally controlled ventilation system. As a resident, it has not been possible to regulate this - and it is out of order. When the ventilation system worked, it provided a relatively good indoor climate.	Open windows or turn on the kitchen extractor or radiators.
15.a	3	7	6	5	6	3	1
15.b	7	6	7	7	6	6	1

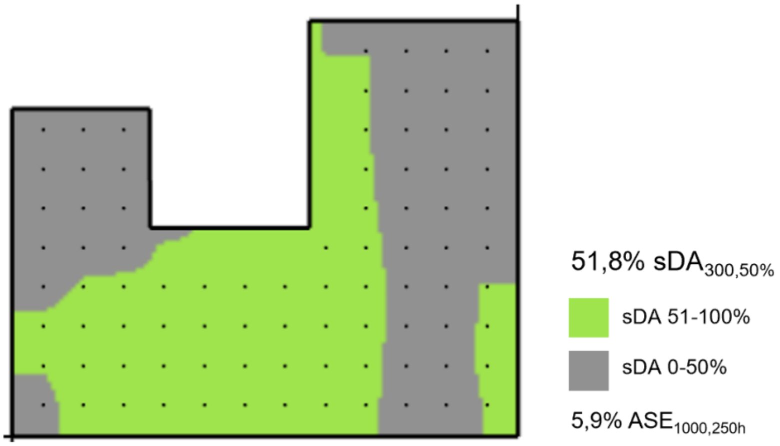
15.c	6	7	6	1	6	6	1
15.d	5	7	4	7	4	3	1
15.e	5	7	4	6	5	4	1
16.	Yes	No	Yes	No	No	No	Yes
17.	I can clearly hear when the resident in the apartment above plays music and has a party, can also hear the ventilation system running if you just think about it or notice it and then I can also hear if someone comes by car or something outside.	Right now, the municipality is laying new roads out here in the area, it affects a lot. I think this is very normal and will be almost the same no matter what home you live in.	There is a constant noise from the kitchen extractor/ventilation extraction. The technical room located in a room generates noise 24/7. When neighbors above or below use the toilet, it can clearly be heard.				Loud music and generally (it is) very noisy, ventilation is noisy, there is a construction site right outside the door.
18.a	7	7	7	7	6	7	6
18.b	7	7	7	7	6	7	6
19.	No	No	No	Yes	No	No	No
20.				With curtains.			

Appendix C – Case study apartments

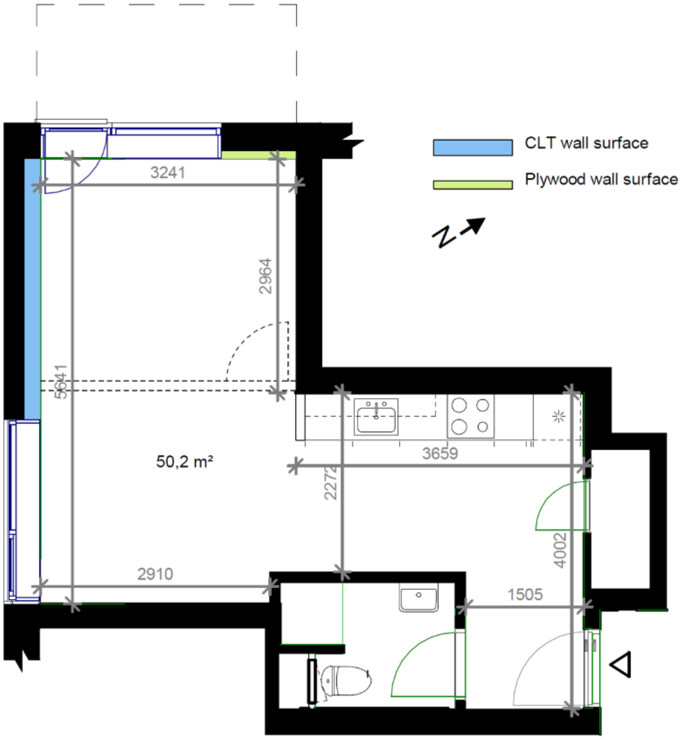
This appendix presents the layouts of the investigated case study apartments at Lisbjerg Bakke, and the simulated daylight results reflected on the layout of each apartment.

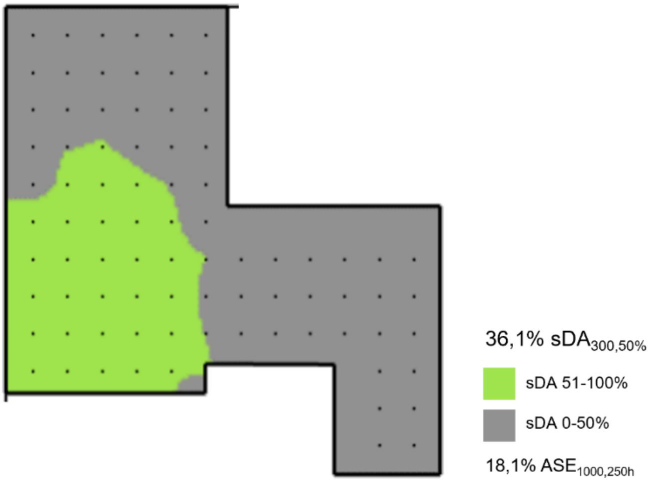
Apartment B1-A1



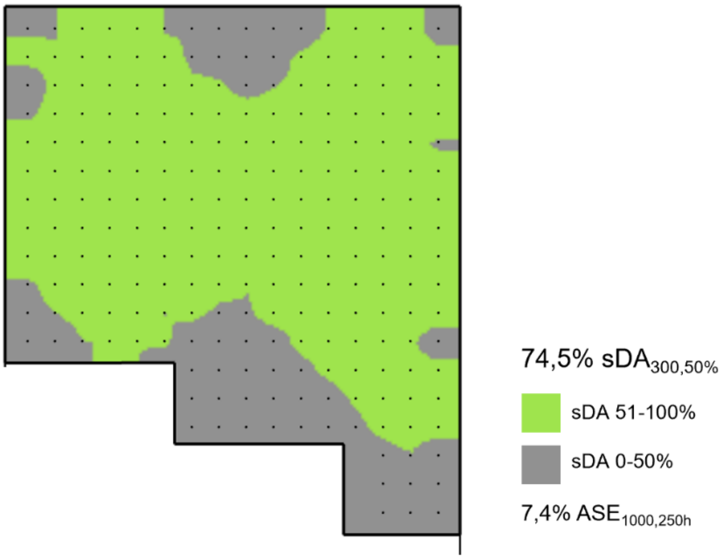


Apartment B1-A2

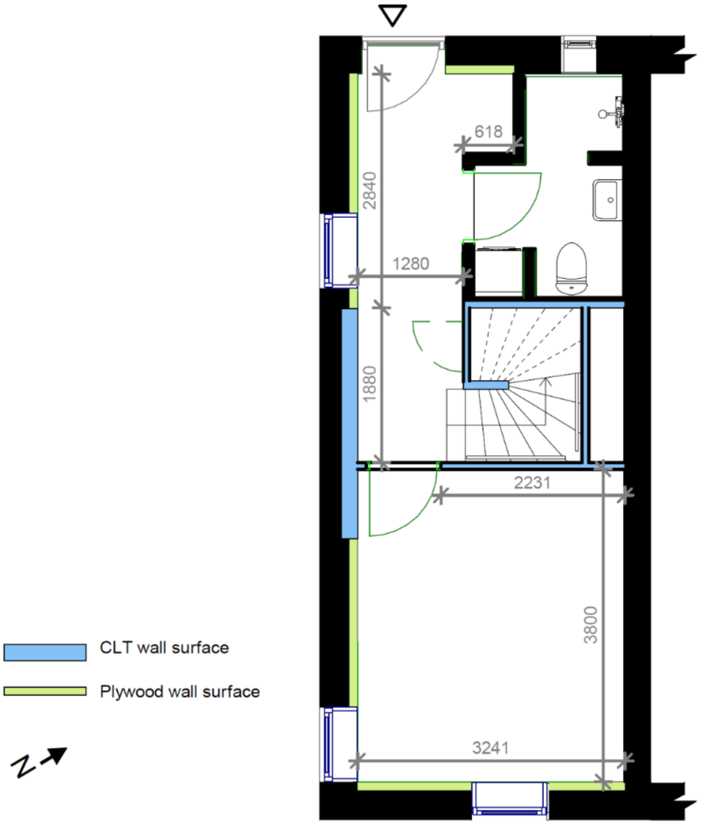


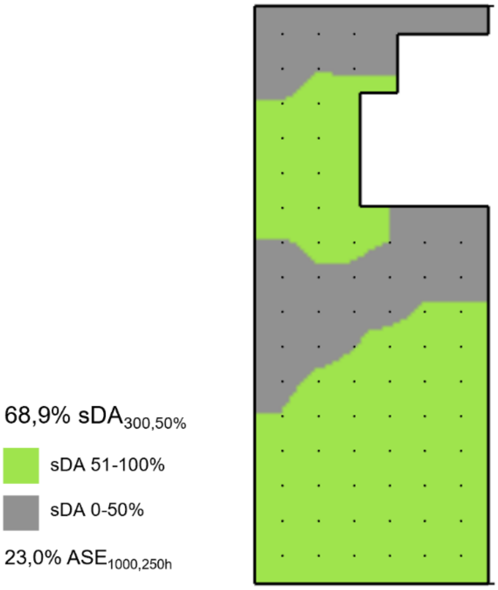


Apartment B2-A1

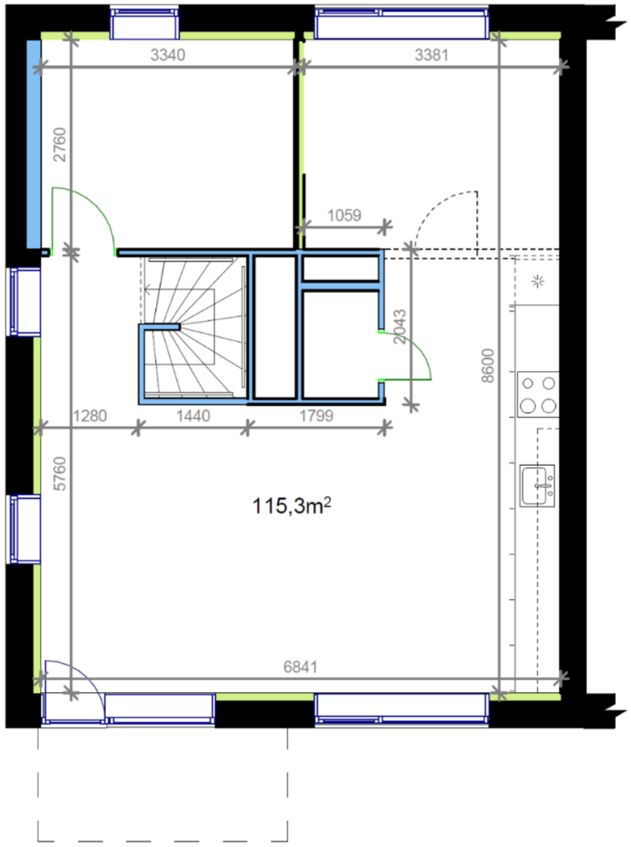


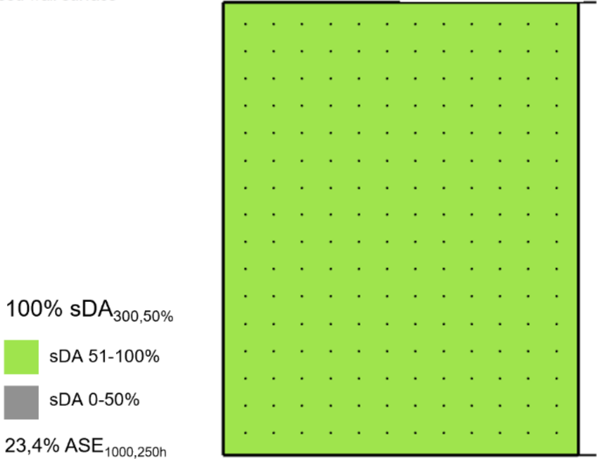
Apartment B3-A1 – Lower floor



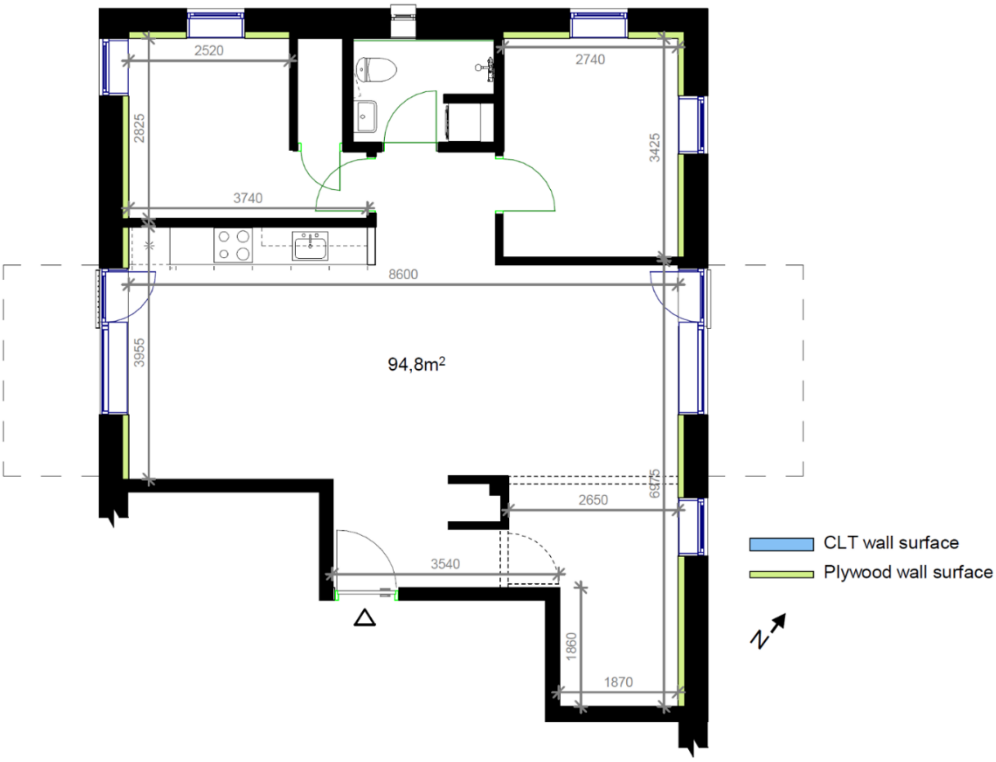


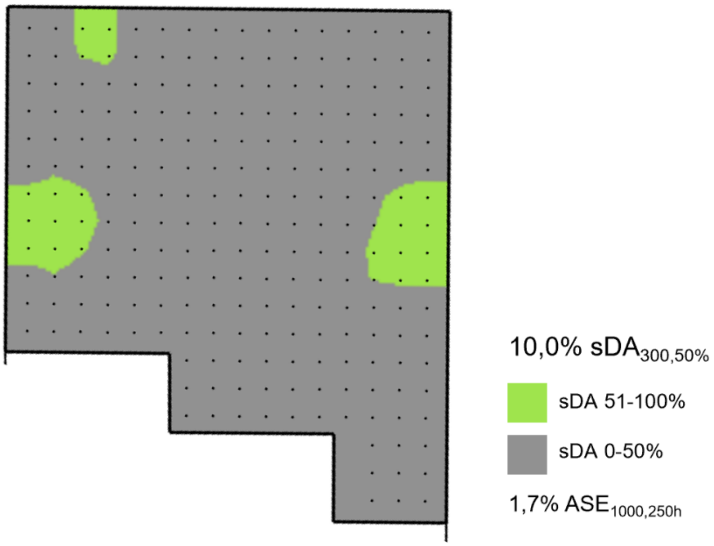
Apartment B3-A1 – Upper floor



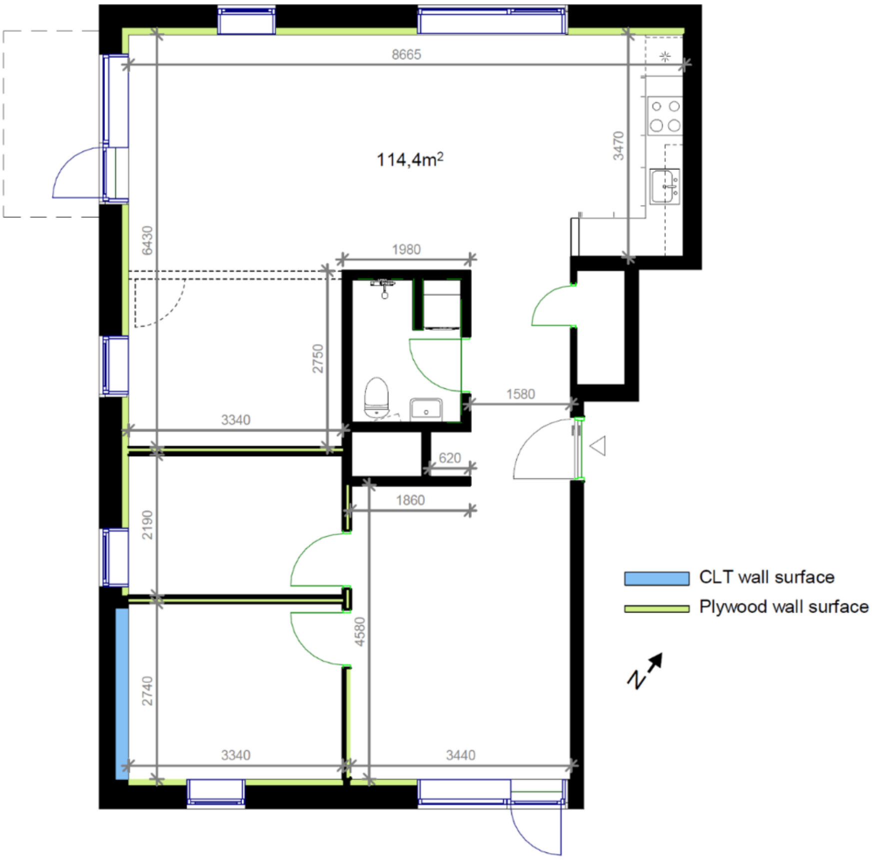


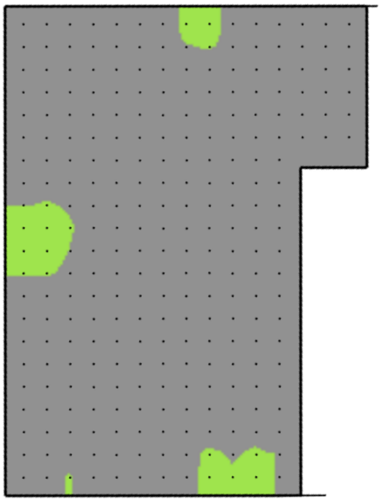
Apartment B4-A1





Apartment B5-A1





6,7% $\text{sDA}_{300,50\%}$

🟩 sDA 51-100%

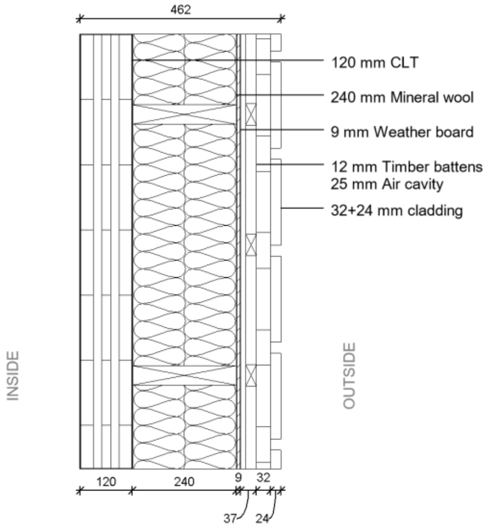
⬛ sDA 0-50%

1,1% $\text{ASE}_{1000,250h}$

Appendix D – Standard constructions

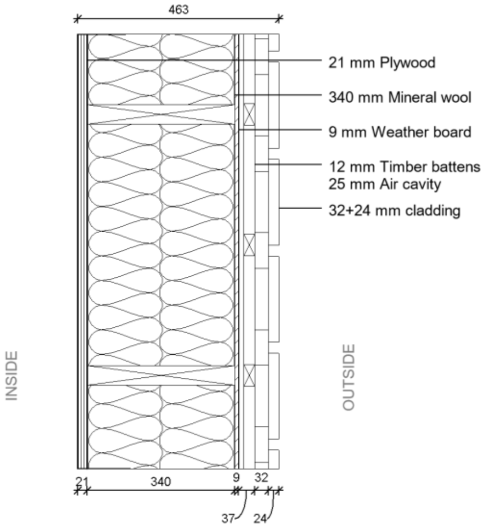
This appendix presents the standard constructions of the case study apartments at Lisbjerg Bakke.

Plan section of exterior wall
with CLT finish on the interior



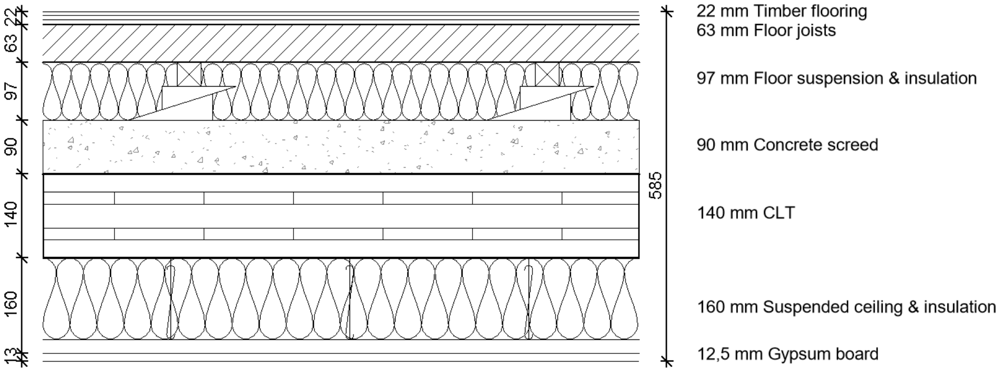
Documented U-value: 0,12 W/(m²·K)
Calculated U-value: 0,10 W/(m²·K)

Plan section of exterior wall with
plywood finish on the interior

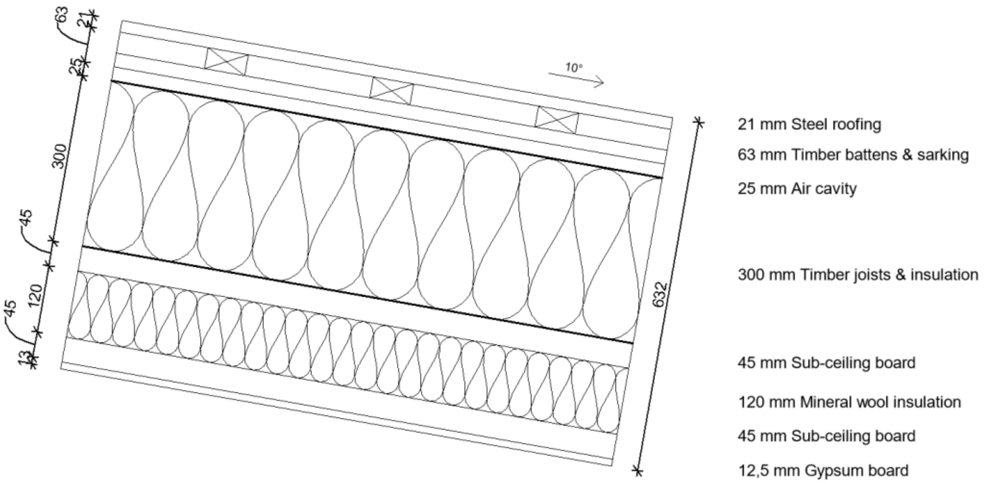


Documented U-value: 0,12 W/(m²·K)
Calculated U-value: 0,08 W/(m²·K)

Cross-section of storey partition build-up



Cross-section of roof build-up



Documented U-value: 0,08 W/(m²·K)
Calculated U-value: 0,07 W/(m²·K)

Appendix E – Correlation results

Correlation analysis results of the various measured, simulated and surveyed results from Lisbjerg Bakke. Results with a strong or very strong correlation coefficient are highlighted.

	Correlation coefficient r_s [-]	**Correlation interpretation**	**α-value [-]**	**Level of confidence [%]**
Wood wall ratio vs. Thermal satisfaction in winter	0,10	Insignificant	> 0,25	< 75
Wood wall ratio vs. Thermal satisfaction in summer	-0,10	Insignificant	> 0,25	< 75
Wood wall ratio vs. satisfaction with indoor humidity in winter	-0,41	Moderate	0,25	75
Wood wall ratio vs. satisfaction with indoor humidity in summer	0,10	Insignificant	> 0,25	< 75
Thermal sensation, mean vs. Calculated daily temp. range	**-0,70**	**Strong**	**0,10**	**90**
Thermal sensation in winter vs. Thermal satisfaction in winter	0,50	Moderate	0,25	75
Thermal sensation in winter vs. Mean To in winter	0,20	Weak	> 0,25	< 75
Thermal sensation in winter vs. Mean Ta in winter	-0,14	Insignificant	> 0,25	< 75
Thermal sensation in winter vs. Indoor MRT in winter	-0,29	Weak	> 0,25	< 75
Thermal sensation in winter vs. Calculated daily temp. range	-0,13	Insignificant	> 0,25	< 75
Thermal sensation in summer vs. Thermal satisfaction in summer	**-0,86**	**Very Strong**	**0,05**	**95**
Thermal sensation in summer vs. Mean To in summer	0,17	Insignificant	> 0,25	< 75
Thermal sensation in summer vs. Mean Ta in summer	0,11	Insignificant	> 0,25	< 75
Thermal sensation in summer vs. Indoor MRT in summer	0,17	Insignificant	> 0,25	< 75
Thermal sensation in summer vs. Calculated daily temp. range	**-0,84**	**Very Strong**	**0,05**	**95**
Temp. satisfaction in winter vs. Mean To in winter	0,44	Moderate	0,25	75
Temp. satisfaction in winter vs. Mean Ta in winter	0,10	Insignificant	> 0,25	< 75
Temp. satisfaction in winter vs. Indoor MRT in winter	0,16	Insignificant	> 0,25	< 75
Temp. satisfaction in summer vs. Mean To in summer	**-0,74**	**Strong**	**0,10**	**90**
Temp. satisfaction in summer vs. Mean Ta in summer	**-0,73**	**Strong**	**0,10**	**90**

Temp. satisfaction in summer vs. Indoor MRT in summer	**-0,74**	**Strong**	**0,10**	**90**
Satisfaction with odors vs. Satisf. with indoor humidity in winter	**0,93**	**Very strong**	**0,03**	**97,5**
Satisfaction with odors vs. Satisf. with indoor humidity in summer	**0,87**	**Very strong**	**0,05**	**95**
Satisfaction with indoor humidity vs. Mean RH in winter	0,10	Insignificant	> 0,25	< 75
Satisfaction with indoor humidity vs. Mean RH in summer	-0,53	Moderate	0,25	75
Satisfaction with IAQ vs. Mean indoor RH in winter	-0,11	Insignificant	> 0,25	< 75
Satisfaction with IAQ vs. Mean indoor RH in summer	**-0,80**	**Very strong**	**0,10**	**90**
Satisfaction with IAQ control vs. Mean indoor RH in winter	0,11	Insignificant	> 0,25	< 75
Satisfaction with IAQ control vs. Mean indoor RH in summer	-0,04	Insignificant	> 0,25	< 75
Pleasantness of IAQ vs. Mean indoor RH in winter	0,19	Insignificant	> 0,25	< 75
Pleasantness of IAQ vs. Mean indoor RH in summer	-0,57	Moderate	0,25	75
Ease of temperature control vs. Temp. satisfaction in winter	**0,67**	**Strong**	**0,10**	**90**
Ease of temperature control vs. Temp. satisfaction in summer	-0,27	Insignificant	> 0,25	< 75
Ease of temperature control vs. Satisfaction of temp. control	**0,91**	**Very strong**	**0,03**	**97,5**
Ease of temperature control vs. Mean To in winter	**0,67**	**Strong**	**0,10**	**90**
Ease of temperature control vs. Mean To in summer	**0,87**	**Very strong**	**0,05**	**95**
Ease of temperature control vs. Mean Ta in winter	0,56	Moderate	> 0,1	< 90
Ease of temperature control vs. Mean Ta in summer	**0,86**	**Very strong**	**0,05**	**95**
Ease of temperature control vs. indoor MRT in winter	0,59	Moderate	0,25	75
Ease of temperature control vs. indoor MRT in summer	**0,87**	**Very strong**	**0,05**	**95**
Ease of IAQ control vs. Mean indoor RH in winter	0,03	Insignificant	> 0,25	< 75
Ease of IAQ control vs. Mean indoor RH in summer	-0,04	Insignificant	> 0,25	< 75

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