The Influence of Indoor Environmental Factors on Sleep Quality

Development of a predictive model for assessing the potential sleep quality in Danish apartments

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Building Energy Design, LM-1, 2025-01

Master's Thesis

STUDENT REPORT
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This thesis uses Overleaf with LaTeX to achieve a professional and structured document presentation. A custom-made Excel tool evaluates and analyzes the data, specifically designed to assess the impact of indoor environmental quality on sleep quality in Danish residential buildings.

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Abstract:

This study examines the impact of **Indoor Environmental Quality (IEQ)** parameters—**thermal comfort**, **indoor air quality (IAQ)**, **acoustic comfort**, and **visual comfort**—on sleep quality in residential buildings. **IAQ (**$r = 0.88$**)** and **thermal comfort (**$r = 0.78$**)** emerge as the most influential factors, while acoustic and visual comfort were secondary.
The research introduces the **Sleep Quality Assessment Tool**, an innovative Excel-based model that integrates stricter thresholds for sleep-supportive conditions, including **CO_2** ≤ 750 **ppm**, **noise levels** ≤ 20 **dB**, and **thermal ranges of 18–24°C**. These thresholds surpass existing standards like **BR18** and **WELL**.
A comparison reveals gaps in current regulations, particularly for **night-time conditions** and **dynamic environmental controls**. Recommendations include enhanced thermal regulation, low-noise ventilation systems, and circadian-aligned lighting. Future work should validate this study through field studies and explore real-time monitoring technologies.
This thesis uniquely contributes by developing **the first tool** for assessing and improving residential sleep quality, offering actionable insights for policymakers and designers.

The content of this report is freely available, but publication (with reference) may only be pursued due to agreement with the author.

Contents

Preface

As master's students in Building Energy Design at Aalborg University, we saw the opportunity to explore indoor environment quality's impact on human well-being through this thesis. With our architecture and construction engineering backgrounds, we realized that surprisingly, little attention is given to sleep quality—a fundamental part of life—in building design and regulations, considering people spend almost a third of their lives sleeping.

Statistics have shown that poor sleep quality has become a common problem in Denmark, a societal issue, raising the question of how indoor conditions influence sleep and overall recovery. Although some studies address specific aspects of indoor environmental quality (IEQ), such as thermal comfort, indoor air quality, visual comfort, and acoustic comfort, little research exists on how the combined effect of these elements affects sleep. With motivation from our lives, this gap encouraged us to look closer at these relationships.

Our work rests on the system and method of the Holistic indoor environmental quality assessment (Today known as IEQ-Compass), with its four areas in building design: thermal comfort, indoor air quality, and visual and acoustic comfort. However, models and calculations are significantly different. Our work examines how these four areas interact and affect sleep quality. We used a systematic approach to understand the combined effect sufficiently and identify practical ways to improve indoor environments for sleep quality. We also included factors like the nudging of the user and safety, which are often overlooked but important in achieving sleep quality.

This thesis explores how interdisciplinary ideas can be combined to improve indoor environments, helping people sleep better and live healthier lives. By balancing energy efficiency with residents' comfort and needs, we hope our work will inspire the creation of more sustainable and livable spaces.

The results of our research are meant to guide the improvement of sleeping environment quality at all levels, from user to owner to designer to policymakers.

By following thoughtful design practices and updating regulations, homes can be created that support better sleep and improve public health and productivity.

Improving sleep quality has the potential to bring benefits that extend far beyond personal health. Better sleep environments can help decrease workplace absenteeism, conserve resources, and encourage more sustainable approaches to building design. This thesis serves as an initial step in this direction, and we hope it inspires further research and the creation of standards that focus on health and comfort in sleep environments.

Aalborg University, January 8, 2025

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We also thank Aalborg University for providing the resources and support necessary for our research. Access to the IEQ Compass tool was a key factor in developing the sleep quality assessment method that forms the core of our work.

Finally, we owe tremendous gratitude to our families and friends, who stood by us throughout this journey. Their understanding and constant encouragement motivated us to persevere, even during the most challenging moments. This accomplishment would not have been possible without their support. Last, we also thank those nine respondents for the pilot Sleep Quality Assessment Tool.

Abbreviation

- (DGNB):Deutsche Gesellschaft für Nachhaltiges Bauen
- (LCA):Life Cycle Assessment
- (NIPH):The Danish National Institute of Public Health (Statens Institut for Folkesundhed)
- (EEG):electroencephalogram
- (IAQ):Indoor Air Quality
- (AC):Air-conditioning
- (NMV):Naturally/Mechanically Ventilated
- (NREM):Non-Rapid Eye Movement
- (REM):Rapid Eye Movement
- (SWS):Slow Wave Sleep
- (IEQ):Indoor Environment Quality
- (ppm):part per million
- (VOC):Volatile Organic compounds
- (TVOC):Total Volatile Organic compounds
- (dB(A)):decibel with A-filter
- (RH):Relative Humidity
- (PM):Particulate Matter
- (AHI):Apnea-Hypopnea Index
- (AAMA):a metabolite of acrylamide
- (CCT):correlated color temperature
- (WHO):The World Health Organization
- (ANN):Artificial Neural Network
- (HVAC):Heating, ventilation and Cooling system
- (ACR):Air Change Rate
- (OES):Overall Environmental Satisfaction
- (TSVs):thermal sensation votes
- (UTCI):Universal Thermal Climate Index
- (PAQ):perceived air quality

Chapter 1

Introduction

The purpose of this study is to investigate how buildings can increase well-being in people via improved sleep conditions. First, the concept of well-being is examined, after which a literature search is made on the influence of buildings on sleep. This knowledge is then used to develop a tool that can evaluate the quality of a bedroom. The tool was tested on cases. On the basis of analysis and assessment of those cases, improvement proposals for bedrooms were found.

Each of the following sections starts with a short introduction, after which the section begins.

1.1 Well-being in built environment

This section explores the relationship between well-being, sleep quality, and the built environment. It examines the concepts of hedonic and eudaimonic well-being, their connection to Maslow's hierarchy of needs, and how sleep is a critical factor in both dimensions. This chapter uses recent literature on sleep and well-being in Denmark to underscore the increasing need to prioritize sleep quality in building design. It also explores how indoor environmental quality (IEQ) parameters can enhance sleep and well-being.

Well-being can be divided into hedonic or eudaimonic components[3][20][47][54][61]. Hedonic components of well-being involve positively experienced psychological outcomes revolving around the experience of pleasure as positive affect and the avoidance of pain. On the other hand, eudaimonic components involve engaging in behaviors that are good for the individual and focused on cultivating one's potential, benefiting others, and experiencing meaning. Thus, when designing buildings, both hedonic and eudaimonic components must be considered to create good conditions for the users' positive subjective states and adaptive behaviors[54][61].

In addition to this argument, Maslow's hierarchy of needs, created by Abraham Maslow, describes human motivation as a progression through five levels: physiological needs, safety and security, love and belonging, self-esteem, and self-actualization. The theory suggests that individuals experience greater fulfillment and motivation as they meet these needs, which offers insights into human behavior and well-being. Looking at Maslow's hierarchy 1.1shows that hedonic happiness is associated with the lower levels of Maslow's hierarchy of human motivation, including basic demands like physiological needs, safety, and security. On the other hand, eudaimonic is linked to higher levels, where love and belonging, self-esteem, and self-actualization are found.

Some needs, such as sleep, can be seen as both hedonic and eudaimonic pleasures since poor sleep quality will affect both the experience of pleasure and the ability to learn, thus making self-development more difficult. Therefore, addressing both hedonic and eudaimonic components is essential to providing well-being in the built environment [83].

Figure 1.1: Maslow's hierarchy of needs
[58]

The latest report in 2023 on the current health situation in Denmark, including mental health, sleep, and well-being, which is produced by The Danish National Institute of Public Health (NIPH), stats that 21.7% of Danes reported experiencing fatigue within the last 14 days, and 14.3% of Danes had sleep difficulties or sleep problems within the last 14 days. The proportion of both fatigue reporting and sleep difficulties or problems has been increasing since the beginning of the report in 2011[60].

This issue becomes remarkable when no standards, norms, or legislation aimed directly at the quality of the sleep environment in buildings where found ineither BR18, LEED, WELL, ASHRAE, DGNB or the database Web-of-Science, while every adult spends an average of 8 hours a day in bed. Hence, regarding the existence of this issue and its significant effect on the well-being of society, this paper will discuss the importance of sleep quality and all the parameters that have an impact on it and analyze the indoor environment quality parameters in the built environment sector to improve the quality of life and well-being. For more background knownledge on well-being see Appendix A.

1.2 Problem analysis

People spend approximately eight hours per day sleeping[71]. Sleep is crucial for overall health and well-being. Insufficient sleep and sleep disorders are widespread among both adults and children, posing a significant public health issue due to their association with adverse health outcomes[35]. In addition to the impact on quality of life, poor sleep also results in a decreased level of functioning and economic costs for society and the public sector in the form of reduced work capacity, sick leave, welfare benefits, and treatment in the healthcare system[60].

Lack of sleep negatively affects task performance, post-physical activity recovery, cognitive function, and mood, increasing fatigue and reducing energy levels. Poor sleep quality impairs decision-making, slows task performance speed, reduces accuracy, and hampers recovery after exercise. Age, psychological and physiological conditions, culture, and the environment influence sleep duration and quality. Skin temperature, rapid temperature changes, and sweating during sleep can greatly diminish sleep quality[79]. The sleep environment can either support or disrupt the mental and physiological processes needed for good-quality sleep. Important physical factors include light, noise, temperature, sleeping surface texture, aromas, the presence of others, and electronic devices. Other environmental aspects, such as bodily, mental, and behavioral factors, also influence sleep[56].

A study on bedroom environment and sleep quality in apartments in Seoul indicated that people face different kinds of sleep environment issues, such as too low or high air temperatures, relative humidity, and high CO_2 concentrations.

Also, the sleep quality depends on the season, with the best quality in spring and the worst in the summer. Interestingly, the impact of the sleep environment on sleep quality differed depending on age[36]. It has been investigated that subjective experiences of environmental factors (light, temperature, safety, noise, comfort, humidity, and smell) were linked to symptoms of insomnia and overall sleep quality[29].

Preliminary investigations have highlighted several factors influencing sleep quality, both directly and indirectly, all factors have been addressed with equal weighting. The exact percentages for each factor remain uncertain, as they are influenced by various elements such as gender, age, country, genetics, environment, and medical history. All factors found have been illustrated in the pie chart 1.2, this study is specifically concerned with how indoor environmental conditions affect residents' sleep quality in the built environment. Addressing the influence of other factors falls outside the scope of this study and will require future input from specialists in related fields.

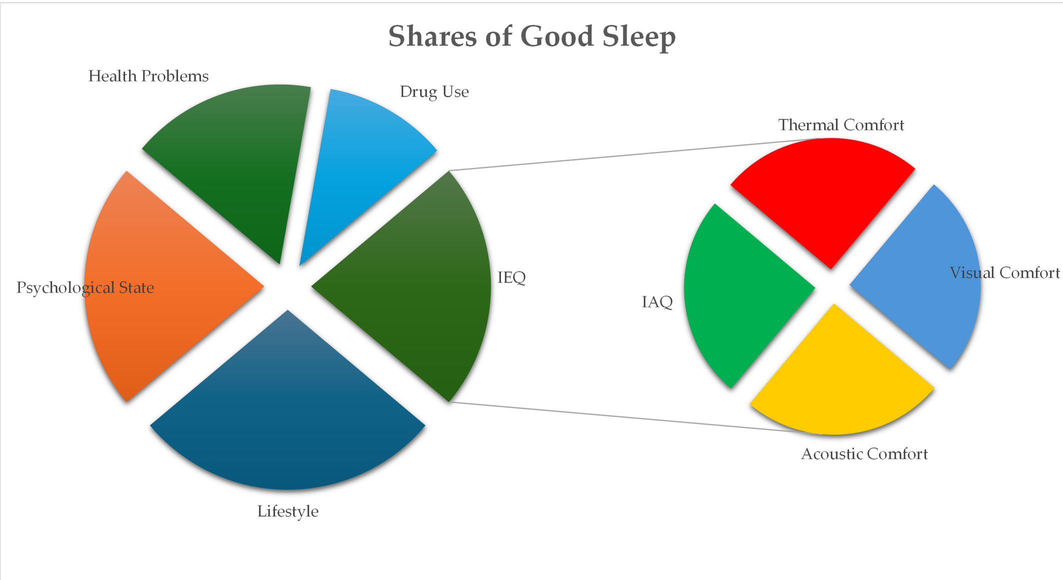

Figure 1.2: Indicators for assessing sleep quality

1.3 Problem formulation

1.3.1 Problem statement

This study discusses and investigates the influence of indoor environmental factors on sleep quality in Denmark and develops a predictive model to assess potential sleep quality in Danish dwellings.

1.3.2 Research Questions

1. How does each parameter of indoor environmental factors affect sleep quality? What is their combined effect?
2. How can the indoor environment be evaluated concerning sleep quality that fits the IEQ-compass?
3. How far are the current indoor environment quality standards from promoting appropriate sleep quality in Danish dwellings? Which modifications can enhance the standards for having adequate sleep quality?

1.4 Objectives

The study aims to analyze the influential IEQ factors that impact sleep quality and develop an assessment tool for sleep conditions in dwellings in Denmark.

1.5 Significance of the Study

This study will add some valuable information by:

1. Identifying IEQ parameters relevant for sleep quality.
2. Finding and prioritizing combined effects of parameters influencing sleep.
3. Suggesting a possible way of evaluating the conditions for good sleep.
4. Making recommendations for the bedroom conditions to promote sleep quality.

Chapter 2

Literature Search

This chapter examines research that addresses the connection between Indoor Environment Quality (IEQ) and sleep quality, with a particular emphasis on residential settings. It begins with exploring the key characteristics of quality sleep, focusing on the physiological and psychological aspects essential for restorative rest. The chapter then reviews the effects of the four primary IEQ components (thermal comfort, indoor air quality, visual comfort, and acoustic comfort) on sleep quality. Additionally, it considers the interactions between these factors, offering insights into their combined effect on the indoor environment.

2.1 Characteristics of a quality sleep

This section aims to provide the reader with an overview of sleep quality and its importance for humans by compiling the concepts of normal sleep and its stages from various literature.

A subjectively good night's sleep is characterized by[46]:

- Falling asleep quickly
- Staying asleep throughout the night without fully waking up
- Not waking up too early
- Feeling refreshed in the morning

An objectively good sleep is measured by sleep stages and their distribution, etc. Sleep research can contribute with knowledge about optimal sleep stage distribution, whereby the parameters of the sleeping environment can be adjusted accordingly. Sleep is divided into two main phases. REM sleep, where vivid dreams occur, and non-REM sleep (NREM), the part where no dreams occur. NREM sleep is divided into three stages.2.1 The higher the stage of NREM sleep, the harder it is to wake up a person. Throughout the night, these stages are distributed in 4 - 6 cycles[46].

Sleep Stages	Type of Sleep	Other Names	Normal Length
Stage 1	NREM	N1, sleep onset	1-7 minutes
Stage 2	NREM	N2, light-sleep stage	10-25 minutes
Stage 3	NREM	N3, slow-wave sleep, deep sleep	20-40 minutes
Stage 4	REM	REM Sleep	10-60 minutes

Table 2.1: Sleep Stages in a Normal Sleep Cycle
[46]

NREM 1 sleep is a light sleep stage in which the body and brain slow down. If undisturbed, the person quickly transitions to NREM 2 sleep, where the body becomes more relaxed with a drop in temperature, muscle relaxation, and a slower heart rate and breathing. Brain waves develop a new pattern, eye movements stop, and brain activity slows with brief bursts that help prevent waking up. NREM 2 sleep typically lasts 10-25 minutes, about half of total sleep time[64]. NREM 3, or deep sleep, is more challenging to wake from and is crucial for physical recovery, growth, and immune function. Brain activity slows further, characterized by delta waves, with most deep sleep occurring in the night's first half[19] [93].

REM sleep is a stage where brain activity increases to near-waking levels, while most muscles are temporarily paralyzed, except those controlling eye movement and breathing. This stage is essential for memory, learning, and creativity. REM stages become longer as the night progresses, making up about 25% of total sleep in adults. Deep and REM sleep is crucial for recovery and development, and a lack of these stages can negatively affect cognitive function, emotions, and physical health[10].

The ideal sleep pattern changes due to age, sex, seasonal changes, and geographic latitude. The following table shows the comparison between a national study in the USA reported that good sleep for adults aged 26–64 years,[49] and a Danish medical handbook[74]:

The Danish medical handbook does not see individual urination urges as disturbing sleep. Similarly, the American study did not see waking up for less than 5 minutes as a problem. Here, it is assumed that urination takes less than 5 minutes.

Sleep Parameter	**USA Study[49]**	**Denmark[74]**
Sleep latency	$\leq$ 30 minutes	5–15 minutes
Number of awakenings	One or less	Not specified
Wake after sleep onset (WASO)	$\leq$ 20 minutes	10–15 minutes
Sleep efficiency	Higher than 85%	Not specified
NREM 1 sleep	$\leq$ 5%	5–10%
NREM 2 sleep	Less than 81%	40–50%
NREM 3 sleep	16–20%	20–25%
REM sleep	21–30%	20–25%

Table 2.2: Comparison of Sleep Patterns: USA Study and Danish Handbook

However, the Danish medical handbook says disturbing stimuli can make falling asleep again in this phase difficult[74].

2.2 Effects of Indoor Environmental Factors on Sleep Quality

This section compiles credible literature that specifically examines the impact of indoor environment quality (thermal comfort, indoor air quality, visual and acoustic comfort) on sleep quality and the combined effect between IEQ parameters. The findings are a foundation for establishing a list of significant parameters that affect sleep quality most and weighting them through thresholds or relevancy to design a robust sleep assessment tool in Excel for residential buildings.

2.2.1 Thermal Comfort

Sleep is affected by ambient temperature; for example, the temperature between the blanket and the person sleeping affects sleep. High and low thermal stimuli can cause activation and awakening effects like other sensory stimuli. Indirectly, sweating or shivering can be activating. Thermoregulation in response to room temperature is greatest when awake and somewhat less during deep sleep. During REM sleep, the response to changes in external conditions is absent, and humans are essentially poikilothermic (mediated by environmental temperature) during REM sleep. Due to reduced sweating and blood vessel constriction, body temperature increases during the period, and since the body cannot respond to external temperature changes, sleep structure can be affected. The thermoneutral zone for humans is between 24°C and 28°C. Hence, if the temperature in the thermoneutral zone is too high, the regulation mechanism will increase the sleep stages with better thermoregulation, particularly increased wakefulness. The room temperature that will provide this depends on the insulation from the blanket and clothes. Therefore, the idea that it is healthy to sleep with an open window is not unconditionally accurate[83].

A study using questionnaires and electroencephalograms (EEG) during the winter investigated gender differences in sleep comfort and found that females preferred a higher ambient temperature for sleep than males. Females had a higher average skin temperature but lower finger skin temperature and blood flow than males. Additionally, females' skin temperature and finger and blood flow were more responsive to changes in ambient temperature. Both subjective assessments and EEG data indicated that males experienced better sleep quality at the same temperatures. Moreover, changes in skin temperature throughout the night showed that males had longer periods of deep sleep than females[51]. Another study investigated gender differences in thermal comfort during summer by conducting experiments with varying ambient temperatures. It involved measuring sleep quality through physiological indicators in both men and women. Results showed that women preferred higher temperatures and exhibited greater temperature sensitivity concerning sleep quality versus men. The study also found that the discrepancy in sleep-related thermal needs between genders was greater than during wakefulness[11].

An evaluation of the perceptions of thermal comfort and indoor air quality in the bedrooms while people are sleeping, as well as their overall sleeping conditions, was conducted by using data from a questionnaire that compared Air-conditioning (AC) bedrooms with the Naturally/Mechanically Ventilated (NMV) bedroom that identified NMV as a superior sleeping environment. Also, the subjects' immediate impressions of perceived air quality and thermal comfort showed a reasonable correlation with their past impressions. Additionally, there was a fairly close relationship between the subjects' perceptions of perceived air quality and thermal comfort[66].

Song, Z. et al.[69] investigated that the current air conditioner sleep modes often use fixed temperature settings, which fail to account for individual preferences and changing room conditions, leading to discomfort. Then, the authors tried to make a new dynamic thermal parameter model to address this issue by adjusting based on users' metabolic rates and the thermal properties of their clothing and bedding, detected before sleep and through feedback after waking. This model could simulate the individual needs better and improved sleep satisfaction by 17% versus fixed settings. It creates personalized temperature control without needing private data.

In another study, six male participants slept wearing only shorts on a bed made of nylon webbing, experiencing five different ambient temperatures between 21°C and 37°C. Their sleep stages were monitored using standard electrophysiological methods. It was found that temperature significantly affected sleep, with a similar sleep disruption for both high and low temperatures compared to the thermoneutral temperature of 29°C. The 21°C condition was the most disruptive, with low temperatures generally being more disruptive than high temperatures. Individuals' sensitivity to low temperatures varied among participants. The reduction in REM sleep from temperature changes is likely due to an overall disruption of sleep rather than specific effects on the body's thermoregulation during REM sleep[31].

In a literature search, the following temperature settings have been recommended for indoor temperature. It has been observed that the recommended temperature is higher for residents closer to the equator2.3.

Source	Interval of Room Temperature	Region/City
[83]	14°C - 18°C	Scandinavia
[9]	17°C - 28°C	China, Shanghai
[98]	23.8°C for presleep & 26.5°C for sleep state	China, Beijing
[87]	24.8°C	China, Shanghai
[97]	24.2°C	China, Tsinghua
[12]	20°C	China, Shanghai

Table 2.3: The recommended indoor temperature based on literature

2.2.2 Indoor Air Quality

CO_2 concentration:

Multiple studies have investigated the influence of CO_2 concentrations on indoor air quality (IAQ) and its subsequent effect on sleep quality. Mishra et al.[48] conducted a study in the Netherlands and found that the average CO_2 level was 717 ppm with open windows and 1150 ppm with closed windows when the bedroom relied on natural ventilation. The study demonstrated a significant difference in sleep depth between open and closed window conditions, as measured by both questionnaire-based and actigraphy-based methods.

Zhang et al.[97] observed that CO_2 concentrations tend to increase during the night, stabilizing at an average of 1750 ppm. The authors reported that higher CO_2 levels were associated with lower IAQ satisfaction among the participants. Xiong et al.[86] used wrist-worn sensors to estimate the percentage of deep sleep (NREM) and found a negative correlation with bedroom CO_2 levels. For every 100-ppm increase in CO_2 concentration, there was a 4.3% decrease in deep sleep after adjusting for other variables. Higher CO_2 levels also resulted in poorer self-reported sleep quality the following day. Additionally, the authors found the effect of CO_2 on light sleep percentage to vary based on the operative temperature of the bedroom.

Strøm-Tejsen et al.[71] showed that lower CO_2 levels significantly improved both objectively measured sleep quality and the perceived freshness of the bedroom air. These improvements were also linked to better next-day performance, reduced sleepiness, and enhanced concentration, especially in tasks requiring logical thinking. Xu et al. [87] found consistent results, indicating that higher air temperatures, elevated CO_2 concentrations, and increased noise levels reduced sleep quality, particularly during summer. Slow-wave sleep was negatively correlated with air temperature and CO_2 levels, with lower CO_2 concentrations resulting in improved comfort and sleep quality. Lo et al.[41] emphasized that exposure to elevated CO_2 and reduced oxygen levels can lead to sleep disruption, further highlighting the importance of proper ventilation in maintaining a healthy sleep environment.

A literature review by Sekhar et al.[65] suggested a tentative relationship between bedroom ventilation and sleep quality based on CO_2 concentration ranges. Their analysis indicated that CO_2 concentrations below 750 ppm did not affect sleep quality. The effects were inconsistent between 750 ppm and 1150 ppm, with some studies observing negative impacts and others not. However, CO_2 levels above 1150 ppm consistently showed a deterioration in sleep quality, both subjectively and objectively measured. Notably, CO_2 concentrations exceeding 2600 ppm were associated with reduced cognitive performance the following day.

Relative Humidity (RH)

Kim et al.[36] highlighted that lower relative humidity (RH) during winter negatively impacted sleep quality, particularly in older individuals. This issue was evidenced by an increased apnea-hypopnea index (AHI), which measures the average number of sleep-disordered breathing events (apneas and hypopneas) per hour during sleep. A higher AHI indicates poorer sleep quality due to disrupted breathing patterns.

Ambient temperature and humidity are interconnected, with optimal relative humidity levels for human comfort ranging between 40% RH and 60% RH [70]. When humidity exceeds this range, the perceived ambient temperature becomes hotter than the dry bulb temperature. Conversely, the ambient temperature feels colder when humidity falls below this range. Low humidity, particularly during cold winter, is associated with discomfort, including an increased incidence of nosebleeds, itching, and dry eyes [59] [94].

On the other hand, high humidity is linked to reduced air quality, as it promotes the growth and presence of dust mites, airborne fungal spores, bacteria, viruses, and other airborne contaminants [4]. Humidity levels outside the 40–60% RH range are known to affect sleep quality negatively, with excessively high and low levels contributing to discomfort and poor sleep outcomes [9].

Volatile Organic Compounds (VOCs)

World Health Organization (WHO) recommendations for healthy levels of VOCs depend on the specific VOC, but for the frequently occurring formaldehyde, levels should be below 100 $\mu g/m^3$ to ensure that no adverse effects are experienced. High formaldehyde levels are common in many newly produced building materials, furniture, paints, cleaning products, and textiles. It is also released from cigarette smoke and wood-burning stoves[1].

Sun et al.[72] investigated the impact of VOCs on sleep using urine samples and subjective questionnaires. The authors classified sleep disturbances into two categories: short duration of sleep and sleep difficulties. The study found that VOCs should be avoided to avoid sleep disturbances, especially when cleaning products containing VOCs at home and perfumes. Since the study examines VOCs through urine samples, it does not differentiate between how VOCs are absorbed into the body. The study also found other sleep-disrupting chemical substances. For example; AAMA(a metabolite of acrylamide), can be used for water purification and treatment or internal pipe coating and is, therefore, probably ingested via drinking water. Unlike paint, where VOCs off-gassing is inhaled. AAMA was positively linked to both sleep disorders and short sleep duration. A mix of different VOC metabolites in the body was associated with an increased frequency of short sleep duration and sleep disturbances in the adult American population. The American population is assumed to be comparable to the adult Danish population. The study emphasizes that little is known about VOC metabolites in the body. Therefore, all

TVOCs in indoor environments are assumed to disrupt sleep.

Particulate Matter (PM)

Assumed that humans spend approximately one-third of their lives in the bedroom, long-term exposure to smaller particles, such as PM2.5, poses an increased health risk. PM2.5 penetrates deep into the lungs and bloodstream, raising the likelihood of severe diseases, while PM10 tends to cause respiratory issues in the nose and throat.

Wang et al.[80] found that long-term exposure to particulate matter (PM), including PM1, PM2.5, and PM10, as well as Nitrogen dioxide (NO_2), was significantly associated with prolonged sleep latency, particularly in individuals who had suffered a stroke. PM2.5, in particular, has been shown to cause inflammatory reactions in the brain by damaging the blood-brain barrier, allowing pollutants to enter the central nervous system. Furthermore, PM2.5 can alter the expression of genes involved in vascular regulation in the brain, indicating that air pollutants can induce cerebrovascular effects. These findings suggest a connection between air pollution, stroke, and prolonged sleep latency through neurotoxic pathways[77].

Li et al.[40] conducted a study in Singapore and observed that PM numbers in the indoor environment increased when windows were opened in urban areas. Their findings indicated that 90.4% and 70.1% of the particle mass for open and closed windows during sleep originated from indoor sources, respectively. However, regarding particle count, only 28.2% (open window) and 7.5% (closed window) came from indoor sources. These results suggest that while opening windows may reduce PM from activities exposure during waking hours, keeping them closed during sleep is advisable to minimize exposure to smaller particles from outdoors. The geographical differences[18] between Singapore and Denmark must be considered, as Denmark's agricultural activities and use of wood-burning stoves may contribute to higher levels of PM2.5[8]. This issue makes it important to keep windows closed during the fertilizer season or as a neighbor to a wood stove.

Recent findings by Bønløkke et al.[8] highlight that there is no clear threshold for the harmful effects of air pollution, with health impacts observable even at the lowest concentrations. This research has contributed to the World Health Organization's (WHO) decision to significantly lower their recommended maximum concentration limits for PM2.5 and (NO_2) in the 2021 air quality guidelines, which are now much stricter than the current European Union regulations.

2.2.3 Visual Comfort

Some people may struggle to sleep because total darkness makes them anxious, or a partner might wake up at night and turn on the lights. Research indicates that highly dark sleeping environments are linked to poor sleep quality, higher levels of perceived stress, and increased feelings of neighborhood disorder[29]. In reality, natural night-time light, such as that from a full moon (ranging from 0.1 to 0.3 lx), is considered harmless to human health due to its relatively low intensity[25]. The difference between light and darkness is the basis for the circadian rhythm in many physiological functions. Light is also a sensory stimulus that is awakening in itself. Lack of light can be deactivating and cause sleepiness. In contrast, the summer midnight sun can activate and alter circadian rhythms[83].

A systematic review and dose-response meta-analysis identified a positive correlation between night-time light exposure and sleep disturbances, with indoor light (electronic devices + bedroom lights) posing a potentially greater risk than outdoor light (street lights + lights of other buildings). Furthermore, the dose-response analysis showed that the light intensity exceeding 5.8 $nW/cm^2/sr$ (approximately 0.19 Lux) significantly affected sleep problems. Indicating that light intensity is significantly more disturbing at night than during the day[88]. Another study shows that the average light levels of 11 ± 9 lux during designated sleep periods do not negatively affect the quantity or quality of sleep in ICU patients. Additionally, light levels up to 18 lux just before sleep enhance patients' self-reported sleep quality in the ICU[16].

A study by Wen P. et al. explored how different correlated color temperature (CCT) light environments in bedrooms affect adolescent sleep quality, next-morning sleepiness, and fatigue recovery. Twelve male adolescents were exposed to either high CCT (6000K, fluorescent lamp) or low CCT (2000K, LED light) for one hour before bedtime over 10 days. Key findings indicate that exposure to low CCT light significantly improved sleep quality and reduced next-morning sleepiness compared to high CCT light exposure. Although there was a slight reduction in fatigue in the low CCT group, the difference was not statistically significant. These outcomes align with previous studies on adults and children, suggesting that low CCT light may better support circadian rhythms by inhibiting melatonin, a hormone crucial for sleep regulation. High CCT light, with its higher blue light content, was shown to delay circadian phases, leading to poorer sleep quality and increased morning drowsiness. The results demonstrate that using low CCT lighting in the evening can enhance adolescent sleep and next-morning alertness, potentially promoting better overall health and performance[82].

A study by Dal E. et Al. evaluated the effects of biodynamic lighting, which simulates natural daylight cycles, on sleep patterns in 13 dementia patients in a psychiatric hospital. Over six weeks, the participants were exposed to three weeks of biodynamic lighting followed by three weeks without it. Objective sleep data was collected using bed sensors. Key findings showed significant improvements in sleep quality during the biodynamic lighting phase. Night-time wandering decreased from 11 to 5 instances, daytime napping dropped from 16 to 7 occurrences, total night-time sleep increased by 77 minutes, and time out of bed at night decreased by 76 minutes. These results suggest that biodynamic lighting improves circadian alignment, improving sleep quality and reducing daytime napping[17]. The study supports previous research indicating that lighting interventions can help mitigate circadian disruptions in elderly populations. Though the sample size was small, these findings suggest biodynamic lighting as a promising, non-pharmacological intervention for improving sleep in dementia patients, particularly home care settings. The study can be relevant in ordinary dwellings since previous studies have shown that treatment meant for patients can also improve the well-being of healthy persons[68].

A study examining the impact of sound and darkness interventions on sleep quality in critically ill patients offers clinical evidence supporting the use of eye masks, music, and earplugs to improve sleep. The findings indicate that earplugs, eye masks, and music were the most effective approaches. Among individual interventions, eye masks were the most effective, followed by bedtime music and quiet time, while earplugs had the least impact on improving sleep quality[21]. Another study suggests both sleeping with light on and exposure to external artificial light significantly influence the disruption of the sleep cycle, even when other environmental factors such as noise, population density, a bright bedroom, and watching TV in bed were considered[50].

2.2.4 Acoustic Comfort

Understanding how the brain handles sound during sleep provides insights into our sensory perception in this distinctive state. Although research indicates that sound processing is partially impaired during sleep, the auditory cortex's neural activity is akin to wakefulness. Nevertheless, recordings from the primary auditory cortex of naturally sleeping common marmosets demonstrate that slow-wave sleep (SWS) modifies neural responses in two significant ways: decreasing sensitivity to soft sounds and diminishing the suppression of sound-evoked responses. These modifications do not occur during REM sleep. The findings highlight the constraints on auditory processing during SWS and explain why certain sounds are processed while others go unnoticed during deep sleep[33].

Noise is the sound that has no significance for the individual but is environmental pollution in modern society. Noise is considered a stressor in itself. Most sleep studies found some form of sleep alteration due to noise exposure, especially when the noise is rough. An indoor noise peak of 50 dB(A) is indicated as the threshold for sleep disturbance. However, continuous noise can disrupt sleep when the sound level is high enough. The effect found varies from study to study, suggesting that other factors influence the results. Uncontrollable factors may include sleep problems and expectations, age distribution, and socioeconomic factors. A convergence of results showed that traffic noise led to increased REM sleep and increased awakenings, reduced subjective sleep quality, and reduced performance in reaction time tests on the day after a night with noise. An impact on heart rate was also found[83].

Sound can have an activating and awakening effect. It can be used to study sleep depth, as a stronger sound stimulus is required to wake someone from stage 4 sleep than from stage 2 sleep. The awakening effect of sound will, therefore, depend on its intensity, but it will also depend on the signal value of the sound. For instance, a mother can sleep through a thunderstorm but be awakened by her baby's whimper. Monotonous sounds can have a soporific effect. Test subjects fall asleep faster when exposed to monotonous sound (in this example, 4 seconds with 20-40 seconds intervals, 1000Hz, 80 dB) than when they hear no sound. This issue is due to the habituation mechanism, leading to deactivation, i.e., reducing the central nervous system's activity to a lower level. Low-frequency sound (6-42 Hz) also has a hypnotic effect when presented continuously, whereas an intermittent noise of 1000 Hz causes increased awakening. The impact of low-frequency sounds is due to both the sound itself and the accompanying low-frequency vibration, and it works particularly well when it is regular[83].

The "Sleep Health and Morbidity Survey 2021" report presents self-reported reasons for not getting enough restful sleep. The 11 out of the 13 reported causes relate directly to social conditions, like work, everyday concerns, illness, etc. However, construction can directly address the two remaining reasons[60]:

- Noise disturbances from others in the home (e.g., snoring, television, etc.)
- Noise disturbances from street traffic, trains, airplanes, neighbors, etc.

2.3 Combined Effects

Indoor environmental quality (IEQ) significantly influences occupant satisfaction in buildings through the interaction and combined effects of various environmental domains. A review by Zhao and Li [99] emphasizes the interconnected nature of multi-domain IEQ factors, where their interactions play a crucial role in shaping overall satisfaction. Discomfort caused by an intensified stimulus, termed "annoyance," can trigger a "masking effect" that diminishes the perceptual impact of other environmental stimuli [90]. This issue underscores the complexity of creating balanced indoor environments that simultaneously cater to multiple comfort needs.

The dynamic relationship between IEQ and outdoor conditions further highlights the importance of holistic building design. For instance, HVAC systems bridge indoor and outdoor microclimates, directly influencing parameters such as indoor temperature, relative humidity (RH), and air change rates (ACR). A study by Zhong et al.[100] revealed that RH tends to increase with outdoor temperatures, while indoor pressure closely mirrors outdoor pressure. Additionally, ACR was positively correlated with outdoor temperatures, often resulting in elevated CO_2 levels during colder days. Indoor temperature was influenced by HVAC systems and occupant density, sound levels, lighting, and equipment, which act as internal heat sources. Furthermore, interactions between thermal and lighting conditions were evident, as high humidity impaired light's optical performance. The study also noted that sound absorption varies with temperature and humidity, with drier and cooler air absorbing more sound. Through multivariate and artificial neural network (ANN) analyses, the study identified ACR, lighting systems, and occupant numbers as critical factors affecting IEQ, emphasizing the importance of HVAC systems, operational behaviors, and building location in maintaining optimal conditions.

In high-rise residential buildings, occupant satisfaction is directly linked to key IEQ factors such as air quality, thermal comfort, lighting, and acoustics. According to Xue et al.[89], air quality and thermal comfort are heavily influenced by room orientation and gender. At the same time, lighting satisfaction depends on physical conditions like uniformity and daylight availability, alongside adaptive behaviors such as shading use. Acoustic comfort, in contrast, is affected by factors like floor level, activity intensity, and stress. Notably, residents on higher floors reported better air quality due to reduced exposure to ground-level pollutants. These findings highlight the significant role of adaptive behaviors and environmental features in shaping perceptions of comfort and overall environmental satisfaction(OES).

A study of high-rise social housing in Melbourne reinforces the impact of IEQ on occupant well-being, particularly in low-income settings. Jara-Baeza et al.[23] found that while residents expressed high satisfaction with winter temperatures and daylight, summer conditions often led to discomfort due to limited use of cooling systems, driven by cost concerns. Window ventilation improved air quality and temperature regulation, but external noise frequently disrupted sleep and concentration. Additionally, 94% of residents reported health issues linked to poor air quality and noise. On the other hand, natural stimuli, such as environmental sounds and scenic views, positively influence psychological well-being. These findings emphasize the need for optimized housing designs that enhance IEQ and mitigate health and comfort challenges, particularly for vulnerable populations.

These collective studies demonstrate that the multifaceted interactions within Indoor Environmental Quality (IEQ) are crucial in achieving occupant satisfaction. Hence, this section will thoroughly examine this phenomenon through a comprehensive literature search.

2.3.1 Thermal and Acoustic Comfort

The relationship between thermal and acoustic comfort is a complex but critical aspect of creating comfortable indoor environments. Multiple studies have explored how these two parameters interact, revealing nuanced connections between sound, temperature, and overall satisfaction.

Research shows that noisy environments are often linked to a colder thermal perception, whereas quieter spaces are associated with a warmer thermal experience. These correlations are particularly evident when heating, ventilation, and air conditioning (HVAC) systems are used, as occupants must balance their preferences for thermal, acoustic, and air quality conditions[26]. Furthermore, while changes in air temperature minimally affect acoustic sensation, sound pressure levels can influence thermal perception [57].

The type of sound present in an environment significantly impacts thermal and acoustic perceptions. For example, thermal, acoustic, and overall comfort levels are notably higher in musical sound environments than in noisy ones under the same sound pressure level. This issue suggests that music can enhance indoor satisfaction while promoting energy savings by reducing the need for mechanical cooling [30]. However, extended exposure to sounds like white or background office noise appears to have little effect on thermal sensation, even at varying intensities. For instance, Fanger et al.[22] reported that exposure to 40/85 dB white noise for 2.5 hours does not significantly alter thermal comfort. Similarly, Witterseh et al.[85] found no noticeable thermal impact after 2 hours of exposure to 35 dB quiet background or 55 dB open-plan office noise.

Temperature also influences acoustic perception. At a stable 24°C, acoustic perception improves as this temperature maintains a balanced thermal state. However, at 18°C and 30°C, noise levels are perceived as lower than at 24°C, although the unpleasantness associated with these conditions is not statistically significant. A tendency for greater discomfort at 24°C has been noted, underscoring the interplay between temperature and sound[53].

Occupants' satisfaction with indoor environments is closely tied to their thermal and acoustic comfort. When thermal comfort is achieved, the highest satisfaction levels occur at moderate noise levels, such as 45 dB, which occupants rate as "Quite satisfied." Conversely, dissatisfaction with either temperature or noise makes achieving overall indoor satisfaction difficult, even at low noise levels[32]. Specific sound types also play a role in shaping thermal perceptions. For example, machine noise increases thermal sensation votes (TSVs) in hot conditions while alleviating cold sensations in cooler settings. Natural sounds like running water and birdsong can mitigate thermal discomfort in warm conditions, although this effect diminishes at higher Universal Thermal Climate Index (UTCI) values. Music, meanwhile, has been shown to promote thermal neutrality, while high-pitched dialogue slightly increases TSVs. Interestingly, outdoor crowd noise of similar intensity has minimal impact, potentially due to reduced auditory awareness outdoors[27].

Environmental factors like relative humidity (RH) further mediate the effects of temperature and noise. Babbling sounds, for instance, are perceived as more annoying at higher temperatures (18°C–30°C) and low RH levels (30%) but become less disturbing at higher RH (60%). Notably, no significant interaction between temperature and humidity is observed with fan noise, suggesting that sound type moderates these effects[92].

Probabilistic patterns in thermal and acoustic sensations reveal additional insights. Higher sound levels contribute to colder sensations below the neutral temperature range (23°C–24.7°C) whereas noisier environments evoke cooler perceptions in warmer conditions. Similarly, lower air temperatures slightly increase perceived noisiness when sound levels are below the neutral range of 41.5–43.5 dB[73].

2.3.2 Thermal and Visual Comfort

The interaction between thermal and visual comfort is essential in achieving optimal indoor environmental quality, as these two dimensions nuancedly influence human perception and overall satisfaction.

Air temperature slightly impacts visual sensation, although illuminance levels show a stronger correlation with thermal perception. Subjects often find indoor environments acceptable under moderate temperatures, even when lighting falls outside acceptable ranges, due to lower sensitivity to illuminance changes[57]. Satisfaction with lighting levels minimizes overall comfort, suggesting that appropriately balancing temperature and lighting is more critical than achieving optimal illuminance alone[32].

Reducing illuminance levels in hot environments or increasing them in cold conditions can enhance thermal comfort, as sunlight often evokes associations with warmth and heat, triggering heat-related emotional responses[42]. The relationship between lighting intensity and air temperature further influences visual perception. For instance, dimmer lighting at higher temperatures appears darker, while brighter lighting in cooler conditions creates a heightened sense of brightness[73]. Field studies suggest that brighter lighting (above 300 lux) improves thermal satisfaction but does not significantly alter thermal sensation, indicating a psychological rather than physiological influence. This effect is particularly pronounced in warmer conditions, where dim lighting is associated with lower thermal satisfaction[15][38].

Impact of Light Color and Intensity The color temperature of light plays a critical role in thermal and visual comfort. For instance, exposure to high correlated color temperatures (CCTs) in cooler conditions can increase the sensation of coldness, leading to reported shivering. Conversely, higher CCTs at neutral temperatures (e.g., 22°C) enhance brightness, air freshness, and alertness, potentially reducing energy use by expanding acceptable thermal ranges[63][78][7][13]. Light intensity also interacts with ambient temperature to influence comfort. Bright light exposure in the morning accelerates melatonin reduction, causing core body temperature to rise earlier and creating a warmer sensation. In contrast, evening exposure to intense or blue-enriched light suppresses melatonin, slowing the cooling effect typically experienced in the evening[62].

Using colored glazing in indoor environments highlights the cross-modal effects of temperature and light. For example, blue glazing is less preferred in cold conditions, while orange glazing evokes relaxation and warmth. These findings suggest that smart window technologies that adjust glazing colors based on environmental conditions can enhance visual and thermal comfort while influencing emotional states[14].

Thermal conditions significantly influence glare perception, with discrepancies between predicted and actual glare responses. Warmer environments are associated with increased glare sensations, highlighting the need to include perceived temperature in glare prediction models. Incorporating thermal factors into daylight design can improve energy efficiency and occupant well-being[24].

2.3.3 Thermal Comfort and Indoor Air Quality

The interaction between thermal comfort and indoor air quality (IAQ) is critical in shaping indoor environmental quality (IEQ). A growing body of research highlights the intricate relationship between these factors and their combined impact on human perception, satisfaction, and health.

Warm environments are often associated with poor air quality, characterized by a sense of "stuffiness" due to limited air movement, high humidity, and elevated CO_2 levels. Conversely, cool environments are generally perceived as having better air quality, likely due to enhanced air circulation and lower humidity [26][6]. Studies have found high confidence in the correlation between air temperature and IAQ sensations, as well as between CO_2 concentration and thermal sensations, emphasizing the cross-domain effects of these factors[57].

Air movement is key to improving perceived air quality (PAQ) under varying thermal conditions. For example, at higher temperatures (up to 28°C) and humidity levels (up to 70%), air movement improves PAQ by making air feel fresher and more acceptable. However, its effectiveness diminishes in high-humidity conditions (above 60%), where thermal discomfort and IAQ declines become harder to counter[45]. Moderate temperatures (up to 26°C) and low humidity (30%) provide the optimal range for air velocity to sustain IAQ and thermal comfort.

CO_2 levels, an indicator of IAQ, directly influence thermal sensation through their effects on respiration. Elevated CO_2 concentrations are linked to heightened thermal sensations and diminished thermal preference, which can undermine occupants' adaptive capacity to indoor environments. For instance, high CO_2 levels in classrooms correlate with reduced perceived control over thermal conditions and air quality, underscoring the need to balance ventilation and IAQ for optimal comfort[67][37].

The impact of IAQ and thermal comfort extends to sleep environments, particularly in children's and teenagers' bedrooms. A case study revealed that closing bedroom doors led to poor air quality for 79–86% of the night, significantly reducing sleep satisfaction. Opening bedroom doors reduced CO_2 levels by 55–64% without compromising thermal comfort, suggesting simple strategies can improve IAQ and sleep quality[95].

Thermal comfort perceptions are closely tied to IAQ assessments, with air circulation playing a crucial role in shaping these experiences. For example, maintaining sufficient airflow ensures favorable perceptions of air quality, even when temperatures vary[96]. However, discomfort from extreme temperatures, whether too high or too low, adversely affects both IAQ perception and occupant productivity[28].

A comprehensive approach is necessary to achieve a comfortable indoor environment, accounting for the interplay between thermal and IAQ factors rather than evaluating them independently. For instance, studies suggest improving visual and perceived air quality can mitigate thermal discomfort, especially in naturally ventilated spaces. This holistic perspective is critical for optimizing HVAC control and enhancing occupant satisfaction[37].

2.3.4 Acoustic and Visual Comfort

The interplay between acoustic and visual comfort is complex, with both domains influencing occupant perceptions of indoor environments. Research reveals that while these factors are distinct, author interact in nuanced ways, shaping overall comfort and satisfaction.

Early studies on cross-modal interactions showed asymmetric effects. Visual factors had little to no influence on acoustic pitch and loudness discrimination, and acoustic factors had minimal effect on visual brightness discrimination[44]. However, more recent findings suggest nuanced interactions where variations in light and sound levels influence sensory perceptions. Impact of Illuminance on Acoustic Perception The relationship between illuminance and acoustic sensation varies with sound levels. At lower sound levels (41.5–43.5 dB), increased illuminance slightly amplifies the perception of noise. Conversely, dimmer lighting enhances the perception of quietness. Brighter lighting generally results in higher visual satisfaction, especially when paired with lower sound levels[73][76].

Indoor visual conditions, including brightness and color, significantly influence occupants' noise annoyance evaluations. Low brightness intensifies noise annoyance, particularly in response to road traffic noise. Color and brightness interact, allowing thoughtful combinations to improve indoor comfort. For example, warm colors (e.g., red, yellow) pair well with high brightness, and cool colors (e.g., green, cyan) work best with medium brightness. Thus, adjusting indoor visual factors, such as lighting or wall colors, can reduce noise annoyance and enhance overall comfort[43].

Brighter lighting conditions improve visual satisfaction, mainly when occupants are acoustically comfortable. Acoustically comfortable environments increase tolerance for high illuminance, highlighting the importance of balancing these factors[32].

The effects of sound on visual perception differ based on the context. For instance, sound influences the perception of visual relaxation but does not significantly affect brightness perception. This issue suggests that sound can alter mood or atmosphere in ways that indirectly affect visual comfort[91].

Acoustic and visual factors are more than isolated elements; their interaction shapes the overall comfort of the occupants. For example, darker environments enhance acoustic satisfaction by creating a quieter perception, while brighter environments foster visual satisfaction, particularly when acoustic comfort is already achieved[76].

2.3.5 Acoustic Comfort and Indoor Air Quality

Acoustic comfort and IAQ interact uniquely, influencing human perception and overall comfort. While noise and odor are independently associated with discomfort, their interactions reveal intriguing dynamics.

Noise and odor cause discomfort; however, their interaction demonstrates masking effects. Noise can reduce the perception of odor-related discomfort. Odor has minimal or no effect on the perception of noise. This issue suggests that noise might distract from unpleasant odors, potentially offering insights for environments where odor control is challenging[52].

CO_2 Concentration and Acoustic Sensation Studies indicate no statistically significant relationship between changes in CO_2 concentration and acoustic sensation. Similarly, sound pressure levels have negligible effects on IAQ. This issue implies that these factors operate independently in influencing occupant comfort[57].

Environments with higher acoustic performance are associated with better olfactory comfort. Protocols designed to improve odor control, such as ventilation strategies, may inadvertently enhance acoustic comfort by promoting quieter environments. This issue highlights the potential for integrated approaches to improve both domains[39].

The relationship between perceived air quality and acoustic conditions reveals a counterintuitive pattern: Quiet environments are often associated with poor air quality, and noisy environments correlate with better perceived air quality. This may stem from psychological associations or the masking effects of noise on other discomfort signals, such as odors[26].

2.3.6 Visual Comfort and Indoor Air Quality

The interplay between visual comfort and indoor air quality (IAQ) highlights the complex relationship between environmental and psychological factors in shaping human perceptions. While some aspects, such as CO_2 concentration, show no measurable impact on visual sensations, other factors, particularly illumination levels and lighting configurations, significantly influence how occupants perceive air quality[57].

Research has demonstrated that illuminance levels are closely tied to perceptions of air quality. Higher illumination often enhances the acceptability of the indoor environment, even when IAQ conditions remain constant. This issue suggests that lighting contributes to visual comfort and psychologically elevates occupants' evaluation of air quality[34].

These findings emphasize that subjective air quality assessments are not purely environmental but are influenced by psychological reactions to the lighting environment[34]. Lighting characteristics, such as the correlated color temperature (CCT), affect visual and IAQ perceptions. Blue light, for instance, has been shown to increase alertness while improving perceived air quality[84]. Moreover, different CCTs of white LED lighting alter occupants' overall impressions of the indoor environment[78].

Additionally, the lighting configuration—whether direct or indirect—plays a role, with indirect lighting being associated with better air quality perceptions. In contrast, direct lighting configurations are often viewed less favorably in terms of smell and IAQ[5].

This relationship extends to how lighting design can subtly modify indoor air quality perceptions. For example, indirect lighting schemes may create a more comfortable and acceptable indoor environment than direct lighting. Such nuances highlight the importance of considering lighting as a tool for visual comfort and an influence on the broader indoor environmental experience [5].

In conclusion, visual comfort and IAQ interaction reveal significant opportunities for enhancing indoor environments. By carefully designing lighting strategies—considering factors like illuminance, CCT, and configuration—designers can simultaneously optimize visual comfort and improve occupants' perceived air quality, creating a more holistic approach to indoor environmental quality.

Chapter 3

Methodology

The study systematically identified and assessed key parameters influencing sleep quality through a literature search, developed a robust evaluation tool, and explored practical design solutions. This methodology provides a detailed framework for assessing sleep quality in residential buildings and offers actionable insights for improving indoor environments to support healthier sleep.3.1

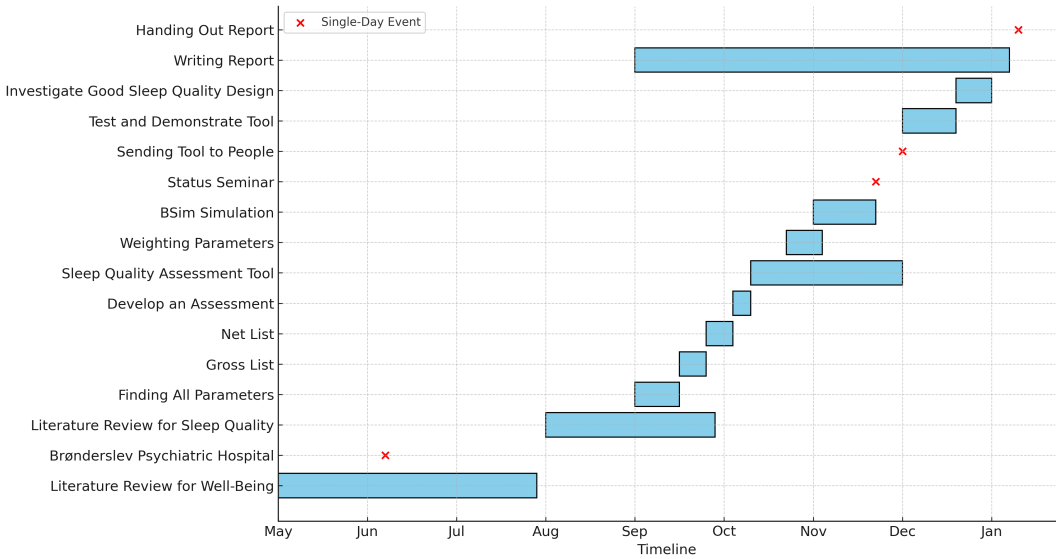

Figure 3.1: Timeline of tasks for the project.

3.1 Literature search

This study employed a systematic methodology to identify, assess, and integrate building-related parameters influencing sleep quality in residential buildings. The process began with compiling a gross list of parameters based on a comprehensive literature search. This initial stage aimed to capture various factors affecting sleep quality, including exposures, symptoms, and building design features, ensuring a holistic understanding of potential contributors to sleep quality.

The methodology for identifying relevant and high-quality scientific publications was centered on a systematic search conducted on the database Web of Science during the period from August 2024 to October 20243.1. This process was divided into three main phases. The first phase focused on sleep structure to comprehensively understand the factors contributing to quality sleep. The second phase explored the effects of IEQ on sleep quality, aiming to identify parameters within the four main domains of IEQ that influence sleep. The third phase investigated the combined effects of IEQ to determine which domain had the most significant impact compared to others.

The search was performed using a variety of keywords, including a combination of Residential Buildings, Bedrooms, Sleep Quality, and IEQ parameters. Additionally, relevant publications were manually included from the reference lists of relevant articles identified through the Web of Science search. These articles were collected into the pool of search results, all of which are screened for relevance to our topic.

Key words in title of articles	**Results**	**Filters**
Thermal Comfort AND Sleep Quality	18	2014-2024, Research articles
Thermal Comfort	5205	
Indoor Air Quality AND Sleep Quality	14	
Indoor Air Quality	1967	
Visual Comfort AND Sleep Quality	0	
Light AND Sleep Quality	84	
Visual Comfort	460	
Acoustic Comfort AND Sleep Quality	0	
Noise AND Sleep Quality	39	
Acoustic Comfort	116	

Table 3.1: This table shows the total number of articles on the Web of Science, considering the specific keywords.

This approach delivered over 1,000 papers,3.1 which were then narrowed down by exclusion- and inclusion criteria and the relevance of their titles and the information presented in their abstracts. Studies focusing on individuals with sleep disorders or specific health conditions were excluded during this shortlisting process. To ensure the review reflected current advancements in building design and technologies, only papers published after 2014 were included. These papers were primarily selected from peer-reviewed or highly cited journals reporting IEQ and sleep quality in bedrooms across various climatic zones. Each study addressed at least one of the previously mentioned keywords. In addition to research articles, standards related to Indoor Environmental Quality for residential buildings were reviewed, with particular attention to requirements and conditions explicitly applicable to bedroom environments. Ultimately, 117 papers3.2 were used for the final literature search and Appendix C. The following tables show an overview of the papers reviewed; more details can be found in7 and Appendix B.

Keywords	Years	Categories	Count
Sleep Quality	2009-2024	Sleep Health, Building Research and Information, Sleep Medicine, Current Biology	7
Thermal Comfort AND Sleep Quality	1981-2024	Building and Environment, Building Engineering, Electroencephalography and Clinical Neurophysiology, Thermal Biology, Indoor Air	9
IAQ AND Sleep Quality	1979-2024	Indoor Humidity and Human Health, Building and Environment, Indoor and Built Environment, Indoor Air, Sleep, Applied Meteorology, Environmental Research, Science and Technology for the Built Environment, Thermal Biology, Physiological Anthropology	20
Visual Comfort AND Sleep Quality	1988-2024	Building and Environment, Nursing in Critical Care, Biological Reviews, Science of The Total Environment, Sleep	10
Acoustic Comfort AND Sleep Quality	1988-2024	The Society for Neuroscience	3
Combined Effects of IEQ	1988-2024	Energy and Buildings, Building and Environment, Sustainability	5
Thermal Comfort AND Acoustic Comfort	1977-2024	Ergonomics, Building and Environment, Indoor Air, Building Engineering, Indoor and Built Environment	10
Thermal Comfort AND Visual Comfort	2000-2024	Building and Environment, Building Research and Information, Lighting Research and Technology, Acta Physiologica, Building Engineering	13
Thermal Comfort AND IAQ Comfort	2011-2024	Energies, Building and Environment, Applied Sciences, Building Research and Information	9
Acoustic Comfort AND Visual Comfort	2003-2024	Building and Environment, Psychophysiology, Building Engineering, Applied Acoustics	6
Acoustic Comfort AND IAQ Comfort	2003-2024	Building Acoustics	4
Visual Comfort AND IAQ Comfort	2011-2024	Intelligent Buildings International, Building and Environment, Lighting Research and Technology	5

Table 3.2: An overview of the papers used

Development of parameters based on the literature search

The development involved the following steps:

- Initial rough sorting and discussion led to the creation of a gross list
- The gross list was refined into parameters that could be objectively measured or evaluated, forming a net list.
- Based on the net list were four parameters developed for each evaluation area, with a consistent pattern across the areas:
  1. The first parameter is based on databases using location-based input.
  2. The second parameter is building-oriented.
  3. The third parameter focuses on room-specific factors.
  4. The fourth parameter is user-oriented.

Each parameter consists of up to several indicators. For example, IAQ 3; "Impact from activities in the home", consists of a OLF/m² calculation and a CO_2 calculations. Points based on the CO_2 calculation is based on the dilution formula with input on the number of sleepers in the bedroom, their age, weight and gender, as well as input values on air change rates and room volumes, gives a theoretical CO_2 level after 8 hours. For more insight of the indicators, see Appendix C.

This refinement from gross list to net list was guided by three key criteria: the significance of the parameter's influence on sleep quality, its relevance to building design and indoor environment quality (IEQ), and its feasibility for operational assessment using simple inputs rather than complex measurements. This filtering process allowed the study to prioritize the most critical and practical parameters for further analysis4.1.

Once refined, each parameter in the netlist was individually assessed. This phase involved identifying potential evaluation methods for each parameter, selecting the most suitable method, and establishing scoring criteria on a 1–10 scale, informed by existing literature. The same systematic approach was applied to all selected parameters, ensuring consistency and robustness in the assessments.

3.2 Developing the Sleep Quality Assessment Tool

The tool development is based on experimental work, integrating the authors' empirical knowledge (described in the literature search methodology, section 3.1) and the practical application in Microsoft Excel. The following section outlines key steps in the process. It is not intended as a fully replicable method.

Throughout the literature search, a simple diagram was gradually developed to outline all building-related parameters affecting sleep. The aim was to create a checklist that could be used by the general public to optimize their sleep environment. To ensure accessibility, the checklist was designed with simple questions, where input values were directly linked to output scores. However, it became evident that this approach could lead to incorrect prioritization for users, prompting the decision to introduce weighting for each parameter.

To achieve this, a more complex evaluation tool was developed(The Sleep Quality Assessment Tool), where input values influenced one another. Insights gained from the applied use of this more advanced tool could later be translated back into the simpler diagram, providing a more robust basis for parameter weighting.

During the development of the tool, one participant, a graduated production engineer, was passively observed as the assessment was filled out, and their ongoing feedback was recorded to address any challenges encountered. Choosing a production engineer was deemed appropriate, as it was assumed that if they could successfully complete the evaluation, would also the intended responder be able to. For individual indicators in the Thermal comfort area, output values from BSim were initially used. Due to limited familiarity with and access to the BSim program, the necessary input values for BSim were provided to the test participant. Completing the remaining inputs took the production engineer 25 minutes. Errors and feedback from this initial test were used to refine the tool, and the improved version was sent back to the production engineer for further feedback. During presentations to fellow students, it became clear that BSim was a limiting factor for the tool. As a result, the 24H Heat Calculation method was implemented as a replacement to allow individuals without access to BSim or with limited expertise in the program to participate.

In addition to correcting errors in the setup of Excel formulas, significant effort was devoted to enhancing the intuitive understanding of the tool to support responders as effectively as possible. This was achieved by implementing more multiple choices, improvements in layout, color use, and removal of unnecessary distractions within the form. Any elements deemed irrelevant for the respondent were locked and hidden, thereby minimizing the risk of clicking on fields with hidden calculations by the participants, at the same time removing the possibility of independent troubleshooting.

The inputs of the responders can be divided into two categories; location and building:

1. **Location inputs from Publicly Available Data Sources:**
    - *Noise Chart:* Modeled data from the Danish Environmental Protection Agency.
    - *Observed Sunshine Hours:* Data from the Danish Meteorological Institute for 2023.
    - *Air Pollution Chart:* Modeled data from the National Center for Environment and Energy at Aarhus University.
    - *Burglary Risk Chart:* Modeled data from the Danish National Police.
2. **Residence Description of the building:**
    - Resident demographic data.
    - Residential areas and geometry.
    - Surface types.
    - Construction types.
    - Various home installations, including ventilation systems, solar shading, burglary protection, and more.

Once reviewed, the evaluation tool was deemed ready for broader distribution. A one-week response period for the evaluation tool was considered appropriate.

For details on weighing and scaling, see Appendix B. The table below 3.3 shows an overview of all areas, categories, and criteria with their given weight in the Sleep Quality Assessment Tool.

Evaluation Area	Parameter	Criteria	Description	Criteria Weight (%)	Parameter Weight (%)	Area Score (%)
ACOUSTIC COMFORT	ACOU1	1.1	External noise	100	30	20
	ACOU2	2.1	Airborne sound	50	30	
		2.2	Step sound	50		
	ACOU3	3.1	Noise from installations and home appliances	50	30	
		3.2	Noise from mechanical ventilation inlet	50		
	ACOU4	4.1	User-Control Options	100	10	
INDOOR AIR QUALITY	IAQ1	1.1	PM2.5 (filtration/particle level)	100	30	20
	IAQ2	2.1	Humidity	50	30	
		2.2	TVOC and harmful chemistry	50		
	IAQ3	3.1	PAQ	50	30	
		3.2	CO_2	50		
	IAQ4	4.1	Controllability of ventilation, Mechanical	100	10	
THERMAL COMFORT	THER1	1.1	Too high temperature	100	30	20
	THER2	2.1	Insulation of Building Elements	50	30	
		2.2	Controlling heating system	50		
	THER3	3.1	Temperature fluctuations	50	30	
		3.2	Temperature-controlling software	50		
	THER4	4.1	Increased ventilation, Natural	50	10	
		4.2	Increased ventilation, Mechanical	50	10	
VISUAL COMFORT	VIS1	1.1	Sunshine hours	100	30	20
	VIS2	2.1	Intensity and distribution	50	30	
		2.2	Window/floor ratio	50		
	VIS3	3.1	View in, privacy	50	30	
		3.2	View out, visual contact with the outside	50		
	VIS4	4.1	Sun protection, adjustment possibilities	50	10	
		4.2	Sun protection, activation options	50		
PERSON COMFORT	PER1	1.1	Criminality mapping	50	40	20
		1.2	Safety measures in the building	50		
	PER2	2.1	IEQ indicator	100	30	
	PER3	3.1	Manuals for good sleep condition	100	30	

Table 3.3: Scaling and Weighting of Parameters in Sleep Quality Assessment Tool

Segment of Responders

The segment of possible respondents is limited to people with an understanding of U-values, building technology and general understanding of buildings. Furthermore, due to a desire for wider dissemination of the topic, we chose not to carry out the evaluations ourselves. The limited segment to our network, ie. students and lecturers at their own university, as well as colleagues, friends and acquaintances.

As an alternative to multiple choice, you could have asked for specific values. However, this was not chosen, as it will place even higher demands on the respondent. Depending on the characteristics of the residence, respondents were required to answer up to 282 questions.

Sending out the assessment tool

An email was sent via the university mailing list to 38 students in the program, all of whom have a prior building-related bachelor's degree as a prerequisite for admission to the master's program. To encourage participation, a column was added to the results, providing generic feedback on how respondents could improve their sleep environment.

After 72 hours of the one-week deadline, no responses had been received. Consequently, practicing building engineers within the authors' personal networks were contacted directly, yielding eight responses.

Handling the responses to the Sleep Quality Assessment Tool

Due to the combination of limited troubleshooting options and the initial inadequacy of the Excel formula setup, 7 out of 8 respondents failed to receive a score upon completing the form. Given the low number of responses, all identified errors were subsequently corrected during the quality assurance process. Although the form included a designated field for feedback, no additional feedback was received. Screenshots of the Sleep Quality Assessment Tool can be seen in appendix D.

After the quality assurance proces of the distributed the Sleep Quality Assessment Tool in Excel format, the collected data were subjected to statistical analysis used for the discussion.

Chapter 4

Results

This chapter consists of three parts. The first is a table summarizing the results from the literature search analysis. Next, the findings related to the analysis of renovation measures implemented in the base case, with renovations spanning from May 2024 to December 2024, are described. Finally, the outcomes from 11 houses using the Sleep Quality Assessment tool, including the base case, are detailed(Appendix F).

4.1 Literature search analysis

Findings in the literature search on building design elements influencing user sleep were documented and analyzed. The result of this parameter development can be seen at4.1.

Evaluation Area	Gross List	Net List	Assessed Parameter
ACOUSTIC COMFORT	Church bells, Rail noise, Aircraft noise, Traffic noise, Wind turbine noise, Rain	Outdoor noise	ACOU1: Noise from surroundings
	General noise in the sleep environment	Air sound insulation, In apartment	ACOU2: Noise from the building
	High and Low-frequency sound		
	Reverberation time in an apartment	Technical installations, in apartment	ACOU3: Noise from the dwelling
	Mechanical Ventilation	Mechanical Ventilation	
	Noise from neighbour		ACOU4: User-Control Options
INDOOR AIR QUALITY	Particle matters	PM 2.5	IAQ1: Influence from outside air
	Relative Humidity	Relative humidity	IAQ2: Influence from building and materials
	Indoor environmentally based pollution	VOC (TVOC)	
	Sensory perceived	Perceived Air Quality	IAQ3: Impact from activities in the home
	Person-based pollution	CO_2	
	Allergens and biological factors		IAQ4: User-Controlled IAQ
THERMAL COMFORT	Summer and winter Comfort	Too high temperatures	THER1: Summer comfort
	Radiant temperature asymmetry	Too low temperatures	THER2: Winter comfort
	Rapid Temperature drop or increase	Draft	
	Thermal properties of bedding	Temperature fluctuations	THER3: Sleeping temperature
	Operative Temperature		
	Metabolic Rates	Occupants' possibilities to adjust	THER4: Controlled thermal comfort
VISUAL COMFORT	Daylight for circadian rhythm	Daylight for circadian rhythm	VIS1: Influence from outside
	Direct Sunlight	Flexibility to adjust shading	VIS2: Influence from building and windows
	Window/floor ratio	Colour of artificial light	
	Lights of other buildings	View in and out	VIS3: Impact from activities in and around the home
	View in and out		
	Bedroom light		VIS4: User-Controlled visual comfort
PERSON COMFORT	Safety measures	Safety and Privacy	Per1: Criminality and safety
	The presence of others		
	Subjects' Perception	Knowing of the Bedroom IEQ by display/indicator	Per2: Knowing of bedroom IEQ
	Physiological and Psychological Conditions		Per3: Manual for good sleep condition

Table 4.1: The table shows the gross list and net list found in the literature search and the final assessment parameters in the Sleep Quality Assessment Tool.

4.2 Base Case

The Base Case was the first actual use of the Sleep Quality Assessment Tool, where iterations were made at the same time. The Base Case is based in inner Odense, Denmark. An apartment on the 1st floor, from the 1980s with two residents. Four variants of the initial case study(Base Case), were developed and analyzed.

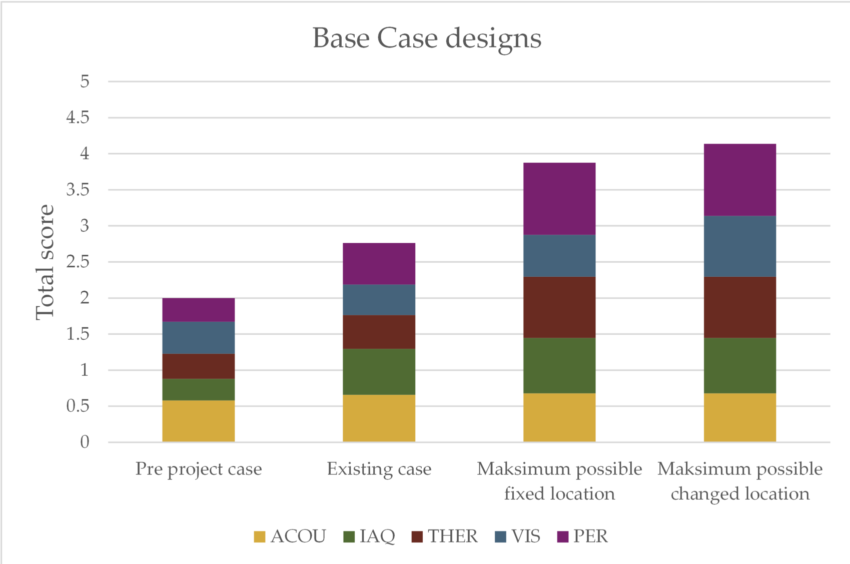

Figure 4.1: Four versions of the Base Case. Scoring 5 points in the graph equals scoring maximum (5 points = 100%).

Pre project case: The first variant represents the accumulated score for the apartment prior to the project's initiation. In this variant, all categories scored lower than the existing conditions, except for VIS (visual comfort). The only relevant changed input is double-glazed windows, with higher LT value of 82%, compared to the current triple-glazed energy-efficient windows with an LT value of 72%.

Existing Case: In the existing conditions, several changes had been implemented: the entire apartment was painted with eco-certified paint, floors were certified, a central ventilation system with 0.5 ACH was installed featuring low-noise air supply and a 60% PM2.5 filter. Additional gypsum boards were added between installations in adjoining rooms and the bedroom, acoustic panels were installed throughout the apartment, and walls were treated with diffusion-open mortar. Noisy installations were soundproofed using mineral wool and vibration mats. Finally, triple-glazed energy-efficient windows with maximized glass area and acoustic glass were installed.

Maximum possible fixed location: In this variant, all the possible renovation measures were implemented, irrespective of restrictions from local plans or the homeowners' association. These upgrades included doubling the ACR from 0.5 ACH to 1.0 ACH, solar shading, cooling systems, a building management system (BMS), reinforced burglary protection for all windows and doors, an indoor environmental quality (IEQ) indicator, and flooring with high-impact sound insulation. The most significant improvements were observed in the following order: THER (thermal comfort), PER (personal security), VIS (visual comfort), and ACOU (acoustics).

Maximum possible changed location: The fourth variant mirrors the third but relocates the apartment geographically to either Samsø or Bornholm. This relocation optimized sunlight exposure, reduced air pollution, improved views, and minimized noise disturbances. The only category with further improvement over the third variant was VIS.

4.3 The Sleep Quality Assessment Tool

The combined effects of Comfort parameters on total score

The graph demonstrates the combined impact of four IEQ parameters (Acoustic Comfort, Indoor Air Quality, Thermal Comfort, Visual Comfort), and Person Comfort on the total sleep quality scores of 11 houses. Each bar represents a house, with parameter values listed beneath, and the total score is plotted against the threshold of 0.65 (C+ label), representing acceptable sleep quality.4.2

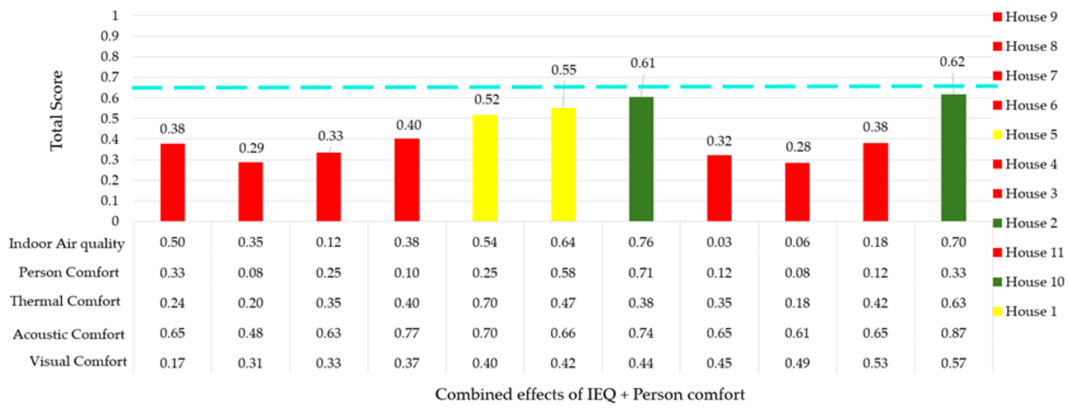

Figure 4.2: The combined effect of Comfort parameters on total score.

House 1 achieves a score of 0.55, supported mainly by moderate acoustic comfort (0.66) and IAQ (0.64). Personal comfort (0.58) also makes a positive contribution, while thermal comfort (0.47) and visual comfort (0.42) are slightly below the threshold. Despite these deficiencies, the balanced nature of the scores across parameters helps House 1 achieve a relatively strong total score. Incremental thermal and visual comfort improvements could help this house cross the 0.65 threshold.

House 2 achieves one of the higher total scores, at 0.61. This performance is driven by strong IAQ (0.76), acoustic comfort (0.74), and personal comfort (0.71). Thermal comfort (0.38) and visual comfort (0.44), while still moderate, are the weaker contributors in this house. The results demonstrate that strong performance in a few key parameters, especially IAQ and acoustic comfort, can compensate for moderate scores in others, leading to improved sleep quality.

In stark contrast, House 3 records the lowest total score of 0.28. Poor IAQ (0.06), thermal comfort (0.18), and personal comfort (0.08) are the primary limiting factors. Moderate acoustic comfort (0.61) and visual comfort (0.49) cannot counteract these deficiencies. Similarly, House 4, with a total score of 0.32, suffers from extremely poor IAQ (0.03) and personal comfort (0.12) despite moderate scores in acoustic comfort (0.65) and visual comfort (0.45). Both houses highlight the critical role of IAQ and personal comfort, as very low scores in these parameters significantly suppress sleep quality.

House 5 achieves a total score of 0.52, supported by firm acoustic comfort (0.70), IAQ (0.54), and thermal comfort (0.70). However, lower scores in visual comfort (0.40) and personal comfort (0.25) limit further improvements. This issue demonstrates the importance of a balanced approach; while high scores in some parameters help, deficiencies in others prevent the house from reaching the threshold.

House 6, with a total score of 0.33, suffers from low IAQ (0.12), thermal comfort (0.35), and personal comfort (0.25). Despite moderate acoustic comfort (0.63) and visual comfort (0.33), the poor performance in critical parameters limits the total score. Similarly, House 7 records a total score of 0.38, with moderate acoustic comfort (0.65) and IAQ (0.50) offset by poor thermal comfort (0.24), visual comfort (0.17), and personal comfort (0.33). These cases emphasize the compounding adverse effects of deficiencies in multiple parameters.

House 8 achieves a total score of 0.40, supported by high acoustic comfort (0.77) and moderate IAQ (0.38). However, low scores in visual comfort (0.37) and personal comfort (0.10) prevent further improvement. On the other hand, House 9 records one of the lowest total scores at 0.29, with deficiencies across all parameters. Acoustic comfort (0.48), IAQ (0.35), thermal comfort (0.20), visual comfort (0.31), and personal comfort (0.08) all contribute to its poor performance, highlighting the need for a comprehensive improvement strategy.

House 10 achieves the highest total score of 0.62, demonstrating the importance of balanced high scores across parameters. Firm acoustic comfort (0.87), IAQ (0.70), and thermal comfort (0.63) drive the score, while visual comfort (0.57) and personal comfort (0.33) provide additional support. This house is a benchmark, showing that strong performance in multiple parameters is essential for optimal sleep quality. Lastly, House 11, with a total score of 0.38, shows moderate performance in acoustic comfort (0.65) and visual comfort (0.53) but suffers from poor IAQ (0.18), thermal comfort (0.42), and personal comfort (0.12). These deficiencies highlight the significant masking effect of low IAQ and personal comfort.

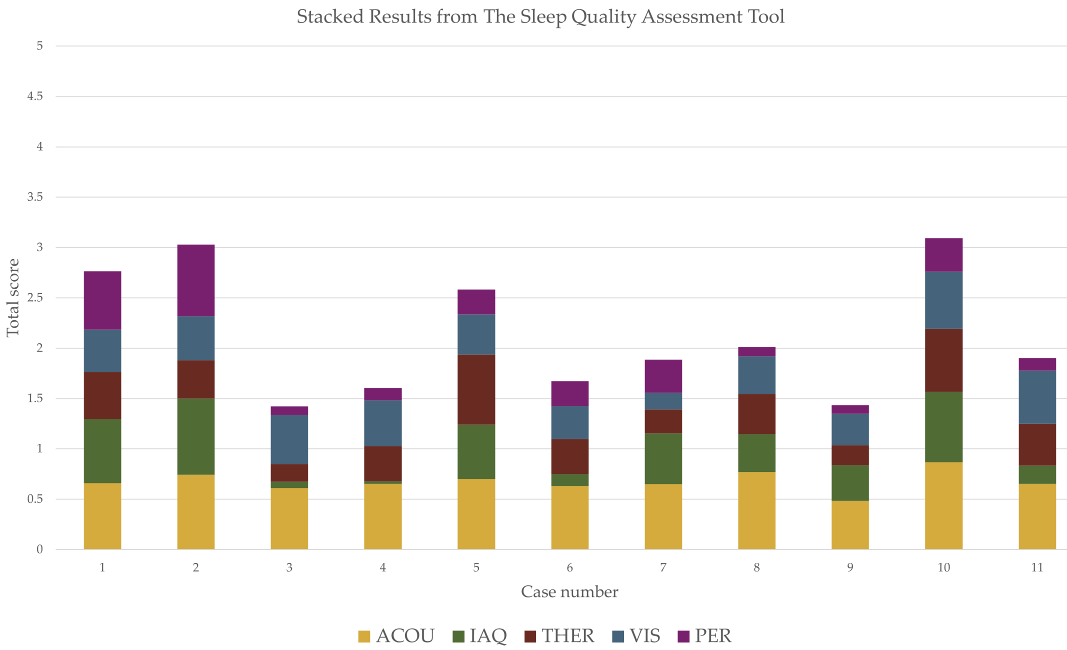

Figure 4.3: A total of eleven individual responses to the sleep quality assessment tool. Showing contributions from ACOUstic and THERmal comfort, IAQ, VISual comfort and PERsonal comfort. Scoring 5 points in the graph equals scoring maximum (5 points = 100%)

Across all cases, the total average score achieved was 42% of the maximum possible.

ACOU (Acoustics) scored an average of 67%, VIS (Visual Comfort) scored 41%, THER (Thermal Comfort) scored 39%, IAQ (Indoor Air Quality) scored 39%, and PER (Personal Security) scored 27%. The smallest variation in scores was observed in ACOU, with a range of 38.5 percentage points. The categories followed in increasing order of variation as VIS, THER, PER, and IAQ.

The greatest variation was seen in IAQ, where the best-performing case scored 75.7%, and the worst-performing case scored 6.2%. Both homes had comparable floor areas of 69m² and 70m² and were occupied by couples aged 30–60. The most significant differences between these cases were:

The construction year of the buildings (2020 vs. 1948). The energy performance rating (A vs. D). Presence or absence of a ventilation system. The size of the bedrooms (8m² vs. 20m²) the larger bedroom being the poorer-performing one.

The three bedrooms with combined usage belong to the three smallest dwellings (all one-room dwellings).

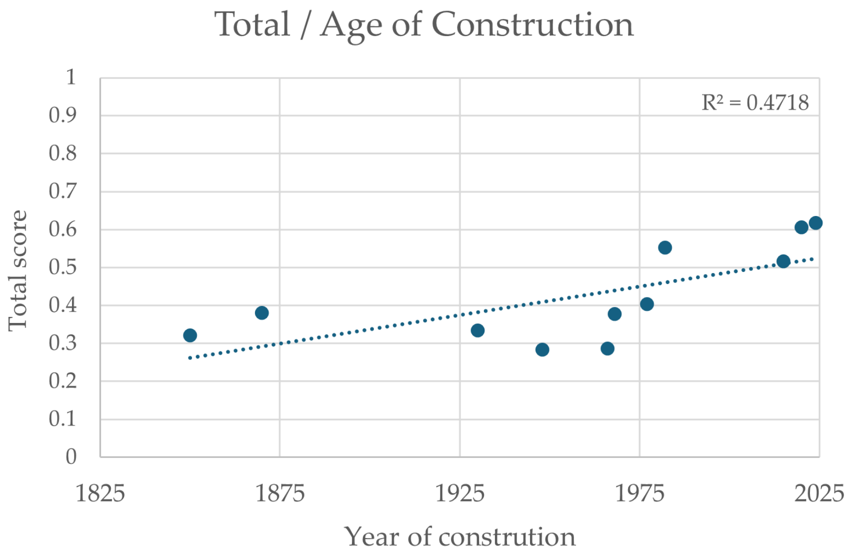

Figure 4.4: It is observed that the age is collated to the total score.

Considering that in Denmark it is assumed that the average house lives for 100 years, the replacement of all Denmark's building stock would be correspondingly long.

Respondents were evenly split between renters and owners. There is no clear influence of this aspect on the total score. However, the data shows that the newer homes were to a greater extent rental homes. This is seen as positive, as it means that older homes are more likely to be owner-occupied. It is assumed that owners have more options in the home than tenants, and since the older homes often had poorer sleeping environments, this provides a good framework for improvements.

Renovation of older homes is therefore highly advantageous compared to Total score.

No correlation is seen between the volume of the house and the total score. Correspondingly, there is also no correlation between heat capacity and total score or MBV and the total score. The influence of the material choices in the home on the total score is not visible. There is a greater influence from the characteristics of the installations in the home.

The data set shows that the presence of mechanical ventilation has a correlation with the total score.

The connection is particularly due to factors in IAQ such as CO_2 amounts, perceived air quality and PM handling. In 3 cases respondents had filled in 0.5 ACH themselves, in the remaining 3 cases the ACR was not known, therefore it is assumed to be 0.5 ACH. With iterations, it is seen that the total score increases with ACH.

There is no correlation between the number of people sleeping in the bedroom and the total score of the bedroom.

Chapter 5

Discussion

5.1 Interpretations of the Base Case

The following prioritized actions were implemented in the Base Case:

- **Introduction of educational material for the user based on the existing home.**
- **Installation of an IEQ indicator:** Airthings View Plus (DKK 2,010).
- **Floor-to-ceiling curtains in the bedroom:** Light fabric curtains and rod (DKK 600).
- **Low-emission paint:** Swan-certified painting (DKK 3,000).
- **Examination for Non-toxic materials:** External consultant (DKK 3,500).
- **Soundproofing noisy installations and adding acoustic isolation to bedroom walls:** Gypsum boards, screws, mineral wool, vibration mat, and acoustic panels (DKK 1,252).
- **Mechanical ventilation:** Vent Axia S200C with fittings and pipes, achieving 1.5 ACH in the bedroom, with CO_2, TVOC sensors, and quiet operation away from the bed (DKK 16,750).
- **Acoustic windows:** Four low U-value, high LT acoustic windows (DKK 17,500).

These measures improved the Base Case total score by 15.3%. Subjective feedback is difficult to evaluate as improvements were made incrementally. However, key observations include significant noise reduction from traffic, enhanced visual contact with surroundings, reduced odor from pets, and noticeable acoustic improvements in the bedroom due to floor-to-ceiling curtains. The discomfort of sleeping next to the window feels improved.

Objective Observations

There is no moisture recovery or dehumidifier in the ventilation system. The minimum and maximum relative humidity value in the dwelling is therefore still deeply dependent on the moisture levels of the supply air, air change rates and the activities inside the home. It is therefore obvious that the importance of the resident's behavior, such as indoor clothes drying, cooking and bathing, is described in a sleep manual for this home.

The average CO_2 levels during sleep dropped from around 1,300 ppm to around 1,100 ppm with the bedroom door closed, after implementation of 0.5 ACH mech. ventilation combined with infiltration sealing guided by a thermal camera. Further CO_2 reductions could be achieved by increasing ACH, but current setup generates low-frequency disturbing noise below 100 Hz at higher ACR. The addition of a 1-meter ventilation silencer reduced the specific noise frequency by +10 dB, a significant improvement. The 2024 consumption of degree days in the apartment is close to one-third of the 2023 bill.

5.2 Interpretations of the Sleep Quality Assessment Tool

The Sleep Quality Assessment Tool provides designers and builders with a foundation for creating better buildings by making iterations of cases. The iterations can encouraging the mapping of all constraints during the design phase, such as window-wall ratio, LT values, view quality opportunities, and opportunities for flexibility in the dwelling.

By sending out the Sleep Quality Assessment Tool by e-mail we achieved a relatively large recipient group. However, due to the relatively high theoretical complexity of the assessment tool, the responder segment was limited. Furthermore, the reward for the relatively long time spent on the assessment was limited to learning from the scoring and this thesis. This means that this project is based on only 11 cases. However, these cases show a certain amount of diversity in terms of age, size, occupants, energy certification, building typology, and more.

With the learning from this and inspiration from the framework and methodology described in the tool ’ARCHITECT - Document Your Value Creation, 2018,’ attention has been given to creating a simplified version of the Sleep Quality Assessment Tool. With the intention to inspire action among architects, investors, and ordinary citizens rather than deter practitioners with academically demanding standards. Assuming that it is better to begin addressing the problem, even if imperfectly, than not to address it at all. The simplest way to foster good sleep environments and teach better habits is to innovate based on technologies and approaches people are already familiar with [82].

The simplified version of the Sleep Quality Assessment Tool was developed using insights from:

- The more advanced the Sleep Quality Assessment Tool,
- The local sensitivity analysis of the Base Case,
- A prioritization of implementability; for instance, relocating a home to achieve more sunlight and higher score, is not practical.

The simplified version of the tool can be found in Appendix E.

It can be argued that the IEQ-Compass(Version: IV-20 2.2019) rewards controllability in housing by weighting "user options" with approximately 15% of the total score distribution. We have placed 10% in this area, with a stronger focus on sleeping users. The bedroom should have the ability to various conditions to meet the sleepers exact preferences.

The developed parameters share a degree of subjectivity, making it challenging to propose broadly applicable solutions. As a result, we decided to allocate points for the presence of a sleep manual that can present the significance of various factors to users.

5.2.1 Interpretation of the parameters

An average total score of 42% of the maximum was surprisingly low, considering that the dwellings of the responders do not seem like poor-quality homes. There is a slight bias in the study, as all homes are inhabited by at least one resident with a background in building sciences, which is expected to positively influence the average score.

Acoustic comfort scored the highest among the five categories; however, insights from the base case revealed that the scoring method here is incomplete regarding noise through windows and openings. Therefore, the score in this category should be reduced.

Visual comfort ranked second with a score of 41%, which is surprising given the indicators difficulty to improve through renovation. Both VIS1(Sunlight hours) and VIS3(View-in and View-out) require a good geographical location, while VIS4(Sun protection) is often constrained by local planning regulations, homeowners' associations, or similar restrictions, as it depends on the presence of external shading. Additionally, all VIS1-4 indicators are factors renters cannot independently modify.

Thermal comfort scored 39%, which was expected since none of the 11 cases had shading, cooling systems, or Building Management Systems, which would improve the score.

Ventilation plays a significant role in Indoor Air Quality (IAQ). Given the generally low ventilation rates in the 11 cases, this is reflected in the low average score. However, it should be noted that IAQ1, related to outdoor air quality, is expected to underperform significantly due to errors in input values from the data provider.

Personal comfort scored only 27%, unsurprising as this area has not been prioritized in building design historically.

The greatest variation appeared in IAQ, where the best-performing case scored 75.7%, while the worst scored only 6.2%. Given comparable conditions, this suggests that IAQ scoring is reliable.

The results of the Sleep Quality Assessment Tool indicate that older buildings perform worse. This is likely influenced by indicators such as OLF/m^2, penalizing older buildings, along with poorer thermal insulation and a lack of mechanical ventilation systems. Additionally, a correlation between age and energy labels was observed (R^2=0.56). Older dwellings are expected to have higher infiltration rates, but in this assessment, infiltration was low because high infiltration benefits CO_2, OLF/m^2, and maximum temperature indicators.

Older dwellings thus show potential for improving both sleep environments and energy ratings, allowing for renovation schemes targeting these areas. Denmark could gain a more robust return on investment through energy savings and societal benefits, including reduced sickness absence, increased work efficiency, and decreased medication consumption.

No correlation was found between construction materials and the total score, suggesting that regulations may not need to emphasize specific materials. Instead, the greatest influence came from home installation characteristics. Future homes should prioritize low-noise installations. Mechanical ventilation showed a correlation of 0.63 with the total score, justifying its prioritization in potential renovation funds.

Surprisingly, no correlation was found between the number of people sleeping in the bedroom and the total bedroom score, despite CO_2 levels, OLF/m^2, and temperature being directly influenced by the number of occupants. This can be explained by upper thresholds for these indicators being exceeded regardless of whether one or two people were present.

5.2.2 Correlation Analysis of Comfort Parameters and Total Score

The heatmap displays how strongly the Comfort parameters' variables relate to one another and the total score. In this visualization, red indicates a strong positive correlation, while green represents a weak or no correlation. The analysis reveals significant insights into how these parameters interact and their relative importance in overall sleep quality.5.1

	Acoustic Comfort	Indoor Air Quality	Thermal Comfort	Visual Comfort	Person Comfort	Total score
Acoustic Comfort	1.00	0.51	0.67	0.43	0.35	0.74
Indoor Air Quality	0.51	1.00	0.50	-0.02	0.76	0.88
Thermal Comfort	0.67	0.50	1.00	0.42	0.28	0.74
Visual Comfort	0.43	-0.02	0.42	1.00	0.00	0.35
Person Comfort	0.35	0.76	0.28	0.00	1.00	0.78
Total score	0.74	0.88	0.74	0.35	0.78	1.00

Figure 5.1: Heatmap of Correlation Analysis of Comfort Parameters and total score. Values in the matrix are the correlation coefficient(R).

When examining the combined interactions of parameters, it becomes clear that IAQ is the most critical parameter to manage. This is because strong performance in this area is also correlated with good performance in other areas. Considering further that the literature search indicates poor IAQ conditions exacerbate the negative perception of other parameters, this hypothesis is reinforced. In the analysis, this is particularly evident as the total score and IAQ score demonstrate a correlation of R=0.88.

It is also noteworthy that there is a correlation of R=0.78 between Person Comfort and the total score. The underlying cause of this is not entirely clear, but there may be hidden correlations within the indicators. For example, if a main door has a five-point locking system, it is likely to also have a good U-value. Similarly, if one lives in a low-crime area, it is possible that the same area experiences low outdoor air pollution.

Indoor Air Quality as the Most Influential Parameter

Indoor Air Quality (IAQ) exhibits the strongest correlation with the total score, with a value of 0.88, making it the most critical factor for improving sleep quality. This issue indicates that dwellings with better air quality tend to achieve higher total sleep quality scores. Moreover, IAQ shows strong interdependencies with other parameters, such as Person Comfort (0.76) and Thermal Comfort (0.50). This issue suggests that improving air quality not only has a direct impact on sleep quality but also enhances perceptions of safety and overall environmental comfort. These findings establish IAQ as the top priority for interventions to optimize indoor environments.

Acoustic and Thermal Comfort as Key Contributors

Both Acoustic Comfort (0.74) and Thermal Comfort (0.74) demonstrate strong correlations with the total score, tying as the second most influential parameters. Acoustic comfort, which measures the impact of noise levels on sleep, is a crucial determinant of a restful indoor environment. Similarly, thermal comfort underscores the importance of maintaining a stable and comfortable temperature for better sleep. The strong correlation between these two parameters (0.67) highlights their interrelated nature, indicating that homes with better noise control often exhibit better temperature regulation. These findings emphasize the need for dual-targeted strategies to address these parameters simultaneously.

Person Comfort's Significant Role

With a correlation of 0.78, person comfort plays a significant role in determining sleep quality. This parameter reflects perceptions of safety and well-being, essential for restful sleep. Its relationship with IAQ (0.76) underscores how air quality improvements can positively influence person comfort. However, person comfort shows weaker correlations with other parameters, such as thermal comfort (0.28) and acoustic comfort (0.35), suggesting that its influence is more independent. Interventions targeting person comfort can be highly effective, especially in homes with low perceptions of safety or well-being.

Visual Comfort as a Supporting Parameter

Visual comfort shows the weakest correlation with the total score (0.35), indicating that its role in influencing sleep quality is relatively limited. It also has minimal relationships with other parameters, such as IAQ (-0.02) and personal comfort (0.00), highlighting its independence. While visual comfort contributes to overall indoor quality, it is a secondary factor compared to the more impactful parameters. Improving visual comfort should be treated as complementary measures, implemented after addressing higher-priority parameters.

Inter-Parameter Relationships

The heatmap reveals notable interdependencies between parameters. For instance, the correlation between IAQ and Personal Comfort (0.76) suggests that addressing air quality can enhance perceptions of safety and well-being. Similarly, the relationship between Acoustic Comfort and Thermal Comfort (0.67) underscores the importance of addressing noise and temperature conditions together. These interdependencies highlight the value of holistic strategies that leverage the natural synergies between parameters to maximize improvements in sleep quality.

5.2.3 Analyzing the distributions of variables and relationships between parameters

The scatterplot matrix provides a detailed visual representation of the relationships between five key variables and the sleep quality total score. The diagonal histograms depict the distributions of each variable, while the scatterplots reveal the pairwise relationships between them.5.2

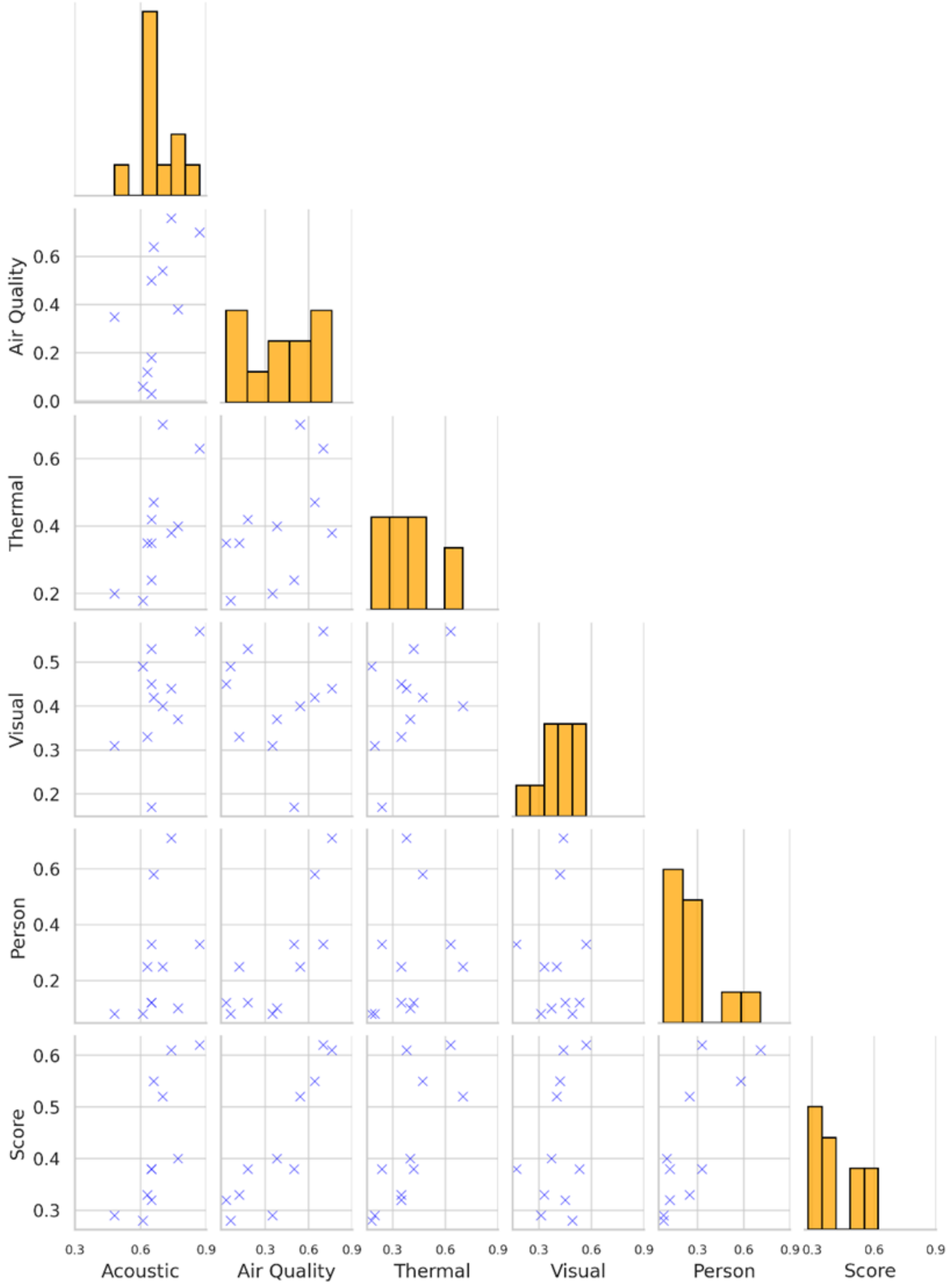

Figure 5.2: Distributions of variables and relationships between parameters using scatterplot matrix. The X and Y axis is the scoring, 1.0 is maximum.

Variable Distributions

The histogram for Acoustic Comfort shows that most dwelling score between 0.6 and 0.8, peaking around 0.7. This issue suggests that acoustic performance is generally moderate to high in the sampled dwellings. In contrast, Indoor Air Quality exhibits a broader range of values, with many dwellings scoring poorly below 0.3. This issue indicates challenges in ventilation or air filtration across the dataset.

For Thermal Comfort, the scores are distributed more evenly, with a noticeable proportion of dwellings scoring below 0.5, reflecting lower thermal performance. Similarly, Visual Comfort shows a narrow distribution, with most values clustering between 0.3 and 0.5, indicating consistent but average performance. Person Comfort is heavily concentrated below 0.4, pointing to a need for improvements in addressing personal preferences or ergonomic needs. Lastly, the Total Score histogram reveals a clustering of values between 0.3 and 0.6, with no dwelling achieving a perfect Comfort score.

Pairwise Relationships

The scatterplots below the diagonal illustrate the interactions between the variables. Acoustic comfort shows a weak positive relationship with Indoor Air Quality, suggesting that dwellings with better acoustic performance may also benefit from improved air quality, although the correlation is not strong. The relationship between Acoustic Comfort and Thermal Comfort is more pronounced, indicating that better thermal design often coincides with improved acoustic conditions. Acoustic Comfort significantly correlates with the Total Score, highlighting its significant contribution to overall comfort.

Indoor Air Quality demonstrates the strongest positive correlation with the Total Score. This issue emphasizes its critical role in IEQ and suggests that improving air quality can directly impact overall comfort. The relationship between Indoor Air Quality and Thermal Comfort is moderate, reflecting some overlap in HVAC system performance.

Thermal comfort exhibits a moderate positive correlation with the Total Score, confirming its importance in overall comfort. However, its relationship with Visual Comfort is negligible, indicating their independence as separate design considerations. Visual Comfort, while consistent, shows only a weak influence on the Total Score, suggesting its limited role compared to other factors.

Lastly, Person Comfort is moderately correlated with the Total Score, indicating its influence on overall comfort. However, its consistently low scores across the dataset limit its impact relative to other variables.

5.3 Broader Interpretations

If, as observed in the base case, it is not possible to implement all sleep enhancing measures in the sleep environment, should it then be considered increasing discomfort in certain parameters to mitigate issues in others? For example, the literature review indicates that implementing orange-tinted glass enhances relaxation but this compromises LT values critical for maintaining circadian rhythm.

Similarly, if a dwelling experiences high OLF levels, the negative perception of poor air quality can be reduced by lowering the temperature, although this may increase thermal discomfort. Conversely, findings also show that achieving high comfort in certain parameters, such as excellent acoustic conditions, can reduce the perceived impact of disturbances from other areas. This suggests potential benefits in adopting a differentiated scoring system rather than the typical linear point allocation used currently.

The literature and general guidance recommend sleeping with the bedroom door open to avoid poor IAQ. However, this compromises ACOU, as internal noise within the home becomes more noticeable. A clear solution to this trade-off is the implementation of quiet mechanical ventilation systems with adequate ACH.

The 30% of the Sleep Quality Assessment Tool is tied to geographic location, requiring relocation to achieve improvements. Additionally, the Base Case was restricted from installing solar shading or privacy screens. This highlights the need for dual scoring systems, one for renovations and another for new constructions, as seen in energy frame calculations in BR18; BE18.

5.3.1 Energy label

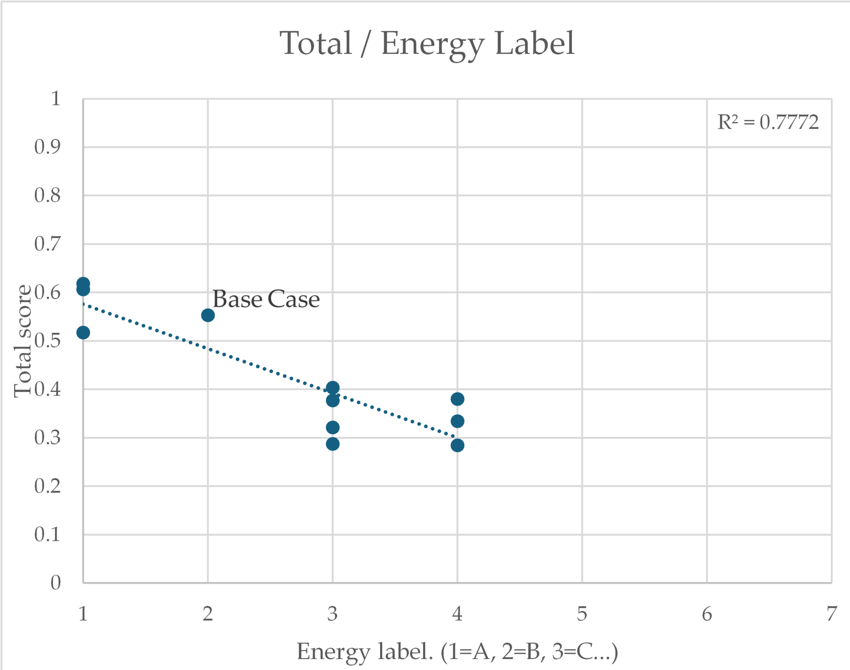

Figure 5.3: Correlation between total score and energy label.

It is interesting to see the relatively strong correlation in this particular case, as the energy label scheme and its evaluation methods have not been considered at all in this project. Especially areas as Person Comfort and Visual Comfort has indicators, which is not expected to influence Energy Labelling. The strong correlation is assumed to be due to the fact that energy optimization also provides comfort. For example, ventilation systems make a positive contribution to both the energy label and the sleep environment. Likewise with high insulating value of the wall and windows.

Four of the evaluated dwellings did not have an energy label, in those cases statistical energy labels for the year and typology have been used.

The pre-renovation version of the Base Case would give a total score of 0.4 which would give R^2=0.75.

5.3.2 Psychological Considerations

Given the subjective nature of sleep quality, it is challenging to determine when improvements are necessary. Psychiatric research shows that interventions meant for patients with mental disorders can also enhance conditions for healthy individuals. This project aims to uplift all users—regardless of starting conditions. The overall score average of 42% and the best score of 75.5% demonstrate that improvements are possible for all dwellings.

Psychological factors should be prioritized since sleep environments are often judged during the pre-sleep phase (when going to bed), whereas the sleeping phase receives less attention. Legislation could address both areas by requiring environments that can momentarily adapt, such as activating privacy screens, cooling, or other controls, and ensuring optimal conditions throughout the night, including IAQ, acoustics, and temperature control, which users cannot actively manage during sleep.

5.3.3 Sleep Quality and Its Dependence on Cultural and Geographical Factors

This section investigates cultural and geographical aspects that affect sleep quality with a general focus on contexts relevant to Denmark. Studies targeting Danish residential buildings are scarce, therefore, it is important to consider cultural and climatic differences when reading about sleep quality in foreign studies. This review identifies significant findings and research gaps, forming the basis for the analytical approaches and evaluation criteria of this study.

When considering climate-related sustainability, it is noteworthy that according to Statistics Denmark(Danmarks Statestik) did 14% of the Danes change homes within 2023. Assuming that the occupier consciously or unconsciously strives to create a sense of home each time, it can be expected[55] that the occupant will make some alterations to the apartment. These changes will inevitably consume resources and have an environmental impact. Encouraging flexibility in housing design can mitigate these impacts by reducing the need for extensive modifications during transitions between occupants, and thus be a good match between a good sleeping environment and downscaling of energy consumption (the goal of the energy label).

It has not been possible to find statistics on the use of pajamas or other nightwear in Denmark. Historically, Europeans have slept naked or in their everyday clothing. Only in England has development been different since German aircraft began night bombing British cities during World War I. As a result, pajamas became popular in England. This development did not occur in Denmark. In addition, in the last 50 years, we have achieved better thermal comfort in our homes, making everyday clothing for sleep unnecessary. Therefore, it is assumed in this report that the typical Dane sleeps naked.[75]

A simplified version of the Sleep Quality Assessment Tool can help individuals identify personal minor issues that may disrupt sleep, such as the lack of blackout curtains. These are elements that can assist individuals in making better decisions about the layout and design of their homes[81]. Watzlawick et al. refer to this as first-order change—addressing individual behavior rather than the structural problems of society.

Elements such as ACOU1, IAQ1, VIS1 and PER1(all location based inputs) highlight what Watzlawick et al.[81] would describe as second-order change, which focuses on designing systems better suited to promote sleep, such as choosing better housing locations. By looking at the results as a whole, combined with insight into the culture, should the next question of this master thesis be: "How should dwelling be designed at a macro level (e.g. urban design, housing policies, expectations) to support good sleep?" The natural path for this project is therefore to increasingly incorporate societal problems and structures to achieve a more robust solution. After all, why is it necessary to rely on blackout curtains and ventilation systems? Humans evolved to sleep without such interventions

The Köppen climate classification:

Denmark is classified under the Cfb climate zone according to the Köppen climate classification. This climate zone is known as the temperate, maritime-influenced climate, also called temperate oceanic or coastal climate. The following table lists all countries and regions classified as Cfb, along with notable areas within each:

Note that a large proportion of our sources are based in China and Korea. Whereby special recommendations on the temperature and humidity are kept up against the different climate.

Add to that the cultural difference, which results in some uncertainty in the conclusions from these studies.

Country/Region	Notable Areas
Denmark	Entire country
United Kingdom	England, Wales
Ireland	Entire country
Norway	Southern and western coastal areas
The Netherlands	Entire country
Belgium	Entire country
France	Northern regions (e.g., Brittany, Normandy)
Germany	Western and northwestern areas
New Zealand	North Island, northern South Island
Australia	Southern Victoria, parts of Tasmania
Chile	Southern regions
Portugal	Northern and coastal regions
USA	Western Oregon, Washington, northwestern California

Table 5.1: Countries and Regions with Cfb Climate Zone under Köppen Classification

5.4 Comparison with existing legislation and recommendations

The sleep quality assessment tool offers a novel approach to evaluating indoor environmental quality (IEQ) parameters that specifically impact sleep. It sets thresholds that strike a balance between scientific rigor and practical applicability. Compared to existing standards and regulations such as BR18, ASHRAE, LEED, WELL, and DGNB, our tool aligns with key benchmarks while introducing significant enhancements.5.2

For instance, our **Thermal Comfort** thresholds for optimal sleep conditions (16–24°C) are consistent with BR18 and WELL. However, our tool further incorporates dynamic scoring for insulation, heating system control, and temperature fluctuations—factors not explicitly addressed in these standards. Similarly, our **Acoustic Comfort** thresholds are more strict, defining optimal conditions as ≤ 20 dB, compared to BR18's ≤ 30 dB(A) and WELL's ≤ 35 dB(A). This stricter standard focuses on mitigating noise sources that disrupt sleep.

Regarding **Visual Comfort**, our tool mirrors BR18, LEED, and WELL by emphasizing daylight access. However, it enhances these frameworks by integrating circadian rhythm considerations and user-controlled shading systems, filling critical gaps. For **Indoor Air Quality (IAQ)**, our tool sets strict thresholds for $PM_{2.5}$ ($\leq 4.9\ \mu g/m^3$), CO_2 (≤ 750 ppm), and TVOCs ($\leq 500\ \mu g/m^3$), aligning with WELL's stringent criteria while surpassing the specificity of other standards. Additionally, it incorporates perceived air quality (PAQ) metrics and user-controlled ventilation options, making the evaluation process more adaptable and occupant-focused.

Our tool aligns with and builds upon existing standards, introducing stricter thresholds, broader criteria, and greater flexibility, which ensures a comprehensive and actionable framework for optimizing sleep quality in residential environments.

Standard/Certification	**Thermal Comfort**	**Acoustic Comfort**	**Visual Comfort**	**Indoor Air Quality**	**Person Comfort**
BR18 (Denmark)	For homes with opening windows possibility, Max 100 hours/year> 27°C; Max 25 hours/year > 28°C	Sound insulation requirements per DS 490: Class C for dwellings; Indoor ambient noise levels:≤30 dB(A)	Daylight factor: min. 2% in habitable rooms; Window area: min. 10% of floor area; Daylight≥300 lux over 50% of the floor area for 50% of daylight hours	Ventilation rate: min. 0.5 air changes per hour; or 0.30 l/s per m² of heated floor area; CO_2 levels:≤1000 ppm	-
ASHRAE Standard 55	PMV:-0.5 and +0.5;PPD≤10%	-	-	-	-
ASHRAE Standard 62.1	-	-	-	Ventilation rates: 5-10 L/s per person; CO_2 levels:≤1000 ppm	-
LEED	Aligns with ASHRAE 55:PMV:-0.5 and +0.5; PPD ≤ 10%	Strategies to minimize background noise; specific standards for rooms	Daylight factor: 2%-5%; Views for 75% of spaces	CO_2 levels:≤1000 ppm; $PM_{2.5} \leq 15\ \mu g/m^3$	-
WELL Building Standard	PMV between -0.5 and +0.5; PPD ≤10%, RH=30%-60%	Average background noise levels in bedrooms ≤ 35 dB(A)	Envelope glazing area ≥ 7% of the occupied floor area. 300 lux illuminance covers >50% of the area for 50% of annual daylight hours	$PM_{2.5} \leq 12\ \mu g/m^3$; TVOC ≤ 500 $\mu g/m^3$; CO_2 levels ≤900 ppm	Quarterly mental health education offered in-person or virtually
DGNB (Germany)	Thermal comfort assessment per ISO 7730; PMV:-0.5 and +0.5	The mean reverberation time T ≤0.8 seconds	Daylight factor:min 2% in living spaces; Glare-free lighting design	CO_2 levels: ≤800 ppm; TVOC ≤300 $\mu g/m^3$; Formaldehyde ≤60 $\mu g/m^3$	-

Table 5.2: Comparison of Standards for IEQ and Well-being

5.5 Limitations, errors and uncertainties

5.5.1 The Literature search

The foundation for defining the parameters in the Sleep Quality Assessment Tool is fragile and therefore associated with significant uncertainty. The literature search provided insights into the sleep environment from multiple perspectives. The findings were extensive research conducted by experts in their respective fields, however the aggregated number is often limited and untested, meaning that basing the weighting on this is accompanied by great uncertainty.

5.5.2 The Base Case

Noise remains a challenge, despite scoring well in evaluations. Noise ingress occurs primarily through the main and terrace doors, which were not replaced with acoustic window panes. The most challenging noise is from a neighbor's baby. Biological studies show baby cries fall within frequencies most sensitive to the human ear, making them difficult to attenuate. Also Step noise and washing machine vibrations from upstairs neighbors remain clearly audible.

The results from both BSim and 24H overheating calculation are both highly dependent on ventilation volumes and weather conditions. Which in itself gives high uncertainty. In the project's 1st and 4th Sleep Quality Assessment, have a BSim simulation been made, and in both cases the same result is scored regardless of the method, "0 pts", due to overheating.

The reason for choosing BSim in the first place is primarily because the output also provides information about the time of the overheating. Due to the ever-changing working hours in Denmark, it was decided that the bedroom must be usable around the clock, and the importance of the time was therefore devalued.

When measuring $PM_{2.5}$ in the Base Case at 20th December 2024, indoor levels rose explosively to +100 μg/m³ during kitchen activity, outdoor air showed 3 μg/m³ before sleep and indoor air showed 1 μg/m³ during sleep. These discrepancies indicate shortcomings in Aarhus University's DCE model (last updated in 2019), which predicted outdoor levels at 11.5–17 μg/m³ for the Base Case location, which in the assessment tool gave estimated level at 7 μg/m³ during the night. Local environmental changes, such as stricter emission controls and electric vehicle adoption, likely account for the reduced outdoor levels.

A study by Algarni et al.[2] conducted in Saudi Arabia found that larger particles were more prevalent in kitchens than bedrooms and halls, primarily due to cooking activities and the use of incense in living spaces. Fitting well with the sensor findings in the base case.

5.5.3 The Sleep Quality Assessment Tool

There is a weakness in the responder-based method, that the actual conditions of the dwelling are not externally controlled. For example, the parameter "Visual relations to surroundings" is relatively subjective.

All eight responses were reviewed for quality assurance. None were discarded, though in each case, the respondents required assistance with specific values, such as LT values, U-values, and floor constructions. Indicating that the bar for the assessment tool may be set too high or that more guidance is required.

Similar to the case of the IEQ Compass, our initial approach assumed we would personally conduct the evaluations rather than distribute them as questionnaires. While this approach would have eliminated response uncertainties caused by respondents' unfamiliarity with the topic or misinterpretations, it would also have been time-intensive for us and limited the tool's dissemination.

If repeated, the study should ask users for subjective assessments of their sleep environment before filling out evaluation forms. This acknowledges that good sleep relies on more than objective parameters such as CO_2 levels. Literature suggests that improving hedonic well-being in sleep environments directly impacts eudaimonic well-being, as a lack of hedonic comfort may elevate sleepers' arousal levels, reducing deep sleep.

Several deficiencies in the assessment tool has been identified:

- Missing consideration for shadowing effects on the construction. Estimated influence on result: low.
- LT assessment averages values without accounting for window area. Estimated influence on result: medium.
- Moisture buffer choices neglect layer thickness. Estimated influence on result: low.
- Noise maps lack lower sound pressure limits. Estimated influence on result: low.

- Ambiguity in the term "Expected sleepers," leading to inconsistent answers. Estimated influence on result: low-medium.
- Doors, windows, and openings are not considered in noise evaluations or adjacent room assessments. Estimated influence on result: high.
- Cooking appliances and fireplaces are not factored into assessments. Estimated influence on result: high.

5.5.4 Local Sensitivity Analysis

All listed inputs on the x-axis represent individual adjustments to the Base Case. Each adjustment corresponds to a 10% change within the observed range across all 11 cases. For example, for windows, the highest U-value is 2.9 W/m^{2}K, and the lowest is 0.6 W/m^{2}K, resulting in a range of 2.9 - 0.6 = 2.3. Adjustments are thus made by ±0.23 W/m^{2}K. Exceptions include:

- The number of occupants, where one person is either added or removed.
- Cooling, where a cooling capacity of 600 W is introduced.

All adjustments are expected to affect the outcome linearly. If an adjusted input shows no impact, this could be due to one of two reasons:

- The indicator's score is already at or above the maximum threshold.
- The indicator's score is below the minimum threshold.

Findings Derived from the Adjustments

None of the 11 cases include a cooling system. Overheating, which negatively affects sleep, is an issue in all but one bedroom. For the Base Case, implementing cooling significantly improves THER1 and THER3.

The finding that reducing the size of the dwelling improves sleep quality is noteworthy since the only indicator directly influenced by this is OLF/m^2. Additionally, there is no correlation between dwelling size and total score among the other 10 cases. Similarly, increasing the dwelling size results in a lower score for the Base Case.

Removing one person from the bedroom has a substantial positive impact, while adding an additional occupant shows no impact at all. This is because the score for the CO_2 indicator is already below the minimum threshold, so the additional occupant does not affect the score, although actual conditions do worsen.

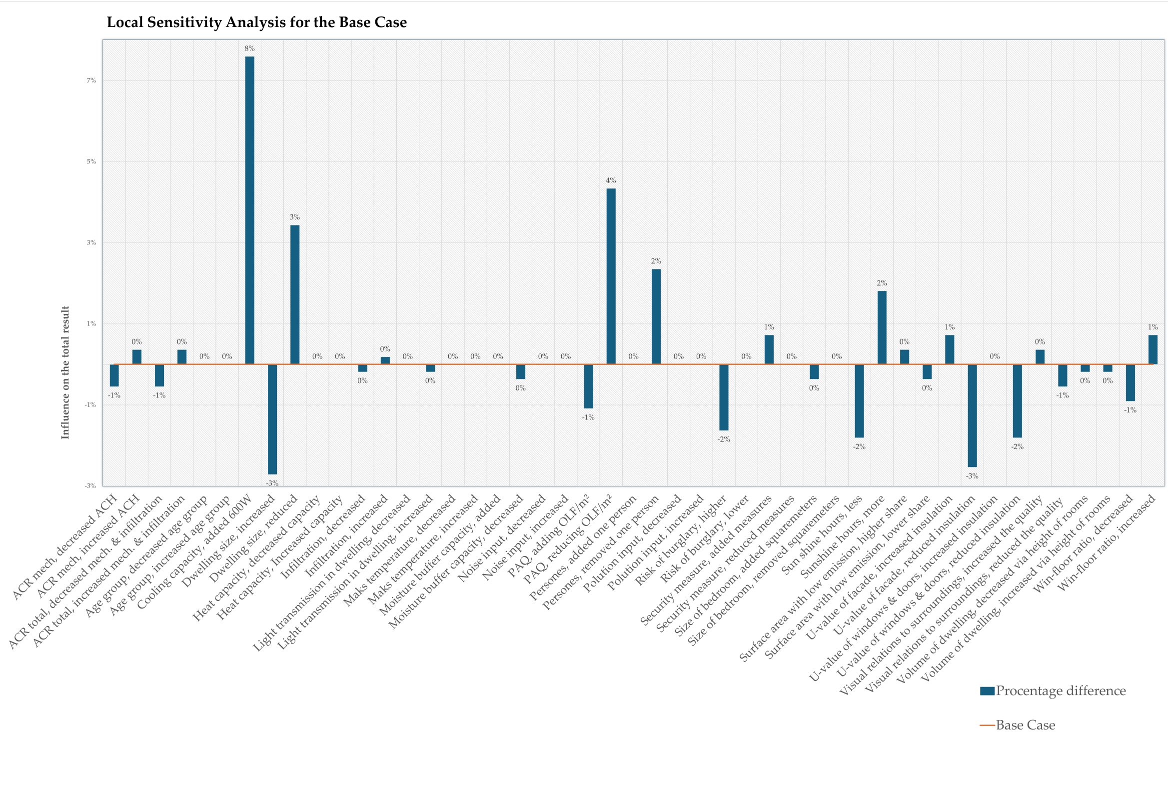

Figure 5.4: The columns show the difference in total score as percentage from the Base Case.

5.5.5 Bias and stakeholders

As authors of this thesis we are stakeholders in this project, we are biased toward reaching an interesting conclusion, useful for our exams. Influence = High

The respondents may have exaggerated responses to promote hidden agendas. Influence = Low

Our supervisors, will become examiners after hand-in, they may have a vested interest in our success, influencing our methods and results. Influence = Medium/High

5.6 Future Research Directions

At the outset of this project, emphasis was placed on including previously unevaluated parameters, such as colors, shapes, art, the presence of plants, and phenomenological experiences like tactile sensations influenced by materials (e.g., floating laminate flooring vs. wood planks, which offer different perceptions of softness and body impact). Few studies discuss the impact of design lineations on IEQ. Intentional noise and olfactory design were also considered. With further work, all of this can be implemented as bonus points.

The Sleep Quality Assessment Tool uses 22°C indoor temperature. For further research it may be advantageous to contact a sleep-expert as there may be advantages in developing a model for active room temperature control overnight. This active temperature control can take place on several levels. Ex. Passive cooling can now be obtained in mattresses via metal wires; but the mattress manufacturer Tempur has also experimented with active cooling in the mattress, unfortunately causing disturbing noise.

If this project were to continue, further work could also focus on:

- Rewarding the flexibility in the bedroom with elements as moving ceiling height for enhanced security feeling.
- Changing the colors of window panes and doors to affect circadian rhythm.
- Rewarding geometry and room disposition of the dwelling.

The importance of flexibility becomes especially evident in smaller homes, as reflected in the correlated lower total score from the cases when a bedroom is used for combined purposes.

Many choices in building design often have an indirect impact on well-being. Due to the scope of the task, it is not possible to cover all perspectives. Potential perspectives to cover in future work could also be:

- Development of bedroom concepts for all types of people.
- Reduction of diseases that can be directly related to buildings, often seen with Sick Building Syndrome.
- Social aspects such as loneliness; 5% of the population shows signs of social isolation, and 9.6% of adults show signs of loneliness. Indirectly influencing sleep quality.

- In Denmark, 54.7% do not meet WHO's minimum recommendation for exercise. Therefore, Danish building style should be developed so that a greater part of this exercise occurs unconsciously. Indirectly influencing sleep quality.

During our field trip to the Brønderslev Psychiatric Hospital, we observed a significant potential for mutual learning between ourselves and psychiatrists, doctors, psychologists, and individuals affected by stress. It was evident that the literature on well-being was actively implemented in the facility. This included strong connections to nature, colors, art, phenomenological and sensory experiences, and tranquility. Conversely did the hospital appeared, visually, to be suffering from poor thermal insulation, overheating issues, and other parameters of the tool.

Chapter 6

Conclusion

Investigation of influential factors on sleep quality in Denmark was done via a literature search. The literature search identified IAQ and Thermal Comfort as key parameters due to their strong correlations with assessment scoring outcomes. The literature study also highlighted research gaps, especially Acoustic Comfort and Person Comfort. If a prioritization is necessary would Indoor Air Quality and Thermal regulation be primary factors in optimizing sleep environments in Denmark. In this study, the heatmap analysis revealed that Acoustic Comfort plays a moderate role in ensuring a good sleep quality environment while Visual Comfort shows the least impact on the sleep quality environment.

To address gaps in this study area, this research extends the IEQ-Compass framework by introducing a new parameter, Person Comfort, and developing an innovative Excel-based Sleep Quality Assessment Tool able to produce new empirical data. The tool integrates scientifically validated thresholds, location-based environmental data, and building-specific inputs to provide a user-friendly, scalable framework for evaluating and improving residential sleep environments. It emphasizes systems tailored to sleepers rather than awake individuals, prioritizing conditions conducive to good sleep quality. Developing the Sleep Quality Assessment Tool addresses the gaps in existing standards, such as BR18, WELL, LEED, and DGNB. While these standards provide general thresholds for Comfort, they fail to account for sleep-specific needs.

The following chapter *Recommendations* proposes amendments for the existing legislation. Core fields for stricter standards for sleep-specific conditions could be:

IAQ thresholds of CO_2 750 ppm which would be stricter than WELL's 900 ppm, ensuring better respiratory outcomes during sleep. Prioritize night-time ventilation systems in older or poorly rated buildings.

Limits of 20 dB instead of BR18's allowance of 30 dB, to reduce sleep disruptions.

Enhanced circadian-aligned lighting thresholds, such as 400 Lux for 50% of the floor area, extend beyond traditional daylighting metrics by addressing daytime productivity and good sleep quality. Implement shading, view-in- and glare control systems to support circadian rhythm and privacy simultaneously.

The cases in this study revealed an average total IEQ score of 42%, with the best-performing dwelling scoring 62%. Older buildings and those with poor energy labeling performed correspondingly worse, highlighting the need for targeted renovations. Practical strategies, such as implementing good conditions for night-time ventilation using low-noise mechanical installations, were identified as critical for improving sleep environments. A differentiated scoring system similar to Denmark's energy framework for renovations could provide tailored recommendations.

Thermal Comfort: Limit overheating to a max of 24°C for 100 hours annually and 25°C for 25 hours annually.

Emphasize cross-domain interactions, such as the impact of noise on thermal perception.

To validate the findings in this study should future research: Conduct large-scale studies to test the Sleep Quality Assessment tool across diverse residential settings combined with integration of IoT-enabled sensors for real-time monitoring of IEQ parameters, and subjective questionnaires for the occupiers.

This thesis represents a significant advancement in sleep quality research, bridging the gap between theoretical frameworks and practical applications. The Sleep Quality Assessment Tool extends the IEQ-Compass by introducing personal Comfort and providing actionable insights tailored to sleepers. By addressing gaps in existing standards and integrating stricter thresholds, adaptive systems, and cross-domain interactions, this research offers a robust foundation for enhancing residential sleep environments. Future work should focus on scaling the tool's adoption, validating its scoring methodology, and integrating emerging technologies to optimize indoor environments for restorative sleep.

Chapter 7

Recommendations

Our proposed solutions are a product of iterative thinking throughout the project—observing input values, analyzing results, adjusting perceptions, reviewing new inputs, and so on.

Based on the dilution equation and our literature search, we propose the following rule of thumb for maintaining CO_2 levels below 800 ppm over an 8-hour period in a 10 m^2 bedroom:

- For 1 sleeping person: 1.5 ACH
- For 2 sleeping persons: 2.5 ACH
- For 3 sleeping persons: 3.5 ACH

All three cases place strict requirements on the noise level of the ventilation inlet. Users are likely to turn off ventilation systems if they are noisy. Therefore, the placement and type of inlet must be carefully considered. Disadvantages from OLF, TVOC, overheating and PM are also expected to be alleviated. CO_2 is assumed to be the most demanding compared to ventilation quantity.

BR legislation

Acoustic Comfort Legislation could benefit from being transformed from specific requirements to function-based requirements, where the ultimate goal is for the intended bedroom to achieve a maximum noise level of 25 dB, including consideration of noise from household installations. How this limit is met is up to the designer.

Indoor Air Quality Building regulations could introduce stricter requirements for supply air quality to ensure adequate airflow for the number of occupants and maintain air cleanliness. Additionally, funding programs could be established to support the installation of mechanical ventilation systems. Introducing mandatory service inspections for ventilation systems, similar to current requirements for heat pumps and wood stoves, would help ensure proper operation. This requirement should be accompanied by a minimum filter standard.

Thermal Comfort Current summer comfort rules allow overheating up to 25 hours above 28°C and 100 hours above 27°C, far exceeding the optimal sleep temperature range of 18°C to 24°C. This often forces compromises such as sleeping with open windows, which can cause noise disturbances or feelings of insecurity. As work schedules in Denmark grow increasingly irregular, allowing daytime sleep, the current assumptions about ventilation and overheating are inadequate for maintaining a healthy sleep environment. The regulation could be tightened, for example:

For bedrooms where venting is possible, compliance is typically achieved if calculations show that the room temperature exceeds 24°C for no more than 100 hours per year and 25°C for no more than 25 hours per year. This is contingent on the availability of ventilation as it allows for higher tolerable temperatures.

BR18 already advises considering room usage relative to overheating and timing, but this vague formulation could be strengthened into a clear requirement. Alternatively, a maximum PMV range of -0.5 to +0.5 could be introduced. Additional requirements for night-time temperature reduction in bedrooms could be mandated to achieve low-energy certification.

Visual Comfort To significantly impact circadian rhythm regulation, exposure to light levels exceeding 10,000 Lux is necessary. Current requirements specify 300 Lux over 50% of the floor area for 50% of daylight hours. This minimum Lux requirement could be raised to enhance circadian rhythm stimulation, such as:

400 Lux over 50% of the floor area for 50% of daylight hours, and at least 600 Lux on 10% of the floor area for 50% of daylight hours.

Window specifications could also be revised:

Light transmittance (LT) for 470 nm must be at least 70%, and LT for 625 nm must be *at least 70%.*

Studies should be conducted to refine LT distribution and minimum percentages. Performance-based requirements for shading systems should also be introduced to ensure visual comfort.

Person Comfort Currently, no enforced regulations exist for Person comfort. The following to points should be added:

- All entry points, including windows, must have a minimum three-point lock.
- Low-energy certification requires a user manual for building operation, and an IEQ barometer must be pre-installed.

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Chapter 8

Appendices

All appendices are attached to the report separately.

- Appendix A: Well-being
- Appendix B: An overview of the papers reviewed
- Appendix C: Framework for Scaling and Weighting Parameters Affecting Sleep Quality in Residential Buildings
- Appendix D: Screenshots of Sleep Quality Tool
- Appendix E: Simplified version in PDF
- Appendix F: Result analysis