BUILD DEPARTMENT OF THE BUILT ENVIRONMENT AALBORG UNIVERSITY

Master's thesis

Indoor environmental quality performance - Screening through mandatory workplace assessments

How mandatory physical workplace assessments can be used in developing new Danish indoor environmental performance labels for publicly owned buildings in the future.

Authors:

Kristian L. Woxholt

Lasse G. Wolff

Department of the built environment, Aalborg University

Study program: Building Energy Design

Supervisor: Lasse Rohde

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Abstract

All public buildings in Denmark are required to perform workplace assessments (APV's) to evaluate the wellbeing of employees. The APV is a tool to evaluate the workplace environment in a systematic way. The questionnaires are distributed at least every third year, and all staff are asked to evaluate their psychological and physical workplace environment. Some of these questionnaires collect valuable information on the indoor environmental performance, while others do not.

Since these questionnaires are rarely prepared by experts within indoor environment and qualitative methods, the questions are typically neither specific nor in-depth enough, leading to incomplete results from the analysis. The current physical APV's are developed individually in every municipality, and there is complete freedom of method in type and number of questions. In addition, there is a lack of a uniform label of results, making it hard to compare the quality of the indoor environment.

The National Association of Municipalities in Denmark (KL) has developed a model for assessing indoor environmental quality and wants to use the indoor environmental-related questions in the current APV models to illuminate the occupants' perception of the indoor environment within municipal buildings. Hence, there is a general interest in being able to use the questions to design strategic key performance indicators that can be included in the basis for bench-learning between municipalities.

In this study, physical measurements, and results from a pilot test of the questionnaire have been gathered within a case building, and afterwards treated and analyzed to identify the advantages and disadvantages of these methods of data acquisition. The assessment of the indoor environmental quality has been done, according to the model developed by KL, which follows the requirements and guidelines from the Danish building regulations (BR18). This is done to propose recommendations for how the indoor environmental performance can be evaluated using KL's model and how it could be improved in the future.

The results of the study showed that the measurements worked well in identifying comfort concerns in individual rooms, but it is difficult to assign a cause of the problems from measurements alone. The questionnaire is a valuable source when identifying the origin of indoor environmental concerns in an effective way. When assessing the occupant's satisfaction, the questionnaire is also a valuable source.

The recommendations developed through this study shows the potential of different methods of indoor environmental evaluation. The study showed the potentials of each evaluation method through actual use in a case building.

Keywords: Indoor environmental quality, Data gathering, Publicly owned buildings, Workplace assessments, Strategic planning,

Contents

1 Introduction

All Danish companies with employees must prepare a written Health and Safety risk assessment (APV). The APV is the company's tool for assessing the workplace environment and gives a company the opportunity to work systematically and effectively with the workplace environment based on the employee's own experiences.

The APV revolves around mapping out the organization's workplace environment, identifying areas where action is needed, and planning for how to improve in these areas in the future. Many companies achieve both a better workplace environment and increased wellbeing as a result of implementing and improving their APV. (Arbejdstilsynet, 1873)

It is required that all employees participate in the entire APV-process. This applies to planning, implementation, follow-up, and revision of the APV. In companies with more than 10 employees, it is the Occupational Health and Safety Organization (AMO) that must participate in the APV-related work. In small companies with no requirements for AMO, employees must participate in the same way.

Companies must revise their APV when major changes occur in the work happening within the company, or in working processes and -methods. It may also be necessary to adjust the APV if new knowledge or experience is acquired. In any case, the APV must be revised at least every three years. (Arbejdstilsynet, 1873)

A part of the APV has a clear focus towards the indoor environmental quality at the workplace. A bad indoor environment is almost always a combination of several different factors, like the overall air quality, the indoor temperature, relative humidity, glare and reflections or problems related to the acoustics of the building.

People often react differently to the same influences, and the experience of discomfort is therefore also individual and subjectively judged, and this can manifest itself in many different ways. It can cause a reduction in productivity, concentration, and efficiency, and can also cause problems with the skin and respiratory tract or discomfort in the form of headaches and nausea. (Arbejdstilsynet, 1873)

Recognizing the importance of how a good indoor environment promotes concentration and efficiency amongst employees, and how the APV essentially attempts to improve upon the workplace environment in general, APV's are a source of unidirectional data on the perceived indoor environment, but they often suffer from insufficient questions and extreme diversity between the various municipalities in Denmark.

Therefore, it would be wise to prepare new standardized questions specifically about the indoor environmental aspects in the municipal APV's, in order to establish a baseline for the municipalities to be able to collect valid and uniform data for the occupants' experience of the indoor environment, using the already existing APV's across the municipality's buildings and across all Danish municipalities. (Slottved, 2022)

2 Problem Statement

Danish municipalities are mandated to gather data concerning their building usage, physical conditions, and the quality of the indoor environment to support the execution of the municipal core functions. A standardized framework to bridge the questionnaire data with actual measurements could be a proficient way of gaining more knowledge and understanding of the data gained through future standardized questionnaires.

Knowledge of the building's indoor environmental quality is a decisive factor when the municipalities assess which buildings are best suited for a given activity. It is also vital for the health, wellbeing, and productivity of occupants, as well as for the general public and socio-economic aspects i.e., absence due to illness. Furthermore, it also provides important factors for the municipalities' strategic planning of the maintenance and renovation projects for their buildings. (Realdania, 2023)

Indoor environmental assessments in publicly owned buildings are important, and designated IEQ labels has the potential for enabling prioritization of renovation and cross-sectional comparison in a much more streamlined way. Based on the knowledge gathered, solutions to challenges across departments within a municipality and across municipal boundaries can be identified, instead of solving workplace challenges in various ways depending on individual municipalities. (Petersen, 2023)

How can data on the measured and perceived indoor environmental performance be used to develop standardized IEQ labels for future workplace assessments in Danish public buildings?

To get a better understanding on the individual steps to cover the problem, a set of research topics has been developed and serves as a roadmap for this study.

2.1 Research topics

How can long-term measurements of temperature, CO_2-concentration and relative humidity contribute to develop IEQ labels? The potentials and limitations of using these results for IEQ labels will be investigated by comparing conclusions made based on physical measurements with the perceived IEQ from the questionnaire.

How can questionnaire responses contribute to develop IEQ labels? The questionnaire results used for this study are collected from a public case building: The Town Hall of Ringkøbing-Skjern Municipality. The questionnaire is a pilot test of a new systematic method to collect questionnaire responses as part of the mandatory APV questionnaires. The potentials and limitations of using these results for IEQ labels will be investigated by comparing conclusions based on questionnaire results alone to measured performance as long-term and spot measurements made in the case building.

How can a combination of data sources contribute to IEQ assessments? Based on the potentials and limitations identified in the previous research topics, it will be investigated if a combination of the measured and perceived IEQ can increase the robustness and resolution of the labels.

3 Delimitation

In this section, the boundaries of the study will be defined. Considerations and choices made throughout this study are also highlighted in the following. By describing limitations, key parameters are defined and explained in order to manage and align expectations.

3.1 Measurement delimitation

The measurement campaign performed in this study is limited to monitoring specific indoor environmental parameters including CO_2-concentration, relative humidity, temperature, airborne sound between two offices, and illuminance of artificial lighting within a designated area at the case building.

The spot measurements were limited to be performed on the 21st and 22nd of September 2023. The long-term measurements are limited to 7 weeks starting from 22nd of September. Data collection was not extended beyond the defined period.

The measurement campaign is limited to the 1st floor of the case building. Spot measurements were made on the selected dates and not necessarily on dates with the maximum possible level of occupation. Placement of the measurements in the case building is primarily based on perceived indoor environment and by information given by the responsible janitor at the case building.

The accuracy and precision of the measurement equipment used, was approved by checking that the measurements aligned on the equipment before the measurement campaign. If any deviation in the obtained data is found, it will be acknowledged in the analysis. The measurement campaign does not account for external factors such as outdoor environmental conditions that may have impacted the monitored parameters.

Long-term measurements were made based on two priorities. First priority was to measure in rooms where it was confirmed that there would be a high level of permanent workplace occupation. This is done to ensure that rooms where the indoor environment was measured could also be evaluated by employees questioned in the questionnaire as this link between the questionnaire and the physical measurements is crucial for the study. Second priority for the long-term measurements was to measure rooms where there was an expectation of useful feedback in the questionnaire, this is ensured by prioritizing rooms designated by the janitor.

3.2 Questionnaire delimitation

The questionnaire data collected in the case building was limited to responses obtained using a questionnaire developed and executed by Transition ApS. Collection of the data occurred over the first two weeks of November, with the questionnaire specifically instructing respondents to reflect on the past year. Despite this instruction, the possibility of seasonal bias impacting the results cannot be entirely excluded. For the questionnaire, both the exact locations and identities of all respondents were known. Regarding the questionnaire there was a potential risk to bias the respondents with our visible presence with the measurement equipment since this was conducted prior to the questionnaire. It is also important to mention that the questionnaire was originally designed for the broader project initiated by Realdania, and not specifically developed for this study.

Additionally, the method of data gathering is dependent on information being reported by the occupants. This also raises concerns about the accuracy and honesty of the responses, potentially leading to a response bias. This consideration highlights the importance of critically analyzing the data and taking any possible constraints into account.

4 Theory

Throughout this study, various means of gathering the empirical evidence has been used. This includes physical measurements conducted in early autumn 2023 in which various IEQ aspects were measured and evaluated, as well as a questionnaire based on the mandatory municipal health and safety risk assessments developed and conducted by the company Transition Aps, a company with competencies and know-how within anthropology and human relations. In the following chapters, the theory and different methodologies will be explained.

4.1 Workplace assessment

Incorporating APV-related tasks into an organization in Denmark, five essential topics concerning the workplace environment, must be covered, as defined by legislation. These are:

- Identification and mapping of the overall current health and safety situation in the organization.
- A description and assessment of the problems currently residing within the workplace environment.
- An assessment of how many employees in the organization has had absence due to illness, and how often employees are taking days off due to illness, as well as how long.
- Prioritization of identified solutions to the problems in the workplace environment and development of an action plan.
- Develop guidelines describing how to follow-up on the aforementioned action plan.

Specifically for office related work, the most commonly occurring problems are related to seated desktop work in the same position for long periods of time, potentially causing musculoskeletal complications, communication problems amongst coworkers and leaders, undefined or badly worded expectations, as well as offensive behavior and inappropriate comments at the workplace. (Arbejdstilsynet, 1873)

Other common problems are related specifically to the indoor environment. These are problems concerning air quality at the workplace, which most commonly is the result of bad cleaning or faulty mechanical ventilation systems, but can also be caused by suspended dust particles, new furniture, paints, or sealants introducing volatile organic compounds to the indoor air, or because of too many people in the same room, at the same time for a longer period.

Problems concerning temperature is also commonly found in office buildings. When identifying indoor environmental quality concerns related to temperature and draft it is important to remember that the temperature in office spaces should be kept at 20-22°C when seated at a desk and should not exceed 25°C more than 100 hours during the summer months. When seated or during light activity, like walking from one office to another, the temperature should not get below 18°C at any time. (Arbejdstilsynet, 1873)

It is also important to note that major variations in temperature between rooms can cause condensation and lead to mold- and bacterial growth. To avoid this, it should always be monitored if moisture patches appear inside. Additionally, attention should be on whether the relative humidity is either too low (0-20% for risk of virus and bacteria) or too high (80-100%

for risk of mold and fungus). Condensation and mold growth usually appears within basements, unheated rooms, or buildings with poor insulation capabilities in the exterior walls.

On slightly more rare occasions, noise can cause discomfort for employees. Typically, noise originates from technical installations and machines such as mechanical ventilation systems and copy machines, as well as from colleagues.

It could be colleagues talking in the background, or a ringing phone that goes unanswered. Sometimes, noise can also occur if the reverberation and attenuating properties of a room is poor, causing speech in the room to get "muddy" and "washed out". This can be significantly annoying when many people are in the same room for a conference or for educational purposes. Noise is rarely damaging to the hearing but can cause headaches, reduced ability to concentrate, insomnia, fatigue, and reduced wellbeing. (Arbejdstilsynet, 1873)

Problems concerned around the visual indoor environment like daylight penetration and sufficient illumination from artificial lighting should also be considered. Mostly because glare and reflections from direct sunlight can impact computer monitors and projector screens but also because gloomy or dark areas can increase the risk of tripping or falling, especially if combined with a cluttered workspace with lots of boxes on the floor, etc. Tripping accidents are often downplayed, compared to other work-related accidents but they are responsible for more than one in five serious accidents happening at the workplace. (Arbejdstilsynet, 1873)

A generally poor workplace environment can actually worsen reactions to a poor indoor environment, amplifying the perceived discomfort. People who work in an otherwise good workplace environment are often more tolerant of problems related to the indoor environment. Therefore, problems concerning indoor environment should not be treated as isolated problems but should be considered as part of the entire workplace environment. (Arbejdstilsynet, 1873)

4.2 The indoor environmental quality

The quality of the indoor environment is very important because people spend close to 90% of the time indoors, at home and at work. The indoor environment must therefore be of such quality that it not only reduces the risk of contracting ailments or diseases, but also ensures overall pleasant conditions within the building. Furthermore, scientific studies have shown that a good indoor environment has a positive effect on concentration, efficiency, and productivity in workplaces. The primary factors used to describe and evaluate the indoor environmental quality of a building are: (Valbjørn, et al., 2000)

- Thermal conditions, evaluated by air temperature, radiant temperature, air velocity and relative humidity inside the building.
- Air quality, evaluated by the content of airborne pollutants such as dust, humidity, gases, and vapors, and odors be it pleasant or foul. The most common method of assessing the atmospheric quality of a building is to monitor the CO_2-concentration in one or more rooms.
- Lighting conditions described by brightness, light color, contrasts, as well as glare and reflections from direct sunlight.
- The acoustic conditions, evaluated most commonly by measuring the reverberation and attenuative properties of a room over various octave bands and frequencies from 100Hz to 4.000Hz. Other methods like evaluating airborne noise and impact noise between rooms are also a possibility.

Another important element when assessing and evaluating the indoor environmental quality is recognizing that people have different needs and demands in order to be able to carry out their activities or work-related tasks. In some situations, for example, there is a need for a higher temperature or greater illuminance than in other situations. Likewise, some people can be more sensitive than others to influences, like in the form of hypersensitivity to air pollution or noise from machinery or colleagues. (Valbjørn, et al., 2000)

A good indoor environment therefore should not only be defined by an absence of influences that are experienced or can be unpleasant or cause diseases, it should also be considered if it contributes to positive sensory impressions, especially with regard to lighting conditions and acoustics. It is important that new buildings are projected, designed, and procured in such a way that the indoor environment can be adapted to the activities carried out and that there is a possibility of individual influence on the overall indoor environmental quality. (Valbjørn, et al., 2000)

If problems related to the indoor environment arises at the workplace, it is important to find a solution. A poor indoor environment can cause inconvenience to employees and negatively affect their wellbeing and productivity.

Indoor environmental problems can often be solved using the same methods as used in preventing poor indoor environmental quality, since it is essentially the source of the problem that must be eliminated. Prevention of poor indoor environmental quality can in most cases be solved by utilizing simple measures such as suitable ventilation, cleaning and control of temperature, humidity, and drafts. (Arbejdstilsynet, 1873)

It is important that the employer, ensures that the right cleaning method is chosen, as it can have negative effects on the indoor environment if harsh cleaning agents are used. Cleaning agents can, for example, give off an unpleasant smell for a shorter or longer duration of time, which contributes to a poor indoor environment.

An employer should also be aware that direct sunlight through large glass windows as well as lamps and office machines can contribute to increasing the temperature in the workplace. In office spaces with few employees, the employer can usually lower the temperature alone by employees being able to open the windows to regulate the temperature as often as necessary, but in large offices, a ventilation system often has to be installed. If a mechanical ventilation system is established it is important that the facility management knows how to operate it correctly, as incorrect operation can create unwanted drafts or cold spots, which is an indoor environmental concern on par with the high temperature that was the original problem to be dealt with. (Arbejdstilsynet, 1873)

4.3 Acoustic Comfort

The field of physics that focuses on the study of sound are called *Acoustics*. In building physics, *room acoustics* focuses on sound originating inside a room, while *building acoustics* focuses on sound and sound propagation between rooms. (Petersen, et al., 2014).

A comfortable indoor environment includes, among other things good acoustic properties of the building, to ensure good sound conditions. The specific requirements on acoustics are written in Chapter 17 of the Building Regulations which states that: *Buildings must be designed, procured, and carried out so that the occupants have satisfactory sound conditions that are healthy and comfortable in relation to the use of the building.* (Bolig- og Planstyrelsen, 2018)

A very central part of creating good acoustic properties within buildings consists of limiting the sound pressure levels and reducing sound from external and internal sources i.e., neighbors, traffic, and technical installations. A method for creating good acoustics is to properly insulate the building envelope and partition walls in the buildings with sufficient sound insulation. (Petersen, et al., 2014)

When the aforementioned considerations are not taken, the occupants may experience noise. Noise is most often associated with sounds that are unpleasant, annoying, or harmful for the human hearing. It can be due to the sound power, inharmonic frequency composition, irregularities, or the context in which the sound forms. What is perceived as noise is to some extent a matter of subjectivity, but in general the term “noise” applies to all sounds that affect a person negatively. (Petersen, et al., 2014)

4.4 Thermal comfort

Indoor thermal comfort can be expressed as the total effect of the radiative temperature caused by heat radiating from all surfaces in a room, the indoor air temperature, air velocity and turbulence intensity as well as the relative humidity of the air. Whether or not comfortable conditions can be maintained depends on the requirements for the individual parameters of the building occupant's activity, clothing, and individual physiological needs. (Valbjørn, et al., 2000)

Indoor thermal comfort as a field of study has been researched to such an extent, that it is possible, based on a statistical assessment, to predict how many are expected to be dissatisfied with the thermal indoor environment under various given conditions. However, this assumes that activity- and clothing levels are known. In practice, it is difficult to achieve more than 80 or 90 percent who are satisfied in an office space with several people. (Valbjørn, et al., 2000)

4.5 Visual comfort

Visual comfort plays a crucial role in office buildings, as it can significantly impact the well-being and productivity of the occupants. The amount of lighting in offices does not only affect the productivity but also has a huge impact on how well the occupants consider the quality of the indoor environment. Additionally, lighting can be used to increase aesthetics in buildings and office spaces. Finally, the goal of visual comfort is to strike a perfect balance between aesthetics and functionality without over dimensioning it, resulting in unnecessary energy consumption.

Typically, when the building is in use, there will be daylight contributions in the offices. However, one should make sure that artificial lighting alone is enough to provide sufficient illuminance in the case that the occupants are working late or can work after sunset in the winter months. According to the Danish Standards Association, the sufficient illuminance for office spaces is 300lux (Dansk Standard, 2021) and this is taken into consideration when evaluating the measurements conducted in the case building and later when comparing with the results from the questionnaire collected from the employees occupying the measured spaces.

4.6 Atmospheric comfort

Stale or bad air is often caused by the ventilation in the workplace not being able to remove the substances and materials that pollute the indoor air. Problems with air quality can therefore often be solved by using natural ventilation to vent out, by opening windows. If venting is not enough to solve the problem, it will often be necessary to establish a mechanical ventilation system. According to the Danish Standards Association, CO_2 in the indoor environment in office buildings should not exceed 1000ppm over a longer period of time (Dansk Standard, 2021). When the CO_2-concentration gets too high, other bio effluents like virus or bacteria may also be present at unsafe levels in the indoor air. The relative humidity levels can also be the reason for a poor indoor environment, as if it gets too high or too low it can be responsible for either mold growth or dry and itchy skin.

Dust and dirt are a source of indoor air pollution, so if there are problems with the air quality, it may be necessary to provide better cleaning at the workplace. However, as a rule, to avoid doing unnecessary amounts of cleaning, there should always be visible dirt before assuming that this could become a significant problem for the indoor environmental quality. (Arbejdstilsynet, 1873)

4.7 Model for registration and evaluation of indoor environment

The association and interest organization for the Danish municipalities, KL, among other things, facilitates cooperation between municipalities with the objective to create more and better information about the municipally owned properties. This initiative was put into motion due to a recognition that few and incomparable data on municipal properties limited the possibilities for effective management and sustainable operation at local and national levels. The larger purpose is to improve the baseline for decision making in sustainable management of the municipal resources (Kommunernes Landsforening, 2001).

In order to address this challenge, the municipalities, in collaboration with KL, have developed models for key performance indicators (KPIs) such as the number of properties, building expenses, energy consumption, building condition, indoor environmental performance and building use. The development of a common municipal model for registration, among other things, the state of maintenance and indoor environmental quality as well as a chart of accounts constitute important milestones. Such tools could form the baseline for analyzing and communicating performance and efficiency of a building which in return, supports the larger purpose of sustainable development within the Danish building sector (Kommunernes Landsforening, 2001).

Therefore, in taking the first steps, a taskforce in the Joint Municipal KPI Cooperation over 2021-2022 has prepared a model for registration of the indoor environmental quality in Danish municipal buildings. The taskforce consists of municipal employees with professional and practical knowledge of indoor environment. They have great insight into the balance between complexity and simplicity, which is necessary to create a robust model. Subsequently, all municipalities in the KPI collaboration have given their objections to the taskforce and the model before proper testing began (Ejendomsområdet, 2022).

The model consists of a five-point grading scale, shown on Table 1 that can convert indoor environmental performance, from individual rooms, to buildings, and lastly to the entire property portfolio (Ejendomsområdet, 2022).

Table 1: The gradings used in KL's IEQ Labels (Ejendomsområdet, 2022)

Grade	***Meaning***	***Description***
1	Excellent	No need for further observation.
2	Very good	Need for preventive observation or action.
3	Good	May require remedial and preventive observation or action.
4	Bad	Need for action or improvements as soon as possible.
5	Unacceptable	Urgent need for action or improvement.

The main evaluation model contains three indicative sub-models for categorizing data into the five grades. These being the measured, perceived, and potential indoor environment. Only the measured and perceived indoor environment is used in this study, but the potential indoor environment will be used as part of a discussion later on. These sub-models have each their strengths and weaknesses and can be used to gather information on the indoor environmental performance at various levels of the building, spanning from individual rooms to the entire building, and even to entire properties with two buildings or more (Ejendomsområdet, 2022).

The measured indoor environmental performance involves the use of measurement equipment for various IEQ parameters. The equipment can be a fixed part of the rooms interior that measures continuously, like a BMS-system or temporary installations or measurements made as part of a specific investigation. There are many indicators that can be measured in relation to the indoor environmental performance, but the taskforce estimates that the following indicators have the greatest impact on the indoor environment:

- Atmospheric: CO_2-concentration
- Acoustic: Reverberation time
- Thermal: Degrees Celsius
- Visual: Lux

These have been selected to keep the model as simple as possible, and they are also the indicators that the municipalities are legally required to meet. Placement of the equipment is of great importance for registration of the indoor environment and the results of the measurements. It is therefore recommended to support with data on the occupants' experience using the perceived indoor environment (Ejendomsområdet, 2022).

The perceived indoor environmental performance seeks to evaluate how the building users experience the quality of light, sound, and air within. The taskforce has investigated the use of APV's for collecting data on the users' experience of the indoor environment but came to the conclusion that it is not currently possible to use APV's because they are significantly different dependent on municipality and use charged formulations, so instead a pilot test of a recently developed questionnaire has been sent out to the occupants of the case building, that asks questions much in the same way that an APV would (Ejendomsområdet, 2022).

Data acquisition for the perceived indoor environment is a relevant method, to create an overview of how users experience the indoor environment regardless of whether the building can deliver a good indoor environment, or whether the indicators comply with common requirements and standards for a good indoor environment. It is recommended that data from the perceived indoor environment is supplemented with data from measurements or with data from the potential indoor environment (Ejendomsområdet, 2022).

The potential indoor environment is about the prerequisites for a building to provide a good indoor environment i.e., how the rooms are built, and does not consider how they are used. Data acquisition of the potential indoor environment involves registering a number of physical conditions in the rooms through assessments based on a building review (Ejendomsområdet, 2022).

The potential indoor environment is a relevant method for creating an overview of the physical prerequisites that a building has for delivering a good indoor environment, but it is recommended to support it with data of the occupants' experience and measurements, which can provide insights into how the use of the rooms affects the indoor environment (Ejendomsområdet, 2022).

The KPI collaboration focuses the data gathering on a property level, whereby it is data for properties that must be reported for the joint municipal data model and bench-learning tool. The taskforce has decided that it is necessary to either register or measure the indoor environment at room level. An indoor environmental score of individual rooms is therefore the basis for grading on building- and property levels, as illustrated on Figure 1.

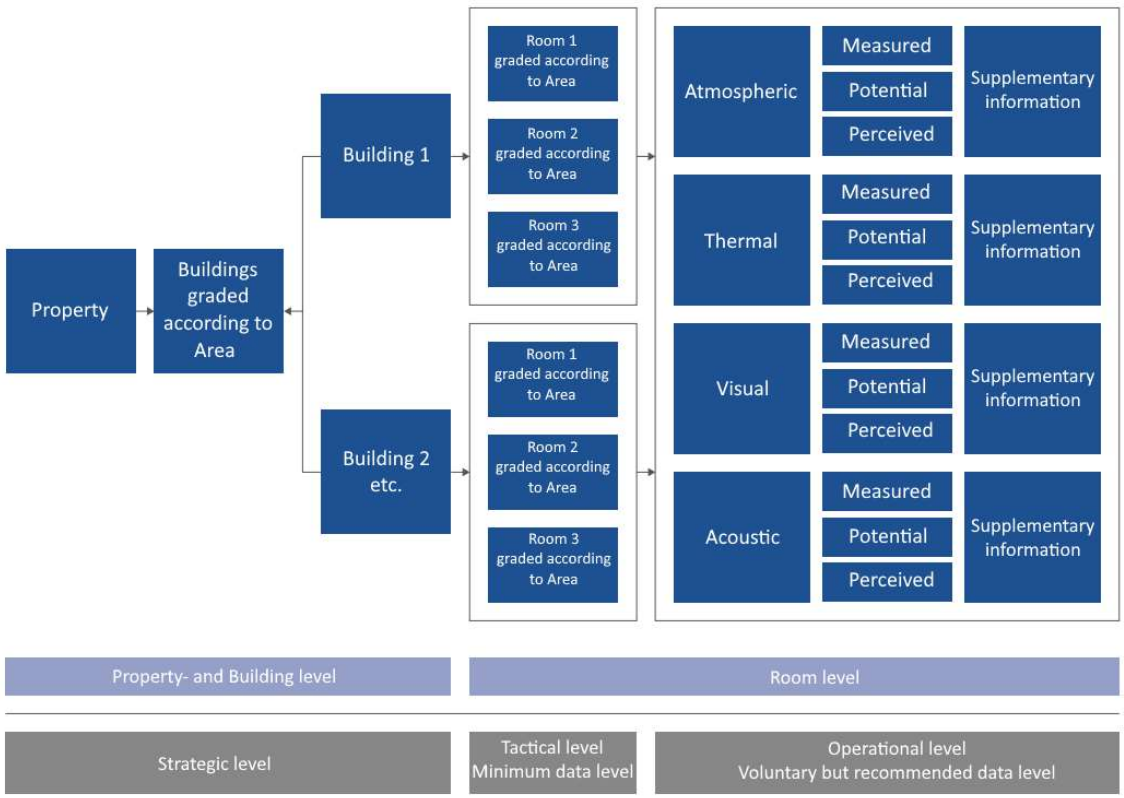

Figure 1: Weight of indicators and methods of grading in KL's IEQ Labels (Ejendomsområdet, 2022)

5 Methodology

In this chapter, the principles behind the methods used to acquire and treat the empirical evidence of this study will be described. The underlaying structure of the study, such as research principles, data collection, -treatment, -validity, and considerations. The limitations of the methodology and possible biases will as well be acknowledged as an extension of the limitation.

5.1.1 Research design

The research design is built upon the comparison of physical measurements and post occupancy evaluations, in this case a pilot test of a questionnaire based on the mandatory workplace assessments (APV). The study seeks to offer insights on the indoor environmental quality and provide a better understanding of how the occupants perceives it. The mandatory APV serves as a valuable data source for assessing the perceived indoor environment and unlocking the potential within the gathered data. However, the data frequently faces issues due to insufficiently constructed questions and discrepancies across different municipalities. The scope of the broader project initiated by Realdania is to find a way of standardizing the questionnaires to get a key indicator on future APV's across all municipalities in Denmark. A standardized key indicator would be very cost effective compared to the costly alternative which would be to always measure the indoor environment. Today there is a lack of a standardized approach for conducting APV evaluations, leading to outcomes that may not be optimally useful in enhancing the indoor environment. KL and Transition ApS suggests that the current approach to APV's encompasses a wide range of buildings with diverse purposes. This complexity makes it challenging to standardize the APV model effectively.

The main objective for the broader project is to create a uniform high quality assessment model to register the IEQ. Specifically, this study focuses on linking the standardized APV's with measured indoor environmental performance data. The methodology of this study includes the development of these standardized APV's and their evaluation against actual environmental conditions in municipal facilities. Therefore, the methodology also includes reflections concerning both types of empirical data.

5.1.2 Participants

Measurements were made within a case building with expectations of indoor environmental issues. Data obtained through measurements or questionnaires analyzed in this study covers Ringkøbing-Skjern municipality and its employees. Ringkøbing-Skjern municipality has made their town hall (from now on called case building) and relevant employees in the building available for the APV study. In total 45 employees participated actively by responding to the questionnaire.

Transition Aps has been responsible for the questionnaire sent to employees and the questions in it. The questionnaire questions are focused on the same criteria as an APV, but with noticeable changes in the questioning technique. Questionnaire participants involved in this study will not be anonymous. For this study, only the names and the rooms in which the employees are working needs to be known to be able to establish a comparison between physical measurements and the results of the questionnaires.

The only concern during the measurement campaign was to not bias the employees since the it was conducted before the questionnaire was sent out. Participants in the questionnaire were not informed about the results, nor purpose of the measurements in advance of the questionnaire.

The participants in the questionnaire were chosen primarily based on their workplace location. This was done to be able to compare results of the questionnaire results with the results from physical measurements.

5.1.3 Data collection

It is crucial to consider the subjective nature of individual perception of the indoor environment, which could introduce an element of uncertainty when evaluating this way. Qualitative empiricism focuses on the special qualities and characteristics of what is studied. The gathered data are usually based on the experiences of people gathered through interviews or observations.

The other dataset used was collected through physical measurements providing objective data of the indoor environmental performance constituting the quantitative data of the study. Quantitative empiricism are usually patterns and evaluations that can be gathered through numerical analysis, statistics, and simulations. The following parameters were measured during the measurement campaign.

- *Indoor air quality:* Long-term measurements of temperature, relative humidity, and CO_2-concentration over a period of 7 weeks.
- *Thermal comfort:* Air temperature, radiant temperature asymmetry, air velocity and relative humidity was measured to calculate the operative temperature.
- *Lighting:* Amount of artificial lighting was measured to estimate whether the office spaces have sufficient illuminance levels.
- *Airborne sound:* Airborne sound between rooms was measured, as well as the reverberation time in an office space.

The measurement campaign in the case building was carried out on the 21st and 22nd of September 2023, long-term measurements were made over the following 7 weeks in 11 different rooms, ensuring that the gathered data is representative for the entire floor. The questionnaire was sent out and data was collected within the first two weeks of November.

5.1.4 Data analysis

As part of the analysis, the measured data and questionnaire data will be compared. The datasets will be analyzed and evaluated independently of each other and subsequently the results are compared. The measured data will be analyzed as the objective evaluation of the indoor environmental performance. These data shows that the actual conditions in the building and evaluation are valuable, but not normally possible to conduct simultaneously with the APV due to the costs.

Questionnaire data will be analyzed as the subjective evaluation of the indoor environmental performance. The questionnaire data in relation to the measured indoor environment makes it possible to evaluate the methods and possibilities of performing an APV.

The study is supposed to bring a new perspective on evaluating indoor environmental performance in Danish workplaces by effectively putting the relation between subjective evaluation and measured data on a numerical form in terms of quality. The data used in this study two datasets will be compared, and the comparison will be the foundation of the analysis.

5.1.5 Considerations

During the measurement campaign several considerations was made regarding the validity of the data outcome. A lot of different measurements were made, some requiring more considerations than others. As mentioned earlier the measurement campaign divides into two different types: spot measurements and long-term measurements. Within both types some measurements required that offices were occupied, and some measurements had to be conducted outside occupation hours.

The measurements were made in the end of September, this might not be the optimal time of the year to perform measurements on temperature, nor relative humidity, since the extremes on these parameters are typically found mid-summer or mid-winter. However extreme periods on these parameters would also be the periods with the lowest occupation density meaning that it would not show the extremes on the CO_2-concentration measurements. According to KL, comfort temperatures should be measured as an average during spring or fall, since it differs significantly during winter and summer.

In the subjective evaluation, the occupants are asked to evaluate the indoor environmental quality over the past year, whereas the frame work of this study does not allow for conducting long term measurements covering a full year.

During the measurement campaign, a mechanical ventilation system called "Airmaster" was installed in the measured rooms, obviously affecting the gathered data from around 4^{th}-5^{th} of October (Airmaster start). This most likely affected the data obtained by the measurements and has also been considered in the evaluation of the responses of the questionnaire.

5.1.6 Data validity

Ensuring the validity of the collected data is crucial to guarantee the accuracy and reliability of the study. Since the measured data is an objective evaluation of the indoor environmental performance, the validity is ensured if the measurements are performed correctly and uncertainties such as season or occupation are considered. Further sources of possible errors are mentioned in *Chapter 6.5*.

Another important consideration made during the measurement campaign was to not establish a bias for the employees by sharing subjective opinions or evaluations of collected data. The questionnaire was sent out in the beginning of November; therefore, it was crucial not to bias the employees in any way leading the participants to respond in a particular way.

It is assumed that participants have a knowledge of normal questionnaire evaluation and that they will provide the desired information through the questionnaire. It is not expected that respondents have expert knowledge about indoor environmental conditions.

5.2 Measurements

In order to verify and validate the subjective perception of the indoor environmental quality in the case building gathered from the APV-based questionnaire, a series of physical measurements evaluating the indoor comfort has been conducted. The measurements have been conducted in relation to the thermal, atmospheric, acoustic, and visual comfort aspects to get the most precise evaluation of the indoor environmental performance.

Thermal comfort covers the estimation of operative temperature, which is important for the health and productivity of occupants, based on expected clothing and activity levels. Atmospheric comfort covers the pollutant levels in selected office spaces measured through CO_2-concentration, which acts as a tracer gas.

Acoustic comfort covers the reverberation time in an office and airborne sound between two office spaces outside occupation hours. The attenuating properties of the construction elements and furniture plays an important role in making sure that noise from colleagues is kept at a minimum. Visual comfort covers the illuminance from artificial lighting in designated office spaces in order to assess whether or not the electrical lighting should be dimmed or brightened.

All measurements were conducted in late September 2023, when the building was assumed to be in regular operation. The measurements are split into two categories, these being spot measurements and long-term measurements.

Spot measurements are all types of measurements, where test setup and execution can be done in less than a day and the result of the measurement arrives quickly. Long-term measurements are usually performed with discrete equipment that measures several indoor environmental quality parameters for a period of more than one full week in order to deliver a detailed picture of the average indoor environmental performance in individual offices as well as on the entire ground floor. Occupation patterns and building activity can also be analyzed in more detail from the results of long-term measurements. The locations of the various measurements are shown in Figure 2 and Table 2.

Figure 2: Floor plan of the case building with measurement locations added

Table 2: Explanation of physical measurements and room numbers

Indicated by	***Measurement***	***Room number***
	IC-Meters – Long-term	79 + 80 + 86 + 100 + 101 + 107 + 109 + 114 + 121 + 124 + 125
	Airborne sound – Spot	124 + 125
	Artificial lighting – Spot	79 + 114
	Assessment of operative temperature – Spot	86 + 125

5.2.1 Expectations

The purpose of the broader project initiated by Realdania is to establish a baseline for the municipalities to be able to collect valid and uniform data for the occupants' experience of the indoor environmental quality, using the APV's, across municipalities and municipal buildings.

The municipalities see a separate challenge for recording the perceived indoor environment in that the cause of the recorded indoor environmental comfort concerns must often be found in psychological unhappiness as opposed to problems related to the indoor environmental performance (physical unhappiness). Existing models for APV's are therefore challenged by the absence of a more in-depth qualitative understanding of the difference between these problems.

An anthropological approach represents such a qualitative understanding that can ensure that a better distinction is made between physical and psychological unhappiness. Since the questions contained in the APV are rarely prepared by experts within the field of indoor environmental quality and qualitative methods, the questions are typically not specific and in-depth enough, which produces incomplete results from the analysis. In addition, there is a lack of a uniform minimum level of questions for the municipalities.

Measuring the actual indoor environmental performance in the case building, yielding quantitative data, and comparing it with the results from the questionnaire can provide valuable insights of whether the indoor environmental comfort concerns perceived by the occupants in the building exists or this discomfort could originate from a subjective and psychological point of view.

6 The measured indoor environmental quality

In order to assess the current indoor environmental conditions in the case building, it is important to have a firm understanding of the activities going on, and the various indoor comfort parameters and aspects present. To make the results comparable, the measurement locations inside the building are chosen based on the physical location of the respondents in the questionnaire. This is done to assure that the measured and perceived indoor environment are performed for the same conditions. In this chapter, the selection process of the designated office spaces, as well as the setup, results, and evaluation of each measurement covered in *Chapter 5.2* will be elaborated.

6.1 Acoustic comfort

6.1.1 Setup

The rooms chosen for the acoustic measurements in the case building are two adjoining office spaces: Room 124/125, shown on Figure 2 with light blue polka dots, separated by a partition wall with a door, as well as Room 86, which houses the citizens advice.

To investigate whether the ability to work in either of the offices is or is not impaired by activities in the adjoining office, an airborne sound measurement has been conducted. Airborne sound measurements consist of four stages with varying setups. For this measurement, Room 124 will be the source room of the sound and Room 125 will be the receiving room for the sound.
The four stages are explained in Table 3.

Table 3: Stages when conducting airborne sound measurements

Measurement type	***Description***
L1	Average sound pressure level in source room.
L2	Average sound pressure level in receiving room.
B2	Background noise in receiving room.
T2	Reverberation time in receiving room.

The equipment used to conduct the measurements consists of two microphones designed for high-precision measurements and architectural acoustics (Brüel & Kjær, 1942), as well as a sound source, which in this case is a omnidirectional loudspeaker designed to measure sound insulation and perform measurements related to room acoustics (Brüel & Kjær, 1942).

The four different speaker- and microphone positions are presented in Figure 3 to Figure 6 On the figures, S_X indicates speaker positions and M_X indicates microphone positions.

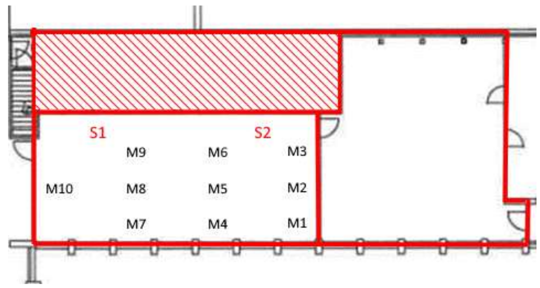

Figure 3: Microphone and speaker positions for L1 (source room)

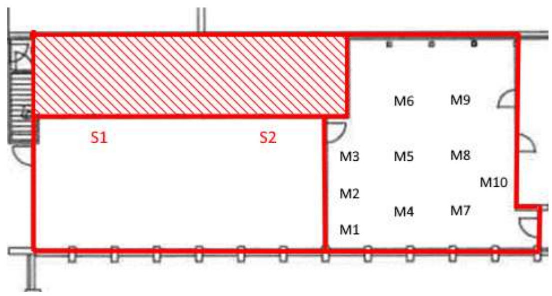

Figure 4: Microphone and speaker positions for L2 (receiving room)

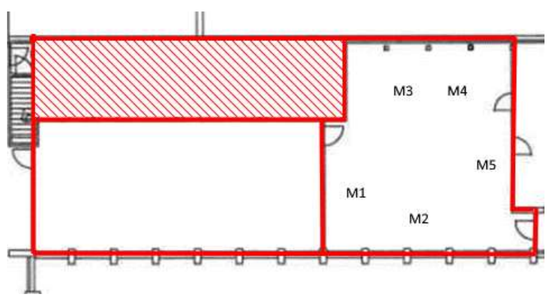

Figure 5: Microphone and speaker positions for B2 (receiving room)

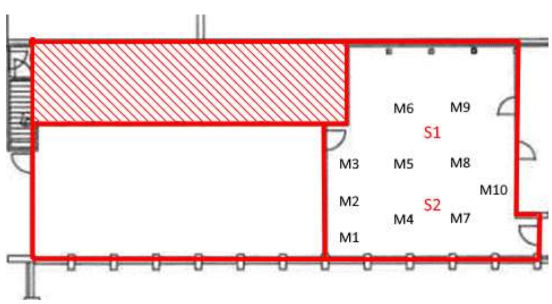

Figure 6: Microphone and speaker positions for T2 (receiving room)

When measurements related to acoustic comfort are carried out, the main objective is to identify whether a room has satisfying attenuating properties so that occupants can avoid talking loudly or causing sound in the room to be perceived as muffled. The background noise is also a good parameter to measure, since low frequency sounds from traffic noise and mechanical ventilation systems are some of the main culprits when it comes to low frequency sounds between 100 and 200Hz. The results from the measurements have been plotted into Figure 7 and Figure 8. All measured data and equipment can be seen in *Appendix A – Acoustic comfort measurement results*.

6.1.2 Results

Airborne sound refers to the sound pressure reduction that occurs when a sound is transmitted from one room to another. For example, speech that can be heard on the other side of a partition wall is the result of the airborne sound that is transmitted through that wall and gets attenuated. (Petersen, et al., 2014)

The ability of construction elements to insulate against airborne sound transmission between two rooms in a building are indicated as an index number in the form of the weighted sound reduction index, R'_w [dB]. Requirements for airborne sound insulation are usually expressed as requirements for R'_w, calculated on the basis of measurements in 16 octave bands in the frequency range 100 to 3150Hz (Petersen, et al., 2014). The reduction index for field measurements between two rooms is calculated according to Equation 1:

Equation 1: Calculation of the reduction index for field measurements between two rooms

$$R'_w = L_1 - L_2 + \log_{10}\left(\frac{S}{A}\right) [dB]$$

Where:

L_1 is the average sound pressure level in the source room [dB].

L_2 is the average sound pressure level in the receiving room [dB].

S is the area of the separating construction element [m^2].

A is the equivalent absorption area in the receiving room [m^2].

$A = 0,16 * V/T$, where V is the volume of the receiving room [m^3] and T is the reverberation time in the receiving room [sec] (Petersen, et al., 2014).

On Figure 7, the blue graph shows the weighted sound reduction index. For office buildings, the Danish building regulations requires that the weighted sound reduction index should be no higher than 35dB across all the aforementioned frequencies, illustrated by the orange dashed line. Every dot on the blue graph represents a new octave band. (Bolig- og Planstyrelsen, 2018)

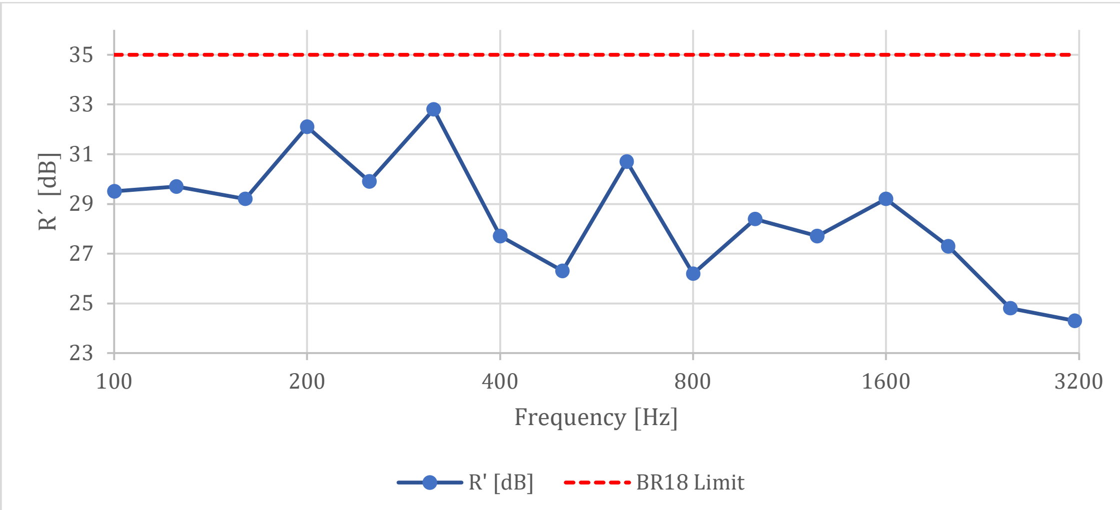

Figure 7: Measured weighted sound reduction index

When the omnidirectional loudspeaker starts emitting sound, the sound coming directly from it is heard first. Inside a room, the indirect sound will then be heard from where the direct sound is reflected off of the walls.

Reverberation is sound that bounces back many times from the surfaces of a room after the loudspeaker is switched off. The reverberation depends on the size of the room and the acoustic properties of its surface materials. As a room increases in size, the time between the individual bounces also increases, and therefore the reverberation is audible for longer time than in a smaller room with similar surface materials. (Petersen, et al., 2014)

The direct sound decreases with distance, but the reflected sound is approximately the same throughout the room. Reverberation time is defined as the time it takes in seconds from a sound source is stopped until the sound pressure level has decreased by 60dB. In practice, due to background noise, reverberation curves that long can rarely be obtained, and therefore the reverberation time for this measurement is determined over a range of 30dB instead. (Petersen, et al., 2014)

As part of the airborne sound measurement, the reverberation time for the receiving room was also measured, shown on Figure 8, where the blue graph is the measured reverberation time at a certain frequency. The orange dashed line illustrates the requirement of max 0,6sec given by the Danish building regulations for offices, meaning that it should take no longer than 0,6sec from when a sound source is stopped to get attenuated by 30dB. Every dot on the blue graph represents a new octave band.

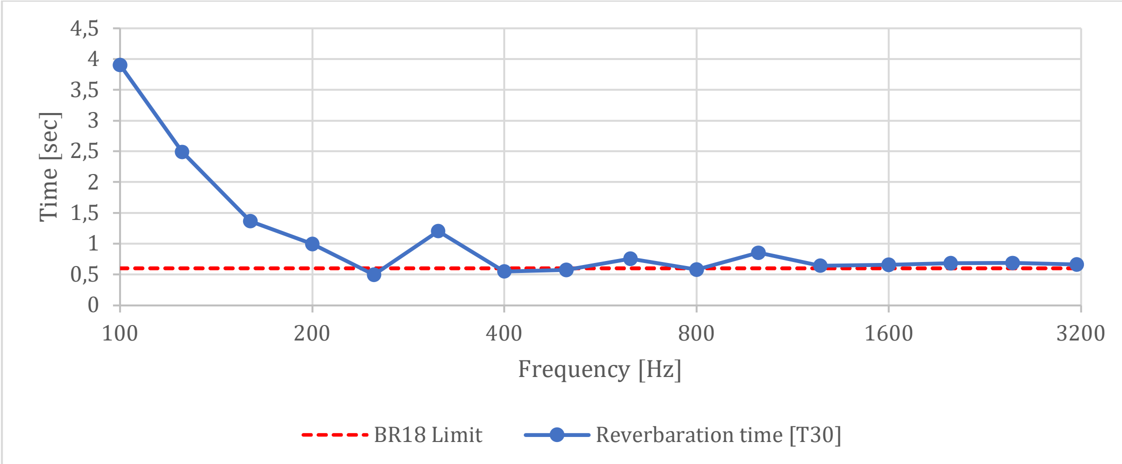

Figure 8: Measured reverberation time

6.1.3 Evaluation

As mentioned before, the weighted sound reduction index is an expression of how good or bad a construction element like a partition wall is at absorbing airborne soundwaves. In order to obtain this value however, several measurements have to be performed across a wide range of frequencies, depending on the size of the room. The measurement results are shown in Table 4.

Table 4: Results from the airborne sound measurement

Room no.	***Min/max L1 [dB]***	***Min/max L2 [dB]***	***Min/max B2 [dB]***	***Min/max T2 [sec]***	***Min/max R'$_w$ [dB]***
124	65,56 / 74,46				
125		33,64 / 50,47	7,01 / 27,09	0,5 / 3,9	24,3 / 32,8

In accordance with the measurement, the noise levels in Room 125 varied between 24 and 33dB. The partition wall between Room 124 and 125 are complying with the minimum requirements stated within BR18 and therefore no further action is required in soundproofing between the office spaces.

The BR18 requirement for reverberation time has been exceeded primarily in the low frequencies from 100 to 315Hz. In the higher frequencies, the reverberation time matches that of the BR18 requirement pleasantly, with only minor breaches of 0,7sec at 630Hz and 0,85sec at 1kHz.

While the measurements show that the reverberation time in the lower frequencies are not complying with BR18 limits, subjective observations while inside the offices yielded acceptable acoustic comfort. The offices also had carpet for flooring, ceiling panels with attenuating properties, and lots of furniture that would be able to absorb sound waves, reducing the reverberation. It should be noted that relatively large window sections are common in the building, which increases reverberation. This can clearly be heard out in the hallway, where the floor is also made of tiles increasing reverberation even further.

According to KL's IEQ labels the acoustic grading are given based on the reverberation time. To get a top score of 1, the reverberation time should be less than 0,4 seconds. The measurements performed in the case building shows a reverberation time equal to a grading of 5 until reaching 315Hz, after this the reverberation time are decreased to around 0,5 seconds. If the measurements performed were to be graded, the grade would be 2-3 but at the lower frequencies it would exceed a grade of 5.

6.2 Thermal comfort

6.2.1 Setup

The measurements needed for estimating the operative temperature has been conducted in Room 86 and 125 of the case building, shown on Figure 2 with green polka dots. Room 86 is used for citizen service and Room 125 is an ordinary open office space with 7 employees, each with their own desks. The exterior wall is facing southwest for Room 86 and for Room 125, the exterior walls are facing east and west. The measurement probes used with an indoor climate analyzer is set up to measure air temperature and irradiant temperature from the surfaces. An anemometer is used to measure air velocity and an IC-meter has been used to measure relative humidity.

The parameters used to determine the operative temperature are measured twice at each location in the chosen room to find the temperature difference between ankle height and head height of a seated person. Ankle height and head height is measured 0,1m and 1,1m above the floor respectively. The change in temperature between these values should deviate no more than 3°C.

6.2.2 Results

On Figure 9 a schematic of Room 86 is shown. Three measurement points have been chosen and indicated by M_x. One close to a door, one in the middle of the room, and one close to a window. Table 5 shows the measured results in each location.

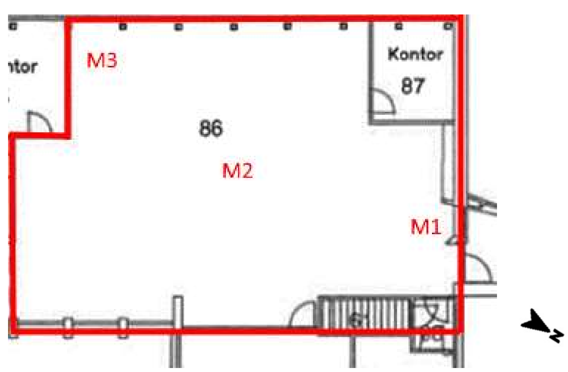

Figure 9: Measurement locations for assessing the thermal comfort in Room 86

Table 5: Measurements on thermal comfort in Room 86

Location	Position height	Air temp. [°C]	Radiant temp. [°C]	Air velocity (avg) [m/s]	Relative humidity [%]
M1	Head	23,5	22,9(i) | 22,8(i) 23,6(i) | 24,3(i) 23,0(f) | 23,8(c)	0,01	58%
	Ankle	23		0,01	
M2	Head	23,8	-	0,02	
	Ankle	23,6	-	0,02	
M3	Head	23,7	22,0(e) | 22,9(e) 23,5(i) | 22,4(i) 22,8(f) | 22,8(c)	0,02	
	Ankle	23,2		0,02	

On Figure 10 a schematic of Room 125 is shown. Like the previous measurement, three measurement locations have been chosen close to a door, centrally located and close to a window. Table 6 shows the measurements in each location.

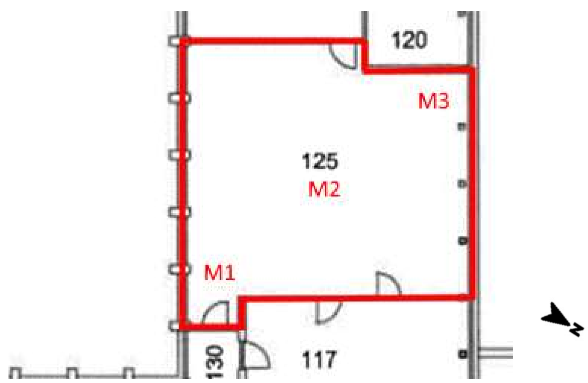

Figure 10: Measurement locations for assessing the thermal comfort in Room 125

Table 6: Measurements on thermal comfort in Room 125

Location	Position height	Air temp. [°C]	Radiant temp. [°C]	Air velocity (avg) [m/s]	Relative humidity [%]
M1	Head	22,2	22,6(e) | 22,2(e) 22,4(i) | 22,5(i) 22,3(f) | 22,0(c)	0,18	51%
	Ankle	21,9		0,18	
M2	Head	22,8	-	0,05	
	Ankle	22,6	-	0,05	
M3	Head	22,7	22,6(e) | 22,2(e) 22,8(i) | 23,4(i) 22,3(f) | 22,8(c)	0,02	
	Ankle	22,7		0,02	

6.2.3 Evaluation

From the measurements conducted in Room 86 and 125, and from knowing the activity level and insulation value from clothing, an optimal operative temperature for the rooms can be estimated. After the measurements have been conducted, the operative temperature can be calculated.

Using the indoor comfort standards and guidelines from the Danish Standards Foundation it can be assumed that the activity- and clothing level in the case building is 1,2met and 1,0clo on Figure 11. When plotted into the figure, a theoretically optimal operative temperature can be assessed.

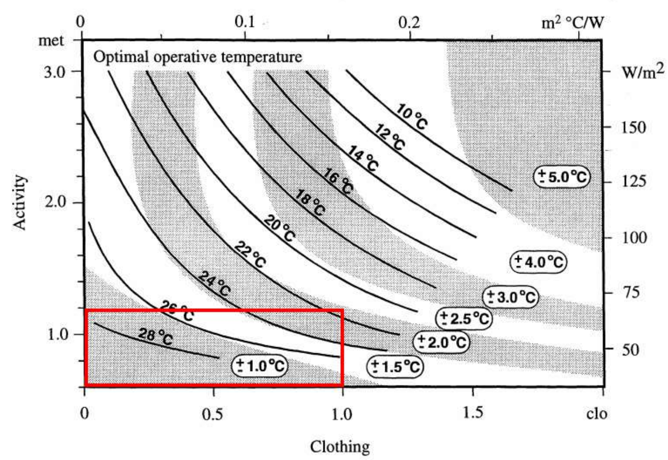

Figure 11: Relation between activity-, clothing level, and operative temperature (Dansk Standard, 1995)

It is shown that the optimal operative temperature is app. 21°C with a deviation of no more than ±2,0°C allowed. Using 21°C as the ideal temperature, a zone between 19 and 23°C is established for both rooms.

In order to calculate the mean radiant temperature, Equation 2 is used:

Equation 2: Calculation of mean radiant temperature

$$t_r = \frac{t_{yd} * a_{yd} + t_{in1} * a_{in} \quad + t_{in} \quad * a_{in2} + t_{in3} * a_{in3} + t_g * a_g + t_l * a_l}{\sum a}$$

Where t [°C] is the radiant temperature and a [m^2] is the area of the surface measured. The meaning of the abbreviations is presented in Table 7.

Table 7: Explanation of the abbreviations used in Equation 2

Abbreviation	***Meaning***
yd	Exterior wall
in	Interior Wall
g	Floor
l	Ceiling

The average values of the of the thermal measurements are shown in Table 8 and will be used primarily for evaluation.

Table 8: Results from thermal comfort measurements

	Mean radiant temp. [°C]	***Min/Max radiant temp. [°C]***	***Avg. air temp. [°C]***	***Min/Max air temp. [°C]***	***Avg. air velocity [m/s]***	***Min/Max air velocity [m/s]***
Room 86	23,11	22,0 / 24,3	23,46	23,0 / 23,8	0,016	0,01 / 0,02
Room 125	22,44	22,0 / 23,4	22,49	21,9 / 22,8	0,083	0,18 / 0,02

Since the absolute temperature deviation between the radiant- and air temperature is below 4°K and the air velocity is less than 0,2m/s in both cases, a simplified way of calculating the operative temperature is used, described by Equation 3:

Equation 3: Simplified calculation of the operative temperature

$$t_o = \frac{t_{air} + t_r}{2}$$

Using this equation, the operative temperature for Room 86 and 125 is found to be 23,3°C and 22,5°C for both rooms respectively. Based on the analysis of these measurements, it is clear that only the operative temperature in Room 86 is exceeding the boundary by 0,3°C while the operative temperature in room 125 is 0,5°C below the upper limit

$$t_o(86) = 19 < 23{,}3 < 23℃$$
$$t_o(125) = 19 < 22{,}5 < 23℃$$

The total influence on the indoor environmental quality as a result of the parameters described above can be evaluated by means of the PMV index (PMV = Predicted Mean Vote). The index predicts the mean value of how a large group of people is expected to feel about the thermal indoor environment.

The quality of the thermal environment can be expressed by means of the PPD index (PPD = Predicted Percentage of Dissatisfied) indicating the predicted percent of dissatisfied people. The relation between PMV and PPD can be seen from Figure 12:

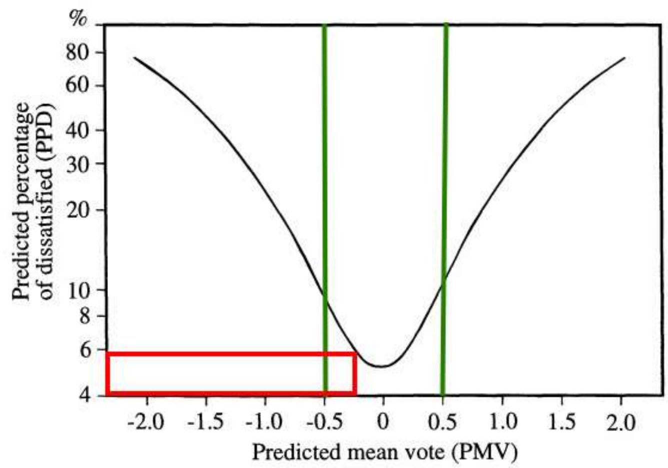

Figure 12: Relation between PMV and PPD indices (Dansk Standard, 1995)

If the thermal indoor environment shall be considered acceptable, the following boundary is normally used: $-0{,}5 < PMV < 0{,}5$, which means that less than 10% is predicted to be dissatisfied with the general thermal indoor environment. This boundary is marked with green borders on Figure 12.

For this assessment of the thermal indoor environment, the comfort criteria has not been exceeded, as it is shown with the red square, since the PMV is app. -0,3 yielding a PPD of 6%

It has not been possible to evaluate the draft rating, because the air velocity measurements are effectively 0m/s, so the percentage dissatisfied is assumed to be close to 0, since almost no air movement could be measured inside the rooms.

According to KL's IEQ grading scale, the building is graded based on the temperature, and how much it fluctuates up or down from 22°C. If the thermal comfort were to be graded based on the measurements conducted in both offices the score would be a grade of 1-2. The grade of 1 is given for temperatures of 22°C (±1°C) and the grade of 2 is given for temperatures of 22°C (±2°C).

6.3 Visual Comfort

6.3.1 Setup

As shown on Figure 2 and Table 2, visual measurements of artificial lighting were made in Room 79 and 114 illustrated with the dark blue dots. Both rooms measured are used as offices and has several office desks. Measurements were made in a grid pattern, where the maximum distance between points were calculated using Equation 4.

Equation 4: Calculation of maximum distance between measurement points

$$p = 0{,}2 * 5^{\log_{10}(d)}$$

Where:

p is the maximum distance between measurement points.

d is the largest of either the length or the width of the room where measurements are conducted.

The number of points required to perform the measurement can then be calculated according to $\frac{d}{p}$. To eliminate daylight contributions, measurements on artificial lighting were made after sunset. To ensure the accuracy of the measurements, a baseline measurement was made with all artificial lights turned off. This step was taken to confirm that external light sources, such as streetlights or electrical equipment, did not influence the measurements. The results of the baseline measurement verified that no external light sources were contributing to the levels of artificial lighting.

6.3.2 Results

The measurements were made in a grid covering as much of the operative zone (office desks) as possible in each of the 2 measured rooms. As seen on Figure 13, workplaces are getting above 300lux in all measurements except from two measurements in Room 79 and one measurement in Room 114. Both rooms have measurement points deviating from the recommended level of lighting.

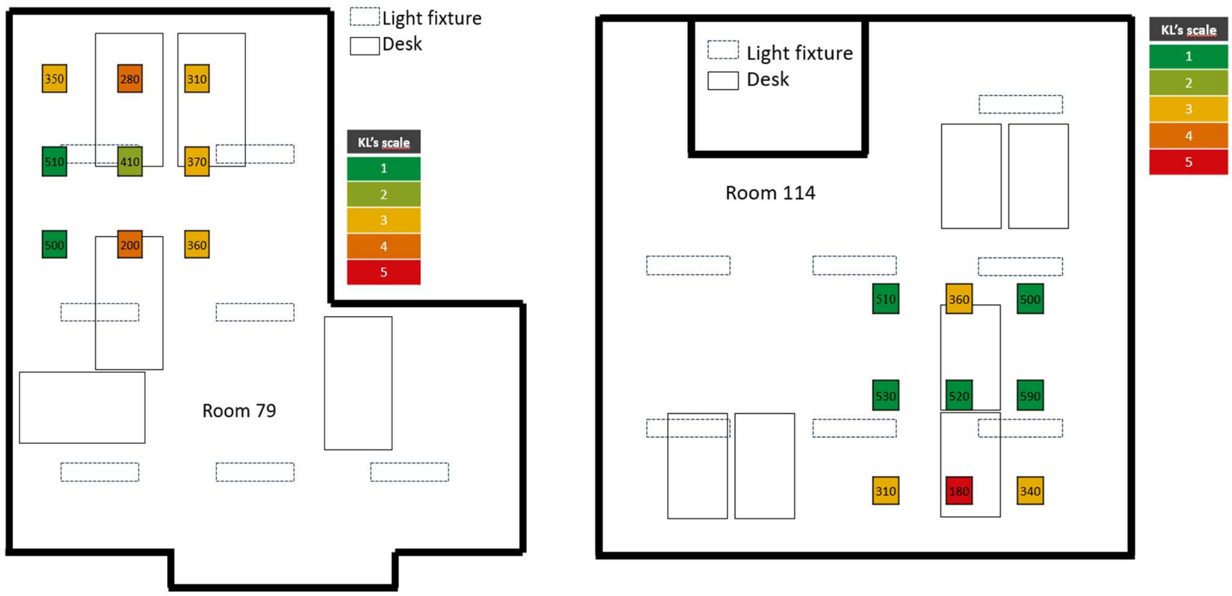

Figure 13: Results from measurements on visual comfort in Room 79 and 114

6.3.3 Evaluation

Including the expected daylight contributions for most of the year, the measured results are considered sufficient in both rooms according to DS/EN 12464-1. Even though two measurements in Room 79 and one measurement in Room 114 are below 300lux, it is assumed that the natural daylight will compensate for the deficient illuminance levels, thereby achieving the required level of lighting. Furthermore, measurement points with insufficient lighting are not placed on office desks, but between these, meaning that the points are not exactly inside the operative zones.

In KL's grading system, a grade of 1 is given for a lux level of 500 lux, 400-499 is given the grade of 2 and so on. The measurements for both offices are scoring between grade 1-3 and even down to 4 on the measurements conducted on the office tables in Room 79.

6.4 Atmospheric comfort

IC-meters are used to evaluate crucial parameters in the indoor environment over an extended period of time. The IC-meters used in this study measures temperature, relative humidity, and CO_2-concentration. Proper regulation of the three factors mentioned is vital in relation to maintaining a comfortable and healthy indoor air quality.

By implementing IC-meters in the case building it has been possible to strictly monitor and log the conditions on the parameters mentioned over a period of 7 weeks. The IC-meters measures and logs data every 5 minutes.

The weather is an important factor when analyzing atmospheric comfort, since the temperature and weather affects the indoor environment a lot. During the measurement campaign we did not see very big fluctuations, only around the 2nd of November where the temperature dropped for one night. In general, the temperature slowly decreases throughout the measurement period, as seen on Figure 14.

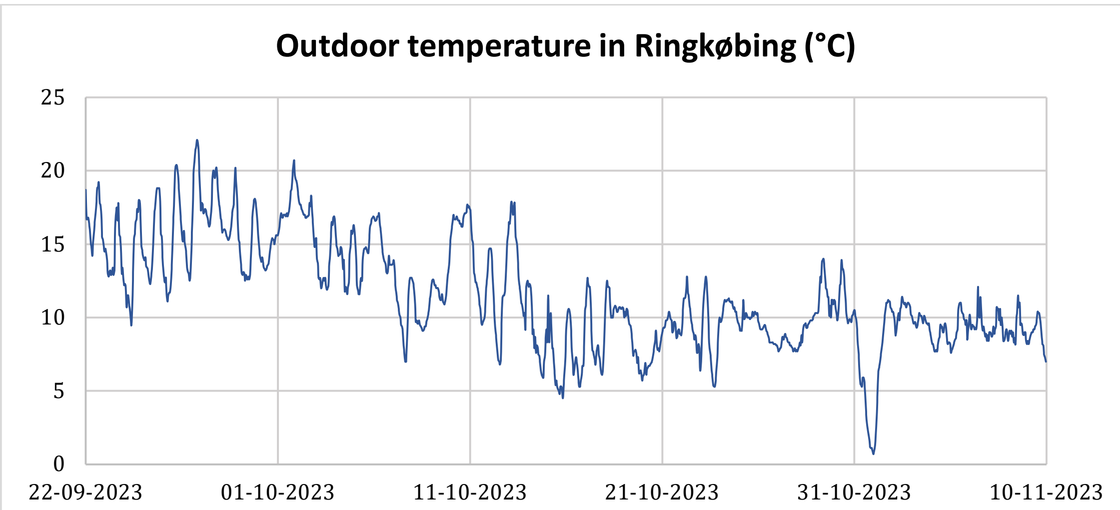

Figure 14: Outdoor temperature in Ringkøbing from September to November 2023

6.4.1 Setup

IC-meters were placed in rooms marked on Figure 15 and Table 9 and carried out in accordance with IC-meters guides. IC-meters are placed at least 1,2m above the floor on interior walls and at least 1,5m away from heaters and seating areas. IC-meters will, when connected, measure and log data concerning the indoor environment. The IC-meters needs 7 days to calibrate the CO_2-sensor and it is important that rooms with IC-meters are not constantly occupied. A total of 11 IC-meters were placed throughout the case building. Rooms were chosen based on the janitors' knowledge about complaints etc., but also with the questionnaires in mind, meaning that IC-meters should cover as many employees as possible.

During the measurement period, Airmasters were put into use in most of the rooms measured, affecting the quality of the indoor environment. Rooms where Airmasters were installed is marked on the graphs indicating the date where the Airmasters was put into use.

Figure 15: Floor plan of the case building with IC-meter locations added

Table 9: IC-meters and the respective rooms they were placed in

AAU number	BoxID	Airmaster (Yes/No)	Placement (Room)
2	b8d04ff2	No	80
3	872d5688	Yes	125
6	30426fd2	Yes	124
8	4d14bef3	Yes	109
13	8e9b41b0	Yes	86
14	c9ec1032	Yes	79
17	eb72abcc	Yes	107
19	13fb89ce	Yes	101
21	b9b44de9	Yes	114
24	fbd2c3d3	Yes	100
26	3f0576d0	No	121
28	4df8bcea	Yes	86

6.4.2 Results

Measurements were conducted and logged for 7 weeks in total (22nd of September to 10th of November 2023). Unfortunately, the period is not covering the summer- nor winter season where one could expect to see the extreme fluctuations on the relative humidity and the temperature, but the measurements provides a good indication of the indoor environment. Additionally, the conditions were also measured on the date where the questionnaires were being tested in the case building.

In this chapter the results from the IC-meter measurements will be discussed. All the rooms monitored shows a consistently stable CO_2-concentration, as well as relative humidity and temperature. As shown on Figure 16 the optimal relative humidity level is between 40-60%.

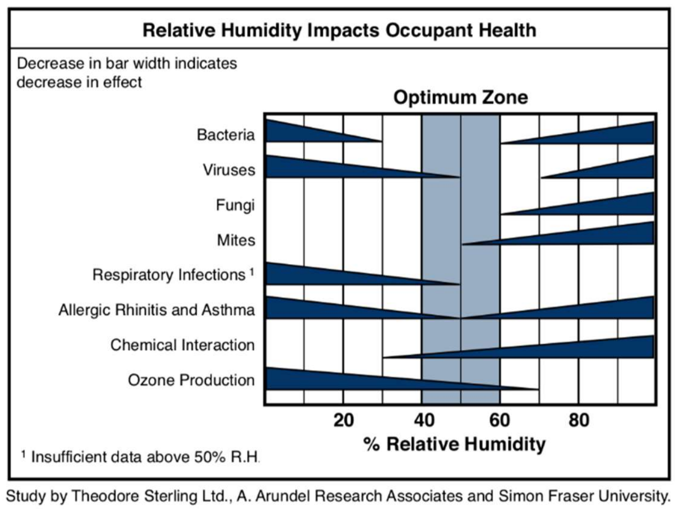

Figure 16: Relative Humidity impacts on occupant health

CO_2-concentrations remain within acceptable limits, despite minor sporadic spikes above 1000ppm, which are brief. Illustrated on Figure 17 for Room 80, this room experiences the largest fluctuations on all parameters, the CO_2-concentration rise above 1000ppm daily, sometimes reaching up to 2500ppm. Notably, Room 80 is a single-occupancy office that does not utilize an Airmaster.

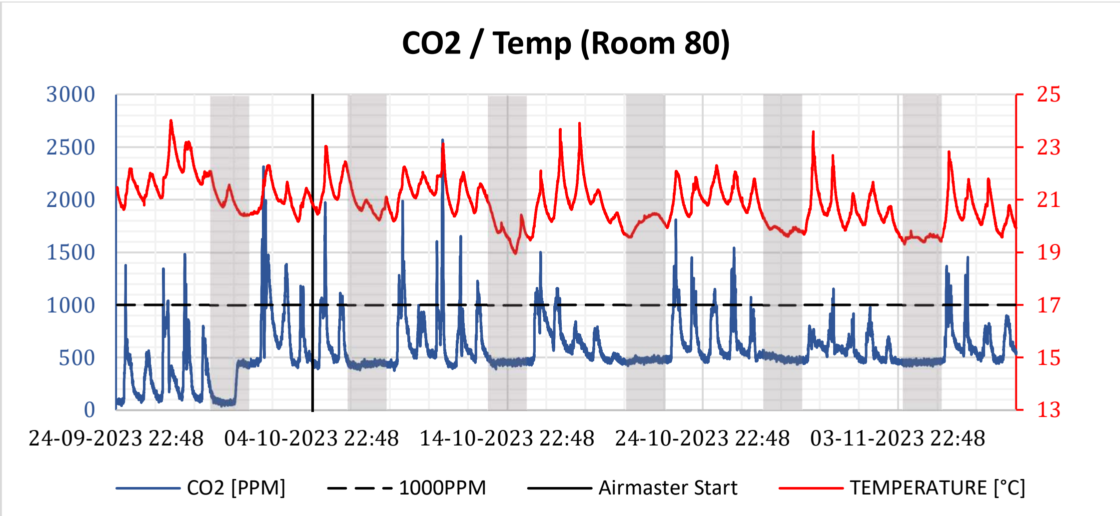

Figure 17: CO_2 and temperature measurements in Room 80

In general, all measurements registered shows numbers around acceptable levels, even though there are some fluctuations above 1000ppm on the CO_2, it levels out when the occupation is low. As seen on Figure 18 the Airmaster are put into work around the 4th of October and the general level of relative humidity decreases from this date. The drop of the relative humidity could also be caused by the outdoor temperature dropping slightly from this date as seen on Figure 14.

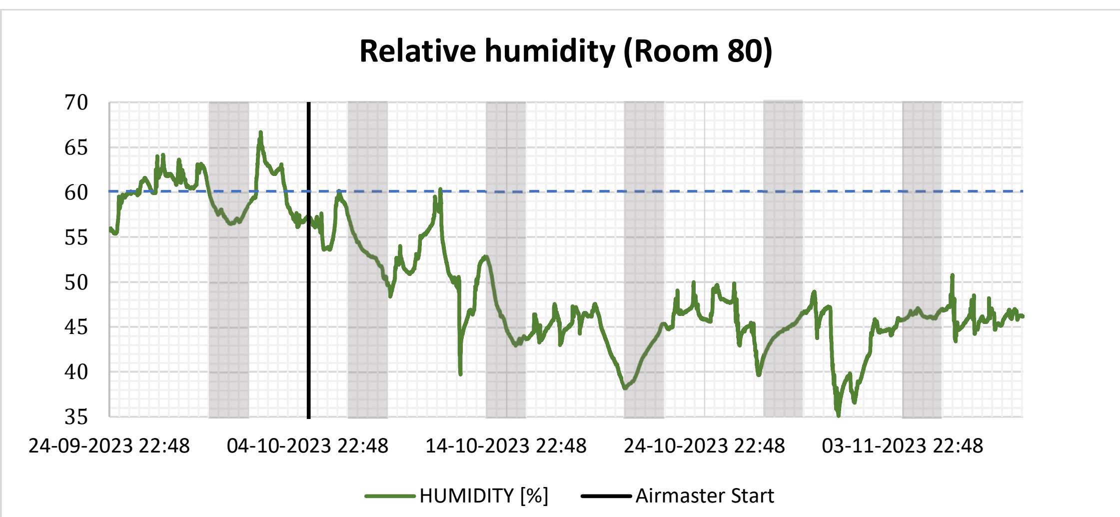

Figure 18: Relative Humidity measurements in Room 80

The impact of the Airmasters can as well be seen on the temperature and CO_2 measurements conducted. Before starting the Airmasters, the CO_2-concentration in Room 124 shown on Figure 19 often increased to above 1000ppm, and shortly after starting the Airmasters, these spikes are eliminated.

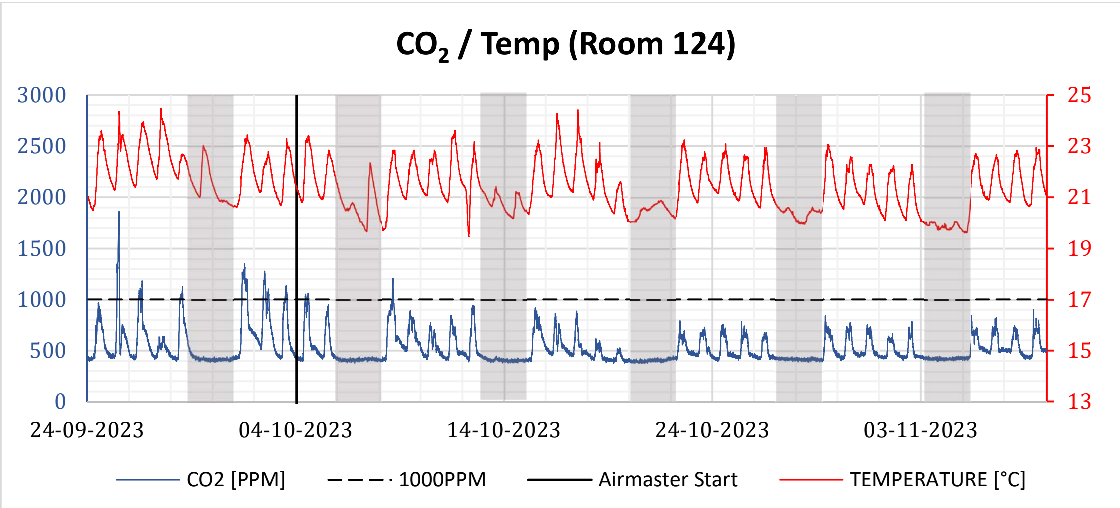

Figure 19: CO_2 and temperature measurements in Room 124

6.4.3 Evaluation

Considering the indoor environment based on the long-term measurements conducted with IC-meters, the indoor environmental quality is overall acceptable. It is seen on Figure 19 that CO_2-concentration are below the recommendation of maximum 1000ppm most of the time. Fluctuations in the measured values were observed in all rooms and even though there are several spikes on the CO_2-concentrations, the periods with loads above 1000ppm is so short that it is not concerning. For Room 124 the average CO_2-concentration during the whole measurement period is 527ppm. Noting that this includes all measurements, both on weekends and during night, the CO_2 concentrations are considerably higher during occupation time. Table 10 shows the average CO_2-concentration from 8:00-17:00 in all rooms during the measurement period and these values also determines what IEQ label the room receives. All rooms, except Room 80 has been graded 1, because the average CO_2-concentration is less than 800ppm, while Room 80 has been graded 2, because the CO_2-concentration is between 800 and 1.000ppm.

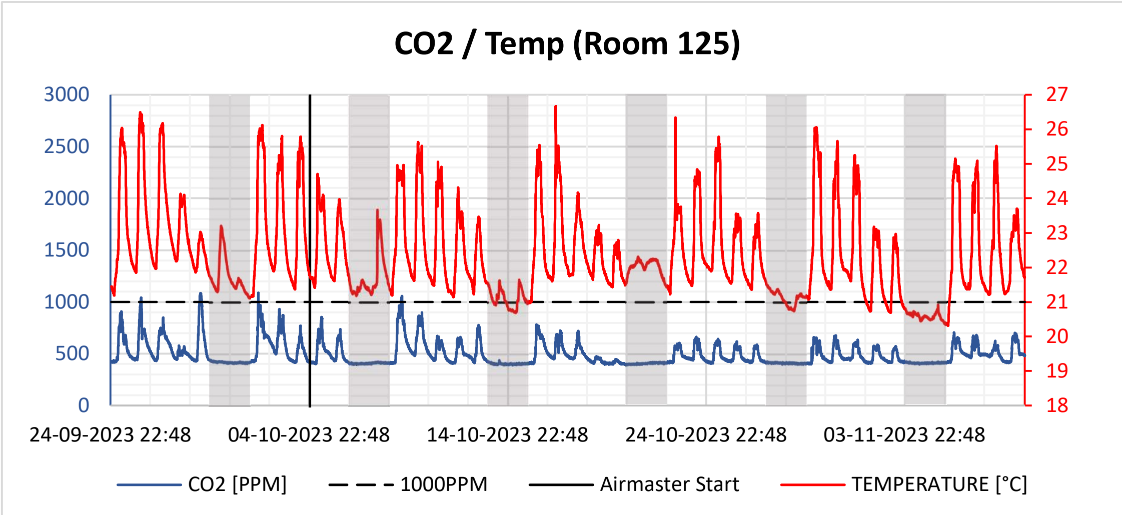

Figure 20: CO2 and temperature measurements in Room 125

The measured temperature remains within a range of 20-23°C in most rooms, even though it spikes to 24-25°C occasionally. As seen on Figure 20 the temperature in Room 125 fluctuates a lot and almost reaches 27°C. This observation is in contrast to the results from the assessment of the operative temperature, which showed an operative temperature of 22,5°C. The temperature varies a bit but remains overall stable during the measurement period. It is worth noting that the measurement period was in October, a time not typically characterized by extreme temperatures or relative humidity levels. This should be considered since; it would not be expected to see extreme levels of relative humidity nor temperature during this period.

Table 10: Average temperature during measurement period during workdays 8:00-17:00

Room number	79	80	86	86	100	101	107	109	114	121	124	125
Orientation	SW	SW	SW	SW	SE	SE	NE	NE	NE	NW	SE	NW
Average CO_2 concentration	662	803	558	644	625	563	657	639	630	738	708	623
Hours >1000ppm	7	60,5	4	12	3	0	15	16,5	4	31	25	5
IEQ Label Atmospheric	1	2	1	1	1	1	1	1	1	1	1	1
Average temperature	22,1	21,4	21,7	22,2	21,5	22,0	23,6	23,4	22,2	23,3	22,5	24,0
Hours >25°C	0	0	0	0	0	0	14	16	0	0	0	67
IEQ Label Thermal	1	1	1	1	1	1	1	1	1	1	1	2

Table 10 provides an overview of the measured rooms within the case building, presenting the average temperatures in each room. The average temperature is based on the measurements performed through the IC-meters on workdays between 8:00-17:00. A key finding is the correlation between orientation of the rooms and the average temperature. Specifically, Room 107(NE) and 109(NE) experienced average temperatures of 23,6°C and 23,4°C. Room 125 had an average temperature of 24,0°C, and 67 hours above 25°C. At the same time, rooms with opposite orientation experienced low average temperatures. Room 80(SW) and Room 100(SE) had average temperatures of 21,4°C and 21,5°C, respectively.

On the contrary it would be expected to see higher average temperatures in rooms with a northern orientation, and lower average temperatures in rooms with a southern orientation. This means that, at least at this time of the year, the high average temperatures cannot be attributed to the solar gains in the building but might instead be attributed to either settings of the heating system or higher people load in the rooms. The findings from the measurements will be compared to the results of the questionnaire to see whether the pattern of each analysis corresponds with each other.

Table 10 also grades each room according to KL's IEQ labels. All rooms, except Room 125 receives the grade of 1 because none of those rooms deviates more than 1°C from 22°C on average during the measurement period. Room 125 receives the grade of 2 because it deviates 2°C from 22°C.

The relative humidity is not at a critical level in any of the measured rooms. It varies between 35-60%, although it occasionally peaks at 70%. The relative humidity is most of the time between 40-60%. After implementation of the Airmaster, the relative humidity in most cases stays at an acceptable level. It should be considered that the outdoor temperature drops from around the same date as the Airmaster are put into work.

All data from physical measurements are presented in *Appendix B - CO_2 and temperature data*.

6.5 Source of error

In this chapter, the various sources of error and possible uncertainties related to the measurement campaign will be described and discussed.

6.5.1 Acoustic comfort

Under the acoustic comfort, one measurement was conducted: the airborne sound reduction. Sources of errors considered under acoustic comfort is background noise disturbing the measurements and inaccuracy in the calibration of the equipment. Both sources of errors mentioned were significant enough to consider when performing the measurements.

Background noise was measured outside occupancy and considered when analyzing the data. To eliminate insecurities of the data validity, the equipment was tested in advance of the measurement campaign to approve the accuracy of the measurements.

6.5.2 Thermal comfort

The primary source of error related to thermal comfort was that the spot measurements were conducted when the seasons were changing (late summer/early autumn) not allowing for evaluation during extreme periods i.e., June or January to assess the thermal comfort during peak summer or winter.

Estimating activity- and clothing levels can be challenging, since the values can change dramatically from person to person. Especially the clothing value, which can vary between 0,75 or 1,2clo depending on what gender is observed and their respective clothing. For this assessment, a value of 1clo was chosen, corresponding to indoor clothing worn by men during the winter i.e., long shirt and trousers, socks, and shoes.

A minor source of error to also consider is the very small air velocity measurements, making a draft rate assessment practically impossible. This could possibly have been solved by bringing a more precise anemometer and extending the measurement period, but in theory one would prefer to have indoor air velocities not exceeding 0,2m/s.

6.5.3 Visual comfort

To eliminate influence from daylight, the measurements were conducted after sunset. After sunset there was still a possibility for influence from streetlight or from equipment within the offices polluting light and disturbing the measurements. To eliminate such errors the light pollution was measured with all artificial lighting turned off. The measurement of the pollution showed that it was practically 0.

Another source of error on the artificial light measurements could be inadequate calibration of the equipment, but since the equipment was tested before the measurement and compared to another lux-meter, this concern is considered irrelevant.

6.5.4 Atmospheric comfort

Some graphs showed extreme fluctuations in the relative humidity at the exact same time each week and only for 2-3 measurement points (a period of 10-15 minutes), as shown on Figure 21. The cause of this was investigated, and seemingly the room were cleaned each week at this exact time of the day. The explanation for this anomaly is assumed to happen, because the cleaning maintenance are happening at that time.

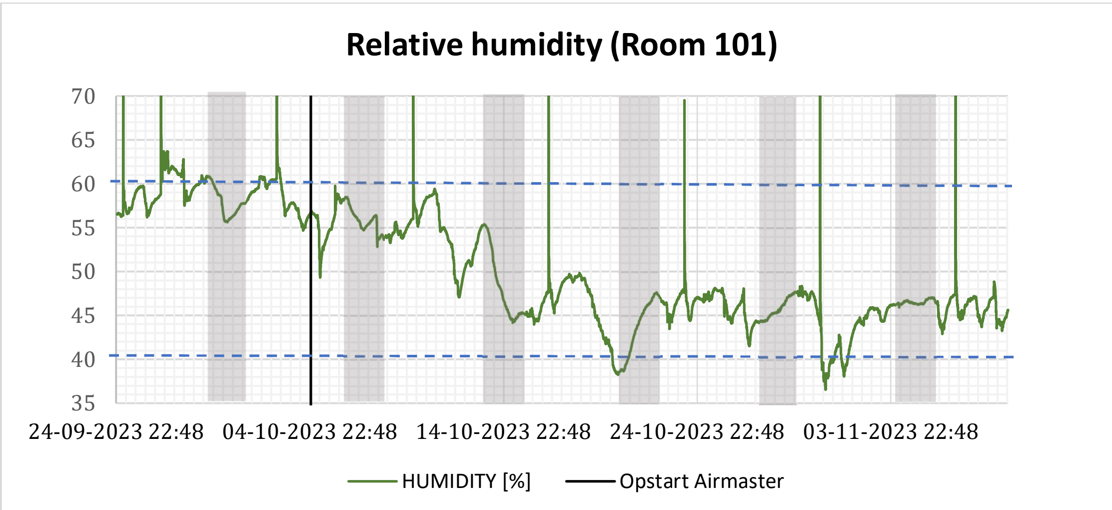

Figure 21: Relative Humidity measurements conducted in Room 101

Furthermore, a source of error is that the CO_2-sensors takes 7 days to calibrate, as shown on Figure 22. From the measurements made, only one IC-meter seems to be measuring incorrectly for the first 7 days.

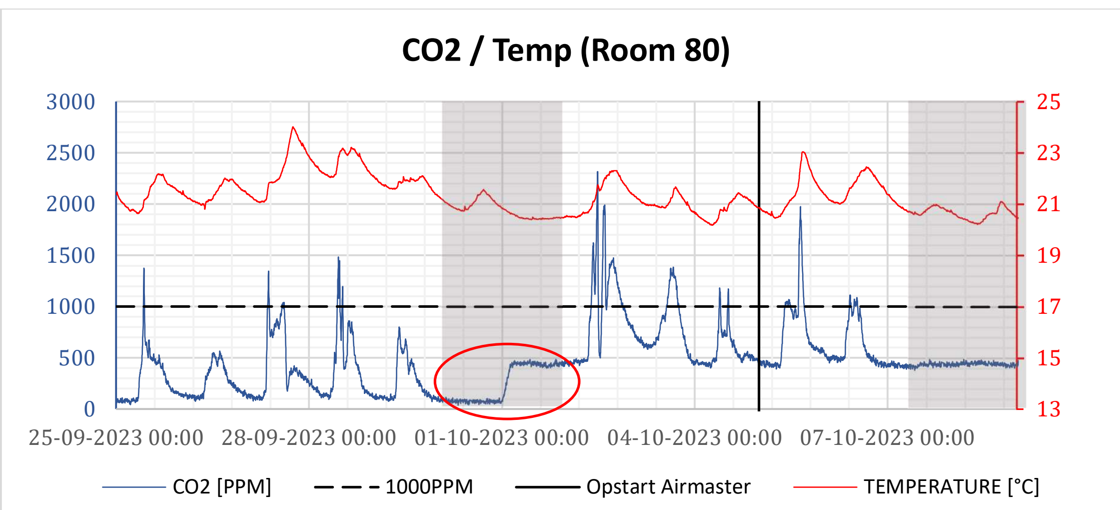

Figure 22: CO_2 and temperature measurements conducted in Room 80

Lastly, one IC-meter was unplugged for a week in the beginning of the measurement period. Because of this, the IC-meter was not measuring nor logging anything for this period.

Besides from the above-mentioned sources of errors, no further critical sources were observed. IC-meters were placed correctly throughout the building, according to instructions provided by IC-meter. All IC-meters were photographed when placed, and the location of the IC-meters were approved to be the same before dismantling.

7 The perceived indoor environmental quality

In Danish municipalities the indoor environment is evaluated as a smaller part of the physical APV. Arbejdstilsynet demands that the APV is delivered written either digital or physical and therefore it is ideal to conduct these as questionnaires (Arbejdstilsynet, 1873). The APV evaluates a wide range of perspectives within workplace environment, in the broad project initiated by Realdania, the focus is primarily on the indoor environmental quality. The broad project aims to improve the quality of the knowledge gained through the questionnaires.

7.1 Evaluation of questionnaire

For the research project initiated by Realdania, Transition Aps developed two variations of a questionnaire examining the perceived quality of the indoor environment. One questionnaire had main questions asking whether the participants experienced issues with thermal, atmospheric, visual, and acoustic comfort. The other questionnaire narrowed down the questions to specific areas within each individual category. The questionnaire was handed out to respondents on the same floor as where the physical measurements were conducted. An overview of the location of participants can be seen on Figure 23.

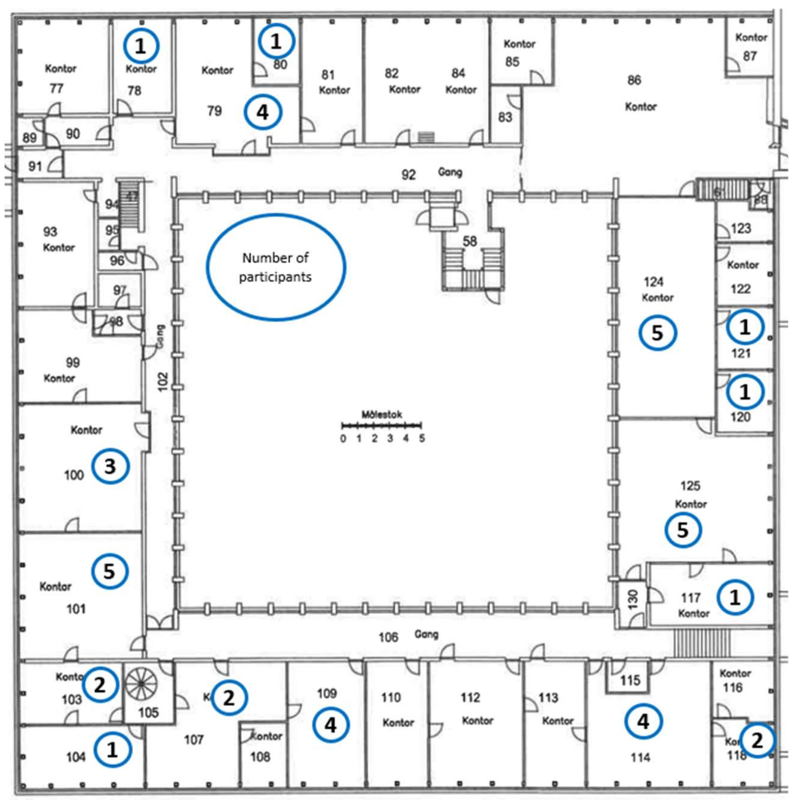

Figure 23: Floor plan of the case building with number of participants and their locations

7.2 Questionnaire results

The results used in this study presents the findings from two distinct questionnaires designed to examine the indoor environmental quality within the areas of the four categories outlined by KL's guidelines. The questionnaires were distributed to employees in the case building, ensuring that the participants were evenly divided at the room level, with each questionnaire covering half of each room’s occupants as far as possible. In the further analysis of the subjective perception of the indoor environment, the two questionnaire results will be considered as one unified dataset. Figure 24 shows the total reported discomfort across all categories in all rooms with respondents. Thermal discomfort constitutes 28 of the 65 reported

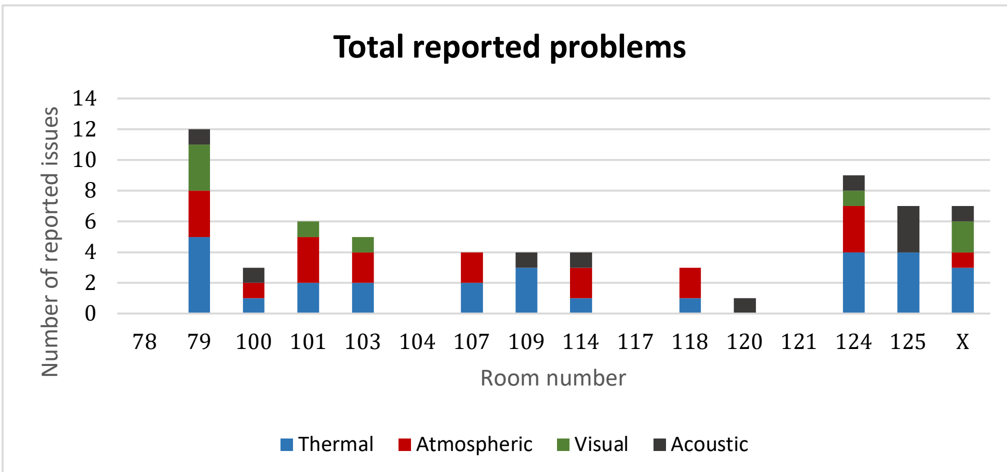

Figure 24: Total amount of reported problems from both questionnaires

cases of discomfort.

7.2.1 Thermal comfort

Thermal comfort was evaluated in the questionnaire, asking the participants if they experienced any problems with drafts, cold or warm temperatures. Overall, the questionnaire responses indicate that the thermal comfort is the most significant concern for the occupants within the case building's indoor environment. In total 28 of the 45 participants or 62% reports problems with the thermal comfort. Furthermore, discomfort is registered in 12 of the 17 rooms used for the analysis.

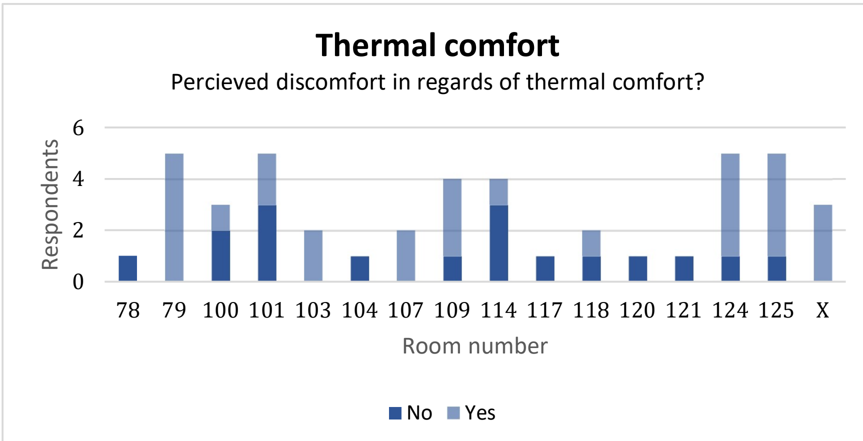

Figure 25: Reported cases of thermal discomfort in the case building

On Figure 26 it is visualized where in the building the thermal discomfort is reported.

Table 11 presents the findings from the questionnaire in regards of thermal comfort. The table presents how many percentages of the occupants are dissatisfied per room. The rate of dissatisfaction per room is varying a lot from room to room, and this observation is interesting since the only difference is the orientation and the occupation load. A complete dissatisfaction is found in Room 79(SW) and Room 124(SE) has a dissatisfaction level of 80%, this suggests an orientation specific thermal comfort issue, which will be further analyzed in the discussion. Based on the percentage of dissatisfied occupants, rooms have been graded according to KL's IEQ labels, where the grade increases as the percentage of dissatisfied increases.

It should also be kept in mind that the questionnaire only has 45 respondents and between 1 and 5 occupants per room this could lead to a distorted view of the rooms (i.e. Room 121 has 1 occupant and 0% dissatisfaction).

Table 11: Thermal dissatisfaction per room in percentage

Room	79	80	86	86	100	101	107	109	114	121	124	125
Respondents	5	0	0	0	3	5	2	4	4	1	5	5
Orientation	SW	SW	SW	SW	SE	SE	NE	NE	NE	NW	SE	NW
Overall thermal dissatisfaction	100%	N/A	N/A	N/A	33%	40%	100%	75%	25%	0%	80%	80%
IEQ Label	5	N/A	N/A	N/A	2	2	5	4	1	1	4	4

Figure 26: Visualization of rooms experiencing thermal discomfort

As it would be expected, the rooms with facades towards north in general reports thermal discomfort. When comparing reported problems between too warm temperatures and too cold, the expectation would be to see a clear pattern and divide between the north and southern part of the building.

Unfortunately, this pattern is not shown very clear. But this could be because the problems are related to other factors of the building, or the fact that there is a big courtyard in the middle of the building, meaning that most rooms has both north and southern facades.

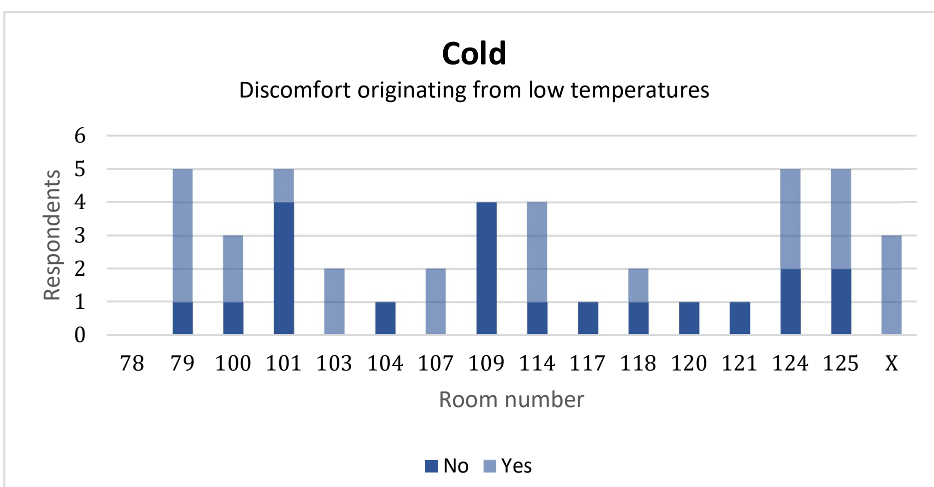

Figure 27: Thermal discomfort originating from low temperatures.

The questionnaire delves deeper into identifying the underlying causes of the issues related to thermal comfort. First of all, the participants are asked to identify in what area of the thermal comfort they experience problems. In the questions asking whether it is too cold or too warm, the question about when the problem occurs shows very clear that these problems in all cases are seasonally dependent.

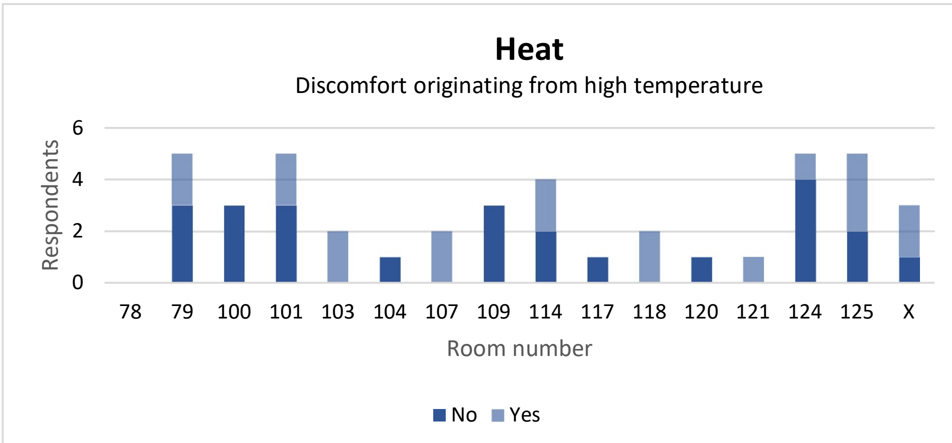

Figure 28: Thermal discomfort originating from high temperatures.

The evaluation of the thermal comfort is more interesting when it comes to drafts. The drafts are evaluated in the same way, with yes/no questions. The response from the questionnaire shows that perceived drafts are fairly spread between the designated origins across all rooms as seen on Figure 29.

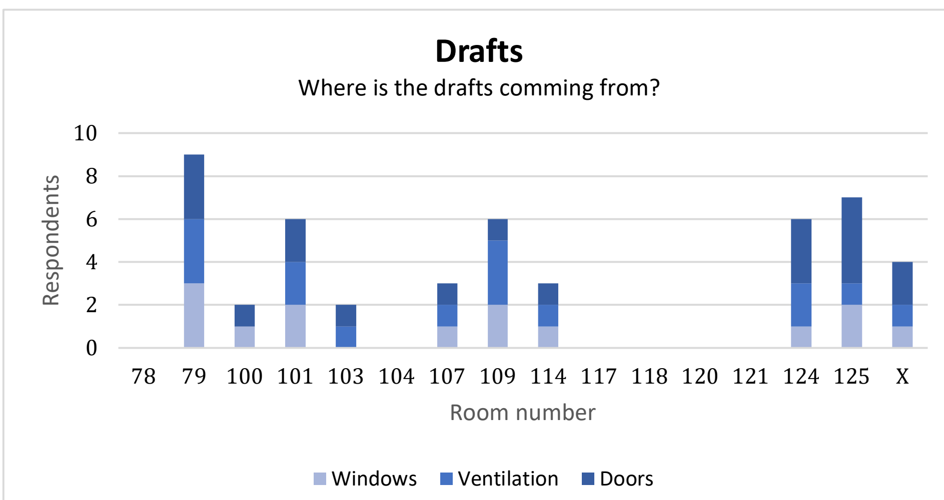

Figure 29: Thermal discomfort due to drafts and locations of drafts

The questionnaire also evaluates where the participants perceive that the drafts rise from. This is interesting with thoughts of the new ventilation system installed, but from Figure 29 it is seen that the perceived origin is fairly spread between windows, doors, and ventilation. The assessment of the source prompts an inquiry into the influence of the seasons. Figure 30 demonstrates that droughts are commonly experienced during conditions of wind, cold, or a combination of the two.

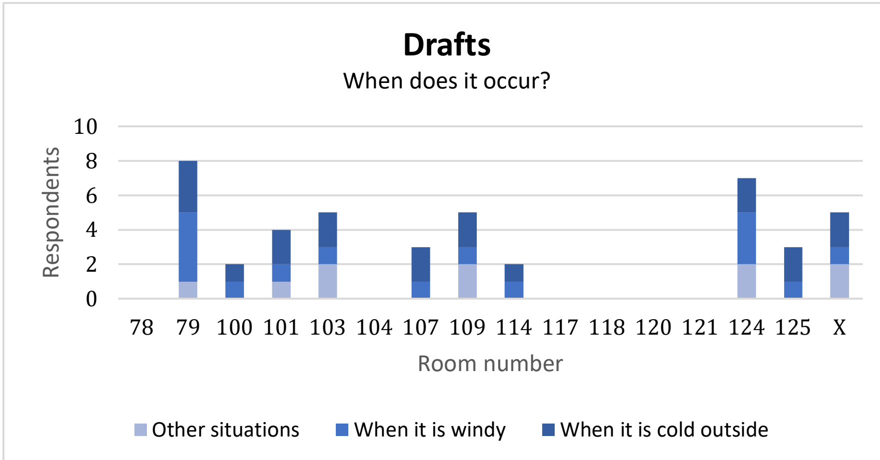

Figure 30: Thermal discomfort due to drafts and the frequency of occurrence

7.2.2 Atmospheric comfort

Atmospheric comfort was evaluated in the questionnaire. Atmospheric comfort in this analysis is focusing on the perceived quality of the air. In 8 of the 15 rooms used for the study, at least one of the occupants register that they have experienced atmospheric discomfort as seen on Figure 31.

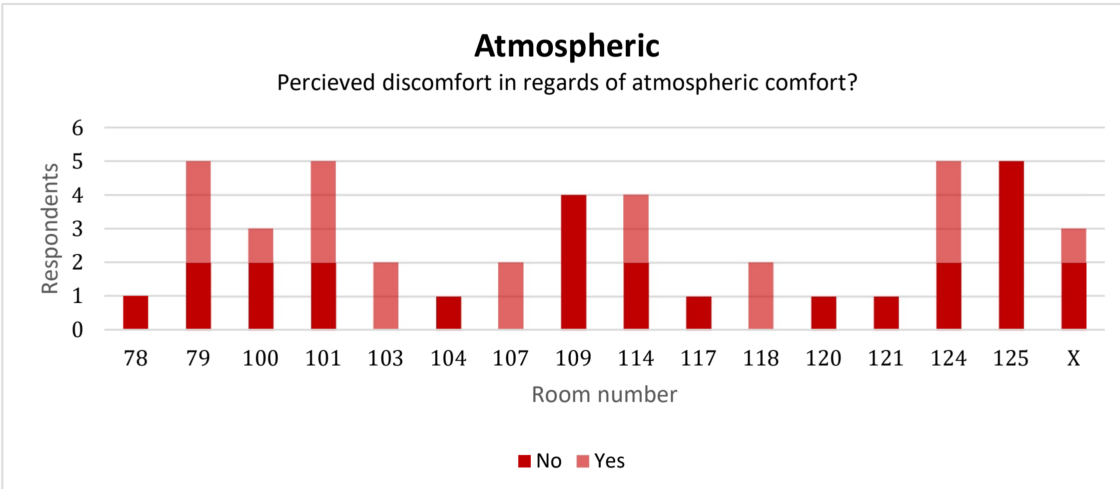

Figure 31: Reported cases of atmospheric discomfort in the case building

Table 12: Atmospheric dissatisfaction per room in percentage

Room	79	80	86	86	100	101	107	109	114	121	124	125
Respondents	5	0	0	0	3	5	2	4	4	1	5	5
Orientation	SW	SW	SW	SW	SE	SE	NE	NE	NE	NW	SE	NW
Atmospheric dissatisfaction	60%	N/A	N/A	N/A	33%	60%	100%	0%	50%	0%	60%	0%
IEQ Label	3	N/A	N/A	N/A	2	3	5	1	3	1	3	1

Table 12 shows the respondents evaluation of atmospheric comfort. Room 109 and 125 responds that they do not experience any atmospheric discomfort while 100% of the occupants in Room 107 respond that they do experience atmospheric discomfort. The atmospheric comfort relies on the quality of the air and in the questionnaire, it is evaluated by how stale the air is or foul odors in a room. Table 12 also shows the grade that has been determined according to KL's IEQ labels for the individual rooms. The grade is determined based on the percentage of dissatisfied occupants, where the label increases as the percentage also increases.

The atmospheric discomfort is widely spread across the building and even very divided within each analyzed room. There is no pattern showing that rooms with newly installed Airmaster have better nor worse atmospheric comfort. It is interesting to investigate the number of occupants in the rooms. Rooms with higher density also experience more atmospheric discomfort.

Almost 26% of the total respondents reports atmospheric discomfort and that they experience it every day, while 57% of the respondents say that they never experience any atmospheric discomfort. This shows a big division in the respondents' perception of the atmospheric comfort.

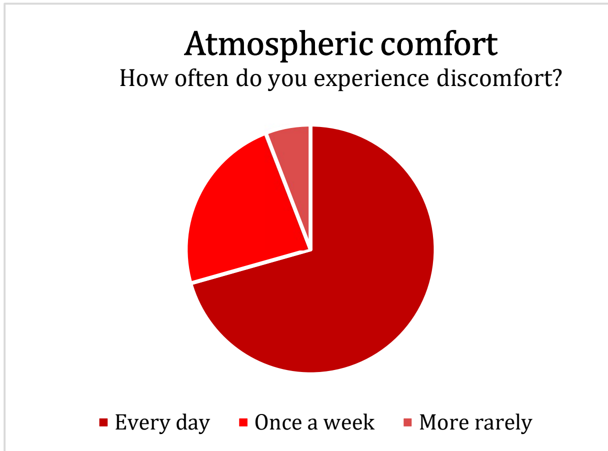

Figure 32: Atmospheric discomfort and the frequency of occurrence

Figure 33: Visualization of rooms experiencing atmospheric discomfort

7.2.3 Visual comfort

The visual comfort was evaluated in the same way as the other categories. But for the visual comfort it is seen that less events of discomfort are reported. Discomfort is only reported by 1 or more participants in 5 of the 15 rooms and only 8 of the 45 participants perceive discomfort on the visual comfort.

Figure 34: Visualization of rooms experiencing visual discomfort

When visualized on the plan view of the building there is no pattern of the visual discomfort. The questions asked in the questionnaires are also very specifically headed towards glare. The visualization does show that glare/discomfort is reported primarily in rooms with windows towards south and southeast. On top of this observation, we do also have rooms in the building facing the same direction, meaning that the discomfort could most likely be related to the specific placement of the office tables/workplaces in the rooms.

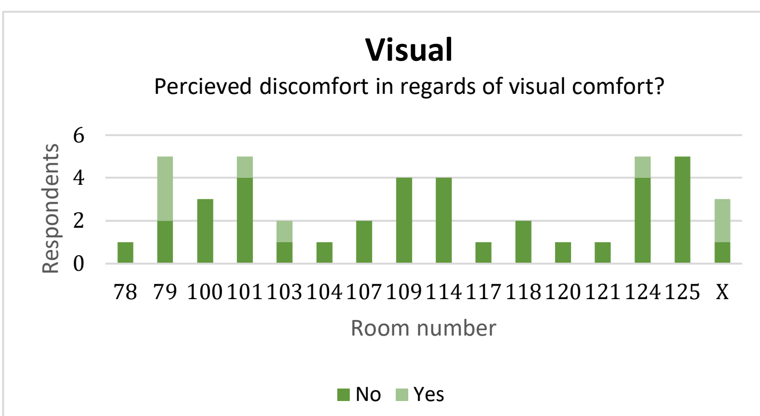

Figure 35: Reported cases of visual discomfort in the case building

7.2.4 Acoustic comfort

The expectation for the acoustic comfort was to see discomfort in the rooms with most people load and less reported discomfort in those with a lower density. Overall, the theory and expectation for the questionnaire was right, there is one room where the theory is proven wrong. In Room 120 there are only one participant and there are two workplaces in this room. Discomfort is reported in this room, but the room is also connected to a larger office with the biggest people load in the building.

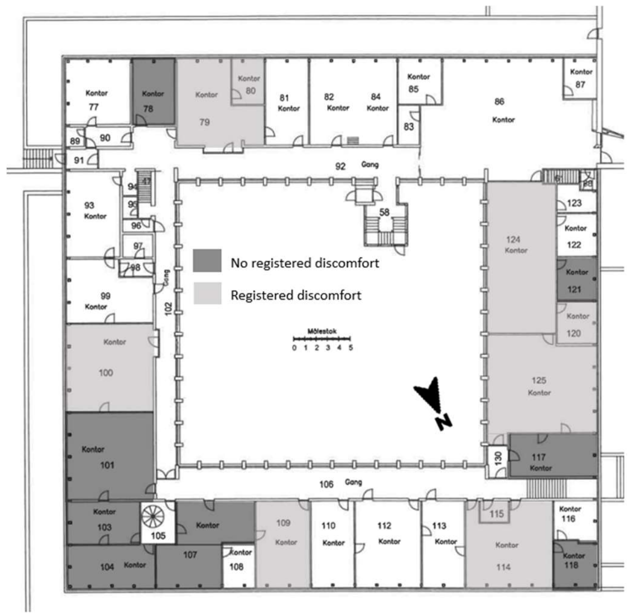

Figure 36: Visualization of rooms experiencing acoustic discomfort

As seen on Figure 36 the rooms with registered discomfort are mostly the biggest rooms and naturally the rooms with the biggest people load. It could be investigated further which tasks are performed in these rooms. Room 124 and 125, which were examined during the measurement campaign, contains workspaces designed for call center-like activities.

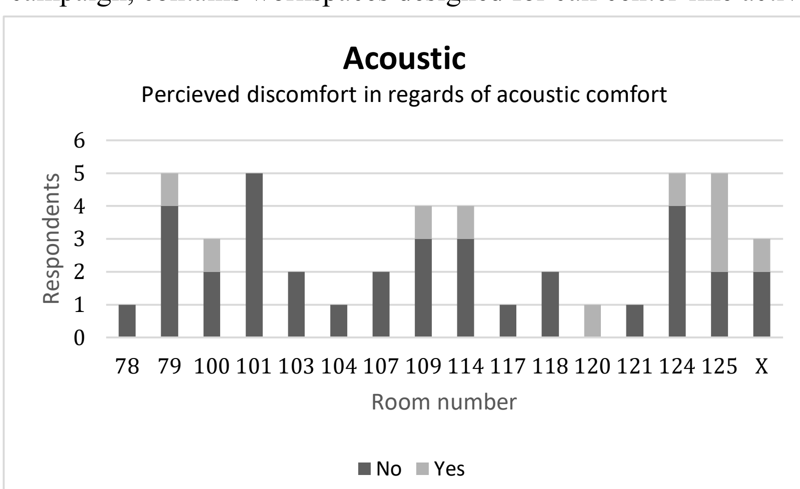

Figure 37: Reported cases of acoustic discomfort in the case building

The rooms visualized without reported issues on Figure 36 are also rooms with very low people load or activities not creating much noise pollution.

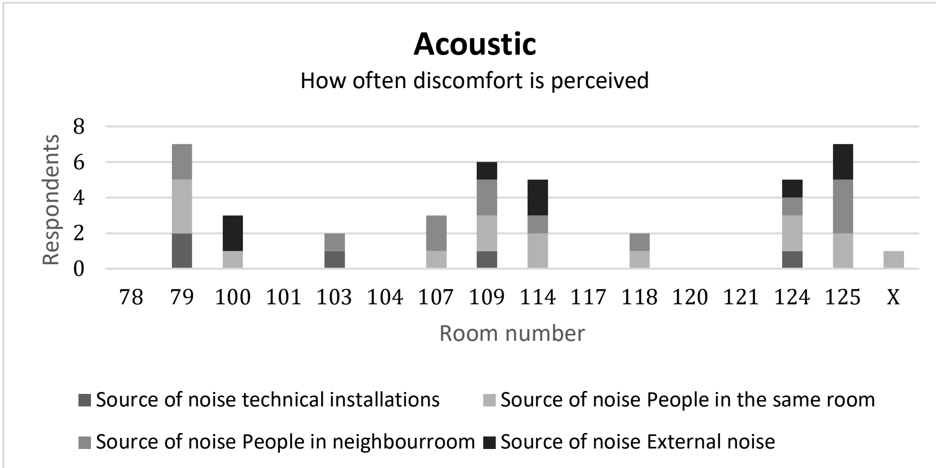

Figure 38: Acoustic discomfort and the frequency of occurrence

To further investigate the origin of the noise pollution or the cause of the discomfort, the participants were asked to point out their suspected source of the noise creating discomfort. As it is seen on Figure 38 the sources pointed out by the participants are widely spread between all categories.

7.2.5 Analysis of open-ended questions

The questionnaire used in this study consists partly of what is referred to as "binary questions and answers" which are questions that can for example be answered by either "yes" or "no", or other types of questions asked in a similar way. The questionnaire also consists of a series of "open-ended" questions, placed at the end of each round of questions related to a specific indoor environmental aspect. Open-ended questions are where the participants are given the opportunity to, in their own words, explain where the participants are free to explain, argue or elaborate upon their previous answers. Since approximately half of the questions are asked as open-ended questions, this chapter will examine how these can be used as a supplement to the binary questions in *Chapter 7.1* and the measurements in *Chapter 6* by providing information about the reasons why certain indoor environmental problems are reported in the way in which they are. This chapter will only summarize the findings from the Content's analysis, which can be seen in full context as *Appendix C – Content's Analysis of open-ended questions*.

Based on all answers from the open-ended questions in the questionnaire it can be established, that in relation to the thermal indoor environment, discomfort caused by drafts have been present in the building both before and after the Airmaster was put into operation, but the location in which the drafts occur has changed. Before start-up, discomfort from drafts were limited primarily to the ankles, but after start-up, several employees reported that the drafts have now moved up near shoulder and head level. This could be explained by the fact that the ventilation systems supply diffusers are placed closer to the ceiling than the windows are.

"Before our ventilation system was turned on, I was sitting in a draft zone between my managers office and the door to the hallway. Here, I would sometimes feel the draft on my legs. Now after the Airmaster has been turned on, I constantly feel drafts on my neck and shoulders." ~ R114

The employees report that because of the buildings age and large window sections, downdrafts and low temperatures for employees who have their workplace close to such windows increases significantly during the winter season. In winter, large cold surfaces such as windows can cause discomfort due to radiant temperature asymmetry. Due to the aforementioned, and based on the employees' statements, the weather seems to largely determine the quality of the indoor environment i.e., if it is cold outside, it is also cold inside and if it is hot outside, it is also hot inside.

"It is an old building, so the indoor temperature is quickly affected by the weather conditions. Especially in the summer, the sun can really shine in and heat up the offices. However, the heat is mostly a problem in the afternoon for me, as this is when the sun bursts through the windows of the office that I sit in. However, I know that other offices with windows facing south, and east are affected by the heat at other times of the day." ~ R79

For the atmospheric indoor environment, it can be established that the employees are already well aware of the importance of good air quality and regular replacement of the indoor air. The employees themselves have acquired devices that measures the CO_2-concentration and changes color based on the measurement (blue is good and red shows a need for venting, most likely after a limit set at 1000ppm). However, the employees have expressed that they can feel when the air becomes too heavy and vents out, regardless of the color of the measurement device.

"The ventilation system has not been put into operation in all rooms yet, and therefore there is still problems with stale air when everyone is present in the office or sit for a long time in the meeting rooms." ~ R79

It should be noted that natural ventilation has always been an option within the case building and the employees use it regularly in the summer, but the weather can make it very difficult to utilize it due to strong winds and low temperatures in the fall and winter.

For the visual indoor environment, it can be established that the employees experience the most inconvenience as a result of problems with artificial lighting. Specifically, the source of the annoyances are the motion detectors that control when and how long the light is on.

"The motion sensors are not sensitive enough. In the winter months, the lights are turned off regardless of whether there are people in the building." ~ R124

Very few cases of glare and reflections due to daylight are reported in the questionnaire. This is likely because glare from daylight has been considered in the design of the building, with large overhangs casting shadows on the windows. In addition, the windows are equipped with curtains, so annoyances caused by direct sunlight can be solved within the building.

"The motion sensor switches off when I am sitting and working at my desk. I can simply roll the curtains down, and cover for the sun, so glare is not a big problem." ~ Unknown room

For the acoustic indoor environment, it can be established that the sources of nuisance are primarily due to the number of employees working together in one office space. It creates internal problems with small talk, placement of breaks, conversations about work and spare time alike in the workplace.

"There is a lot of noise at the Town Hall in general, and we sit a lot of people close together in the offices, and therefore challenges with noise from colleagues occurs on a daily basis." ~ R79

"The office that I sit in has recently started being used as a shortcut to get around the building. This creates an incredible amount of noise because people do not consider the fact that we are sitting and working while they have conversations on their way through." ~ R125

The sources of the nuisance are therefore not building related, nor do they arise from outside (highways, airports, heavy industry, etc.). It can therefore be established that the source of acoustic problems in the case building are related more to behavior rather than being caused by the building itself and the surroundings.

8 Discussion

This study has investigated how different methods of data gathering can be used to evaluate the indoor environmental quality in public buildings. The study is based on a municipality owned case building in Denmark and its employees. One dataset was collected through physical measurements and the other was gathered from a questionnaire testing two different frameworks of the questions asked. In this chapter, the results obtained from the analysis in *Chapter 6 and 7* will be discussed to identify how the methods can be used to describe and eventually improve the indoor environmental performance. Furthermore, it will be discussed how these methods evaluates the IEQ and whether the result of the methods is similar.

8.1 The measured indoor environment

From *Chapter 6* it can be established, that the indoor environmental performance complies with the requirements and guidelines from BR18 on all aspects. Immediate action to improve upon the indoor environment is not necessary but minor preventive initiatives and monitoring is advised. The physical measurements provided knowledge on the IEQ in the case building in 11 different rooms.

The buildings acoustic properties manage to keep low frequency noise from external sources like traffic and mechanical equipment on acceptable levels. The thermal environment within the building meets the criteria for acceptable comfort levels for the occupants indicated by the PMV of -0,03 and PPD of 6% from the spot measurement conducted in Room 125, which measured a temperature of 22,5°C. When the long-term measurements for the same room are taken into consideration, the average temperature is 24°C for the entire measurement period, bringing the PMV to 0,26 but the PPD remains at 6%. When the air velocity was measured in the room, values between 0,18 and 0,02m/s were registered, suggesting that discomfort related to drafts should not be a problem, however drafts are reported to be a cause of thermal discomfort according to the questionnaire.

When it comes to visual comfort, the measured areas are well suited for office use and the measurements shows that the conditions meet the standard requirements. Even though some of the measurement points fall below the optimal level of illuminance, the placement of these points falls outside the primary work zone. The daylight contributions are also expected to further increase the amount of illuminance for most of the year. Work performed during night hours are expected to occur very rarely but should be considered in buildings where it is relevant. The long-term measurements performed in the building showed an acceptable indoor environmental performance. It is worth mentioning that the performance might look different depending on the season. The CO_2-concentration showed occasional spikes but remain within acceptable levels when looking at the average levels for all rooms.

The indoor environmental performance of the assessed rooms appears to be well suited for the purpose of the building. All measured parameters indicates that the building has an acceptable indoor environmental quality leading to low or no concerns.

8.2 The perceived indoor environment

The results from the pilot test of the APV has been analyzed in *Chapter 7*. The primary idea is that APV's can potentially be used as a method of data acquisition if the questions asked are systematized, organized, and qualified. Data acquisition for the perceived indoor environment is a relevant method, to create an overview of how users experience the indoor environment regardless of whether the building can deliver a good indoor environment, or whether the indicators comply with common requirements and standards for a good indoor environment.

45 employees spread throughout the first floor of the case building were asked a series of questions related to the same four indoor environmental aspects.

Another interesting observation from the analysis was that most complaints related to acoustic comfort is neither related to technical installations nor related to the surroundings but originated from the building's occupants. Therefore, this was not observed in the analysis of the measured indoor environment since this method only evaluates how construction elements and furniture with attenuating properties dampens soundwaves. The same thing was observed in relation to the visual indoor environment, in which the participants reported that the motion detectors was turning off the artificial lights way too fast. It is a visual comfort concern which was not detected while conducting measurements, and it is an observation that was only gathered because of the questionnaire.

From the questionnaire, it can be established that the indoor environmental performance in the case building is generally perceived as good. The questionnaire shows that the quality of the indoor environment is rated unacceptable for some rooms. The category with most of the respondents reporting issues is the thermal comfort where 62% reports that they have experienced issues with too warm or cold temperatures, or drafts.

8.3 Comparison of evaluation methods

Questionnaires can be accompanied by physical measurements. Doing this, can in many cases extend the basis of decision making when considering renovations or improvements of a building. In some cases, however the opposite can be observed, for example as seen for thermal comfort. 62% of the respondents reports thermal discomfort while the measurements showed no issues with thermal comfort, neither by temperature nor drafts. From the long-term measurements, overtemperatures can be observed for some of the occupant hours but this is not in line with the results of the questionnaire.

As mentioned earlier, the visual comfort also had some differences between the obtained results. The measurements showed a varied quality of the visual comfort, while the respondents reports that they are not bothered by insufficient illuminance, but the fact that the sensors turn off the lights too fast. Even though the measurements prove sufficient, the occupants are still reporting problems related to acoustics in the building. The reported problems mainly originate from sharing offices with other colleagues.

Table 13 shows a comparison of the measured data and the results of the questionnaire. The respondents presented in this Table are only the number of respondents replying on the questionnaire and does not represent the actual number of occupants in each room.

Table 13: Perceived atmospheric discomfort compared with measured data

Room	Respondents	Orientation N/E/S/W	Average CO2 concentration	Hours >1000ppm	Atmospheric discomfort
79	5	SW	662	7	60%
80	0	SW	803	61	N/A
86	0	SW	558	4	N/A
86	0	SW	644	12	N/A
100	3	SE	625	3	33%
101	5	SE	563	0	60%
107	2	NE	657	15	100%
109	4	NE	639	17	0%
114	4	NE	630	4	50%
121	1	NW	738	31	0%
124	5	SE	708	25	60%
125	5	NW	623	5	0%

According to the evaluation using the criteria on KL's grading scale for measured IEQ, the CO_2-concentration does not look alarming in any of the rooms. There are some hours exceeding 1000ppm but not enough to constitute any concerns, because exceeding 1000ppm does not equal to a poor indoor environment. Room 80 is the room with the highest average CO_2-concentration and also the room with most hours of concentration above 1000ppm. The average is counting 314 hours in total, and 61 hours, therefore constitutes around 20% of the time. From the measurement period, it is known that Room 80 is a single person office making it more volatile against poor ventilation.

Table 14 shows the comparison of the average temperature measured and the results from the questionnaire. Rooms with highest temperature is also the rooms with the highest reports of perceived discomfort.

Table 14: Perceived discomfort due to overheating compared with measured temperatures

Room	Respondents	Orientation N/E/S/W	Average temperature	Hours >25°C	Thermal discomfort
79	5	SW	22,1 °C	0	100%
80	0	SW	21,4 °C	0	N/A
86	0	SW	21,7 °C	0	N/A
86	0	SW	22,2 °C	0	N/A
100	3	SE	21,3 °C	0	33%
101	5	SE	22,0 °C	0	40%
107	2	NE	23,6 °C	14	100%
109	4	NE	23,4 °C	16	75%
114	4	NE	22,2 °C	0	25%
121	1	NW	23,3 °C	0	0%
124	5	SE	22,5 °C	0	80%
125	5	NW	24,0 °C	67	80%

Comparing Room 107, 109 and 125, these are the rooms with the highest average temperature of 23,6°C, 23,4°C and 24°C, respectively. In these three rooms, 100%, 75% and 80% of the occupants reports thermal discomfort. Room 121 has a relatively high average temperature but no reports of thermal discomfort, this could suggest a high tolerance for high temperatures among the occupants or other factors contributing to a better thermal comfort. It should be noted that there are only 1 respondent in this room, making the result more volatile.

When evaluating the thermal and atmospheric comfort in regards of KL's grading scale for measured and perceived IEQ, it is interesting to see if both methods of evaluation end on the same level of grading.

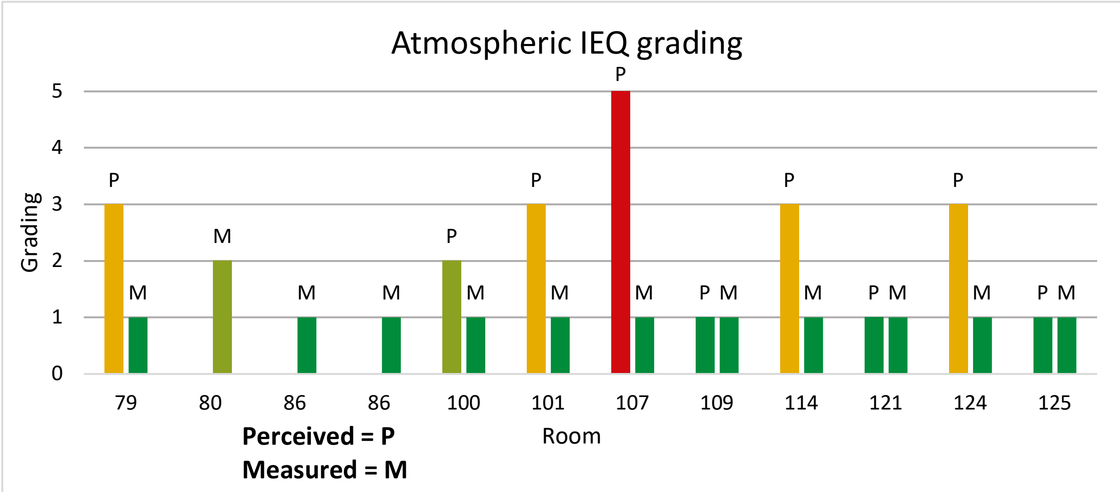

Figure 39: Comparison of atmospheric IEQ grading

Figure 39 compares the IEQ labels presented in *Chapter 6.4* and *Chapter 7.2.2*. The grading based on the measurements results in a grade of 1 in all rooms except Room 80 where the average CO_2-concentration is equivalent to a grade of 2. The perceived IEQ label varies a bit more. Worst rated room is Room 107 where the perceived discomfort reaches 100% resulting in a grading of 5. The comparison of the atmospheric IEQ grades for measured and perceived comfort shows a large discrepancy. There are several possible sources of influences especially on the perceived comfort evaluation, i.e., number of occupants and room size.

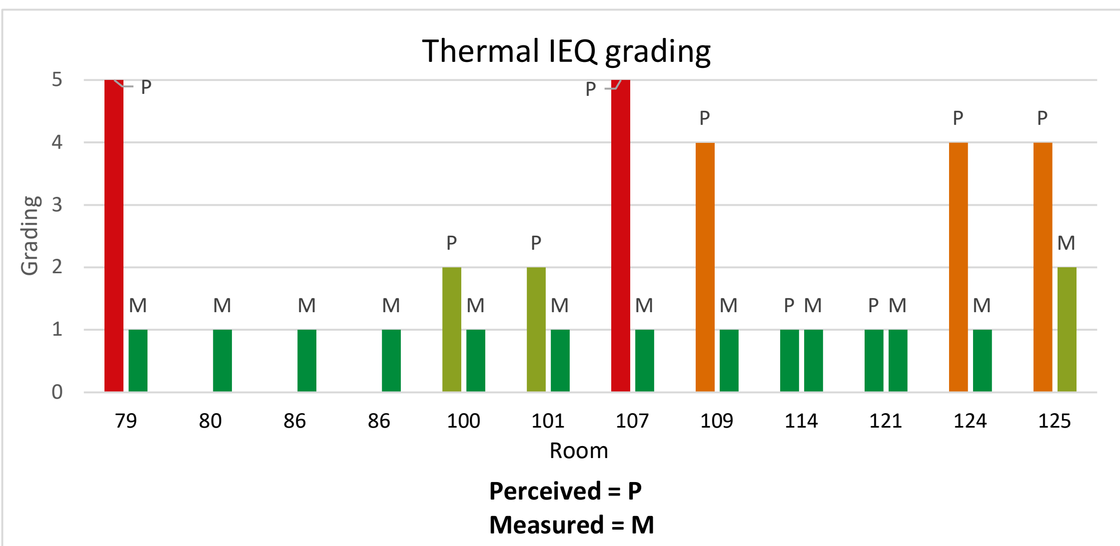

Figure 40: Comparison of thermal IEQ grading.

Figure 40 shows the evaluation of the thermal indoor environment from physical measurements and the questionnaire. The color on the bars illustrates the grading that individual rooms receive according to KL's IEQ labels. While the measured IEQ is fairly uniform, the perceived IEQ is very diverse depending on the room.

9 Conclusion

This study has investigated how physical measurements and post occupancy evaluations can be used to gather information on the indoor environmental performance. Furthermore, the study investigates how knowledge obtained can be used to develop IEQ labels for Danish public buildings.

For the measured indoor environment, it can be concluded that even though the method can be time consuming it has also shown to be a useful source when evaluating the indoor environmental quality. When evaluating the IEQ through physical measurements, the result will always be an actual number comparable to requirements or standards for indoor environments. This way of evaluating the IEQ makes it very easy to label the actual quality, but it does not consider the occupant satisfaction at all. When evaluating the indoor environment, it will often be beneficial to have a BMS-system measuring the same indoor environmental parameters as used for this study. Buildings with BMS systems offers the opportunity to extend the measurement period and evaluate the IEQ based on a full year of data. A BMS-system would make the building owner able to accurately choose what actions to prioritize when improving the indoor environment. When assessing the indoor environment using long time measurements, it can be difficult to find the origin of identified problems. This can either be done by performing spot measurements or asking the occupants.

For this study, the use of questionnaires to gather information on the occupants' satisfaction has proven to be an effective method for achieving essential insights. Primarily the questionnaire has given a perspective of the occupants' satisfaction within the 4 IEQ aspects. These insights are a great opportunity when distinguishing whether discomfort arises from the building's characteristics, its surroundings, or the behavior of its occupants. The occupants are also a good source when trying to find the origin of an indoor environmental comfort concern. Even though the occupant insights are valuable, it can be hard to put the occupant perception on a formula. The occupant perception can be very different between different respondents. Because of this, it can be hard to either put a number on the evaluation or directly ask the respondent to label the IEQ based on a numerical scale. If the goal of the APV is to only estimate the occupant's satisfaction with the workplace environment, an APV questionnaire is in many cases sufficient. If the aim of the evaluation is to estimate the actual properties of the indoor environment, the questionnaire will often be inconsistent.

Evaluating the indoor environmental quality through both questionnaire and measurements can reinforce the view of the building's overall properties. The fact that individuals perceive the indoor environment quite different from the measurements draws attention to the limits and requirements followed in the measurements. It can be concluded that even though the indoor environment has properties complying with regulations and requirements, it can still be perceived as a discomfort by some occupants. There are three possible origins of this discrepancy, either the required properties are too high, or the perceived discomfort originates from other sources than the actual IEQ. A third possible origin of the discrepancy could be the method of evaluating the IEQ. The parameters used in the measured evaluation might not be the parameters leading to the occupant's discomfort. Even though this study showed this large discrepancy in many of the rooms, the measured evaluation can also validate the occupants' experience of discomfort.

In relation to how the indoor environmental performance has been determined, it can be concluded that the labeling scale developed by KL works as intended. However, it was found that when the building is complying with all requirements stated in BR18, the grade will land between 2 (very good) and 3 (good), but to score a 1 (excellent), it needs to go beyond the requirements. Measurements can also validate the occupants' experience of discomfort, and even improve the understanding of a building's properties. The combination of the two different types of data sets is reinforcing the result of the evaluation. Even though a combined labeling system for evaluating public buildings, comes with some uncertainty, the combined evaluation reflects both measurable qualities of the indoor environment and the occupants' satisfaction. This approach ensures a comprehensive assessment of the IEQ, which labels both the technical properties and the occupant satisfaction.

10 Managerial implications

Results found through this study shows that the two datasets used for the analysis, reinforces each other. Both types of evaluations of the indoor environmental quality can be done as individual evaluations, but the perspective of the IEQ only gets more unambiguous when combined. The future in APV and assessing the quality of the indoor environment at workplaces can of course be evaluated through either of the methods used in this study, but when estimating or prioritizing where to focus when improving or renovating buildings, it is a huge advantage to have both evaluations backing up the decision basis.

It might be unrealistic to always have access to both datasets as done through this study, mainly because of the focus on costs, but if the building itself has a BMS-system logging data on the building, it is a huge opportunity to combine the automatically collected data with an improved version of the APV questionnaire.

Using this study could be a basis to convince building owners or developers to push forward on installing BMS-systems in new buildings or when renovating older buildings. The advantages of BMS-systems and the use of collected data are very beneficial for both the owner and the occupants. With this said it should be kept in mind that BMS-systems are an extra cost, but in many cases if the data are used properly, the knowledge gained would be worth the extra cost.

Besides the benefits of comparing the two methods of data acquisition explored throughout this study, the potential indoor environment should also be considered as a beneficial method of determining how rooms in a building manages to deliver a good indoor environment, independently on how the occupants are using the rooms. In KL’s model, only a registration based on a building review is required but in future works it should be investigated how indoor environmental simulation tools could elevate this method of data collection even further.

The results presented through this study could also benefit the municipals and KL when developing APV’s either when developing a new standard for the municipalities to do the APV’s in the same way, or for the individual municipalities when deciding how they would like to perform and use the APV, as well as its results. The study should be seen as a test and should be considered possible to conduct on a larger scale.

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11.1 Index of Figures

11.2 Index of Tables

11.3 Index of Equations

12 Appendix A – Acoustic comfort measurement results

12.1 Measured data for assessing airborne sound in Office spaces 124/125:

Measurement type	*Description*
L1	Average sound pressure level in source room.
L2	Average sound pressure level receiving room.
B2	Background noise in receiving room.
T2	Reverberation time in receiving room.

Frequency [Hz]	*L1 [dB]*	*L2 [dB]*	*B2 [dB]*	*T2(30) [sec]*	*R'w [dB]*
100	74,64	50,47	27,09	**3,90**	**29,5**
125	76,34	49,22	21,45	**2,49**	**29,7**
160	76,4	47,89	21,28	**1,36**	**29,2**
200	75,32	44,07	20,75	**0,996**	**32,1**
250	75,91	40,57	18,72	**0,498**	**29,9**
315	74,71	41,74	17,88	**1,20**	**32,8**
400	72,52	39,74	18,36	**0,553**	**27,7**
500	70,97	39,88	23,87	**0,575**	**26,3**
630	69,01	36,47	14,48	**0,758**	**30,7**
800	65,65	34,76	17	**0,581**	**26,2**
1000	66,54	33,64	13,92	**0,855**	**28,4**
1250	66,44	34,29	10,53	**0,645**	**27,7**
1600	69,08	35,58	11,65	**0,66**	**29,2**
2000	66,08	34,7	7,64	**0,681**	**27,3**
2500	67,34	38,36	7,18	**0,686**	**24,8**
3150	65,56	36,95	7,01	**0,665**	**24,3**

The equipment used for acoustic measurements consists of two ½-inch free-field pre-polarized microphones on tripods designed for high-precision measurements and architectural acoustics requiring high sensitivity across a wide range of frequencies (Brüel & Kjær, 1942), as well as an omni power sound source, which is a dodecahedral, high-power, omnidirectional loudspeaker designed to measure sound insulation and perform room acoustics measurements. It uses 12 individual loudspeakers in a dodecahedral configuration to radiate sound evenly with a spherical distribution (Brüel & Kjær, 1942).