A Systematic Approach to Integrated Building Performance Assessment and Visualisation

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Abstract

The aim of this project was to develop a holistic approach to building-performance assessment without limiting it to energy use (usually expressed in kWh m\(^2\) year\(^{-1}\)), but rather include more parameters that represent the following aspects: Economic, environmental, and quality of service provided to the occupant/client. If it can be shown that buildings can be operated not only in an energy-efficient way, but also in a way that takes into consideration the needs of the occupants, a case could be built that a higher quality of indoor environment does not necessarily mean a higher economic impact. It is also important to show that having access to high-quality building-performance data leads to high-quality analysis and visualisation, and consequently to a chance to detect faults and improve building operation. To answer these questions, a large office building in Stockholm, Sweden was used as a case study. The building was equipped with energy meters and 1,700 sensor points, uniformly distributed over the occupied areas, that measured room temperature, duct temperature, occupancy presence/absence and supply airflow, in addition to other states. The data was processed using RStudio, and various types of visualisation plots were used, including carpet plots, masked scatter plots, bar plots, line graphs, and boxplots. The data pointed to some interesting results. First, just knowing the energy use is not sufficient for understanding the quality of the service provided to the occupants. Second, performing a thorough analysis of room unit data can detect faults. Third, using carpet plots for energy-data visualisation is effective for energy-use pattern recognition. Finally, visualising the building performance parameters in a parallel coordinate plot is a more informative representation of integrated building performance compared to the energy performance certificates typically used today.
Sammanfattning

Tydliga kopplingar mellan effektiv byggnadsdrift och förvaltning, byggnadstjänster av hög kvalitet, hög kunskap och god lönsamhet förväntas utgöra ett starkt argument för en värdebaserad och marknadsförs varning till en mer energieffektiv och hållbar byggd miljö. Huvudsyftet med detta forskningsprojekt var att utveckla en helhetlig metod för utvärdering av byggnads energiprestan. Istället för att endast mäta energiflöden (t.ex. mängden kopt energi, kWh/m²år) var avsikten att ta hänsyn till relevanta ekonomiska och miljörelaterade faktorer, samt aspekter rörande kvaliteten av tjänster som levereras till kunder/brukare (t.ex. inomhusklimat).

Ett ytterligare mål var att visa att kontinuerlig analys och visualisering av kvalitetsäkra måtdata kring byggnads energiprestan avsevärt underlättar identifieringen av fel i byggnadsdriften och snabbare leder till effektivitetshöjande åtgärder.


Resultaten visade tydligt att energiflödesmätningar för sig inte räckte för att bedöma kvaliteten hos levererade tjänster (t.ex. inneklimat). Noggranna analyser av multifaktoriell mätdata ledde till att olika fel i byggnadsdriften kunde identifieras. Mätdataanalysen visade att användningen av ”carpet plots” och ”pattern recognition” med fördel kunde användas för effektiv felsökning, samt att användningen av ”parallel coordinate plots” resulterade i en betydligt mer helhetlig bild och förståelse av byggnadens energiprestanda än som normalt kan erhållas med hjälp av energideklarationer.
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I would like to thank my colleagues Cong Wang, Hesham El Gazzar, Lamis Ahmed, and Sasan Sadrizadeh for all the coffee breaks. I would also like to thank my friends Marc Azar, Eddison Manrique Garcia and Isac Nilsson for making my time in Stockholm memorable.

Finally, special thanks to my family for all their encouragement and endless support.
List of Publications

This thesis is based on the following research papers:


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Chapter 1

Introduction

In 2010, the European Union (EU) issued Directive 2010/31/EU, which states that by 2020, the energy use and CO₂ emissions in European states must be reduced by 20 per cent. Additionally, 20 per cent of the total energy use must be obtained from renewable resources [1]. The energy used by the building sector in the EU corresponds to 40 per cent of the total energy use. However, the Swedish building sector accounts for 36 per cent of the total energy use [2]. Moreover, when it comes to energy from renewable resources, Sweden has already achieved the 2020 target [3]. Nevertheless, Sweden still faces many challenges to achieve the long-term energy policy that requires a reduction of 50 per cent by 2050 [4]. Therefore, it is increasingly important to make sure that buildings perform as intended. At the national level, building-energy certificates classify the building’s energy use according to available categories. However, that only ensures that the building complies with the requirements during the certification period. Nothing is known about the performance of the building at other times. In addition, the national certifications proposed by Directive 2010/31/EU only focus on the building energy use, with no indication of the economic and social aspects of sustainability. Therefore, there is a need for a more holistic approach to building certification and performance assessment that not only focuses on energy use, but also on the economic aspect and the quality of service provided to the occupants.

1.1 Motivation for the project

At the national level, building energy performance certificates mainly deal with the energy use of the building, represented by the annual amount of energy used in $kWh/m^2$. Directive 2010/31/EU does not bind European states to include other aspects of building performance in their assessment. Only a few states have included the environmental impact by reporting the equivalent CO₂ emissions. More information on certification systems, from both a Swedish and global perspective, is presented in Chapter 2. Moreover, a report issued by the European Commission studied the impact of energy certificates on the value of buildings and found a positive correlation between price tags and the energy category, in which the building’s energy use falls [5]. The study was conducted in five European states and showed that customers are aware of the importance of buildings’ energy use and the economic implications. On the other hand, the Swedish National Audit Office performed a study on energy-performance certificates [4]. The study showed that in about 48 per cent of the cases, building owners received no recommendations for improving their building’s energy performance.
The evidence presented above shows that most certifications only focus on energy use and that people are aware of the benefits of occupying an energy-efficient building. On the other hand, researchers have conducted several studies to link the effect of the quality of the indoor environment on occupants’ productivity. A study that focused on 18 office buildings shows that productivity is not highly correlated to occupants’ thermal comfort. However, the relationship between work engagement and the indoor environment quality is highly correlated [6]. Moreover, Wyon states in [7] that employee productivity is greatly affected by the indoor temperature and the quality of the indoor environment. These findings are of great importance, especially in office buildings, since employees constitute the biggest asset. In addition, a poor indoor environment in any type of building negatively affects occupants’ health, so has economic implications. This makes it hard to believe that with all the studies that have been carried out, there is still no price tag on a good indoor environment.

From a business perspective, a building that is energy efficient, cost efficient, environmentally friendly, and provides a high-quality indoor environment for its occupants results in a satisfied customer/tenant that is more willing to stay in the same building for a longer time [39]. With more case studies unravelling the underlying connection between the quality of the service provided to building occupants, efficient operation and economic value, building developers and operators will be able to create better conditions for efficient and profitable building operation. A market-based society recognizing the value of wholesomely efficient building performance has the potential to achieve a faster transition to a sustainable built environment that complies with environmental targets (2020/2050) at the national and EU levels.

1.2 Objectives

The purpose of this project was to measure, analyse and evaluate an office building’s performance after being occupied for two years. The assessment was performed in a holistic manner, focusing not only on energy use, but also on the environmental impact, economic impact, and the quality of the service being provided to the occupants. This overarching objective can be further divided into three main goals.

Presentation of innovative criteria for building-performance assessment. By this, we aimed at diverting from the narrow focus on energy use, represented as $kWh \ m^2$, and focused more on the other aspects of sustainability, which can be summarised in the following:

- Energy (purchased energy [$kWh \ (m^2 \ year)$] and power output [$kW, kW \ m^2$])
- Operational cost
- Environmental impact (expressed in $kgCO_2 \ m^2$)
- Service quality (measured quality of the indoor environment)
- Occupancy efficiency

This creates a more detailed assessment and allows for a better understanding of the underlying relationships of the different performance parameters. Paper I focused on this objective by presenting an assessment of an office building in Stockholm. Paper III dealt with occupancy patterns and how efficiently spaces are used in the building studied in Paper I.

Developing a holistic measurement, analysis and visualisation methodology for the evaluation of a building’s performance. Based on the previously mentioned key
performance parameters, we presented a methodology for assessing the building’s performance, from measurements to analysis, and finally to visualisation. Some tools are available for such energy-use visualisation, but most lack the ability to convey a holistic picture of the building’s performance. Moreover, a comparison between designed, measured and perceived performance was possible, leading to a better understanding of the dynamics of a building.

While Paper II revolved around visualisation, Paper IV presented a holistic approach to the performance assessment of ventilation systems, in specific, autonomous, demand-controlled ventilation units. Assessing the building’s systems is as important as assessing the whole building performance and provides a clearer picture of the building’s operation.

**Integrating the results of this study with the existing Green Fingerprint application**
Adopting the holistic approach in a commercially available application enables us to deliver the right information to the right stakeholder.

### 1.3 Hypothesis

The thesis investigates if:

- Availability of high-quality building-performance data
- High-quality analysis of building-performance data (in-depth, long-term, holistic/system approach, high-resolution)
- Efficient, user-friendly visualisation

leads to:

- Better understanding of system-level building performance
- Greater ability to identify and interpret faults in system operation
- Improved building-system control

and eventually to higher:

- Profitability
- Energy efficiency
- Occupant/customer satisfaction

### 1.4 Limitations

One of the initial aims of the study was to reach a better understanding of building dynamics through the comparison of designed, measured and perceived performance. Although the methodology is described later on in Chapter 3, it was not possible to measure the perceived performance due to the security concerns of the tenants. Sensor data was gathered through the building automation system (BAS) rather than by separate measurement equipment. Making use of the BAS data is more practical and ensures the applicability of the methodology on any building equipped with a BAS.
1.5 Summary of appended papers and author’s contribution


National and commercial energy certification systems are discussed in this paper, highlighting the focus and the shortcomings of these systems. While national building-certification schemes rarely mention the quality of the service delivered to the occupants in a building, commercial certification systems have some points allocated for indoor air quality and thermal comfort. However, the way buildings are assessed only ensures that the performance meets the certification requirements at the commissioning phase with no follow up. Furthermore, key parameters concerned with occupant satisfaction, and environmental and economic aspects are presented along with building energy use, in order to make a holistic assessment of a building’s performance. An office building in Sweden is used as a case study, where all the parameters are assessed and presented for a short period. The visualization of such data, including the presented key parameters and energy use, allow a better understanding of the dynamics of a building.

**Author’s contribution:** This paper was entirely written by the author of this thesis. The calculations and visualizations were the result of the work of the author.


The paper presents a tool for the calibration of building-energy performance simulation models and applies the tool on a case study of the IEA Annex 58 single-housing model. The methodology of the tool was presented in a previous paper, *Narrowing the gap - A framework for connecting and auto-tuning a design BPS model to a physical building*. The tool aims to close the gap between building simulations and real measurements by using physically meaningful parameters that happen in real time. This leads to virtual sensing and the ability to know anything that is happening in the building at any moment, including variables that are hard to measure in real life, such as the operative temperature in a room.

**Author’s contribution:** This paper was jointly authored by Marc Azar and Samer Hassanie. The author of this thesis was responsible for all data processing and analysis.

The paper presents a numerical model for predicting occupancy profiles in office buildings based on simple measures like the time of the day, the day of the week (a weekday or a weekend), the outdoor temperature (the month), and the type of room. Data collected by the building automation systems is utilised and the data is processed in R. The model resulted in an out of sample error of 81 per cent. The availability of such tools could help energy modellers and designers have a more realistic perspective of the behaviour of occupants in a building.

**Author’s contribution:** Marc Azar wrote the literature review, while the author of this thesis, who also performed all the data processing, model construction and visualisation of the results, wrote the other parts of the paper.


The paper aims at providing a long-term performance assessment of autonomous, demand-controlled ventilation units. These units have all the sensors and flow control built in the diffuser, without the need for detached VAV boxes or wall-mounted sensors for temperature and/or occupancy, unlike with other units. It is also important to present such data to the scientific community, since most case studies regarding variable air volume or demand-controlled ventilation systems comprise short-term measurements or simulation results.

**Author’s contribution:** The author of this thesis has written this paper, in its entirety.
Chapter 2

Literature Review

This chapter provides an overview of some of the available energy certification schemes, and focuses on the areas they cover and what they are lacking. The results of recent studies in building-performance assessment are then presented. The chapter ends with a discussion on the Internet of Things and in which direction the building sector should be heading in order to make the best of the technology available today.

2.1 Certification Systems

Building performance is usually assessed using various certification methods. Building-certification methods can be classified into two main types: National and commercial. National certification methods are specific to the country of origin. In contrast, commercial certification methods are used worldwide, with some being more popular in certain countries than in others. As mentioned in Chapter 1, Directive 2010/31/EU urged the European states to implement an energy-certification scheme for buildings, which only focused on the energy use (kWh/m²/year). That left each state with the freedom to include other building-performance indicators. Some of these national certification schemes include the environmental impact, which is expressed in g\(CO_2\) m² year. However, the energy declaration in Sweden only includes the annual energy intensity with seven categories ranging from A to G. This leaves the building occupant, or anyone who might be interested in renting out the building/apartment, with no information about the quality of the indoor environment, operational costs, and environmental impact.

On the other hand, there are several commercial certification methods, including Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Miljöbyggnad, and Well [8–11]. Table 2.1 shows the different categories, life-cycle stages and levels for each of the above-mentioned certification methods. While LEED, BREEAM, and Well are international, Miljöbyggnad is only used in Sweden. In addition, Miljöbyggnad is a compliance-based certification scheme, as opposed to a credit-based one (as is the case with the other methods). For example, knowing that a building is certified under Miljöbyggnad Guld directly indicates that less than 20 per cent of the occupants are dissatisfied with the thermal environment.
Table 2.1: Commercial certification methods (general information)

<table>
<thead>
<tr>
<th>Certification scheme</th>
<th>Categories</th>
<th>Life-cycle Stage</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEED</td>
<td>New construction, homes, schools, retail, data centres, warehouse and distribution centres, hospitality, health care</td>
<td>New construction, renovation, interior fit-out, existing, neighbourhood development</td>
<td>Certified, Silver, Gold, Platinum</td>
</tr>
<tr>
<td>BREEAM</td>
<td>Data centres, education, health care, industrial, mixed-use, office, other buildings, residential, retail</td>
<td>New construction, master planning (communities), in-use, refurbishment and fit-out</td>
<td>Acceptable, Pass, Good, Very Good, Excellent, Outstanding</td>
</tr>
<tr>
<td>Miljöbyggnad</td>
<td>Single family housing, multifamily housing, office, schools, hospitality, retail, other</td>
<td>New construction and existing (renovation in process)</td>
<td>Bronze, Silver, Gold</td>
</tr>
<tr>
<td>Well</td>
<td>Education, residential multifamily, athletic facilities, retail, arenas, health care</td>
<td>Core and shell, new construction, and tenant improvement (renovation)</td>
<td>Silver, Gold, Platinum</td>
</tr>
</tbody>
</table>

Table 2.2 includes a full list of the focus areas of each of the certification methods mentioned above. Although LEED and BREEAM have the indoor environment and some aspects of the occupants’ wellbeing as their focus areas, the prerequisite points assigned to these areas are not strict. This led to the emergence of Well, which focuses on all aspects of occupants’ wellbeing and has stricter requirements in each of the focus areas to get the minimum level of certification. However, knowing that a building is Well-certified does not give any indication of its energy performance. Similarly, knowing that a building is LEED- or BREEAM-certified does not ensure a high-quality indoor environment. That is what makes Miljöbyggnad special. It encompasses different aspects of building performance and ensures that the building complies with the requirements.

Table 2.2: Commercial certification methods (focus areas)

<table>
<thead>
<tr>
<th>Certification scheme</th>
<th>Focus areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEED</td>
<td>Location and transportation, sustainable sites, energy and atmosphere, regional priority, innovation, water efficiency, materials and resources, indoor environmental quality</td>
</tr>
<tr>
<td>BREEAM</td>
<td>Transportation, waste, water, energy, health and wellbeing, pollution, innovation, management, materials, land use</td>
</tr>
</tbody>
</table>
2.2 Building-Performance Assessment (recent studies)

<table>
<thead>
<tr>
<th>Certification scheme</th>
<th>Focus areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miljöbyggnad</td>
<td>Energy, indoor environment, material and chemicals</td>
</tr>
<tr>
<td>Well</td>
<td>Comfort, water, air, light, mind, fitness, nourishment, mind</td>
</tr>
</tbody>
</table>

Another area in which these certification methods fall short is in conveying to the users the value of having the building certified. Having a LEED, BREEAM, Well, or Miljöbyggnad logo at the entrance of a building does not tell the users anything, especially if they have no deep knowledge of the certification methods. Better ways of visualising the certification are needed.

In this section, four commercial certification methods were discussed, highlighting their strengths and shortcomings. In the case of BREEAM and LEED, more restrictions/pre-requisites must be defined to ensure a high-quality indoor environment and generally provide better service to the building’s users/occupants. All the certification methods mentioned above must improve certification visualisation and ensure that all stakeholders are well aware of the meaning of the certification. Results from recent studies in building performance assessment are presented and discussed in the following section.

2.2 Building-Performance Assessment (recent studies)

Following the discussion in the previous section, a literature review focusing on more than 10 building-assessment methods is presented in [12]. The timing and circumstances for using the respective assessment method are not explicitly indicated and create confusion. Moreover, comparing these methods and their results was very difficult, which makes it impossible to know how reliable these results are. Another aspect of building classification that has been used without serious verification is the assumption that buildings that are the same type or serve the same purpose, are similar. A study in [14] showed that this is not the case and proposed a methodology of building clustering based on the assessment of multiple building features. This allows the classification of buildings to be founded on the actual performance and characteristics of buildings, rather than an unverified assumption. Another aspect of building performance that is often neglected is the perceived performance, which, along with the designed/simulated and measured performance, closes the building-performance loop. Long-term assessment of the designed/simulated, perceived and measured building performance leads to a better understanding of the dynamics of a building, and ensures that systems perform as expected and the occupants are provided with high-quality service. However, there are still challenges to achieving this integrated assessment, among which are economic and social factors. Reports of the PROBE (Post-occupancy Review of Building Engineering) project, carried out in the United Kingdom over a period of three years, showed that stakeholders are usually concerned about who pays for the post-occupancy evaluation (POE) and if taking part in POEs affect their reputation [16, 17]. There is a need for a holistic
approach to building performance assessment, instead of a narrow focus on just energy use. The scope should also include quality factors that affect the building’s occupants [13,28]. In what follows, various methodologies for building assessment and proposed features are presented.

In [15], Casals pinpoints two important indicators of a building’s performance that are usually neglected. The first indicator involves presenting the energy use in terms of primary energy, which takes into consideration the efficiency of the installed systems. The second indicator is the unit of the building energy use, in which kWh per inhabitant is proposed, rather than kWh per m². However, the latter will face much socio-political resistance. However, it could be argued that different building types have different occupancy densities, and it might be unfair to compare the performance of buildings of different types based on the energy used in kWh per inhabitant.

A building assessment tool is presented in [29] that provides the user with single- and multi-criteria assessment options. The available set of criteria includes: Energy use, primary energy use, indoor thermal comfort indicators (highest and lowest operative and radiant temperatures, relative humidity and discomfort degree hours), in addition to other life-cycle parameters. On the other hand, a methodology that focuses on economic aspects (energy intensity), social aspects (occupancy density and percentage of air-conditioned area), and environmental aspects (indoor environment) is presented in [18]. Other studies presented methodologies along the same lines as those mentioned above, taking into account aspects other than the energy intensity while assessing building performance [19,30,20,22,25]. Another methodology, presented in [21], only focused on the investment and return period. Although these are important in early design stages, the operational cost becomes more important later on in the life cycle of the building and should be incorporated into the building-performance assessment.

In a case study carried out in Denmark, a building-performance assessment was done on a plus energy house [23], focusing on onsite energy production, total energy use and the quality of the indoor thermal environment, as represented by the operative temperature. This is important in that it shows that these types of buildings are not only theoretically possible, but also perform as expected in reality and provide the occupants with a high-quality indoor environment. This is one of the advantages of a holistic approach to building performance and makes these buildings attractive to prospective occupants/clients, who are aware of the energy use from both an environmental and economic perspective [24]. Moreover, the paper also states that occupants are concerned about the quality of the indoor environment.

On a wider scale, the IEE iSERVemb project [27] inspected 330 buildings in 15 different European countries and concluded that the total energy use in the EU can be reduced by 1–5 per cent if the same methodology of operational data analysis is adopted. Moreover, it was proposed in [26] to use the operational data from the project for legislative compliance. This will ensure that a building complies with local regulations that are not based on its simulated performance, but rather on the measured performance. This would be a great step in the building sector, but one should not forget the quality of the service provided to building occupants. After all, occupants are the most important asset in any building. If the quality of the service is included alongside the energy use as part of new legislation, it will be a great leap forward toward not only energy-efficient buildings but also a high-quality indoor environment. Both the legislators and the building owners should have the occupants’ best interest in mind.
2.3 Internet of Things and Big Data

Nowadays, most buildings are equipped with a BAS, which provides facility managers with real-time insights into the performance of their buildings, depending on the level of detail the BAS provides. Perhaps the most connected building in the world today is the Edge, which is the Deloitte headquarters in Amsterdam. One of the features of the building is that the environment in flexible-seating offices is customised, depending on the occupant, taking into account their previous preferences for factors such as lighting and temperature. In addition to individualised ventilation and lighting, what can a detailed analysis of building operational data show?

A study conducted in [31] showed that building performance could be estimated by taking measurements in approximately 20 per cent of the building, reducing the data points and excessive amount of data and corresponding costs. This was done after full-scale measurements were taken in two floors of a building to identify the key points that are representative of the other spaces.

Another use of high-quality data is to produce occupancy schedules that represent reality, since the main differences in measured and simulated performance arise from discrepancies between the expected and actual behaviour of the occupants [32]. However, only just enough data should be utilised [33]. The data can also be integrated with BIM models in order to obtain a visualisation of the sensors so that facility managers can more easily follow up with the performance of the building.

The entire potential for operational data has not yet been utilised. New methodologies are on the rise for fault detection and diagnosis at both the building and system levels. In addition, a more detailed insight and visualisation of the building operation leads to a better understanding of the underlying connections between the building’s energy, customer satisfaction, and environmental and economic impact.
Chapter 3

Methods

In this chapter, the methods used to acquire, analyse and visualise building-performance data are described, and an integrated building declaration is presented.

3.1 Data Acquisition and Processing

The dataset analysed in Chapter 4 consists of two subsets. The first dataset contains hourly values obtained from all the energy meters installed in the building and will be described in detail in Chapter 4. The energy meters measure the total district heating, domestic hot water, floor heating, cold-water preheating, comfort cooling, cooling delivered to the air-handling units (AHUs), free cooling, process cooling, electricity used for services, tenant-related electricity use, and other energy streams. The second dataset is acquired by the BAS through sensors installed in the supply diffusers. The diffusers contain room temperature, flow, duct temperature, pressure difference, and passive infrared (PIR) sensors, and other types of sensors. The building is equipped with 1,700 such diffusers (sensor points), which are uniformly distributed throughout the occupied spaces. Table 3.1 includes some of the sensors’ specifications.

Table 3.1: Sensor specifications

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Accuracy / Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room temperature</td>
<td>± 0.3 degrees Celsius</td>
</tr>
<tr>
<td>Airflow</td>
<td>± 2 litres per second</td>
</tr>
<tr>
<td>Occupancy presence</td>
<td>Can detect movements of 20 cm</td>
</tr>
</tbody>
</table>
Figure 3.1 shows a schematic of how raw data is transformed into useful information that can be acted upon. The thick arrows represent processes that automatically happen in real time. The sensors in the diffusers measure various states and deliver the information to the BAS. Based on a change-on-value compression scheme, the data is then stored on a local server. The thin lines represent tasks that must be done manually, including exporting, processing, analysing and visualising the data. These tasks can be automated in the future since the same data structure will be exported from the database, therefore increasing the efficiency and speed of the process. All data processing was done using RStudio [38].

![Figure 3.1: Process schematic of transforming raw data into useful visualisations](image)

The raw data from the energy meters is exported in a straightforward structure, with one file per meter and hourly values representing the amount of energy that was used between that measurement and the next one. The raw data from the diffusers is directly exported from the server and has the structure shown in Figure 3.2. The unique ID refers to the diffuser identification number, which is unique to each diffuser. The token represents the measured state that is being reported (such as temperature, flow and occupancy status).
3.1. Data Acquisition and Processing

![Figure 3.1: Raw data structure](image)

In order to fill in missing values and get a regular time step, the data structure must be transformed into a wide format, in contrast to the current long format. This is done for each measured state, so the result will be several data files with a similar structure (Figure 3.2). This is an example of a 10-minute temperature data file for all the diffusers with IDs from 11001 to 11004.

![Figure 3.2: 10-minute data](image)

Having the data in this format makes it easier for further visualisation and manipulation, depending on the objectives. In addition, having the data separated according to measured state reduces the size of the file that must be read at a specific instance, making it more feasible to manage from a computational power viewpoint.
Different types of visualisation methods were used in this thesis and the appended papers, depending on the message being conveyed. For example, two main methods were used in Paper 1: Line graphs and bar charts. The line graphs were used to represent the operational costs (in Swedish Kronor) and the environmental impact (in \(kg CO_2 m^2 year\)), whereas the bar charts were used to represent the monthly energy profile of a building, masked with different colours for the different uses (such as heating, cooling, and domestic hot water). Carpet plots were used for a more detailed energy analysis, presented in Chapter 4. Carpet plots have often been used for this purpose and present the possibility of following patterns in daily energy use and detecting any anomalies [34]. Moreover, scatter plots of the supply airflow were presented in Paper IV. The points were masked with a colour representing the respective occupancy status of the unit. This method of representation provided a better understanding of the performance of the diffusers and detected a fault of which the building managers might not be aware.

### 3.2 Integrated Building Performance

In the previous section, the means by which data can be transformed and visualised into useful plots was described. As discussed in the Introduction, there is a need for a holistic approach to building performance, based upon not only the building’s energy use, but also other economic, environmental and quality factors: energy use, operational costs, environmental impact, service quality, power and occupancy efficiency. Long-term analysis of these parameters allows for a better understanding of their underlying correlations, which can eventually lead to more efficient building operation. Moreover, a better version of the currently available energy declarations that incorporates those parameters is also needed.

Recently, there have been many discussions on whether to express energy in \(kWh m^2 year\), \(kWh inhabitant year\), \(kWh bed year\) (in hospitals) or \(kWh room year\) (hotels). However, \(kWh m^2 year\) is the most widely accepted representation. The representations for hospitals and hotels could be misleading and assume that buildings of the same type behave similarly. This is not the case, as mentioned in Chapter 1. The representation \(kWh inhabitant year\) fails for the same reason, since buildings of the same type are inherently designed according to similar occupancy densities. Instead, we propose to use \(kWh m^2 year\) and add a factor called occupancy efficiency. The occupancy efficiency is calculated as follows:

\[
\text{Occupancy Efficiency} = \max \left( \frac{\sum_{j=1}^{m} PIR_{signal}}{n} \right)
\]

(3.1)

The \(PIR_{signal}\) represents the output of the PIR sensor, \(m\) represents the number of sensors in a zone and \(n\) is the total number of zones of the same type in a building. The type of zone referenced here is the one that is mostly representative of the building. For example, in the case of the office building, the zones under study will be offices. In the case of a hotel, it is rooms.
The operational costs in the Swedish context are represented in Swedish Kronor, and the environmental impact is represented by $kg CO_2 m^2 year$. Finally, the service quality indicates how satisfied the occupants are with the indoor environment. This includes satisfaction with certain aspects of the indoor environment: Thermal, acoustic, visual and indoor air. The best way to capture occupants’ satisfaction is through questionnaires that directly convey the occupants’ perception of the indoor environment. A questionnaire that allows the facility manager to capture the daily occupants’ perceptions is presented in Appendix A.1. Another questionnaire, based on the Occupant Indoor Environment Quality (IEQ) survey (developed at the Center For The Built Environment, at the University of California, Berkeley), is presented in Appendix A.2 [35]. This longer survey should be used on a quarterly basis. It is more comprehensive than the shorter questionnaire and leads to a better understanding of the relationship between the occupant and the indoor environment. The survey also helps in detecting possible faults that might not be obvious through the BAS.

Since the questionnaire could not be deployed in this thesis, BAS data was utilised. However, the available data only allowed for assessment of satisfaction in the thermal environment. This was done by calculating the average of the daily degree hours outside the ranges recommended by standard EN 15251 (2007) [36].

We define the Integrated Building Performance Declaration (IBPD) as a parallel-coordinates plot, including all the above-mentioned parameters. An IBPD of the case study building is presented in Chapter 4.
Chapter 4

Results and Discussion: A Case Study of an Office Building in Stockholm

As a case study, we chose an office building located in Stockholm. The building had a total floor area of 39,300 m² and encompassed spaces with various types of usage, including open office spaces, flexible-seating offices, meeting rooms, a gym and changing rooms, a restaurant and a café. The reason for choosing this building is that it was well equipped with sensors on the zone levels that monitored not only room temperatures, but also the flow, presence, duct temperature, pressure difference and other important variables. Moreover, the installed energy meters don’t just offer insight into the building energy use on the global level, but also provide a detailed perspective into the sublevels. In particular, the building consists of many energy-recovery paths, which are well monitored. In this chapter, we present a detailed dissemination of the building energy use, as well as an occupancy assessment based on which types of rooms are used the most, how often occupancy changes due to external factors, environmental impact, operational cost of the building and the quality of the thermal environment. Finally, we conclude with a visualisation of the IBPD, based on the methodology described in Chapter 3.

4.1 Energy Performance Assessment

The building is divided into three zones, for which a system of two AHUs and two circulating units (CU) is used for ventilation purposes. The ventilation system is a demand-controlled ventilation (DCV) system and provides air to the zones through autonomous supply diffusers that consist of several sensors and control the flow by the percentage of their openings, depending on the room temperature and the presence/absence of occupants in the zone. In addition, a CO₂ sensor, located on the return air duct of each AHU-CU system, controls the amount of fresh air introduced into the mixing box.

The main heating terminal units are radiators that are fed by hot water from district heating. The cooling system supplying the air-handling units, server rooms and other areas, consists of several components (Figure 4.1), and has two chillers, five wet-cooling towers, and a borehole field. Moreover, the building makes use of several heat and cooling recovery pathways to decrease energy use. The building will be certified under Miljöbyggnad Guld and ran smoothly for the duration of the study, as the following subsections will show. Each
subsection deals with a specific energy stream, including district heating, cooling (free cooling and electric), and electricity use (services tenants, and facilities). This shows how many of these streams use energy and their required maximum power, in addition to shedding light on the operation schedules ensuring the systems are operating as expected.

Figure 4.1: The building’s cooling (blue) and heating (red) systems.

4.1.1 District Heating

There is no on-site heat production available in this building, and the only source of hot water is district heating, which is further used for heating through radiators, domestic hot water, floor heating, and cold water preheating.

Figure 4.2 shows the hours of the day as a function of days between Jan. 1 and Sept. 29, 2015. The colour indicates the heating part of the utilised district heating, with the white and blue colours corresponding to powers of 600 kW and 0 kW, respectively. The grey colour indicates negative values. This might be a result of an error in the energy meters, since the results shown in the figure are calculated by subtracting the domestic hot water from the total district heating part. However, in this particular figure, we consider the grey points equivalent to the blue points, corresponding to a value of 0 kW. Without a weather file for the period of the obtained measurements, we were unable to correct the utilised heating energy to a normal year values using the degree-days method. Therefore, the reported values are the unaltered measured values. The average heating power is 56.3 kW. When extrapolated to a yearly
4.1. Energy Performance Assessment

average, we obtain an energy use of 12.54 kWh/m²/year. This result might contain bias, especially without data for November and December, which require a considerable amount of heating. On the other hand, it is interesting that the highest energy use during the heating season occurs as expected, during the operational hours between 6 am and 7 pm and a base load during the night between 200 kW and 300 kW.

Figure 4.2: Heating power (kW)

Figure 4.3 represents the energy used for domestic hot water during the same period as above. In this plot and all subsequent plots, we apply the same concept as in Figure 4.2. The hours of the day are plotted as a function of days, and the colour corresponds to the energy stream at hand. In this case, the energy stream is domestic hot water use. The white and blue colours represent 150 kW and 0 kW, respectively. The average power needed for domestic hot water is 31.61 kW, which yields an energy use of 7.05 kWh/m²/year. The result is more accurate than the heating energy intensity since there is little variation in the use of domestic hot water throughout the year, except for weekends, and Easter and summer vacations (Figure 4.3). The minimum use of domestic hot water is approximately 10 kW, shown in the figure below by the purple colour, even outside the range of working hours. This could be a result of a defect in the energy meter or leaks/losses occurring on this side of the energy system, which requires a more thorough check.

Figure 4.3: Domestic hot water (kW)
Figure 4.4 shows the variation in the energy required for floor heating, which is applied in limited areas. The blue and white colours correspond to 0 kW and 50 kW, respectively. The average power is 1.51 kW and yields an annual energy intensity of approximately 0.34 kWh/m²/year. From the figure, one is unable to identify a constant pattern in the utilisation of floor heating in which the maximum energy use occurs during various times of the day for different days.

![Figure 4.4: Floor heating (kW)](image)

Finally, the last energy stream using district heating is cold-water preheating (Figure 4.5). The blue and white colours represent 0 kW and 50 kW, respectively. The energy use follows the occupancy schedule (working hours) to a great extent, with varying use between 6 am and 7 pm, and no use at all during the rest of the day. The average power is 5 kW and leads to an annual energy intensity of 1.11 kWh/m²/year.

![Figure 4.5: Cold water preheating (kW)](image)

The district heating parts that will be included in the building energy use (as defined by BBR) are the heating, domestic hot water and floor heating, shown in (4.1), below.

\[
BuildingSpecificEnergyUse(Heating) = 12.54 + 7.05 + 0.34 = 19.93 \frac{kWh}{m^2 \cdot year}
\]  (4.1)
4.1.2 Cooling

As defined by BBR, *comfort cooling* is the energy used to ensure an acceptable indoor thermal environment. Any cooling that is directly extracted from the environment is not considered part of comfort cooling and is known as *free cooling*. Figure 4.6 shows the energy used for comfort cooling during the study period. The blue and white colours correspond to 0 kW and 400 kW, respectively. The energy use is within the operation hours, except for some days in July when the systems operate outside regular hours. The average power provided for comfort cooling is 5.18 kW, and results in an annual energy intensity of 1.15 kWh/m²/year. This is already the basic energy use multiplied by a factor of 3, as required by BBR for buildings with heating sources other than electric heating, which is the case here.

![Figure 4.6: Comfort cooling (kW - according to BBR)](image)

The following figures focus on the AHUs’ cooling energy use, including free cooling from separate streams. The AHUs are the main cooling providers to the building. Figure 4.7 represents the total cooling provided to the AHUs during the study period. The blue and white colours correspond to 0 kW and 1000 kW, respectively. The main energy use falls within the operation hours (6 am to 7 am), except for some days in July as also seen in Figure 4.6. It is obvious that this is mainly provided through electric cooling, which normally should not be running outside the operation hours, so requires a closer look. The average power required for cooling is 48.28 kW and corresponds to an uncorrected annual energy use of 10.76 kWh/m²/year for cooling.

![Figure 4.7: Cooling delivered to the AHUs (kW)](image)
There are two streams of free cooling that provide chilled water to the AHUs cooling coils. The first is through evaporative cooling using cooling towers (KB13), and the second is delivered using the condenser side of the chillers, by-passing the compressor (KB14). Figure 4.8 shows the cooling energy delivered by KB13 during the study period. The blue and white colours correspond to 0 kW and 300 kW, respectively. The average delivered power is 19.95 kW and results in an annual energy intensity of 4.45 kWh/m²/year. This is part of the total cooling delivered to the AHUs. There also seems to be a base load outside the regular operation hours in some days during July.

![Figure 4.8: Free cooling from the cooling towers delivered to the AHUs (kW)](image)

The energy delivered to the AHUs from KB14 is visualised in Figure 4.9. The blue and white colours represent 0 kW and 500 kW, respectively. The average delivered power is 21.4 kW, and the annual energy intensity is 4.77 kWh/m²/year. The comments above regarding the operation hours also apply for KB14. Although the average of the delivered power from KB13 and KB14 are very close, KB14 provides a relatively higher capacity when needed.

![Figure 4.9: Free cooling from the chillers, by-passing the compressor, delivered to the AHUs (kW)](image)

Figure 4.10 shows the proportion of delivered free-cooling energy by source during the studied period. Both streams are equally important and provide a significant amount of the cooling demand required by the AHUs.
Figure 4.10 shows the proportion of delivered free-cooling energy by source during the studied period. Both streams are equally important and provide a significant amount of the cooling demand required by the AHUs.

![Pie chart showing the proportions of free-cooling energy delivered via KB14 and KB13]

**Figure 4.10: Sources of delivered free-cooling energy to the AHUs**

Two zones in the building require process cooling (according to the Swedish building code). The server and trading rooms. The energy used for process cooling is not included in the total building energy use (BBR). Figure 4.11 shows the amount of cooling delivered to the server room during the study period. The blue and white colours represent 0 kW and 200 kW, respectively. The average power is 83.76 kW, and the resulting annual energy intensity is approximately 18.67 kWh/m²/year for server-room cooling. The cooling is provided throughout the day. However, there are many hours following normal cooling load requiring 0 kW of cooling. It is interesting to see whether or not the system should be operating in this manner, since faults may arise in the future due to cycling effects.

![Graph showing process cooling delivered to the server room (kW)]

**Figure 4.11: Process cooling delivered to the server room (kW)**
Figure 4.12 shows the energy delivered to the trading area, with the blue and white colours corresponding to 0 kW and 100 kW, respectively. The average required power is 37.31 kW and yields an annual energy intensity of 8.32 kWh/m²/year. The same cyclical behaviour noticed in the server room can be seen in the trading-area delivered process cooling.

![Figure 4.12: Process cooling delivered to the trading area (kW)](image)

The total free cooling delivered to process has an average power of 97.47 kW, corresponding to approximately 21.73 kWh/m²/year. This is almost 80 per cent of the total process-cooling demand. This is divided between four sources, as shown in Figure 4.13, in which all the sources have a significant contribution to the total, delivered free cooling for processes. The fourth stream, cooling recovery, refers to heat mainly available from the borehole field.

![Figure 4.13: Sources of delivered free cooling energy to the processes](image)

The cooling part that will be included in the building energy use (as defined by BBR) is the comfort cooling, shown in (4.2), below.
\[ \text{Building Specific Energy Use (Cooling)} = 1.15 \frac{kWh}{m^2 \cdot \text{year}} \] (4.2)

4.1.3 Electricity

Property energy is defined by the Swedish building code as the electricity used to make the building ready for use. Figure 4.14 shows the property energy during the studied period. The average required power is 55.21 kW and results in an annual energy intensity of 12.32 kWh/m²/year. The blue and white colours reflect a power of 0 kW and 300 kW, respectively. The demand seems to be in line with operation hours, except for a load of around 100 kW occurring two hours before 6 am from mid-June until the end of September, which requires a closer look.

![Figure 4.14: Property energy (kW)](image)

Domestic energy is related to the use of spaces, including lighting, computers and any other appliances. In Figure 4.15, we focus on the domestic energy used in the office areas. The blue and white colours correspond to 0 kW and 200 kW. The average required power is 96.59 kW, yielding an annual energy intensity of 21.53 kWh/m²/year. The energy use seems to be within operational hours, with a normal base load of approximately 25 kW and a base load of approximately 100 kW during February and March. This would require further investigation. It is interesting to note that there has not been a drastic decrease in the electric energy use in the offices during the vacation months, which raises the question of if the lighting and computers are on even with are no, or few, occupants.
4.1. Energy Performance Assessment

![Diagram of Domestic energy for the office areas (kW)](image)

**Figure 4.15:** Domestic energy for the office areas (kW)

Figure 4.16 presents the electric energy used by the restaurant on the building’s ground floor. The blue colour represents 0 kW, and the white colour represents 150 kW or greater. The average required power is 32.34 kW, corresponding to an energy intensity of 7.2 kWh/m²/year. The main energy use in the restaurant is between 8 am and 2 pm. As for the other times of day, there seems to be a base load that could be justified by appliances such as refrigerators.

![Diagram of Electricity used by the restaurant (kW)](image)

**Figure 4.16:** Electricity used by the restaurant (kW)

The café requires an average power of 4.86 kW, which yields an energy intensity of 1.08 kWh/m²/year. The demand is uniform throughout the day, at approximately 15 kW. This load was outside the normal operation hours, probably due to the same reasons mentioned above for the restaurant.
According to BBR, the part of electricity use that is included in the building’s specific energy is the property energy, visualised in Figure 4.14.

\[
\text{Building Specific Energy Use (Electricity)} = 12.32 \frac{\text{kWh}}{\text{m}^2 \cdot \text{year}} \quad (4.3)
\]

The total estimated building-specific energy use is then calculated, which sums up the heating, cooling and electricity components to yield:

\[
\text{Building Specific Energy Use} = \text{Building Specific Energy Use (Heating)} + \text{Building Specific Energy Use (Cooling)} + \text{Building Specific Energy Use (Electricity)}
\]

\[
\text{Building Specific Energy Use} = 19.93 + 1.15 + 12.32 \quad (4.4)
\]

\[
\text{Building Specific Energy Use} = 33.4 \frac{\text{kWh}}{\text{m}^2 \cdot \text{year}}
\]

The building’s specific energy use complies with the requirements for Miljobyggnad Guld.

### 4.2 Occupancy Assessment

Users are one of a building’s most important assets. It is crucial to study users’ behaviour to better understand their needs and provide them with a service of high quality. One aspect of users’ behaviour is their absence/presence in a building’s zones. This answers many questions, such as which spaces are mostly occupied, when are they occupied and if there are certain factors that govern such variations in presence/absence.
As mentioned earlier, air is supplied into the spaces through diffusers that are well-equipped with PIR sensors. For the purpose of finding patterns in occupants’ presence, the data provided by the PIR sensors through the BAS was utilised. The building was divided into 346 zones, per the architectural plans. The signals from each zone were averaged to get an occupancy percentage, which gives us an idea of how full the room is. The results were further averaged for the following factors:

- Time of the day
- Type of day
- Month
- Type of room

The idea was to relate the occupancy presence to physically meaningful parameters. The time of the day is self-explanatory. The type of day signifies if it is a weekday or a weekend. The month was a measure of outdoor temperature, since no actual weather file was available. The type of room, which represents not only the activity taking place in the space, but also occupant arrangement, such as open office spaces, individual offices or flexible-seating spaces. Moreover, the study period is from March until September, excluding June and July, which were not available in the dataset. In order to ensure that the distributions representing each type of room are different, we applied a Mann-Whitney U test against the null hypothesis that two distributions have the same, or similar, means. Table 4.1 shows the results of the Mann-Whitney U test, which considers the type of room as the characteristic variable. The ✓ indicates that the test resulted in a p-value less than 0.05, in which case the difference between the two distributions is significant. Otherwise a ✗ is used. In this case, the room type is an important factor in the occupants’ presence/absence. All the types of rooms possess a different occupancy percentage distribution compared to each other.

### Table 4.1: Results of the Mann-Whitney U test for room type

<table>
<thead>
<tr>
<th></th>
<th>Changing Room</th>
<th>Conference Room</th>
<th>Flexible Seating</th>
<th>Meeting Room</th>
<th>Open Office</th>
<th>Single Office</th>
<th>Sports Facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changing Room</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Conference Room</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Flexible Seating</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Meeting Room</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Open Office</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Single Office</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
</tr>
<tr>
<td>Sports Facilities</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.2 shows the results from the Mann-Whitney U test performed during different months for open offices. Since the month was used, instead of the outdoor temperature, it is hard to
find differences in this dataset. However, the occupancy percentage varies the least for open offices and different months compared to other types of rooms (Figure 4.18). In this case, the difference is less than 5 per cent between the month with the highest occupancy percentage distribution and that with the lowest. On the other hand, the difference resulting from the type of day is clearly demonstrated in Figure 4.18, in which the occupancy percentage is almost zero during weekends for all the months.

Table 4.2: Results of the Mann-Whitney U test for different months (Open office spaces)

<table>
<thead>
<tr>
<th></th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>August</th>
<th>September</th>
</tr>
</thead>
<tbody>
<tr>
<td>March</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>April</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>May</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>August</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>✓</td>
</tr>
<tr>
<td>September</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 4.18: Open office spaces

Meeting rooms show a higher rate of variability between different months, which is evident in Figure 4.19. The difference between the month with the highest occupancy percentage distribution and the lowest percentage may be as much as 20 per cent (Table 4.3). The difference between the distributions is almost as significant between the months in comparison to the results obtained for open office spaces (Table 4.2).

Table 4.3: Results of the Mann-Whitney U test for different months (Meeting rooms)

<table>
<thead>
<tr>
<th></th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>August</th>
<th>September</th>
</tr>
</thead>
<tbody>
<tr>
<td>March</td>
<td>-</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>April</td>
<td>x</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>May</td>
<td>x</td>
<td>✓</td>
<td>-</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>August</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>September</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>-</td>
</tr>
</tbody>
</table>
Moreover, Figure 4.20 shows an even greater difference in the occupancy percentage distributions for each month in the case of conference rooms. This is confirmed by the results in Table 4.4. The test only applied on the distributions of May and April, so failed to reject the null hypothesis of equal means. The purpose of showing both the results of the Mann-Whitney U test and the visualisation of the distributions was to emphasise that the difference is not only visual, but also can be statistically proven. We will focus only on the visual representation for the other types of rooms in order to avoid redundancy.

Table 4.4: Results of the Mann-Whitney U test for different months (Conference rooms)

<table>
<thead>
<tr>
<th>March</th>
<th>April</th>
<th>May</th>
<th>August</th>
<th>September</th>
</tr>
</thead>
<tbody>
<tr>
<td>March</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>April</td>
<td>✓</td>
<td>-</td>
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<tr>
<td>May</td>
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<tr>
<td>August</td>
<td>✓</td>
<td>✓</td>
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<td>-</td>
</tr>
<tr>
<td>September</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
</tr>
</tbody>
</table>
Offices with flexible seating are another type of room. These are office spaces that employees might occupy on a certain day. Figure 4.21 reveals that the maximum occupancy percentage in offices with flexible seating is approximately 60 per cent. This is lower than the maximum percentage in meeting rooms, conference rooms and open office spaces (75 per cent – 80 per cent). Moreover, the occupancy percentage distribution for March and September are similar. There were small differences in the distributions for April, May and August. This is one limitation of using the month instead of the outdoor temperature in either the form of a daily average or a three-day average, especially when little is known about the actual outdoor conditions during those months for 2015.

![Figure 4.21: Offices with flexible seating](image1)

There is only one individual office space in this building. On average, it is 40 per cent occupied at any time of the day (Figure 4.22). There are no clear variations with the months. This can be justified by being the only individual office with this setup, and the position and responsibilities of the person occupying this office.

![Figure 4.22: Single office](image2)

Other types of rooms with minimal, or no, variation in occupancy percentages include the sports facilities (gym, squash and spinning rooms) and the changing rooms. There are three clear peaks in Figure 4.23 and Figure 4.24 during times that correspond to before work, the lunch break, and after work. In addition, the figures show a difference in the occupancy
percentage distributions of both types of rooms between weekdays and weekends. However, these are the only rooms that show a significant presence during the weekends.

![Occupancy Graph](image)

**Figure 4.23: Sports facilities**

One thing to notice in Figure 4.24 is that the occupancy levels are at their highest (100 per cent). This could be because there are only two changing rooms in the building, which are served by four diffusers each. The presence of one occupant can trigger all four sensors, leading to the false conclusion that the entire room is fully occupied.

![Occupancy Graph](image)

**Figure 4.24: Changing rooms**

Finally, since this is an office building, the occupancy efficiency (defined in Chapter 3) will be calculated for the open office spaces.

\[
\text{Occupancy Efficiency} = 87.3\% \quad (4.5)
\]
4.3 Operational Cost and Environmental Impact

To calculate the operational cost and the environmental impact, the annual energy use is divided into two parts: Electric and heat. Energy prices presented in [2] were used. However, energy contractual data corresponding to each building should be used for more accurate results. The environmental impact factors introduced in [37] were taken into consideration.

\[
\text{Operational Cost} = [1.75 \times (1.15 + 12.32)] + (0.9 \times 19.93) = 41.51 \frac{kWh}{m^2 \cdot \text{year}} \quad (4.6)
\]

\[
\text{Environmental Impact} = \frac{[36 \times (1.15 + 12.32)] + (89 \times 19.93)}{1000} = 2.26 \frac{kg \text{CO}_2}{m^2 \cdot \text{year}} \quad (4.7)
\]

4.4 Service Quality Assessment (Thermal Environment)

As mentioned in Chapter 3, the degree hours method described in standard EN 15251 is utilised to assess the quality of the thermal environment. The recommended Level II limits are considered for both the heating (20°C–24°C) and cooling (23°C–26°C) seasons, since that complies with the requirements of Miljøbyggnad Guld. The resulting average of daily degree hours outside the range can be shown in (4.8).

\[
\text{Average Daily Unmet Thermal Conditions} = 0.17 \degree \text{C.h} \quad (4.8)
\]

4.5 IBPD

Figure 4.25 shows the IBPD of the building and includes the energy use, operational cost (OpC), environmental impact (EI), occupancy efficiency (OccEff) and average, daily unmet hours (AvgUH).
Figure 4.25: IBPD of the case study building
Chapter 5

Conclusions

This thesis, along with the appended papers, aimed at introducing a holistic approach to building performance by assessing a building as a whole, as well as individual systems and room units. The focus was to deviate from narrowly assessing building performance in terms of just energy use in $kWh/m^2\cdot year$ and instead include environmental, economic, and qualitative aspects of building performance. The parameters studied were the energy use ($kWh/m^2\cdot year$), emissions ($kg CO_2/m^2\cdot year$), operational cost (SEK), occupancy efficiency (%), and quality of the thermal environment (average unmet degree hours). All parameters were visualised in an IBPD that is easier for users to understand, instead of a letter that represents just one level of energy use or a certification logo. However, the method of representation and assessment is not limited to just these parameters. More parameters can be added, depending on the available data. The results of the case study show that gaining access to high-quality building-performance data and undertaking an integrated assessment lead to a better understanding of building performance. Based on the results presented in this thesis and the appended papers, the following conclusions can be presented:

- Just knowing the energy use is not sufficient for understanding the quality of the service provided to the occupants. That is evident from the results in Paper I, in which two days with the same energy use had different qualities of the thermal environment.
- Performing a thorough analysis of room unit data, as presented in Paper IV, allows for detection of faults that otherwise wouldn’t be possible to discover with the usual BAS data.
- The use of carpet plots for energy-data visualisation shows a very clear picture of the daily variations in energy use and extra energy use at unlikely times of the day.
- Visualising the building-performance parameters in a parallel coordinate plot is a more informative representation of the integrated building performance in comparison to the declarations available today.
- The results presented in Paper III show that occupants do not always behave as designers expected. By performing similar kinds of occupancy checks, we can detect patterns in occupant behaviour and have a better understanding of how the building must be run.
Chapter 6

Future work

The long-term, integrated assessment of building performance still uses not only the designed and measured performance, but also the perceived performance. Future work will aim at:

- Performing a long-term survey campaign using the survey available in Appendix A.1 by presenting it in a user-friendly application.
- Studying the differences between the perceived (surveys), measured (sensors and meters) and designed (as-built drawings) building performance.
- Measuring satisfaction through not only room sensors but also using biometric data measured by newly available wristbands that are capable of measuring important variables including but not limited to blood pressure and skin temperature. Such measurements performed over long periods lead to a better understanding of the various factors affecting the occupants’ comfort and perception of the thermal environment.
- Conducting studies on more buildings to answer the question of whether or not certain types of systems perform better for certain applications.
References


Appendix A.

Questionnaires
Questionnaires: A Short Survey
Hur upplever Du den termiska komforten på Din arbetsplats just nu? Det är:

- Kallt
- Svalt
- Något svalt
- Neutrat
- Något varmt
- Varmt
- Mycket varmt

Upplever Du detta som:

- Behagligt
- Något obehagligt
- Obehagligt
- Mycket obehagligt
- Extremt obehagligt

Skulle Du just nu föredra att ha det:

- Mycket svalare
- Svalare
- Något svalare
- Oförändrat
- Något varmare
- Varmare
- Mycket varmare

Hur upplever Du luftkvaliteten på Din arbetsplats just nu:

- Extremt nöjd
- Nöjd
- Något nöjd
- Varken nöjd eller missnöjd
- Något missnöjd
- Extremt missnöjd

Hur upplever Du belysningskvaliteten på Din arbetsplats just nu:

- Extremt nöjd
- Nöjd
- Något nöjd
- Varken nöjd eller missnöjd
- Något missnöjd
- Extremt missnöjd

Hur upplever Du den akustiska kvaliteten på Din arbetsplats just nu:

- Extremt nöjd
- Nöjd
- Något nöjd
- Varken nöjd eller missnöjd
- Något missnöjd
- Extremt missnöjd

Hur är Du klädd idag (underkläder räknas ej med) med avseende på antal lager på överkroppen:

- Ett lager
- Två lager
- Tre lager
- Fyra lager
- Fem lager
Questionnaires .2 Long Survey
Bakgrund

Hur många år har Du arbetat i denna byggnad?
  o Mindre än 1 år
  o 1-2 år
  o 3-5 år
  o Längre än 5 år

Hur länge har Du arbetat på Din nuvarande arbetsplats?
  o Mindre än 3 månader
  o 4-6 månader
  o 7-12 månader
  o Över ett år

Hur många timmar tillbringar Du på Din arbetsplats under en typisk vecka?
  o 10 eller mindre
  o 11-30
  o Över 30

Hur skulle Du beskriva Ditt arbete?
  o Administratör
  o Tekniker
  o Tjänsteman/Sakkunnig
  o Chef
  o Annat

Din ålder
  o 30 eller under
  o 31-50
  o Över 50

Ditt kön
  o Kvinna
  o Man
Arbetsplatsens belägenhet

På vilken våning är Din arbetsplats belägen?
- Nedre botten
- 1 tr
- 2 tr
- 3 tr
- 4 tr
- 5 tr
- 6 tr
- 7 tr

I vilken del av byggnaden är Din arbetsplats belägen?
- Norra delen
- Östra delen
- Västra delen
- Södra delen
- Mitt i byggnaden
- Vet ej

Åt vilket håll vetter fönstret/-en närmast Din arbetsplats?
- Norr
- Öst
- Väst
- Syd
- Inga fönster
- Vet ej

Befinner sig Din arbetsplats inom 5m från en yttre vägg?
- Ja
- Nej

Befinner sig Din arbetsplats nära ett fönster (inom 5m)?
- Ja
- Nej
Beskrivning av Din arbetsplats

Vilket beskriver Din arbetsplats bäst?

- Eget kontorsrum
- Delat kontorsrum
- Kontorsbås med skilleväggar (högre än 1,5 m)
- Kontorsbås med skilleväggar (lägre än 1,5 m)
- Arbetsplats i öppet landskap utan skilleväggar
- Annat:
Kontorslayout

Hur nöjd är Du med utrymmet för individuellt arbete och förvaring?
Där 3 innebär ”Mycket nöjd” och -3 innebär ”mycket missnöjd”

- 3
- 2
- 1
- 0
- -1
- -2
- -3

Hur nöjd är Du med nivån av insyn?
Där 3 innebär ”Mycket nöjd” och -3 innebär ”mycket missnöjd”

- 3
- 2
- 1
- 0
- -1
- -2
- -3

Hur nöjd är Du med layouten av Din arbetsplats i förhållande till möjligheten till smidigt samarbete med Dina medarbetare?
Där 3 innebär ”Mycket nöjd” och -3 innebär ”mycket missnöjd”

- 3
- 2
- 1
- 0
- -1
- -2
- -3

Stödjer layouten (i det stora hela) utförandet av Dina arbetsuppgifter?
Där 3 innebär ”Stödjer helt” och -3 innebär ”Stödjer inte alls”

- 3
- 2
- 1
- 0
- -1
- -2
- -3

Vg beskriv andra aspekter av layouten som Du anser ha betydelse.
Kontorsmöblering

Hur nöjd är Du med komforten på din arbetsplats (arbetsstol, bord, dator, annan utrustning)?
Där 3 innehåller "Mycket nöjd" och -3 innehåller "mycket missnöjd"

- 3
- 2
- 1
- 0
- -1
- -2
- -3

Hur nöjd är Du med möjligheten att anpassa möblemangen på Din arbetsplats till Dina behov?
Där 3 innehåller "Mycket nöjd" och -3 innehåller "mycket missnöjd"

- 3
- 2
- 1
- 0
- -1
- -2
- -3

Hur nöjd är Du med färgerna och materialen hos golv, möbler och ytor
Där 3 innehåller "Mycket nöjd" och -3 innehåller "mycket missnöjd"

- 3
- 2
- 1
- 0
- -1
- -2
- -3

Utgör Din kontorutrustning och –möblemang ett stöd eller ett hinder i Ditt arbete?
Där 3 innehåller "Utgör ett stöd i mitt arbete" och -3 innehåller "Utgör ett hinder i mitt arbete"

- 3
- 2
- 1
- 0
- -1
- -2
- -3
Vg beskriv andra aspekter hos kontorsutrustningen och -möblemanget som Du anser ha betydelse.

Termisk komfort

Vilket av det följande har Du möjlighet att själv ställa in och/eller styra på Din arbetsplats? (Kryssa i allt som stämmer in)
  o Rullgardin, persienn eller annan typ av solskydd
  o Öppningsbart(a) fönster
  o Termostat
  o Bärbar/mobil värmekålla
  o Fast installerad värmekålla
  o Luftkonditionering
  o Bärbar fläkt
  o Takfläkt
  o Inställningsbart ventilationsdon i vägg eller tak
  o Inställningsbart ventilationsdon i golv
  o Innardörr
  o Ytterdörr
  o Inget av de ovan nämnda
  o Annat:

Hur nöjd är Du med rumstemperaturen på Din arbetsplats?
Där 3 innebär ”Mycket nöjd” och -3 innebär ”mycket missnöjd”
  o 3
  o 2
  o 1
  o 0
  o -1
  o -2
  o -3

Om du är missnöjd med rumstemperaturen på Din arbetsplats, vilket av det följande bidrar till Ditt missnöje:
  Vid varmt/mycket varmt väder är rumstemperaturen på min arbetsplats (kryssa i det som stämmer in bäst)
    o Alltid för hög
    o Ofta för hög
    o Ibland för låg
    o Ofta för låg
    o Alltid för låg

  Vid svalt/kallt väder är rumstemperaturen på min arbetsplats (kryssa i det som stämmer in bäst)
    o Alltid för hög
    o Ofta för hög
    o Ibland för låg
    o Ofta för låg
    o Alltid för låg
När är detta oftast ett problem? (kryssa i allt som stammer in)
- På morgonen (före 11)
- Mitt på dagen (11-14)
- På eftermiddagen (14-17)
- På kvällen (efter 17)
- Under helger/helgdagar
- Montag morgon
- Vid ingen särskild tid
- Alltid
- Annat:

a. Hur skulle Du bäst beskriva källan till detta obehag? (kryssa i allt som stammer in):
- Alldeles för fuktigt
- Alldeles för torrt
- För intensiva luftrörelser
- För svaga luftrörelser
- Solinstrålning
- Värme från kontorsapparater
- Fönsterdrag
- Drag från ventilationsdon(en)
- Min arbetsplats är varmare/kallare än andra zoner
- Termostaten är ej tillgänglig
- Termostaten justeras av andra personer
- Klädkoden är inte flexibel
- Värme-/kylsystemet påverkas ej tillräckligt snabbt av termostaten
- Varma/kalla omgivande ytor (golv, tak, väggar eller fönster)

Utgör den termiska komforten på Din arbetsplats sammanlagt ett stöd eller ett hinder i Ditt arbete?
Där 3 innebär “Utgör ett stöd i mitt arbete” och -3 innebär “Utgör ett hinder i mitt arbete”
- 3
- 2
- 1
- 0
- -1
- -2
- -3
Luftkvalitet

Hur nöjd är Du med luftkvaliteten på Din arbetsplats (t.ex. odörer, stillstående/unken luft, luftrenhet)?
Där 3 innebär "Mycket nöjd" och -3 innebär "mycket missnöjd"
  o 3
  o 2
  o 1
  o 0
  o -1
  o -2
  o -3

Utgör luftkvaliteten på Din arbetsplats sammanlagt ett stöd eller ett hinder i Ditt arbete?

Där 3 innebär "Utgör ett stöd i mitt arbete" och -3 innebär "Utgör ett hinder i mitt arbete"
  o 3
  o 2
  o 1
  o 0
  o -1
  o -2
  o -3
Belysning

Vilken av de följande reglenheterna kan Du styra på Din arbetsplats? (kryssa i allt som stämmer in)
- Strömbrytare (belysning)
- Dimmer
- Rullgardin, persienn eller annat solskydd
- Desk (task) light
- None of the above
- Other:

Hur nöjd är Du med belysningsstyrkan på Din arbetsplats?
Där 3 innebär "Mycket nöjd" och -3 innebär "mycket missnöjd"
- 3
- 2
- 1
- 0
- -1
- -2
- -3

Hur nöjd är Du med belysningskvaliteten (t.ex med avseende på bländningseffekter, reflexer, kontrast)?
Där 3 innebär "Mycket nöjd" och -3 innebär "mycket missnöjd"
- 3
- 2
- 1
- 0
- -1
- -2
- -3

Utgör belysningskvaliteten på Din arbetsplats sammanlagt ett stöd eller ett hinder i Ditt arbete?
Där 3 innebär "Utgör ett stöd i mitt arbete" och -3 innebär "Utgör ett hinder i mitt arbete"
- 3
- 2
- 1
- 0
- -1
- -2
- -3
Akustisk kvalitet

Hur nöjd är Du med ljudnivån på Din arbetsplats?
Där 3 innebär "mycket nöjd" och -3 innebär "mycket missnöjd"
- 3
- 2
- 1
- 0
- -1
- -2
- -3

Hur nöjd är Du med lyhördheten på Din arbetsplats (respektive möjligheten att leda samtal utan att bli avlyssnad eller störd av omgivande samtal)?
Där 3 innebär "mycket nöjd" och -3 innebär "mycket missnöjd"
- 3
- 2
- 1
- 0
- -1
- -2
- -3

Utgör den akustiska kvaliteten på Din arbetsplats sammanlagt ett stöd eller ett hinder i Ditt arbete?
Där 3 innebär "Utgör ett stöd i mitt arbete" och -3 innebär "Utgör ett hinder i mitt arbete"
- 3
- 2
- 1
- 0
- -1
- -2
- -3
Byggnadens egenskaper

Hur energieffektiv tror Du att Din byggnad är?
Där 3 innebär "Mycket energieffektiv" och -3 innebär "Inte alls energieffektiv"
  o  3
  o  2
  o  1
  o  0
  o  -1
  o  -2
  o  -3

Om kontoret är utrustat med termostater, hur nöjd är Du med dessas funktion:
Där 3 innebär "Mycket nöjd" och -3 innebär "mycket missnöjd"
  o  3
  o  2
  o  1
  o  0
  o  -1
  o  -2
  o  -3
Kommentar:

Hur nöjd är Du med utrustningen/reglage som styr den artificiella belysningen?
Där 3 innebär "Mycket nöjd" och -3 innebär "mycket missnöjd"
  o  3
  o  2
  o  1
  o  0
  o  -1
  o  -2
  o  -3
Kommentar:

Om kontoret är utrustat med reglage för dagsljusstyrning, hur nöjd är Du med funktionen?
Där 3 innebär "Mycket nöjd" och -3 innebär "mycket missnöjd"
  o  3
  o  2
  o  1
  o  0
  o  -1
  o  -2
  o  -3
Kommentar:
Om Ditt kontor är utrustat med närvarostyrd belysning, hur nöjd är Du med denna funktion?
Där 3 innebär ”Mycket nöjd” och -3 innebär ”mycket missnöjd”
- 3
- 2
- 1
- 0
- -1
- -2
- -3
Kommentar:

Om Ditt kontor är utrustat med persienner hur nöjd är Du med deras funktion?
Där 3 innebär ”Mycket nöjd” och -3 innebär ”mycket missnöjd”
- 3
- 2
- 1
- 0
- -1
- -2
- -3
Kommentar:

Om Ditt kontor är utrustat med rullgardiner hur nöjd är Du med deras funktion?
Där 3 innebär ”Mycket nöjd” och -3 innebär ”mycket missnöjd”
- 3
- 2
- 1
- 0
- -1
- -2
- -3
Kommentar:

Om Ditt kontor är utrustat med extern solavskärmning hur nöjd är Du med dess funktion?
Där 3 innebär ”Mycket nöjd” och -3 innebär ”mycket missnöjd”
- 3
- 2
- 1
- 0
- -1
- -2
- -3
Kommentar:
Hur väl informerad känner Du Dig om användningen av den ovan nämnda utrustningen?
Där 3 innebär ”Välinformerad” och -3 innebär ”Dåligt informerad”
- 3
- 2
- 1
- 0
- -1
- -2
- -3
Kommentar:

Vg beskriv andra aspekter avseende funktionen/användningen av den ovan nämnda utrustningen som Du upplever som betydelsefull.
Generella kommentarer

Hur nöjd är Du sammanlagt med Din personliga kontorsplats?
Där 3 innebär "Mycket nöjd" och -3 innebär "mycket missnöjd"

- 3
- 2
- 1
- 0
- -1
- -2
- -3

Vg uppskatta i vilken utsträckning kvaliteten på inomhusmiljön i denna byggnad (termisk komfort, luftkvalitet, belysningskvalitet, akustisk kvalitet) höjer eller sänker Din produktivitet:
Där 20% innebär "Höjs avsevärt" och -20% innebär "Sänks avsevärt"

- 20%
- 10%
- 5%
- 0%
- -5%
- -10%
- -20%

Hur nöjd är Du sammanlagt med byggnaden?
Där 3 innebär "Mycket nöjd" och -3 innebär "mycket missnöjd"

- 3
- 2
- 1
- 0
- -1
- -2
- -3

Andra kommentarer eller rekommendationer avseende Din personliga arbetsplats eller byggnaden som helhet:
Appendix B.

Field Studies in Thermal Comfort
<table>
<thead>
<tr>
<th>Study Title</th>
<th>Location</th>
<th>Type of building</th>
<th>Type of study</th>
<th>Objectives</th>
<th>Measurements</th>
<th>Questionnaire</th>
<th>Statistical Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>A comparison of occupant comfort and satisfaction between a green building and a conventional building</td>
<td>Albury Wodonga, Australia</td>
<td>Academic office buildings</td>
<td>NA</td>
<td>To generally study the effect of the type of building on occupant satisfaction (NV vs. MV)</td>
<td>-Background information (room number, age, type of work, gender, weeks away) -Room perception (beautiful, ugly, relaxed, tense, colourful, dull, too bright, too dim, glare, no glare, draughty, still, too hot, too cold, too noisy, too quiet, too dry, too humid, too sunny, not enough sun, poor working environment, excellent working environment) -Comfort inside the room (how often were you too cold/hot, availability of window and time of day that sunshine enters, oparable window and how often do you open it, availability of blinds and how often do you use them, availability of fan and how often do you use it, availability of lighting and how often do you turn it on)</td>
<td>Adaptive strategies</td>
<td>Subjects who did not answer the survey were removed from the studied population. Hotelling's T2 test was used to find correlations between the type of building and occupant satisfaction and comfort. A regression model with perceived temperature as the outcome was developed as a function of all aspects of the survey. AIC stepwise elimination was used. A chi-squared test was done to see if there is an association between perceived comfort and satisfaction. A chi-squared test was performed to test if there was an association between building type and perceived satisfaction. Population size: 40 (NV) and 53 (MV).</td>
</tr>
<tr>
<td>A data-driven method to describe the personalized dynamic thermal comfort in ordinary office environment: From model to application</td>
<td>Beijing</td>
<td>Academic office building</td>
<td>Longitudinal (November 2009–January 2010)</td>
<td>Constructing a data-driven model for the personalized thermal vote model. PIV=m0+m1x1+...PIM=m0+m1x1+...m3(R+C)</td>
<td>In other words, using the occupant’s votes to find the values of m0,m1,m2 and m3 for that specific occupant.</td>
<td>-Air temperature sensor -Mean radiant temperature sensor -Air speed sensor -Humidity sensor</td>
<td>-Every third of the data is used as validation data. The model is updated using the training subset of the data. -The mean square error and bias is calculated between the predicted values using the validation dataset and the actual votes.</td>
</tr>
<tr>
<td>Study Title</td>
<td>Location</td>
<td>Type of building</td>
<td>Type of study</td>
<td>Objectives</td>
<td>Measurements</td>
<td>Questionnaire</td>
<td>Statistical Analysis</td>
</tr>
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<td>-------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>A field study of thermal environments and comfort in office buildings</td>
<td>San Francisco</td>
<td>Office buildings</td>
<td>Longitudinal (over a period of one week, once in summer and once in winter)</td>
<td>Developing instrumentation for the measurement of indoor thermal environment</td>
<td>Mobile:&lt;br&gt;- Air temperature&lt;br&gt;- Globe temperature&lt;br&gt;- Air velocity&lt;br&gt;- Humidity&lt;br&gt;- Radiant temperature&lt;br&gt;- Asymmetry&lt;br&gt;- Surface temperature&lt;br&gt;- Illumination&lt;br&gt;- Stationary&lt;br&gt;- Mobile&lt;br&gt;- Air velocity&lt;br&gt;- Humidity&lt;br&gt;- Radiant temperature&lt;br&gt;- Asymmetry&lt;br&gt;- Surface temperature&lt;br&gt;- Illumination&lt;br&gt;- Stationary</td>
<td>Thermal assessment [thermal sensation, McKity's scale]&lt;br&gt;- Comfort in respect to airflow, lighting and general comfort&lt;br&gt;- Clothing and activity checklist&lt;br&gt;- Background information</td>
<td>Multivariate regression with the thermal sensation vote as the outcome and the personal and background factors as covariates&lt;br&gt;Gender difference tests&lt;br&gt;Regression model with the neutral temperature as the outcome and the mean indoor temperature as the predictor&lt;br&gt;Regression model with the thermal sensation as the outcome and the effective temperature as the covariate</td>
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<tr>
<td>A preliminary evaluation of two strategies for raising indoor air temperature setpoints in office buildings</td>
<td>Melbourne, Sydney, North Sydney and Brisbane, Australia</td>
<td>Office buildings</td>
<td>Longitudinal [Nov. 2, 2009 - March 31, 2010]</td>
<td>Increase occupant comfort&lt;br&gt;- Decrease greenhouse gas emissions&lt;br&gt;- Increase operating income</td>
<td>-Energy meters&lt;br&gt;- Outdoor temperature&lt;br&gt;- Outdoor relative humidity</td>
<td>NA</td>
<td>-Regression model with energy as the outcome and outdoor temperature and humidity as the predictors</td>
</tr>
<tr>
<td>A tale of two populations: Thermal comfort in air-conditioned and naturally ventilated offices in Thailand</td>
<td>Bangkok</td>
<td>Office buildings</td>
<td>Right-rank evaluation</td>
<td>Investigate if a new thermal standard is required for occupants accustomed to more temperate conditions</td>
<td>Dry bulb temperature&lt;br&gt;- Relative humidity&lt;br&gt;- Globe temperature&lt;br&gt;- Air velocity</td>
<td>-Subjective ratings [thermal sensation, McKity's scale, humidity scale, Airflow scale]&lt;br&gt;- Recent food or beverage intake&lt;br&gt;- Clothing checklist&lt;br&gt;- Demographic information</td>
<td>Population size: 1146 (800 during the hot season and the rest during the wet season)&lt;br&gt;Two thirds of the sample were from the NV buildings and the rest from the NY buildings&lt;br&gt;Univariate regression models with the thermal sensation as the outcome and the CI or SET as the predictor</td>
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<td>Study Title</td>
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<td>A theoretical adaptive model of thermal comfort—Adaptive Predicted Mean</td>
<td>Chongqing, China</td>
<td>Academic buildings (mainly</td>
<td>Longitudinal</td>
<td>- A black-box, data-driven approach into thermal comfort (aPMV)</td>
<td>- indoor air temperature</td>
<td>- Background information (gender, age...)</td>
<td>- Linear regression model to relate aPMV to PMV</td>
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<td>Vote (aPMV)</td>
<td>mainly lecture</td>
<td>rooms)</td>
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<td>- outdoor air temperature</td>
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<td>- humidity</td>
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<tr>
<td>Adaptive analysis of thermal comfort in university classrooms:</td>
<td>Perugia, Terni,</td>
<td>Academic buildings</td>
<td>Right now</td>
<td>- Forced dry bulb temperature</td>
<td>Forced air dry bulb temperature</td>
<td>Personal data (age, sex...)</td>
<td>- Linear regression model to relate aPMV to PMV</td>
</tr>
<tr>
<td>Correlation between experimental data and mathematical models</td>
<td>and Pavia, Italy</td>
<td>(classrooms)</td>
<td>evaluation</td>
<td>- Forced air wet bulb temperature</td>
<td>Forced air wet bulb temperature</td>
<td>Thermal aspects (judgement about tolerability of</td>
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<td>- Dew point temperature</td>
<td>Dew point</td>
<td>thermal environment, air movement,</td>
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<td>- Globe mean temperature</td>
<td>Globe mean temperature</td>
<td>temperature difference between head and ankle,</td>
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<td>- Mean radiation temperature</td>
<td>Mean radiation</td>
<td>activity performed in the last 10, 20, 30 and</td>
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<td>- Plane asymmetry</td>
<td>Plane asymmetry</td>
<td>60 min, eventuality preference for different</td>
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<td>- Radiant temperature</td>
<td>Radiant temperature</td>
<td>conditions)</td>
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<td>- Mean air velocity</td>
<td>Mean air velocity</td>
<td>Individual microclimatic control interaction</td>
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<td>- Floor surface temperature</td>
<td>Floor surface temperature</td>
<td>possibility with environmental</td>
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<td>- Temperature</td>
<td>Temperature</td>
<td>microclimates correlations</td>
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<td>through doors and windows opening, building</td>
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<td>services' regulations, and satisfaction</td>
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<td>classroom plan</td>
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<td>Adaptive comfort temperature model of air-conditioned building in Hong Kong</td>
<td>Humid, sub-tropical Hong Kong</td>
<td>Office buildings</td>
<td>Cross-sectional- 29 offices in the summer and 26 offices in the winter</td>
<td>Developing new notions about adaptive comfort temperature in humid, sub-tropical Hong Kong and correlating the indoor comfort temperature to the outdoor temperature</td>
<td>- Air temperature sensor-Globe temperature-Air velocity (V; -0.35+0.02*To); Relative humidity</td>
<td>- Thermal sensation-Clothing checklist (Clo=1.76+0.04*Tn)-Activity level</td>
<td>Univariate regression models between different parameters- Tn=18.303+0.158<em>To [outdoor temperature]- Tn=0.3835+0.9922</em>Tt [operative temperature]- Tn=0.4342+1.0161*Tf</td>
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<td>Air quality and thermal comfort in office buildings: Results of a large indoor environmental quality survey</td>
<td>USA, Canada, Finland</td>
<td>Office buildings</td>
<td>Right now evaluation</td>
<td>Presenting results of surveys</td>
<td>NA</td>
<td>-CBE occupant EQ survey</td>
<td>Exploratory data analysis</td>
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<tr>
<td>An investigation into thermal comfort in the summer season of Ghadames, Libya</td>
<td>Ghadames, Libya</td>
<td>Residential buildings</td>
<td>Right now evaluation</td>
<td>Verifying the use of PMV/PPD in hot climates</td>
<td>-Air temperature</td>
<td>-Clothing</td>
<td>-Exploratory data analysis</td>
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<td>-Air velocity</td>
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<td>-Globe temperature</td>
<td>-Background and personal information</td>
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<td>-Social interaction</td>
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<td>-Thermal environment and personal influences</td>
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<td>-Occupants' perceptions of the environmental conditions in the whole building</td>
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<td>-Occupants' thermal comfort</td>
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<td>-People's general feeling and personal wellbeing</td>
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<tr>
<td>Comfort temperatures for naturally ventilated buildings in Hong Kong</td>
<td>Hong Kong</td>
<td>NA</td>
<td>Right now evaluation</td>
<td>Studying the results of ASHRAE project RP-884, specifically those from studies done in countries with a climate similar to HK</td>
<td>NA</td>
<td>NA</td>
<td>Univariate regression model with thermal sensation as the outcome, and average indoor temperature as the predictor. In=16.05+0.333*T0</td>
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<td>Study Title</td>
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<td>Comparison of thermal comfort algorithms in naturally ventilated office buildings</td>
<td>near Lyon, France</td>
<td>Office buildings</td>
<td>Right-now evaluation</td>
<td>Evaluate different algorithms from both static and adaptive approaches in naturally ventilated buildings</td>
<td>-Air temperature</td>
<td>-Thermal sensation</td>
<td>Univariate regression model with average thermal</td>
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<td>-Operative temperature</td>
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<td>-Relative Humidity</td>
<td>-Air movement acceptability</td>
<td>and operative temperature as the predictor</td>
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<td>-CO2</td>
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<td>Warm Season</td>
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<td>-Air velocity</td>
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<td>-Outdoor air temperature</td>
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<td>-Outdoor relative humidity</td>
<td>-Lighting quality</td>
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<td>-Wind speed and direction</td>
<td>-Overall IEQ</td>
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<td>-Solar radiation</td>
<td>-Adaptive device use (window, local fan, shading device...)</td>
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<tr>
<td>Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251</td>
<td>France, Greece, Portugal, Sweden and the UK</td>
<td>Office buildings</td>
<td>Longitudinal</td>
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<td>-Air temperature</td>
<td>Thermal sensation scale</td>
<td>Univariate regression model with the comfort</td>
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<td>-Globe Temperature</td>
<td>Overall comfort</td>
<td>temperature as the outcome, and the running mean</td>
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<td>-Relative humidity</td>
<td>Perceived air quality</td>
<td>outdoor temperature as the predictor</td>
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<td>-Air velocity</td>
<td>Perceived productivity</td>
<td>l Tottenham=0.33*Top-18.8</td>
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<td>-Sound pressure level</td>
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<td>-Illuminance on the working place</td>
<td>Clothing</td>
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<td>-CO2 concentration</td>
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<td>Effects of artificially induced heat acclimatization on subjects' thermal and air movement preferences</td>
<td>Tokyo</td>
<td>Climate chamber</td>
<td>Right-now evaluation</td>
<td>Investigate the effects of short-term physiological acclimatization on subjects' perception of thermal and air movement preferences</td>
<td>-Air temperature</td>
<td>-Clothing</td>
<td>ANOVA and t-test to identify differences between two groups</td>
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<td>-Relative Humidity</td>
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<td>-Daily exposure to air conditioning</td>
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<td>-Air movement assessment</td>
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<tr>
<td>Energy use and thermal comfort in a rammed earth office building</td>
<td>Albury, Wodonga,</td>
<td>Office building</td>
<td>Longitudinal</td>
<td>Fill the information gap between design and reality of occupancy and operation</td>
<td>Globe temperature, Wet bulb temperature, Wall surface temperature, Fan rotation, Window status</td>
<td>-Background information (age, sex, type of work, and amount of time spent on leave over the summer period) -Seven point scale questions about perception of the room with respect to aesthetics and comfort -Information on the thermal adaptive strategies of respondents (use of fans, lights, blinds, and windows)</td>
<td>Exploratory data analysis</td>
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<tr>
<td>Experimental evaluation of the thermal comfort in an occupied office under transient conditions using a hydronic radiant ceiling cooling system</td>
<td>Cordoba, Spain</td>
<td>Thermal chamber</td>
<td>Period of 22.5h and 28.5h</td>
<td>Assess the changes in thermal comfort indices (PMV/PPD) under transient conditions in an office</td>
<td>Surface temperature (walls, floor, roof), Air temperature, Globe temperature, Air velocity, Relative humidity</td>
<td>NA</td>
<td>Exploratory data analysis</td>
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<tr>
<td>Extension of the PMV model to non-air-conditioned buildings in warm climates</td>
<td>Bangkok, Thailand</td>
<td>Office buildings</td>
<td>NA</td>
<td>Explain the discrepancies in the PMV model by correcting for metabolic rate and including an expectancy factor</td>
<td>NA</td>
<td>NA</td>
<td>Exploratory data analysis</td>
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</table>
| Field experiment on occupant comfort and office thermal environments in a hot-humid climate | Townsville, Australia | Office buildings | Right-now evaluation | - Develop a database of the thermal environments and subjective responses of occupants in existing office buildings in a hot-humid climate  
- Determine the neutral and preferred thermal conditions found to be thermally acceptable by the occupants  
- Assess the effectiveness of insulators like ET*, SET DISC*, and PMV/PPD  
- Investigate the influence of gender and clothing | - Outdoor air temperature  
- Outdoor relative humidity  
- Indoor air temperature  
- Indoor dew point temperature  
- Globe temperature  
- Radiant asymmetry  
- Air velocity  
- Illuminance | Online  
- Seven point scale questions on: Air movement, thermal acceptability, temperature preferences, and thermal sensation  
- Clothing checklist  
- Activity checklist | Probit analysis  
- Exploratory data analysis  
- Linear regression  
- MTTS = 0.522* to 12.67 (operative temperature) |

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<th>Questionnaire</th>
<th>Statistical Analysis</th>
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</table>
| Field experiments on thermal comfort in campus classrooms in Taiwan | Taiwan            | Campus classrooms | Right-now evaluation | The purpose of this study is to find the range of thermal acceptability, neutral temperature and preferred temperature in hot-humid classrooms | - Air temperature  
- Relative humidity  
- Air velocity  
- Globe temperature | Demographic information  
- Age, gender, weight, height, country of residence, usage of home air conditioning system  
- Seven point scale thermal sensation question  
- Thermal preference  
- Thermal acceptability  
- Other aspects (acoustics, air quality, lighting, desk, seating comfort, schoolwork satisfaction, health status)  
- Clothing checklist | T test  
- Univariate regression models  
- Exploratory data analysis  
- Probit analysis |
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<th>Statistical Analysis</th>
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</table>
| Field study of a thermal environment and adaptive model in Shanghai      | Shanghai, China         | Residential buildings | Right-now evaluation | - Develop a database of the thermal environments and subjective responses of occupants in Shanghai with long-term thermal comfort surveys  
- Determine the neutral temperature for occupants and study the relationship between neutral temperature and relative humidity in existing residential buildings  
- Provide an adaptive model for setting comfortable indoor temperatures for residential buildings in Shanghai | - Air temperature  
- Relative humidity  
- Air velocity  
- Globe temperature | Background parameters  
- Demographic characteristics  
- Health status | Univariate regression models  
- Exploratory data analysis |
| Field study on occupants’ thermal comfort and residential thermal environment in a hot humid climate of China | Changsha, Guangzhou, and Shenzhen, China | Residential buildings | Right-now evaluation | To find differences between calculated and perceived thermal comfort (PMV/PPD)  
To compare results to other studies done in different climate zones | - Air temperature  
- Relative humidity  
- Air velocity | Demographic information  
- Name, age, sex, number of years living in current dwelling  
- Clothing checklist  
- Activity level checklist  
- Thermal sensation (7-point)  
- Thermal preference (3-point)  
- Thermal acceptability  
- Methods of personal control over the thermal environment | Exploratory data analysis with the mean thermal sensation as the outcome and operative temperature as the predictor:  
$$TSV = 0.409 T + 11.71$$  
$$R^2 = 0.8927$$ |
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<tbody>
<tr>
<td>Green occupants for green buildings: The missing link?</td>
<td>Sydney, Australia</td>
<td>Office buildings</td>
<td>Right-now evaluation</td>
<td>- Finding a relationship between occupants’ environmental attitudes and the forgiveness factor</td>
<td>- Air temperature</td>
<td>BUS POE</td>
<td>- Exploratory data analysis</td>
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<td>- Globe temperature</td>
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<td>- T tests</td>
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<td>- Outdoor air temperature</td>
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<td>- Univariate regression with NEP as the predictor, and the forgiveness factor as the outcome</td>
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<td>FF = 0.0472 * NEP + 0.909</td>
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<td>R2 = 0.89</td>
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<tr>
<td>Indoor climate and thermal comfort in high-rise public housing in an equatorial climate: A field study in Singapore</td>
<td>Singapore</td>
<td>Residential buildings</td>
<td>Right-now evaluation</td>
<td>Measure microclimatic conditions inside a sample of public housing flats in Singapore’s new towns</td>
<td>Indoor air dry bulb temperature</td>
<td>NEP (The New Ecological Paradigm)</td>
<td>5 point response questions on the occupant’s environmental concern</td>
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<td>Measure subjective thermal sensation</td>
<td>Indoor air wet bulb temperature</td>
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<td>Come up with models for Singapore</td>
<td>Globe temperature</td>
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<td>Air velocity</td>
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<td>Questionnaire</td>
<td>Statistical Analysis</td>
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<tr>
<td>Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan</td>
<td>Taichung, Taiwan</td>
<td>Schools</td>
<td>Longitudinal (September 2005–January 2006)</td>
<td>To understand the adaptive model through a long-term study in schools in Taiwan</td>
<td>Air temperature, Relative humidity, Globe temperature, Air velocity</td>
<td>Background information (age, sex, height, weight), Thermal sensation, Thermal preference, Thermal acceptability, Clothing checklist, Activity checklist</td>
<td>Multivariate linear regression with MSV as the outcome, and operative temperature as the predictor: For cool conditions MSV=0.17<em>Top-1.94, R2=0.93 For mild conditions MSV=0.01</em>Top-0.3, R2=0.04 For warm conditions MSV=0.035*Top-10.27, R2=0.89</td>
</tr>
<tr>
<td>Linking occupants' thermal perception and building thermal performance in naturally ventilated school buildings</td>
<td>Taichung, Taiwan</td>
<td>Schools</td>
<td>Longitudinal (September 2005–February 2006)</td>
<td>Investigate the effects of the building envelope energy regulations on thermal comfort level in naturally ventilated classrooms in primary and secondary schools in Taiwan</td>
<td>Air temperature, Relative humidity, Globe temperature, Air velocity</td>
<td>Background information (age, sex, height, weight), Thermal sensation, Thermal preference, Thermal acceptability, Clothing checklist, Activity checklist</td>
<td>Multivariate regression model with the neutral temperature as the outcome, and the mean monthly outdoor temperature as the predictor: t=2.23, p=0.025, R2=0.523</td>
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<tr>
<td>Patient thermal comfort requirement for hospital environments in Taiwan</td>
<td>Taiwan</td>
<td>Hospital</td>
<td>Longitudinal (January 2005–June 2005)</td>
<td>Examine the comfort criteria of ASHRAE 55 for their applicability in hospital environments</td>
<td>Air temperature, Relative humidity, Globe temperature, Air velocity</td>
<td>Demographic information (age, gender, length of hospitalization), Physical strength checklist, Thermal sensation, Thermal preference, Thermal acceptability</td>
<td>Exploratory data analysis, Probit analysis</td>
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<tr>
<td>Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design</td>
<td>Australia, Canada, Finland, Italy and USA</td>
<td>Office buildings</td>
<td>Right-now evaluation</td>
<td>Examine relationship between subjectively evaluated indoor environmental parameters and building features mostly affecting occupants' satisfaction in US office buildings</td>
<td>NA</td>
<td>CBE survey</td>
<td>Proportional odds ordinal logistic regression with satisfaction as the outcome and indoor environmental quality, and building features as predictors. Wald tests. Spearman rank correlation</td>
</tr>
<tr>
<td>Spot monitoring: Thermal comfort evaluation in 25 office buildings in winter</td>
<td>Berlin, Braunschweig, Hamburg, Hannover, Gelsenkirchen, Heerhugowaard, Munich, Mannheim, Osnabrück and Wolfsburg, Germany</td>
<td>Office buildings</td>
<td>Right-now evaluation</td>
<td>Surveying 25 buildings that are not older than 10 years after being built or renovated, and are affected by central European climate</td>
<td>Indoor air temperature</td>
<td>-Thermal sensation -Clothing checklist -Metabolic rate (Activity and eating checklist) -Chances to control the thermal environment</td>
<td>Univariate regression model with thermal sensation as the outcome, and the operative temperature as the predictor: TSV=0.247, T=5, 3, 7. Univariate regression model with neutral temperature as the outcome and the operative temperature as the predictor: T=0.82, T=3.85</td>
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<td>The potential for increasing cooling set-points in air-conditioned offices in the UK</td>
<td>London</td>
<td>Office building</td>
<td>Longitudinal</td>
<td>Investigate the potential of increasing the set-point in office buildings in the UK during summer</td>
<td>Indoor air temperature, Indoor relative humidity, Operative temperature at the warmest spot in each floor, Outdoor humidity</td>
<td>BUS, NEP</td>
<td>Exploratory data analysis - Univariate regression model with comfort temperature as the outcome, and the outdoor temperature ranging mean as the predictor. Upper margin: Icom=0.09<em>Tm - 24.6 Lower margin: Icom=0.09</em>Tm + 20.6</td>
</tr>
<tr>
<td>Thermal acceptability assessment in buildings located in hot and humid regions in Brazil</td>
<td>Curitiba, Curitiba, and Campo Grande, Brazil</td>
<td>Office buildings</td>
<td>Right-now evaluation</td>
<td>Perform an analysis on thermal acceptability in naturally ventilated and air-conditioned buildings located in hot, humid climates in Brazil</td>
<td>Indoor air temperature, Indoor relative humidity, Globe temperature, Air velocity, Outdoor temperature, Outdoor relative humidity</td>
<td>Thermal acceptability: Background information (age, height, weight, and clothing)</td>
<td>Exploratory data analysis - Univariate regression models</td>
</tr>
<tr>
<td>Thermal comfort and behavioural strategies in office buildings located in a hot-and climate</td>
<td>Kalgoorlie, Boulder, Australia</td>
<td>Office buildings</td>
<td>Right-now evaluation</td>
<td>Present a case study - Focus on the effects of indoor climates on thermal perceptions and adaptive behaviour of office workers.</td>
<td>Indoor air temperature, Indoor air dew-point temperature, Indoor relative humidity, Globe temperature, Radiant Asymmetry, Air velocity</td>
<td>-Demographic information, Work area satisfaction, Personal environment control, Job satisfaction, Health, Thermal sensation, Thermal preference, Clothing checklist, Activity checklist, Air movement perception</td>
<td>Exploratory data analysis - Univariate regression models</td>
</tr>
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</table>
| Thermal comfort and workplace occupant satisfaction: Results of field studies in German low energy office buildings | Karlsruhe, Germany | Office buildings | Longitudinal (four weeks, July 2005) | - Investigate thermal comfort in energy efficient buildings  
- Compare calculated and subjective thermal comfort indices in a NV building  
- Compare the results with other adaptive models | Indoor air temperature, indoor relative humidity, Globe temperature, Air velocity | - Demographic information  
- Thermal sensation  
- Clothing checklist  
- Activity checklist  
- Overall satisfaction with the indoor climate  
- Thermal preference | Chi-square tests, Exploratory data analysis |
| Thermal comfort evaluation of naturally ventilated public housing in Singapore | Singapore     | Residential buildings | Longitudinal  | - Investigate the occupants' perception of the degree of comfort  
- Examine the adaptive behavior of the residents on the usage of available climatic controls in modifying the indoor thermal environment  
- NA | - Thermal sensation  
- Thermal preference  
- Air movement acceptability  
- Adaptive behavior questions | - Exploratory data analysis  
- Univariate regression models  
- Thermal Pref: 0.5605  
- TS: 0.18 |
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<tr>
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</thead>
</table>
| Thermal comfort in naturally ventilated and air-conditioned buildings in humid subtropical climate zone in China | Changsha, Wuhan, Shanghai, Beijing, and Nanjing, China | Various          | Right-now evaluation | Investigate the thermal comfort perception and preference of the occupants living in the humid, subtropical climate zone in China. Determine the neutral temperature and acceptable temperature range for both naturally ventilated and air-conditioned buildings and compare the results with previous studies. Investigate the influences of air velocity on occupant thermal sensation and analyze the quantitative relationship between indoor air velocity and perceived draught sensation. Check if the indoor set-point temperature of 26°C or even higher is appropriate for occupants. | -Air temperature  
-Relative humidity  
-Air velocity  
-Globe temperature |
| -Demographic information  
-age, gender, clothing, etc.  
-usage of AC  
-Thermal sensation  
-Thermal preference  
-Thermal acceptability  
-Use of control actions |
| Statistical Analysis                                                     | Exploratory data analysis  
-Univariate regression models |
|                                                                           | N=2  
-LSR=0.25  
-p<0.05  
-R2=0.47  
-AC  
-LSR=0.32  
-p<0.10  
-R2=0.57  
-Probit analysis |

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</table>
| Thermal comfort in office buildings: Two case studies commented           | Brussels, Leuven, Belgium | Office buildings | Right-now evaluation | Investigate discrepancies between calculated and perceived thermal comfort. Find an explanation for the discrepancies. | -Air temperature  
-Relative humidity  
-Air velocity  
-Globe temperature  
-Global thermal comfort  
-Local thermal comfort (draught, temperature feeling at the lower legs and feet, temperature feeling at the head, temperature feeling at the hands)  
-Health issues as a result of the indoor environment |
| Statistical Analysis                                                     | Exploratory data analysis  
-Univariate regression models |
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</thead>
<tbody>
<tr>
<td>Thermal comfort in sub-Saharan Africa: Field study report in Jos-Nigeria</td>
<td>Jos, Nigeria</td>
<td>Various</td>
<td>Right-now evaluation</td>
<td>Obtaining a broad understanding of occupants’ thermal comfort sensations within buildings as a contributory factor to energy services’ demand and use.</td>
<td>Air temperature, Relative humidity, Air velocity, CO2 levels, Illuminance, Surface temperature</td>
<td>Demographic information (age, gender), Clothing checklist, Activity checklist, Thermal sensation, Thermal preference</td>
<td>Exploratory data analysis</td>
</tr>
<tr>
<td>Thermal comfort investigation of naturally ventilated classrooms in a subtropical region</td>
<td>Changsha, China</td>
<td>Classrooms</td>
<td>Right-now evaluation</td>
<td>Generate a general profile of the thermal environment in naturally ventilated classrooms in Hunan Province, China. Investigate occupants’ perception of the level of thermal comfort in classrooms. Find out the characteristics of thermal conditions in classrooms and students’ thermal perceptions in comparison with previous studies and relevant standards. Compare data with thermal sensation models.</td>
<td>Air temperature, Relative humidity, Air velocity, Globe temperature</td>
<td>Demographic information (age, gender), Clothing checklist, Activity checklist, Thermal sensation, Thermal preference, Thermal preference, Relative humidity sensation, Velocity sensation</td>
<td>Exploratory data analysis, Univariate regression models, Probit analysis</td>
</tr>
</tbody>
</table>